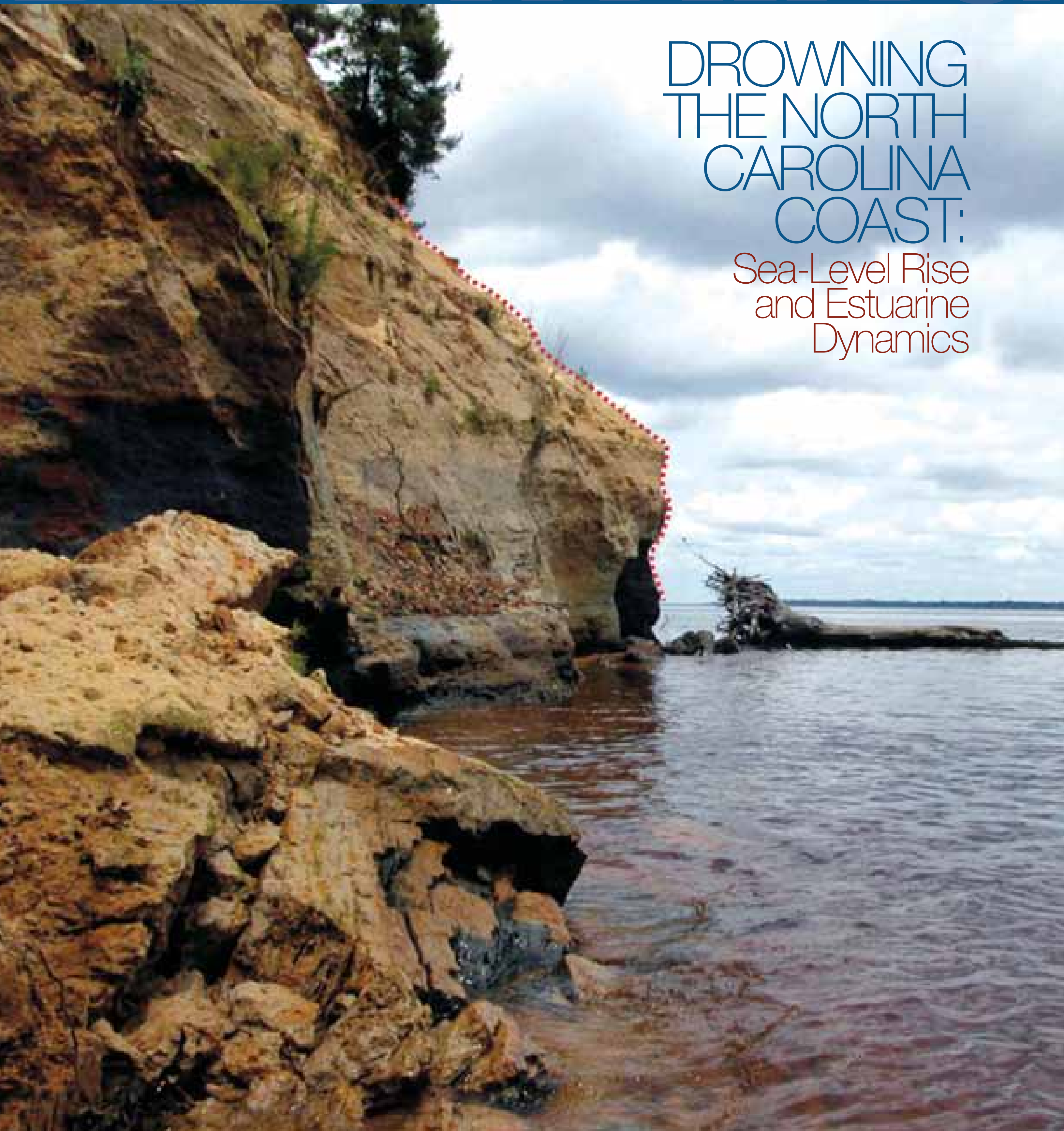
DROWNING

By Stanley R. Riggs and Dorothea V. Ames
Published by North Carolina Sea Grant



DROWNING THE NORTH CAROLINA COAST:

Sea-Level Rise and Estuarine Dynamics

ON THE FRONT COVER. *Pre-Hurricane Isabel photograph of the lower portion of sediment bluff that occurs along the Chowan River estuary western shoreline. The red star, on the satellite image inside the back cover, indicates the specific site location. This bluff is approximately 75 feet high and consists of a lower clay bed that is about 30 feet thick (to the top of this photograph), with an overlying sand bed that is 45 to 50 feet thick. Because bluff shorelines normally erode at average rates between –2.0 and –2.5 ft/yr (Table 8-1-3) and because the lower sediment bank is composed of clay, there is no sand beach preserved on the eroded wave-cut scarp and platform (Fig. 4-2-1). Notice the red dotted line along the wave-cut scarp and compare this to the respective location on the post-Hurricane Isabel photograph on the back cover. Photograph was taken in August 2003. See the back cover for the post-Hurricane Isabel photograph of the same site and inside back cover for a satellite image showing the site location and post-Hurricane Isabel, sediment-laden, estuarine water conditions.*

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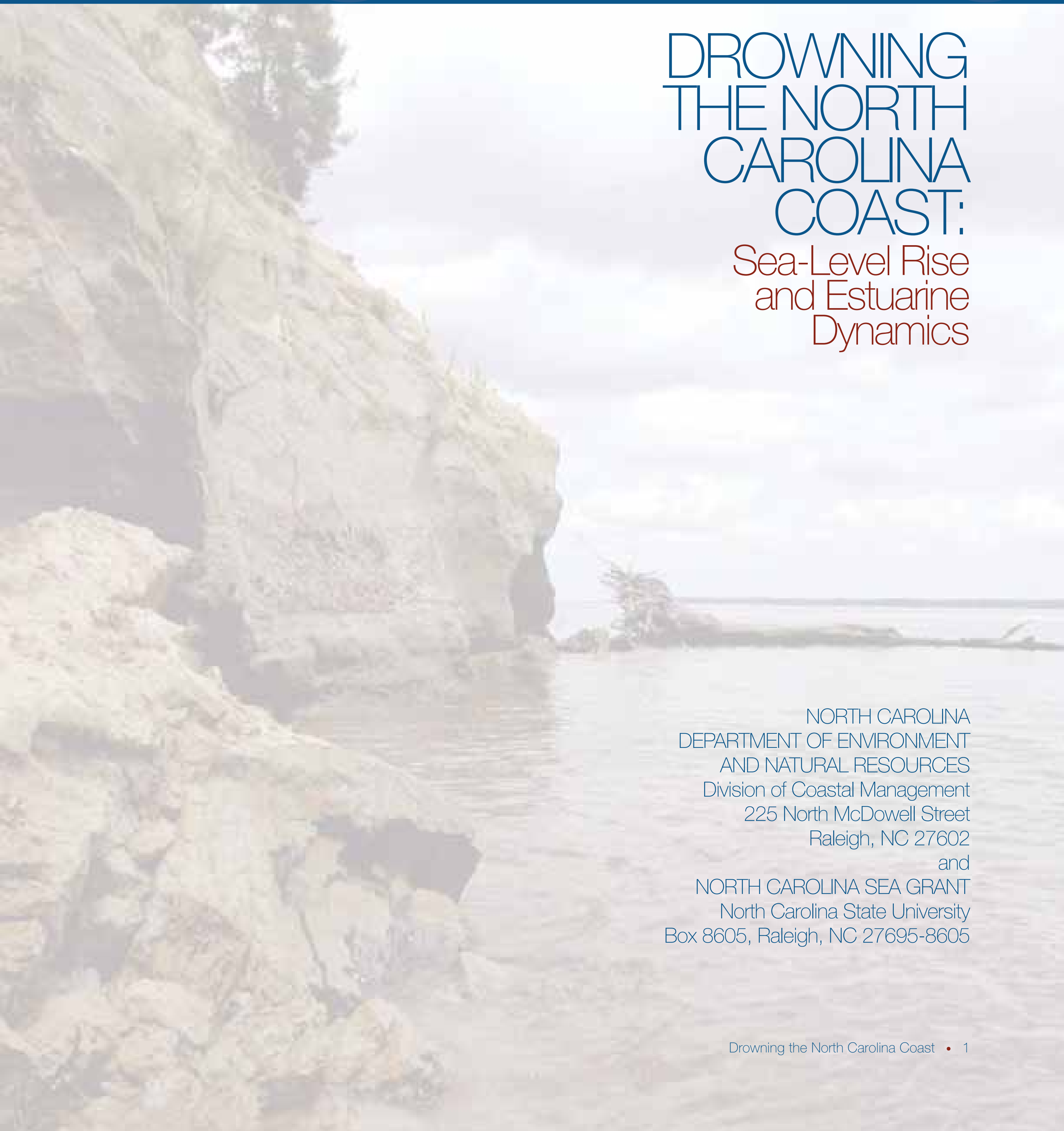

DROWNING THE NORTH CAROLINA COAST:

Sea-Level Rise and Estuarine Dynamics

NORTH CAROLINA
DEPARTMENT OF ENVIRONMENT
AND NATURAL RESOURCES
Division of Coastal Management
225 North McDowell Street
Raleigh, NC 27602
and
NORTH CAROLINA SEA GRANT
North Carolina State University
Box 8605, Raleigh, NC 27695-8605

DROWNING THE NORTH CAROLINA COAST: SEA LEVEL RISE AND ESTUARINE DYNAMICS

Written by Stanley R. Riggs and Dorothea V. Ames
Edited by Ann Green • Designed by Linda J. Noble
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Acknowledgments

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DROWNING

CHAPTER ONE: Introduction

Shoreline recession exposes the cypress root structures of the cypress headland swampforest shoreline along the south shore of the Neuse River estuary. Photograph is from Flanner Beach Recreational Area in Croatan National Forest.

CHAPTER ONE:

Introduction

The seam where continent meets ocean

is a line of constant change,

where with every roll of the waves,

every pulse of the tides, the past

manifestly gives way to the future.

There is a sense of time and of growth

and decay, life mingling with death.

It is an unsheltered place, without pretense.

The hint of forces beyond control,

of days before and after the human span,

spell out a message ultimately important,

ultimately learned.

— David Leveson (1973)

1.1. THE COASTAL DILEMMA

The history of development in coastal North Carolina is unlike other human endeavors due to the high-energy and dynamic character of the coastal system. The evolutionary formation of the North Carolina coastal system has taken place during the past 10,000 years and continues today as a work in progress. More importantly, change is the only constant within the coastal system, and this change happens at rates that defy conventional human perception and development patterns on more stable and inland terrains.

In 1975, Bellis et al. used the demise of Batts Island in the Albemarle Sound to demonstrate ongoing estuarine shoreline erosion in direct response to the intimately coupled processes of wave action and rising sea level. This island, which occurred about 0.75 miles offshore of Drummond Point at the entrance to Yeopim River, first appeared on the 1657 Comberford map (Cumming, 1938) as Hariots Island. The island subsequently became the home of Captain Nathaniel Batts, the first Virginian to settle in the Albemarle region and the Governor of "Roan-oak." The island is referred to as Batts Grave on the 1733 Moseley map (Cumming, 1966) (Fig. 1-1-1A). In 1749 the island consisted of 40 acres occupied by houses and orchards (Powell, 1968). Bellis et al. (1975) estimated that the island was about 10 acres in size on an 1849 U.S. Coast and Geodetic Survey bathymetric survey map. By the early 1970s, a lone cypress skeleton marked the total demise of the island as indicated on the 1976 nautical chart (Fig. 1-1-1B, 1C). By the early 1990s, only a red buoy marker reflected the presence of shallow shoals (Fig. 1-1-1D).

Native Americans inhabited North Carolina prior to 10,000 years ago. However, today little record of their occupancy of the coastal zone exists. Even the record of the first European settlement on the north end of Roanoke Island in 1584-85 has been obliterated by the dynamic processes of shoreline recession. The processes of change continues to take its toll today as every nor'easter and hurricane place their mark upon the shifting sands of time. If the rapid rates of coastal evolution presently taking place within our coastal system continue, no great remnants from our present coastal civilization will survive into antiquity. This is our coastal heritage.

Geologists are generally perceived as dealing only with millions of years of geologic time. Yes, when considering Earth history, geologists do think in terms of millions, and even billions of years. However, when considering modern earth processes such as earthquakes, volcanic eruptions and riverine floods, the time scales shift to hours, days, years, decades and centuries. Likewise, in considering high-energy coastal systems, geologic time is synonymous with time as experienced during a trip to the beach, a unique winter, an individual life span or even a few generations. Thus, modern coastal processes result in geologic events that range in human time frames — from individual storm events to the rise and fall of specific civilizations. At this scale, *geologic time is human time*.

1.2. THE ESTUARINE SHORELINE

Wherever calm, flat estuarine water intersects the irregular land surface, there is a shoreline. However, rarely is the estuarine water surface horizontal. Rather it fluctuates slightly in response to both astronomical and wind tides and severely during storm tides. These changes in water level cause the shoreline to move up and down and produce a shore zone that extends over some area determined by the geometry of the adjacent land surface. If the land is dominated by low slopes, such as occur in the outer portions of coastal North Carolina, the shore zone tends to be very broad, forming vast areas of marsh and swamp forest. Wherever the land has steeper slopes, such as dominate the inner portions of the North Carolina coastal zone, the shore zone is narrow and characterized by sediment and rock banks.

In addition, the shore zone is an environment of highly variable physical energy conditions — ranging from dead calm water to

FIGURE 1-1-1. *Map and photo series showing the demise of Batts Island at the mouth of the Yeopim River in the Albemarle Sound.* ***Panel A.*** *The Moseley map of 1733 (Cumming, 1966) refers to the island as Batts Grave.* ***Panel B.*** *Photograph in the early 1970s showing a lone cypress skeleton marking the final demise of the island.* ***Panel C.*** *Portion of the National Oceanographic and Atmospheric Administration (NOAA) Nautical Chart 12205, Page E, 1976, showing the former location of Batts Grave. The area shaded in blue represents less than 6-foot water depth. The area outlined in red is the former location of Batts Grave, which is the seaward extension of Drummond Point as indicated by the dashed red lines. As sea level rises, water floods onto the land, and wave energy causes the shoreline to recede by erosion.* ***Panel D.*** *Photograph in the early 1990s showing the red buoy that marks the shallow shoal remnants of Batts Grave.*

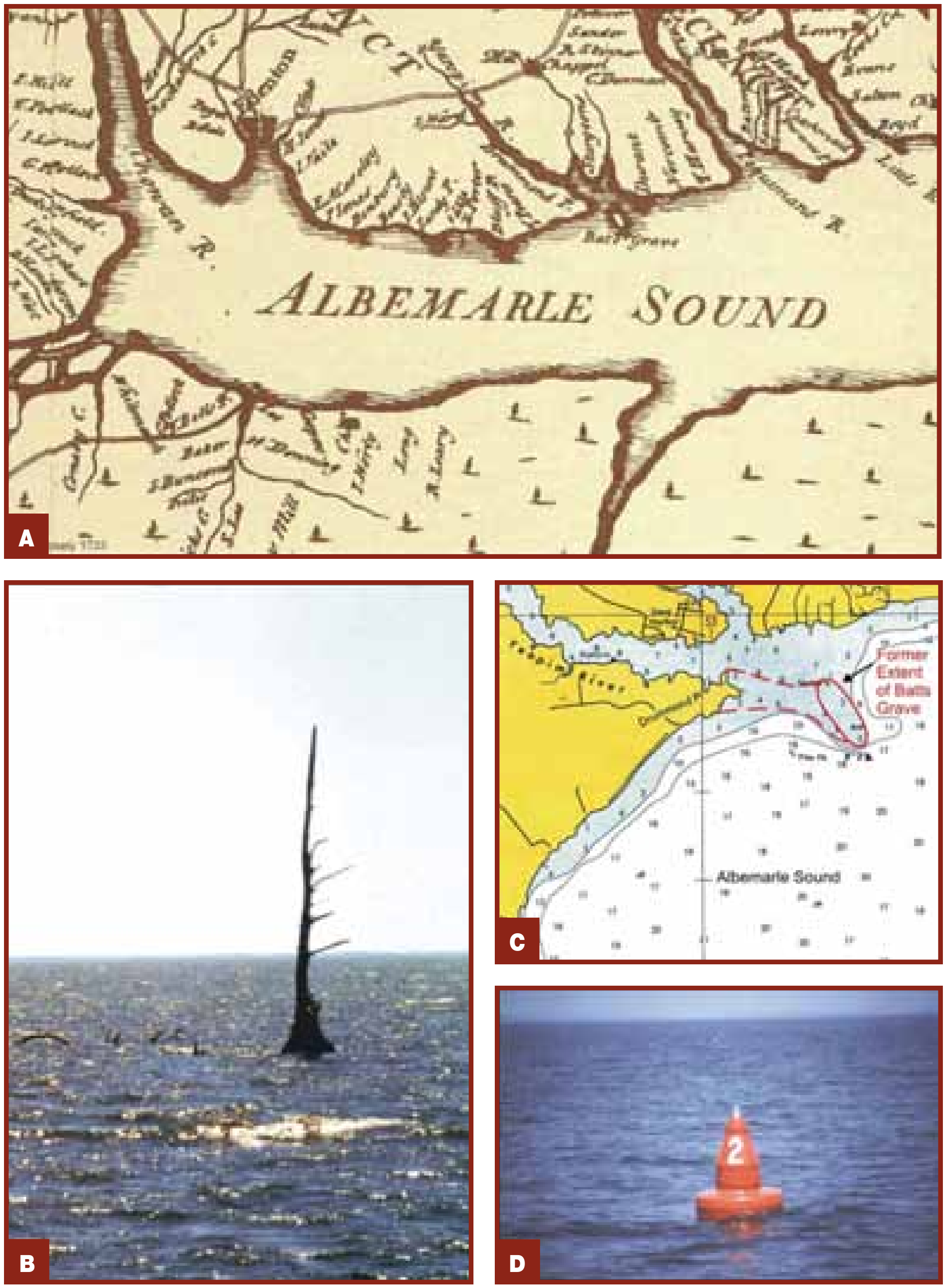

FIGURE 1-1-2. *A beautiful and serene coastal system on a clear and calm summer day produces the general public perception of estuarine shorelines. However, a closer look along most shorelines suggest other forces and processes at work over annual- to decadal-time scales and during short-term, high-energy storms when few people experience the shoreline. Notice that the shoreline in the foreground has receded, leaving a large oak tree to slowly drown offshore, and wave erosion at the shoreline has exposed the roots of two trees. These clues attest to the systematic rise in sea level that slowly moves upward and landward, eroding a shoreline as the former land surface is drowned. This photograph of a low sediment bank shoreline occurs along the back-barrier portion of Nags Head Woods.*

the extreme wave and storm-tide conditions associated with major storm events. As a result, the shore zone is like a great energy transfer station, where physical energy of waves, tides and currents in the water is transferred to the land through work processes that accomplish the erosion, transport and deposition of sediments. The amount of work accomplished within an estuarine shore zone depends upon the topography and composition (i.e., shoreline type), as well as the source, amount and duration of energy expended. Each new input of energy (i.e., storm event) causes shorelines to change and evolve through time. This is the function of a shoreline — to absorb the physical energy occurring at the contact between sea and land. Thus, storm events that input major amounts of energy can result in significant shoreline modification. Whereas, little happens on calm summer days.

Sand beaches are important not only as habitats for specific types of organisms, but they also are extremely efficient, energy-absorbing sponges of wave energy. A sand beach will form on a given shoreline if three general conditions are met. There must be adequate wave energy, a low, sloping ramp for the beach to perch upon at the shoreline, and an adequate supply of sand available for waves to build a beach. Most sand for mainland estuarine shoreline beaches within North Carolina is derived directly from the erosion of the adjacent sediment bank. If no sand exists in the sediment bank, there is no sand beach. Or, if the eroding sediment bank is hardened, the sand beach often disappears — unless there are cooperative neighbors that won't modify their eroding banks.

Wherever water level and associated waves intersect the land, waves will erode a shoreline that consists of a wave-cut cliff and a wave-cut terrace eroded directly into the sediment or rock that comprises the shoreline. If the material is unconsolidated sand and wave energy is high, the recession rates will be severe. Whereas, if the shoreline material is hard rock, the erosion rates will be slow or negligible.

As energy input, character of land, or sea level changes through time, the shoreline responds with dramatic evolutionary changes. Herein lies the dilemma. Rates of change along the North Carolina estuarine shorelines occur in time frames of days and years, in severe contrast to the expectations of permanence and economic values placed upon waterfront properties. Raleigh-style approaches to development are not possible in a high-energy coastal system. For long-term success for both society and the estuarine ecosystem, use and development of coastal resources must recognize and be done in harmony with the energy and processes of the natural system.

1.3. CONCLUSIONS

Thus, shoreline erosion is an ongoing natural process within the North Carolina estuarine system, resulting from the short- and long-term coastal evolution. While various methods are available to combat erosion and land loss, none are permanent solutions, and all have significant environmental trade-offs. Recognizing and understanding the complex causes and dynamic processes involved in shoreline erosion is the first step towards minimizing the impact of erosion and managing our shoreline resources and economic investments. Ultimately, to both preserve our coastal estuarine resources and maximize human utilization, long-term management solutions of estuarine shoreline erosion problems must be in harmony with the dynamics of the total coastal system.

DROWNING

CHAPTER TWO:

Geologic Framework of the North Carolina Coastal System

As this low sediment bank shoreline at Jockey's Ridge State Park slowly erodes, pine trees drown and ultimately break off during storms. The receding shoreline leaves their stumps on deep tap roots as lone sentinels to mark the former location of upland. The sandy beach is derived from the eroding shoreline. In the background is a remnant of a fringing marsh headland that is eroding more slowly than the adjacent low sediment bank.

Geologic Framework of the North Carolina Coastal System

2.1. PHYSICAL SETTING OF THE COASTAL SYSTEM

Figure 2-1-1 is a physiographic map of North Carolina with an overlay of the drainage basins. A vast and complex network of creeks, streams and rivers moves the surface water systematically off the uplands of the Appalachian, Piedmont and Coastal Plain provinces towards the Atlantic Ocean. These never-ending ribbons of fresh water flow through their self-eroded valleys downhill to sea level, where they intermingle with the salty waters of the Atlantic Ocean. At sea level, a broad, low-sloping transition zone forms the vast estuarine system connecting the rivers to the ocean (Fig. 2-1-2). The estuaries, which are more extensive in the northern region, are great mixing basins of fresh and salt waters within the coastal system (Figs. 2-1-3, 2-1-4).

Fronting the estuarine zone is a narrow strip of barrier islands that act as a dam between the estuaries and ocean (Figs. 2-1-3, 2-1-4). This extensive strip of sand islands was produced by the interaction between high-energy ocean storms and the low-sloping Coastal Plain. The sand dam is broken by a series of small openings commonly called “inlets” that are essential for ultimately discharging riverine fresh water into the sea. Barrier islands are like icebergs with only a small portion rising above the sea surface, and the greatest portion hidden below sea level. The barrier islands are perched at the top of the shoreface, which slopes steeply to between 8 to 20 meters below sea level, where it flattens out onto the inner continental shelf. The shoreface ramp is the portion of a barrier island that functions as an important energy-absorbing surface for wave, tidal and current energy within the ocean margin.

2.2. NORTH CAROLINA COASTAL PROVINCES

The generalized geologic map of the North Carolina Coastal Plain (Fig. 2-2-1) suggests major differences between the northern and southern coastal regions that reflect their geological heritage — the underlying geologic framework. A line drawn from Raleigh through Kinston and Cape Lookout separates the coastal system into the Northern and Southern Coastal provinces. Each province has a unique geologic framework that results in distinctive types of barrier islands, inlets and estuaries.

The unique spatial geometry of the North Carolina barrier islands further characterizes the

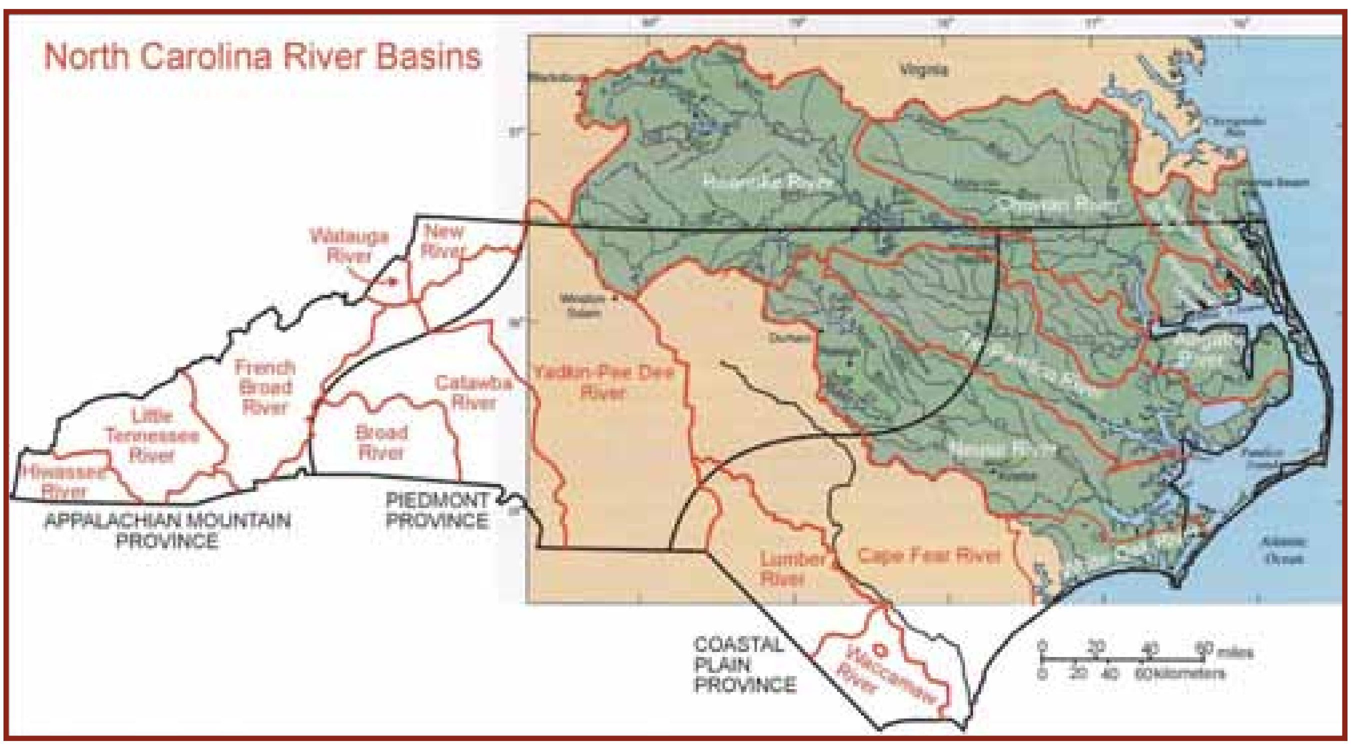

FIGURE 2-1-1. *Location map of the three physiographic provinces (in black) and drainage basins (in red and white) that interact to produce the vast North Carolina coastal system. The estuarine zone occurs between the freshwater riverine drainage system and saltwater oceanic system. Separating the estuarine and oceanic zones is the barrier island sand dam with a few small inlets/outlets through the dam, allowing the ultimate escape of fresh water into the Atlantic Ocean.*

CONTINUED:

Geologic Framework of the North Carolina Coastal System

coastal system. The coast consists of four geomorphic compartments (Fig. 2-2-1), each with its own characteristic physical and chemical dynamics and resulting biological and geological components that comprise the coastal system. These compartments are known as "cuspate embayments" because of their cusp-like shape and are defined by the capes and associated cape shoals (Fig. 2-2-1). Each cape shoal consists of an extensive shore perpendicular to a shallow sand shoal system that extends seaward for 10 miles (Diamond Shoals off Cape Hatteras), 15 miles (Lookout Shoals off Cape Lookout), and 30 miles (Frying Pan Shoals off Cape Fear). These vast, shallow-water shoal systems gave many mariners their demise and the North Carolina coast the dubious honor of being called the "graveyard of the Atlantic."

In the Northern Province, the Hatteras compartment faces northeast to east and reaps the head-on impact of frequent nor'east storms. In contrast, the Raleigh Bay compartment generally faces southeast and only receives glancing blows from powerful nor'easters. In the Southern Province, the Onslow Bay compartment faces south to southeast, and the Long Bay compartment faces totally south, both of which are dominated by broad, shallow and rock-floored continental shelves. This setting results in offshore winds and waves from nor'easters, but the islands receive a high proportion of direct hits from less frequent, but higher energy tropical storms and hurricanes.

Continued on page 20

FIGURE 2-1-2. *Location map of major towns and coastal features for the North Carolina coastal system.*

Geologic Framework of the North Carolina Coastal System

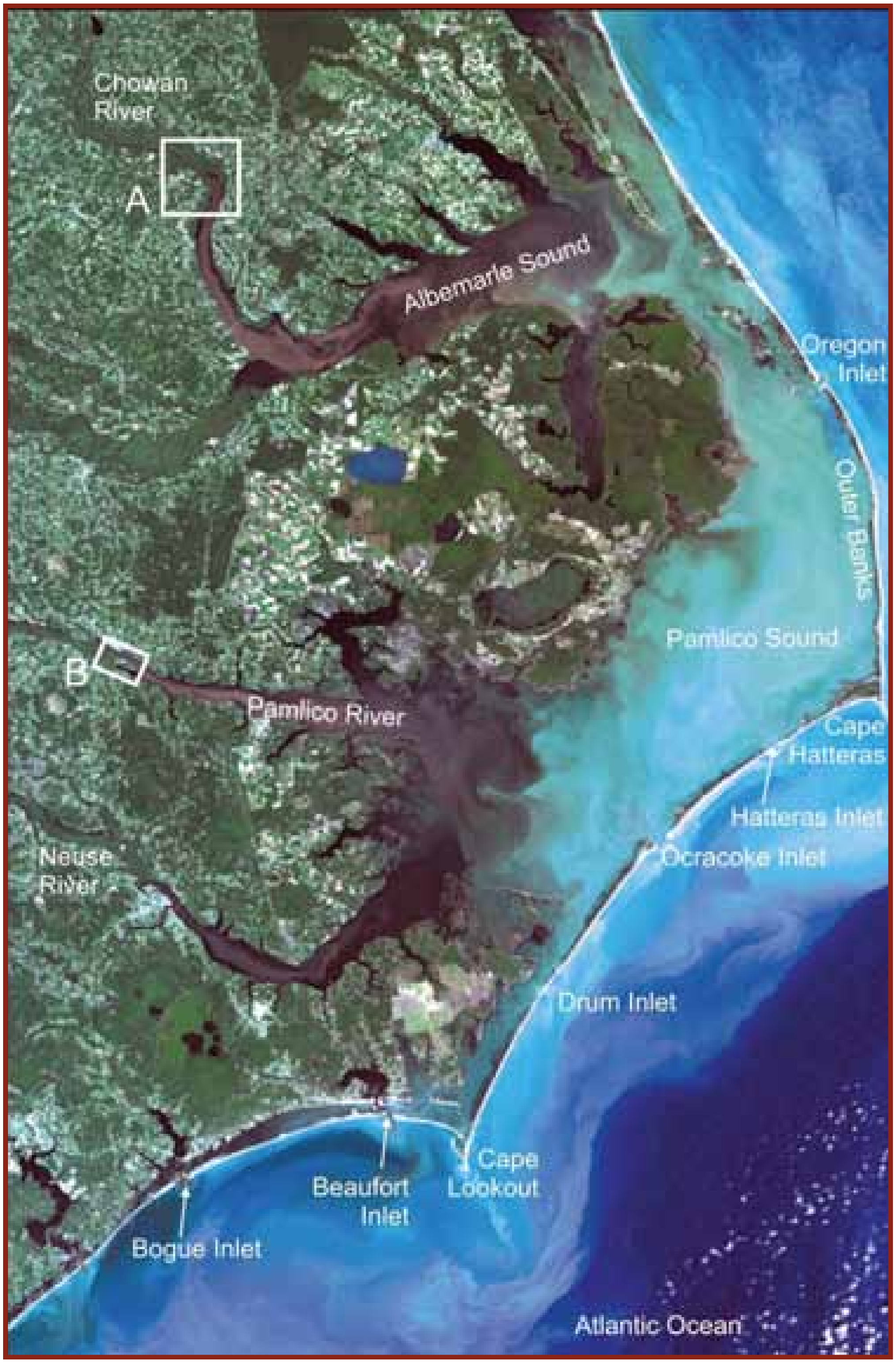

FIGURE 2-1-3.
A 1999 satellite image of northeastern North Carolina coastal system. The image shows the freshwater riverine systems, vast network of brackish-water estuaries and the saltwater oceanic system that is separated by the barrier island sand dam with a few small inlets/outlets that allow interchange with the Atlantic Ocean. Notice how the extensive riverine swampforest floodplains give way to the drowned-river estuaries as they approach and interact with sea level. Hurricane Floyd made landfall on September 15-16, 1999. This satellite image was taken September 23, 1999, when discharge waters were at their peak flood stage as indicated by the black sediment-laden waters. This photograph is a joint product of the NASA Landsat Project Science Office, Goddard Space Flight Center and the U.S. Geological Survey EROS Data Center. Boxes A and B are the location of Panels A and B of Figure 3-4-1, respectively.

Geologic Framework of the North Carolina Coastal System

2.3. GEOLOGIC CONTROLS OF COASTAL PROVINCES

To better comprehend the coastal system, it is imperative to understand the basic geologic controls that define the two coastal provinces. The spatial geometry, in consort with the geologic framework, defines the character of the North Carolina coastal system: size and type of estuarine and barrier island habitats, water salinity, wave and tidal energies and processes, plant and animal communities, and problems resulting from human interaction and intervention.

2.3.A. Southern Coastal Province

Relatively old rocks (Fig. 2-2-1) underlie the coastal system in the Southern Province, from Cape Lookout south to the South Carolina border. These rocks range in age from Upper Cretaceous (about 90 million years ago) through the Miocene (about 5.3 million years ago). In this region, only a thin and highly variable skin of Pliocene marine sands and clays (about 5.3 to 1.8 million years ago) and surficial sediments of Quaternary age (about 1.8 million years ago to the present) were deposited. The dominant older units are generally composed of hard rocks, including mudstone, sandstone and limestone associated with a large geologic structure called the Carolina Platform that underlies the region between Myrtle Beach, S.C., and Cape Fear, N.C.,(Riggs and Belknap, 1988). This structural platform rises close to the earth's surface, causing the older and harder rocks to be eroded and truncated by the shoreline (Fig. 2-2-1). Today, these older rocks

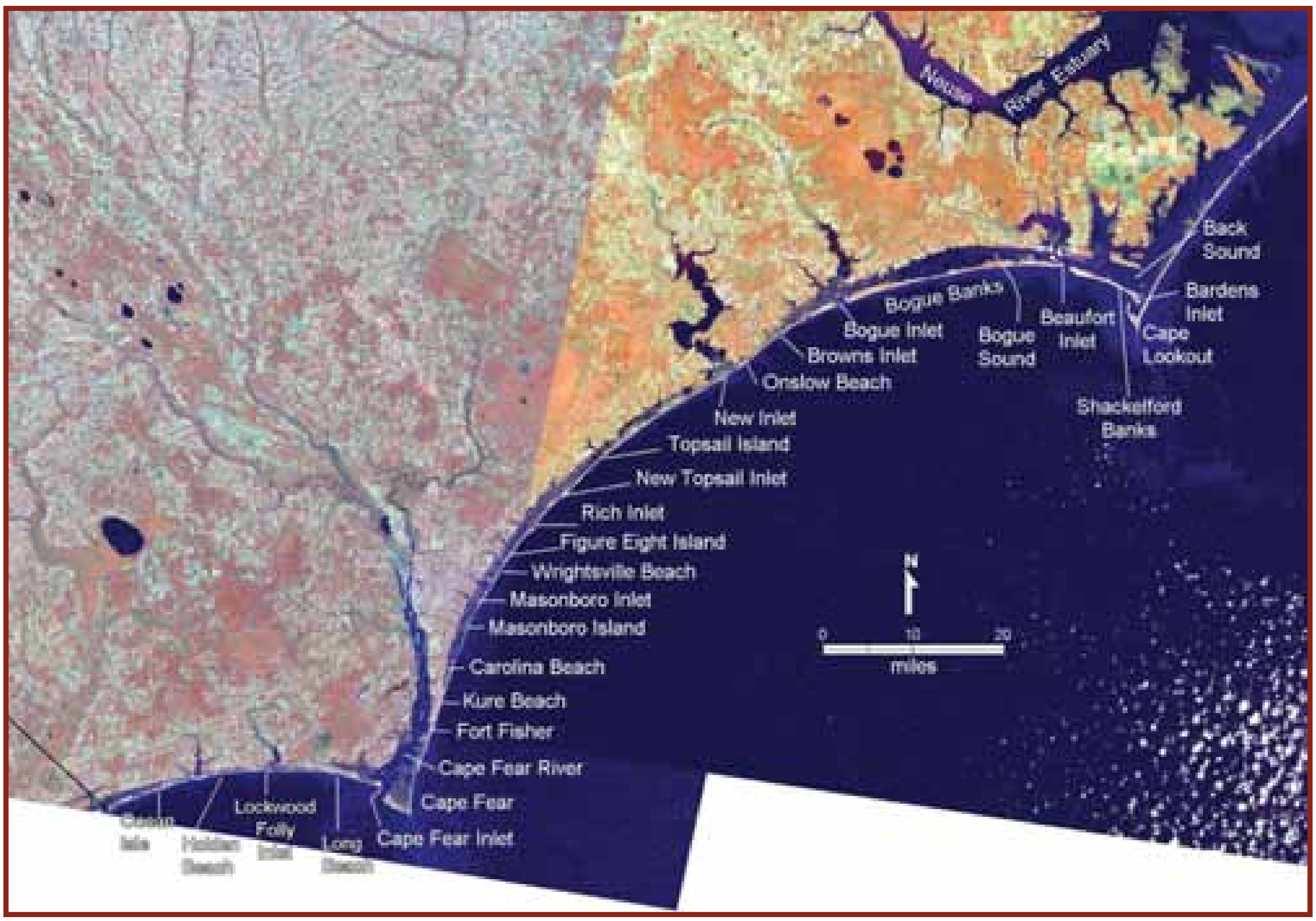

FIGURE 2-1-4. *A 1996 false color satellite image of southeastern North Carolina (Southern Province), extending from Cape Lookout south to the South Carolina state line. The image shows the abundant short barrier islands with many inlets/outlets, allowing for a major exchange of salt water that mixes with the small Coastal Plain rivers. The small drowned-river estuaries and narrow shore-parallel sounds are direct results of a relatively steep land gradient. The Cape Fear River is the only trunk stream that drains off the Piedmont Province. All other drainages are small blackwater streams that drain the Coastal Plain pocosin swamp forests. This is a 1996 IRFAN satellite image obtained from the Web site of NOAA.gov.*

occur in the shallow subsurface, buried beneath a surficial skim of soil and modern coastal deposits. However, the erosional topography of these older rock units produce relatively steep slopes that control the coastal geometry and character within the Southern Coastal Province (Riggs et al., 1995).

2.3.B. Northern Coastal Province

In contrast, the coastal system in the Northern Province, from Cape Lookout north to the Virginia border (Fig. 2-2-1) is underlain primarily by sediments of Pliocene age (about 5.3 to 1.8 million years in age) and the younger, surficial sediments of Quaternary age (less than 1.8 million years in age) (Riggs et al., 1992). The Quaternary sediments generally consist of slightly indurated to unconsolidated mud, muddy sand, sand and peat that thicken northward to fill the subsiding Albemarle Embayment, with up to 70 meters of sediments. The generally soft Quaternary sediments form the surficial units and soils deposited during the many sea-level fluctuations resulting from multiple glaciations and deglaciations of the Quaternary ice ages. Consequently, a gentle depositional topography is common along the present northern coastal system, and the older rock units are deeply buried beneath these surficial sediments (Riggs et al., 1995).

2.3.C. Consequences of the Geologic Differences

Table 2-3-1 summarizes the basic differences between the Southern and Northern Coastal Provinces. The different geologic frameworks for each province results in dissimilar

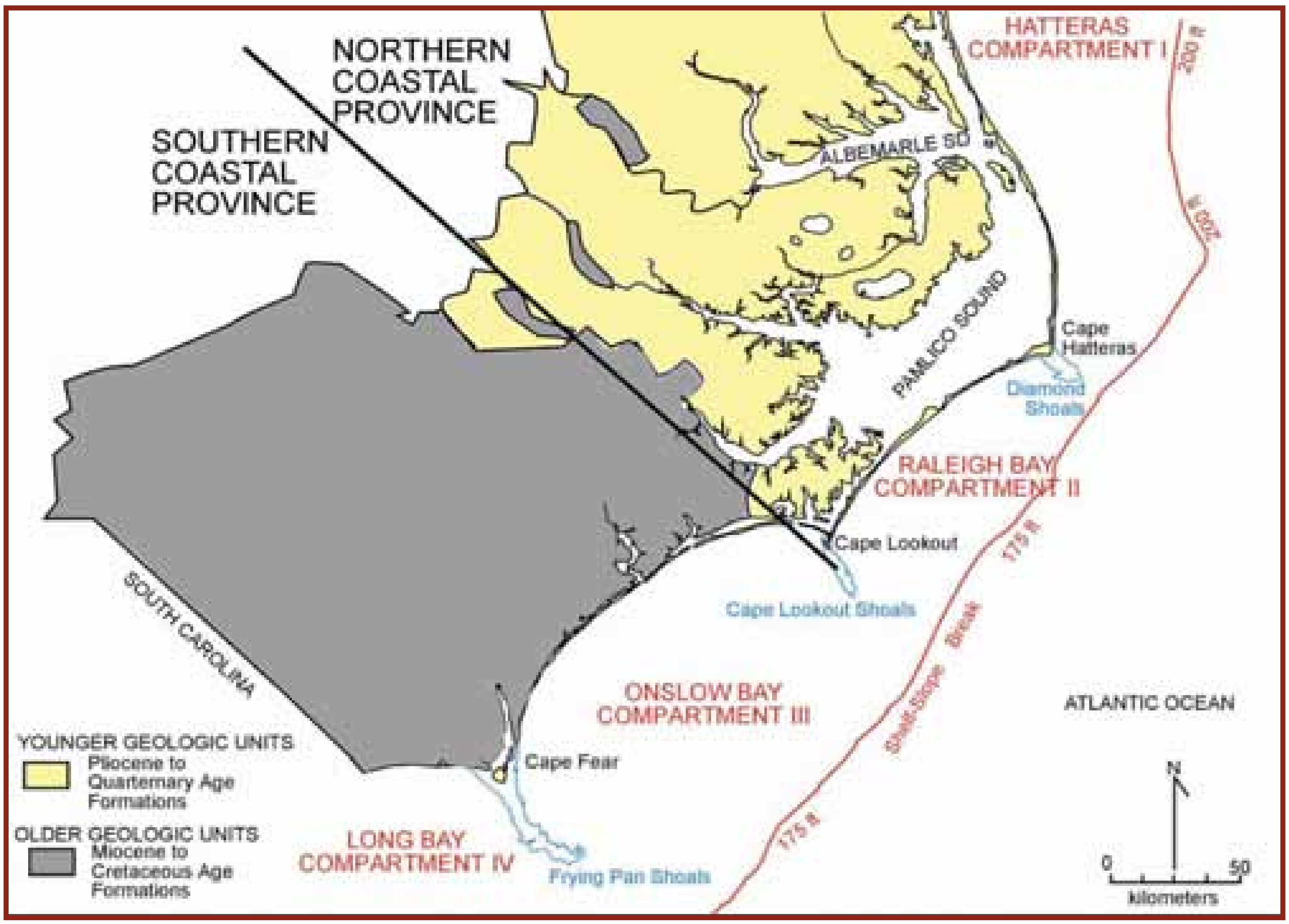

FIGURE 2-2-1. *Generalized geologic map of the North Carolina Coastal Plain showing the two coastal provinces and four geomorphic compartments of the coastal system. These cuspate embayments are defined by the classic Carolina capes and their associated cross-shelf sand shoals. Due to different spatial geometry, the coastal system within each compartment is significantly different from the other compartments. Geologic outcrop patterns are summarized from the Geologic Map of North Carolina (NCGS, 1985).*

Geologic Framework of the North Carolina Coastal System

land slopes, sediment supplies and physical oceanographic conditions. The Southern Province coastal region is characterized by an average land slope of 3 feet/mile compared to 0.2 feet/mile in the Northern Province. Thus, rising sea level floods the disparate slopes, producing different kinds of barrier island — inlet systems and associated estuaries (Fig. 2-2-1). The steeper slopes of the Southern Province produce short, stubby barrier islands with 18 inlets and narrow back-barrier estuaries. The gentle slopes of the Northern Province produce long barrier islands with only four inlets and an extensive sequence of drowned-river estuaries that form the vast Albemarle-Pamlico estuarine system. The northern barrier islands project seaward, forming the famous Cape Hatteras and associated Outer Banks — a sand dam that semi-isolates the Albemarle-Pamlico Estuarine System from the ocean.

The different long-term geologic histories for these two provinces have resulted in broad, shallow continental shelf geometries for the two southern coastal compartments; whereas, the two northern compartments tend to be narrower and steeper (Fig. 2-2-1). This results in very different oceanographic processes dominating each of the two provinces. The Southern Province generally has a much higher astronomical tidal range and lower wave energy relative to the Northern Province, which has a low astronomical tidal range and significantly higher wave energy (Table 2-3-1). In addition, the underlying geologic framework also controls the riverine drainage basins and their long-term delivery of sediments to the coastal system (Riggs et al., 1995). Four major Piedmont-draining rivers dominate the Northern Province, whereas only one major river system drains into the Southern Province. This is one of the major controls over sand supplies that are essential for building and maintaining barrier islands through time.

2.4 SHORELINES AND STORMS

2.4.A. The Flow of Energy

The shoreline, where water meets the land, is a zone of extremely high physical energy. This energy occurs in the form of waves, currents, astronomical tides and storm tides and is derived from two important sources. The first and most extensive energy input to the coastal system is solar energy, which differentially heats the earth's atmosphere, ocean, and land surfaces. This differential heating drives the great heat pump operating between the air-sea-land interfaces and produces storms and winds that result in wind tides, waves and currents. The second energy

Table 2-3-1 Geologic Framework of North Carolina Provinces

Coastal characteristics of the Southern and Northern provinces of North Carolina result from differences in the underlying geologic framework. See Figure 2-2-1 for location of the two provinces.

SOUTHERN PROVINCE	NORTHERN PROVINCE
• Cretaceous-Miocene Geologic Framework Dominantly Rock Control	• Pliocene-Quaternary Geologic Framework Dominantly Sediment Control
• Steep Slopes (avg. = 10 ft/mile)	• Gentle Slopes (avg. = 0.5 ft/mile)
• Coastal Plain-Draining Rivers (many) Black-Water Rivers Low Sediment Input Low Freshwater Input	• Piedmont-Draining Rivers (4) Brown-Water Rivers High Sediment Input High Freshwater Input
• Short Barrier Islands — Many Inlets (18) Maximum Astronomical Tides/Currents Maximum Saltwater Exchange	• Long Barrier Islands — Few Inlets (4) Minimal Astronomical Tides Minimal Saltwater Exchange
• Results: Narrow Back-Barrier Estuaries Regularly Flooded Astronomical Tide Dominated High-Brackish Salinities	• Results: Deeply Embayed Estuaries Irregularly Flooded Wind-Tides and Wave Dominated Highly Variable Salinities

input is gravity. Gravity causes rivers to flow downhill and delivers both water and sediments to the coastal system. Also, the gravitational forces acting between the moon, sun and earth as they revolve about each other in their endless journey through space produce the astronomical tides and associated currents that are important within coastal systems. These great and continuous inputs of energy into the earth system must either directly do work, be converted to some form of energy that can do work, or be released back into space — energy does not just disappear.

Some of the energy input into the earth's water system does the geologic work of eroding and building beaches — in other words maintaining the shoreline system. Thus, the shorelines are high-energy, dynamic portions of the coastal system that are generally event-driven by individual storms or sets of storms and can result in massive changes within time frames of hours to years. The cumulative impact of energy resulting from multiple storms and numerous winter storm seasons, severely impacts the shoreline — eroding some, building others — but always moving sediment about like chess pieces on a game board.

2.4.B. Role of Barrier Islands and Their Inlet/Outlet Systems

North Carolina's barrier islands act as a large sand dam separating the open waters of the Atlantic Ocean from the semi-enclosed waters of the estuarine system. The string of sand barriers, built and maintained by the higher energy levels of the oceanic system, act as an energy buffer, largely protecting the back-barrier estuarine system from the extremely high-energy oceanic conditions. Consequently, when considering estuarine shoreline dynamics, the processes are similar to those on an ocean shoreline, but they occur at significantly lower energy levels. This results in slower rates of change with higher probabilities of successfully manipulating and managing the shoreline in the short term.

Associated with barrier islands are small holes through the sand dam, better known as inlets, that historically have allowed shipping of goods and movement of people (Figs. 2-1-3 and 2-1-4). But inlets really should be called "outlets." This is because one of their primary functions in life is to let fresh water flowing off the land, pass through the barrier island sand dam, and discharge into the ocean, which is the ultimate base level. However, once an outlet is open, it also functions as an inlet, since astronomical tides create water level differentials, resulting in active tidal exchange of ocean water through inlets and into adjacent estuaries. It is the regularity and strength of tidal currents produced by this tidal pumping that maintains an inlet/outlet system on the short-term scale of hours to years. Whereas, storm pumping, resulting from major storm tide events, maintains an inlet/outlet system on the longer-term scale of years to centuries.

Two sources of water feed the estuarine system. Gravity causes fresh water in rivers to flow downhill to the oceans, and ocean water is pushed through the inlets by astronomical and storm tides. Consequently, estuaries act as great mixing basins where the two water masses intermix to form the following general salinity gradients: (1) fresh water in the upstream or riverine portions; (2) low brackish water in the inner estuaries; (3) high brackish water in the outer estuaries and inlets; and (4) normal seawater salinity in the offshore oceanic regions.

It is the interplay between the regularity of astronomical tides, irregularity of wind tides and vast array of brackish waters characterizing the estuarine system that largely determines what coastal plant communities grow where within the estuarine system. This in turn determines the type of organic shoreline that results and whether it is dominated by constructive (depositional) or destructive (erosional) processes. As barrier island inlets open, migrate and close through time, the chemical and physical conditions also change within the associated estuaries. These changes result in major shifts in physical dynamics and regional biota, which in turn may cause a given shoreline to shift from a stable, accreting shoreline to an unstable, erosional shoreline or vice versa.

2.4.C. Role of Paleotopography in Estuarine Dynamics

When an estuary forms in response to rising sea level, the sea systematically floods a previously exposed land surface with topography developed by the pre-existing drainage system. The estuaries form in low valleys of the drainage system as they are flooded, while the higher ridge crests or interstream divides between stream valleys form the upland regions. The geometry of this paleo-drainage system and composition of underlying sediment units form the geologic framework that the coastal system inherits — this is the gene pool that determines the character and evolutionary history of the estuarine system.

Just as a drainage system displays extreme variability, so does the resulting drowned river estuarine system — each estuary is unique because its inheritance is different from the other estuaries. The geologic framework dictates the shape of the coastal system, geometry of the land surface being flooded, types of shorelines and associated sand supplies, and rates of shoreline recession or accretion. The interstream divides between major drainage systems at the large scale (i.e., the Dare-Hyde Peninsula between the Roanoke River-Albemarle Sound and the Tar River-Pamlico River), as well as those between tributary streams on the smaller scale, are paleotopographic highs, forming today's land peninsulas that are composed of pre-existing rocks and sediments (Fig. 2-1-3).

Where the water surface intersects these peninsulas, wave energy is expended and erodes the older geologic deposits that form the landmass. Composition of these older geologic units being excavated by wave energy in part determines the presence and health of the associated beach. If the deposits are hard rocks such as limestone or cemented sandstone, there will be little to no sediment contributed to a beach, and rates of shoreline recession will be minimal. If the shoreface is composed of cohesive mud, there will be no sediment input to the beach, with moderate to minimal erosion rates. Whereas, a shoreface consisting of unconsolidated sand, will have a major input of new sediment to a beach along with high relative rates of beach erosion and shoreline recession.

CHAPTER THREE:

Character of Drowned-River Estuarine System

An eroding high sediment bank shoreline at Nags Head Woods is located on the eastern side of Albemarle Sound. This high bank recedes rapidly during storm tides when the water level rises and oversteps the beach. This allows waves to directly erode the bank, causing the sandy sediment to slump onto the beach. As the shoreline recedes, the overhanging soil mat and associated trees are undercut and fall onto the beach. The slumped sediments are then reworked by the day-to-day waves to form the broad sand beach.

Character of Drowned-River Estuarine System

3.1. TYPES OF ESTUARINE BASINS

The North Carolina estuaries are the drowned lowlands behind the barrier islands. They are the river and tributary stream valleys with bottoms below sea level that are flooded by ocean waters (Figs. 2-1-3, 2-1-4). The ocean floods up the low river valleys to the point where the valley bottom rises above sea level. The tributary estuaries are like long fingers reaching far into the heart of the Coastal Plain and perpendicular to the trunk estuaries (Fig. 2-1-2). Because of differences in slope of the land and resulting barrier island and inlet systems in the two provinces, the estuarine basins have dramatically distinct geometries, physical processes and biological communities.

3.2. THE ESTUARINE BASINS

3.2.A. Basin Morphology

The drowned-river estuarine system of North Carolina consists of an extensive and complex sequence of habitats and shorelines, resulting in a vast array of biodiversity within a highly variable, but productive coastal system. Figure 3-2-1 uses the Albemarle estuarine system to identify the different types of estuarine basins that occur within North Carolina. This figure is also used as an example of the different zones within the trunk river estuaries and of the salinity gradients and dominant tidal processes within each estuarine zone. However, it is important to remember that each estuarine system has its own characteristics, as will be discussed in subsequent sections.

Figure 3-2-2 is a schematic map view of an idealized drainage system that is being systematically flooded by rising sea level to

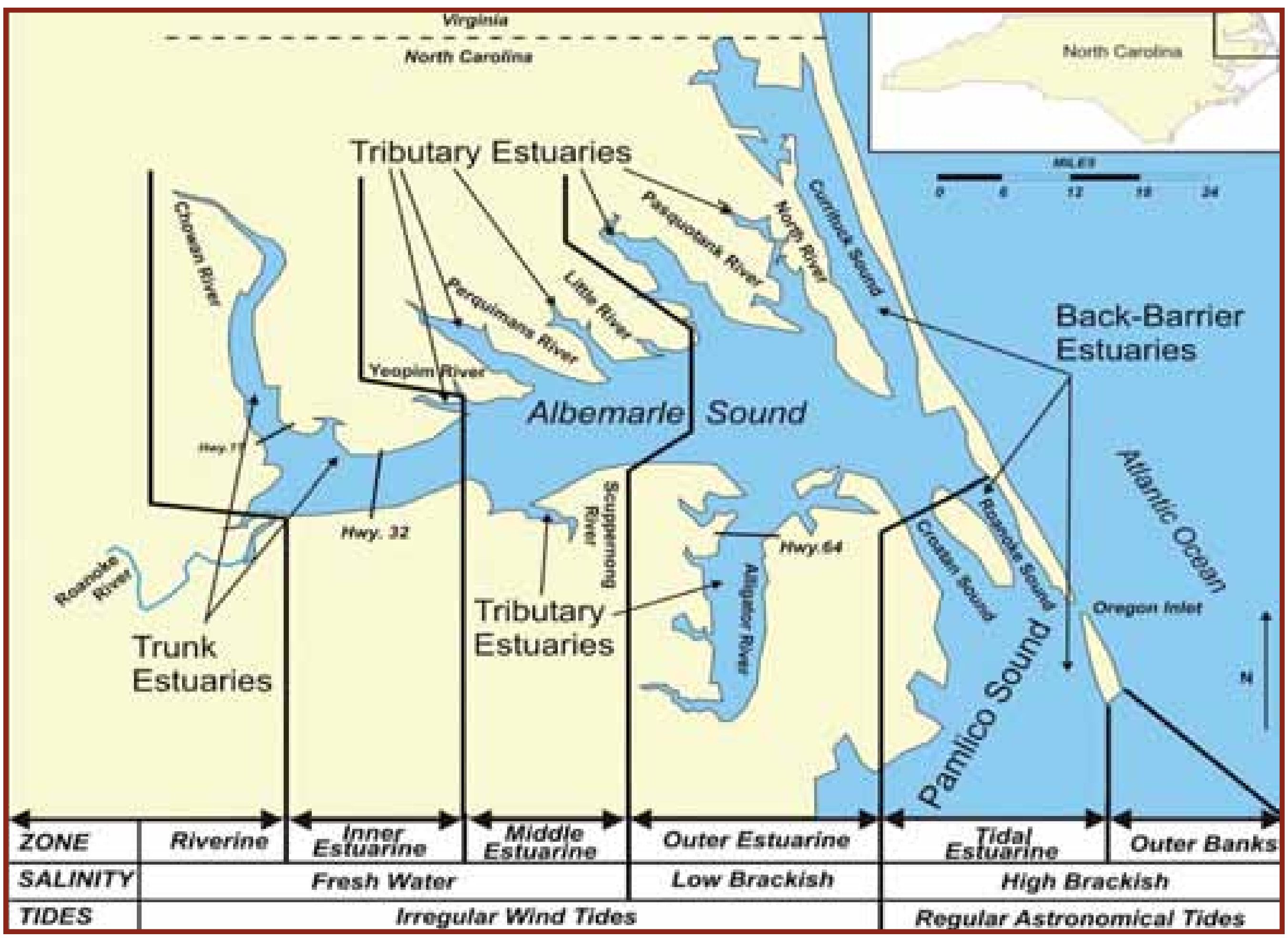

FIGURE 3-2-1. *Map of the Albemarle estuarine system delineating the zones within the estuarine trunk-river basin, along with the general salinity gradients and dominant tidal processes that characterize each zone.*

Character of Drowned-River Estuarine System

produce the various types of estuaries as outlined. Cross-sectional profile A-A' (Fig. 3-2-3) demonstrates the geometry and associated sediment types down the longitudinal axis of a trunk estuarine system and extending from the riverine system downstream to the barrier island sand dam. Cross-sections B-B' (Fig. 3-2-4A) and C-C' (Fig. 3-2-4B) are perpendicular profiles across the riverine and trunk estuarine systems, respectively.

The cross-sectional morphology of most North Carolina Piedmont-draining, brown-water rivers in the lower Coastal Plain is characterized in Figure 3-2-4A. A primary channel is flanked on one or both sides by broad swampforest floodplains, which in turn is bounded by sediment banks of the adjacent uplands. The floodplain consists of active swampforest wetlands that are secondary channels occupied annually during the wet season and whenever the riverine discharge exceeds the primary channel capacity. The organic peat sediments underlying the floodplain accumulated through time in response to rising sea level.

As sea level continues to rise and begins to flood up the riverine section, the swamp forest is drowned and eroded, producing the geometry outlined in Figure 3-2-4B. Subsequent sediment deposition fills the eroded basin with estuarine organic-rich mud. The resulting estuarine geometry is like a shallow, flat-bottomed dish with a narrow perimeter lip or platform (Fig. 3-2-4B). The shoreline is a cut-bank incised into older upland sediments, with the narrow and shallow perimeter platform sloping gradually away from the shoreline to depths of 3 to 7 feet below mean sea level (MSL) and then slopes more abruptly to the broad, flat floor of the central basin with depths between 12 to 24 feet below MSL. Within the trunk estuaries, the flat central basin floor gradually deepens from the inner estuary seaward to the outer estuary (Fig. 3-2-3).

Tributary streams and their drowned-river estuaries have similar, but smaller-scale, cross-sectional profiles as the trunk rivers and estuaries (Fig. 3-2-4). In addition, each tributary estuary is characterized by a downstream transition from the riverine zone to the drowned river trunk estuary (Fig. 3-2-2) or a back-barrier estuary and barrier island (Fig. 2-1-4). Within the back-barrier estuaries, the central basin shallows eastward onto

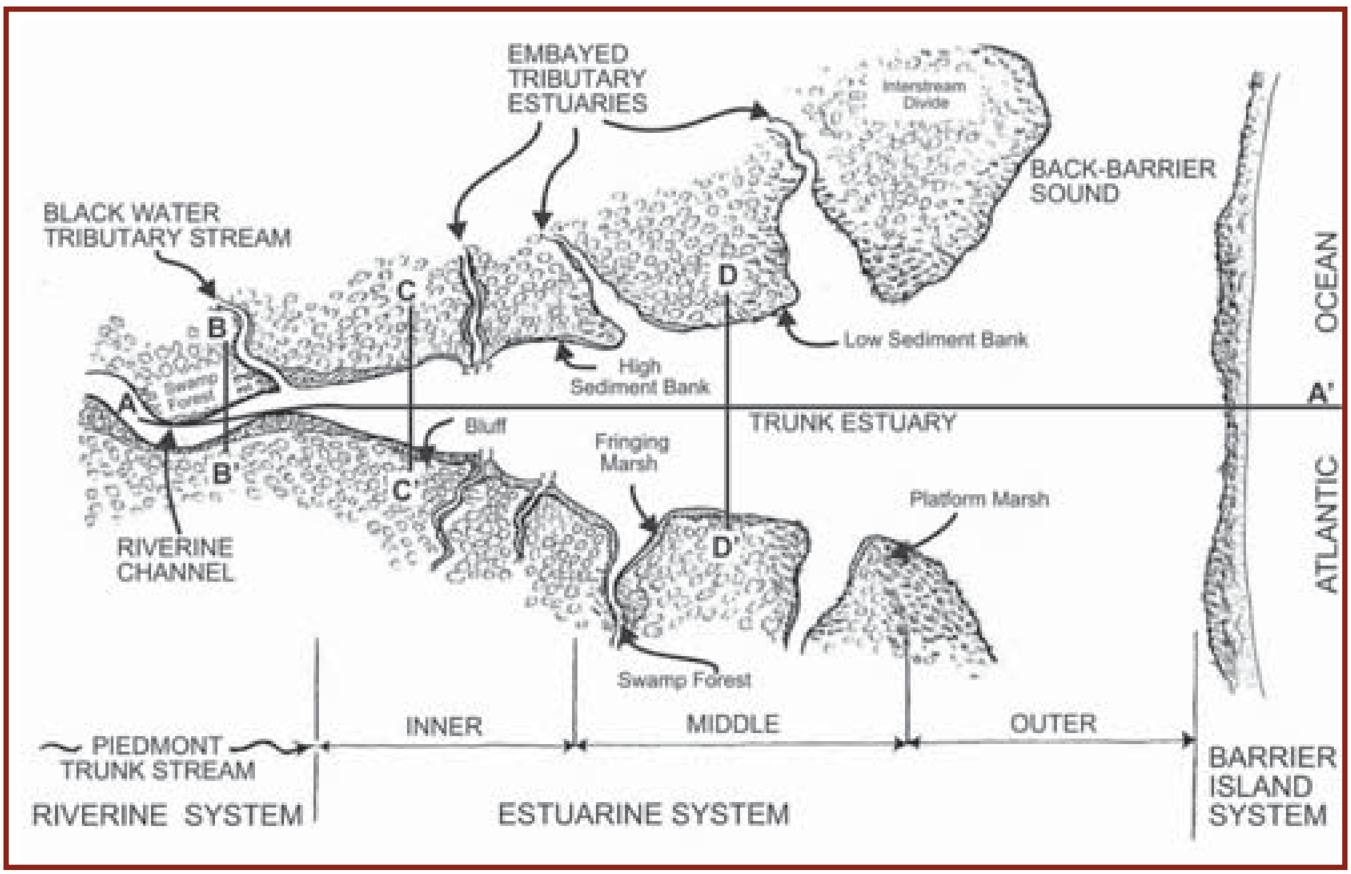

FIGURE 3-2-2. *Schematic map of the different components of a drowned river estuarine system. The location of four cross-sectional diagrams (Figs. 3-2-3, 3-2-4, and 3-2-5, respectively) are indicated on the map.*

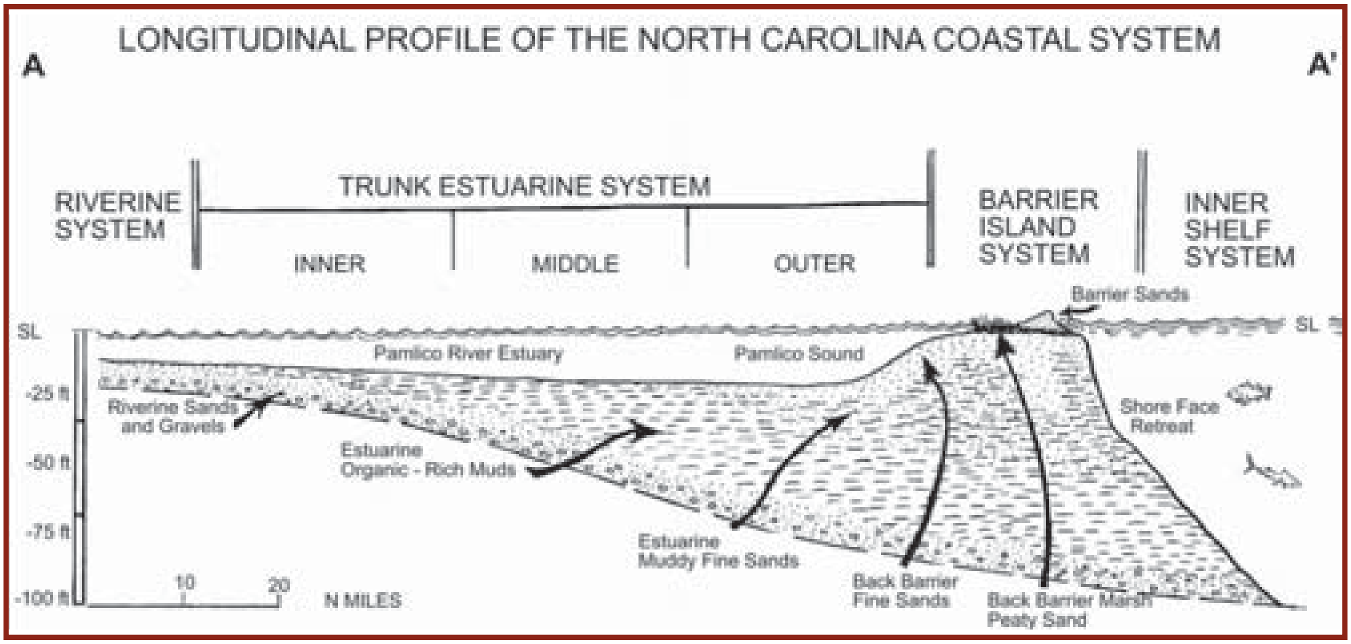

FIGURE 3-2-3. *Schematic cross-sectional profile A-A' shows morphology down the central basin axis of the drowned-river estuaries. The profile extends from the upstream freshwater riverine system to the downstream barrier island sand dam and shows changing bathymetry and sediment composition through the estuarine system. Tributary estuaries have the same basic geometry, but downstream they flow into the trunk stream. See Figure 3-2-2 for location of profile A-A'.*

extensive fine-sand flats behind the barrier islands (Fig. 3-2-3). Back-barrier sand flats form as the estuary fills with sediment from barrier island processes that include wind-blown sand and storm overwash sand and gravel. In addition, barrier island segments dominated by either modern or ancient inlets are characterized by flood-tide deltas deposited within the back-barrier estuarine system. Flood-tide deltas are large lobes of subaerial to subtidal fine sand that form on the inside of the inlet and readily convert to back-barrier marsh platforms when the inlet closes down.

Often, the mouths of tributary estuaries contain extensive fine-sand shoals that extend across much of the central basin. These shoals can severely restrict and modify the physical and chemical dynamics within the tributary estuary. The shoals form in response to higher wave energy within the trunk estuary that actively erodes sand from the rapidly receeding shorelines. The sand, which is concentrated along the beach and adjacent perimeter platform, is then transported along the perimeter platforms by storm winds and currents, and deposited as a prograding bar into the central basin at the tributary mouth.

3.2.B. Basin Sediments

The estuarine basins generally act as repositories that trap and accumulate sediments through time. Thus, most estuarine habitats have shallow water depths (less than 24 feet). Sediments that floor the estuarine system interact with waves and currents and play integral roles in the life and health of the estuarine system. Sediments provide substrate for the bottom community of plants and animals, as well as interacting with the water column as a sink and a source for nutrients, gases and contaminants. As the sediment type varies, so do the bottom communities and the water column interactions.

The type of sediments that comprise the North Carolina estuarine system generally consist of three basic end-members: sand, peat and organic-rich mud — all are highly erodable. These sediments are derived from four sources as follows.

1. Peat and organic-rich sediments accumulate in response to vegetation growth in riverine swamp forests and in freshwater, brackish water, and saltwater marshes.
2. The brown-water rivers that drain the Piedmont and Appalachian Provinces deliver a significant suspended sediment load of mud to the estuaries, primarily during flood stage.
3. Sand, mud and organic matter are supplied to the estuaries through the erosion of sediment bank and marsh shorelines that surround the estuaries.
4. Fine sands are transported from the oceans into the estuaries by wind and water currents either through inlet processes or over the top of barrier islands during storms.

The input of new sediment into the estuarine system from the latter three sources is largely

Character of Drowned-River Estuarine System

storm dependent and associated with high-energy winter seasons or individual hurricane or nor'easter storm events.

The distribution pattern of each sediment type is related to basin morphology, sediment source and estuarine processes (Figs. 3-2-3, 3-2-4, 3-2-5). The central basin of the estuaries consists of a very uniform, soft, dark gray, organic-rich mud (ORM) (Riggs, 1996). Figure 3-2-5 displays the average composition of organic matter, mud and sand in the ORM and its distribution within the central basin. Notice how the ORM gives way to total sand in the high wave-energy environments of the shallow perimeter platforms on both estuarine sides. The perimeter platform sand consists primarily of chemically inert quartz. The fine quartz sand in the ORM grades into medium- to coarse-quartz sand on the perimeter platforms and strandplain beaches (Fig. 3-2-5). Quartz sand also is the dominant sediment in the riverine channels of all trunk and tributary rivers (Fig. 3-2-4A), as well as the back-barrier estuaries where the fine sand is derived from the oceans and barrier islands by storm winds and overwash processes (Fig. 3-2-3).

Concentration of organic matter in the sediments is highly variable throughout the estuaries and ranges from 0 to 86 % of the total sediment. Sediments with 50 % or greater organic matter are called peats that form either in the swamp forests of riverine floodplains (Fig. 3-2-4A) or in coastal marshes (Fig.3-2-3). If a significant source (> 50%) of sand or mud is available to a riverine floodplain or coastal marsh, the resulting sediment will be a peaty sand or peaty mud, respectively. Fine-grained organic detritus, in concentrations less than 50%, is mixed with inorganic clay to form the extensive deposits of organic-rich muds (Figs. 3-2-3, 3-2-4B, 3-2-5). Organic-rich mud is the most pervasive sediment that forms the benthic habitat for about 70% of the estuarine system and generally fills the central basins (Riggs, 1996). Fine-grained organic detritus is derived internally by storms flushing swamp forests and marshes and erosion of associated peat shorelines. The interface between organic-rich

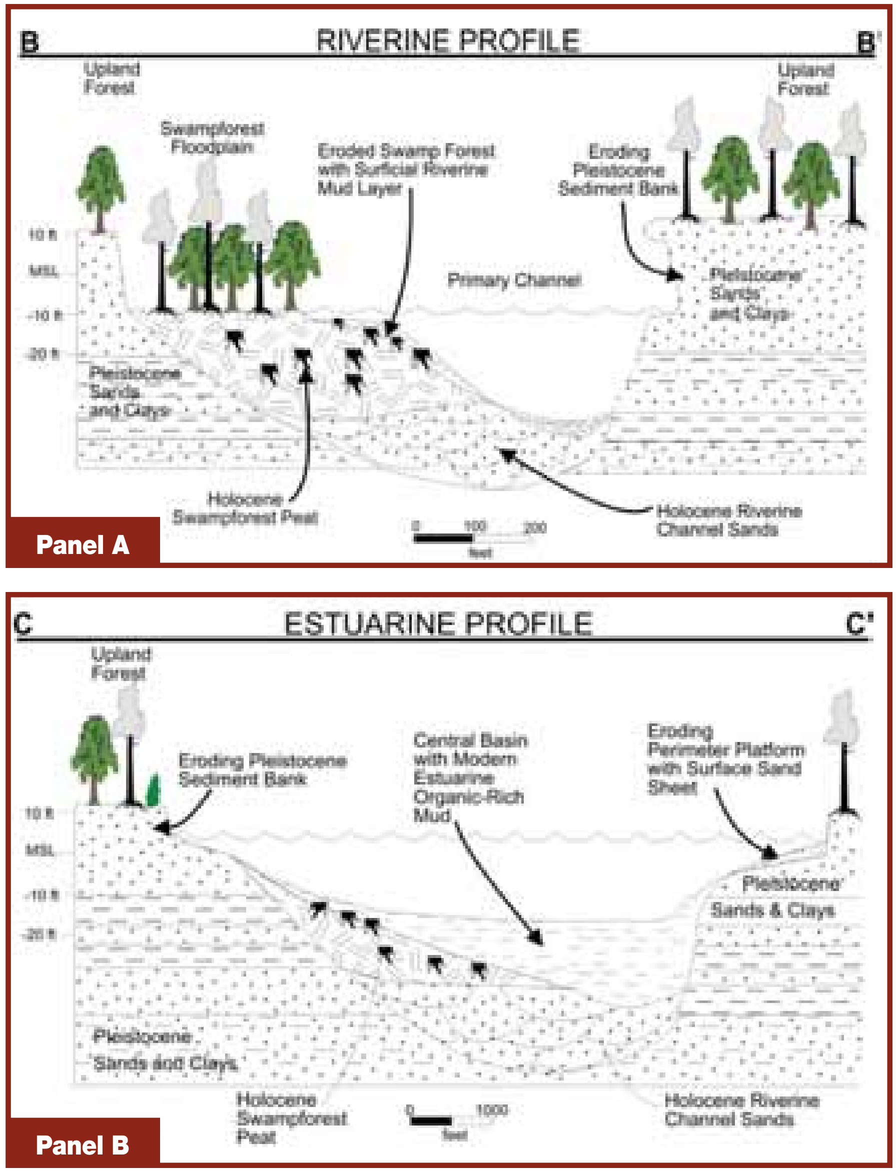

FIGURE 3-2-4. *Schematic cross-sectional profiles of the transition zone from riverine to estuarine ecosystems within the drowned-river estuaries of North Carolina. See Figure 3-2-2 for location of profiles B-B' and C-C'.* ***PANEL A.*** *Schematic cross-sectional profile B-B' across the riverine portion of the drainage system. Notice the riverine channel is characterized by deposition of sand and gravel, while the associated floodplain is characterized by deposition or organic matter and riverine mud to form peat, muddy peat, and peaty mud sediment.* ***PANEL B.*** *Schematic cross-sectional profile C-C' across the upper estuarine portion of the drainage system. Notice how the swampforest floodplain peat deposit has been largely eroded away and only locally buried and preserved in the transition from a riverine to an estuarine system. A sediment inversion has taken place with the organic-rich mud being deposited within the central basin and sand deposition occurring on the shallow perimeter platform in response to shoreline erosion of the older sediment units.*

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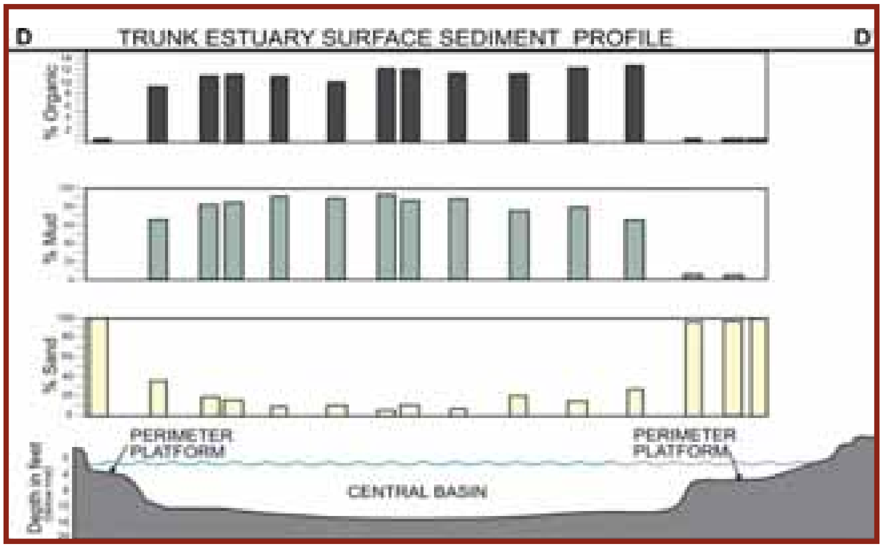

FIGURE 3-2-5. *Schematic cross-sectional profile D-D' showing the morphology and distribution and composition of general sediment types perpendicular across a drowned-trunk river estuary. The general profile shape is that of a shallow, flat-bottomed dish and is characteristic of most North Carolina estuaries. The shoreline grades into the shallow-sloping perimeter platform eroded into older sediments and then drops into the deeper central basin, the most extensive habitat within the North Carolina estuarine system. See Figure 3-2-2 for location of profile D-D'.*

mud and the overlying water contains a major population of micro-organisms, as well as a large community of worms, clams, shrimp, crabs and fish. Many of these benthic organisms are filter- and detritus-feeders that concentrate, pelletize and redeposit the organic-rich mud sediment.

Peats have greater than 50% organic matter and form in two ways. First, peat can form as in-place growth of vegetation in swamp forests or grass marshes. This type of peat contains a framework of plant roots and stems in growth position mixed with organic detritus and inorganic mud from sediment-laden storm waters. Swampforest peats form in floodplains of the trunk and tributary rivers (Fig. 3-2-4A). Marsh peats form around low-energy shorelines in the outer portions of the trunk and tributary estuaries and contain much finer-grained organic matter than swampforest peats (Fig. 3-2-2). Second, detrital peat formed as organic detritus is derived from the erosion of swamp forest and marsh peats and is transported and redeposited as secondary accumulations of organic matter.

3.3. BACK-BARRIER SOUNDS

3.3.A. Back-Barrier Sounds of the Northern Province

The back-barrier sounds of the Northern Province (Figs. 2-2-1, 3-2-2) are medium to large coast-parallel estuaries that include: Currituck Sound in the north (Fig. 3-3-1A); Roanoke and Croatan sounds separated by Roanoke Island (Fig. 3-3-1B); Pamlico Sound, the largest estuary (Figs. 3-3-1C, 1D, 1E); and Core Sound (Fig. 3-3-1F) in the south. Only four inlets exist in over 190 miles of barrier islands, limiting the influence of oceanic water and processes to this estuarine system. In addition, there is a major input of fresh water from both Piedmont- and Coastal Plain-draining rivers. This results in an estuarine system with very low amplitude astronomical tides and highly variable salinities that range from freshwater to medium-brackish waters throughout extensive portions of these large water bodies. Only in the regions of direct oceanic influence around the inlets do the waters have regular astronomical tides and develop high-brackish salinities.

Core Sound has the highest salinities due to the presence of inlets at both ends and in the middle of the sound (Fig. 2-1-2), in combination with a minimum of freshwater input from rivers. Pamlico Sound ranges from high-brackish salinities around the three major inlets to medium- to low-brackish salinities along the western shores due to the high volume of freshwater river discharge. Currituck Sound is generally fresh today due to the absence of inlets. However, depending upon the storm and rainfall patterns, some seasons are characterized by the incursion of low- to moderate-salinity waters. Historically, Currituck Sound was a high salinity estuarine system due to the presence of several major inlets. Roanoke and Croatan sounds tend to have highly variable salinities that range from fresh- to medium-brackish, depending upon the amount of fresh water discharge and wind patterns.

Because these sounds have relatively large surface areas with moderately uniform depths and no interior salt marshes, there is maximum response to waves and wind tides (Fig. 3-3-1). Thus, the water is generally well mixed, both vertically and horizontally, by wind waves and currents as water sloshes back and forth in response to irregular and rapidly changing weather events. Normal wind tides are minor (< 1 foot) with storm-tide amplitudes commonly up to 3 to 5 feet and, rarely, up to 10 feet or more in response to major hurricanes. The direction, intensity and duration of wind determines the currents and tide levels. For example, a nor'easter that blows strongly for several days produces strong south-flowing currents. This will blow much of the water out of Currituck, Roanoke and Croatan sounds (with 3- to 5-foot lower water levels) and produce flood conditions in southern Pamlico and Core sounds (with 3- to 5-foot higher water levels). This sloped water surface will hold as long as the wind continues to blow. As soon as the wind relaxes in intensity or shifts direction, the water flow responds immediately.

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Character of Drowned-River Estuarine System

FIGURE 3-3-1. *Oblique aerial photographs of back-barrier estuaries in the Northern Province.* ***PANEL A.*** *Photograph of Currituck Banks (1998) shows the back-barrier marshes and marsh shorelines that formed on the flood-tide delta of an historic inlet into Currituck Sound. This marsh shoreline erodes only slightly due to the shallow waters and moderate fetch of Currituck Sound. The Currituck County mainland is in the distance.* ***PANEL B.*** *The very wide barrier island at Nags Head (1991) contains Jockey's Ridge State Park. This back-barrier shoreline is open to the extremely large fetch of Albemarle Sound to the northwest, causing this stretch of low sediment bank shoreline in Roanoke Sound to be severely eroded. Roanoke Island is in the distance.* ***PANEL C.*** *This photograph (1991) looks through Oregon Inlet to the extensive, barely emergent sand flats associated with the inlet's flood-tide delta. If Oregon Inlet closed, these sand flats would quickly revert to salt marsh similar to Figure 3-3-1A. The vast Pamlico Sound extends southwest into the distance.* ***PANEL D.*** *The very narrow, overwash dominated barrier island segment (1991) between*

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On the other hand, during low energy periods or seasons, considerably less mixing occurs, resulting in much longer residence times for the estuarine water. Consequently, these back-barrier sounds tend to be irregularly flooded, wind-tide dominated coastal systems that are surrounded by scarped and rapidly eroding sediment bank and marsh shorelines.

3.3.B. Back-Barrier Sounds of the Southern Province

The back-barrier estuaries of the Southern Province are narrow, coastal parallel estuaries (Fig. 2-1-2) that range from areas dominated by open water to areas dominated by salt marsh and tidal creek systems. The widest systems consist largely of open water, occur just south of Cape Lookout and include Back Sound and most of Bogue Sound (Fig. 3-3-2A). As the estuarine system narrows to the southwest, the size of Bogue Sound diminishes significantly and becomes dominated by salt marsh (Fig. 3-3-2B). Further to the SW, the estuaries become very narrow and include Stump and Topsail sounds behind Topsail Island and Middle and Myrtle Grove sounds behind Wrightsville Beach and Masonboro Island, respectively. In the latter regions and in the area south of Cape Fear, from Long Beach to Sunset Beach, the very narrow back-barrier estuaries are dominated by salt marshes that are highly dissected by tidal creeks (Figs. 3-3-2C, 2D). In the Figure Eight Island to Wrightsville Beach area, Middle Sound, Masons Inlet, Banks Channel and Masonboro Inlet have been severely modified, with development and extensive dredging for navigational channels and recovery of beach nourishment sands over the decades (Figs. 3-3-2D, 2E).

The coastal segment at Onslow Beach is underlain by a submarine headland composed of older limestone with the barrier island perched on top of the rock headland. This has resulted in the narrowing and final disappearance of the estuaries over a small area that can be seen in Figures 3-3-3 and 3-3-4A. The Intracoastal Waterway (ICCW) occurs as a ditch cut through a small upland segment where this headland extends to the beach without a natural estuary. A similar situation exists along portions of the Brunswick County coast with little to no natural estuary along segments of Oak Island and Holden Beach and the ICCW ditch cut through upland (Figs. 3-3-4B, 4C, 4D). West of Shallotte Inlet to the Little River Inlet, the barrier islands front narrow back-barrier estuaries filled with salt marsh and tidal creeks.

In the coastal segment from the southern portion of Carolina Beach to Fort Fisher, the coast has no barrier islands. Here, older geologic units of the mainland form a subaerial headland with a shoreline eroded into the older cemented sandstone units. Locally, the sandstones crop out on the beach north of Fort Fisher and form the only natural rocky ocean beach in North Carolina. Because the shoreline is eroded into the mainland, there is no natural estuary, and the ICCW occurs as a ditch, known as Snows Cut, through the upland to the Cape Fear River.

The Southern Province is characterized by about 18 inlets through the short, stubby barrier islands (Fig. 2-1-2). The combination of abundant inlets, high astronomical tidal ranges, and a few small Coastal Plain rivers draining into the coastal zone results in an estuarine system dominated by ocean water and ocean processes. Mixing within these estuaries is driven from the ocean by the highly regular astronomical tides, with amplitudes of 3 to 5 feet that generally increase southward. The regular tides have strong tidal currents associated with them, that transport large volumes of ocean water into the estuaries, mix it with small volumes of fresh water discharge to form the resulting high brackish waters.

Because of the relatively small surface area (Fig. 3-3-2), the water in these estuaries experiences minimal effects from waves and wind tides. Consequently, large portions of the estuaries are dominated by sloped mud flats riddled with tidal channels and extensive salt marshes and oyster reefs. These narrow estuaries are regularly flooded, astronomical tide-current dominated coastal systems. Locally, these marshes have been highly modified by human activity, including an extensive network of dredged navigation channels and associated spoil islands, marsh drainage ditches for mosquito control and landfill for development purposes.

3.4. TRUNK ESTUARIES

3.4.A. Trunk Estuaries of the Northern Province

Four major Piedmont-draining rivers flow into the Northern Province of the coastal zone (Fig. 2-1-2). The Chowan and Roanoke rivers become the Albemarle Sound estuary, the Tar River becomes the Pamlico River estuary and the Neuse River becomes the Neuse River estuary. These estuaries form the major coast-perpendicular or trunk estuaries. The trunk rivers drain the Piedmont and Appalachian provinces,

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Buxton (in the foreground and out of the picture) and Avon (at the top of the picture). This back-barrier segment is characterized by old overwash fans with minor salt marsh platforms that are eroding. Notice N.C. Hwy. 12 and the highly scarped barrier dune ridge constructed to the east of the road and designed to prevent the overwash process. Without regular overwash events, the back-barrier shoreline will not be frequently renourished, resulting in increased rates of shoreline erosion. ***PANEL E.*** *An overwash barrier island segment on Ocracoke Island (1998) shows the destruction of the barrier dune ridge that has buried N.C. Hwy. 12. The overwash flats are still largely intact, covered with extensive salt marshes, and now being eroded on the estuarine side. Pamlico Sound is in the distance.* ***PANEL F.*** *This photograph (1982) shows the overwash processes of Core Banks, with extensive salt marshes that formed on the flood-tide delta of an historic inlet into Core Sound. This marsh shoreline erodes only slightly due to the shallow waters and low fetch of Core Sound. The Carteret County mainland is in the distance.*

C O N T I N U E D :

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FIGURE 3-3-2. *Oblique aerial photographs of back-barrier estuaries in the Southern Province.* ***PANEL A.*** *Photograph of Emerald Isle on Bogue Banks (1982). The low to high sediment bank, back-barrier shoreline faces the open waters of Bogue Sound with the Carteret County mainland in the distance.* ***PANEL B.*** *A 1982 photograph looking southeast across the extensive shallows towards Emerald Isle. The west end of Bogue Sound is dominated by shallow flats and associated salt marshes.* ***PANEL C.*** *A 1998 photograph of Figure Eight Island shows the extensive development of an internal estuarine salt marsh and tidal channels that dominate Middle Sound. Notice the one major shore perpendicular channel that connects the Intracoastal Waterway (ICWW) with the Atlantic Ocean through Mason Inlet to the left off the photo (see Figure 3-3-2E). The Pender County mainland is in the distance.* ***PANEL D.*** *A 1998 photograph of the tidal creeks and salt marshes that fill Middle Sound. The photo is looking east across the eastern side of Figure Eight Island.* ***PANEL E.*** *A 1998 photograph looking northeast from Shell Island in the foreground, across Mason Inlet, to Figure Eight Island in the distance. The Shell Island Resort is the high-rise building in the foreground.* ***PANEL F.*** *A 1998 photograph of the highly developed estuarine area at Wrightsville Beach. Banks Channel has been extensively dredged over the decades to supply beach nourishment sands to the ocean beach and to maintain the extensive network of navigational channels. Most of the estuarine shoreline has been bulkheaded to prevent shoreline erosion.*

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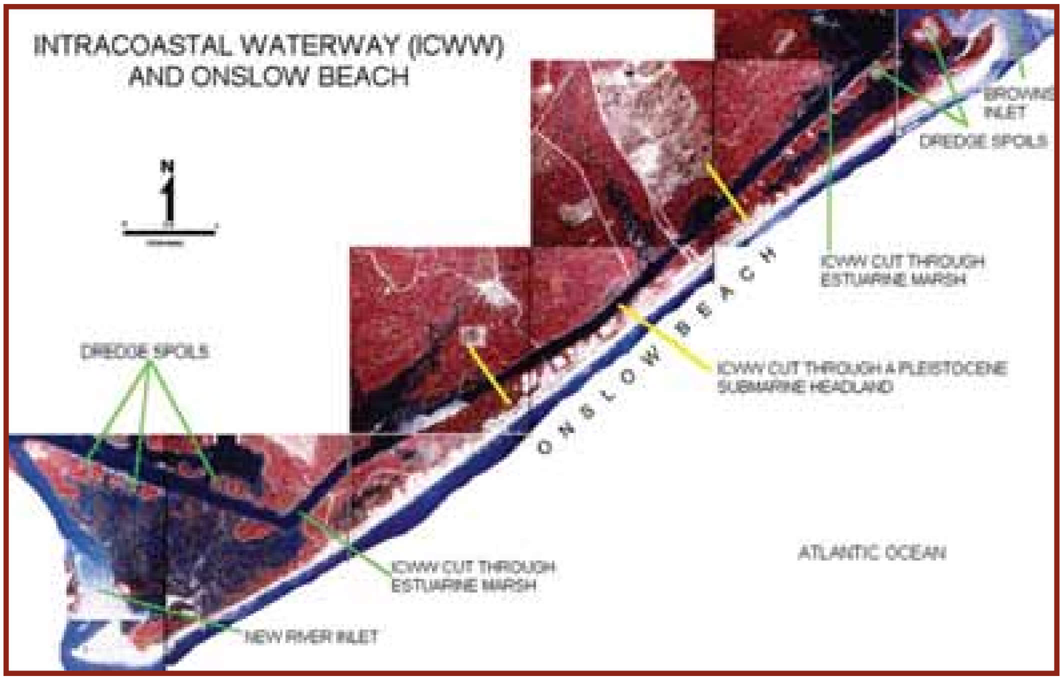


FIGURE 3-3-3. *Infrared aerial photograph mosaic of the Intracoastal Waterway (ICWW) dug channel between the mainland and Onslow Beach. This image shows the ICWW cut through the Pleistocene subaerial headland and the estuarine marsh (dark-colored vegetation) on either side of the headland (bright red-colored vegetation). Notice the abundant dredge spoil piles along the ICWW (bright red circular forms). Both the estuarine marsh and sediment bank shorelines are severely eroding along this entire length of the ICWW ditch. Infrared digital orthophotography was flown in March 1996 for the U.S. Marine Corps, Camp Lejeune, N.C.*

discharging large volumes of fresh water into the estuarine system. They also carry significant loads of sediment derived from the weathering and erosion of the upland clay soils, from which they derive their designation as brown-water rivers.

The transition zone from river to estuary (Fig. 3-4-1) occurs in a broad zone where the river valley reaches sea level and is flooded by estuarine waters. Within this broad transition zone, riverine processes give way to estuarine processes. Due to the low sloping land in the Northern Province, coastal flooding occurs far upstream, producing the deeply embayed estuarine system. Considering all of the trunk estuaries and associated tributaries that have been flooded by sea level, North Carolina has over 3,000 miles of estuarine shoreline within the Northern Province alone (Fig. 2-1-3).

Because the total volume of ocean flow through the four inlets is small and the freshwater discharge is high, the trunk estuaries have low salinity. The Neuse and Pamlico River estuaries range from medium- to low-brackish salinity on the seaward side, and grade into low brackish to fresh water in the landward direction. Albemarle Sound is almost totally fresh water due to the absence of inlets north of Pamlico Sound. This lack of oceanic influence also results in the absence of regular astronomical tides and associated tidal currents in the Albemarle Sound region.

Since the trunk estuaries have extremely large expanses of surface water, wind and storm tides are very important physical processes that irregularly mix the water column and set up the current patterns. The wind-tide fluctuations in water level are driven by major weather patterns and individual storm events causing these large embayed estuaries to be irregularly-flooded, wave-dominated coastal systems that are only well mixed during storms and the stormy seasons. Thus, during the generally dry, hot, and calm summer months, the denser salt water forms a bottom layer that moves up the estuarine system, with the freshwater river discharge flowing seaward over the surface. This sets up a major vertical stratification with little to no mixing during the calm "dog-days" of July and August. As water temperatures rise and oxygen levels diminish, the highly stratified water becomes anoxic, causing significant chemical and biological consequences, including massive fish and clam kills.

3.4.B. Trunk Estuaries of the Southern Province

Most rivers draining to the coast in the Southern Province are small black-water streams that discharge low volumes of fresh water (Fig. 2-1-2). These rivers carry relatively low sediment loads, but contain large quantities of organic components giving the water the color of over-brewed tea. The one major exception is the Cape Fear River that does drain into the Piedmont. Consequently, the Cape Fear River is a brown-water river due to the presence of abundant sediment derived from erosion of the clay Piedmont soils. It also has a much larger river valley and greater water discharge. The Cape Fear River estuary is the only major trunk estuary in North Carolina that discharges directly into the Atlantic Ocean, without passing through a back-barrier sound first.

Character of Drowned-River Estuarine System

FIGURE 3-3-4. *Photographs of shoreline erosion along the Intracoastal Waterway (ICWW) channel.* ***PANEL A.*** *Oblique aerial photograph of the east side of Onslow Beach and Browns Inlet in Figure 3-3-3 showing the ICWW cutting through the estuarine marsh (light green-colored vegetation) behind Onslow Beach in the foreground and the Pleistocene subaerial headland (dark green-colored vegetation) in the background. Notice the string of old, high and circular dredge spoil piles and the active, irregular-shaped dredge disposal site along the left side of the ICWW and covered with upland vegetation (dark green-colored).* ***PANEL B.*** *Photograph of the eroding estuarine marsh shoreline along the ICWW at low astronomical tide. Notice that at this tide level, boat wakes will erode the soft peat beneath the tough modern marsh root mass, producing a severe undercut peat block that will ultimately break off.* ***PANEL C.*** *Photograph of an eroding low to high sediment bank shoreline along the ICWW at low astronomical tide. Shoreline erosion will not take place during this tide level as the wave energy is expended on the very broad strandplain beach. However, during high tide, the boat wakes break directly on the base of the wave-cut cliff, severely eroding the bank with the ultimate failure of large slump blocks and associated trees. Notice the Pleistocene iron-cemented sandstone in the foreground that is slightly more resistant to the erosional process.* ***PANEL D.*** *Photograph similar to Panel C with a desperate, but unsuccessful effort to stop the erosional process. Assuming that the steps in the background are four feet wide, this shoreline has receded approximately 100 feet since the ICWW was cut in the 1930s, resulting in an erosion rate of about 1 to 2 feet per year.*

The numerous small trunk river valleys form a series of coast-perpendicular, drowned-river estuaries that include the North, Newport, White Oak and New River estuaries (Fig. 2-1-2). These water bodies are much smaller than those in the Northern Province since they are totally Coastal Plain drainage systems with high land slopes (Figs. 3-2-2, 3-2-3, 3-2-4 and 3-2-5). These drowned-river estuaries often have deeper water then the back-barrier sounds and have similar characteristics to the northern trunk river valleys, except for the marshes. In general, the outermost portions contain some fringing marshes that are controlled by regular astronomical tides. However, the main portions of these estuaries are large, open water bodies that cause wind waves and irregular wind tides to be the important processes. Thus, the trunk estuaries tend to be irregularly flooded, wave-dominated coastal systems with shorelines characterized by eroding sediment banks and perimeter marshes.

Character of Drowned-River Estuarine System

FIGURE 3-4-1. *Two infrared aerial photograph mosaics of the riverine-estuarine transition zone. Photographs were flown by the High Altitude Program of the U.S. Department of Agriculture. See Figure 2-1-3 for the location of these panels.* ***PANEL A.*** *Aerial photograph (4/1/1982) of the Chowan River. Notice that the swampforest shoreline of the floodplain is being eroded by the systematic drowning of the swampforest vegetation in response to ongoing sea-level rise.* ***PANEL B.*** *Aerial photograph (3/29/1982) of the Tar-Pamlico rivers. Notice that the swampforest shoreline of the floodplain is being eroded by the systematic drowning of the swampforest vegetation in response to ongoing sea-level rise.*

Many of these southern trunk estuaries are partially cut off from the back-barrier estuaries as a result of human activities. Construction of the ICCW and associated navigational channels resulted in an extensive network of dredge-spoil piles that have greatly modified the water flow (Figs. 3-3-3, 3-3-4A). In addition, some trunk estuaries, such as the North River, have bridges that act as partial dams and restrict current flow. These changes have dampened the oceanic influence, resulting in estuaries that are not as well mixed as the back-barrier estuaries and with a significantly decreased influence of salt water and regular astronomical tides. Consequently, the waters grade over short distances — from high-brackish salinity on the ocean side, to low-brackish and fresh water away from the coast.

3.5. TRIBUTARY ESTUARIES

Flowing into the trunk estuaries is a network of tributary streams (Fig. 3-2-2) that are like the capillaries flowing into the arteries of the human circulation system. The lower portion of each tributary valley is also drowned when it reaches sea level to form a generally coast-parallel estuary (Fig. 3-2-2). In contrast to the trunk estuaries, the myriad of black-water tributary streams are all derived from the Coastal Plain. These estuaries consist primarily of fresh water that is black due to the decomposition of organic matter derived in the upland swamps and pocosins from which they drain.

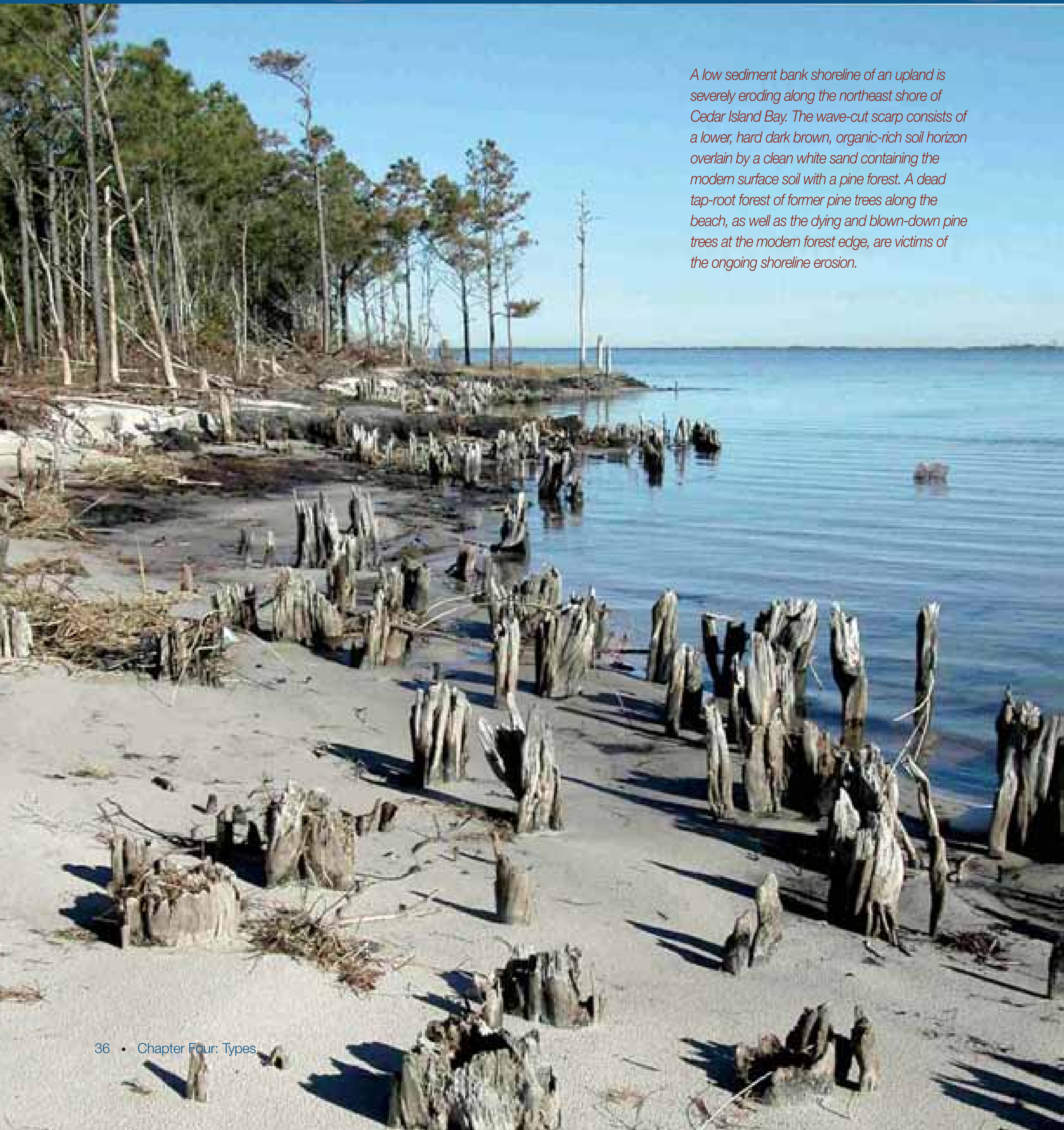
Small tributary estuaries tend to have irregular riverine geometry and are characterized by low wind and wave energy. Thus, the shoreline is generally stable and covered by a heavy growth of vegetation composed of either swamp forests in the upper reaches or fringing marshes throughout the remaining shoreline segments (Figs. 3-2-2, 3-2-4).

Tributary estuaries are smallest on the western or inner portions of the trunk estuaries and become generally larger in the eastward direction as the slope of the land approaches sea level (Fig. 3-2-2). Finally, on the eastern side where much of the land is now below sea level, the tributaries have flooded completely to form the very large back-barrier estuaries that include Core, Pamlico, Roanoke, Croatan and Currituck sounds.

CHAPTER FOUR:

Types of Estuarine Shorelines

DROWNING



A low sediment bank shoreline of an upland is severely eroding along the northeast shore of Cedar Island Bay. The wave-cut scarp consists of a lower, hard dark brown, organic-rich soil horizon overlain by a clean white sand containing the modern surface soil with a pine forest. A dead tap-root forest of former pine trees along the beach, as well as the dying and blown-down pine trees at the modern forest edge, are victims of the ongoing shoreline erosion.

CHAPTER FOUR:

Types of Estuarine Shorelines

4.1. SHORELINE TYPE

All North Carolina estuaries result from the post-glacial rise in sea level and resulting flooding up the stream valleys of the Coastal Plain drainage system. Table 4-1-1 outlines the general shoreline types that characterize the North Carolina estuarine perimeters. The estuarine shorelines occur either along the banks within the drowned-trunk and tributary rivers or along the backside of the barrier islands. Four basic categories of shorelines occur within the North Carolina estuarine system: sediment bank shorelines, organic shorelines, combination shorelines and back-barrier shorelines (Table 4-1-1).

4.2. SEDIMENT BANK SHORELINES

Sediment bank shorelines are subdivided based upon bank height: low bank, high bank and bluff (Table 4-1-1). Most sediment bank shorelines are eroded into older sand and clay sediment units. If the eroding sediment bank contains adequate sand supplies, a strandplain beach will form as a thin and narrow feature delicately perched on top of a wave-cut platform (Fig. 4-2-1). The sand that comprises the beach is derived primarily from the erosion of the adjacent sediment bank and forms a beach along the water line to absorb wave energy.

4.2.A. General Characteristics

Sediment bank shorelines consist of a gently seaward sloping, wave-cut platform below water level and the associated steeply sloping, wave-cut scarp on the landward side of the beach (Fig. 4-2-1). Sand that forms the beach along the shoreline is derived from erosion of older units comprising the sediment bank. Bluffs (> 20 feet) and high sediment banks (5 feet to > 20 feet) occur primarily in the westernmost portion of the estuarine system, are the least abundant types of shorelines, and are in great demand for home-site development (Fig. 4-2-2). Low sediment banks (< 5 feet) are the most abundant type of sediment bank shoreline,

Table 4-1-1 Shoreline Categories and Parameters

Types of shorelines that characterize the North Carolina estuarine parameters.

SHORELINE CATEGORIES	SUBTYPES	DEFINING PARAMETERS
• Sediment Bank Shorelines	Bluff	> 20 feet high
	High Bank	5-20 feet high
	Low Bank	< 5 feet high
• Organic Shorelines	Swamp Forest	Freshwater Riverine Floodplains & Freshwater Pocosins
	Marsh	Fresh, Brackish, & Salt Waters
• Combination Shorelines	Sediment Bank with Cypress Fringe	
	Sediment Bank with Marsh Fringe	
	Sediment Bank with Fringe of Log & Shrub Debris	
	Low Sediment Bank with Stumps	
	Swamp Forest with Strandplain Beach	
	Marsh with Strandplain Beach	
	Human-Modified Shorelines	
• Back-Barrier Shorelines	Overwash Barriers	Mixed Sand Fans & Marsh Platforms
	Complex Barriers	Sediment Banks & Organic Banks
	Inlet	Flood-Tide Deltas

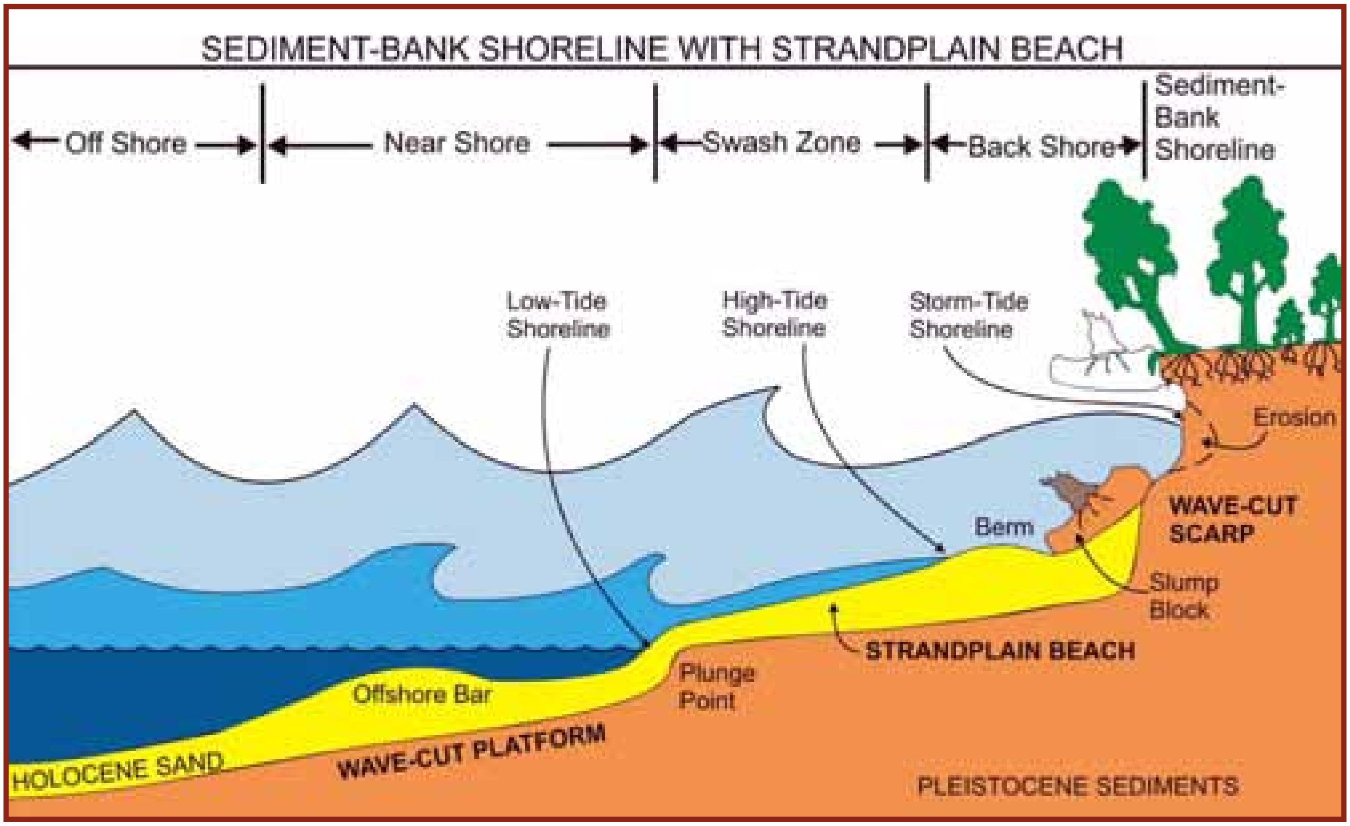


FIGURE 4-2-1. *Schematic model of a sediment bank shoreline showing the following geomorphic features. 1) A wave-cut scarp and wave-cut platform have been eroded into older sediment units (orange) with a strandplain beach (yellow) perched on the platform. 2) Different water levels (blue) and wave sizes that do the work of shoreline erosion, beach building and beach maintenance. 3) The process of eroding and undercutting the bank top during high storm tides and subsequent slumping and reworking of slump blocks to produce the beach sediments.*

and are the dominant type as the uplands slope eastward towards sea level (Fig. 4-2-3).

Almost all sediment bank shorelines are eroding, however, at different rates, depending upon the geographic location within the estuarine system, the exposure to wave energy, and the type and extent of vegetative cover. Erosion rates are extremely variable, ranging from a few feet per decades in the innermost trunk estuaries and small tributary estuaries up to tens of feet per year for exposed low sediment banks in the middle and outer estuarine reaches. Most shoreline erosion takes place in direct response to high-energy storms. Thus, the amount of recession at any location is quite variable from year to year.

4.2.B. Strandplain Beaches

Strandplain beaches are those beaches that occur in front of many sediment bank shorelines within the estuarine system (Figs. 4-2-2B, 2C; 4-2-3A, 3B). A strandplain beach is a thin sand body perched on an erosional wave-cut platform and backed by a wave-cut scarp (Fig. 4-2-1), both of which are composed of older sediment or rock units. This is in contrast to barrier beaches that have water bodies behind the beaches or organic-dominated shorelines (marsh or swamp forest), which rarely have any beach at all. The latter are dominated by the wave-cut scarp and platform with a minimal or no sand beach due to lack of a sand source in the eroding bank (Figs. 4-2-2D; 4-2-3C, 3D).

Every sediment bank shoreline consists of a wave-cut scarp and a wave-cut platform that have been eroded into the older sediments underlying the upland regions (Fig. 4-2-1). If an eroding wave-cut scarp is composed of gravel, sand, muddy sand or even sandy mud, it will produce sands and gravels for building a beach as the sediment bank recedes. In this situation, the coarse sediment derived from the receding shoreline will produce a thin beach that is perched directly on the wave-cut platform. The extent and composition of the beach is directly dependent upon the abundance and composition of sand and gravel in the wave-cut scarp, as well as the rate of shoreline recession. However, if the wave-cut scarp is composed of indurated rock or

FIGURE 4-2-2. *Photographs of eroding bluff and high sediment bank estuarine shorelines.* ***PANEL A.*** *A bluff sediment bank is actively eroding due to the sand composition of the bluff. The wave-cut scarp is dominated by continuous slumping and reworking into an extensive strandplain beach.* ***PANEL B.*** *A high sediment bank shoreline is actively eroding. Notice that erosion was not taking place at the time of the photograph when winds were not blowing, and water level was normal. Large slump blocks, with trees on top, have collapsed onto the beach and are being reworked into a strandplain beach. The trees ultimately will be laid down and act as natural groins to help trap and hold the beach sands in place.* ***PANEL C.*** *A high sediment bank shoreline is actively eroding, as indicated by the location of the colonial farmhouse, which was probably not built on the waters edge. Notice that the size of strandplain beach decreases as the wave-cut scarp height and sand volume decreases.* ***PANEL D.*** *This high sediment bank shoreline is composed of a very tight, fossiliferous, blue mud and consequently is eroding very slowly. Since this is a slowly receding mud bank, there is not an adequate source of sand to build a strandplain beach.*

mud, there probably won't be any sediment from which to build a beach (Fig. 4-2-3D). In this case, the wave-cut platform will consist of indurated rock or compacted clay that is exposed directly to wave action.

Bluffs and high sediment banks tend to have well-developed strandplain beaches, while low sediment banks tend to have only minor strandplain beaches associated with them. The size of strandplain beaches is directly dependent upon the volume of sand potentially available from the receding shoreline. Undercut bluffs and high-bank shorelines collapse and supply large sediment volumes in slump blocks directly to the beach for reworking by wave energy (Fig. 4-2-1, 4-2-2B). As these banks slump, large trees frequently come down with the slump blocks. As waves rework the slump block sediments, the fallen trees and shrubbery accumulate on the beach as natural groin fields trapping and holding the sand in place (Figs. 4-2-2C, 4-2-3B). Since erosion is an ongoing process, new sediment and trees are continuously added to the beach as sediment is lost both alongshore and offshore and trees decompose.

The beach sand on most mainland estuarine sediment bank shorelines is generally derived from the erosion of adjacent sediment banks with no other known sources. Bulkheading and other forms of shoreline hardening on eroding sediment banks terminate the internal sand supply, and beach sands soon begin to disappear (Fig. 4-2-4). Thus,

FIGURE 4-2-3. *Photographs of low sediment bank shorelines.* ***PANEL A.*** *An actively eroding low sediment bank. The size of the strandplain beach has decreased significantly as the height of the wave-cut scarp has decreased (see Figure 4-2-2). Notice that the rate of erosion is so high that the tractor turning area has been eliminated since the crop was planted.* ***PANEL B.*** *A segment of low sediment bank that is stabilized by a heavy growth of vegetation. The sand that forms the strandplain beach was derived from adjacent properties after the banks were cleared for development. Notice how the amount of sand dramatically diminishes into the background and the role of tree trunks as natural groins in trapping and holding the beach sand.* ***PANEL C.*** *An actively eroding low sediment bank that is too small to produce a wave-cut scarp and there is no sand available in the bank to produce a strandplain beach. Consequently, the muddy sediment is slowly washed out from around the trees, leaving the pine forest ghosts and their many stumps standing in shallow water.* ***PANEL D.*** *A low sediment bank that is being converted to a freshwater marsh in response to the ongoing rise in sea level. The soil upon which the pines and live oak were growing has been buried by a thin layer of peat produced by the freshwater grasses. Ongoing shoreline recession produced minimal amounts of sand for development of a minor strandplain beach and has left stumps exposed in the shoreface.*

construction of any hardened structure designed to stop shoreline recession will cut off the sole source of sand for the associated beach. Unless there is a generous neighbor that will continue to let the adjacent shorelines erode, the sand on the strandplain beach will begin to disappear. Hardening of one piece of property along a shoreline will generally increase the rates of erosion on adjacent properties. This is the domino effect that usually forces the neighbors to begin hardening their shoreline, thus accelerating the rate of beach loss.

4.3. ORGANIC SHORELINES

Organic shorelines are subdivided into marshes and swamp forests. They consist of water-tolerant flora, including trees, shrubs, and grasses that grow at the land/water interface and are able to endure temporary but not permanent flooding. Coastal marsh shorelines occur in estuaries that range from fresh to salt water, whereas swampforest shorelines occur only in freshwater wetlands. Swampforest shorelines are associated with riverine floodplains or upland pocosins, which are nonfloodplain swamps that are now at the shoreline due to coastal erosion.

FIGURE 4-2-4. *Photographs of human-modified sediment bank shorelines and no sand strandplain beaches.* ***PANEL A.*** *A high sediment bank shoreline with multiple efforts to stop the erosion using combinations of rock rip-rap, rock revetments and wooden bulkheads.* ***PANEL B.*** *A massive rock revetment protects the high, sediment bank at the Lost Colony on the north end of Roanoke Island.* ***PANEL C.*** *A wooden bulkhead in concert with a small groin field protects a low sediment bank on the northwest end of Roanoke Island.* ***PANEL D.*** *A concrete bulkhead protects a low sediment bank in Bogue Sound. A fringing marsh grass, planted in front of the bulkhead, baffles the wave energy and has trapped some sediment to build up a shallow platform for marsh development. Photo is from North Carolina Sea Grant, N.C. State University.*

The floral communities that dominate organic shorelines and their zonation patterns change laterally as water salinity and tidal processes change. All organic shorelines are characterized by sediment composed either of > 50% organic matter (peat) or composed of < 50% organic matter intermixed with fine sand and mud (peaty sand and peaty mud, respectively), depending upon the specific location within the estuarine system.

4.3.A. Swampforest Shorelines

Swampforest shorelines are dominated by numerous types of wetland trees and shrubs (i.e., cypress, gum, swamp maple, bay, wax myrtle, etc.) and occur within the fresh water, riverine floodplains of the uppermost portions of trunk and tributary estuaries (Fig. 3-4-1). As sea level rises, the lower portions of riverine floodplains become permanently flooded, causing the shrubs and trees to become stressed and die by drowning and producing a swampforest shoreline (Fig. 4-3-1). The vegetation that is least tolerant of flooding dies off first, leaving the most tolerant, the elegant cypress, to stand as lonely sentinels in open water beyond the shoreline (Fig. 4-3-2). This produces one of the most characteristic and beautiful sights within the North Carolina estuarine system. Ultimately, the cypress die and are blown over by storms or undercut by the eroding peat bank along the outer edge of the floodplain as the swampforest shoreline slowly receeds.

Much of the land area that makes up eastern North Carolina in the Northern Province consists of vast upland wetlands known as pocosins. As the shoreline receeds, many of these pocosins are intersected by the coast (Fig. 4-3-3). Some pocosins are cypress- and gum-dominated wetlands (Fig. 4-3-3A, 3B) while others are shrub, bay and pine dominated (Fig. 4-3-3C, 3D). Irregardless of the type of vegetation, the receeding shoreline is

Types of Estuarine Shorelines

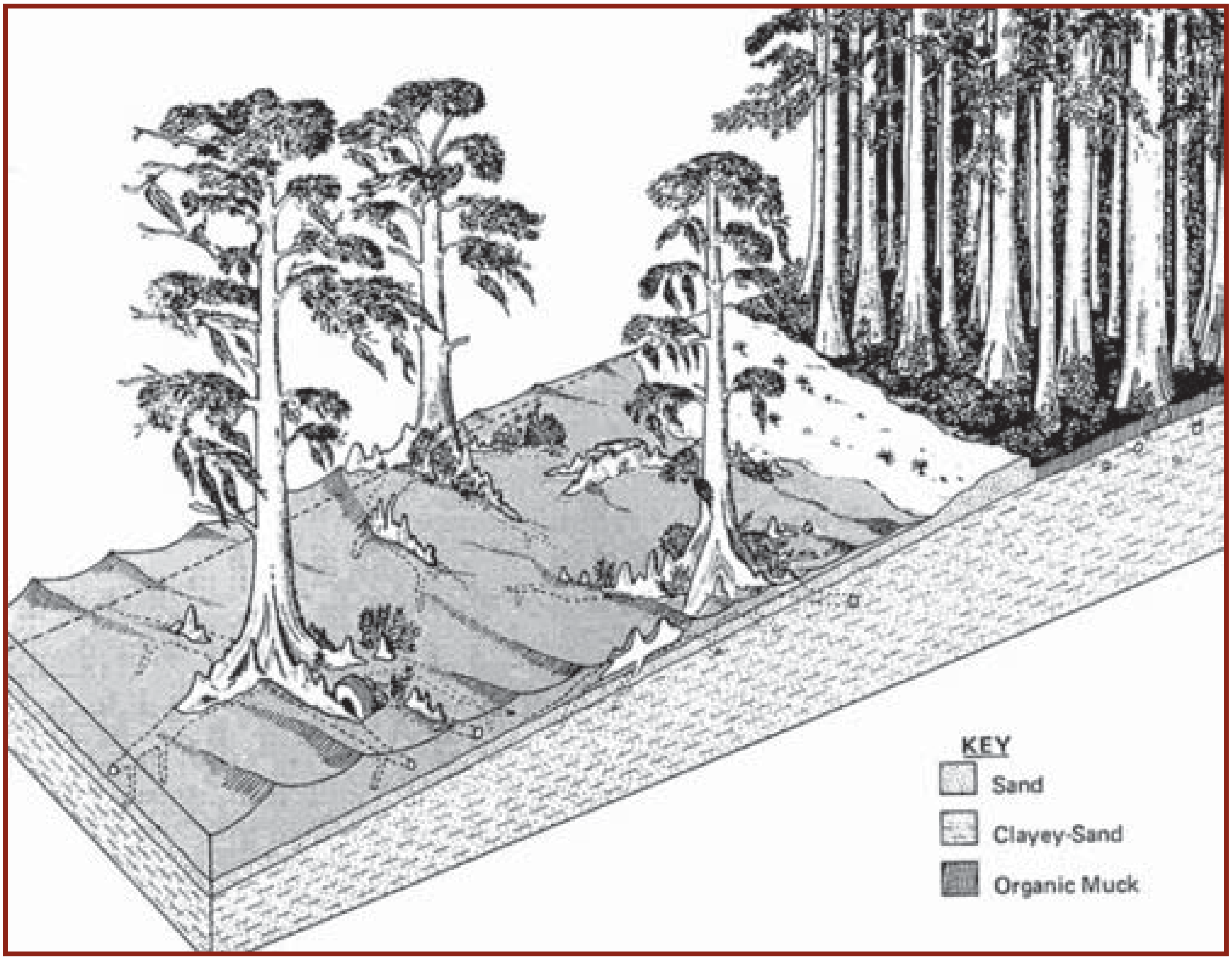


FIGURE 4-3-1. *Schematic model of a swampforest shoreline (modified from Bellis et al., 1975). This type of shoreline has two general occurrences. The primary occurrence is in the transition zone where riverine floodplains intersect mean sea level along the innermost portion of drowned river trunk and tributary estuaries. Within the outer portions of the estuarine system, swampforest shorelines occur wherever shoreline erosion intersects a former upland pocosin. This is a common occurrence in the lowlands of the outer counties such as Currituck, Dare, Hyde, Tyrrell, Pamlico, and Carteret.*

characterized by the ghost remnants of drowned trees and extensive stumps and root masses scattered through the shallow nearshore waters (Fig. 4-3-3D). Locally, the cypress trees are so dense that their large buttressed bases actually produce natural bulkheads or breakwaters (Fig. 4-3-3C).

Swampforest shorelines also occur along coastal segments on the western or more inland side of the coastal system, where small drainages with steep gradients enter a trunk or tributary estuary. Wherever the floodplain is slightly above sea level at the point the stream enters the estuary, the water-tolerant floodplain vegetation is more resistant to shoreline erosion than adjacent sediment bank shorelines, and a cypress headland forms (Fig. 4-3-4A, 4B). This erosion-resistant cypress headland extends into the estuarine water body and acts as a natural groin or breakwater that traps sand on the shallow perimeter platform within the adjacent coastal segments. Ultimately, with rising sea level, the trees die, and the floodplain is drowned to form a small embayed tributary estuary.

If the tributary stream flows diagonally into the estuary, remnants of the floodplain vegetation can be preserved in front of a sediment bank

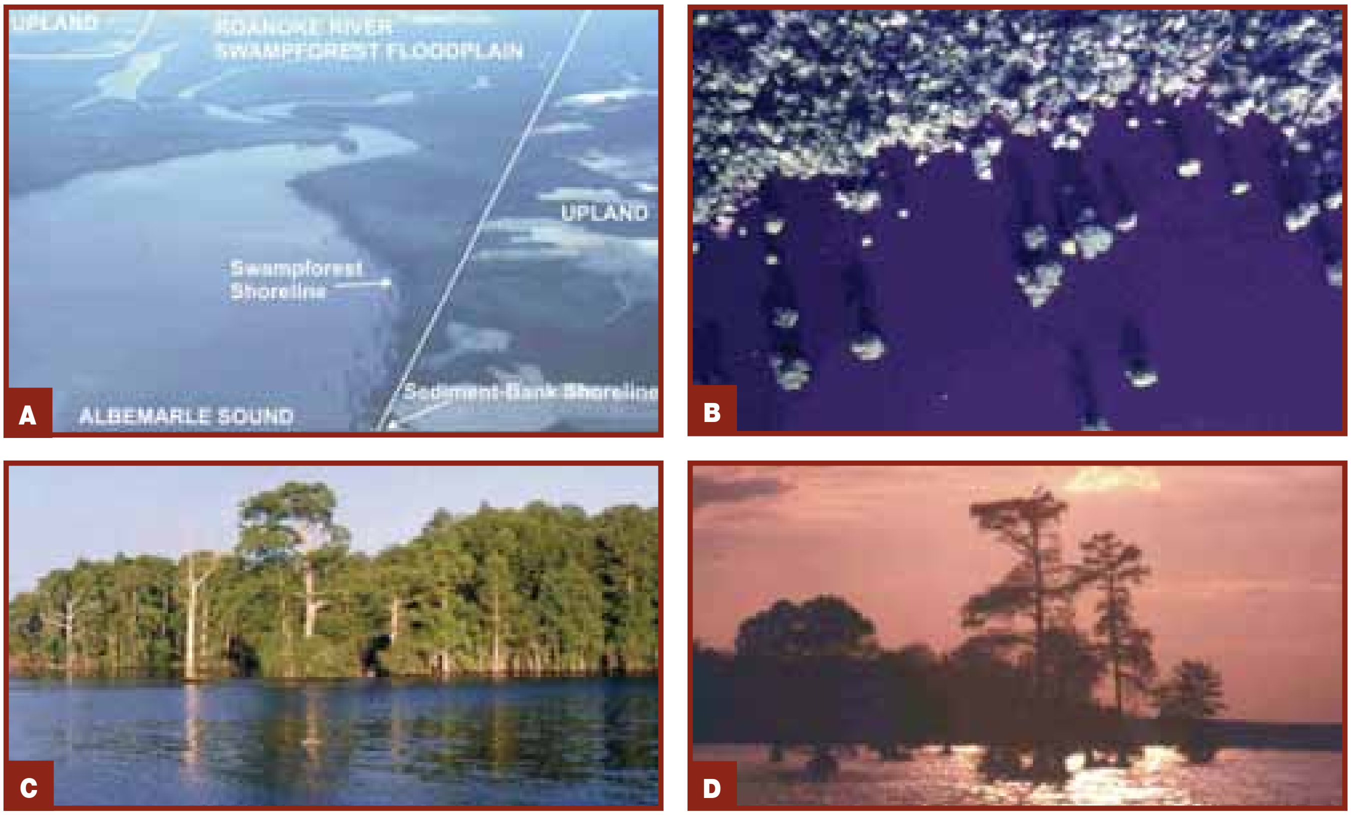


FIGURE 4-3-2. *Photographs of swampforest shorelines in the riverine-estuarine transition zone of the Roanoke River and Albemarle Sound.* ***PANEL A.*** *An oblique aerial photograph of the transition zone between the Roanoke River swampforest floodplain and Albemarle Sound estuary. Notice the abundant cypress trees that can tolerate permanent drowning more readily than other species. Species that are less tolerant of flooding, such as the swamp maple and gum, die off fairly quickly as sea level rises and leave the cypress standing alone in the water as the shoreline slowly recedes by drowning. Notice how the floodplain is totally eroded on the seaward side where the upland comes into direct contact with the estuary to produce sediment bank shorelines.* ***PANEL B.*** *A vertical aerial photograph looking straight down on a receding swampforest shoreline with abundant cypress trees left standing in shallow estuarine waters.* ***PANEL C.*** *A water level view of the photograph in Panel B.* ***PANEL D.*** *A classic view of cypress remnants standing offshore within the upper reaches of North Carolina's drowned river estuaries.*

shoreline. This situation results in development of a cypress fringe in front of the sediment bank (Fig. 4-3-4C, 4D). The remnant vegetation is an important natural bulkhead that greatly reduces wave energy and rates of sediment bank erosion. However, the irregular nature of the trees allows some wave energy to pass between trees, causing slow erosion and sediment production from the bank. This sand forms a strandplain beach, which is critical to the overall dynamics and energy absorption. Unfortunately, such cypress fringes are usually considered by developers and homeowners to be a nuisance that breeds snakes, inhibits swimming, and prevents a clear view of the water. Consequently, cypress fringes are often cleared out causing rapid rates of shoreline recession to set in.

4.3.B. Marsh Shorelines

Marsh shorelines occur throughout the estuaries and are dominated by emergent grasses. Upslope, the marsh grades through a transition zone composed of wax myrtle, marsh elder and silverling and into the adjacent upland composed of pines and hardwoods (Fig. 4-3-5). Freshwater marshes occur in the innermost riverine and estuarine regions and are dominated by cattails, bullrushes, reeds and cordgrass (Fig. 4-3-6A, 6B). The freshwater marshes grade seaward into brackish marshes dominated by either saltmeadow cordgrass (*Spartina alterniflora*) or black needlerush (*Juncus roemerianus*) depending upon whether the estuary is characterized by high- or low-brackish water and astronomical or wind tides, respectively (Fig. 4-3-6C, 6D). Within the inner

Types of Estuarine Shorelines

FIGURE 4-3-3. *Photographs of vegetatively bound swampforest shorelines in the headwaters of small tributary estuaries and outer estuaries where the receding shoreline has intersected pocosin swamp forests.* ***PANEL A.*** *A vegetatively bound swampforest shoreline that displays little to no shoreline recession taking place.* ***PANEL B.*** *Estuarine shoreline dominated by a massive bulkhead like zone of cypress trees that effectively protects the shoreline from day-to-day erosional processes.* ***PANEL C.*** *The estuarine headwaters of a tributary stream are heavily dominated by vegetation. Rising sea level is causing a change in vegetation from less wet to more wet adapted species, as evidenced by the scattered and still-standing dead pine trees.* ***PANEL D.*** *Photograph of a pocosin swampforest shoreline where the receding shoreline has intersected a swamp system perched on a low, upland area. Wave action erodes out the enclosing peat sediment, leaving the ghost trees and stumps standing out in the shallow waters. This type of shoreline occurs primarily in the lowland regions of the outer estuaries in Currituck, Dare, Hyde, Tyrrell, Pamlico and Carteret counties.*

and middle estuarine system, freshwater and brackish marshes may either occur as narrow fringing marshes in front of and protecting segments of sediment bank shorelines (Fig. 4-3-6A, 6B, 6C) or may completely fill small tributary estuaries (Fig. 4-3-6D).

In the outer estuarine regions of the Northern Province, the slope of the upland is minimal as it approaches sea level. Also, these estuaries are characterized by few inlets through the barriers and fluctuating water levels caused by irregular wind tides. Thus, the marshes are generally wave dominated with irregular storm-tide flooding and water that ranges from fresh to middle-brackish. This situation determines three basic characteristics of the northern marshes. First, they tend to occur as vast and spectacular wetland habitats that form as broad, flat platforms with few if any tidal creeks (Fig. 4-3-7A, 7B, 7C). Second, the marshes are dominated by black needlerush (*Juncus roemerianus*) (Fig. 4-3-7A, 7C), with occasional narrow outer rims of one or more species of *Spartina* (Fig. 4-3-7B, 7D). Third, the outer shoreline in any area with a significant fetch is in a destructive or erosional phase (Figs. 4-3-5, 4-3-7D).

Marsh shorelines are characterized by the accumulation of thick beds of fairly pure peat deposited in response to rising sea level. If the outer marsh perimeter is exposed to large stretches of open water with high wave energy, the peat sediment is actively eroded, producing vertical scarps that drop abruptly into 3 to 8 feet of water (Fig. 4-3-5). The scarps are generally characterized by severe erosional undercuts into the soft peat below the extremely tough modern

FIGURE 4-3-4. *Photographs of shorelines dominated by cypress headlands and cypress fringes.* ***PANEL A.*** *An oblique aerial photograph showing the differential erosion rates of a tributary stream and associated swampforest floodplain as it enters Albemarle Sound and the adjacent sediment bank shorelines. The swampforest vegetation drowns and recedes at slow rates, leaving the cypress standing in the shallow waters as the adjacent sediment bank shoreline recedes more rapidly.* ***PANEL B.*** *A ground view of a similar cypress headland in the Neuse River estuary. The cypress form a headland that acts as a large-scale groin trapping an extensive strandplain beach in front of the eroding sediment bank in both the upstream and downstream segments.* ***PANEL C.*** *An aerial photograph looking vertically down upon an eroding sediment bank shoreline with a cypress fringe in front of the eroding bank in the Chowan River.* ***PANEL D.*** *Ground view of a similar cypress fringe fronting a bluff shoreline in the Chowan River. The cypress helped trap sand and build the strandplain beach, as well as partially protecting the adjacent bluff on the right side of the photo. The protection has allowed a significant growth of vegetation that further protects this shoreline.*

root mat (Fig. 4-3-7D). With continued undercutting, the overhang surges with each wave until large undulating peat blocks finally break off, supplying eroded organic detritus and large peat blocks to the adjacent estuarine floor (Fig. 4-3-5). Erosion of marsh peat shorelines is one of the major sources of fine organic detritus that forms the organic-rich mud sediments within the estuarine central basins.

The landward side of these marshes is usually in a constructive mode with the marsh migrating onto the adjacent upland areas as sea level rises (Fig. 4-3-5). Thus, as the marshes are eroded on the estuarine side, they are generally expanding onto low-sloped uplands on the landward side. Rising sea level causes the groundwater level to rise, stressing and finally drowning the lowermost line of upland vegetation. The marsh accumulates peat sediment to allow the vertical growth of grasses to keep up with sea level. This vertical growth results in the marsh encroaching upon the upland and burying the old stumps and logs in the processes (Figs. 4-3-5; 4-3-6A, 6B). Landward expansion of the marsh continues until the upland slope becomes too steep or the upland is filled or hardened for development (Fig. 4-2-4D). Then marsh expansion is terminated, and future rise in sea level will result in a net loss of marsh habitat.

The back-barrier estuaries of the Southern Province and areas around the inlets in the Northern Province are characterized by high-

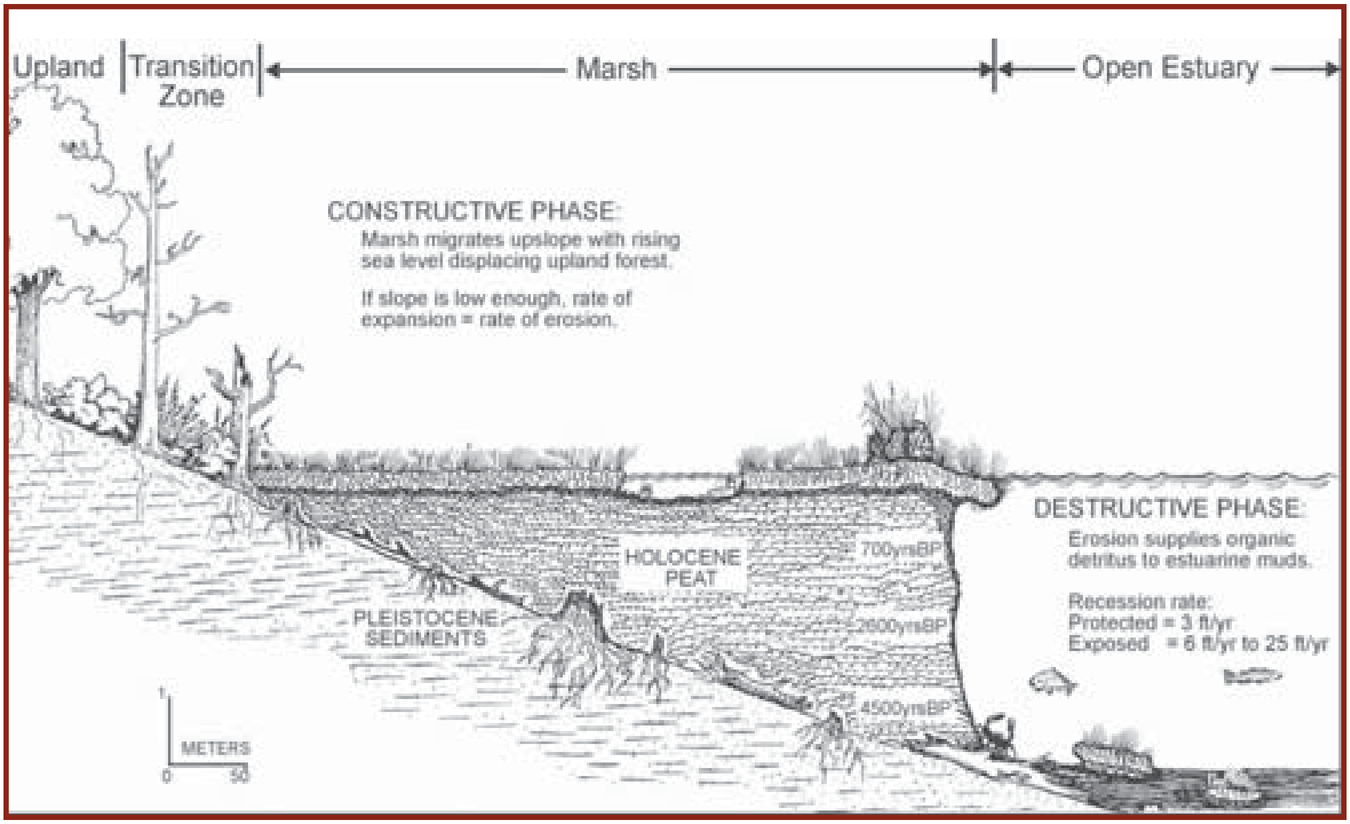


FIGURE 4-3-5. *Schematic model of a marsh platform shoreline. This type of marsh occurs extensively in the Northern Province where the astronomical tides are minimal and wind tides dominate. These flat marshes generally maintain a steady-state condition in response to rising sea level. The marsh itself and the landward side are generally constructive as it responds to rising sea level by the vertical accretion of organic matter and contemporaneous migration upslope. Sea-level rise stresses and kills the upland vegetation that is replaced by the rising marsh vegetation, systematically burying the upland stumps and logs beneath the rising marsh. High wind tides flood the marsh, but wave energy is quickly baffled by the marsh grasses. However, low wind tides allow wave energy to break directly on soft peat beneath the modern root mass, causing severe undercutting of the bank and ultimately break off large peat blocks. Thus, the seaward side of marsh is generally in a destructive phase with recession rates totally dependent upon the fetch and amount of wave energy. The radiocarbon age dates are from the marshes at Wanchese on the south end of Roanoke Island (Benton, 1980).*

brackish salinity and are regularly flooded by astronomical tides. The salt marsh grass generally grows along the upper portions and tops of sloping banks between the mean- and high-tide lines. Salt marsh cordgrass and salt meadow cordgrass (*Spartina alterniflora* and *Spartina patens*) form the dominant vegetation in these salt marshes.

Below the mean tide line and extending into the adjacent tidal channels are widespread, low sloping, mudflats and sandflats (Figs. 4-3-8B, 8C). The lower portions of the marsh and the flats are often covered with vast reefs of oysters (Fig. 4-3-8D). The marsh vegetation grows on the upper portions of these low sloping ramps, where it actively traps sediment and builds the shoreline out into the estuary.

The highly protected character of these narrow back-barrier estuaries, in concert with the astronomical tides, result in the constructive growth and expansion of the salt marshes through myriads of tidal channels. Sediments are actively transported into and deposited within the estuaries. Sand and shell gravel are concentrated within the channels, while mud is deposited from suspension on the mudflats and marshes by filter-feeding organisms and the baffling effect of the grasses. Organic matter is contributed from the marsh grasses to produce sediments that range from muddy and sandy peat to peaty mud and sand. It is only the shifting of natural tidal channels that cause local erosion along one side of the channel, while the trailing

FIGURE 4-3-6. *Photographs of fresh to brackish, irregularly flooded, fringing marsh shorelines.* ***PANEL A.*** *A highly vegetated, low sediment bank shoreline with a fringing marsh composed of freshwater grasses.* ***PANEL B.*** *A highly vegetated, very low, sediment bank shoreline with a fringing marsh composed of fresh water grasses. The effects of ongoing sea-level rise are obvious as the old-growth pine are stressed and ultimately die by drowning and are systematically replaced by more water-tolerant transition zone shrubbery and finally by the marsh grasses.* ***PANEL C.*** *The low sediment bank shoreline, dominated by upland vegetation, is fronted by a broad strandplain beach, with a fringing marsh composed of* Spartina sp. *and transition zone plants. The sand that forms the beach was derived from an eroding shoreline in back of the photograph. Notice the interdependence between the cuspate geometry of the beach and growth of marsh grasses. The marsh grows on the shallow sands on cusp edges, which in turn traps additional sediment, causing the increased growth of the cuspate structures.* ***PANEL D.*** *The shallow waters of this tributary estuary developed a wide fringing, brackish water marsh composed of* Juncus roemerianus*. The fringing marsh has completely filled the shallow perimeter platform to the channel, which is the original stream channel that concentrates the water flow and is too deep for growth of the marsh grass.*

side experiences constructive marsh growth. On the other hand, construction of navigation channels and the resulting boat wakes, cause severe marsh shoreline erosion along both channel sides.

4.4. COMBINATION SHORELINES

Many shorelines are composed of both sediment banks and associated organic components. Combination shorelines occur throughout the estuarine system and in all variations, extending from the pure end members to completely mixed combinations of multiple types of sediment banks and organic shoreline systems. Further complications occur when a given shoreline is modified by humans who either build structures, add new materials or alter the landscape geometry.

Many strandplain beaches contain natural combinations that are beneficial to slowing the rate of shoreline recession. For example, sediment bank shorelines with wide strandplain beaches in the upper reaches of trunk and tributary estuaries often contain a fringe of cypress trees (Figs. 4-3-4C, 4D). Similar shorelines in the middle to outer estuarine reaches develop marsh fringes in areas where the shoreline is somewhat protected (Fig. 4-3-6C). Organic components along sediment bank

FIGURE 4-3-7. *Photographs of low brackish, irregularly flooded, and wave-dominated, platform marsh shorelines of the Northern Province.* ***PANEL A.*** *An oblique aerial photograph shows the broad platform marsh composed of* Juncus roemerianus *encroaching upon the back side of the high and wide barrier island behind Nags Head Woods. Notice the elongate ridges and small circular hammocks scattered through the marsh and characterized by dark green upland vegetation. These hammocks are the high points on the paleotopographic surface that is being drowned and buried by the marsh in response to ongoing sea-level rise. Jockey's Ridge, an active back-barrier sand dune, is visible in the distance.* ***PANEL B.*** *An oblique aerial photograph shows a portion of the broad expanse of* Juncus roemerianus *marsh in the Cedar Island National Wildlife Refuge. Notice 1) the bright green rim of* Spartina alterniflora *marsh grass that forms the outer zone adjacent to the waterway and 2) hammocks in the marsh characterized by dark green upland vegetation.* ***PANEL C.*** *Ground-view photograph of a broad* Juncus roemerianus *platform marsh at mean water level. The marsh shoreline in the foreground has a 3- to 5-foot deep vertical erosional scarp below the water with an extensive undercut just below the water surface. Notice in the distance the obvious effects of ongoing sea-level rise as all the older growth pine became stressed and died by drowning and have been replaced by more water-tolerant transition zone shrubbery.* ***PANEL D.*** *A close-up view of an eroding platform marsh shoreline. The surging wave energy erodes the softer peat below the exposed peat ledge, which consists of a dense root mass of the modern* Spartina alterniflora*. As the undercut becomes more extensive, the surface root mass begins to move with each wave until a large block finally breaks off (see Figure 4-3-5).*

shorelines buffer wave energy and help protect the adjacent shoreline in all but the largest storms.

Very low sediment bank shorelines are extensive in the outer portions of the mainland peninsulas and are frequently dominated by remnant forests of pine stumps in the water. Since pine trees have a deep tap root, the sediment is frequently washed out from around the stump as the shoreline recedes, leaving a ghostly tangle of stumps, roots and logs in the shallow offshore (Fig. 4-3-3D). This results in many obstructions that require boaters and swimmers to beware. However, removal of these relict forests will result in the immediate increase in rates of shoreline recession.

Likewise, any organic shoreline that has a source of sand can develop a small strandplain

FIGURE 4-3-8. *Photographs of high-brackish, regularly flooded marsh shorelines and associated tidal mud flats of the Southern Province.* ***PANEL A.*** *An oblique aerial photograph of the extensive* Spartina alterniflora *marsh that fills Topsail Sound behind the simple overwash barrier island in the distance. Since the photo was taken at summer high tide, the marsh grass is very green, the tidal creeks are totally filled with water, and all mudflat environments are submerged.* ***PANEL B.*** *Groundview of an extensive* Spartina alterniflora *marsh that fills the sound behind Sunset Beach. Since the photo was taken at winter low tide, the marsh grass is very brown, the tidal creeks are almost empty, and the vast mudflat environments are well exposed.* ***PANEL C.*** *A close-up view of the* Spartina alterniflora *marsh, associated mudflats and tidal channel in the previous panel.* ***PANEL D.*** *A close-up view of the abundant oyster reefs that occur on the mudflats and extend into the lower portion of the marsh in the previous panels. None of these oysters are edible due to high pollution levels resulting from extensive development and associated stormwater runoff and septic discharge.*

beach (Fig. 4-3-1). Sand is often derived from the erosion of adjacent sediment bank shorelines and transported laterally by longshore currents. Sand also can be derived from the erosion of a particularly sandy unit underlying the shallow perimeter platform. The presence of a sand apron in front of either a swamp forest or a marsh shoreline will help absorb wave energy and protect the organic shoreline in all but the largest storms.

4.5. BACK-BARRIER SHORELINES

4.5.A. Overwash Barrier Islands

Barrier island segments that are low and narrow with relatively minor amounts of new sediment supplied to the beach form simple overwash-dominated barrier islands (Fig. 4-5-1A). Because these barriers are sediment starved with little "new" sand being supplied to the beach through time, they tend to be extremely dynamic with common and extensive modern and ancient overwash fans and old inlet flood-tide deltas extending into the back-barrier estuary. Examples of these types of barrier islands include Masonboro, Figure Eight and Topsail islands in the Southern Province and Core Banks and much of the northern Outer Banks, including Ocracoke Island, Buxton Overwash and Pea Island (Fig. 4-5-2). The overwash and inlet processes continuously rebuild the back side of the barrier with new shallow water sand deposits that form platforms for development of back-barrier marshes and grass flats.

Types of Estuarine Shorelines

In the Southern Province, the back-barrier estuaries are dominated by astronomical tides and are so narrow that the back-barrier shoreline rarely erodes. Rather extensive mud flats accumulate in the low tide zone along with extensive oyster reefs, and marsh grasses grow in the high tidal zone. Minor erosion occurs along the tidal channels that dissect these complex mud flat and salt marsh systems, as they slowly migrate through time and in response to changes in inlet and overwash processes. Major erosion does occur along navigational channels wherever they are dredged, but especially where they occur within the marsh system. However, in general these estuarine shorelines are extremely stable, and actually are constructive or building shorelines.

In the Northern Province, the back-barrier shorelines associated with the vast Pamlico and Albemarle Sound System are eroding due to the great fetch of these open water bodies as evidenced by their severly scarped character. Those shorelines dominated by overwash prior to dune-ridge construction in the late 1930s (Fig. 4-5-2A) are in a general state of erosion today, partly due to human modification of the barriers. In an effort to hold the line and protect the buildings and roads that occur within the narrow, sediment-starved barrier segments, barrier dune ridges were systematically built and rebuilt to prevent the overwash and inlet formation processes. Consequently, there has been little new sand delivered to the backside of the barrier to renew these shorelines (Fig. 4-5-2B). This has resulted in increased rates of shoreline erosion and subsequent shoreline modification in an effort to stop the erosional processes. Similar processes are happening along Core, Roanoke and Currituck sounds, but not so dramatically due to the smaller size of these water bodies.

4.5.B. Complex Barrier Islands

Complex barrier islands (Fig. 4-5-1B) are common and include Shackelford and Bogue banks, and Bear and Browns islands in the Southern Province and Kitty Hawk, Nags Head and Buxton woods, and Hatteras and Ocracoke villages in the Northern Province. These barrier

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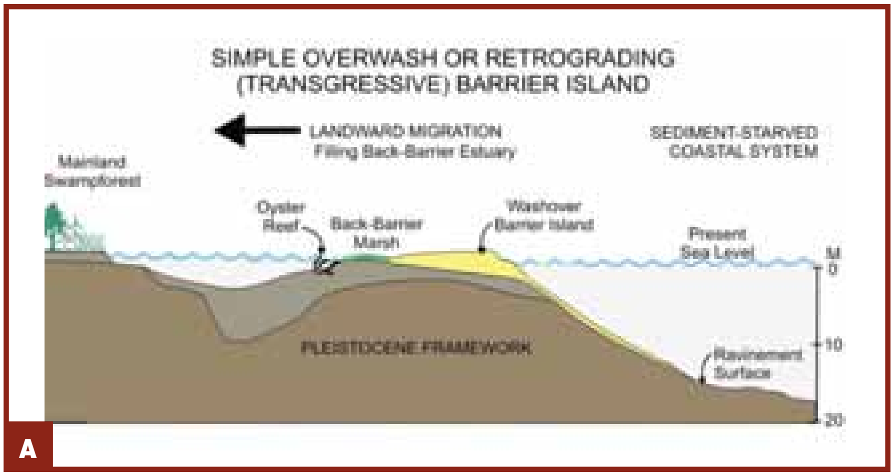


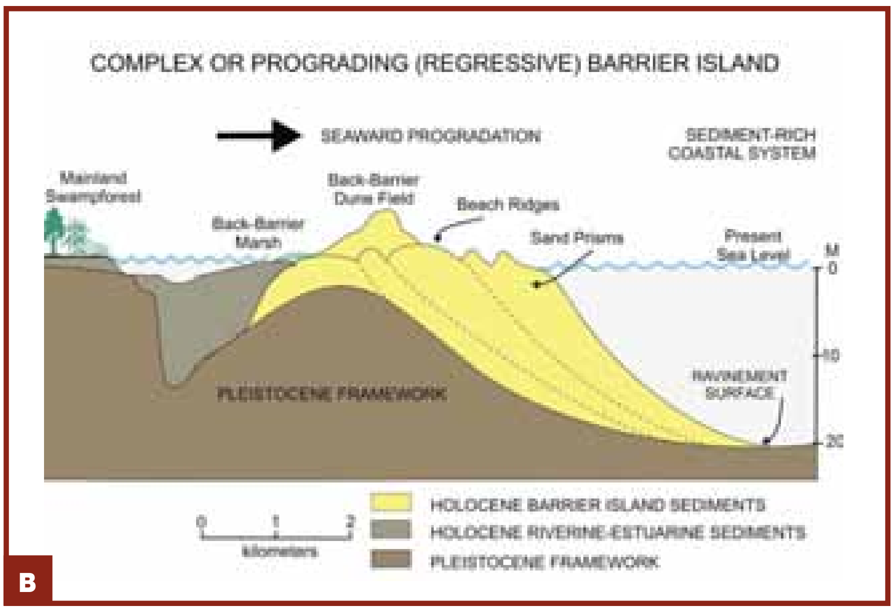
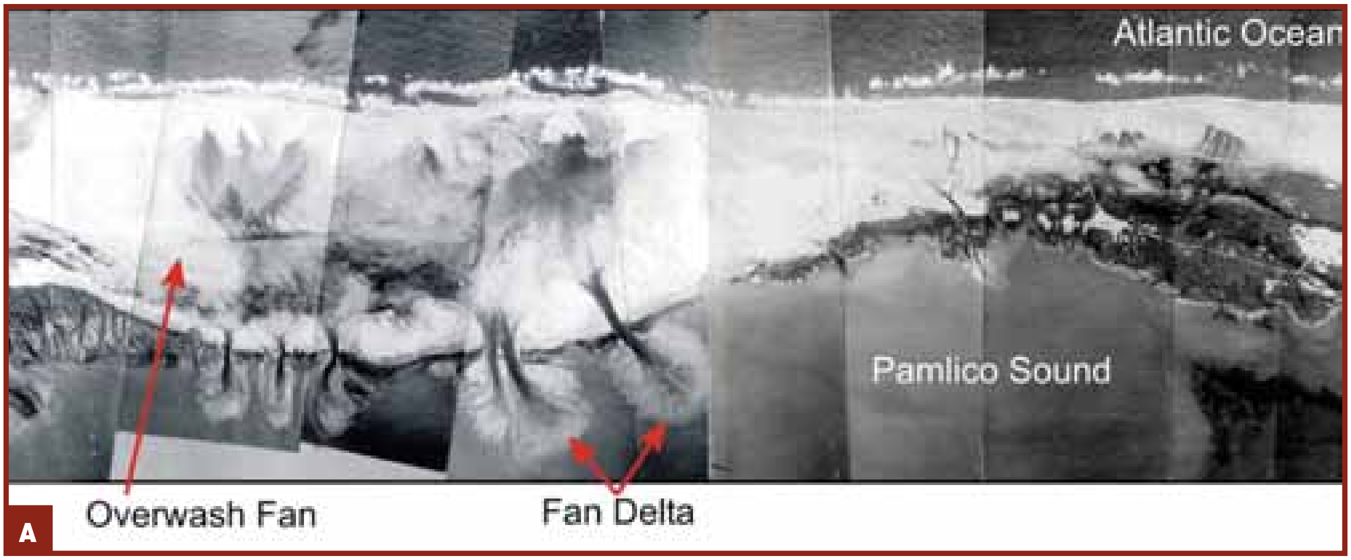


FIGURE 4-5-1. *Schematic cross-sectional diagrams of simple overwash and complex barrier islands and the associated back-barrier estuarine shorelines.* ***PANEL A.*** *Simple overwash barrier islands are dominated by large overwash fans that form during major storm tide events and produce wide and shallow sand habitats extending well into the back-barrier estuaries. These shallow flats are quickly colonized by salt marsh that continues to trap sediment as long as the overwash processes continue unhindered by either natural changes or human development practices (i.e., building barrier dune ridges, roads, and extensive walls of buildings). If the latter happens, the back-barrier estuarine shoreline may shift from one dominated by constructive processes to one dominated by loss of marsh habitat through shoreline recession. See Figures 3-3-1E and 3-3-1D, respectively.* ***PANEL B.*** *Complex barrier islands are high and wide with extensive deposits of sand that prevent storm tides from washing over the top of the island. Thus, the back-barrier estuarine shoreline has no direct connection with oceanic processes and results in estuarine shorelines that are similar to the mainland estuarine system. See Figures 3-3-1B and 3-3-2.*



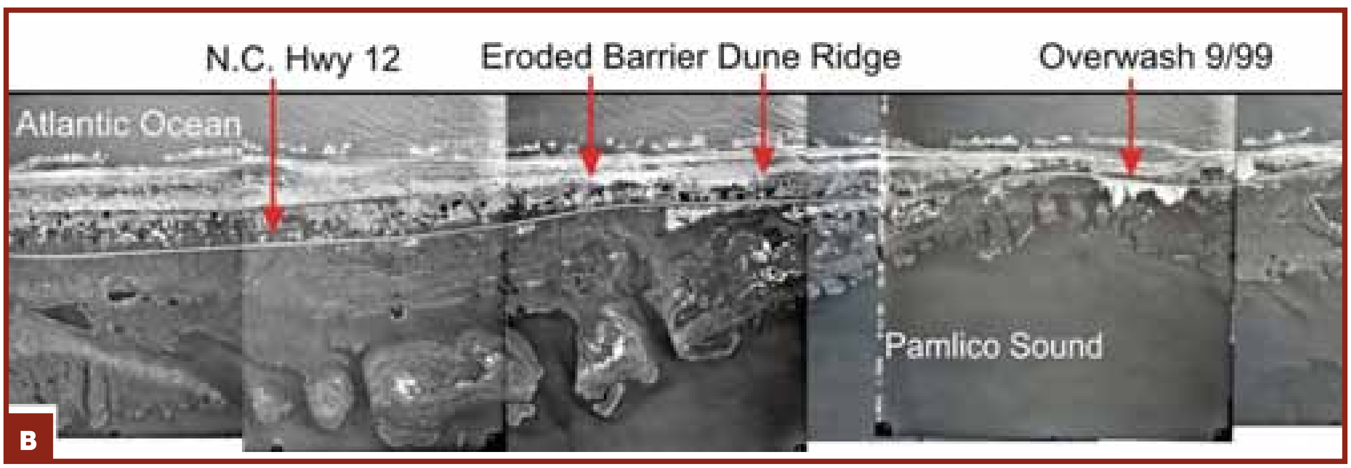


FIGURE 4-5-2. *Comparison of aerial photographs from 1932 and 1999 for a portion of Pea Island immediately north of Rodanthe on the northern Outer Banks. This sediment poor barrier island segment (Fig. 4-5-1A) was dominated by overwash processes that dramatically controlled the back-barrier estuarine shoreline by depositing extensive overwash fans over the island and fan deltas into Pamlico Sound.* ***PANEL A.*** *The aerial photo of this barrier island segment predates any shoreface modification, such as construction of barrier dune ridges, roads, and buildings that would have inhibited the overwash process. The photos were taken after a major nor'easter in March 1932 by the Beach Erosion Board (1935) as background data for a beach erosion study. Notice the massive overwash fan that deposited beach sediment across the entire island and into Pamlico Sound. This renews the estuarine shoreline and produces broad shallow flats for subsequent growth of marsh and submerged aquatic vegetation. The 1932 aerial photographs are from the Field Research Facility of the U.S. Army Corps of Engineers, Duck, N.C.* ***PANEL B.*** *This barrier island segment has been dominated by extensive barrier dune ridges since the late 1930s, which minimized oceanic overwash and allowed for the extensive growth and development of a major vegetative cover. Today, the estuarine shorelines are dominated by eroding salt marsh with local and thin strandplain beaches in coves between the peat headlands. The photo post-dates Hurricane Dennis, which had a major impact upon this coastal segment in late August and early September 1999. Notice that the barrier dune ridge has been severely damaged and was totally eroded away in a few areas, allowing for small overwash fans to develop. However, only in a few areas did overwash cover the roads and in no place did it get back to the estuarine shoreline to naturally renourish the back-barrier beach. To what extent have our changes to barrier island dynamics accentuated the rate of back-barrier estuarine shoreline erosion? The 1999 aerial photographs are from the N.C. Department of Transportation, Raleigh, N.C.*

CONTINUED:
Types of Estuarine Shorelines

islands contain large volumes of sand that occur in old beach ridges and back-barrier dune fields creating high and wide islands. In these situations, oceanic overwash only occurs along the front side of the barrier. Thus, the back-barrier estuarine shoreline is largely independent of oceanic processes and operates in a similar fashion to other mainland estuarine shorelines that respond to estuarine processes as previously described. The back-barrier estuarine shorelines on complex islands are dominately eroded with wave-cut scarps and terraces in either older upland sediment units or marsh platform peat. Strandplain beaches will form if sand is available from either the eroding shoreline, the adjacent shallow estuarine waters or wind blown off back-barrier dune fields. Less well-developed complex islands include the villages of Rodanthe, Waves, Salvo and Avon that are also characterized by typical estuarine shorelines.

In the Kitty Hawk Woods portion of Kitty Hawk (Fig. 4-5-3), neither inlets or modern overwash have occurred. Both panels of Figure 4-5-3 show an extensive series of beach ridge and swale structures that formed Kitty Hawk Woods. The woods are fronted by a major back-barrier dune field that is still active in the 1932 aerial photograph (Fig. 4-5-4A), and then the modern overwash barrier island occurs from N.C. Hwy. 158 and eastward to the Atlantic Ocean (Fig. 4-5-4A). Construction of N.C. Hwy. 12 in 1932 and the initial barrier-dune ridge in the late 1930s, in concert with subsequent development, has led to major stabilization of the back-barrier dune field and apparent elimination of modern overwash processes (Fig. 4-5-4B). However, as a consequence of the latter, the human constructed barrier-dune ridges, ocean-front houses and coastal road are in a serious, no-win conflict with ocean storm dynamics, as is clearly evident in comparing the ocean fronts in the 1999 and 1932 aerial photographs (Fig. 4-5-4).

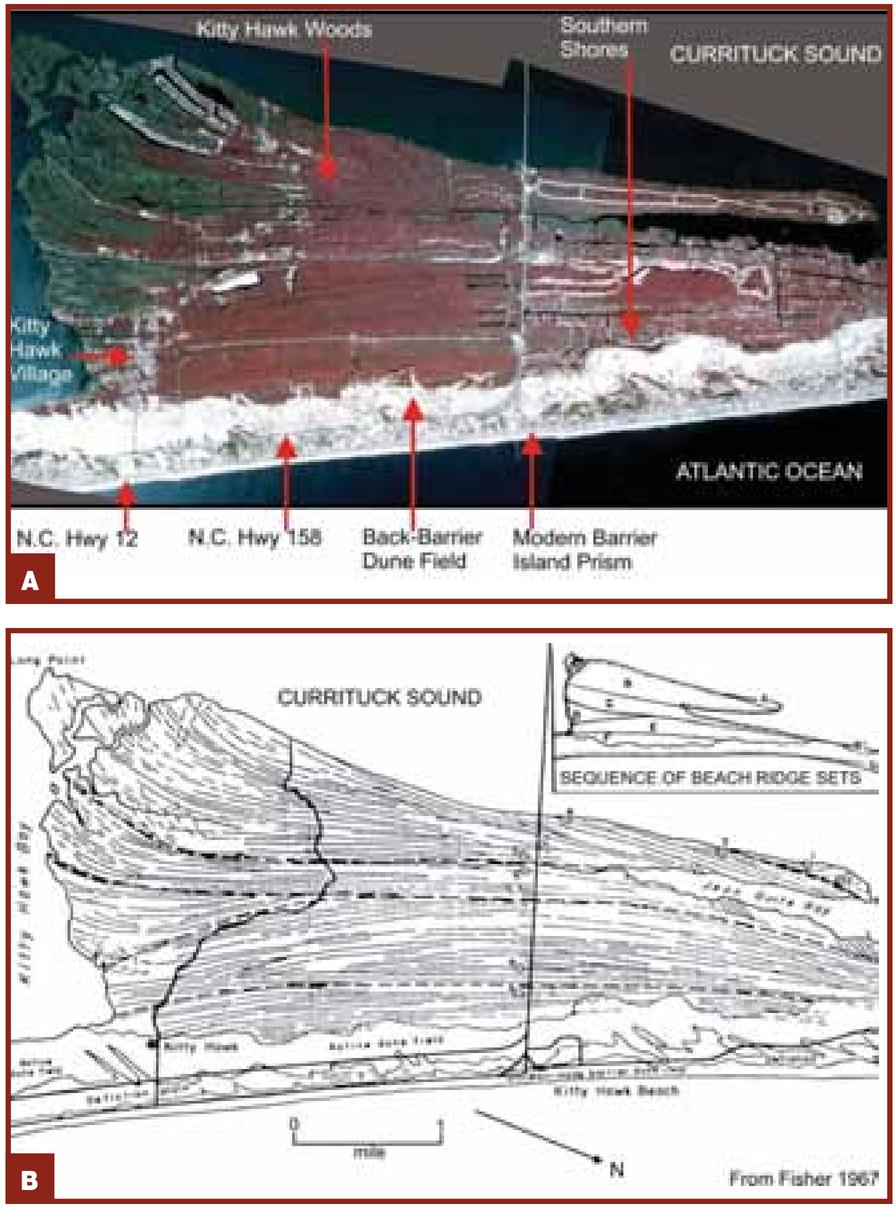


FIGURE 4-5-3. ***PANEL A.*** *A 1983 infrared aerial photograph of the complex barrier island in the Kitty Hawk area of North Carolina. The photo shows the many beach ridges that constitute Kitty Hawk Woods fronted by a back-barrier dune field and the modern beach prism. Infrared aerial photograph was flown on 4/24/1982 by the High Altitude Program of the U.S. Department of Agriculture.* ***PANEL B.*** *Map shows the interpretation of individual beach ridges and sequence of the seven beach ridge sets for the Kitty Hawk Woods by Fisher (1967).*

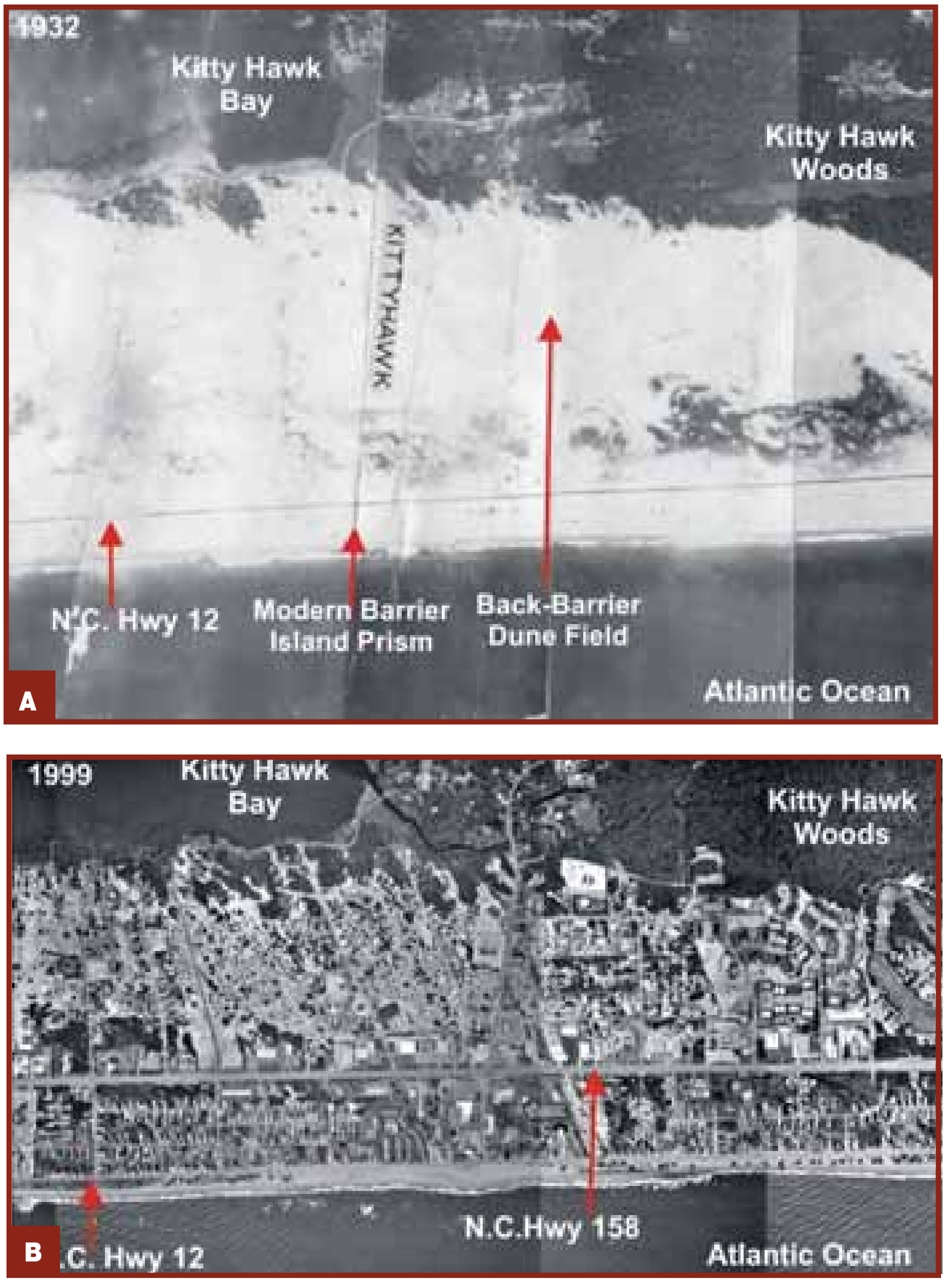


FIGURE 4-5-4. *Comparison of the coastal portion of a complex barrier island (Fig. 4-5-1B) in the Kitty Hawk area using aerial photographs from 1932 and 1999. Due to the high and wide character of this complex barrier island segment, ocean processes do not influence the estuarine shoreline. Rather, it totally responds to estuarine erosion dynamics similar to the rest of the North Carolina estuarine system.* ***PANEL A.*** *The aerial photo of this barrier island segment just postdates the construction of N.C. Hwy. 12, but predates any shoreface modification such as construction of barrier dune ridges and most buildings. The photo was flown after a major nor'easter in 1932 and was done for the Beach Erosion Board (1935) as background data for a beach erosion study. Notice that overwash is restricted to the modern beach prism, which extends to slightly west of N.C. Hwy. 12. The limited overwash fans subsequently supply sand for development of the back-barrier dune field, which nestles up against the beach ridge system and maritime forest of Kitty Hawk Woods. The 1932 aerial photograph is from the Field Research Facility of the U.S. Army Corps of Engineers, Duck, N.C.* ***PANEL B.*** *This barrier island segment has been dominated by the barrier dune ridges and ever increasing urban development since the 1930s, both of which prevent oceanic overwash. The photo postdates Hurricane Dennis, which impacted this coastal segment in late August and early September 1999. Recent storm activity has totally eroded away the barrier dune ridge through most of the area, as well as eliminating many ocean front houses. The 1999 aerial photograph is from the N.C. Department of Transportation, Raleigh, N.C.*

DROWNING

CHAPTER FIVE:

Estuarine Shoreline Erosion Processes

A rapidly eroding low sediment bank shoreline has abandoned this tell-tale pine stump along the south shore of the Neuse River estuary. The stump stands on its deep tap roots, while the shallow lateral roots demonstrate the former soil surface location. This broad sand beach is derived from the eroding Suffolk Scarp, an ocean shoreline formed during a previous interglacial period when sea level was higher than present. Photograph is from the Pine Cliff Recreational Area in Croatan National Forest.

Estuarine Shoreline Erosion Processes

5.1. SHORELINE EROSION VARIABLES

5.1.A. Physical Setting of Coastal Segments

Evolution of both the North Carolina Coastal Plain and present coastal system have included histories of traumatic and constant change. This evolutionary change continues today as it has throughout our past. Ongoing sea-level rise has drowned the highly irregular drainage basin topography of the Coastal Plain, producing about 4,000 miles of estuarine shoreline. Over 3,000 miles of estuarine shorelines occur within the vast Albemarle-Pamlico sound system of northeastern North Carolina and are generally all in a state of shoreline recession (see Chapters 7 and 8).

Most of the estuarine shorelines south of Bogue Sound are extremely narrow, shallow and filled with salt marshes and associated mud flats. These shorelines are generally not eroding as the marshes and flats vertically accrete sediment to keep up with rising sea level. Within this region, shoreline erosion is severe only within the drowned-river estuaries such as the Cape Fear, New and White Oak rivers and along the ICCW and associated navigational channels.

The amount and rate of erosion for any coastal segment is dependent upon the physical setting of that particular shoreline segment (Table 5-1-1). The size and location within the estuarine water body, as well as the spatial geometry of the shoreline itself, are critical

Table 5-1-1 Shoreline Erosion Variables

Definition of major estuarine shoreline erosion variables. Table is modified from Riggs et al. (1978.)

SHORELINE VARIABLES	DEFINITION	POTENTIAL FOR EROSION LOW	POTENTIAL FOR EROSION HIGH
1. Fetch	Average distance of open water in front of shoreline	Short Fetch (< 1,000 ft)	Long Fetch (miles)
2. Geographic Location	Location within the sounds, trunks or tributary estuaries, and within the northern or southern province, etc.	S Province or Head of Tributary Estuaries	N Province Sounds or Trunk Estuaries
3. Offshore Bottom Character	Water depth and bottom slope in the nearshore area	Shallow, Gradual Slope (< 2 ft)	Deep, Steep Slope (> 2 ft)
4. Geometry of Shoreline	Shape and regularity of shoreline	Highly Irregular, or in Cove	Straight or on Headland
5. Height of Sediment Bank	Bank height at shoreline or immediately behind sand beach	High (> 5 ft)	Low (< 5 ft)
6. Composition of Sediment Bank	Composition and degree of cementation of bank sediments	Rock, Tight Clay	Uncemented Sand, Peat
7. Fringing Vegetation	Type and abundance of vegetation (aquatic plants, marsh grasses, shrubs, trees, etc.) occurring in front of sediment bank	Very Abundant, Dense	Absent
8. Boat Wakes	Proximity of property to, frequency and type of boat channel use	Absence of Boats	Marinas, Intracoastal Waterway
9. Storms	Storms are the single most important factor determining specific erosional events	Type, Intensity, Duration and Frequency of Storms	

components of erosion dynamics. Parameters 1 through 6 in Table 5-1-1 represent different and measurable geographic components for any given estuarine shoreline segment.

5.1.B. Fringing Vegetation

Natural vegetation, parameter 7 in Table 5-1-1, often forms the most effective protection from erosion (see Chapter 4-3). Vegetation along the shoreline may occur as zones of trees and shrubs, fringes of marsh grass or tangles of dead brush and logs. Zones of fringing vegetation in the nearshore water or on the beach effectively absorb wave energy during high water events, slow down rates of shoreline recession, and act as natural breakwaters, bulkheads, and groins that trap and hold sand.

However, developers and landowners often attack the vegetation, particularly if it is dead. They cut, clear and remove the trees, shrubs, stumps, logs and snags to obtain a view, improve the swimming and eliminate snake-infested habitats. This clearing process dramatically changes the shallow-water habitats and always increases the rates of shoreline erosion, ensuring the future need for artificial bulkheading or other erosion-control measures. A large proportion of estuarine shoreline that has been and is being developed has now been human modified. This represents a massive change in critical shallow-water habitats.

Submerged aquatic vegetation (SAVs) commonly grows attached to the bottom in shallow waters in front of sediment bank shorelines. SAVs effectively dampen wave energy as the waves move through shallow water towards the strandplain beach. However, these are usually not the waves that cause shoreline erosion. Rather, waves associated with major storm tides directly erode the sediment bank as the rising water level oversteps the beach. During high water conditions, these SAVs become less effective in absorbing wave energy.

Marsh platforms or fringing marshes in front of sediment bank shorelines generally act as very effective energy baffles during high storm-tide conditions. Since marsh grasses grow in the high tide portion of both regularly and irregularly flooded coastal systems, the plants are capable of baffling much wave energy in all except the highest storm tide situations. Thus, little wave energy gets to the sediment bank behind the marsh habitats.

5.1.C. Boats and Shoreline Erosion

All shorelines adjacent to navigational channels that carry significant boat traffic will be characterized by higher rates of shoreline erosion. This is particularly true of the ICWW and other deep channels that carry large amounts of commercial traffic, as well as abundant high-powered recreational boaters. These vessels displace large volumes of water and create large wakes that repeatedly break on the adjacent sediment bank, marsh, or swampforest shorelines.

The population boom associated with the explosion of coastal urbanization and tourism throughout the coastal zone is causing increasing cumulative impacts on the loss and modification of specific coastal habitats. With ever-increasing growth, more shorelines are being cleared and stablized, and shallow waters dredged for navigation channels and marinas, wetlands filled and channelized, and land surfaces paved for buildings and parking lots. All of these activities modify the land surface and alter adjacent shallow water habitats.

The booming boating industry parallels the growth in development and tourism. Everyone wants a dock or a marina with the boat close at hand. This is a prime reason for having a place at the coast. Boats in shallow coastal waters generally require a system of navigational channels — which means dredging initial channels — followed by regular maintenance dredging. Channel dredging significantly alters the morphology of the shallow-water habitats that affects the water circulation system, benthic habitats and marsh hydrology. Thus, channel dredging is a critical component in making our shallow-water estuaries navigable, but also results in the ever-increasing role of boat wakes as an important process in shoreline erosion throughout the estuarine system.

5.2. STORMS, STORM TIDES AND COASTAL EROSION

5.2.A. Storms and Coastal Erosion

Most shoreline erosion does not occur on a day-to-day basis, but rather is a direct product of high-energy storm events. Consequently, in any specific location, erosion is a process that is extremely variable from year to year and depends upon the following climatic conditions:

1. Storm frequency
2. Storm type and direction
3. Storm duration and intensity
4. Resulting storm tides, currents and waves

5.2.B. Storm Tides in Northern Province Estuaries

Many of the estuaries within the Northern Province tend to be large, open water bodies with minimal astronomical tidal fluctuation. Due to the large fetch, in combination with their shallow-water basinal geometry, these estuaries are dominated by storm-tide processes (Fig. 2-2-1) that lead to serious coastal erosion problems.

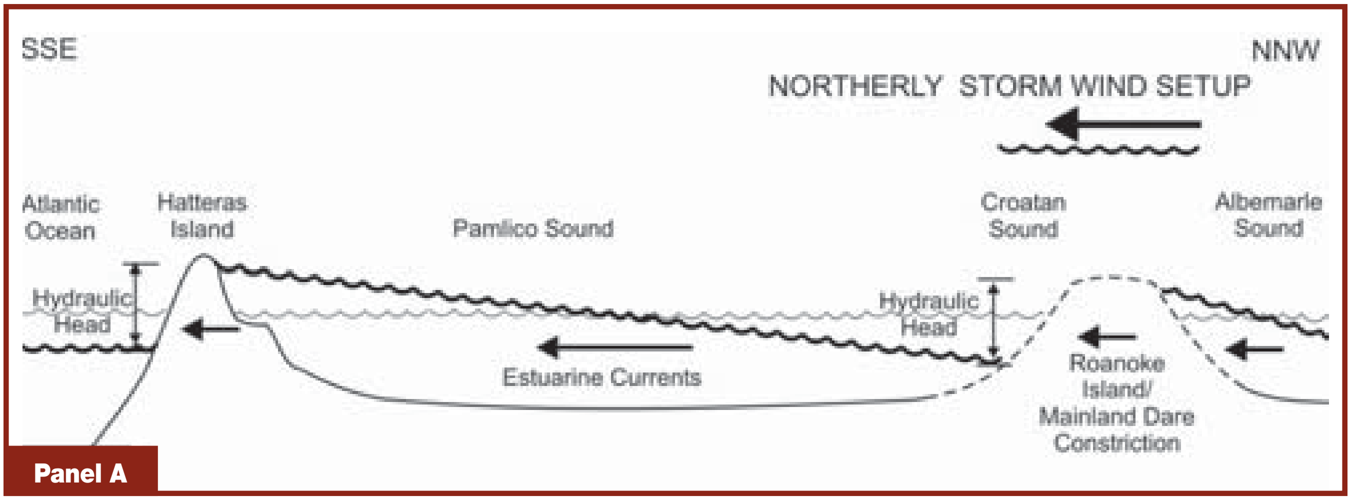
Between the Virginia line and Cape Lookout, there are four outlets to the Atlantic — Oregon, Hatteras, Ocracoke and Drum inlets. Oregon Inlet is the northernmost outlet to the Atlantic Ocean, and it occurs south of Roanoke Island. Albemarle and Currituck sounds are hydrodynamically coupled with Pamlico Sound through Croatan Sound (Pietrafesa and Janowitz, 1991). Consequently, the entire riverine drainage system flowing into Albemarle and Currituck sounds and including the Roanoke, Chowan, Pasquotank, and Dare Peninsula drainage basins (Fig. 2-1-1), must flow through Croatan to Pamlico Sound and exit through Oregon Inlet.

Thus, Croatan Sound plays a critical role in the overall estuarine circulation system (Singer and Knowles, 1975; Pietrafesa et al., 1986; Pietrafesa and Janowitz, 1991; Lin, 1992). Currents near the surface and bottom of Croatan Sound are primarily wind driven. The amount of water flushed during any wind event is strictly a function of wind intensity and duration. North winds cause the water to flow from Albemarle Sound through Croatan Sound into Pamlico

Sound — and with south winds — the water flow is reversed.

Storm winds readily push the water around, blowing it out of upwind areas and piling it up against the opposite, downwind shoreline as large water ramps or storm tide (Fig. 5-2-1). With no wind, the estuarine water surface is a flat, smooth surface without waves or slope. The wind begins to blow, waves form and wave size increases through time. As the wind builds, the water currents begin to move in the direction of the wind flow, lowering the water surface in the upwind direction and raising the water surface in the downwind direction and causing flooding of the adjacent lowlands. The wind waves on top of this sloping ramp, or storm tide, erode the shoreline and cause property damage to docks, marinas and inland structures. The sloped water ramp will be maintained as long as there is a wind holding it up. When the wind diminishes, the water will flow back down the ramp to its original flat surface.

The sloped water surfaces, or storm tides, within the shallow estuaries of northeastern



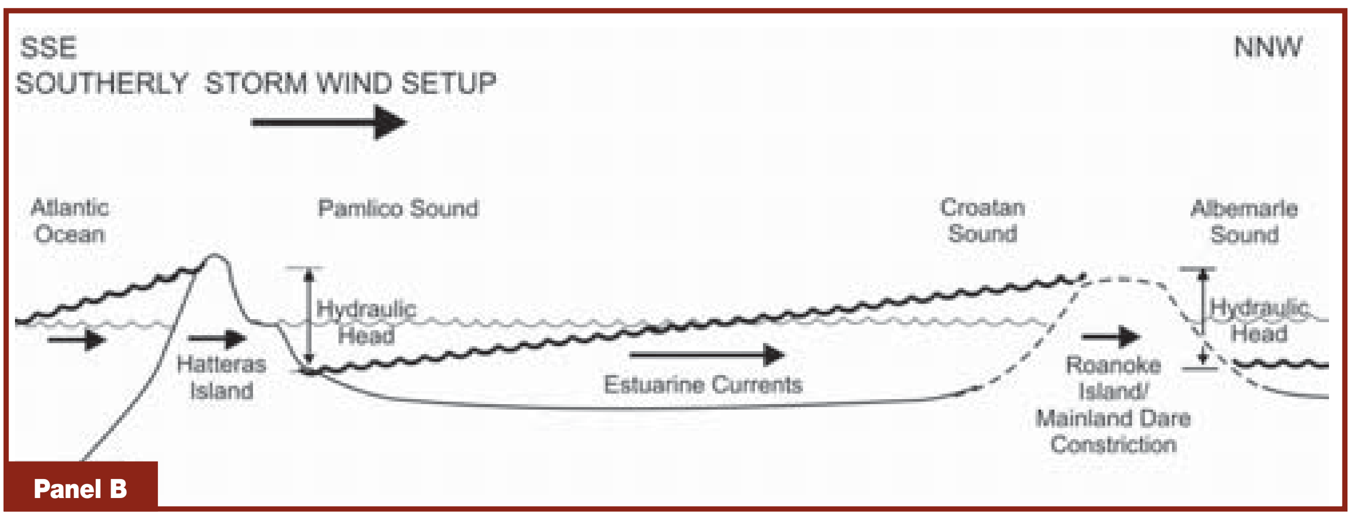


FIGURE 5-2-1. *Model of estuarine storm tides in the North Carolina sounds that form in response to different storm events. Wave energy superimposed upon both high- and low-storm tides is the primary process driving estuarine shoreline recession. This model is based upon the physical oceanographic studies of Pietrafesa et al. (1986), Pietrafesa and Janowitz (1991), and Lin (1992).* ***PANEL A.*** *High-storm tides occur along southern shores in response to events dominated by northeast, north, or northwest wind directions, whereas low-storm tides occur along the northern shores.* ***PANEL B.*** *High-storm tides occur along the northern shores resulting from events dominated by winds from the west, southwest, or south wind directions, whereas low-storm tides occur along the southern shores.*

North Carolina determine both the water level and wave height. Consequently, storm tides resulting from major storms are regional events that generally control the timing, location and rates of shoreline recession within the estuarine system. For example, a strong nor'easter blows much of the water out of the Currituck, eastern Albemarle, Roanoke and Croatan sounds and into southern Pamlico and Core sounds. This results in low tides in the northern regions and high tides and flooding in the southern regions. In this example, the flooding region is characterized by high water overstepping the sand beach, causing the waves to break directly on and erode the sediment bank. However, marsh shorelines experience little erosion because the high storm tide oversteps the shoreline, with the wave energy being rapidly baffled and dissipated by the marsh grass.

In contrast, on the low tide side of the estuarine system, significant wave energy will impact the north- and east-facing shorelines. However, on the sediment bank shorelines, the water surface recedes lower on strandplain beaches or onto the outer wave-cut terrace, where the energy is expended harmlessly. However, on marsh shorelines, the low tide drops water level below the tough root mass of the modern marsh grass, causing waves to break against the underlying, older and softer peat sediment. This results in severe undercutting, with large blocks of marsh peat ultimately breaking off.

5.2.C. Hurricane Storm Tides

Storm tides happen whenever a major storm associated with a weather front blows through, or a hurricane impacts the North Carolina coast. The resulting estuarine storm tide is dependent upon the intensity, duration and direction of movement of each storm. Frontal storms (i.e., nor'easters) are characterized by winds that range from 25 to 50 mph. Whereas, tropical depressions and hurricanes will typically come ashore with winds in considerable excess of this. Consequently, frontal storm tides generally range from 2 to 5 feet above MSL, whereas tropical storms can range upwards to 10 to 15 or more feet above MSL.

Even if a hurricane moves offshore of the barrier islands in a generally coast-parallel fashion without making direct landfall, the winds can create major estuarine storm tides. For example, in 1993 Hurricane Emily grazed Cape Hatteras with sustained winds of 92 mph as it traveled northward (Barnes, 1995). The counterclockwise winds of this storm blew the waters from the northern sounds southward across Pamlico Sound and piled it up in the bend behind Cape Hatteras (Fig. 2-2-1). A maximum storm tide of 10.5 feet above MSL occurred between Buxton and Avon and decreased gradually to the north and south. Emily caused severe sound-side flooding, estuarine shoreline erosion and major wind damage to Buxton maritime forest.

Hurricanes that make a direct landfall across the coast in the Southern Province have a significant impact upon the estuarine waters throughout North Carolina. In 1996, Hurricanes Bertha and Fran made direct landfall between Wrightsville Beach and Onslow Beach (Fig. 2-1-2). The estuarine storm tides in the landfall area were related to the ocean-side storm tide that readily spilled over the barriers and poured through the numerous inlets. The back-barrier estuaries received storm tides that were up to 14 feet above MSL. However, the energy of these flood waters had been significantly diminished from that experienced on the ocean side due to the barrier island buffering effect, relatively small size of the estuaries and abundance of vegetation. These two storms also had a significant impact upon the trunk estuaries in the Northern Province. The counterclockwise winds along the north side of the storms blew the water westward in the trunk estuaries. This resulted in storm tides up to 10 feet above MSL, with significant waves superimposed upon the water ramp (Fig. 5-2-1) that seriously flooded and battered the upper reaches of the Neuse and Pamlico River estuaries.

Hurricanes that cross the Northern Province coast in any direction produce estuarine storm tides that slosh back and forth, impacting both the inner and outer portions of the estuaries. The initial winds will often blow the waters up the estuaries, producing low-wind tides along the barrier islands and high-wind tides in the upper reaches of the trunk estuaries. As the storm passes and storm winds come from the opposite direction, there is a rapid back flow of high water, resulting in catastrophic coastal consequences on the barrier islands. Historically, storm tides or "walls of water" that are 10 feet or higher have roared back upon the Outer Banks as the hurricane passed, wrecking havoc on the sound side and often blowing open new inlets through the barrier islands. In fact, this is the most probable origin for many inlets through the Outer Banks.

Coastal flooding by salt water has numerous consequences. Salt water is toxic to all freshwater plants. Consequently, storm winds containing salt spray and salty flood waters may either kill the vegetation directly, or stress it to the point that it becomes vulnerable to post-storm diseases. Whether flooding occurs in the outer or inner estuary determines how salty the water is. The saltier the water is, the greater the impact will be. Both the salt water and the high-energy waves from extremely large storm tides may severely impact the trees and shrubs that occur in the vegetative fringes that occur along many sediment bank shorelines. Killing and eroding this protective vegetative fringe commonly reactivates the erosional processes along a temporarily stable shoreline.

Six hurricanes directly impacted different portions of the North Carolina coast between 1996 and 1999. Depending upon the specific track of each hurricane, storm surges ranged up to 12 feet high within the estuarine areas for several of these storms. Even though shoreline erosion took place throughout the estuarine system, the hurricane storm surge and resulting erosion was the greatest in the narrow upper reaches of the estuarine system, where normal erosion rates are generally the lowest due to small wind fetches. Consequently, severe erosion was experienced in the New Bern and Washington regions where shoreline erosion locally ranged from 10s to 100s of feet.

All of the storms resulted in major estuarine shoreline erosion. However, it was the cumulative impact of multiple storms that resulted in extremely severe erosion in the upper reaches of the trunk estuaries. The first storm took out a lot of vegetation on strandplain beaches, increasing the exposure of adjacent sediment banks. Large storm surges of subsequent storms overstepped the strandplain beach and severely undercut and eroded the high banks and bluffs. This, in combination with saturated ground from heavy rainfall and high winds, caused massive slumping of the sediment banks onto the beach. Also, the saturated ground and high winds severely impacted swampforest shorelines blowing over many shallow-rooted trees along the outer edge.

Shorelines that had previously been bulkheaded and rip-rapped were not immune to shoreline erosion problems resulting from these storms. Frequently, the structures were undercut, side flanked or overtopped, severely eroding the land from behind the structure and often destroying or at least damaging the structure itself. Unprotected properties adjacent to previously protected properties suffered major land losses that was accentuated as the protected property acted as a headland focusing much of the eroding energy into the adjacent land, resulting in development of cove-like shoreline features.

5.2.D. Storm Tides in Southern Province Estuaries

Within the southeastern North Carolina estuarine system, the principle forcing functions for water motions are astronomical tidal exchange through the numerous inlets and river discharge in decreasing order of significance. Due to the narrow geometry of the estuaries and the abundance of mudflat and marsh habitats, normal wind tides and waves are at a minimum within these coastal systems. However, storm tides associated with major oceanic storm surges are extremely important in the shoreline dynamics as previously described.

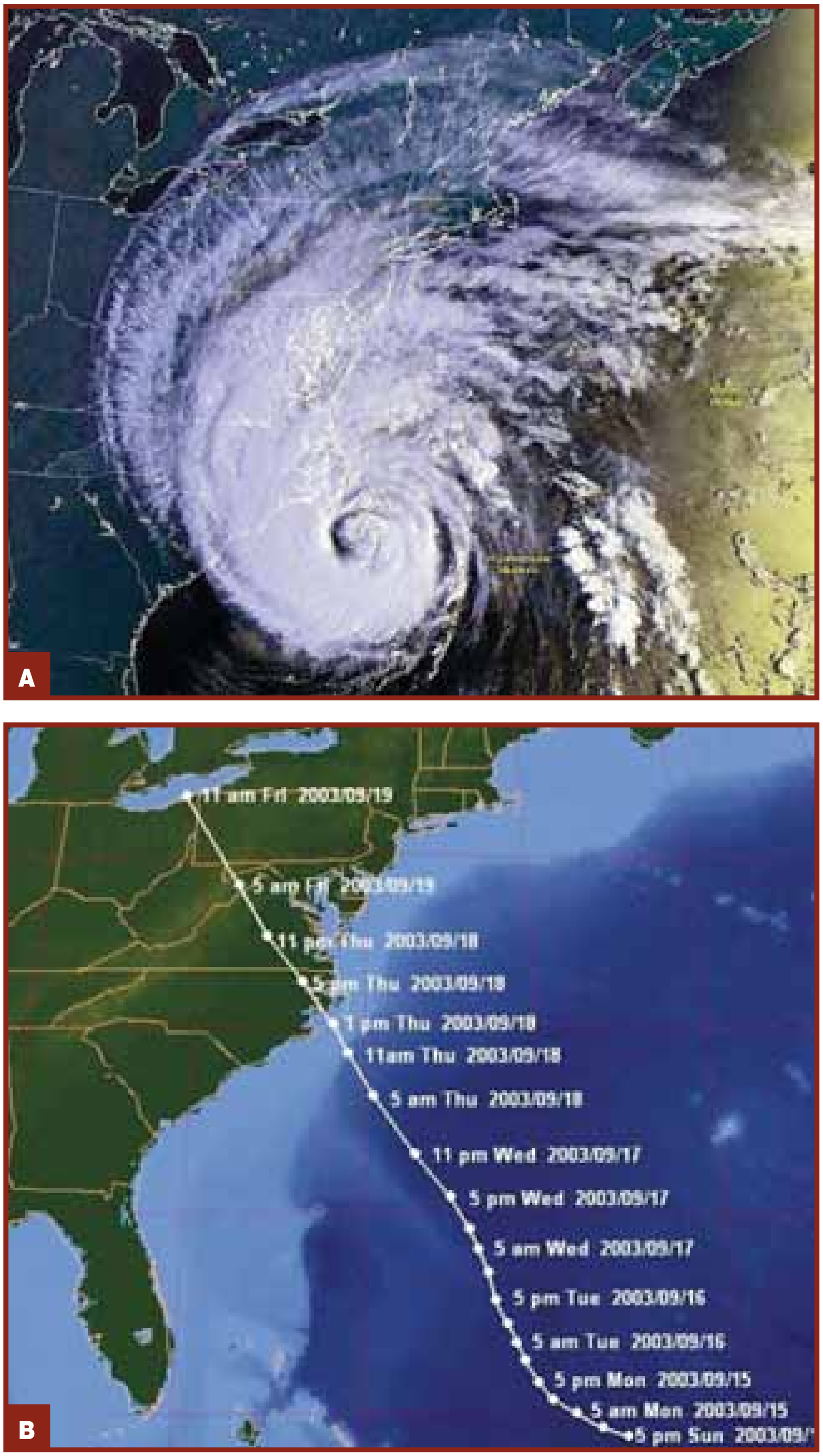
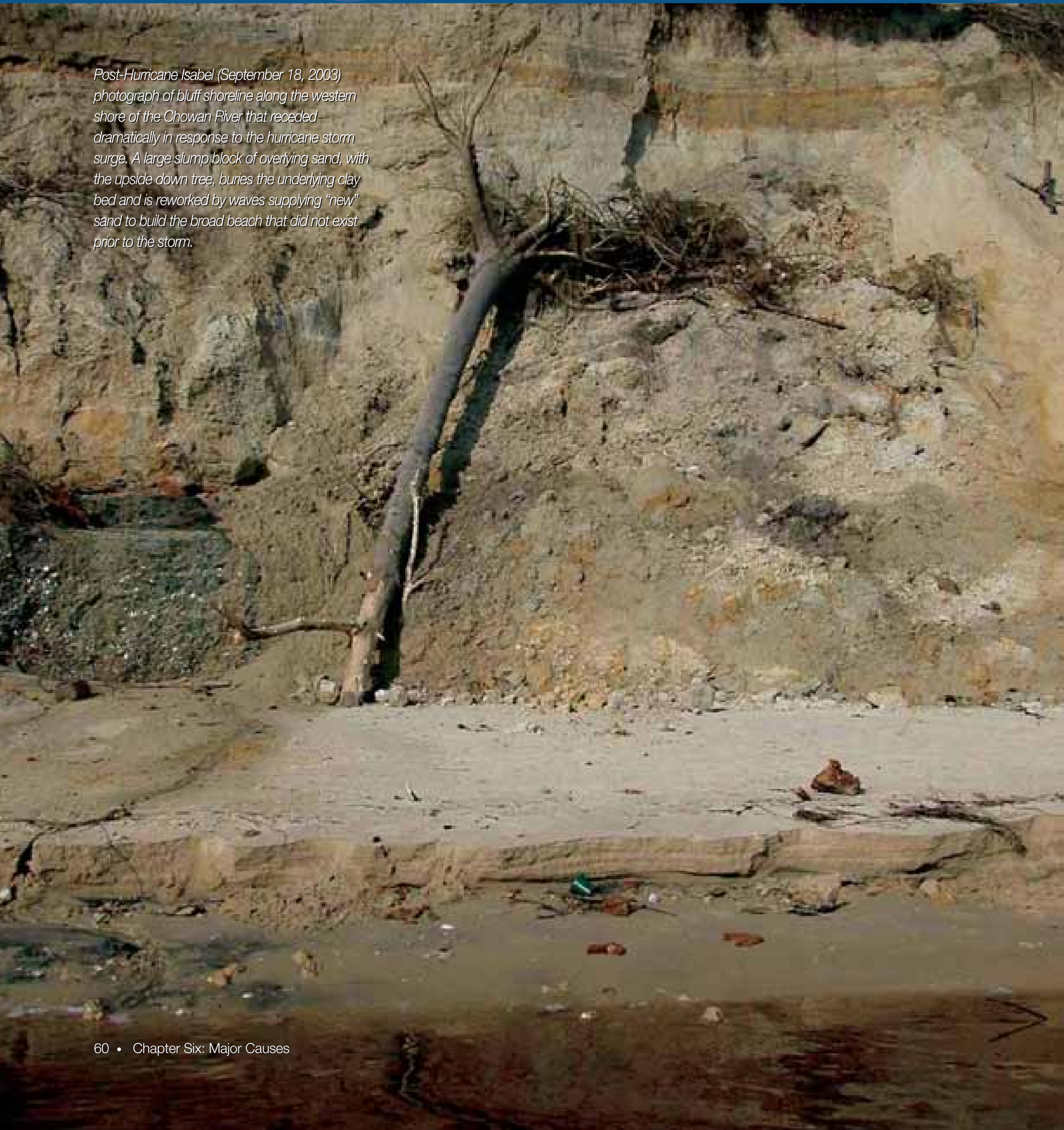


FIGURE 5-2-2. ***PANEL A.*** *Satellite image of Hurricane Isabel as it approached the North Carolina coast as a minimal category 2 storm on September 18, 2003.* ***PANEL B.*** *The track of Hurricane Isabel as it came ashore in the vicinity of Ocracoke Inlet and tracked inland along a northwest course. Both images are from the U.S. National Weather Service Web site at N.C. State University, Dept. of Marine, Earth and Atmospheric Sciences, Raleigh, NC.*

CHAPTER SIX:

DROWNING

Major Cause of Estuarine Evolution



Post-Hurricane Isabel (September 18, 2003) photograph of bluff shoreline along the western shore of the Chowan River that receded dramatically in response to the hurricane storm surge. A large slump block of overlying sand, with the upside down tree, buries the underlying clay bed and is reworked by waves supplying "new" sand to build the broad beach that did not exist prior to the storm.

Major Cause of Estuarine Evolution

6.1. SEA-LEVEL CHANGE AND COASTAL EROSION

Understanding estuarine shoreline erosion in the North Carolina coastal system requires consideration of processes operating at several different spatial and temporal scales. Spatial scales range from global to specific coastal regions and drainage systems, while temporal considerations range from millennial-scale events to individual storm events and daily cycles. This section considers the millennial to centennial or long-term events that are driving large-scale changes within the coastal system, including changes in global climate and sea level.

The long-term processes of climate and sea-level change produce the disequilibrium that results in the slow and systematic reshaping of the North Carolina coastal system by individual hurricanes and northeast storms. Rising sea level slowly and systematically floods up the stream valleys and adjacent land slopes. However, it is wave energy during storms that physically erodes the shoreline and moves it further landward in response to rising sea level. A falling sea level results in the abandonment of an old shoreline as the contact between water and land slowly migrates seaward.

6.2. QUATERNARY PERIOD OF GLACIATION

The Quaternary period of geologic time, the last 1.8 million years of Earth history, was dominated by multiple episodes of glaciation and deglaciation resulting from extreme episodic fluctuations in global climate. The Quaternary is further subdivided into the Pleistocene epoch, better known as the ice age, and the Holocene epoch, the last 10,000 years of Earth history. The Holocene is the time of warm global climates associated with the ongoing interglacial episode and development of modern civilization.

6.2.A. Glaciation and Deglaciation

From about 10,000 to 20,000 years ago, the Earth was locked in the last of a long series of glacial episodes that characterized the last 1.8 million years of geologic history, referred to as the Quaternary period of geologic time (Williams et al., 1998). During the last glacial episode, massive glacial ice sheets, often up to two miles thick, covered the northern half of North America, Greenland, northern Europe, northwestern Asia, mountainous portions of South America, and Antarctica (Anderson and Borns, 1994). In North America, the ice sheets extended southward to Cape Cod, Long Island and the Ohio and Missouri rivers, forcing the climate zones to systematically shift southward (Bradley, 1999). During this glacial episode, North Carolina was characterized by a sparse vegetative cover consisting of boreal forest species, including spruce, fir and jack pine (Lamb, 1977; Nilson, 1983). The climate was cold, semiarid and dominated by severe storm activity with drainage systems occupied by braided rivers and aeolian dune fields. Since the source of water to produce these land-based ice sheets was derived from the world's oceans, global sea level was lowered by over 400 feet worldwide. This drop in sea level placed the North Carolina ocean shoreline on the continental slope between 15 and 60 miles seaward of the present barrier islands, extending the Coastal Plain completely across the present continental shelf.

Major periods of global warming resulted in periods of deglaciation when the ice sheets retreated and discharged the resulting meltwaters back into the world's oceans. These warm climate periods would result in worldwide rise of the sea to levels that were higher than the present. In fact, if all of the present glacial ice in Greenland and Antarctica was to melt, sea level would be approximately 200 feet higher than it is now. This would put the entire North Carolina Coastal Plain below the ocean with the shoreline occurring approximately along Interstate 95 between Roanoke Rapids and Fayetteville.The drowned-river estuaries would extend up the river valleys to Raleigh and adjacent Piedmont regions. Such advances and retreats of the glacial ice and the global oceans have occurred many times during the Quaternary period. In fact, the surface sediments, soils and topography of the North Carolina Coastal Plain are direct products of these major fluctuations in the Quaternary coastal system.

6.2.B. The Holocene Interglacial

During the past 18,000 years, the Earth has been witness to some of the most dramatic changes in our long history (Fairbridge 1961, 1987, 1992; Lamb 1977; Imbrie and Imbrie 1979; Nilsson 1983; Pielou 1991; Anderson and Borns 1994; Broecker 1994, 1995). These changes included: 1) massive global warming; 2) retreat of vast continental ice sheets; 3) over 400 foot rise in global sea level; 4) northward shift of climatic zones; and 5) extinction of large animal species. Evidence now suggests that these dramatic changes in the Earth's climate and associated sea level were rapid with frequent and extreme oscillations (Lehman and Keigwin 1992; Mayewski et al. 1993) In addition, these fluctuations often dictated the path of human history (Lamb 1977, 1988; Grove 1988), as the world's population exploded from scattered nomadic tribes to over 6 billion people today. Since modern civilization is more dependent than ever upon environmental stability, it is imperative that society understands these major environmental shifts during the recent past.

The last Pleistocene glacial episode ended as the Earth's climate warmed, melting the ice sheets in both hemispheres. The glacial meltwaters flowed back into the world's oceans, causing sea level to rise. A classic Holocene sea-level rise curve (Fig. 6-2-1) suggests a unidirectional rise in sea level that started at extremely high rates (about 6.6 feet/ 100 yrs) for a millenia, then slowed to moderate rates (about 3.3 ft/100 yrs) until about 8,000 years ago. At this time the rate of sea-level rise slowed dramatically to the present rates that ranged from 1.6 to 0.5 ft/100 yrs. However, it has been demonstrated by many researchers, including the authors, that there were numerous

Major Cause of Estuarine Evolution

brief periods during this history when sea level actually stopped rising and even temporally dropped.

During the glacial maximum (Fig. 6-2-1), the North Carolina coast would have been about 400 feet lower than present. The shoreline was located below the edge of the continental shelf or between 15 and 60 miles east of the present shoreline. Thus, during the past 17,000 years, the North Carolina coast retreated landward with shoreline recession rates that ranged from an average of 5 ft/yr at Cape Hatteras to an average of 19 ft/yr at Topsail Island. The shoreline recession rates for North Carolina through most of the 17,000 year post-glacial history are slightly greater than current average rates of coastal retreat which range between 3 to 10 ft/yr (Benton et al., 1993).

6.2.C. The Modern Coastal System and Ongoing Sea-Level Rise

Modern history begins with the North Carolina shoreline 15 to 60 miles seaward of and over 400 feet lower than the present shoreline (Fig. 2-2-1). The North Carolina Coastal Plain was significantly larger than presently, with the entire continental shelf characterized by vegetation, animals and flowing rivers. Figure 6-2-2A is a contour map on top of the Pleistocene sediments in Pamlico Sound based upon several hundred miles of high resolution seismic profiles, 44 vibracores and 28 radiocarbon age dates. This is an example of the database that exists for the entire northeastern North Carolina upon which the reconstruction of paleodrainage basins in

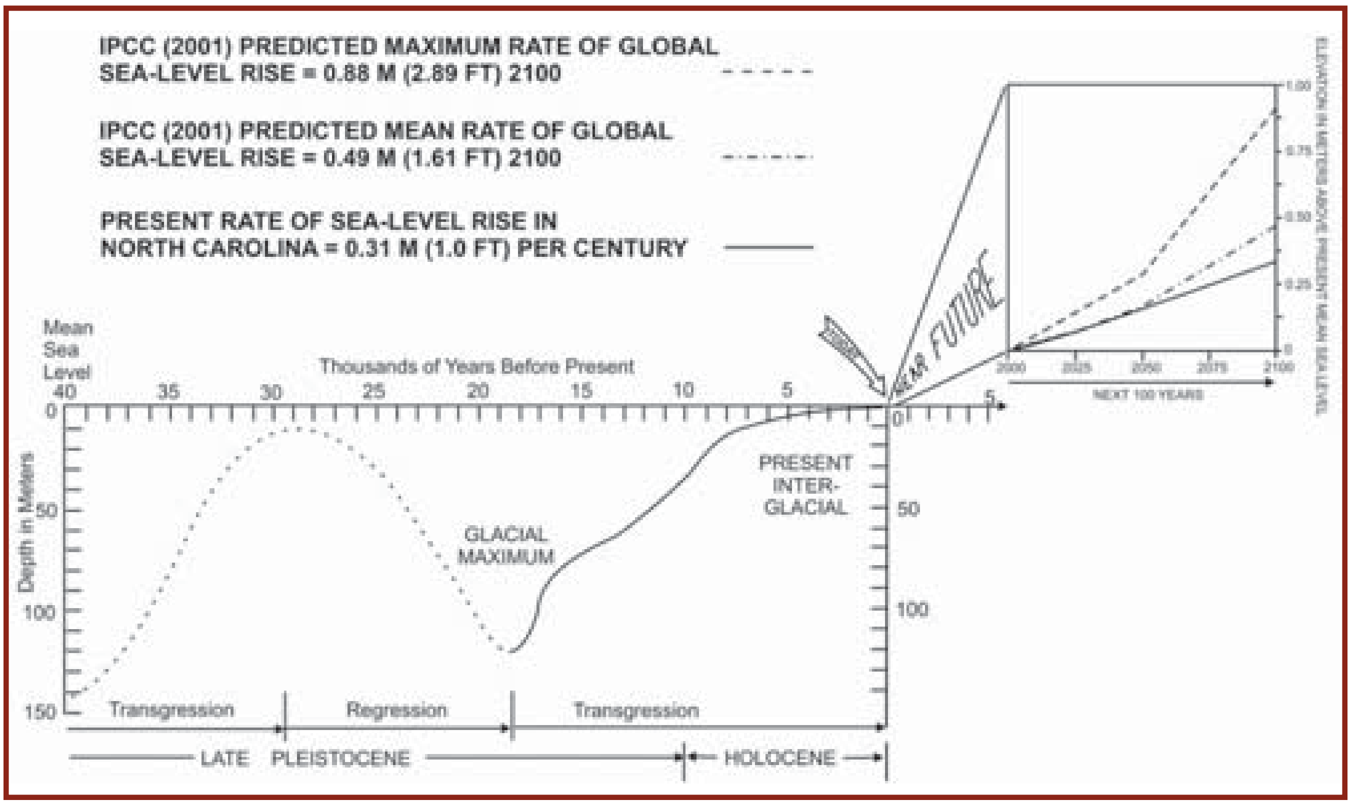


FIGURE 6-2-1. *Generalized sea-level curve for the last 40,000 years of Earth history, including the late Pleistocene, Holocene (the last 10,000 years), and extending 100 years into the near future. The 40,000-year curve is modified from Curray (1965) and the near future curve is based upon data from IPCC (2001). Three potential curves are plotted for the near future and represent predictions that are dependent upon how fast global warming becomes a major factor in the Earth's climate. These curves represent worldwide sea-level rise that will result only from global climate change and do not include sea-level rise from other regional factors, such as changes due to land subsidence or uplift, etc. Therefore, the three curves are conservative and only represent the extent to which climate change will accelerate the rate of sea-level rise. The solid or most conservative line is similar to what the IPCC (2001) considers its "business as usual" sea-level prediction. This plot is approximately equal to the ongoing rate of sea-level rise for North Carolina, based upon tide-gauge data over the past decades (see text and Figure 6-3-2). The middle curve is the IPCC (2001) predicted mean rate, and the upper curve is the predicted maximum rate of global sea-level rise that will result from global warming.*

Figure 6-2-2B is based. This reconstruction depicts the paleo-drainage that existed from at least 20,000 to 8,000 years ago in the area of the present Outer Banks and Albemarle-Pamlico estuarine system.

As the glaciers began to melt and recede in response to the warming climate at the end of the ice age, the meltwaters began to raise global sea level (Fig. 6-2-1). This rising sea level caused the shoreline and coastal system to migrate upward and westward throughout much of the Holocene. The flooding process caused the coastal system to migrate across the continental shelf to its present location (Fig. 2-2-1). The estuaries formed as the rising sea flooded up the topographically low river and stream valleys, starting about 8,000 years ago.

The Albemarle-Pamlico estuarine system is a large system of drainage basins that have been drowned in their lower reaches by rising sea level (Fig. 2-1-1). The drowned-river embayments have been flooded by the ongoing post-glacial rise in sea level. Sediment from sediment-laden rivers is trapped and accumulated through time in these coastal basins. The result is a thick sequence of shallow-water sediment deposits that record a cyclical evolutionary history with periods of coastal deposition (high sea level during interglacial periods) alternating with episodes of erosion

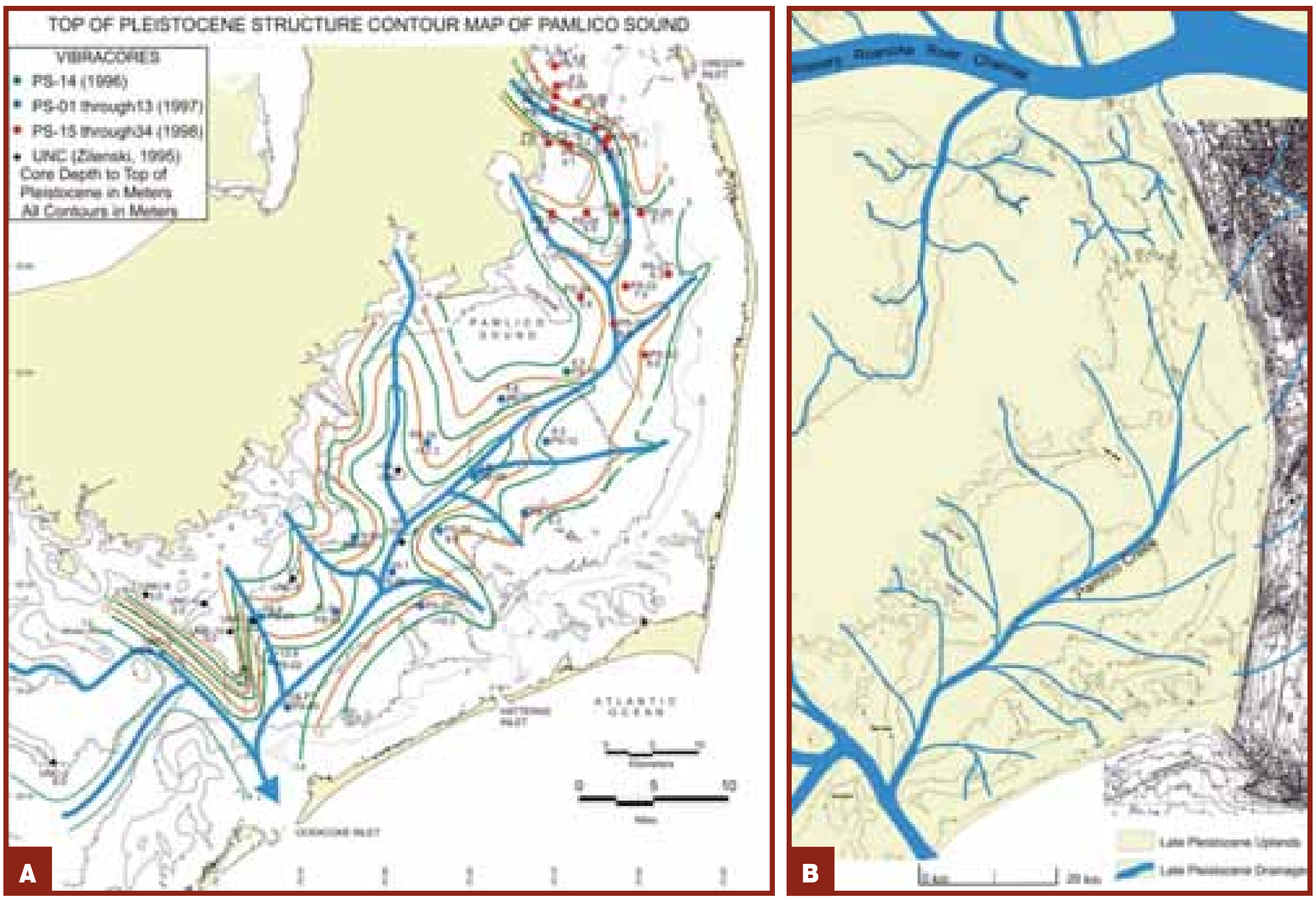


FIGURE 6-2-2. ***PANEL A.*** *Structure contour map on top of the late Pleistocene within Pamlico Sound. The contours are based upon high-resolution seismic data in concert with the analysis of 44 vibracores (up to 10 m deep). Many vibracores were obtained in the thalweg of Pamlico Creek and associated tributary streams active during the last glacial maximum (see Fig. 6-2-1). Notice how the modern bathymetry of Pamlico Sound mimics the paleodrainage system.* ***PANEL B.*** *Reconstruction of the paleotopography and paleodrainage system in northeastern North Carolina during the last Pleistocene glacial maximum. This is what North Carolina looked like between 25,000 to 10,000 years ago when sea level was about 400 feet below present, and the ocean shoreline was on the continental slope between 15 to 60 miles east of today's coast (see Fig. 6-2-1).*

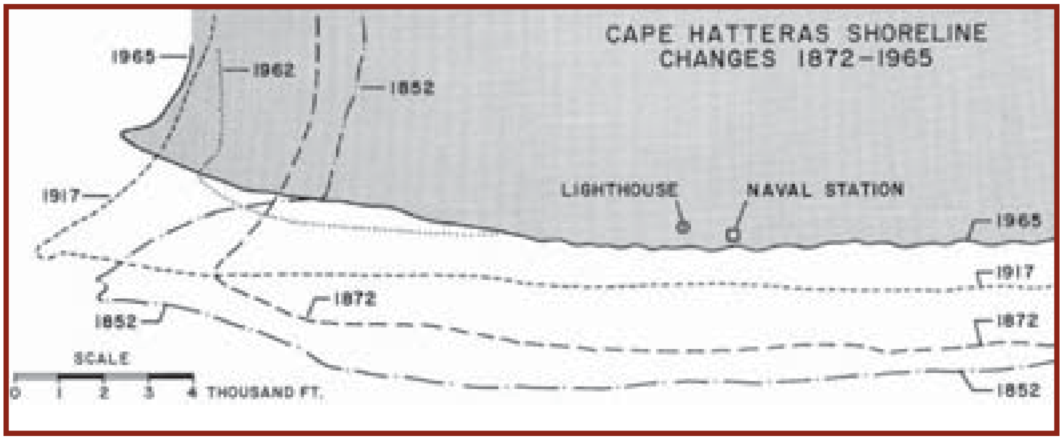


FIGURE 6-3-1. *Map of ocean shoreline changes from 1852 to 1965 by Fisher (1967) demonstrates the ongoing recession of the ocean beach at Cape Hatteras. About 3,000 feet of shoreline erosion in 113 years ultimately led to the decision in 1999 to move the Cape Hatteras Lighthouse 1,600 feet back from the shoreline.*

(low sea level during glacial periods). Post-glacial changes in climate and sea level of the past 10,000 years are reflected in fluctuations in the type and amount of sediment, and patterns of sediment deposition and erosion within the estuaries. Thus, the resulting sediment record is like a 10,000-year tape-recorded history of changing environmental conditions of the North Carolina coastal system.

Riggs and associates (Riggs et al. 1992, 1995, 2000; Riggs 1996; Sager 1996; Sager and Riggs 1998; Rudolph, 1999) found that the estuaries contain a complex history of riverine incisement and marine backfilling. The infill history is characterized by cyclical episodes of sedimentation. Periods of rising sea level deposited a sediment sequence that graded upward from basal riverine sediments into estuarine, barrier island and shallow marine deposition. The depositional periods were followed by falling sea level that caused extensive channeling and erosion of previously deposited sediments. This results in multiple sediment units with complex age relationships to each other. The older units are overlain by a thin layer (from 0 to 3 ft) of organic-rich mud contaminated with heavy metals, organic toxicants and other pollutants from post-colonial industrial and agricultural activities. This surficial mud represents the last 400 years of our history and is in part a product of anthropogenic activities.

6.3. THE FLOODING PROCESS CONTINUES

6.3.A. Present Rates of Sea-Level Rise

Two types of data demonstrate that sea level has continued to rise over the past 150 years. A map (Fig. 6-3-1) by Fisher (1967) displays historic shorelines that reflect a constant landward recession in the Buxton and Cape Hatteras area. Data from tide gauge records (Hicks et al., 1983; Gornitz and Lebedeff, 1987; Douglas et al., 2001) demonstrate similar rates of sea-level rise for both Charleston, S.C., and Hampton, Va., (Fig. 6-3-2). These data suggest that sea level is rising at about 1.01 ft/100 yrs in the Charleston area and about 1.06 ft/100 yrs. in the Hampton area. Limited data for the period from 1980 to 2000 at Duck, N.C., (W. Birkemeier, U.S. Army Corps of Engineers, Pers. Comm., 12/2000) suggest that sea level for the Albemarle Embayment region may be rising slightly faster, possibly up to about 1.5 ft/100 yrs. All of these data demonstrate that sea level continues to rise, resulting in the ongoing flooding of the low coastal land and ubiquitous recession of North Carolina's coastal shorelines.

6.3.B. Future Rates of Sea-Level Rise

The Intergovernmental Panel on Climate Change Report (IPCC, 2001) predicts increased rates of global sea-level rise over the next century in direct response to known global climate warming. Increased rates of sea-level rise will adversely impact coastlines of North Carolina in the following ways:

1. Accelerated rates of coastal erosion and land loss;
2. Increased economic losses due to flooding and storm damage;
3. Increased loss of urban infrastructure;
4. Collapse of some barrier island segments; and
5. Increased loss of estuarine wetlands and other coastal habitats.

However, the scientific community has only a moderate understanding of the linkages and controls between global warming and changing magnitude and rate of sea-level response, resulting in limited levels of predictability from a societal point of view (Warrick et at., 1996; Nuttle et al., 1997; Fletcher et al., 2000a, 2000b).

As glacial ice in Antarctica and Greenland continues to melt and ocean water continues to thermally expand in response to global climate warming, the ongoing rise in sea level will continue to flood the North Carolina coastal lands. Sea level is rising in North Carolina today at a rate between 1.0 to 1.5 feet/100 yrs. Is this rate of flooding significant for the North Carolina coastal system? On your next trip through the outer coastal system, notice how low and flat the land is with extensive, water-filled drainage ditches occurring adjacent to the highways. The water in these ditches is generally at or close to sea level, and the roads are built on fill dirt dug from these ditches.

The coastal system in the Northern Province of North Carolina is a complex of broad, shallow estuarine environments that extend up to 100 miles into the Coastal Plain. Due to the very low regional land slope, the ongoing rate of sea-level rise produces major shoreline recession (see Chapters 7 and 8). With flooding, the coastal system will maintain its general appearance and characteristics through time as it migrates upslope and landward by a gradual evolutionary succession. This evolution is dramatically demonstrated in the two false color, winter aerial photographs (1983 and 1998) of the Pamlico Sound shoreline at Point Peter Road area, Alligator River Wildlife Refuge (Fig. 6-3-3). In 15 years, the green-colored, low-brackish to freshwater marsh along the shoreline has migrated upward and landward hundreds of

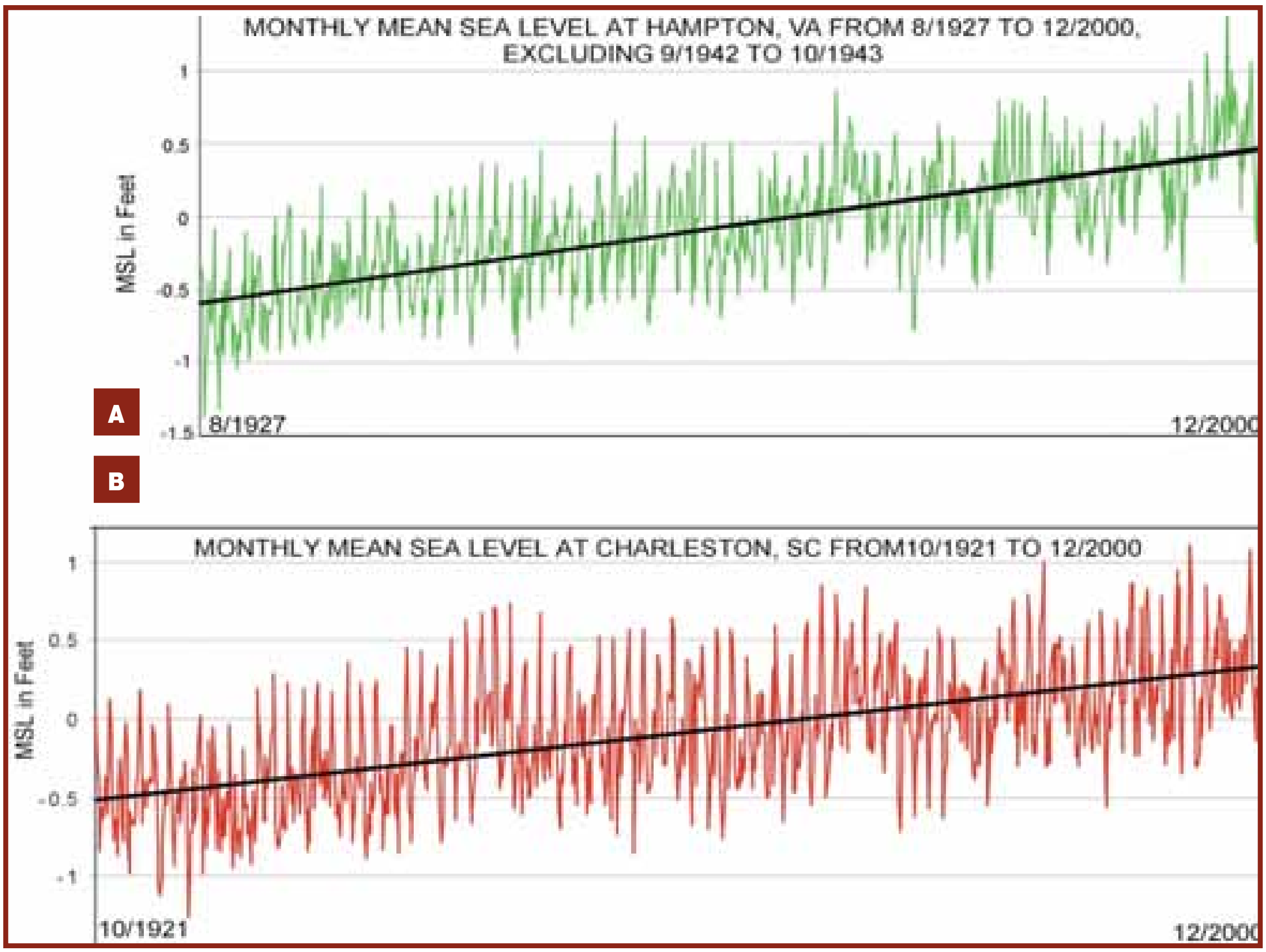


FIGURE 6-3-2. *Tide gauge data from Hampton, Va., and Charleston, S.C., demonstrate the rate of ongoing sea-level rise. The plotted data are monthly averages of mean sea level that extend from August 1927 and October 1921, respectively, to December 2000. The heavy line through each plot is the graphical representation of the trend data obtained by regression analysis, showing the net rise in sea level during this time period. Similar tide-gauge data developed at Duck, N.C., by the U.S. Army Corps of Engineers only goes back to 1980, but in a 20-year time period, the data suggest a slightly higher rate of sea-level rise of about 1.5 ft/100 yrs for the Albemarle Sound coastal region. The two sets of tide-gauge data in Figure 6-3-2 are from the National Oceanographic and Atmospheric Administration (NOAA) National Water Level Observation Network (www.co-ops.nos.noaa.gov/data_res.html).* ***PANEL A.*** *Tide-gauge data for Hampton, Va., suggest sea level has been rising at the rate of 1.16 ft/100 yrs in this region since 1927.* ***PANEL B.*** *Tide-gauge data for Charleston, S.C., suggest sea level has been rising at the rate of 1.01 ft/100 yrs in this region since 1921.*

feet along the southern boundary and up to thousands of feet in the vicinity of the canal. In this region, the marsh vegetation has displaced the red-colored scrub-shrub transition zone vegetation and pocosin swampforest vegetation.

The Intergovernmental Panel on Climate Change (IPCC, 2001) has predicted increased rates of global sea-level rise by the year 2100 (Fig. 6-2-1) up to 2.89 feet (0.88 meters) above present sea level with an average rise of 1.61 feet (0.49 meters). This rise is in response to global warming will result "primarily from thermal expansion and loss of mass from glaciers and ice caps" (IPCC, 2001). If the IPCC predicted values near the average or above turn out to be correct, the North Carolina coast is in for serious consequences. The two new maps displayed in Figures 6-3-4A and 4B are predictions of shoreline changes in coastal North Carolina. These maps are based upon 38 years of detailed research concerning the continental shelf, barrier islands and estuarine and riverine systems of the North Carolina coastal region by the author. The database involves thousands of miles of subsurface seismic, ground-penetrating radar and side-scan sonar data, over a thousand drill holes, and 300 age dates, and innumerable sedimentologic and stratigraphic studies concerning the geologic framework upon which our coastal system is perched.

Large segments of the Outer Banks are already collapsing as evidenced by the lack of space to maintain a viable coastal highway (N.C. Hwy 12) along specific segments. If the intense storm pattern of 1996 through 1999 continues, Figure 6-3-4A could be realized within a few decades. If sea level continues to rise at the present rate and storm frequency is maintained at present levels, the scenario depicted in Figure 6-3-4B could be realized in several centuries. However, if global warming is real and rates of glacial melting increase significantly, as projected by the Intergovernmental Panel on Climate Change (2001) and the U.S. Environmental Protection Agency (Titus and Narayanan, 1995; Warrick et al., 1996) the coast could have the Figure 6-3-4B map geometry by 2100, with major land

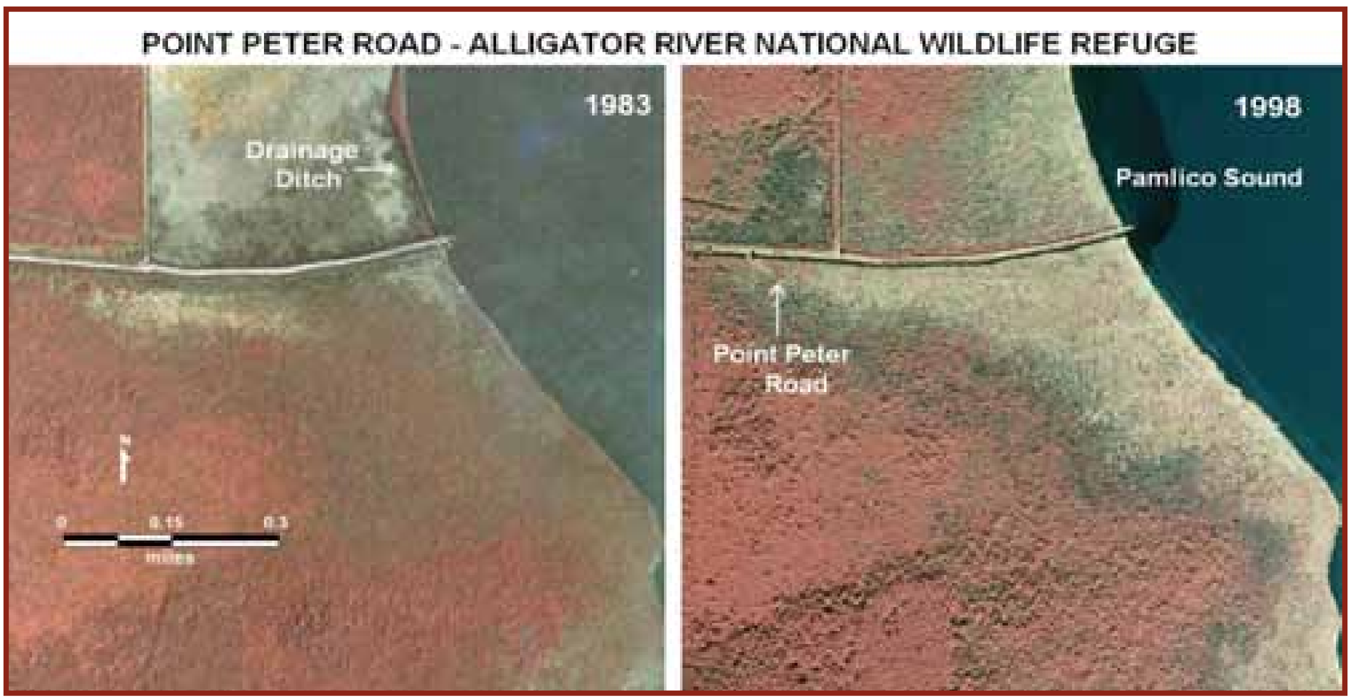


FIGURE 6-3-3. *Due to the extremely low land elevation in the Point Peter Road area of the Dare County mainland (U.S. Fish and Wildlife's Alligator River National Wildlife Refuge), ongoing sea-level rise is having a dramatic effect. The site, on the western shores of Pamlico Sound between Manns Harbor and Stumpy Point, displays marsh expansion at the expense of a pocosin swamp forest. These winter infrared aerial photographs display the marsh grasses (not photosynthesizing) as a pale gray-green color. In contrast, the nondeciduous swampforest trees and scrub-shrubs (photosynthesizing) display a red color. During the period from 1983 to 1998, marsh expansion ranges from about 0.1 to 0.5 miles inland. This dramatic change in the 15-year period is the evolutionary response to ongoing sea-level rise. The 1983 aerial photograph was flown by the High Altitude Program of the U.S. Department of Agriculture. The 1998 aerial photograph is a Digital Orthophoto Quarter Quadrangle from the U.S. Geological Survey.*

losses in Currituck, Camden, Dare, Hyde, Tyrrell, Pamlico and Carteret counties. The change would not be so dramatic for the Southern Province due to the much steeper slope of the mainland.

This ongoing rise in sea level results in the continuing upward and landward migration of the shoreline. The specific process of shoreline migration is better known as ***shoreline erosion***. The fact that sea level is rising worldwide means that erosion is ubiquitous to all of North Carolina's thousands of miles of shoreline. The only differences are the rates of erosion that are dependent upon local tectonic changes in the land, the underlying geologic framework, specific shoreline variables and varying storm conditions. Locally, a segment of the North Carolina shoreline may appear stable or actually accrete sediments. Such a situation represents either an anomalous set of local conditions or is ephemeral in nature.

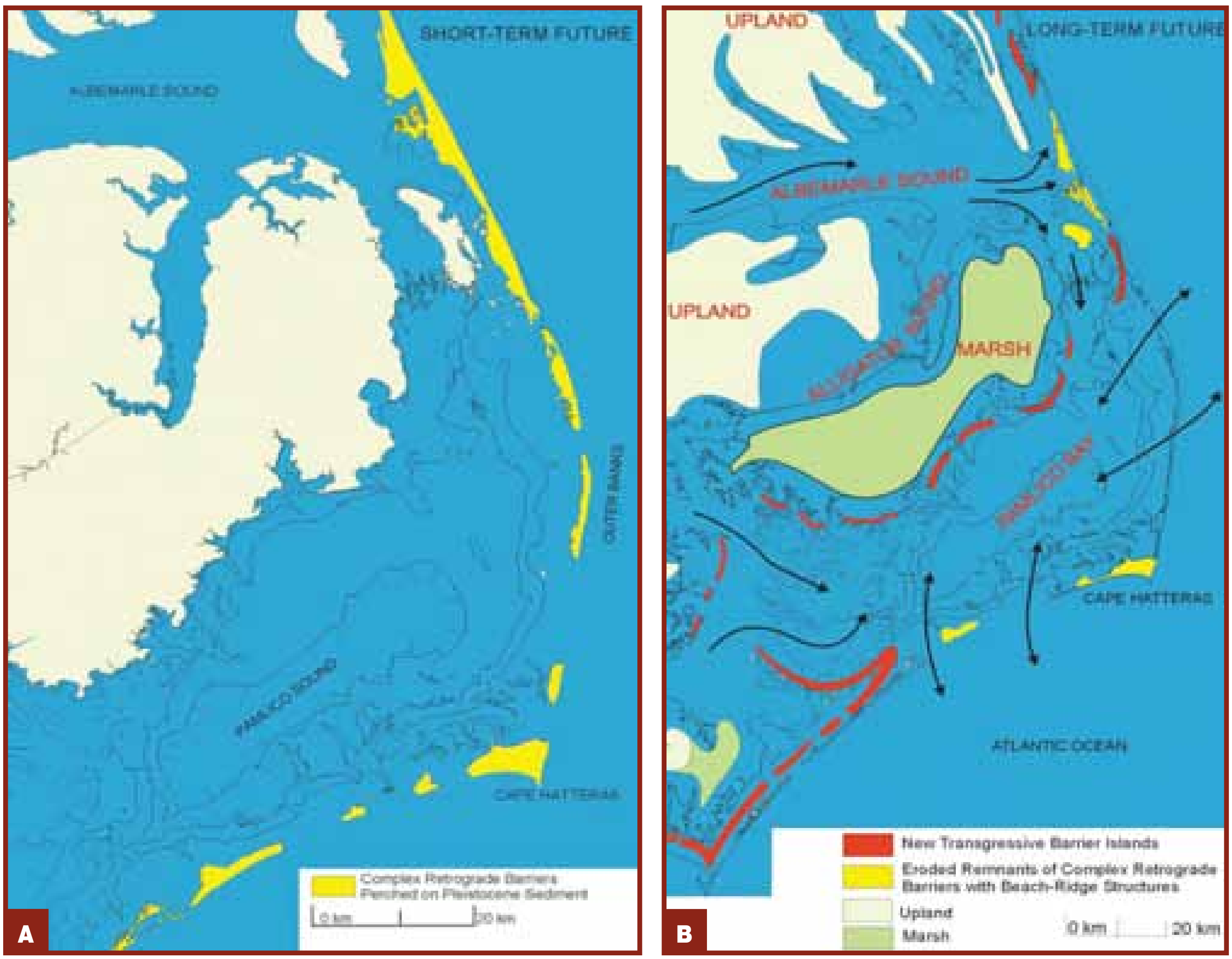


FIGURE 6-3-4. *Prediction for the initial collapse of barrier island segments within northeastern North Carolina. If 1) sea level continues to rise at either the present rate or greater (see Fig. 6-2-1), 2) the quantity and magnitude of storms that have characterized the 1990s continues or increases, or 3) one or more very large coastal storms (category 4 and 5 hurricanes) directly impact the Outer Banks. The portions of the barrier islands that will collapse are the simple overwash barriers that are sediment poor and are characterized by severe shoreline erosion problems.* ***PANEL A.*** *The short-term future (i.e., next few decades) of the northern Outer Banks.* ***PANEL B.*** *The long-term future (i.e., next few centuries) of the barrier islands and associated estuaries within northeastern North Carolina.*

DROWNING

CHAPTER SEVEN:

Long-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

A low sediment bank and associated platform marsh erode along Nags Head Woods shoreline at the eastern end of Albemarle Sound. About 2 feet of sediment and topsoil have been removed by wave action, completely exposing the root structures of the slowly dying oak and pine trees. Notice the erosional scarp that occurs around the Spartina cynosuroides *marsh in the background.*

Long-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

7.1. SEA-LEVEL RISE AND SHORELINE CHANGE IN CROATAN SOUND

7.1.A. Historical Drowning of the Coastal System

For several thousands of years prior to the early 1800s, Croatan Sound was a shallow-water, low-energy, embayed tributary estuary called Croatan Creek (O'Connor et al., 1972; Riggs and O'Connor, 1974; Rudolph, 1999; Riggs et al., 2000). It was actively being backfilled with marsh peats along the margins and organic-rich muds in the shallow central basin. The interstream divide between Croatan Creek and Pamlico Sound (Fig. 7-1-1) was historically known as the Roanoke Marshes (Payne, 1985) and connected Roanoke Island with mainland Dare County in the Wanchese area. This interstream divide was a prominent barrier that completely separated Croatan Creek from Pamlico Sound prior to the European landing on Roanoke Island in 1584.

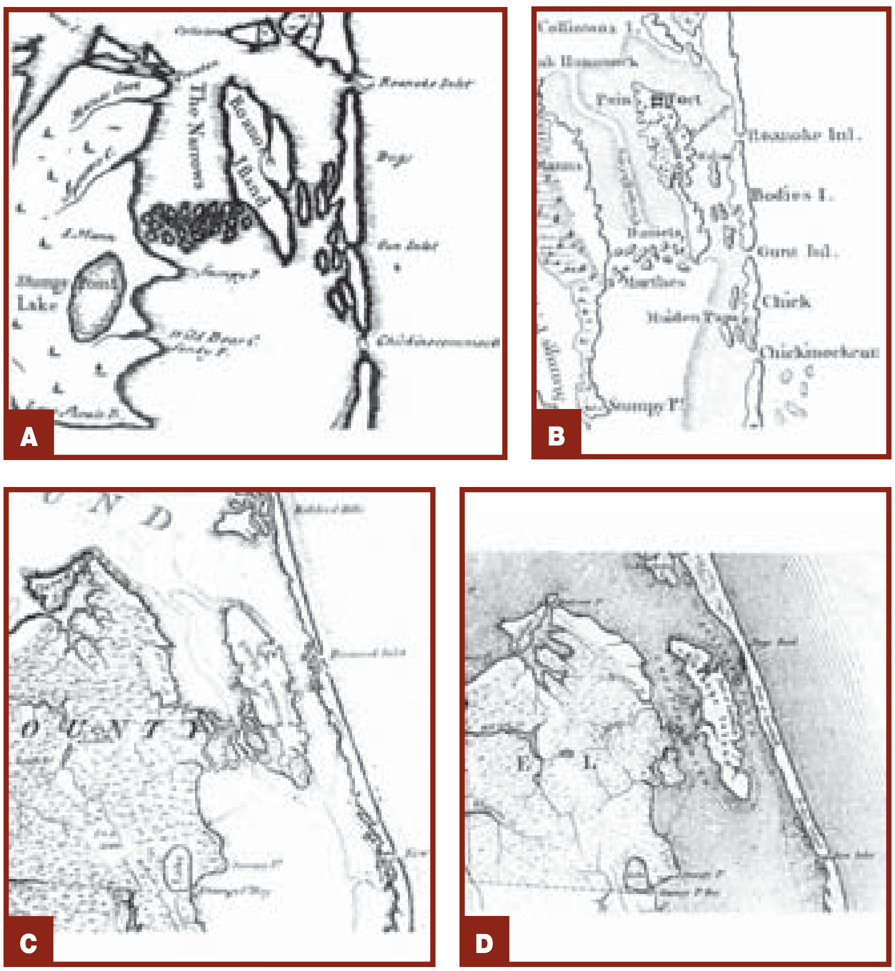


FIGURE 7-1-1. *Historical maps depicting the evolutionary changes for Croatan Sound and the opening of Roanoke Marshes between Croatan and Pamlico sounds. Notice the dramatic changes in inlet location through the barrier islands, the habitat changes within Croatan Sound due to current scour, and the slow dissection of Stumpy Point Lake by the receding shoreline. Maps are not to the same scale.* ***PANEL A.*** *Map of Moseley dated 1733.* ***PANEL B.*** *Map of Collet dated 1770.* ***PANEL C.*** *Map of Price and Strother dated 1808.* ***PANEL D.*** *Map of MacRae and Brazier dated 1833. All four maps are from Cumming (1966).*

Figure 7-1-1 presents four historic maps of the 18th and 19th centuries that depict the final destruction of Roanoke Marshes and erosion of the interstream divide. Observe the closely spaced islands, referred to as "Daniels Marshes" on the 1770 map (Fig. 7-1-1B), and that occur on top of the interstream divide and separate Croatan Creek ("The Narrows" in Figure 7-1-1A and "Through Fare" in Figure 7-1-1B) from Pamlico Sound to the south. The rapid rate of estuarine shoreline erosion causes Pamlico Sound to intersect Stumpy Point Lake to create an open bay. Also, Roanoke Inlet closed by 1817 with the subsequent disappearance of the marsh islands by 1833 (Fig. 7-1-1D). This sequence of events resulted in the formation of Croatan Sound.

O'Connor et al. (1972) and Riggs and O'Connor (1974) related the opening of Croatan Sound during the 18th and 19th centuries to two processes that eventually led to complete erosion of the Roanoke Marshes interstream divide. First, was the ongoing process of sea-level rise and second was the closure of Roanoke Inlet in about 1817 (Figs. 7-1-1C, 7-1-1D). Prior to 1817, the Albemarle and Currituck drainage system connected with the Atlantic Ocean through numerous inlets in Currituck Sound and north of Roanoke Island (Fisher, 1962; Payne, 1985). All Currituck Sound inlets had closed by the early 1800s with the last inlet north of Roanoke Island, Roanoke Inlet, finally closing in about 1817 (Fig. 7-1-1). By the time of Roanoke Inlet closure, sea level had risen high enough to allow the entire Albemarle and Currituck drainage system to flow through Croatan Creek and Roanoke Marshes and exit through Gunt, Oregon and other inlets to the south of Roanoke Island (Fisher, 1962; Payne, 1985). With this increased flow, Roanoke Marshes began to rapidly disappear. Shoreline erosion and bottom scour became the dominant processes changing Croatan Creek to Croatan Sound and opening it to Pamlico Sound (Fig. 7-1-2). By the time of the Civil War battle at Fort Burnsides on Roanoke Island, sailing ships readily moved

Long-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

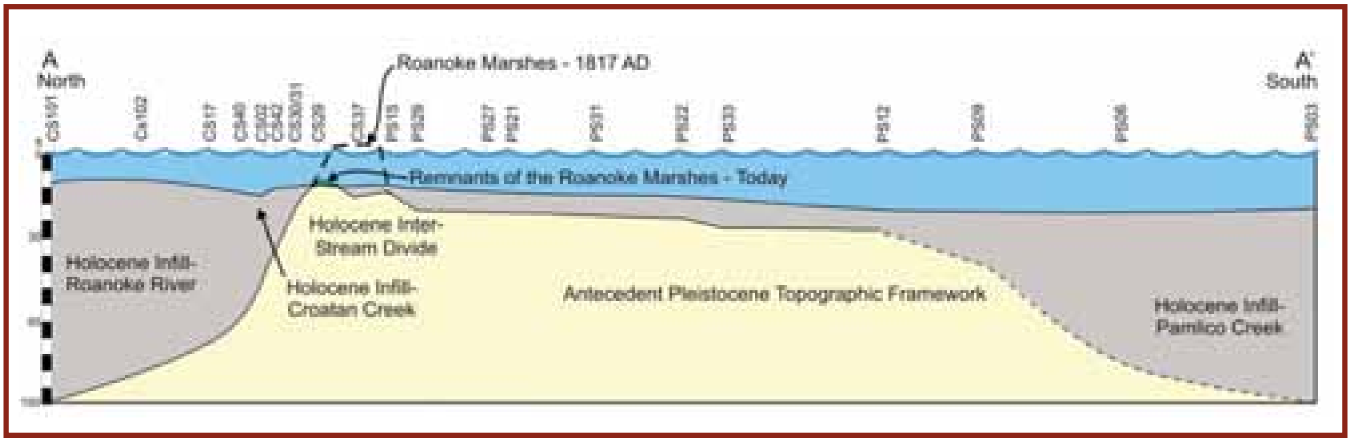


FIGURE 7-1-2. *The A-A' longitudinal cross section (above panel) is drawn along the channel of Pamlico Creek on the south, across the interstream divide at Roanoke Marshes, through the channel of Croatan Creek, and into the Roanoke River on the north. This section shows the general antecedent or paleotopography of the Pleistocene surface and thickness of Holocene sediment that infilled the channel in response to estuarine flooding by rising sea level during the past 10,000 years. Figure is modified from Riggs et al. (2000).*

through the remnants of the Roanoke Marshes and into Croatan Sound. Today, the former Roanoke Marshes area is almost as deep as the rest of Croatan Sound (Fig. 7-1-2).

7.1.B. Shoreline Erosion in Croatan Sound

Is Croatan Sound still expanding in size today? The answer is an emphatic "yes" based upon the following lines of evidence.

1. The estuarine shorelines of all North Carolina's sounds are characterized by recession rates that locally average up to 10 ft/yr, and the bottoms of the larger sounds are being scoured (Riggs et al., 1978, 2000; Riggs, 1996, 2001; Pilkey et al., 1998).
2. The bottoms of the outer estuaries in North Carolina consist of older fossil sediment units that are either exposed on the sound floor or occur just beneath a sporadic, thin veneer of loose surficial sediment (O'Connor et al, 1972; Riggs, 1996). Rudolph (1999) demonstrated that 100 % of the Croatan Sound floor consists of fossil sediment units with a thin and variable (< 2.5 ft) layer of modern surficial sand.
3. The older sediment units contain in situ reefs and individual articulated fossils in growth position that are actively being re-exposed by ongoing bottom scour (Riggs et al., 2000). Radiocarbon dates on these fossils produce ages ranging from 1600 to 2500 radiocarbon years before present. The fossils are dominantly bivalve shellfish (*Tagelus*, *Cyrtopleura*, and *Crassostrea)* that require estuarine waters with high brackish salinity. The modern waters in Croatan Sound range from fresh to low brackish, suggesting that these clams lived in Croatan Creek when it was characterized by very different estuarine conditions.
4. The former interstream divide area containing Roanoke Marshes is today as deep as the other portions of Croatan Sound, excluding the main channel under the old Croatan bridge. The sound bottom in the Roanoke Marshes area is actively being scoured during storms as demonstrated by the erosional character of the basal peat remnants that occur on top of the Pleistocene sediments (Fig. 7-1-2) and crop out on the sound bottom (Fig. 7-1-3).

Thus, Croatan Creek was a low-energy, embayed, tributary estuary in a depositional infilling phase for several thousand years in response to rising sea level. The estuary was systematically infilled with mud, peat and abundant shelled organisms that lived in high-brackish salinity waters resulting from numerous inlets north of Roanoke Island. This condition continued until all northern inlets closed forcing the flow southward through Croatan Creek, across the interstream divide at Roanoke Marshes and into Pamlico Sound. The Roanoke Marshes were totally breached sometime after 1817 when Croatan Sound entered an erosional phase dominated by shoreline recession and bottom

Long-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

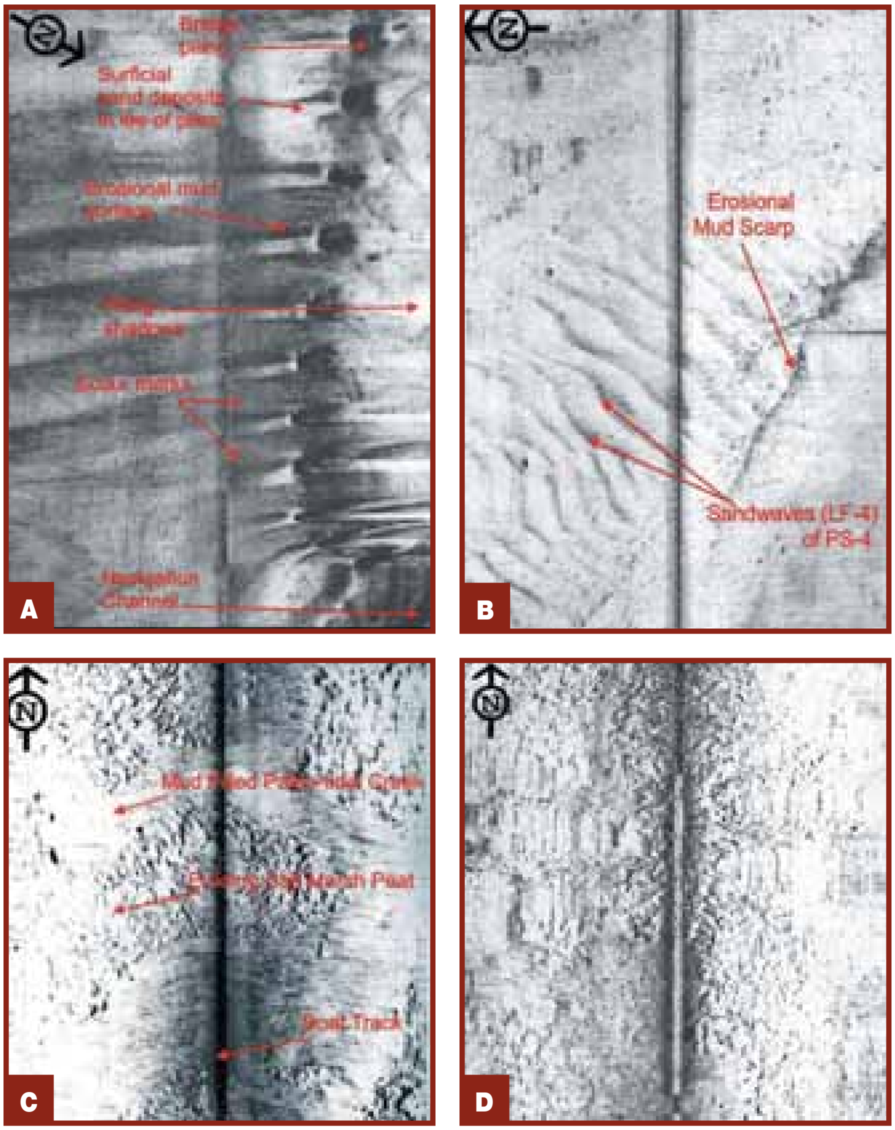


FIGURE 7-1-3. *Side-scan sonar images of Croatan Sound bottom showing relict geologic units exposed on the sound floor. All images are about 666 feet in width.* ***PANEL A.*** *A scour channel located in the center span of the old Croatan bridge (U.S. Hwy. 64) shows linear dark gray patterns (areas of low reflectance) resulting from the exposure of organic-rich mud sediments. These mud sediments infilled Croatan Creek during estuarine flooding in response to rising Holocene sea level. Today, these muds are being severely eroded by the modern flow as displayed in bathymetric profiles on Figure 7-1-4. Also, notice the linear white sand deposits (areas of high reflectance) that occur in the lee (south) of each bridge piling. The broad white reflectance pattern on the north side of the bridge is the sonar shadow with refraction patterns from the bridge pilings.* ***PANEL B.*** *A shallow, sand-covered Pleistocene platform on the western side of the old Croatan bridge (see bathymetric profiles on Fig. 7-1-4). The extensive white pattern is due to the high reflectance character of quartz sand that dominates the platform tops with sand waves having about 33-foot wavelengths. Also, notice the linear scarp that has been eroded into an older mud or peat sediment unit buried below the surficial sand to the east.* ***PANELS C & D.*** *The highly irregular, mottled pattern is the erosional character of marsh peat that crops out on the sound bottom along the southwest side of Roanoke Island. These are the basal remnants of the Roanoke Marshes peat deposits. The peat deposit is dissected by paleo-tidal creeks (smooth areas) that were backfilled with soft mud and very fine sand. These channel-fill muds erode faster than the associated peat, producing lower depressions. The dark gray pattern of peat, closest to the center line, grades to white away from the center line due to the shadow effect of eroding 3-D peat blocks on the sound floor. The peat blocks range from 3 to 15 feet across with vertical relief up to 3 feet. See Figure 7-1-2 for the general location of these eroded peat remnants of Roanoke Marshes.*

scour, and evolved to its present geometry over the next 180 years. The dominant sedimentologic processes occurring in Croatan Sound today are: (1) estuarine bottom scour resulting from diversion of the Albemarle drainage, and (2) shoreline recession associated with an ever-increasing fetch. Figure 7-1-3 contains a series of close-up views of side-scan data demonstrating several dominant sediment patterns left behind on the estuarine floor as the shoreline receded through time.

7.1.C. Changes Along the Old Croatan Bridge Corridor

Riggs et al. (2000) summarized the evolutionary history of Croatan Sound along the old bridge corridor. Figure 7-1-4 overlays four bathymetric profiles through time along the south side of the old bridge for comparative purposes. The profiles include an interpreted reconstruction for 1817, the U.S. Hydrographic Survey profile H257 of 1851, the 1954 N.C.

Continued on page 73

Long-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

Table 7-1-1 Historical Croatan Sound Shoreline Change

Estimated historical shoreline recession rates along the old bridge corridor in Croatan Sound

TIME PERIODS	1817-1851 34 YEARS	1851-1954 103 YEARS	1954-1997 43 YEARS	TOTAL ESTIMATED RECESSION 1817-1997 180 YEARS	MAPPED RECESSION 1851-1997 146 YEARS
• MANNS HARBOR — MAINLAND DARE CO.					
Shoreline Loss	510 m	120 m	60 m	690 m	180 m
	1700 ft	400 ft	200 ft	2300 ft	600ft
Ave. Annual Erosion Rate	50 ft/yr	4 ft/yr	5 ft/yr	13 ft/yr	4 ft/yr
• ROANOKE ISLAND					
Shoreline Loss	620 m	160 m	120 m	900 m	280 m
	2067 ft	533 ft	400 ft	3000 ft	1000 ft
Ave. Annual Erosion Rate	61 ft/yr	5 ft/yr	9 ft/yr	17 ft/yr	7 ft/yr

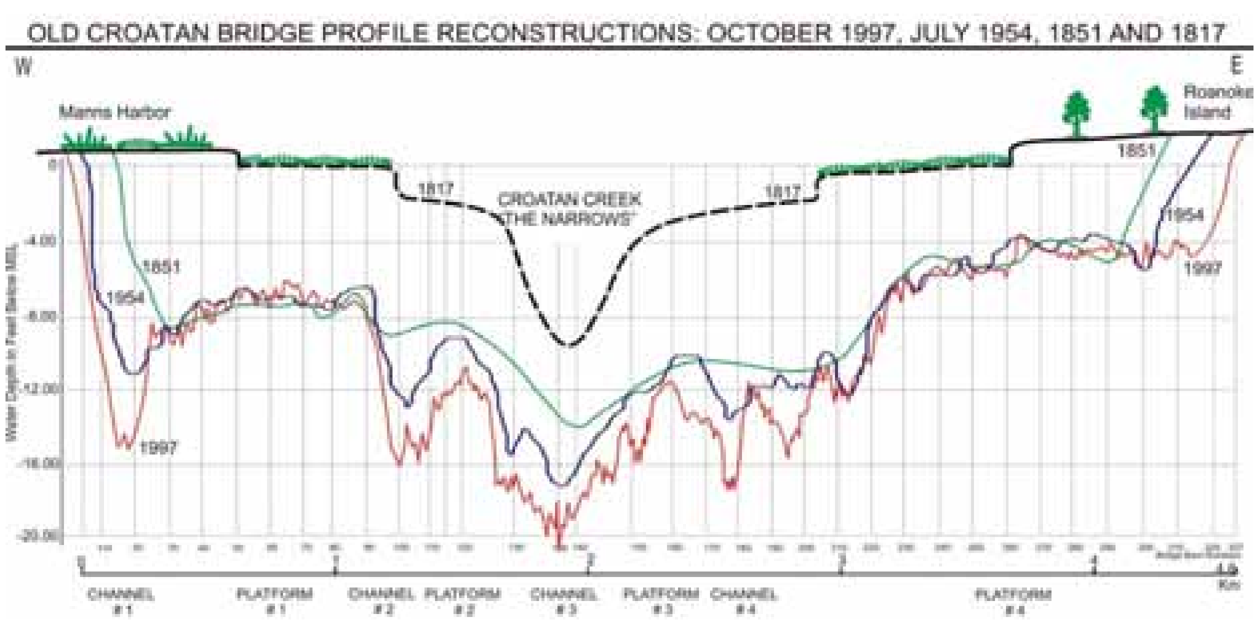


FIGURE 7-1-4. *Composite of four bathymetric profiles along the south side of the old Croatan bridge (U.S. Hwy. 64). The profiles include a general interpretation and reconstruction for 1817 based upon old maps (see Fig. 7-1-1), the U.S. hydrographic Survey profile H257 of 1851, a 1954 N.C. Department of Transportation profile made during the pre-construction survey along the proposed bridge location, and an October 1997 profile from Rudolph (1999). Comparison of these profiles supply the baseline information concerning shoreline and bathymetric changes along the old Croatan bridge corridor through time. Figure is modified from Riggs et al. (2000).*

FIGURE 7-1-5. *Portion of a satellite image (EOSAT from SPACESHOTS, Inc.) of the Cedar Island area showing the modern process of drowning across the Carteret Peninsula interstream divide. The vast Cedar Island* Juncus roemerianus *marsh (gray color) occurs on the interstream divide between West Thorofare and Thorofare bays. With continued flooding due to rising sea level and shoreline erosion, the marsh will rapidly disappear and eventually form an open Thorofare Sound. This is a modern analog for the transition of Croatan Creek to Croatan Bay and finally Croatan Sound.*

Department of Transportation preconstruction survey profile along the location of the proposed bridge, and an October 1997 profile from the Rudolph (1999) study.

The reconstructed bottom geometry for the 1817 time slice represents conditions before Albemarle and Currituck discharge began to flow through and severely erode Roanoke Marshes. This bottom profile is based upon the known geometry of other tributary estuaries in the same stage of drowning, as well as data from historic maps (Fig. 7-1-1). The other three data sets used in Figure 7-1-4 (1851, 1954 and 1997 profiles) are considered to be generally reliable for comparative purposes since the basic geometric pattern persists through time. The ridge tops have changed only slightly from 1851 through 1997. However, there is a systematic decrease in depth of scour-channels. The relative changes are clear even though there are problems with location and production of the profiles, as well as large potential error bars concerning the absolute changes.

7.1.D. Estimated Shoreline Recession Rates

When the Albemarle and Currituck discharge began to flow through Croatan Sound, the sound bottom was severely scoured, and the shoreline receeded at very rapid initial rates over the first 34 years (Table 7-1-1). The initial rapid recession rates probably decreased through time to a slower and more constant rate by 1851. Since 1851, it appears that the annual shoreline recession rate for the Manns Harbor side (mainland Dare County) averaged about 5 ft/yr while the Roanoke Island side averaged about 7 ft/yr (Table 7-1-1). Both of these shorelines consist of low sediment banks and have comparable fetches. However, iron-cemented sandstone dominates the Manns Harbor side. Whereas, soft peat and mud with unconsolidated sand dominate the Roanoke Island side. These recession rates are comparable to those measured on the north Roanoke Island by Dolan et al. (1972, 1986).

7.1.E. Cedar Island Marsh Analog

Croatan Sound is a new open estuarine water body that formed in the North Carolina coastal system since European colonization. It formed in the early 1800s and has continued to widen and deepen. An analogous process is ongoing with many other embayed tributaries such as the Cedar Island Marsh (Riggs and Frankenberg, 1999), which sits astride the Carteret Peninsula interstream divide (Fig. 7-1-5). The *Juncus* marsh shorelines are rapidly eroding, and the bay bottoms are actively being scoured as a result of ongoing sea-level rise and increased flow through the artificially cut waterway across the interstream divide. Ultimately, West Thorofare Bay will totally erode the Cedar Island Marsh, open the connection with Thorofare Bay and produce a wide and deeper Thorofare Sound.

7.2. OTHER EVIDENCE OF ESTUARINE EXPANSION

Preliminary studies in other estuarine systems of northeastern North Carolina have resulted in similar conclusions concerning erosional scour (Riggs, 1996; Sager, 1996; Pilkey et al., 1998; Sager and Riggs, 1998). For example, radiocarbon age dating has demonstrated that older sediments are presently exposed at or near the sediment-water interface in many of the North Carolina estuaries (Riggs, et al., 2000). These radiocarbon age data by numerous investigators suggest that a significant amount of bottom scour is taking place in most of the larger coastal sounds. The older, slightly denser organic-rich mud sediment occurs below a thin and variable layer (from 0 to 2.5 feet thick) of modern organic-rich mud or quartz sand, depending upon location within the estuarine system (Riggs, 1996). This thin, modern sediment layer is readily eroded during high-energy storm periods when the older and denser sediments are exposed and eroded.

DROWNING

CHAPTER EIGHT:

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

Along the west shore of the Pungo River estuary, the eroding platform marsh (foreground) is severely scarped and undercut, while the receding low sediment bank (background) leaves a trail of dead pines in the encroaching water. This Wades Point marsh is eroding at an average rate of –3.2 ft/yr, while the low sediment bank has an average recession rate of –4.1 ft/yr, producing the general embayment. With rising sea level, the Spartina cynosuroides *marsh and peat substrate are migrating up and over the dense clay that rises slightly above sea level to form the low upland covered with pines. As the perimeter pines drown, the tree skeletons are ultimately blown over, leaving a field of submerged stumps and logs in the nearshore area.*

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

8.1. REGIONAL ESTUARINE SHORELINE EROSION STUDIES

8.1.A. Summary of Former Studies

Stirwalt and Ingram (1974) developed a set of maximum annual erosion rates for 16 sites around the perimeter of Pamlico Sound that ranged from –2.5 to –11 ft/yr (Table 3.1 in Riggs, 2001). Their data were re-evaluated by Riggs and subdivided based upon the apparent shoreline type, orientation and fronting water body. This re-evaluation demonstrated significantly different shoreline responses that ranged from –1 to –36 ft/yr (Table 3.2 in Riggs, 2001).

The U.S. Department of Agriculture, Soil Conservation Service (USDA-SCS, 1975) produced shoreline erosion data for 15 coastal counties. Three southern coastal counties were judged to have minimal erosion problems, and the back-barrier estuarine shorelines were beyond the scope of their study. Their data were based upon defining a series of reaches within each county that severely generalized the variables and produced an average number over large distances that ranged from 0.5 to 39 miles in length. The USDA-SCS study calculated an average erosion rate of –2.1 ft/yr for 1,240 miles (87% eroding) of northeastern North Carolina between 1938 and 1971, while the average for the individual coastal counties ranged from –0.9 to –4.5 ft/yr (Table 3.3 in Riggs, 2001).

The author and colleagues in the Geology and Biology departments at East Carolina University carried out numerous studies on estuarine shoreline erosion in the North Carolina coastal system during the 1970s. The location and results of these initial studies are outlined in Riggs (2001). The classification, abundance and distribution of shoreline types studied by Bellis et al. (1975), O'Connor et al. (1978), and Riggs et al. (1978) within northeastern North Carolina are summarized in Tables 8-1-1 and 8-1-2. This estuarine shoreline erosion study consisted of physically mapping the geologic, biologic and hydrologic character of the shorelines within northeastern North Carolina estuarine system on 1:1000 scale maps from shallow draft boats. Approximately 50% of the more than 3,000 miles of estuarine shoreline were included in the study area, which did not include the back-barrier estuarine shoreline, large portions of Pamlico Sound and many of the small tributary estuaries. The numbers in Tables 8-1-1 and 8-1-2 represent only those miles and percentages of shorelines

Table 8-1-1 Distribution and Abundance of Shoreline Types (1978)

Distribution and abundance of shoreline types in the estuarine system of northeastern North Carolina. The numbers represent only those miles and percentages of shoreline actually mapped by the Riggs at al. (1978) study.

STUDY REGION	ALBEMARLE SOUND	PAMLICO RIVER	NEUSE RIVER	CORE-BOGUE SOUNDS	TOTALS
Miles Mapped	436 mi (27%)	483 mi (30%)	452 mi (29%)	222 mi (14%)	1593 mi (100%)
Low Sediment Bank	159 mi (36%)	112 mi (23%)	124 mi (27%)	76 mi (34%)	471 mi (30%)
High Sediment Bank	59 mi (14%)	19 mi (4%)	24 mi (5%)	9 mi (4%)	111 mi (7%)
Bluff Sediment Bank	4 mi (1%)	5 mi (1%)	12 mi (3%)	— —	21 mi (1%)
Swamp Forest	101 mi (23%)	7 mi (2%)	2 mi (<1%)	— —	110 mi (7%)
Marsh	113 mi (26%)	340 mi (70%)	290 mi (64%)	137 mi (62%)	880 mi (55%)

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

actually mapped by the Riggs et al. (1978) study.

Riggs et al. (1978) integrated their mapping results with the (USDA-SCS, 1975) study of estuarine shoreline erosion rates in the coastal counties of northeastern North Carolina. Table 8-1-3 summarizes the average annual rate of recession for each shoreline type (Riggs, 2001).

Hardaway (1980) established 10 shoreline study sites along the Pamlico River estuary (Fig. 8-1-1). These sites were selected to represent combinations of three types of sediment bank, marsh and human-modified shorelines, as well as different physical variables controlling shoreline erosion. Hardaway mapped each site three times over a 16-month period between August 1977 and November 1978. In March 1987, a graduate student (P. Parham in Riggs, 2001) remapped seven of the original Hardaway sites to develop a 10-year erosion record. During the interim, the adjacent land areas at many of the 10 sites were developed and associated shorelines highly modified.

Everts et al. (1983) measured shoreline change for the period between 1852 and 1980 utilizing 42 historical maps and photos for the back-barrier estuarine system between Cape Henry and Buxton Woods. For the period prior to the 1930s, they utilized topographic surveys produced by plane-table mapping. Since the 1930s, they utilized aerial photography and photogrammetric methods. Everts et al. concluded that the average shoreline erosion rate for the north-south estuarine portion of the barriers was — 0.33 ft/yr. Whereas, the east-west estuarine shoreline associated with Buxton Woods was eroding at an average rate of –4 ft/yr. Due to the limitations of the techniques associated with historic surveys, there is a fairly large error bar on absolute amounts and rates of shoreline change.

Murphy (2002) remapped nine of the original Hardaway (1980) sites and mapped five additional sites along the Albemarle-Pamlico mainland shoreline and six sites along the back-barrier shorelines. She carried out a georeferenced aerial photograph analysis of digitized shorelines on aerial photo time slices to develop a short-term erosion record. However, due to the inability to duplicate the erosion rates developed by Murphy, a complete re-evaluation of the Murphy sites was carried out for the present study. It was subsequently determined that serious problems existed with resolution in scanning the aerial photographs and procedures utilized for both georeferencing the photos and digitizing the

Table 8-1-2 Natural and Human Modification Features (1978)

Natural and human features that modify various shoreline types and the erosional and accretionary status of shorelines in the northeastern North Carolina estuarine system. The numbers represent only those miles and percentages of shorelines actually mapped by the Riggs et al. (1978) study.

STUDY REGION	ALBEMARLE SOUND	PAMLICO RIVER	NEUSE RIVER	CORE-BOGUE SOUNDS	TOTALS
Cypress Fringe Sediment Bank	82 mi (19%)	5 mi (1%)	29 mi (6%)	— —	116 mi (7%)
Marsh Fringe Sediment Bank	15 mi (3%)	27 mi (6%)	53 mi (12%)	47 mi (21%)	142 mi (9%)
Sand Apron Marsh	17 mi (4%)	8 mi (2%)	32 mi (7%)	9 mi (4%)	66 mi (4%)
Significant Shoreline Erosion in 1975-1977	390 mi (90%)	457 mi (95%)	408 mi (90%)	200 mi (90%)	1455 mi (91%)
Significant Sand Accretion in 1975-1977	4 mi (1%)	2 mi (<1%)	23 mi (5%)	3 mi (1%)	32 mi (2%)
Human-Modified Shoreline by 1977	41 mi (9%)	24 mi (5%)	20 mi (4%)	19 mi (9%)	104 mi (7%)

shorelines. This resulted in significant errors in data analysis, map presentation and calculations of erosion rates and associated error bars.

Thus, the Murphy study (2002) has serious flaws that make the erosion rate data wrong. Consequently, the present study carried out a total reanalysis of the Murphy study sites, as well as some additional sites. Based upon this re-evaluation, the present estuarine shoreline erosion data for northeastern North Carolina now supercedes the erosional data previously presented for all former studies and publications, including the Murphy study (2002).

These former studies clearly demonstrated the high variability in actual rates of estuarine shoreline recession, as well as the numerous difficulties in developing a good and reliable data analysis. This variability is a direct function of the series of physical, biological, human and analytical variables. The first three of these varibles are considered in Chapter 5 and summarized in Table 5-1-1.

8.1.B. Overview of Present Study

Riggs (2001) summarized the data from known estuarine shoreline erosion studies in coastal North Carolina. Because these pre-existing studies were essentially based upon old aerial photography and done without the benefit of modern computer technology and software, Riggs and Ames initiated the present estuarine shoreline erosion study that would revisit the Hardaway (1980) and Murphy (2002) study sites. The goal was to develop an improved shoreline erosion data base utilizing detailed field descriptions, an array of aerial photography through time and new computer technology. The present study significantly expanded the shoreline area of most previous sites, added a few additional sites, and where significant, subdivided the shoreline into type and physical variable categories.

The 21 sites included in the present study are located on Figure 8-1-1. Table 8-1-3 compares the summary erosion data from the present study by shoreline type with the 1978 data of Riggs et al. The remainder of Chapter 8 describes the sites and presents the newly acquired erosion data in three distinct categories delineated in Figure 8-1-1: the back-barrier sites (1 through 7), the mainland Albemarle-Pamlico sites (8 through 14) and the Pamlico River sites (15 through 21).

Base-line aerial photography control for

Table 8-1-3 Comparison Between the Shoreline Erosion Values (1978) and the Present Study

SHORELINE TYPES*	PERCENTAGE OF MAPPED SHORELINES*	AVERAGE EROSION RATES (FT/YR) RIGGS ETAL., 1978*	RIGGS & AMES PRESENT STUDY**
1. Sediment Bank Shoreline	38%		
A. Low Bank (1-5 Ft)	30%	–2.6	–3.2
B. High Bank/Bluff (> 5 Ft)	8%	–2.0	–2.5
2. Organic Shorelines	62%		
A. Swamp Forest	7%	–2.1	–2.2
B. Marsh Bank	55%	–3.1	
Mainland			–3.0
Back Barrier			–1.4
Weighted Average for all Natural Shorelines***	100%	–2.8	–2.7
Average Range for all Shorelines****		–0.0 to –15.0	+6.1 to –26.3

*The shoreline types, relative abundance and original average erosion rate data are from Riggs, et al (1978).
**The average erosion rate data of the present study are from Table 9-1-4.
*** Excludes strandplain beaches and modified shorelines.
**** Dependent upon Shoreline Erosion Variables (see Chapter 5, and Table 5-5-1).

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this study at each site utilized the 1998 Digital Orthophoto Quarter Quadrangles (DOQQ). The DOQQs are in MrSid format and supplied by the U.S. Geological Survey. All other sets of aerial photography utilized for this study and included in the various plates of Chapter 8 are in the public domain and were obtained from and utilized with permission of the following organizations: U.S. National Park Service (Cape Hatteras National Seashore, Manteo, and Cape Lookout National Seashore, Harkers Island); U.S. Army Corps of Engineers (Field Research Facility, Duck); U.S. Department of Agriculture (various offices of the Soil and Water Conservation Service, including Beaufort, Dare, Hyde, Pamlico and Tyrrell counties); N.C. Department of Transportion, Raleigh; N.C. Division of Coastal Management, Raleigh; and Dare County GIS office, Manteo. All aerial photographs were scanned into the computer, georeferenced, manipulated and shorelines digitized utilizing standard procedures and the following software programs: Adobe Photoshop, MapInfo, Ras Tools and CorelDraw. Most study site photographs in the associated plates are by S. Riggs unless identified otherwise.

8.2. BACK-BARRIER ESTUARINE SHORELINE EROSION SITES

8.2.A. Summary: Back-Barrier Shorelines

The estuarine shorelines occurring along the backside of barrier islands are extremely diverse and variable with respect to types and erosion rates. Shorelines along the estuarine side of complex barrier islands are similar to mainland shorelines. However, generally there is

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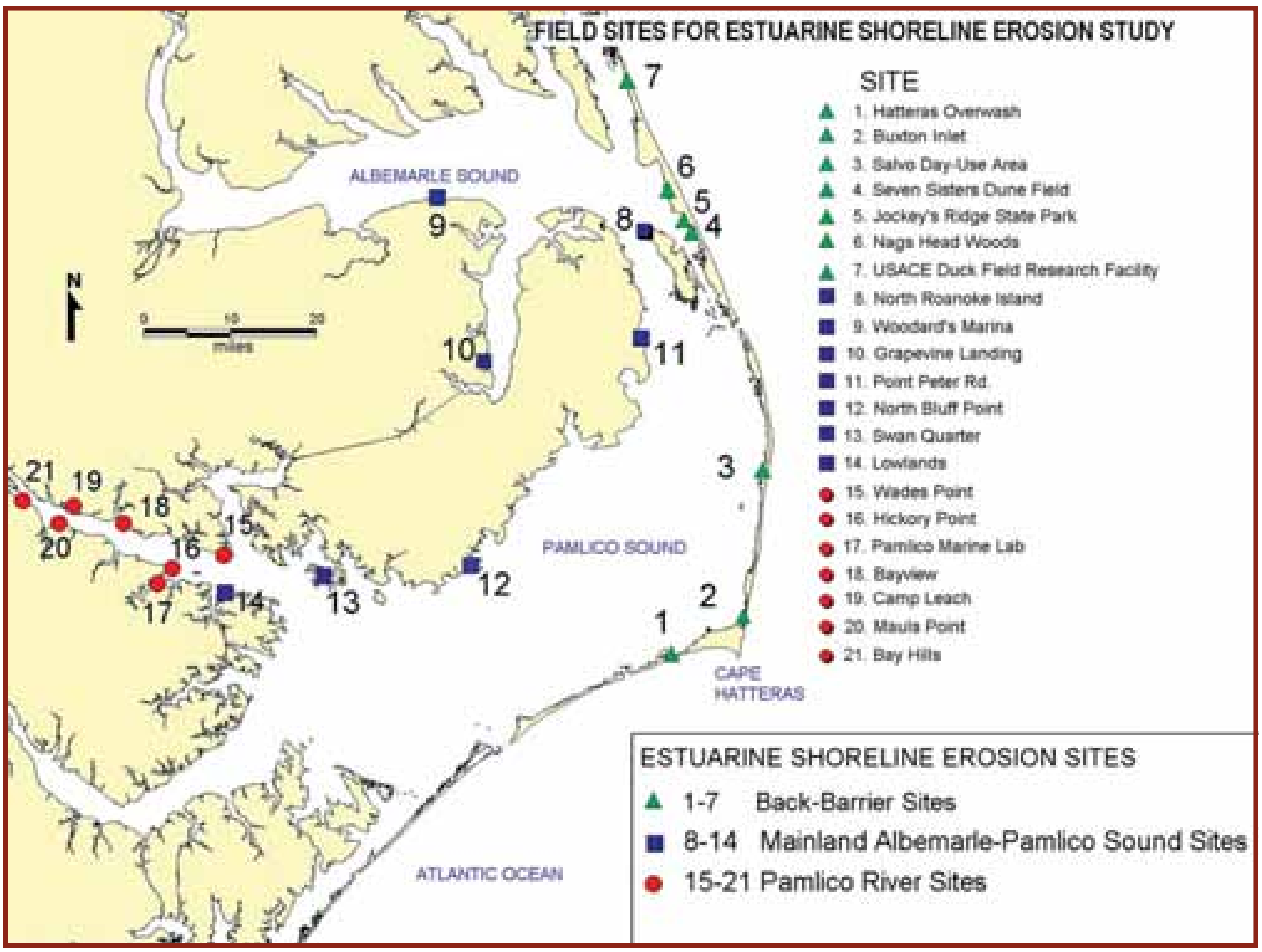

FIGURE 8-1-1. *Map shows the location of estuarine shoreline erosion sites in northeastern North Carolina included in the present study (Chapter 8).*

Table 8-2-1 Summation of Erosion Rates for Back-Barrier Sites

Summation of short-term estuarine shoreline erosion rates for back-barrier sites of the northern Outer Banks based upon the present study. See Figure 8-1-1 for locations of study sites.

SITE AND SHORELINE TYPE	TIME PERIOD (YEARS)	DISTANCE ANALYZED (FEET)	AVERAGE LONG-TERM EROSION RATE DATA — PRESENT STUDY: NET (FT/YR)	RANGE (FT/YR)
1. **Hatteras Site — Middle Pamlico Sound:**				
Marsh Platform—NET	1962-1998	1,000	–0.5	0.0 to –0.8
Strandplain Beach—NET	1962-1998	1,575	+0.8	+3.0 to –0.5
2. **Buxton Site — Middle Pamlico Sound:**				
Marsh Platform—NET	1962-1998	1,800	–2.6*	+4.6 to –18.6
Marsh Platform	1962-1974	1,800	–8.7*	–3.3 to –18.6
Marsh Platform	1974-1998	1,800	+0.2*	+4.6 to –3.0
**A major storm in February 1973 filled the tidal creeks laterally with +250 to +320 feet of overwash sediment. Subsequent storms and resulting overwash formed extensive strandplain beaches in front of major portions of the marsh platform.*				
3. **Salvo Site — Northern Pamlico Sound:**				
Marsh Platform—NET	1962-1998	1,500	–0.9	–0.2 to –2.4
4. **Seven Sisters Dune Field — Eastern Albemarle Sound:**				
Low Sediment Bank—NET	1932-~1973**	9,234	–5.2	0.0 to –8.2
*** Shoreline was only locally modified prior to 1973, but has been almost totally modified through major development since 1973.*				
5. **Jockey's Ridge Dune Field — Eastern Albemarle Sound:**				
Low Sediment Bank—NET/Northern Section	1964-1998	3,290	–3.5	–0.6 to –8.3
Strandplain Beach—NET/Southern Section	1964-1998	1,400	+1.7	+6.1 to –1.7
6. **Nags Head Woods Site — Eastern Albemarle Sound:**				
Open Marsh Platform—NET	1964-1998	8,590	–1.7	0.0 to –4.0
Embayed Marsh Platform—NET	1964-1998	1,000	+0.6	+1.4 to –1.2
7. **Duck Site — Southern Currituck Sound:**				
Low Sediment Bank—NET***	1986-1998	1,947	–0.7	+8.4 to –4.5
Marsh/Strandplain Beach—NET***	1986-1998	1,947	–0.3	+15.5 to –23.5
Marsh/Strandplain Beach	1986-1992	1,947	–6.3	+6.0 to –23.5
Marsh/Strandplain Beach	1992-1998	1,947	+5.7	+15.5 to –3.0
**** The low sediment bank shoreline is modified by a strandplain beach with a dense fringing marsh that occurs in front of the low sediment bank and that comes and goes through time in response to storms and plantings.*				

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more sand in the coastal system due to the presence of various barrier island sources such as back-barrier dune fields. Complex barriers are sediment-rich, resulting in high and wide islands that commonly contain extensive maritime forests. Consequently, there is little to no direct interaction between estuarine shorelines and oceanic dynamics. On the other hand, shorelines along the estuarine side of simple, overwash-dominated islands are extremely different from mainland shorelines. These low and narrow islands are periodically dominated by oceanic processes, resulting in major sediment input in response to overwash events, inlet dynamics and migrating dune sands. Consequently, many low-sediment banks and marsh platforms contain extensive shallow waters with ephemeral strandplain beaches and abundant fringing marsh and offshore aquatic vegetation. These latter processes and responses not only diminish wave energy, but actually build back-barrier platforms critical for barrier island migration processes in response to rising sea level.

Another important variable is the physical character of the back-barrier estuarine water body. For example, shorelines occurring along the narrow and shallow waters of Currituck, Roanoke and Core sounds are generally characterized by shallow water and lower, wave-energy conditions. This results in generally lower erosion rates. On the other hand, shorelines occurring along the very large Albemarle and Pamlico sounds or adjacent to inlets are generally characterized by large water bodies with tremendous fetches and much higher energy and storm-tide conditions. This results in higher erosion rates.

The saving grace for the estuarine shorelines between Oregon Inlet and Ocracoke Inlet is the presence of a very broad and shallow platform called Hatteras Flats (Riggs et al., 1995). Hatteras Flats is a Pleistocene structural platform that extends up to 1 to 2 miles into Pamlico Sound, is generally less than 2 feet deep and contains vast areas of submerged aquatic vegetation. Consequently, Hatteras Flats tend to significantly decrease wave energy approaching the shoreline and resulting rates of shoreline erosion. This structural feature is the top of an interstream divide separating the paleo-Pamlico Creek drainage basin from the next drainage basin to the east that existed on the inner continental shelf during sea-level low stand conditions of the last glacial maximum (see Chapter 6). The modern barrier island system between Oregon and Ocracoke inlets is perched on top of this interstream divide that constitutes Hatteras Flats (Fig. 6-2-2).

Consequently, the rates of shoreline recession along the back barrier are extremely variable and critically dependent upon geographic location and the interaction with oceanic processes. If oceanic processes are cut off by increased island elevation or vegetative growth — whether a product of natural changes or human modification such as construction of barrier dune ridges, road dams and urban development — rates of estuarine shoreline erosion will significantly increase. Table 8-2-1 is a summary of the average annual rates of estuarine shoreline erosion for seven sites occurring along the northern Outer Banks barrier islands. Brief descriptions of each site and a general synthesis of the erosion data occur in the following sections. The sites are located on Figure 8-1-1.

8.2.B. Hatteras Overwash Site

(Figures 8-2-1, 8-2-2 and 8-2-3)

The Hatteras overwash site is located within the Cape Hatteras National Seashore (CHNS) and about 0.5 miles northeast of the northeasternmost road in Hatteras Village. The site occurs immediately adjacent to the CHNS parking lot on the northwest side of N.C. Hwy. 12 and consists of one small marsh platform flanked by two sand strandplain beaches occurring within adjacent coves.

The entire back-barrier island segment between Hatteras and Frisco villages is characterized by a series of marsh platforms that increase in size from the study site northeast towards Frisco and are separated by small embayments or coves. The marsh platforms are terminated on the barrier island side by fairly abrupt 1- to 2-foot topographic rises dominated by transition zone vegetation. These are the terminal ends of more recent overwash fans whose surfaces are dominated by an extremely dense scrub-shrub zone that is narrow at the study site, but widens towards Frisco. In addition, examination of the aerial photographs suggests a major increase in vegetation density within the scrub-shrub zone over the past four decades. This increase corresponds with the minimization of overwash processes by construction and maintenance of N.C. Hwy. 12 and associated barrier-dune ridges.

The coves between platform marshes are former overwash tidal creeks that now contain major sand strandplain beaches and are restricted to the coves. Abundant submerged aquatic vegetation (SAV) grows on the shallow sediments within Sandy Bay and forms extensive wrack lines along various storm water levels on the beach. Frequently, wrack will bury the entire strandplain beach. Wrack is composed primarily of dead SAV grasses that have either been ripped up by storm waves or supplied by seasonal die-off. Accumulated wrack is often thick enough within the coves and along scarped marsh edges to both significantly baffle wave energy reaching the shoreline and aid in trapping sand. Thus, the coves and adjacent portions of the marsh platforms are often protected from severe erosion and may actually accrete sediment during storms. All back-barrier estuarine shorelines associated with Hatteras Flats, extending from Oregon Inlet to Ocracoke Inlet, contain major wrack deposits that vary from season to season as a function of the storm patterns.

The central portion of the Hatteras site is a soundward protruding marsh platform with an erosional scarp cut into firm peat along the outermost edge. Along the platform flanks, the peat scarp generally contains 1- to 10-foot wide sand ramps that bury the scarp and are dominated by *Spartina alternifora*. Landward of the scarp is the outer fringing marsh that has locally been stripped of *Juncus* marsh grass by storms and is dominated with patches of either *Spartina patens* or *Spartina alterniflora*, or both. The outer fringing zone of *Spartina* is separated from the interior marsh by one or more 1- to 2-foot high perimeter wrack berms with abundant sand and

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FIGURE 8-2-1. *Photographs of the Hatteras Overwash site.* ***PANEL A.*** *Looking east along the north side of the eroding marsh platform. The outer zone has been totally stripped of marsh grass during winter storms.* ***PANEL B.*** *Close-up of the peat surface in the outer zone that has been stripped of marsh grass and is now dominated by green algae.* ***PANEL C.*** *Close-up of the outer edge of eroding marsh platform with a large eroded peat block lying in the adjacent shallow waters. The marsh grass is* Spartina alterniflora*. Photograph is from Murphy (2002).* ***PANEL D.*** *Looking east along the inner zone of the marsh platform and the adjacent zone of scrub-shrub that occupies the higher elevation of a more recent overwash fan. Notice the extensive accumulation of wrack along the inner zone of the* Juncus roemerianus *marsh platform.* ***PANEL E.*** *Looking west along the strandplain beach associated with an overwash fan that occurs to the immediate west of the marsh platform. Notice the minor amounts of dead submerged aquatic vegetation (SAV) that has accumulated locally on this summer beach.* ***PANEL F.*** *Same location as Panel E, but now the fall strandplain beach is covered with an extensive accumulation of dead SAV.*

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variable amounts of transition zone vegetation. The interior marsh consists of major stands of pure *Juncus roemerianus*. However, numerous large and irregular patches of former wrack deposition within the interior *Juncus* marsh are now dominated by *Distichlis*, *Borrichia* and *Salicornia*, with some *Spartina alterniflora* and *Iva*.

It appears that the entire marsh platform formerly consisted of *Juncus*, which is becoming a smaller component as erosion diminishes the platform size and wrack covers relatively larger platform areas. Because *Juncus* does not survive wrack burial, the more restricted marsh grasses rapidly take over and dominate these irregular patches as the wrack decomposes. Peat within these irregular patches of wrack deposition tends to be very soft, 2 to 3 feet deep, and consist of decomposed wrack. Generally, a large and irregular wrack line occurs along the landward side of the marsh platform, marking the topographic limit of the former overwash fans.

The marsh platform generally consists of 1 to 3 feet of firm sandy peat with a modern root zone that is thinner than the peat platforms at Nags Head Woods or the mainland marshes. This results in similar erosional processes of the peat scarp, but at much smaller scales. Waves within the much shallower water slowly erode the soft under portions to produce root-bound overhangs that are generally 1 foot thick by 2 to 4 feet wide. These overhangs ramp down to the estuarine floor, ultimately breaking off the overhangs in response to the wave-driven flopping motion, and depositing small peat blocks in the nearshore zone adjacent to the shoreline.

The 1998 DOQQ (Fig. 8-2-2) for the Hatteras overwash site shows the digitized shorelines for 1962 and 1998. The marsh platform had an average shoreline erosion rate of –0.5 ft/yr for the period from 1962 to 1998 (Table 8-2-1), while the strandplain beaches within the adjacent coves actually accreted sediment at the average rate of +0.8 ft/yr. The rates ranged from an accretion rate of +3.0 ft/yr to a recession rate of –0.5 ft/yr. The low net erosion rates, as compared to other sites, are related to the extremely shallow water of Sandy Bay, with abundant surficial sand

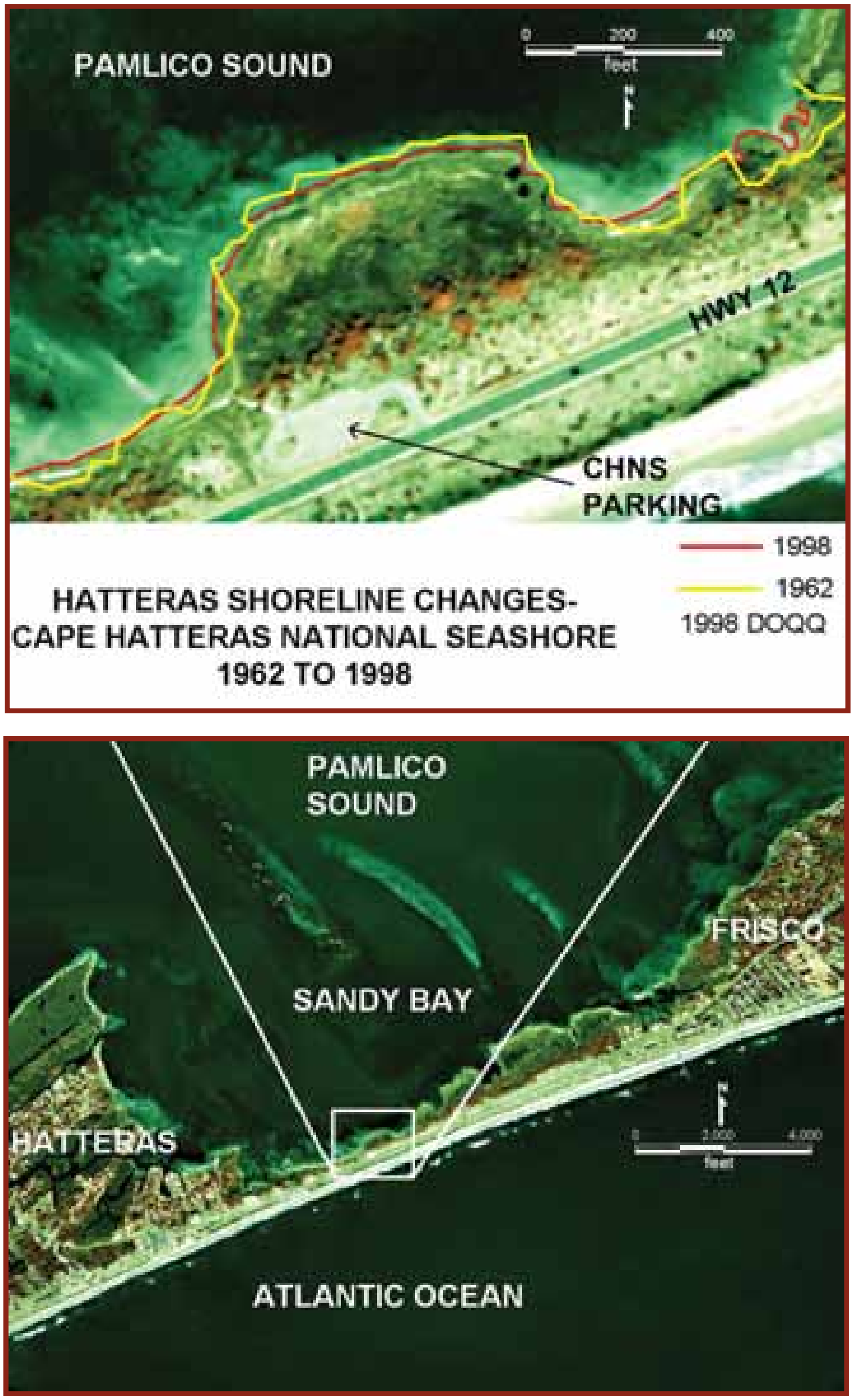

FIGURE 8-2-2. *The Hatteras Overwash site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ), with digitized shorelines for 1962 and 1998.*

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FIGURE 8-2-3. *The Hatteras Overwash site aerial photograph time slices from 1945, 1962, and 1989. The 1945 photo predates construction of N.C. Hwy. 12 and regular maintenance of the associated barrier-dune ridges. Consequently, this barrier segment is dominated by active overwash processes. However, in the 1962 post-Ash Wednesday storm photograph, the overwash is significantly diminished in magnitude. The difference probably reflects the presence of an elevated N.C. Hwy. 12 roadbed and reconstruction of the associated barrier-dune ridge. The 1989 photo shows no overwash due to a major barrier-dune ridge with increased vegetation growth along the landward side.*

from former inlets and overwash processes. In addition, the abundance of dead SAVs tend to diminish estuarine wave energy acting upon the shoreline and aid in trapping and holding sand. The Hatteras marsh platforms are similar to, but larger than the Buxton marsh platforms, possibly due to generally lower erosion rates.

8.2.C. Buxton Inlet Site

(Figures 8-2-4, 8-2-5, 8-2-6 and 8-2-7)

The Buxton site is located within the CHNS and approximately 0.7 miles south of the Haulover Day Use Area, commonly known as the Canadian Hole. This site is what remains of a much more extensive marsh platform as shown on the 1962 aerial photo on the Pamlico Sound side of a narrow, overwash-dominated barrier island segment. The marsh platform has been severely diminished in size as indicated on the 1999 aerial photo.

The 1940 shoreline plot on the 1962 aerial photo demonstrates that minimal estuarine shoreline erosion occurred up to 1962. In spite of a barrier dune ridge and a raised N.C. Hwy. 12, the 1962 Ash Wednesday nor'easter resulted in an extensive series of small-scale overwash fans and opened Buxton Inlet. The highway and protecting dune ridges were subsequently rebuilt, and the inlet was closed by the U.S. Army Corps of Engineers in 1964, with automobiles and sand dredged from the shallow waters immediately behind the barrier. Additional sediment was dredged for several beach nourishment projects during the 1960s and early 1970s, leaving numerous deep holes across the shallow flats that still persist today and are most obvious in the 2000 aerial photo. The fact that these submarine holes have not collapsed and are today, as sharply defined as when they were dredged, suggests that the sediment is not just a thick pile of pure clean sand. Such sediment is not stable enough to hold vertical walls on land, much less beneath shallow waters in a high-energy system.

The Buxton site is a narrow, north-south oriented marsh platform consisting of an outer fringing marsh and interior marsh separated by a well-developed perimeter berm composed of sand

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FIGURE 8-2-4. *Photographs of the Buxton Inlet site.* ***PANEL A.*** *Summer photograph looking north along the backside of the marsh platform with* Spartina alterniflora *in bright green and* Juncus roemerianus *in dark green colors.* ***PANEL B.*** *Winter photograph looking north along the backside of the marsh platform, with the marsh grasses partially eroded off the peat surface. Notice the scarped outer marsh edge and the irregular geometry to the marsh shoreline due to active shoreline erosion processes.* ***PANEL C.*** *Winter photograph looking south along the marsh platform. Notice that there is some sand available to form a high-water sand berm on top of the marsh platform.* ***PANEL D.*** *Summer photograph looking north along the backside of the marsh platform. Notice the abundant sand available to form a major strandplain beach in front of and temporarily protecting the outer-scarped marsh. Also, notice the dead submerged aquatic vegetation (SAV) that formed wrack berms at three different previous water levels. Photograph is from Murphy (2002).* ***PANEL E.*** *Winter photograph looking east across the inner portion of the marsh platform, the narrow scrub-shrub zone, and the newly constructed barrier-dune ridge on the east side of the new N.C. Hwy. 12. Notice the beach berm in the lower right hand portion of the photo that is composed of a lower sand component and two upper SAV wrack components. Also, behind the wrack berms is an irregular patch of rafted wrack within the transition zone vegetation.* ***PANEL F.*** *Looking east at the newly constructed and vegetated barrier-dune ridge built to protect the post-Hurricane Dennis (1999) relocated N.C. Hwy. 12. These structures eliminate the overwash and inlet processes that built this portion of the barrier island and are necessary for maintaining the island for the long term. Without overwash and inlet processes supplying sand to the estuarine side, estuarine erosion rates increase, causing the barrier island to narrow through time.*

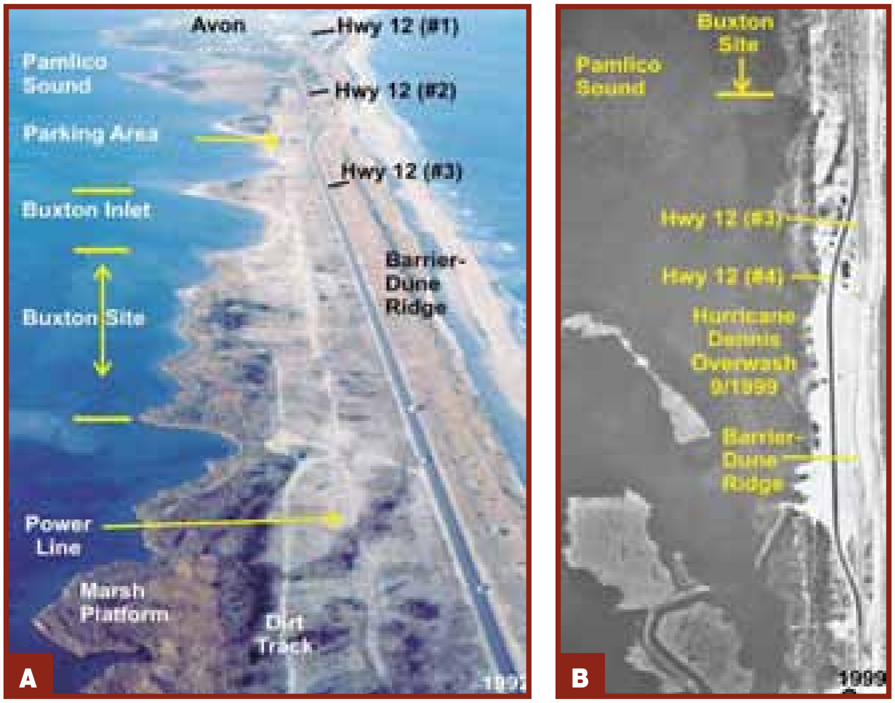

FIGURE 8-2-5. ***PANEL A.*** *A 1992 oblique aerial photograph looking north towards Avon and showing three previous locations of N.C. Hwy. 12, two of which are "going-to-sea" highways. Notice the small marsh platforms that occur along the backside of the barrier island. The dark vegetation occurring between the marsh platforms and upland overwash fans, is dense scrub-shrub growing around the outer lobe of older overwash fans.* ***PANEL B.*** *A 1999 post-Hurricane Dennis aerial photograph (N.C. Department of Transportation) showing N.C. Hwy. 12 (#3) "going-to-sea" and the newly relocated N.C. Hwy. 12 (#4). The new highway was built on the west side of the power lines in the 1992 photograph. However, there is no room to move the road further west in the future, as the island continues to narrow in response to shoreline erosion that is taking place on both sides of the barrier island.*

and SAV grass wrack. Small overwash fan sediments during the 1973 storm filled some former tidal channels between marsh platform segments. Most of these sediment-filled areas have since converted to marsh and been incorporated into the adjacent platforms. More recently, a small sand headland composed of ocean beach sediment formed from a storm overwash that flowed down an ORV roadbed and was deposited into Pamlico Sound as a small overwash fan on the northern end of the study site. North winds transported these overwash sediments southward along the marsh shoreline, which ends abruptly with a steep foreslope at the south end of the fan delta. The overwash sands were subsequently reworked by wave processes, producing a major strandplain beach in front of and on top of the outermost portion of the peat platform and has temporarily stablized the northern marsh platform segment. South of the fan delta deposit, the scarped peat shoreline persists and continues to erode.

The marsh platforms at the Buxton site tend to be very narrow and generally consist of 1 to 2 feet of sandy peat on top of overwash fan sediments. The platform consists of an outer fringing marsh zone composed of *Spartina patens* with local patches of *Spartina alterniflora* that occurs in front of and is displacing the dominant marsh grass *Juncus roemerianus*. Locally, *Juncus roemerianus* occurs right up to the eroding scarp, suggesting more rapid rates of shoreline recession than segments dominated by *Spartina*. Landward of the *Juncus* is a discontinuous, but dense zone of *Borrichia* (sea-oxeye) and *Iva* (marsh elder) that grew within thick accumulations of wrack associated with the perimeter berm. As the wrack decomposes, the resulting soft organic mud sediment is both compacted and/or readily scoured during high storm tides, exposing the extensive root networks.

The outer fringing marsh zone is separated from the narrow interior marsh by a major perimeter berm system composed of SAV wrack and sand. Behind the perimeter berm, the interior marsh is dominated by mixed patches of *Juncus roemerianus*, *Spartina cynosuroides* and wrack. These marsh plants extend landward to a rise in slope that marks the soundside edge of the 1962 storm overwash fans. The slopes of these overwash fans are dominated by transition zone and scrub-shrub vegetation. The erosional processes along the scarped peat platform perimeter are similar to the Hatteras site with soft under portions eroding and producing root-bound overhangs. The overhanging blocks ultimately weaken and break off in response to wave action and are deposited in the zone adjacent to the shoreline, which is littered with small, eroded peat blocks.

It appears that the anthropogenic projects may have altered the pre-1962 stability of this entire back-barrier segment, changing the rates of estuarine shoreline erosion. The post-1962 storm efforts to maintain N.C. Hwy. 12, with increased attention to construction and maintenance of the barrier dune ridge as well as the raised road bed itself, minimized overwash sediments from renewing the back-barrier sand supply. In addition, extensive dredging of up to 20-foot deep holes in firm, nearshore sediments produced traps for shallow surface sands that would normally be used to build strandplain beaches against the marsh platform. This results in slightly deeper water, allowing increased

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wave energy to reach the marsh shoreline and causing increased rates of shoreline erosion. The 1992 oblique aerial photograph shows three subsequent relocations of the "going-to-sea" Hwy. 12. After the fourth N.C. Hwy. 12 relocation (1999 aerial photograph, resulting from Hurricane Dennis, there is no island left for future highway relocations. The combination of natural and anthropogenic processes on a sediment-starved barrier segment — located within the highest wave-energy regime along the northwestern Atlantic margin — will ultimately result in the collapse of this barrier segment as indicated in Figure 6-3-4A.

The 1998 DOQQ (Figure 8-2-6) shows the location of digitized shorelines for years 1962, 1974 and 1998. From 1940 to 1962, there does not appear to be any significant erosion along this shoreline. However, from 1962 to 1974, the shoreline receded at an average rate of –8.7 ft/yr with an average low rate of –3.3 and an average high rate of –18.6 ft/yr (Table 8-2-1). The major tidal channels present in the 1962 aerial photograph were completely filled with washover sand after the Feb. 13, 1973, storm to produce the fairly straight shoreline that appears in the 1974 aerial photograph. During the period from 1974 to 1998, only minimal shoreline change occurred with a net average accretion rate of +0.2 ft/yr. However, accretion was not uniform: the southern 1,450 feet accreted at an average rate of +0.8 ft/yr, while the northern-most 350 feet eroded at an average rate of –2.0 ft/yr. Consequently, the net change for this site from 1962 to 1998 was an average of –2.6 ft/yr.

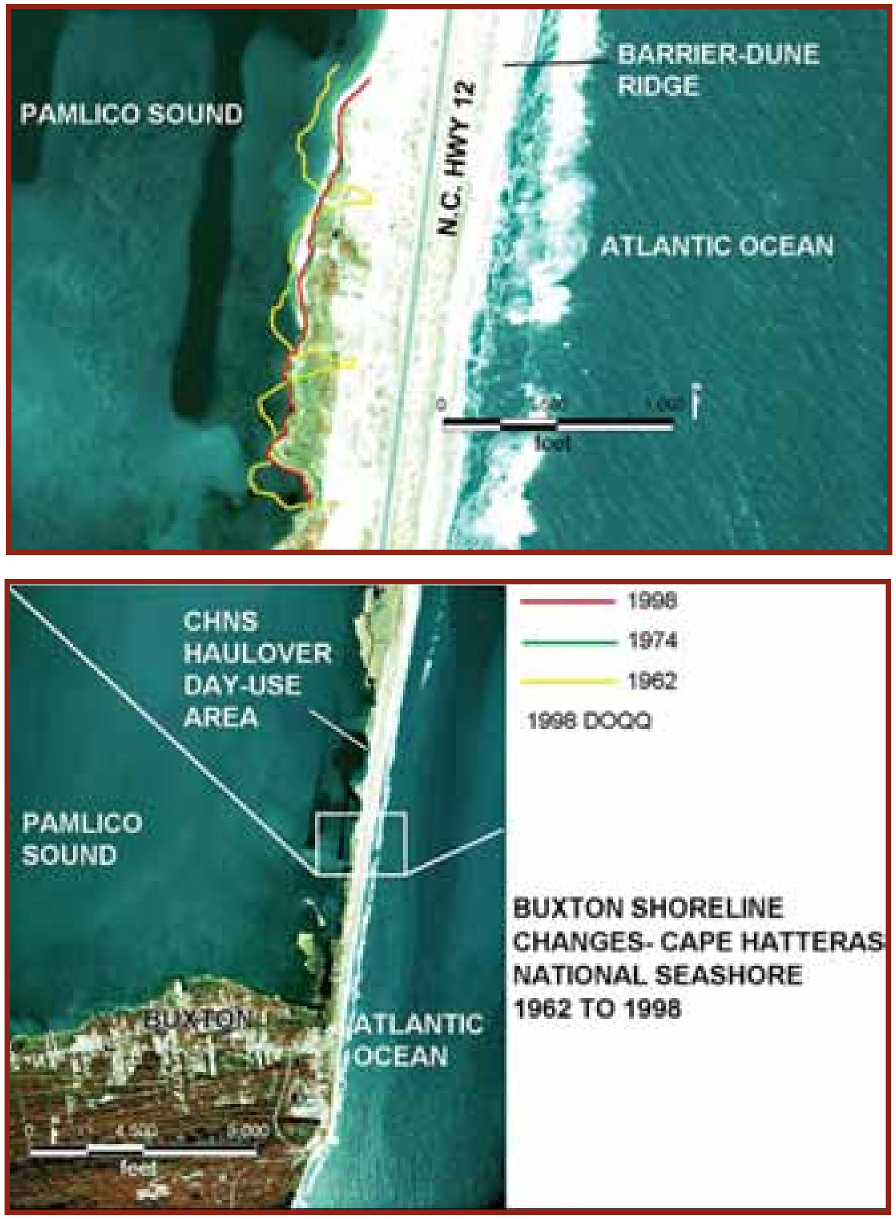

FIGURE 8-2-6. *The Buxton Inlet site 1998 Digital Orthophoto Quarter Quardrangle (DOQQ), with digitized shorelines for 1962, 1974, and 1998.*

8.2.D. Salvo Day-Use Site

(Figures 8-2-8, 8-2-9 and 8-2-10)

The Salvo site is located within the CHNS day-use area, immediately south of the town of Salvo. The site is located west of the northern loop road and between two major tidal creeks that flow into Clarks Bay. The study area is the estuarine side of a major back-barrier berm that contains scattered maritime forest with abundant live oaks and an old cemetery. This back-barrier berm is terminated at both the north and south ends by major tidal creeks, with thick *Juncus roemerianus* marsh shorelines that are not eroding and have been in a constructional phase since the mid-1960s with elimination of overwash processes. The study area does not include these marsh shorelines associated with the flanking tidal creeks.

The study site shoreline consists of the last remnants of an eroding marsh platform with local sand-rich segments and a strandplain beach eroded into the back-barrier berm. Sand for the strandplain beach was derived from both the erosion of the back-barrier berm during high

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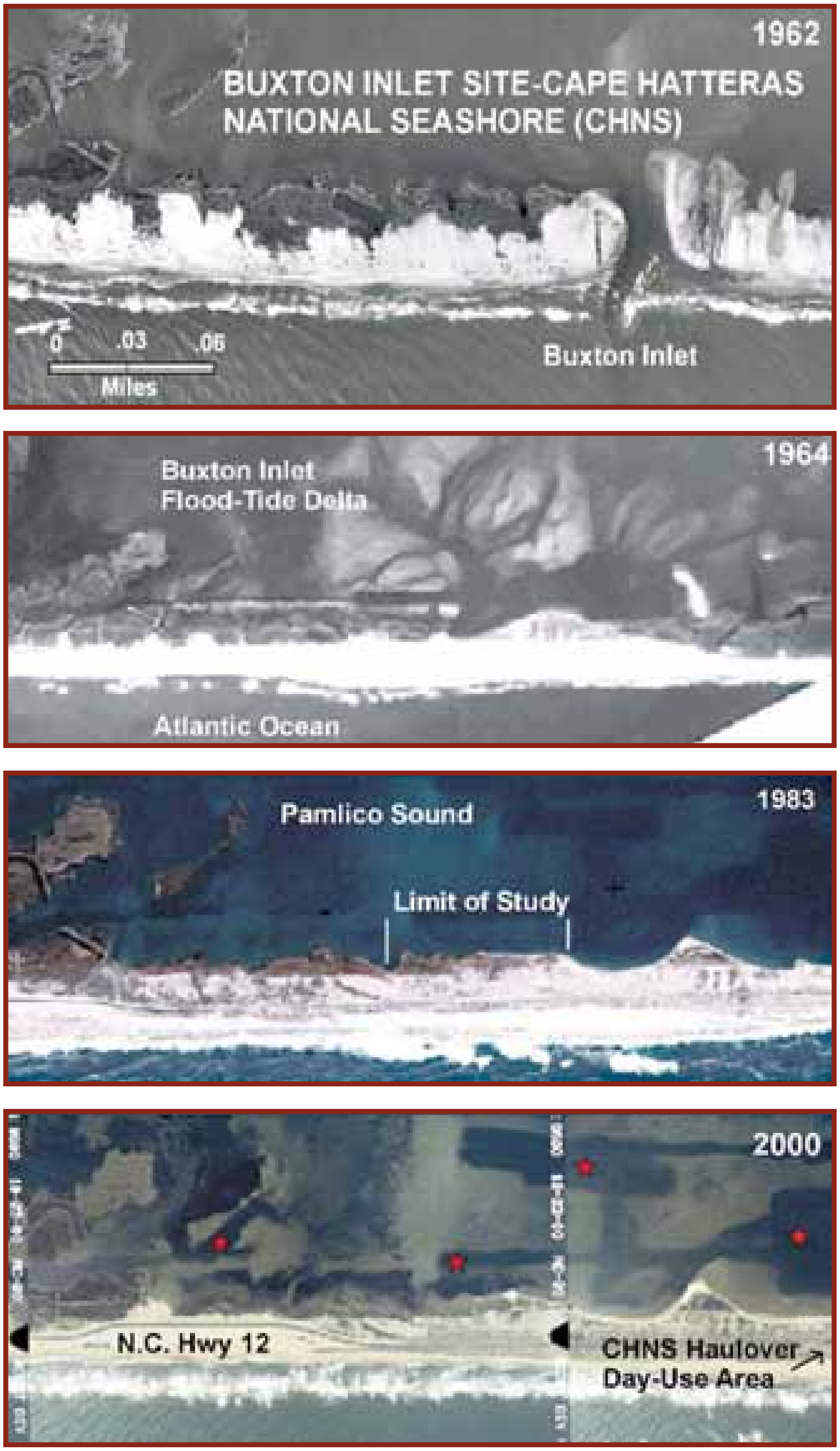

storm tides, as well as former overwash sand deposits supplied to Clarks Bay through the tidal creeks. Clarks Bay is semiprotected with very broad marsh platforms extending soundward onto Hatteras Flats on both the north and south sides. Consequently, the shallow, sand-rich character of this shoreline, in concert with the semi-protected setting and location of the broad and shallow Hatteras Flats, results in this shoreline having relatively low erosion rates.

This marsh shoreline appears to be in the final stages of disappearing, assuming that it originally was more similar to the adjacent marsh platforms. Most of this shoreline consists of an eroding sandy peat that commonly displays small (< 1 foot high) erosional scarps. The small interior marshes are dominated by *Juncus roemerianus* with a narrow outer fringing marsh dominated by *Spartina patens* and *Spartina alterniflora*. Also, the *Spartina* tends to be the dominant marsh grass on the

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FIGURE 8-2-7. *The Buxton Inlet site aerial photograph time slices from 1962, 1964, 1983 and 2000. In the post-Ash Wednesday nor'easter storm aerial photo of 1962, notice the extensive overwash zone and the newly opened Buxton Inlet. In the 1964 photograph, notice the extensive sand body, or flood-tide delta that developed on the sound side behind Buxton Inlet. The inlet was closed by the U.S. Army Corps of Engineers using sand dredged from the dark rectangular holes in the flood-tide delta immediately behind the former inlet. In the 1983 and 2000 photos, notice the two different segments of N.C. Hwy. 12 on the left side of the photo that were sequentially relocated prior to each photograph. Also, notice the numerous and extensive sand mines (red stars in 2000 photo) that were dredged up to 20 feet deep between 1964 and 1983. The sand was used to close the inlet and for several ocean beach nourishment projects. The deep holes allow for increased wave action adjacent to the estuarine shoreline and prevents existing offshore sands from moving into the back-barrier system, causing increased rates of estuarine shoreline recession.*

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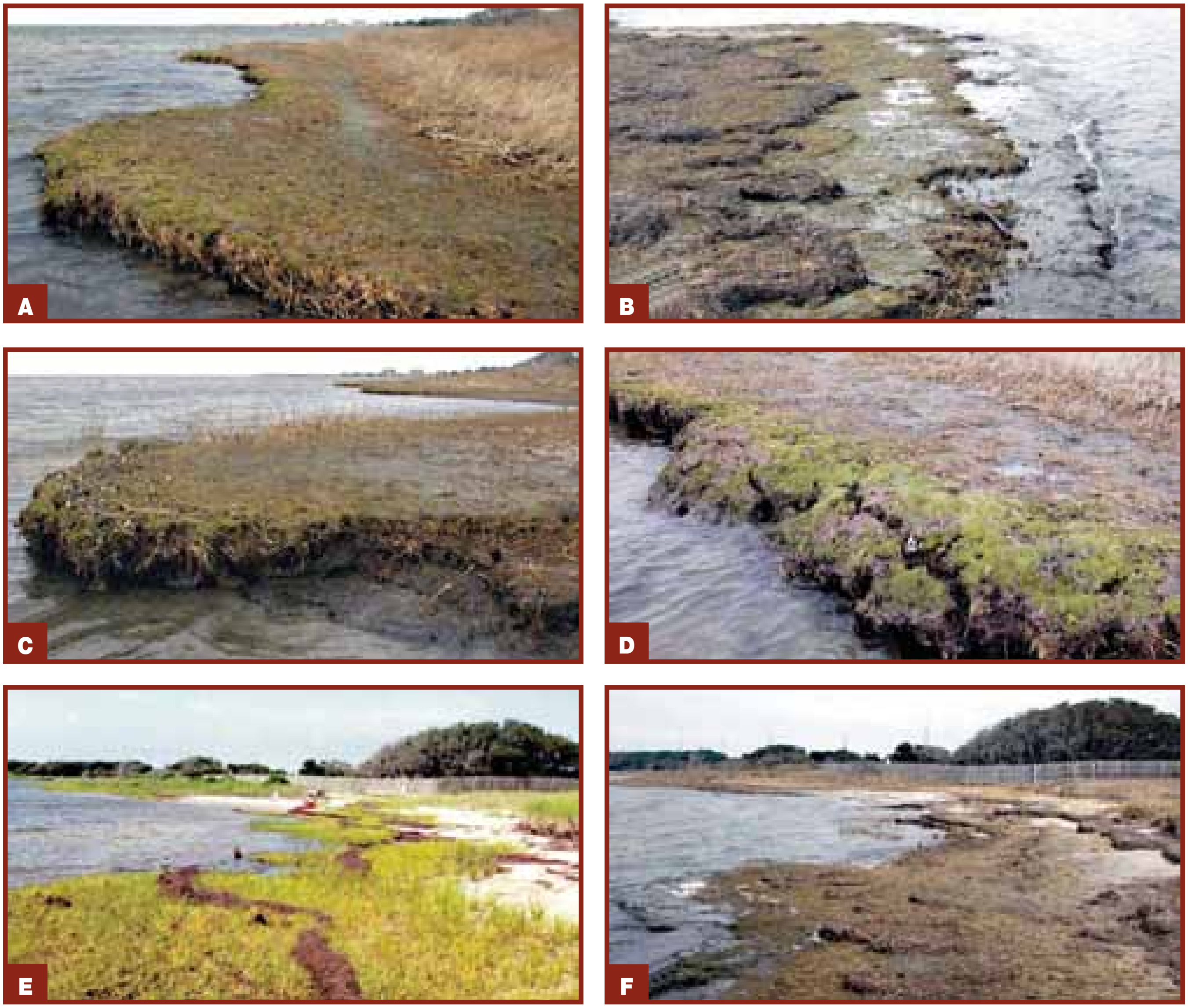

FIGURE 8-2-8. *Photographs of the Salvo Day-Use site.* ***PANEL A.*** *Winter photograph looking north along the outer portion of the peat platform. Low wind tide has exposed the eroding wave-cut scarp in peat along the front side of the marsh platform. Notice that the outer zone is stripped of marsh vegetation by storms and is rapidly colonized by green algae.* ***PANEL B.*** *Winter photograph looking south along the outer portion of the peat platform during low wind tide. Notice how different layers of peat are eroded off in a stair-step fashion and the occurrence of a high water berm composed of dead submerged aquatic vegetation (SAV) with no sand.* ***PANEL C.*** *Close-up of the eroding marsh during a low wind tide. Notice the tough modern root mass forms a sloping overhang (on the left side of the photo) as the softer underlying peat (visible on the lower right side) is easily eroded.* ***PANEL D.*** *Close-up of a block of the modern, root-bound, upper peat surface as it begins to finally crack and break off.* ***PANEL E.*** *Summer photograph of the very narrow* Spartina alterniflora *marsh platform in front of a sand upland dominated by maritime forest and the Salvo cemetery. Notice the occurrence of a high-water level, thin sand berm perched on top of the marsh platform and a low water level, SAV wrack berm without any sand. Photograph is from Murphy (2002).* ***PANEL F.*** *Winter photograph taken at the same spot as Panel E. Notice that there are two SAV wrack berms with most of the sand gone that was associated with the upper sand berm in the previous photo. Also, the marsh grasses have been mostly stripped off the peat surface due to winter wave action.*

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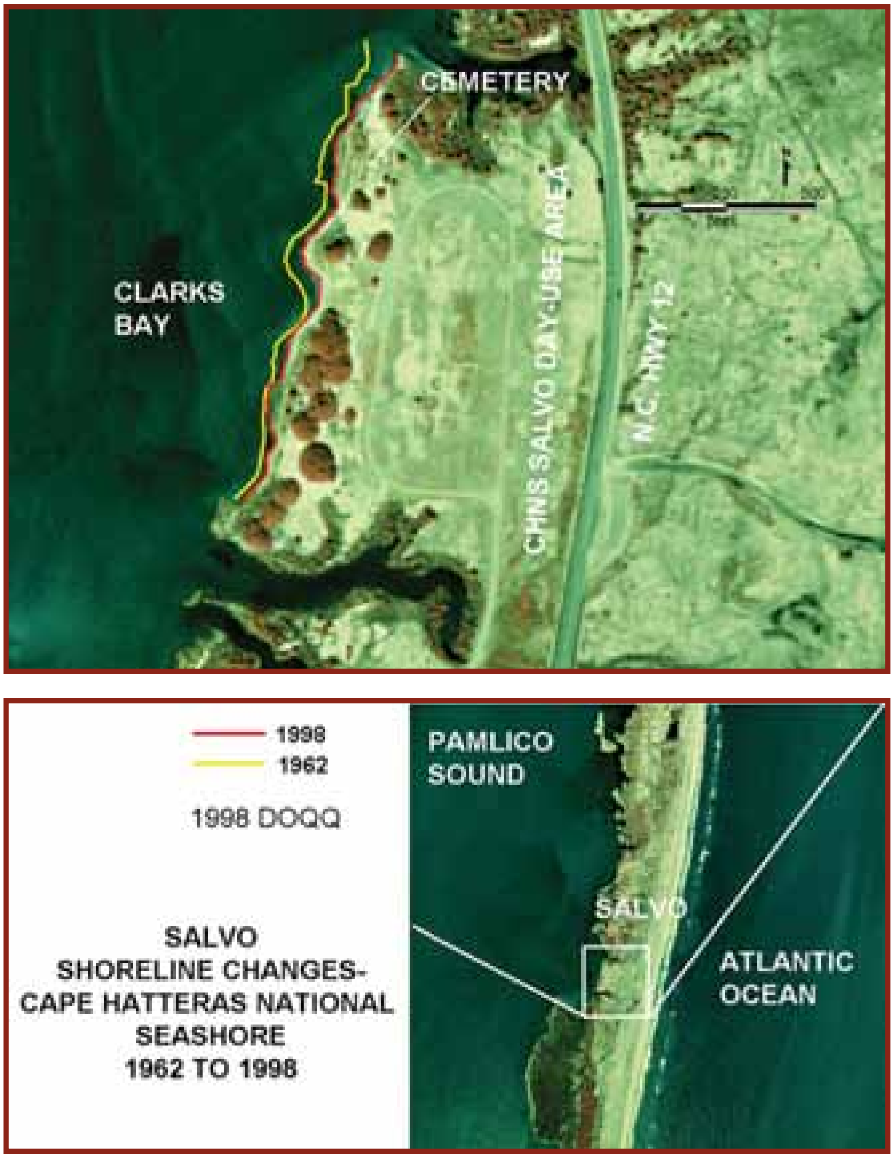

FIGURE 8-2-9. *The Salvo Day-Use site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1962 and 1998.*

strandplain beaches. The outer fringing marsh is separated from the interior marsh by one to several perimeter berms composed of sand and SAV wrack.

The 1962 aerial photograph demonstrates the important interaction between oceanic processes and the estuarine shoreline along this narrow barrier island segment. The study site is the estuarine side of a major overwash plain, with two active tidal creeks that transport sediment into Clarks Bay and drain the overwash events during storms. The overwash sands are subsequently reworked by storm tides associated with sound-side processes into strandplain beaches in front of the scarped marsh peat. This is a constructive and accretionary process that generally protects the backside of overwash barrier islands.

However, since construction of N.C. Hwy. 12 and increased maintenance of associated barrier dune ridges on the ocean side, as demonstrated on the 1978, 1983 and 1998 aerial photographs, the overwash process has essentially been eliminated at this site since the Ash Wednesday 1962 nor'easter. Thus, without the periodic input of "new sand" into this estuarine shoreline segment, this site will probably begin to see increased rates of shoreline erosion and recession through time.

The 1998 DOQQ (Fig. 8-2-9) for the study site shows the location of digitized shorelines for 1962 and 1998. The long-term pattern of shoreline change for this site is a fairly slow and consistent –0.9 ft/yr average erosion rate with a range from an average low of –0.3 ft/yr to an average high of –2.4 ft/yr (Table 8-3-1). This site is moderately well protected inside Clarks Bay with very shallow water and a sand-rich bay bottom. All environmental indicators at this site support slow recession rates. However, major shoreline erosion is noticeable on the large marsh platform that forms the south shore of Clarks Bay (Fig. 8-2-10). The ditched and diked area, dug within the marsh prior to 1940, has been severely breached on the western side by 1998.

8.2.E. Jockey's Ridge and Seven Sisters Dune Field Site

(Figures 8-2-11, 8-2-12, 8-2-13, 8-2-14 and 8-2-15)

The Jockey's Ridge site is located on the Roanoke Sound side of Jockey's Ridge State Park (JRSP). The site extends from Sound Side Road, northwest to the boundary between the park and private sound-side development. The shoreline is oriented NW-SE and occurs at the confluence of the west-east oriented Albemarle Sound and the north-south oriented Roanoke Sound (Fig. 8-1-1). JRSP is an active portion of the back-barrier dune field that constitutes the area from Nags Head Woods to the Seven Sisters dune field. Figure 8-2-14 dramatically demonstrates the severe modification this vast

CONTINUED:

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

dune field has undergone between the 1932 and 1999 aerial photographs. Extensive urban development in concert with heavy vegetative growth have essentially fixed the highly mobile back-barrier dune field everywhere except within the park. However, even within the park, there has been significant vegetative growth around the flanks of the main dune field through time, including portions of the study site.

The shoreline is a low sediment bank eroded into small dunes associated with Jockey's Ridge and an associated strandplain beach. Erosion of the dunes results in a very sand-rich, extremely broad and shallow strandplain beach that forms both the dominant shoreline type along the southern 1,400 feet and an excellent swimming beach. Much of the dune field along the shoreline has been stabilized by pine and scrub-shrub vegetation, resulting in the evolution from a slightly curved shoreline in 1964 to a shoreline characterized by a series of headlands and coves today. The headlands are semistabilized by a dense outer fringing marsh composed primarily of *Spartina alterniflora* and *Juncus roemerianus*. Above the sand berm, the inner marsh zone is composed primarily of *Phragmites australis* and *Baccharis* with minor *Spartina cynosuroides*. These headland marshes

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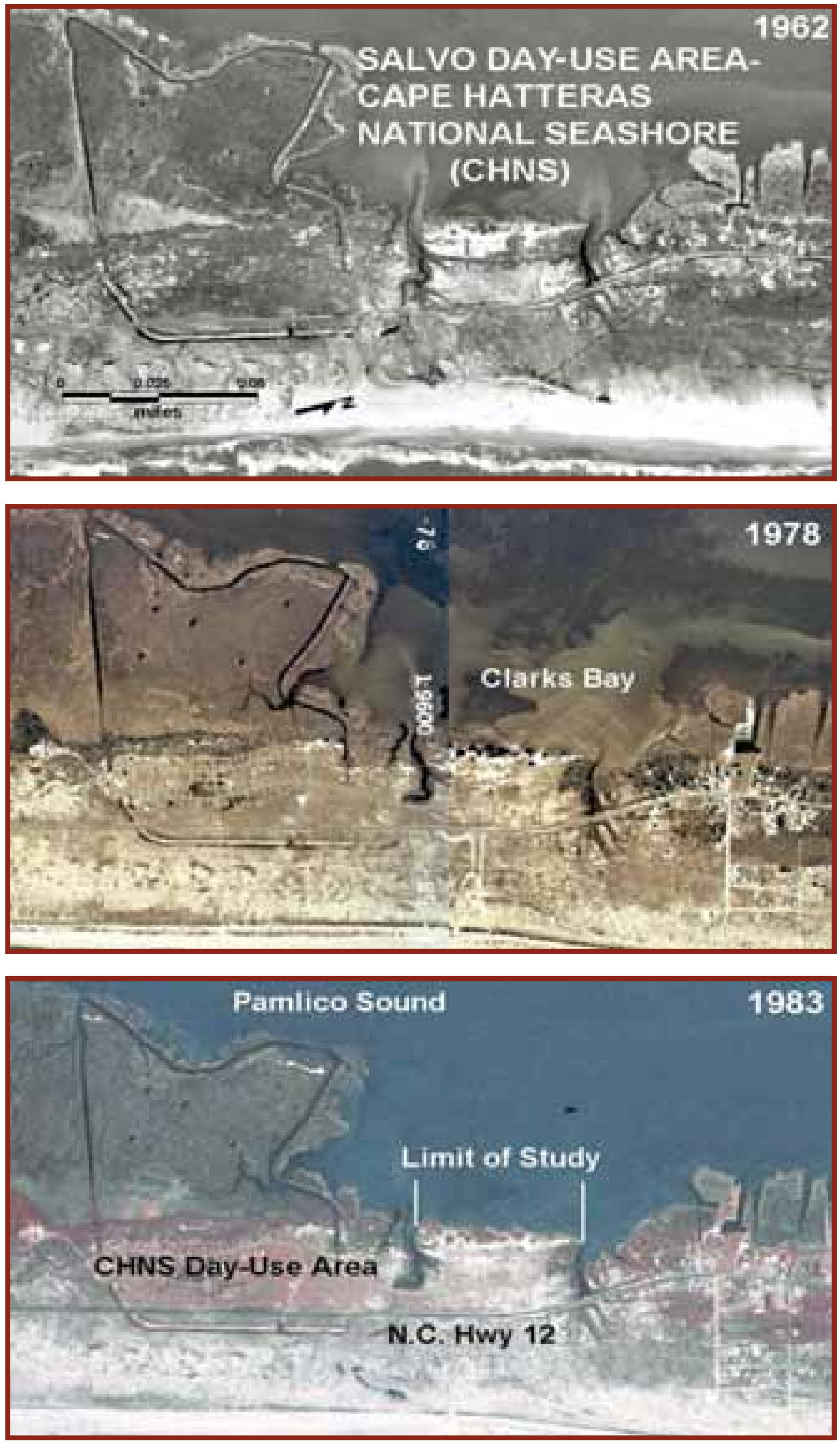

FIGURE 8-2-10. *The Salvo Day-Use site aerial photograph time slices from 1962, 1978 and 1983. In the 1962 photograph, notice that — even though N.C. Hwy. 12 and associated barrier dune ridges were in place prior to the Ash Wednesday nor'easter storm — the old overwash pattern was re-established as the cross-island water flowed into Pamlico Sound through the existing channel structures on either side of the study area. The ongoing process of estuarine shoreline erosion through time is obvious along the outer edge of the impoundment in the upper left portion of the photo sequence (1962 to 1983). By 1998 (Fig. 8-2-9) ongoing shoreline recession had eroded through the adjacent dike and exposed an ever-increasing length of the north-south ditch to the open waters of the Pamlico Sound.*

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Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

FIGURE 8-2-11. *Photographs of Jockey's Ridge site.* ***PANEL A.*** *An oblique aerial photograph showing Jockey's Ridge State Park and the irregular geometry of the estuarine low sediment bank shoreline. Photograph is from the Field Research Facility of the U.S. Army Corps of Engineers.* ***PANEL B.*** *Looking north along the eroding low sediment bank shoreline composed entirely of sand and covered with various types of grass vegetation. The low wind tide has exposed the extremely broad and well-developed strandplain beach that consists of an upper portion occupied during high wind tides and a lower portion occupied during low wind tides. Notice the grassed slump blocks that have collapsed in front of the wave-cut scarp.* ***PANEL C.*** *Close-up view looking south along the eroding low sediment bank shoreline and associated upper strandplain beach. Rapid recession of the wave-cut scarp has required the observation platform, which was sitting on top of the low sediment bank, to be repiled and braced. Notice the exposed roots in the wave-cut scarp.* ***PANEL D.*** *Photo during a low wind tide from a marsh headland and looking east into a cove. The shoreline is a low sediment bank covered generally by pine trees and a very broad and well-developed strandplain beach.* ***PANEL E.*** *Photo looking southwest from inside the cove towards the marsh headland of Panel D. The abundant dead pine trees on the nearshore and strandplain beach demonstrate the active rates of shoreline recession.*

have been growing long enough to form thin and poorly developed peaty sand substrates that now partially bind the sediments. This is an excellent example of a fringing marsh as compared to the marsh platform at the Nags Head Woods site with its thick substrate of pure peat and an eroding scarped shoreline.

The 1998 Digital Orthophoto Quarter Quardrangle shows digitized estuarine shorelines for 1964 and 1998. The Jockey's Ridge shoreline was divided into two segments. The southern segment is about 1,400 feet of well-developed strandplain beach in front of the adjacent dune field. This shoreline displays a net accretion of +1.7 ft/yr during the study period with a range from +6.1 ft/yr to local erosion of –1.7 ft/yr (Table 8-2-1). The northern segment is about 3,290 feet and is dominated by a low sediment bank shoreline that is actively eroding into the adjacent dune field. Due to the sand abundance, there is a small strandplain beach in front of the eroding shoreline. The northern shoreline is receding at –1.7 ft/yr with a range from a low of –0.6 ft/yr to a high of –8.3 ft/yr (Table 8-2-1).

The Seven Sisters dune field occurs due south of Sound Side Road and extends more than 9,000 feet along the Roanoke Sound shoreline. The 1932 georeferenced aerial photograph for the Seven Sisters area shows the location of the 1998 shorelines and roads. This figure suggests that the ocean shoreline has receded along a fairly uniform line approximately 400 feet during this 66-year time period. During the same time interval, the estuarine shoreline receded along a much more irregular pattern with some areas receding up to 360 feet, and other spots experiencing little to no change. This shoreline was only locally modified prior to 1973, but has been almost totally hardened through major development within the Seven Sisters dune field since that time.

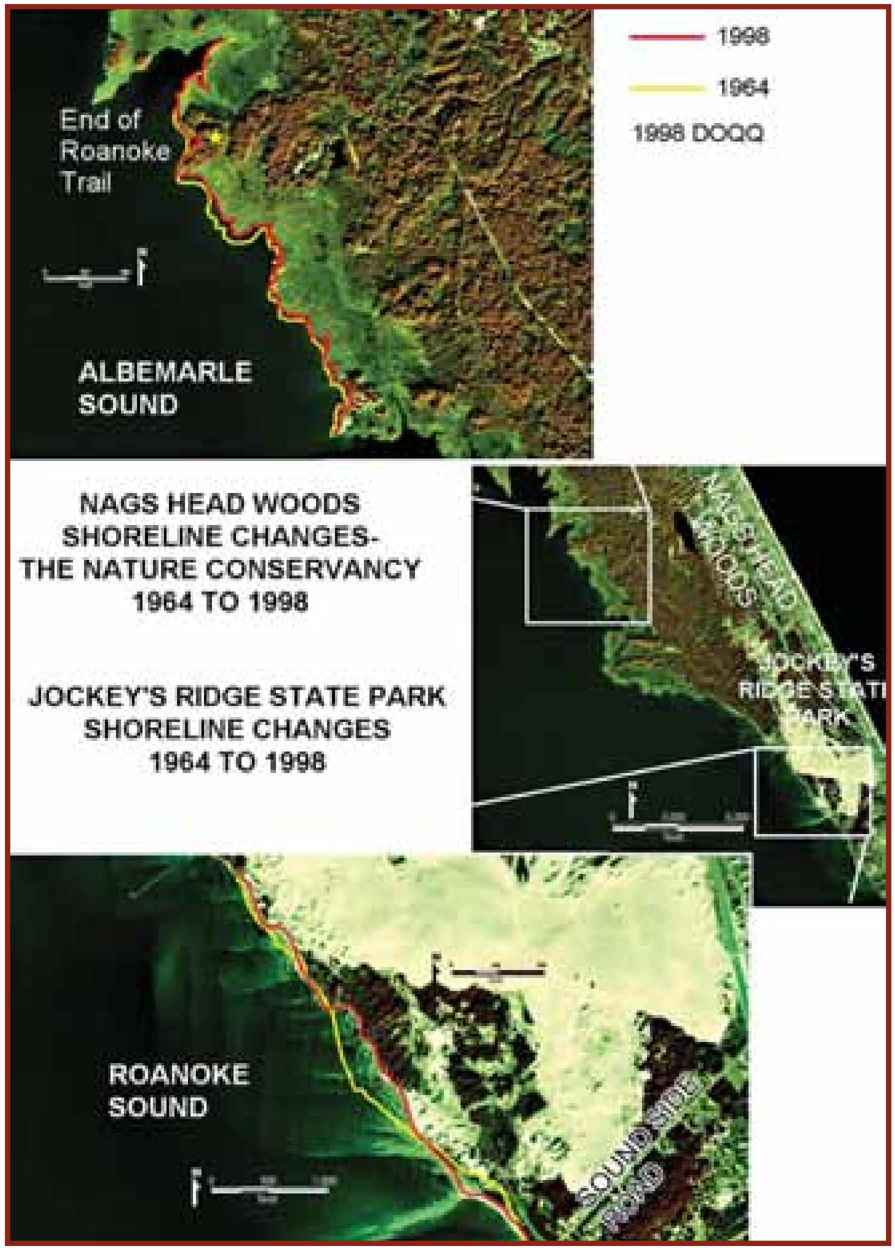

FIGURE 8-2-12. *The Jockey's Ridge and Nags Head Woods sites 1998 Digital Orthophoto Quarter Quadrangle (DOQQ), with digitized shorelines for 1964 and 1998.*

8.2.F. Nags Head Woods Site

(Figures 8-2-16 and 8-2-17)

The Nags Head Woods site is located on The Nature Conservancy (TNC) property at the west end of TNC Roanoke Hiking Trail. The overall shoreline is oriented northwest-southeast and is semiprotected within Buzzards Bay at the easternmost end of the west-east oriented Albemarle Sound (Fig. 8-1-1). The site is a vast marsh platform that drops off into 2 to 4 feet of water, but has an overall unique location with respect to both estuarine and oceanic dynamics. The eastern portion of Albemarle Sound that occurs immediately west of Nags Head Woods is characterized by a vast shallow-water (1 to 6 feet deep) sand deposit known as Colington

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Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

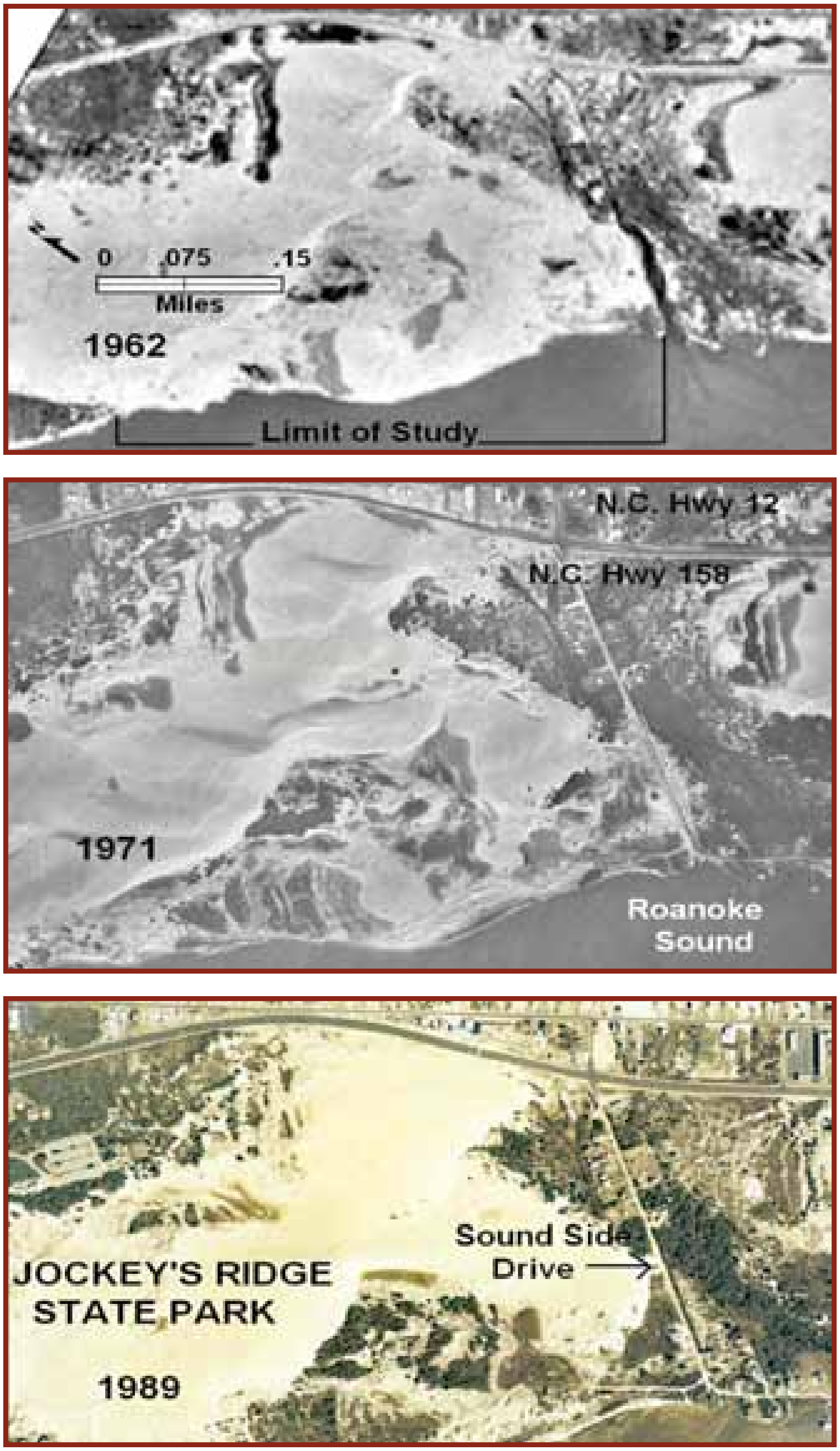

FIGURE 8-2-13. *The Jockey's Ridge site aerial photograph time slices from 1962, 1971 and 1989. In 1962, the study site behind Jockey's Ridge was essentially an all active sand dune with very little vegetation. Erosion of the dune field provided the sand for an extensive strandplain beach. A large portion of the dune field along Roanoke Sound became vegetated with pine and scrub-shrub through time, as indicated on the 1971 and 1989 aerial photographs. This changed the small-scale pattern of the shoreline from a smooth curved shoreline to the present irregular shoreline with numerous vegetated headlands and coves (Fig. 8-2-11).*

Shoals that extends almost 5 miles to the west. On the eastern side of Colington Shoals, and directly opposite the Nags Head Woods site, is a slightly submergent (< 1 foot deep) smaller sand shoal that extends south off of Colington Island and produces the semiprotected Buzzards Bay. These sand bodies absorb much of the wave energy from the long fetch of Albemarle Sound. Thus, oceanic influences do not directly affect this site and the erosion processes are significantly diminished along the backside of Nags Head Woods.

The Roanoke Trail runs west along a finger of uplands that extend soundward to the shoreline. Where the upland intersects the sound it forms a short (~100 ft) zone of low sediment bank shoreline fronted with a strandplain beach and old trees dying from root systems exposed by erosion. However, the greatest portion of this site, both north and south of the cove with the low sediment bank, consists of an extensive marsh platform that projects soundward. The marsh platform consists of organic peat sediment that is up to about 5 feet thick on the headlands and thins to zero feet onto the low sediment bank shoreline dominated by upland forests within the center of the site. The marsh shoreline generally consists of a 1- to 4-foot erosional scarp. Because the peat is generally thicker than the erosion depth, the nearshore estuarine floor

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Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

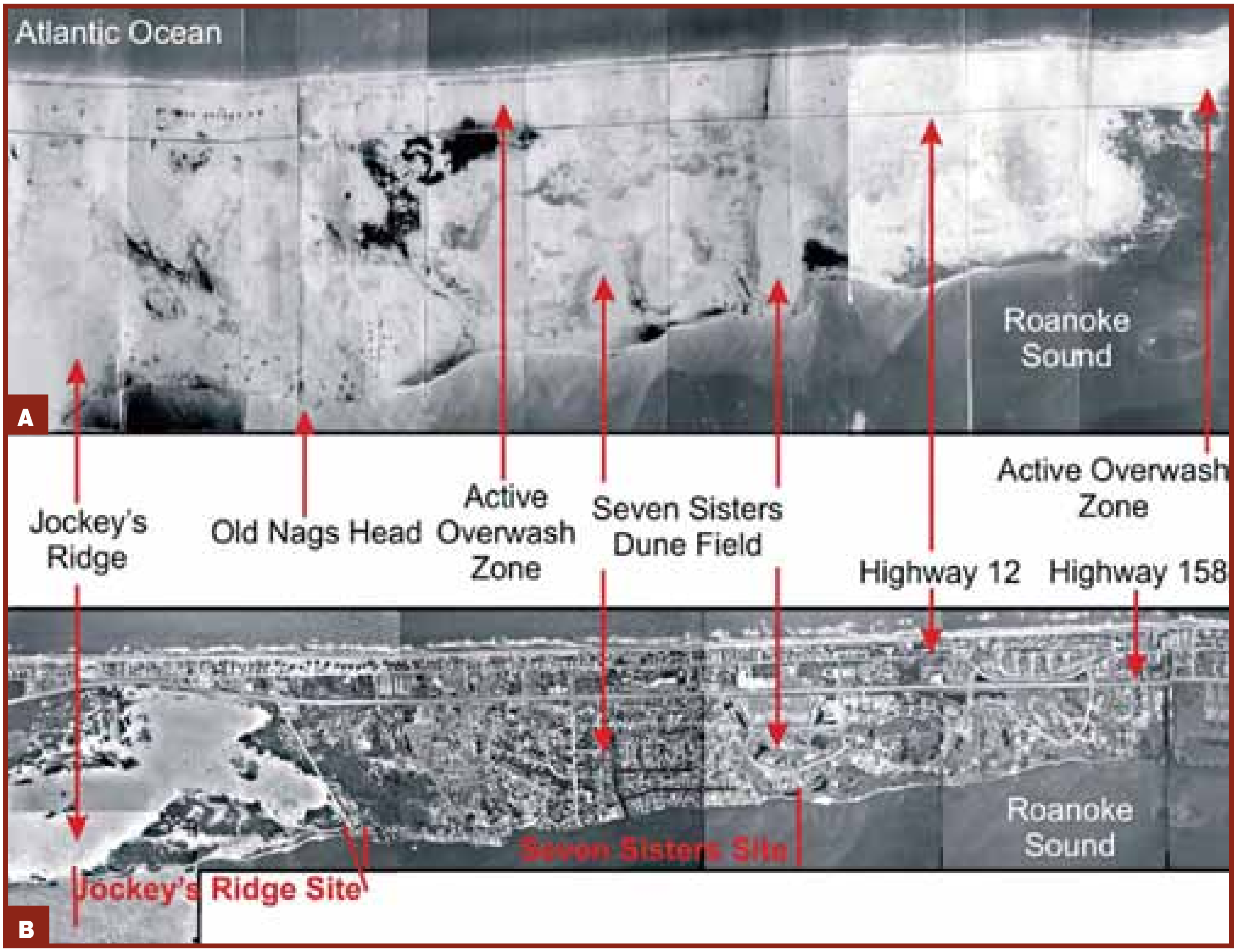

FIGURE 8-2-14. *Comparison of barrier island systems and the estuarine shorelines on aerial photographs from 1932 and 1999 for the northern portion of Nags Head, including Jockey's Ridge and Seven Sisters Dune fields. This segment is a complex barrier island (Fig. 4-5-1B) that is not dominated by overwash. Thus, the back-barrier estuarine shoreline is not under the influence of oceanic processes. Rather, it totally responds to estuarine erosion dynamics similar to a mainland estuarine system.* ***PANEL A.*** *This 1932 aerial photo predates any major shoreface modification such as construction of barrier-dune ridges that would have inhibited the overwash process. However, N.C. Hwy. 12 had just been constructed and the original beach houses built in the late 1800s occur along the ocean shoreline. Notice the village of Old Nags Head on the estuarine side of the island. The Jockey's Ridge and Seven Sisters back-barrier dune fields are extensive and very active. The photos were flown after a major nor'easter in 1932 for the Beach Erosion Board (1935), as background data for a beach erosion study (Field Research Facility, U.S. Army Corps of Engineers).* ***PANEL B.*** *This barrier island segment has been dominated by construction and continuous maintenance of extensive barrier dune ridges since the late 1930s, along with massive urbanization that has minimized oceanic processes and allowed for the extensive growth of a major vegetative cover. Since the estuarine shoreline is dominated by erosion, wherever development occurs, the shoreline has been extensively modified. However, the shoreline behind Jockey's Ridge consists of portions of the older back-barrier dune field that have been partially stabilized by vegetation. Consequently, this area is now in an erosional mode, resulting in a low sediment bank shoreline with a well-developed, sand strandplain beach. The photo was flown by the N.C. Department of Transportation to evaluate shoreline erosion and the condition of N.C. Hwy. 12 following Hurricane Dennis in 1999.*

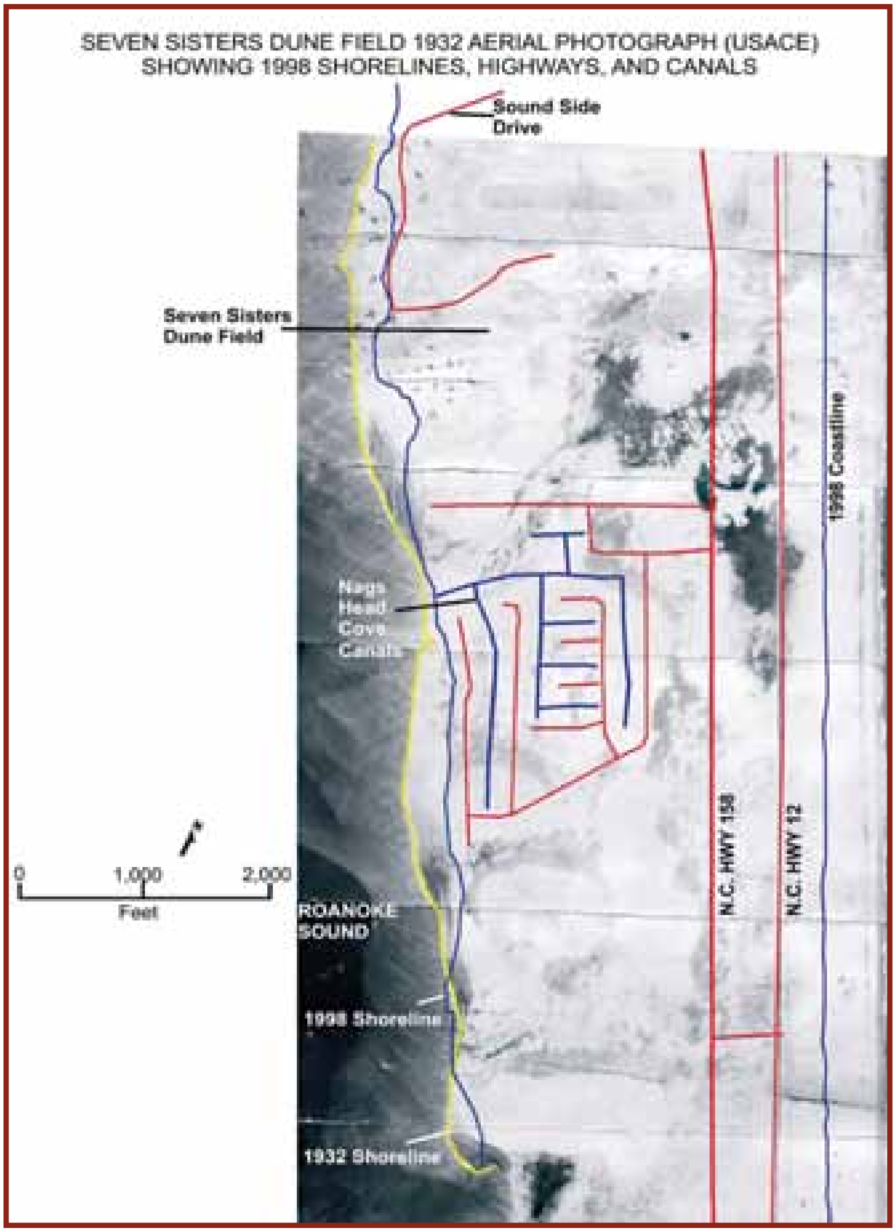

FIGURE 8-2-15. *The Seven Sisters Dune Field site in a 1932 aerial photograph (Field Research Facility, U.S. Army Corps of Engineers), with digitized shorelines (blue) and roads (red) from the 1998 DOQQ.*

consists of soft, in situ peat that extends hundreds of feet offshore. This demonstrates that the marsh itself extended at least this far offshore in the recent past and has been lost to shoreline erosion.

The marsh is dominated by a dense growth of *Spartina cynosuroides* along the outer zone, with *Juncus roemerianus* forming vast areas of the back marsh. Waves erode this classic marsh platform composed of a thick sequence of almost pure organic matter to produce a scarped shoreline. As the soft peat that underlies the <1-foot thick modern root zone is eroded, large blocks of the tightly matted uppermost peat form extensive overhanging blocks, up to 5 to 10 feet across, that undulate with every wave. Ultimately the blocks weaken, finally break and fall to the floor of the adjacent estuarine waters to be slowly broken down with time. Many of these blocks can be seen in the shallow nearshore waters. Along most of the marsh shoreline *Spartina cynosuroides* or *Juncus roemerianus* occurs right up to the eroding edge. However, in some areas erosion strips the main marsh plants off narrow patches on the peat surface, as well as upper plates of the peat itself, producing a stair-step erosional geometry. These barren peat surfaces develop a narrow outer fringe of fast growing *Spartina patens* during periods of low erosion.

The 1998 DOQQ (Fig. 8-2-12) shows the location of digitized estuarine shorelines for 1964 and 1998. The data summarized in Table 8-2-1 support the following interpretation. The open marsh shoreline at this site is eroding at an average rate of –1.7 ft/yr with rates ranging from 0.0 ft/yr to highs of –4.0 ft/yr. The northernmost 1,000 feet analyzed is a similar marsh shoreline that occurs within an embayment and is significantly protected from most wind directions. Consequently, the protected marsh shoreline displayed long-term accretion with an average rate of +0.6 ft/yr as the marsh grew out over sand deposited within the embayment.

8.2.G. Duck Field Research Facility

(Figures 8-2-18, 8-2-19 and 8-2-20)

The Duck Site is located north of Duck Village in Dare County (Fig. 8-1-1) and west of N.C. Hwy. 12 on the Currituck Sound side of the entrance gate to the U.S. Army Corps of Engineer's Field Research Facility (USACE-FRF). Currituck Sound is a narrow and shallow estuarine system that contains low brackish to fresh water. The USACE-FRF is on a very

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FIGURE 8-2-16. *Photographs of Nags Head Woods site.* ***PANEL A.*** *Winter photograph looking northeast along the eroding edge of a narrow marsh platform towards a small segment of low sediment bank dominated by a maritime forest of pine trees. Notice the irregular erosional geometry of the marsh peat shoreline.* ***PANEL B.*** *Summer photograph looking the opposite direction to Panel A, southwest along the eroding edge of a narrow marsh platform that fronts an upland region dominated by a maritime forest of pine trees. The outer zone of marsh grass is a mixed assemblage of* Spartina patens *and* Juncus roemerianus*, while the inner zone of tall grass is* Spartina cynosuroides*.* ***PANEL C.*** *Close-up winter photograph looking southwest along the eroding edge of a marsh platform. Notice the two large eroded peat blocks sticking out of the water just to the right of the eroding shoreline.* ***PANEL D.*** *Close-up view of an eroding marsh peat headland along the shoreline in Panel C during a low wind tide. The deeply undercut modern root zone slopes steeply into the water. A subsequent storm, with a high wind tide and wave action, will cause the overhanging block to break off and produce an offshore peat block as is seen in Panel C.* ***PANEL E.*** *Close-up view of low sediment bank shoreline that occurs in the distance in Panel A. The low wind tide has exposed the rippled sand flats of the lower portion of the strandplain beach. Notice the many trees with the root structures exposed by the erosional processes.* ***PANEL F.*** *Close-up view of a dead live oak tree on the lower portion of the strandplain beach. The entire root system has been exposed through the erosion of the upland soil.*

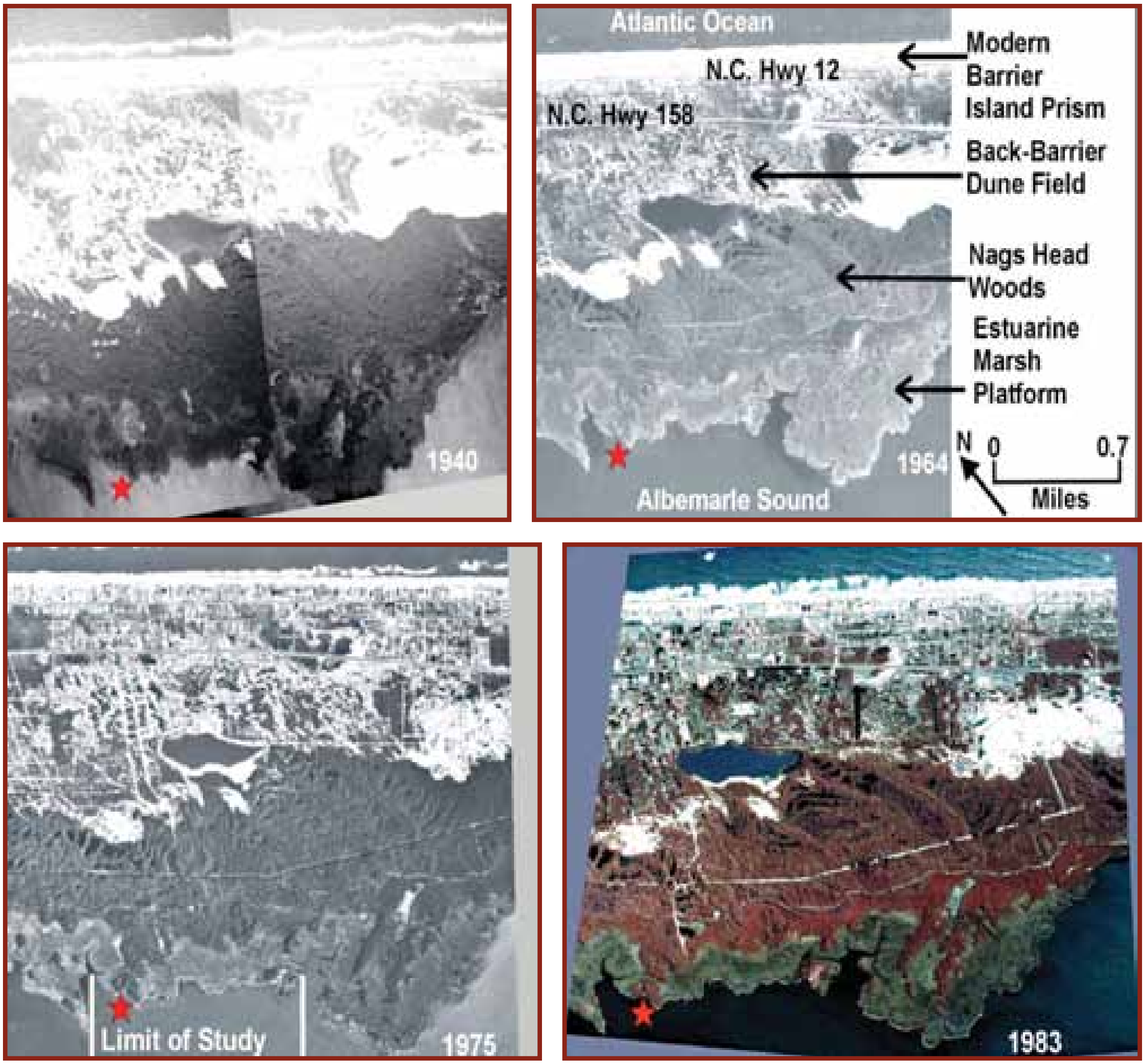

FIGURE 8-2-17. *The Nags Head Woods site aerial photograph time slices from 1940, 1964, 1975 and 1983. These photographs show the four major geomorphic components of this complex barrier island segment. In the 1940 aerial photograph, the modern beach prism and active back-barrier dune field were essentially uninhabited and only slightly vegetated. These two segments have since undergone major urbanization along with significant levels of vegetative stabilization by pines. Nags Head Woods, an older back-barrier dune field that contains a major maritime forest and abundant inter-dunal freshwater lakes, has remained essentially unchanged through the same time period. The marsh peat platform has accumulated up to 7 feet of peat that is systematically burying the irregular paleotopography of the Nags Head Woods dune field in response to ongoing rise in sea level. Notice the long fingers of maritime forest (red color on the 1983 photograph) growing on the dune sands that extend across the marsh platform (dark green color). The Nature Conservancy's Roanoke Trail follows one of these features to the study site (red stars).*

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FIGURE 8-2-18. *Photographs of the Duck Field Research Facility site.* ***PANEL A.*** *An oblique aerial photograph showing the densely vegetated character of the estuarine shoreline at the Duck site. The narrow, outer and lighter green colored zone is marsh grass. Whereas, the darker zone between the marsh and N.C. Hwy. 12 has dense scrub-shrub growing on top of the low sediment bank. Oblique aerial photograph is from the Field Research Facility of the U.S. Army Corps of Engineers.* ***PANEL B.*** *Winter photograph looking north along the strandplain beach towards the eroded low sediment bank scarp in the distance on the right side of the photo. Notice the fringing marsh consisting primarily of* Juncus roemerianus *in the foreground and* Phragmites australis *in the background. In the middle of the strandplain beach is a wrack berm composed of dead marsh grasses.* ***PANEL C.*** *Summer photograph looking east across the shoreline to the upland scrub-shrub. The shorter grass in the foreground is* Juncus roemerianus *with* Phragmites australis *in the background.*

narrow barrier island segment. However, there is a significant sand volume in a major dune field situated between the highway and ocean. The ocean shoreline is anomalously stable within this coastal segment. Consequently, overwash has not been a dominant process along this portion of the barrier during recent times.

The shoreline is oriented northwest-southeast and occurs along the backside of the dune field stabilized by a major scrub-shrub zone west of the highway. At the western edge of the scrub-shrub zone is a low sediment bank up to 3 to 5 feet high that is occupied during high-water storm tides. Erosion along this scarp produces abundant sand that generally fills much of this scarp with a major strandplain beach. Today, the strandplain beach contains a dense fringing marsh consisting primarily of *Phragmites australis* with varying amounts of *Juncus roemerianus* and *Spartina patens*. Wherever *Juncus* becomes established, a fringing peat begins to form that binds the sand and helps hold the outer marsh. In addition, abundant SAV grows on the submerged portions of the strandplain beach where the SAVs help to buffer wave energy, and the fine roots tend to help bind the sand.

The 1998 DOQQ (Fig. 8-2-19) shows the location of digitized estuarine shorelines for 1986, 1992 and 1998. The low sediment bank at this site had a net average shoreline recession rate of –0.7 ft/yr, while the outer marsh/strandplain beach had a net average recession rate of –0.3 (Table 8-2-1). The 1998 aerial photo displays a wide and continuous fringing marsh stabilizing the strandplain beach on the estuarine side of the scrub-shrub zone. However, preliminary data suggest

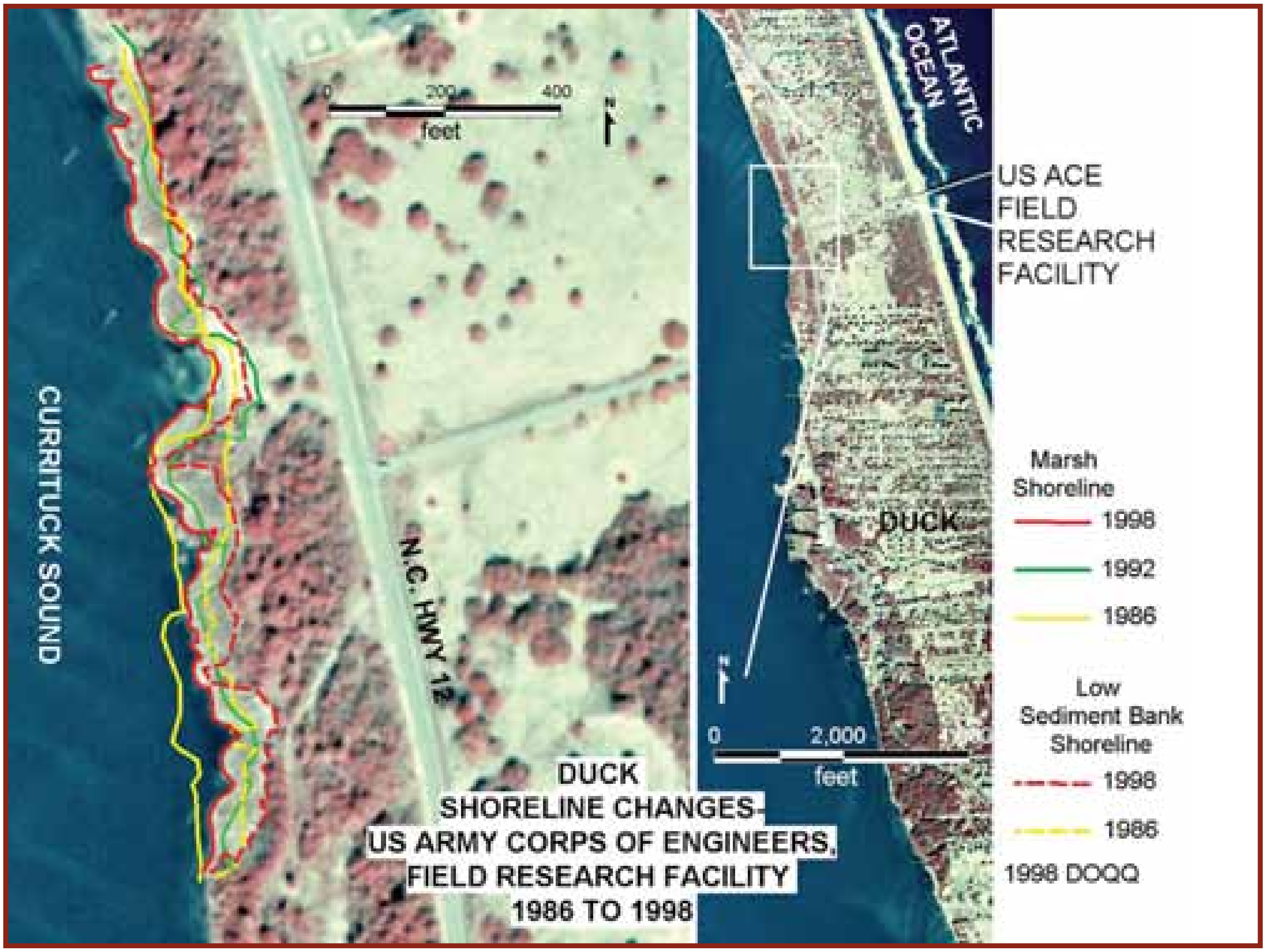

FIGURE 8-2-19. *The Duck Field Research Facility 1998 Digital Orthophoto Quarter Quadrangle (DOQQ), with digitized shorelines for 1986, 1992 and 1998.*

alternating periods of erosion and accretion. For example, significant shoreline erosion occurred between 1986 and 1992 (Ave. = –6.3 ft/yr) with specific locations having average rates that range from +6.0 to –23.5 ft/yr. The 1992 aerial photo demonstrates an eroding shoreline that intersects the low sediment bank covered with dense scrub-shrub. From 1992 to 1998, major sand accretion and shoreline growth occurred (Ave. = +5.7 ft/yr) with specific locations having average rates ranging from +15.5 to –3.0 ft/yr. A more detailed inspection of annual aerial photographs taken at this site by the USACE-FRF suggests that within the time frames presented in this study, there are smaller scale alternations in erosion and accretion.

To understand the dynamics at this site, it is imperative to understand the specific site history. A major effort by the USACE, the U.S. Soil Conservation Service and researchers at North Carolina State University was undertaken between 1973 and 1979 to abate a serious erosion problem. These projects involved extensive planting of many different marsh grasses during different seasons and areas with periodic monitor surveys. During the 1973-79 USACE study period, the erosion rate of the 3- to 5-foot sediment bank was about –5 ft/yr (Birkemeier, et al., 1985). The plantings were carried out on the south side of the access road with an unplanted control area to the north. According to Birkemeier (pers. com.), since 1979 numerous grass planting workshops on the estuarine shoreline have been held at the Field Research Facility.

The Duck site is an excellent example of the role of dense fringing marsh in the short-term stabilization of a low sediment bank and

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Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

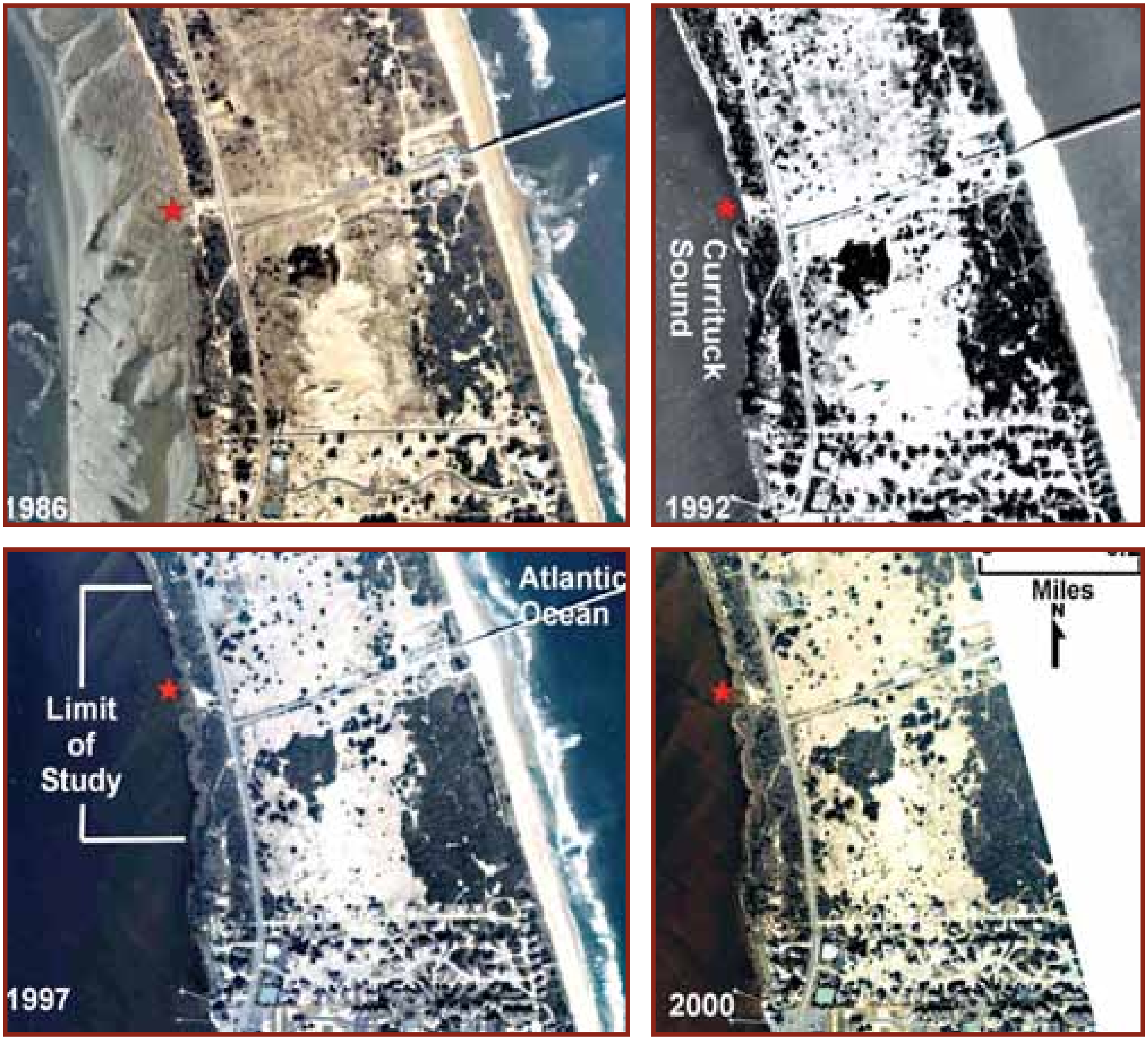

FIGURE 8-2-20. *The Duck Field Research Facility site aerial photograph time slices from 1986, 1992, 1997 and 2000. Notice how the fringing marsh along this low sediment bank shoreline fluctuates through time. In 1986, the fringing marsh occurs only in the southern section of the study area. By 1992, there is no fringing marsh in the study area. A very wide and dense fringing marsh occurs throughout the entire study area in 1997. By 2000, the shallows in front of the access area (red stars) have opened slightly.*

associated strandplain beach. In most situations, the fringing marsh minimizes, but does not eliminate erosion of the associated low sediment bank shoreline. The fringing marsh comes and goes in a complex pattern, depending upon the storm activity and human plantings. This site demonstrates the importance of understanding human events as well as the natural processes associated with any given shoreline, rather than just considering the net rate of change in the fringing marsh of –0.3 ft/yr recession between 1986 and 1998.

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8.3. MAINLAND ALBEMARLE-PAMLICO SOUND SHORELINE EROSION SITES

8.3.A. Summary: Mainland Albemarle-Pamlico Shorelines

The sites selected to determine the shoreline erosion rates for the mainland Albemarle-Pamlico Sound estuarine area and representing all major shoreline types have extremely large fetches. The sites are located on Figure 8-1-1 and occur in the outermost portion of the Pamlico River estuary, Pamlico Sound, Albemarle Sound and along the Alligator River. All of these sites are generally unmodified, except for the north end of Roanoke Island. At

Table 8-3-1 Short-Term Erosion Rates for Mainland Albemarle-Pamlico Sound Sites

Summation of the short-term estuarine shoreline erosion rates for the mainland Albemarle-Pamlico Sound estuarine sites based upon the present study. See Figure 8-1-1 for locations of study sites.

SITE AND SHORELINE TYPE	TIME PERIOD (YEARS)	DISTANCE ANALYZED (FEET)	AVERAGE LONG-TERM EROSION RATE DATA — PRESENT STUDY NET (FT/YR)	RANGE (FT/YR)
8. **North Roaanoke Island — Eastern Albemarle Sound:**				
Sediment Bluff—NET	1969-1998	930	–6.0	–4.8 to –7.1
Sediment Bluff	1969-1975	930	–21.2	–19.8 to –24.5
Sediment Bluff	1975-1998	930	–2.0	–0.8 to –3.3
Sediment Bluff	1969-1975	450	–23.1	–21.3 to –26.3
Modified Bluff	1975-1998	450	0.0	0.0 to 0.0
9. **Woodard's Marina — Middle Albemarle Sound:**				
Swampforest	1963-1998	860	–2.4	–1.5 to –3.9
10. **Grapevine Landing — Southern Alligator River:**				
Swampforest—NET	1981-1998	2,000	–1.8	–0.7 to – 5.8
North of Canal	1981-1998	460	–1.4	
South of Canal	1981-1998	1,540	–2.2	
11. **Point Peter Road — Northern Pamlico Sound:**				
Marsh Platform—NET	1969-1998	1,250	–7.5	–7.1 to –8.3
12. **North Bluff Point — Southern Pamlico Sound:**				
Marsh Platform—NET	1983-2000	6,520	–5.7	–1.1 to –11.5
SW of Canal	1983-2000	4,970	–6.9	–3.6 to –11.5
NE of Canal	1983-2000	1,550	–2.2	–1.1 to –3.8
13. **Swan Quarter Marsh Platform — Southern Pamlico Sound:**				
Open — S Swan Quarter Is.	1956-1998	15,000	–2.9	0.0 to –10.9
Embayed — N Swan Quarter Is. & E Judith Is.	1956-1998	100,620	–1.2	0.0 to –6.4
14. **Lowland — Outer Pamlico River:**				
Low Sediment Bank—NET	1964-1998	7,221	–4.9	–2.7 to – 8.1
Marsh Headlands—NET	1964-1998	2,625	–1.7	–0.8 to – 3.0

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this latter site, a small unmodified bluff segment, located between highly modified sediment bank shorelines, was selected for the study site.

All sites, except the northern end of Roanoke Island, are characterized by extremely low elevations characteristic of the mainland peninsulas. The mainland peninsulas slope gradually seaward, finally intersecting sea level at the coast and giving rise to the name "down-east lowlands." The underlying mineral soil forms the framework of these lands and was formed primarily during previous glacial and interglacial periods of the Pleistocene. The modern swamp forest and marsh systems produced peat that fills the topographic lows and caps the Pleistocene sediment surface. These peat deposits have formed in response to ongoing conditions of sea-level rise during the 10,000 years of the Holocene epoch.

The anomalous bluffs and high banks on the north end of Roanoke Island also obtained their high elevation and sand-rich deposits as products of the present Holocene interglacial events, in a similar fashion to other elevated features such as sand ridges on Currituck Peninsula, Colington Island, Nags Head, Kitty Hawk and Buxton Woods. The erosion rate data for the outer estuarine shoreline sites are summarized in Table 8-3-1. These are the sites where the lowland meets the rising sea level and angry waves of large drowned water bodies. Consequently, the erosion rates are high and land loss is great.

8.3.B. North Roanoke Island

(Figures 8-3-1, 8-3-2, 8-3-3 and 8-3-4)

Dolan and Bosserman (1972) and Dolan and Lins (1986) studied historic rates of shoreline recession at 17 locations along the

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Table 8-3-2 Short-Term Erosion Rates for North Roanoke Island

Generalized shoreline characteristics along the north side of Roanoke Island as of 2001. The shoreline segments, types, modifications and fetch are from this report and are summarized in Figures 8-3-1A and 1B. The station numbers and average erosion rate for 1851-1970 are from Dolan and Bosserman (1972), Dolan and Lins (1986) and their unpublished reports in the CHNS.

RIGGS/AMES SHORELINE SEGMENT	DOLAN STATION NUMBER OF	SHORELINE TYPE	SHORELINE MODIFICATION AS OF 2001	FETCH IN MILES	DOLAN AVE EROSION RATE 1851-1970 (FT/YR)
1	1	Low Sediment Bank	Extensive Strandplain Beach	3	–1
2	2	Marsh Peat	Minor Strandplain Beach	5	–2
3	3	Low Sediment Bank	Rock Revetments/Jetties	25	–5
3	4	Low Sediment Bank	Wood Bulkheads	25	–4
3	5	Low Sediment Bank	Wood Bulkheads	25	–4
4	6	High Sediment Bank	Strandplain Beach/Trees	35	–6
5	7	Bluff	Rock Revetments	30	–8
5	8	Bluff	Rock Revetments	30	–9
6	9	Bluff	Strandplain Beach/Trees	20	–3
6	10	Bluff	Strandplain Beach/Trees	20	–3
7	11	Bluff	Wood Groins/Strandplain Beach	5	–3
8	12	High Sediment Bank	Rock Revetments	5	–3
9	13	High Sediment Bank	Wood Groins/Breakwaters	4	–4
10	14	Low Sediment Bank	Mixed Modifications	3	–4
10	15	Low Sediment Bank	Mixed Modifications	3	–4
11	16	Marsh Peat	Major Strandplain Beach	3	–3
11	17	Marsh Peat	Major Strandplain Beach	3	–4
12		Sand Spit/Marsh	Local Peat Headlands	3	

C O N T I N U E D :

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

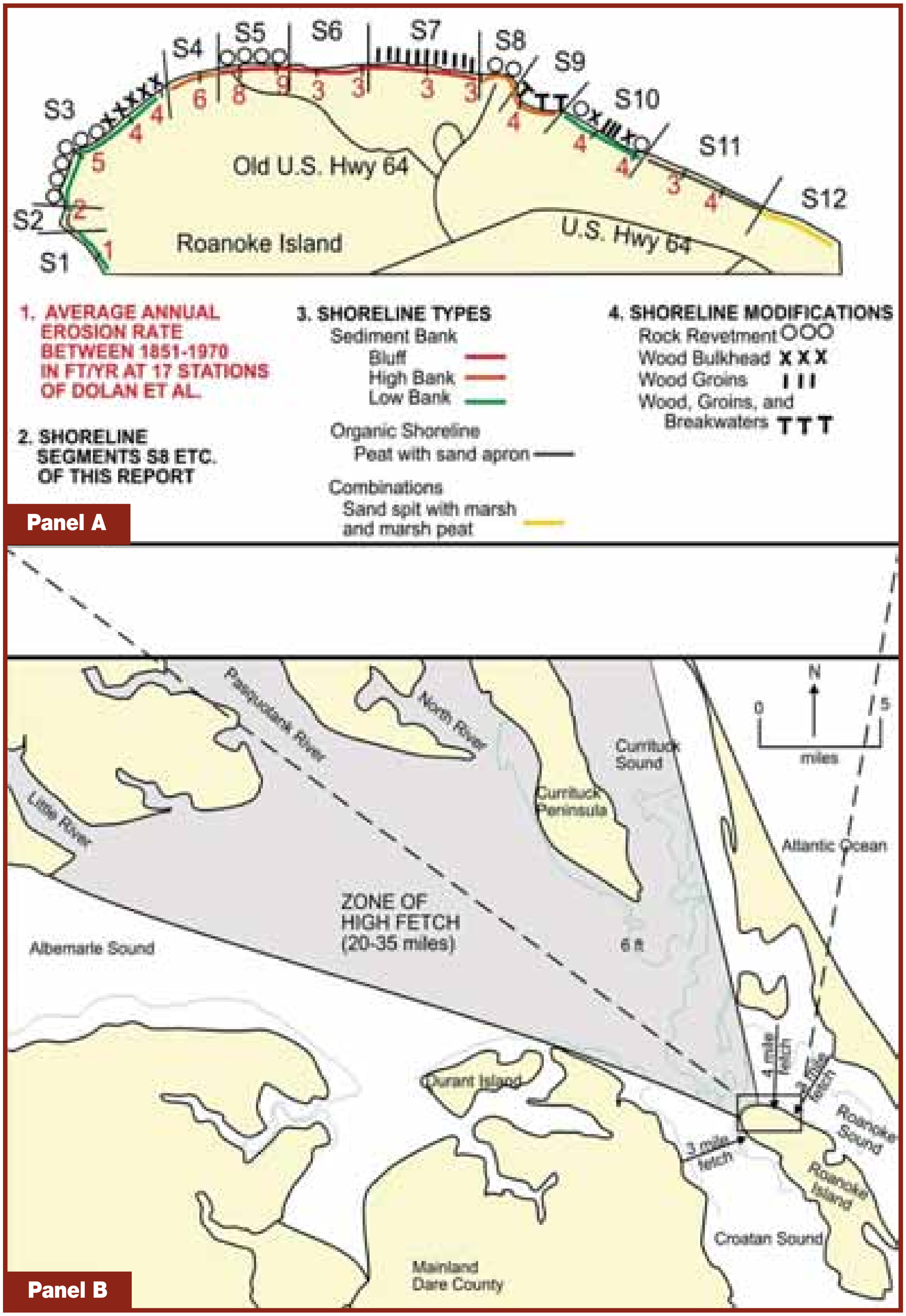

FIGURE 8-3-1. *Maps of northern Roanoke Island showing the average annual estuarine shoreline erosion rates by shoreline segment, shoreline types, types and locations of shoreline erosion-control structures, and the relationship between erosion rates and distance of open water (fetch) that impact different shoreline segments. Actual erosion rates for any given shoreline segment are dependent upon the type of shoreline, in concert with the fetch and a whole series of other variables (see Chapter 5).* ***PANEL A.*** *Map shows the average, annual estuarine-shoreline erosion rate data of Dolan and others (1972, 1986). The erosion data generally predate the construction of most erosion-control structures. Due to the high erosion rates, much of the shoreline has now been armored and is now relatively stable but without sand beaches (Fig. 8-3-2B). The map also shows the location and type of structures, as well as the distribution of shoreline types used in the present study.* ***PANEL B.*** *Map showing the differences in amount of fetch around the northern end of Roanoke Island.*

CONTINUED:

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

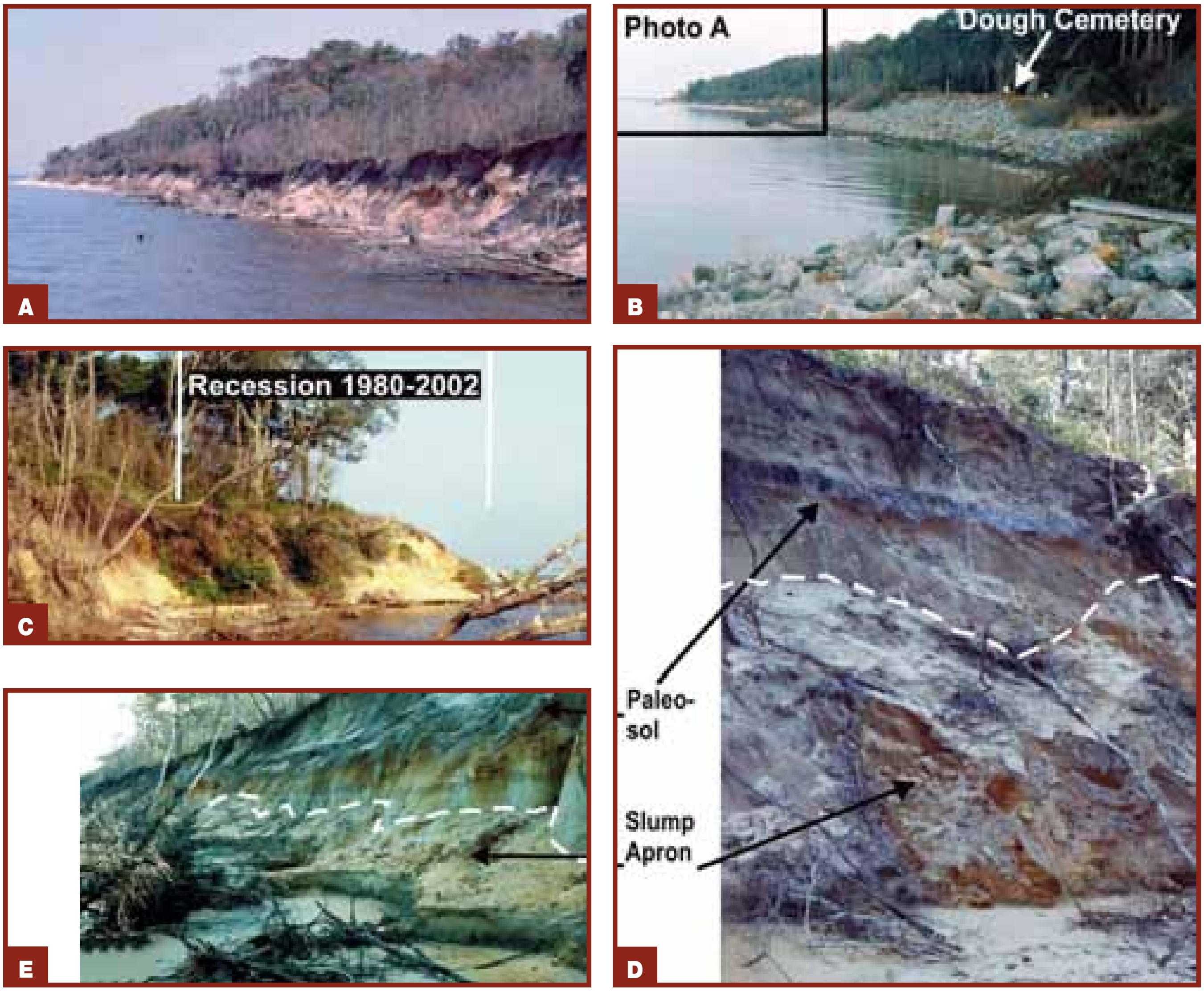

FIGURE 8-3-2. *Photographs of the North Roanoke Island site.* ***PANEL A.*** *March 2001 photograph looking east along the bluff to high sediment bank shoreline of Segment 6 (Fig. 8-3-1A). Photo is from Dough Cemetery at the east end of Segment 5 containing the rock revetment. The eroding bluff shoreline decreases in elevation to a high sediment bank in the easterly direction. Notice the extensive overhang of the modern root-bound soil mat. This overhang will ultimately collapse, dropping the associated trees onto the bluff and strandplain beach, where the continuous supply of trees and shrubs provides an evolving natural debris groin field. The increased size of the strandplain beach in the distance marks the beginning of Segment 7 containing a wooden groin field.* ***PANEL B.*** *March 2001 photograph looking east along the rock revetment of Segment 5 (Fig. 8-3-1A). The rock revetment was built in 1980 by the National Park Service to abate the –23.1 ft/yr of shoreline recession between 1969 to 1975 (Table 8-3-1). Notice that there is no strandplain beach in front of this rock revetment.* ***PANEL C.*** *June 2001 photograph looking west along eroding sediment banks of Segment 6 (Fig. 8-3-1A). The photo shows the amount of recession of the unmodified sediment bank shoreline (Segment 6) since 1980.* ***PANELS D and E.*** *March 2002 close-up views of the wave-cut scarp along Segment 6 (Fig. 8-3-1A). Notice that the bluff is composed entirely of clean sand except in the zone labeled as a paleosol where a thin layer of sand is bound by organic matter and stained by iron oxide. Due to the composition, large blocks of sand slump off the bluff and form a sediment apron along the backside of the strandplain beach (below the white dashed lines). During subsequent high tides, waves systematically erode the slump aprons, forming the cuspate scarps and reworking sand into the strandplain beach.*

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

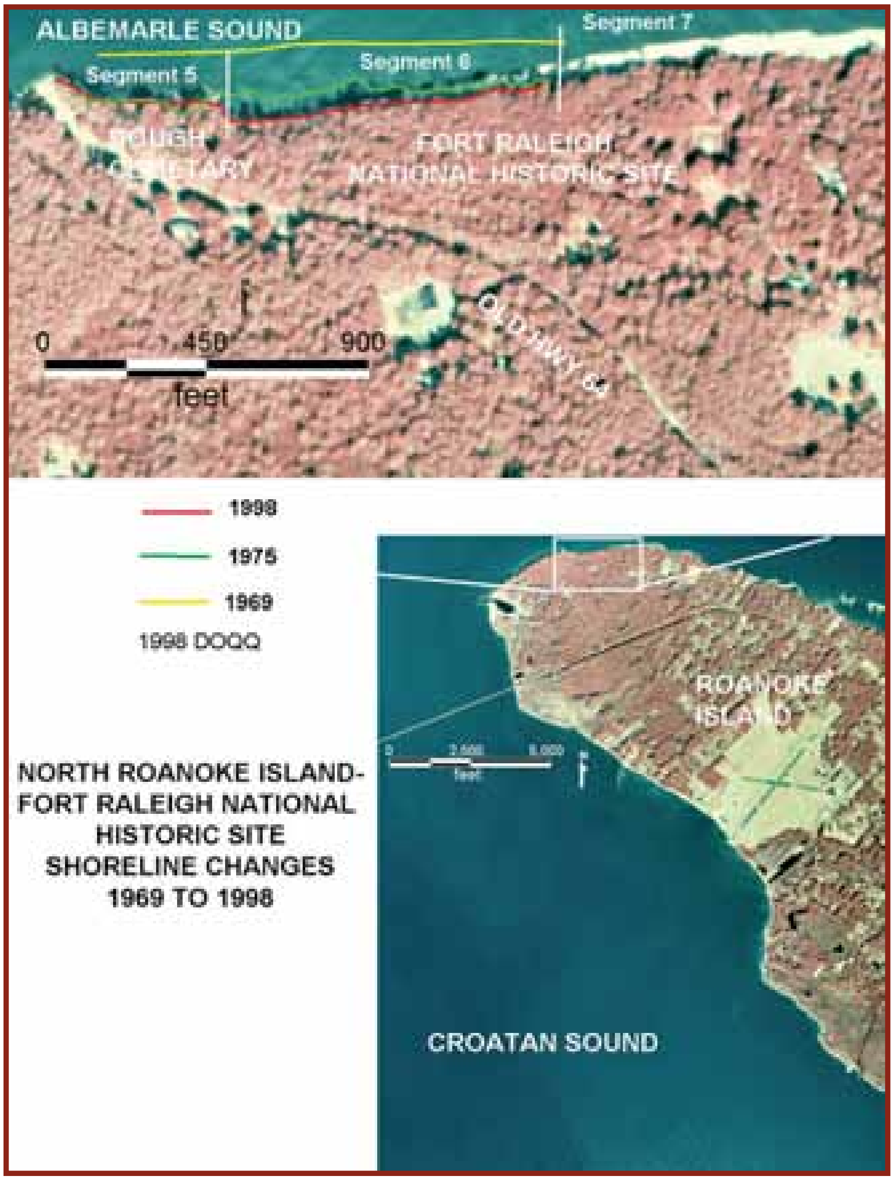

FIGURE 8-3-3. *The North Roanoke Island site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1969, 1975 and 1998.*

north end of Roanoke Island (Fig. 8-3-1). They used aerial photographs (1943, 1963 and 1970) along with estimates of shoreline location obtained off maps from 1851 and 1903. Table 8-3-2 and Figure 8-3-1A show the shoreline data of Dolan and others, as well as the shoreline types of Rigg, fetch determinations for each shoreline segment and present status of shoreline hardening.

The shoreline along Segments 5 and 6 is a 20- to 30-foot high bluff composed almost totally of clean sand with mixed upland hardwood and pine forest cover on top of the bluff. Due to the sand composition, this shoreline has always been sand rich and is characterized by a strandplain beach littered with trees and shrub debris from collapsing slump blocks.

During normal, fair-weather conditions, the water level and wave action is located well down on the strandplain beach. At this time, the bluff is not being eroded by wave action, but it does erode slowly in response to wind activity, groundwater seepage and gravity. However, the major periods of erosion occur during high storm tides, when water level rises above the strandplain beach, allowing wave energy to directly impact the bluff. Undercutting the lower portion of the bluff leads to instability of the steep and often overhanging upper portion that contains trees. Overhanging trees severely blow in strong winds as rain saturates the sand bank. Eventually, large unstable sections of bluff slump onto the strandplain beach to be directly eroded by wave action. As slump blocks are reworked with time, new sand is added to the beach, with the larger vegetation developing natural groins that aid in trapping and holding the strandplain beach.

The 1969 and 1994 aerial photos demonstrate the significant shoreline recession for this area through time. Notice the generally smooth shoreline on the 1969 photo in which old U.S. Hwy. 64 forms a mini-headland as road debris collapses onto the beach. Data from Table 8-3-1 suggest that from 1969-1975, this shoreline was receding at average rates from –21.2 to – 23.1 ft/yr. Dolan et al. estimated their highest shoreline erosion rates of –8 to –9 ft/yr for the shoreline in front of old U.S. Hwy. 64 and Dough Cemetery (stations 7 and 8 of Dolan and Segment 5 of this report) (Fig. 8-3-1A). In response, the National Park Service hardened all of Segment 5. The 1994 and 1998 photos display a much broader headland forming in response to the heavy rock revetment emplaced in front of old U.S. Hwy. 64 and the Dough Cemetery to the east. The natural bluff shoreline of Segment 6, east of the Dough Cemetery, continued to recede at an average of –2.0 ft/yr.

In the 1969 photo, notice the extensive sand spit in front of the main shoreline along

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

the northeast portion of Roanoke Island. The sand to build Crab Claw Spit came from erosion of the northern shoreline and subsequent longshore transport in response to strong northwest winter winds. Notice that by 1994 Crab Claw Spit has largely broken down, and portions have migrated further to the southeast. This dramatic breakup and spit migration is a direct response to loss of the sediment source resulting from hardening most of the northern shorelines (Fig. 8-3-1A and Table 8-3-2).

The shoreline erosion data presented in Tables 8-3-1, 8-3-2 and Figures 8-3-1, 8-3-3 demonstrate several important relationships that can be summarized as follows.

- **1.** Prior to 1970, the overall average rate of shoreline recession for the north end of Roanoke Island ranged from about –4 to –5 ft/yr.

- **2.** Within specific island segments, the average shoreline recession data ranged from –1 to –23 ft/yr. Actual erosion rates along any shoreline segment were directly related to shoreline type and fetch.

FIGURE 8-3-4. *The North Roanoke Island site aerial photograph time slices from 1969 and 1994. Crab Claw Spit formed over time from high rates of sediment bank erosion on the north end of Roanoke Island and the associated long-shore currents driven by northwest storms. However, during the latter part of the 20th century, the amount of sediment feeding Crab Claw Spit rapidly diminished as most of the north end of Roanoke Island was stabilized (Fig. 8-3-1A). Loss of the sediment source led to destabilization, breakup and rapid eastward migration of the Spit remnants as demonstrated in the 1994 photo. As the Spit moves, shorelines formerly protected behind the Spit become re-exposed to open water and increased rates of shoreline erosion. The red star marks the same spot on both photographs.*

- **A.** Low sediment bank and marsh peat = erosion rates of –1 to –4 ft/yr.
- **B.** Bluff and high sediment bank = erosion rates of –4 to –23 ft/yr.
- **C.** Low fetch (3-5 mi) = erosion rates of –1 to –4 ft/yr.
- **D.** High fetch (20-35 mi) = erosion rates of –3 to –23 ft/yr.

• **3.** Shoreline Segments that have abundant sand available to build offshore sand bars, spits and lagoons, or broad strandplain beaches have minimum annual erosion rates and are even accretionary on a local and temporary basis.

- **A.** Shorelines in coastal Segments 1 and 2 on the west (Fig. 8-3-A1) are eroding slightly, in spite of local protective structures. In addition to the low fetch, the –1 to –2 ft/yr rate is partly due to availability of large sand volumes that form an extensive strandplain beach with many shallow sand bars in the nearshore area.
- **B.** The shorelines in coastal Segments 11 and 12 on the east (Fig. 8-3-A1) are only slightly eroding today due to a large sand spit, back-spit lagoon and marsh system. Thirty years ago, the spit system was in front of and protected Segment 11. However, the spit system has migrated SE in front of Segment 12. This has exposed back-spit marsh peat in Segment 11, which is now an eroding peat shoreline.
- **C.** Shoreline protection measures have been implemented, since the Dolan et al. studies, along the rapidly receding shoreline in Segments 3, 5 and 7 through 10. These structures terminated production of "new" sediment that had previously been supplying "new" sand to beaches in Segments 1-2 and 11-12 in response to northeast and northwest storms, respectively. Consequently, unprotected shorelines in Segments 1 and 2 have begun to erode more severely. Also, the spit that protected Segment 11 has increased its rate of migration to the SE and has begun to break up resulting in eroding peat headlands along the shoreline of Segment 12. Segment 11 has now begun to erode the back-spit marsh peat and will begin to erode the adjacent sediment bank in the near future, followed by the Segment 12 shoreline.

• **4.** Prior to 1970, only a few segments of the shoreline were modified by shoreline protection structures. Since 1970, human modifications have hardened many remaining shoreline segments, significantly decreasing erosion rates along most of the North Roanoke Island shorelines.

- **A.** Today about 75% of the north end of Roanoke Island (Fig. 8-3-A1) has been armored with a combination of rock revetments, wooden bulkheads, groins and breakwaters.
- **B.** Shoreline recession appears to have been temporarily stopped along most of these coastal segments. However, many wooden bulkheads and older groins are failing.
- **C.** None of the shorelines with bulkheads or rock revetments have sand beaches. Whereas, those shorelines with only groin fields have trapped sand with major sand strandplain beaches.

• **5.** The 1998 Digital Orthophoto Quarter Quadrangle shows the location of digitized estuarine shorelines for 1969, 1975 and 1998 from the present study with the following conclusions.

- **A.** From 1969 to 1998, Segment 6 had an overall average rate of shoreline recession of –6.0 ft/yr (Table 8-3-1). This is a slightly slower rate than what Dolan et al. obtained for Segment 5 during the period from 1851 to 1970.
- **B.** However, coastal Segments 5 and 6 eroded at average rates of –23.1 and – 21.2 ft/yr. from 1969-1975, respectively (Table 8-3-1).
- **C.** Due to this large erosion rate and threat to the historic Dough Cemetery, a massive rock revetment was built by the National Park Service in Segment 5 in 1980. Since 1980, no further shoreline recession of Segment 5 has occurred.
- **D.** Segment 6 continued to erode since 1980, however, at a much slower average rate of –2.0 ft/yr between 1975 to 1998. Erosion rates in Segment 6 are the highest immediately east of the stabilization at the Dough Cemetery (-3.3 ft/yr) and slowly decrease eastward to Segment 7 that contains a wooden groin field. These groins have trapped significant sand and produced a wide strandplain beach off the Elizabethan Gardens.

• **6.** Long-term shoreline changes have been significant along the North Roanoke Island shoreline.

- **A.** Assume an average shoreline recession rate for nonhardened portions of the north shore to be –6.0 ft/yr and that this rate has been constant over the past 320 or so years since the Lost Colonists landed.
- **B.** The estimated net shoreline recession would be about –1920 feet or –0.36 miles. This would have resulted in the loss of about 461 acres off a 2-mile segment along the northern end of the island.

8.3.C. Woodard's Marina Site

(Figures 8-3-5, 8-3-6 and 8-3-7)

Woodard's Marina site is located about five miles northeast of Columbia in Tyrrell County (8-1-1). The site is on the southern shore of the Albemarle Sound and occurs on the soundward side of a commercial fishing marina excavated within the upland between 1995 and 1998. Along the sound is a narrow wetland consisting of swampforest vegetation that increases in width in both the east and west directions from the marina. This site is a small and accessible swampforest shoreline characteristic of many miles of larger and inaccessible shoreline occurring along vast stretches of the Albemarle Sound and its tributary estuaries.

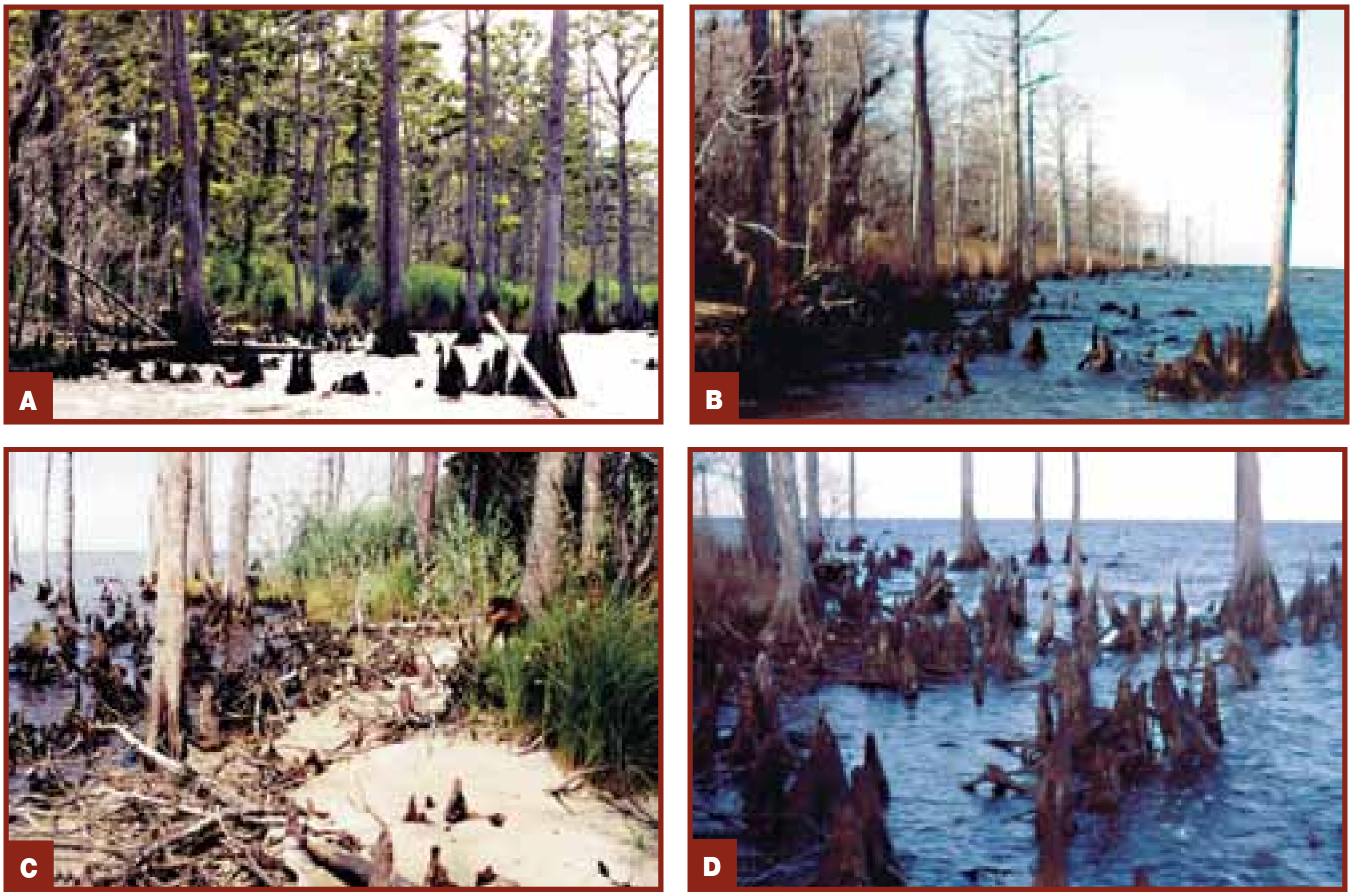

FIGURE 8-3-5. *Photographs of the Woodard's Marina site.* ***PANEL A.*** *Summer photograph looking south into the three common zones that characterize swampforest shorelines. The photo is taken from within the ghost swamp forest of Zone 3 and backed by the dense growth of* Spartina cynosuroides *that characterizes the middle Zone 2 and represents the shoreline. Behind the marsh grasses is the dense and living swamp forest of Zone 1.* ***PANEL B.*** *Winter photograph looking west along the swampforest shorelines from the same general location as Panel A.* ***PANEL C.*** *Close-up photo of the shoreline (Zone 2) characterized by a small sand berm, which supports the dense growth of* Spartina cynosuroides*. Photograph is from Murphy (2002).* ***PANEL D.*** *Close-up photo of the cypress trees and associated knees that are the last survivors within Zone 3 as the shoreline of Zone 2 moves landward.*

This particular swamp forest is a portion of floodplain associated with the small tributaries of an old stream system that is being drowned by rising sea level. The first- and second-order streams of this older drainage system are generally shore parallel and flow into larger third-order tributary streams that are generally shore perpendicular. These drainages are obvious on the associated figures containing aerial photographs of the region. The latter streams flowed north into the Roanoke River during the last glacial maximum and are now slowly being consumed by the ongoing rise in sea level associated with the present interglacial period (Fig. 6-2-1).

As depicted on Figure 8-3-7, rising sea level drowns the land and associated drainage systems, causing the shoreline type to change through time. Shoreline erosion intersects uplands on the interstream divides, producing low sediment bank shorelines. With continued erosion of the low sediment bank, the shoreline ultimately intersects the floodplain swamp forest of the next first- or second-order stream further up the drainage system. Wherever the larger third- and fourth-order streams enter Albemarle Sound, a major cypress headland extends out into the Sound, as seen in the aerial photographs on both the right and left sides of the study site. Notice that the headlands get larger through time and extend further out into the Sound. This results from the differential erosion between low sediment banks, which have higher rates of shoreline recession compared to the more slowly eroding swampforest shorelines.

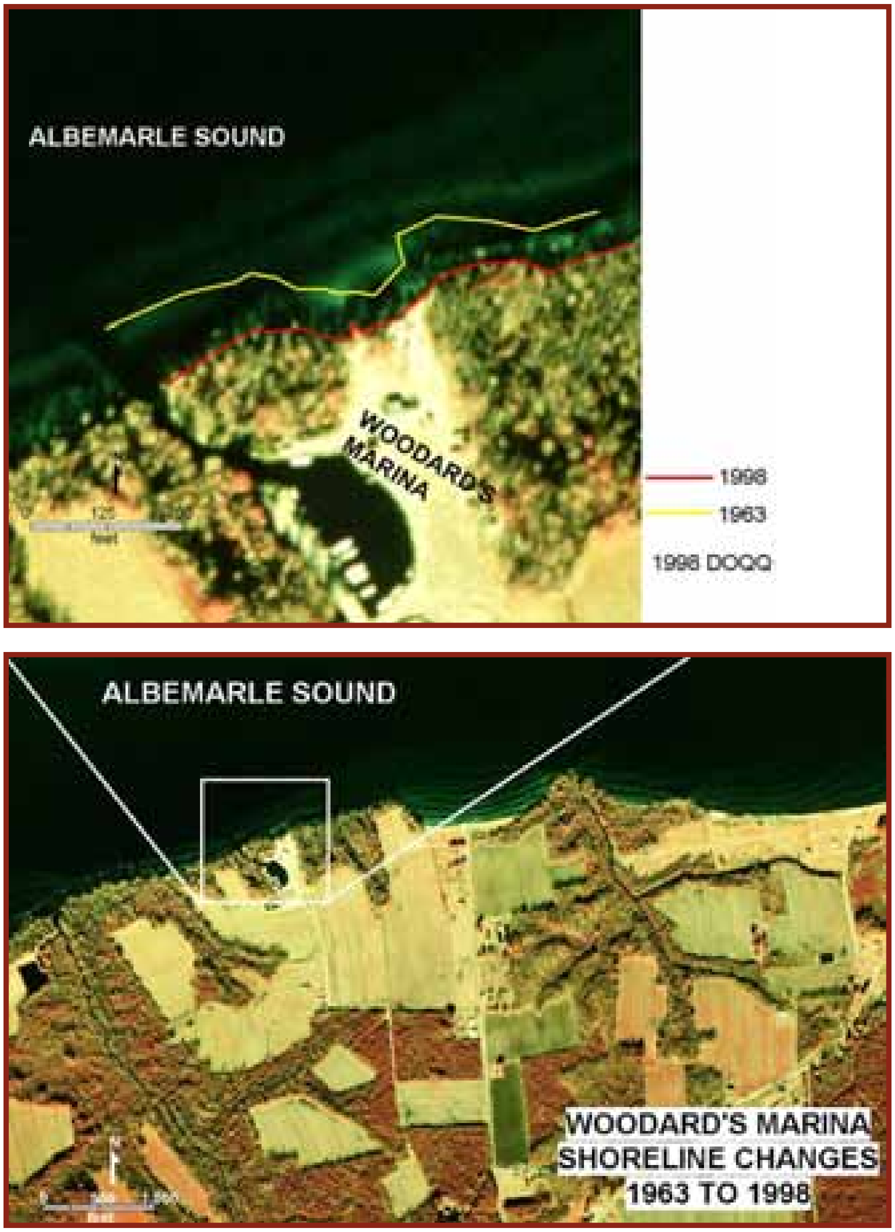

FIGURE 8-3-6. *The Woodard's Marina site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1963 and 1998.*

Swampforest shorelines are difficult to define due to the diffuse nature of the erosion process. Because this is a drowning process, there generally is a series of broad zones that occur from landward to soundward as follows.

- **A.** ZONE 1: The innermost zone is the floodplain swamp forest that is now below sea level, and therefore is continuously flooded with sound water. Swamp maple and gum trees within this zone become stressed and begin to die, in response to a more permanent flooding state. In addition, there is a major growth of new wetland species, including reeds and marsh grasses, as this system transitions from an irregularly and temporarily flooded swamp forest to a permanently flooded condition.

- **B.** ZONE 2: The middle zone is usually defined as the shoreline. It is a highly variable zone that contains the dying and recently dead trees and generally contains a small sand berm, if sand is available in the shallow waters of the adjacent estuary. Most swamp maples are now dead, and gum trees are dying. If cypress is present in the swamp forest, it generally persists through the middle zone and is still viable well into the outer zone.

- **C.** ZONE 3: The outer zone is the ghost forest that resembles the shambled remnants of a once great army, now lying defeated on the battlefield. Solitary, bare, broken and steely gray tree trunks occur in all stages of collapse. Fallen and crumpled logs litter the sound floor like land mines. Ghostly and gnarled tree stumps are excavated by ongoing erosion processes exposing their complex root networks like spider webs that have trapped the invading army. Locally some live, but now stressed cypress trees extend well into the outer zone, where they stand guard like old battle-worn soldiers frozen in time.

Woodard's Marina site is characterized by these three zones. A well-developed sand berm separates the inner and outer zones and semi-isolates the waters within Zone 1 from Zone 3. The berm is a product of storms when it is an active and dynamic beach. A dense growth of *Spartina cynosuroides*, with some *Spartina patens*, forms a fringing marsh on much of the sand berm and extends back into the inner swamp forest. The peat sediment that underlies this swamp forest (Zone 1) was formed within a riverine floodplain and is up to 5 feet thick. Underlying the peat is a tight, Pleistocene age clay. The peat bed extends beneath the shoreline (Zone 2) and onto the floor of

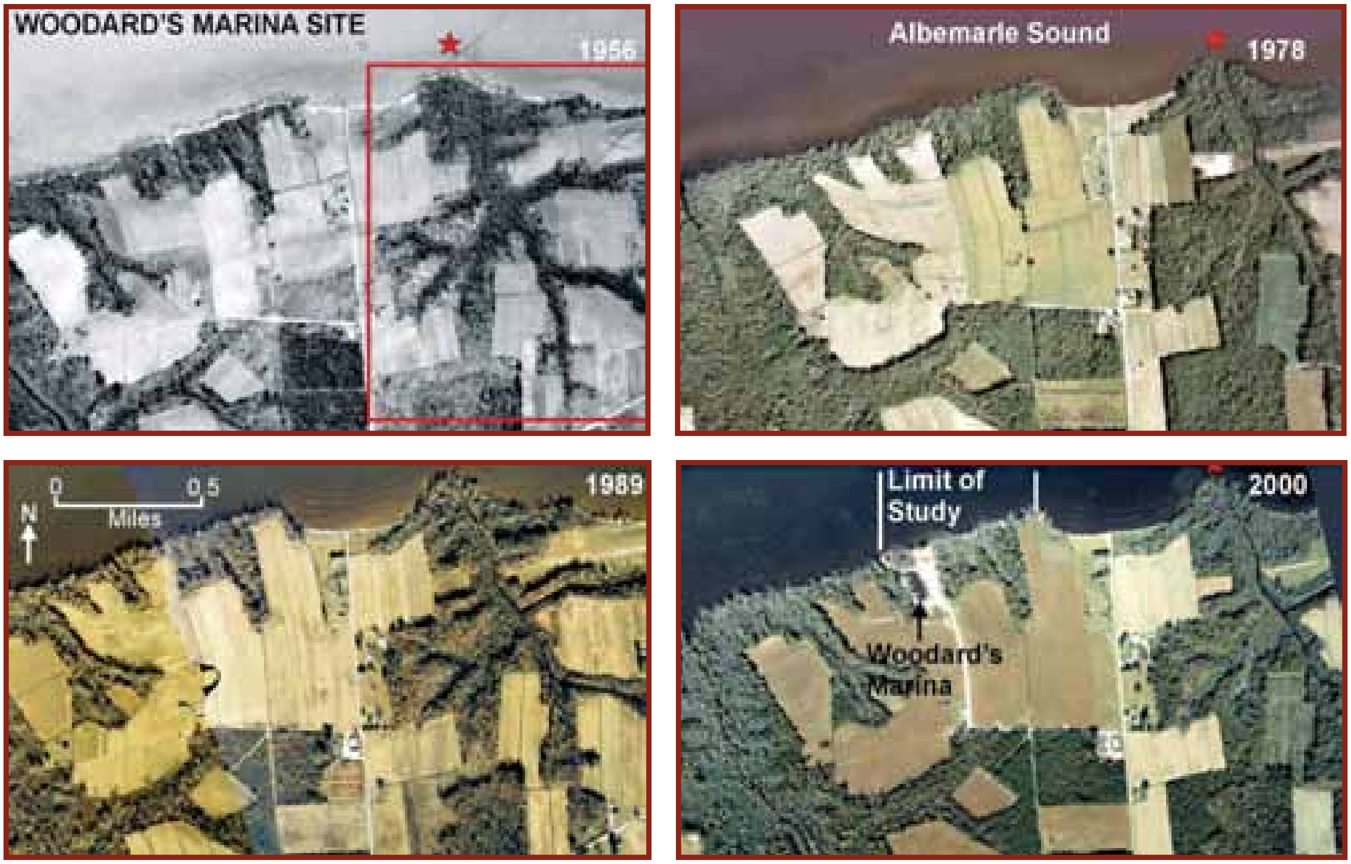

FIGURE 8-3-7. *The Woodard's Marina site aerial photograph time slices from 1956, 1978, 1989 and 2000. Notice the dense swampforest vegetation associated with the stream valleys of the many small drainage systems flowing into Albemarle Sound. A small, classic drainage system occurs within the boxed area on the 1956 aerial photograph. Notice that a very prominent cypress headland (red stars) occurs where the main stem of this stream intersects the Albemarle Sound shoreline. The shoreline within the cove west of this cypress headland is a low sediment bank that has agricultural production. Compare the location of this cove through time as the low sediment bank recedes more rapidly than the adjacent swampforest shoreline. Due to the geometry of the drainage system, the length of swampforest shoreline increases through time at the expense of the sediment bank shoreline, along with a significant increase in the distance the cypress headland extends into Albemarle Sound.*

Albemarle Sound (Zone 3), where this in situ peat forms a soft and spongy estuarine bottom. However, with time, the uppermost portion of peat is systematically eroded away by wave activity in the offshore areas.

The 1998 DOQQ (Fig. 8-3-6) shows the location of digitized estuarine shorelines for 1963 and 1998. The Woodard's Marina site has an average shoreline recession rate of –2.4 ft/yr (Table 8-3-1), with a range in erosion rates from –1.5 to –3.9 ft/yr.

8.3.D. Grapevine Landing Site

(Figures 8-3-8 and 8-3-9)

Grapevine Landing is located within the Pocosin Lakes National Wildlife Refuge of the U.S. Fish and Wildlife Service. The site is situated on the southwestern shore of the Alligator River in Tyrrell County. It is approximately 3 miles east of the Gum Neck community at the east end of Cahoon Road. The road and its adjacent canal intersect the shoreline in the apex of Grapevine Bay. Consequently, the shoreline at this site has two distinct regional orientations: a northeast-facing shoreline segment with a relatively large fetch and a southeast-facing segment with a relatively smaller fetch. The Alligator River is a fresh, blackwater estuary due to the drainage from vast pocosin swamp forests that fringe most of this drowned-river system.

Grapevine Landing is extremely complex and quite irregular on the local scale. It is first and

Continued on page 112

FIGURE 8-3-8. *Photographs of the Grapevine Landing site.* ***PANEL A.*** *Summer photograph looking north along the swampforest shoreline of the Alligator drowned river estuary. This swampforest shoreline has been extensively modified by natural processes, resulting in a broad shoreline zone of marsh and strandplain beaches. The photo shows the southern portion of the study area, the landing (pier) in the center and the northern portion of the study area in the distance.* ***PANEL B.*** *Winter photograph looking south across the southern portion of the study area from the pier. The outer zone of marsh grass is generally* Juncus*, whereas the inner zone occurring within the swamp forest is generally* Spartina cynosuroides*.* ***PANEL C.*** *Close-up of strandplain beach within a cove formed by a small headland of stumps and covered with* Juncus *marsh grass. Photograph is from Murphy (2002).* ***PANEL D.*** *Close-up of an eroded section of swamp forest with the root systems exposed and* Spartina cynosuroides *marsh grass within the existing swamp forest. Photograph is by M. Murphy.* ***PANEL E.*** *Close-up of a strandplain beach within a cove formed by a headland of swampforest trees that have been recently uprooted. The strandplain beach consists of a thin, basal bed of quartz sand burying the eroded peat substrate. The denser quartz sand has been buried by a one-foot thick accumulation of very light organic detritus.* ***PANEL F.*** *Close-up of the depositional and erosional sediment structures produced in the organic detritus layer on the strandplain beach during the last falling wind tide. The coffee-colored water is visible at the bottom left corner of the photo.*

foremost a swampforest-dominated shoreline. However, some sand is available on the bottom of nearshore regions within the Alligator River. Thus, strandplain beaches occur in many coves along the swampforest shoreline. Because this is generally a low energy system, the lower portions of some strandplain beaches are also covered with a dense fringing marsh of *Juncus effusus*, a freshwater species that forms thin sandy peats. The upper portions of strandplain beaches, formed by high water storm surges from northerly winds, are covered with a fringing marsh of *Spartina cynosuroides*, which often extend landward into the swampforest vegetation. When the storm beaches are being formed, high wave energy commonly strips off the lower zone of *Juncus* marsh, exposing the peaty sand substrate for *Spartina patens* recruitment.

Almost the entire Alligator River shoreline is composed of swampforest peat, all of which is slowly eroding. This results in a very large detrital organic sediment component everywhere around the shores. The organic detritus accumulates on top of the heavier quartz sand component of strandplain beaches. As the upper organic layer dries out it becomes slightly indurated. The next wind tide brings in a new layer of quartz sand that buries the semi-indurated organic layer. As the high water subsides, the abundant and lighter organic detritus settles out of the water and is concentrated by the wave energy on the strandplain beach. This results in alternating deposits of sand and organic detritus that accumulate until a large storm erodes the entire strandplain beach and directly attacks the exposed swampforest shoreline. It is then that wave energy erodes the soft peat from around swampforest trees, exposing the root masses. From the time the storm subsides until the next storm, depositional processes rebuild the strandplain beach that temporarily buries and protects the shoreline. However, the exposed trees are now stressed and ultimately either die or are blown over by subsequent storms, leaving a trail of logs, stumps and roots behind on the adjacent estuarine floor.

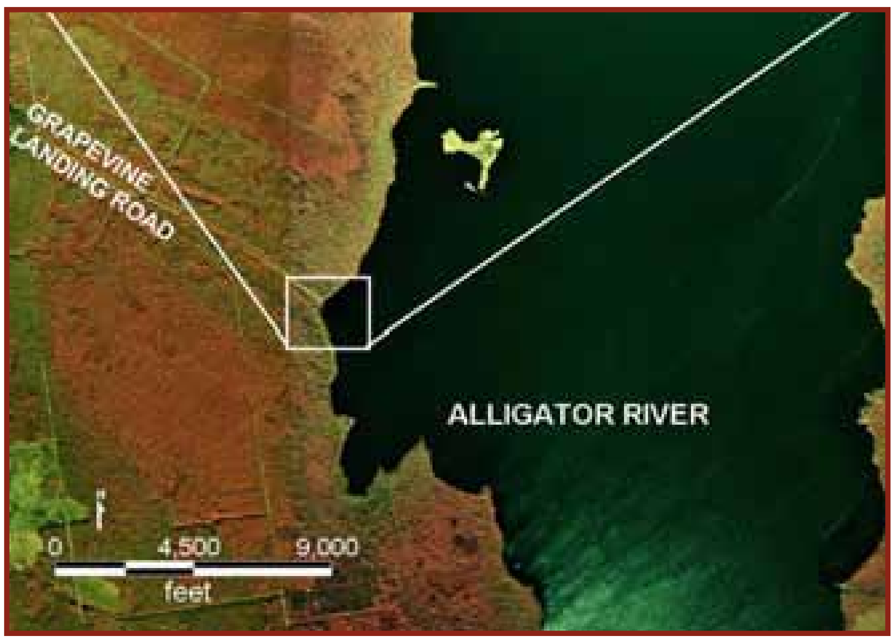

FIGURE 8-3-9. *The Grapevine Landing site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1981 and 1998.*

The 1998 DOQQ (Fig. 8-3-9) shows the location of digitized estuarine shorelines for 1981 and 1998. During this period, the Grapevine Landing site had an average shoreline recession rate of –1.9 ft/yr, with a range from –0.7 to –5.8 ft/yr (Table 8-3-1). This site has two distinct shoreline orientations, with significantly different fetches that erode at slightly different rates. The northeast-facing shoreline, south of

Continued on page 114

FIGURE 8-3-10. *Photographs of the Point Peter Road site.* ***PANEL A.*** *Winter photograph looking west at the former freshwater, swampforest shoreline that has recently evolved into a fresh- to low brackish-water transition zone with marsh vegetation. Today, the vegetation is dominated by* Spartina patens, Cladium, Baccharis, *and* Myrica*.* ***PANEL B.*** *Close-up of the highly irregular eroding geometry of the peat shoreline. The small headlands are held up either by modern* Baccharis *and* Myrica *stumps that occur at the shoreline as it recedes or by larger stumps and logs that occur in the lower portions of the eroding peat bank.* ***PANEL C.*** *Close-up of the irregular peat shoreline displaying the tops of the abundant, large, eroded peat blocks that litter the nearshore area. Notice the irregular wrack berm on top of the* Spartina patens *marsh.* ***PANEL D.*** *Close-up view of erosional wave action that causes the upper and overhanging modern root-bound layer to oscillate as the softer, decomposing under layer is actively eroded away.* ***PANEL E.*** *Similar photo to Panel A, but with a small strandplain beach composed totally of organic detritus eroded out of the underlying peat bed. The presence and extent of this organic detritus is extremely variable and dependent upon the season and storm patterns. Notice how the irregular erosional geometry of the original peat shoreline can be seen on the landward side of the strandplain beach.* ***PANEL F.*** *Winter photograph looking north from the same location as Panel E. Now, the entire eroding peat shoreline is buried beneath an extensive strandplain beach composed totally of organic detritus. This detrital accumulation is over 3 feet thick at the water's edge and extends some distance seaward below the water's surface. Notice the beautifully detailed, and small-scale depositional and erosional sediment structures that are preserved on this beach as the water rises and falls in response to the wind tides.*

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the canal, has a fetch of about 10 miles and erodes at an average rate of –2.2 ft/yr. Whereas, the southeast-facing shoreline, north of the canal, has a fetch of about 4 miles and erodes at an average rate of –1.4 ft/yr.

8.3.E. Point Peter Road Site

(Figures 8-3-10, 8-3-11 and 8-3-12)

The Point Peter Road site is in the Alligator River Wildlife Refuge of the U.S. Fish and Wildlife Service. It is located on the western shore of northern Pamlico Sound about 4.25 miles north of Stumpy Point village in mainland Dare County. It occurs about 1.6 miles east of U.S. Hwy. 264 at the end of Point Peter Road, a seasonal road built on material dredged from the adjacent ditch.

The Dare-Hyde Peninsula is a vast flat, upland, pocosin swampforest with a narrow zone of marsh vegetation around the outer rim. This entire peninsula has been severely ditched and diked through centuries of drainage alteration and land modification. Modifications along the low, outermost rim of the peninsula are generally limited to past construction of impoundments, drainage ditches, and road dams such as U.S. Hwy. 264 that passes near this site. The 1969 aerial photograph shows a major impoundment along the shoreline on the north side of Point Peter Road and an associated ditch.

This low pocosin peninsula is being drowned by the present ongoing rise in sea level, causing major shifts in vegetation zonation around the peninsula perimeter. Rising water levels drown the swamp forest and systematically replace it with transition vegetation and coastal marsh grasses. The 1983 and 1998 aerial photos are both false color images taken in the winter months that differentiate photosynthesizing vegetation in the red colors (i.e., pines, bays, etc.) from inactive plants (i.e., deciduous trees and grasses) as yellow- and gray-green colors. Comparison of these two images 15 years apart demonstrates a significant landward expansion of marsh at the expense of the pocosin swamp forest, particularly up the drainage ditch beside Point Peter Road. As sea level continues to rise, the impact of modification structures will become increasingly important in determining the ultimate transition of vegetative zones.

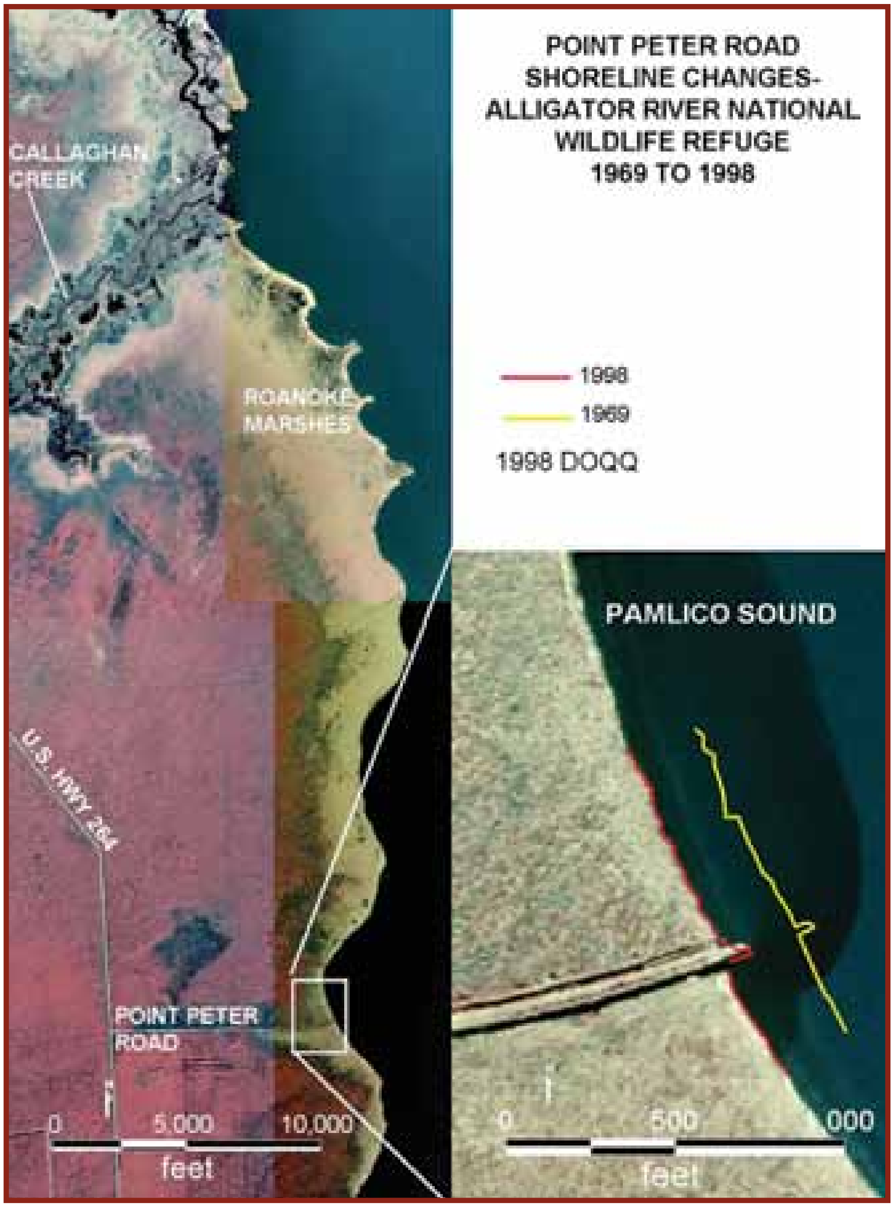

FIGURE 8-3-11. *The Point Peter Road site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1969 and 1998.*

Traveling east from U.S. Hwy. 264, Point Peter Road transects three prominent zones. First, is a vast fresh water pocosin swamp forest that grades into a transition zone of low scrub-shrub vegetation and finally a freshwater marsh along the Pamlico Sound shore. These zones display strikingly different color patterns on the 1998 Digital Orthophoto Quarter Quadrangle. The outer zone is dominated by *Spartina patens*

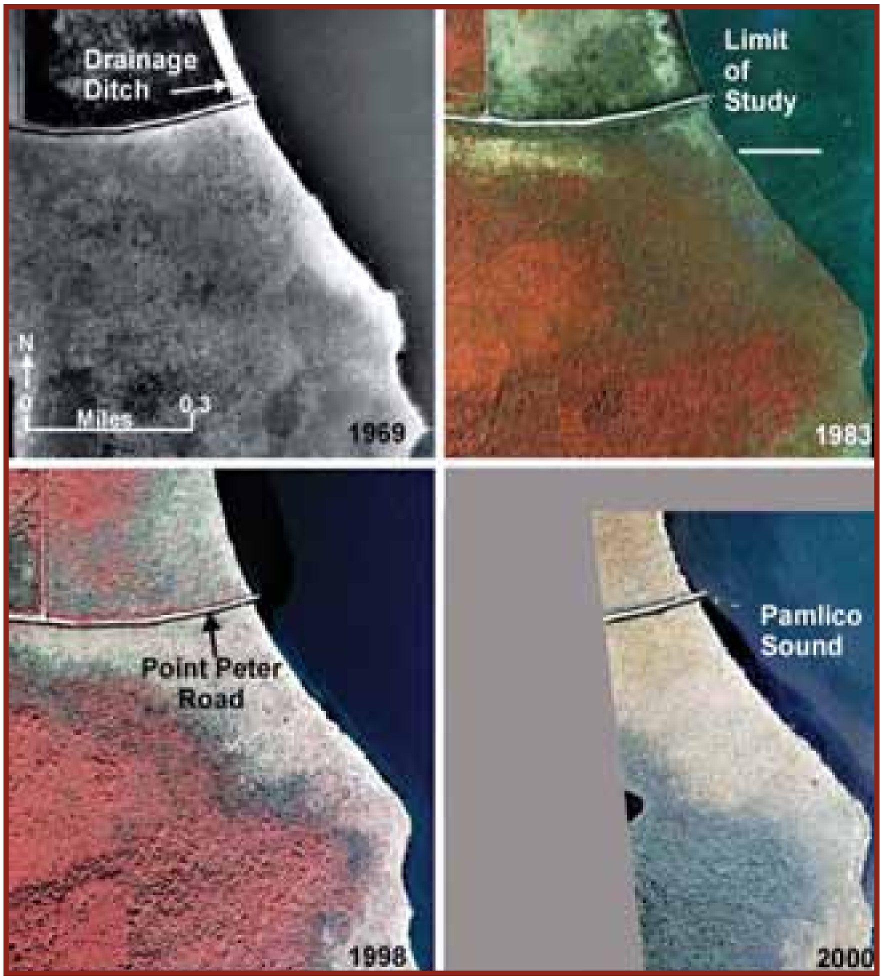

FIGURE 8-3-12. *The Point Peter Road site aerial photograph time slices from 1969, 1983, 1998 and 2000. Notice that the impoundment north of Point Peter Road is separated from Pamlico Sound by a major outer ditch and associated dike. Comparison of land loss along the outer ditch between the 1969 and 1983 photographs demonstrates the rapid rate of shoreline recession. The ditch is long gone by 1998, and the impoundment has reverted to the natural vegetation pattern. Also, notice the major expansion through time of transition zone and marsh vegetation (light gray-green color on the 1983 to 2000 photographs) at the expense of the swampforest vegetation (red color on the 1983 and 1998 photos and dark green on the 2000 photographs). This vegetation change is interpreted to reflect the drowning of those low-lying wetlands in direct response to ongoing sea-level rise.*

(saltmeadow grass) and *Baccharis* (cotton bush), with varying amounts of *Cladium* (sawgrass) and *Myrica* (wax myrtle) scattered throughout. Minor patches of *Phragmites australis* are beginning to appear. The sawgrass and wax myrtle grow primarily in freshwater marshes, but now find themselves extending all the way to the shoreline of a brackish water sound. Most of the *Myrica* is dead in the outermost zone, suggesting that the shoreline marsh is out of equilibrium with the adjacent estuarine system due to either rapid rates of erosion or hydrologic changes in fresh versus brackish water affecting the system. If the shoreline was in equilibrium, the outer marsh zone would evolve into a brackish-water marsh dominated by species such as *Juncus roemerianus*.

The overall shoreline is a north-south feature that contains a large-scale, smooth, cuspate geometry. However, on the smaller scale, the marsh edge is quite irregular and dominated by a series of narrow headlands and associated embayments with amplitudes up to 25 feet. The marsh headlands are slightly more erosion resistant due to the presence of *Myrica* stumps and root systems that temporarily stabilize the points. The marsh embayments drop off into 1 to 2 feet of water, while the headlands generally drop off into 2 to 3 feet of water.

Some small embayments contain strandplain beaches in front of the eroding peat bank. The beaches generally contain a thin (< 0.5 feet) basal layer of sand overlain by a thicker (0.5 to 2.0 feet) layer of lighter wood and other detrital organic matter derived from the erosion of the peat shoreline. At times this dark brown organic detritus beach becomes so thick and wide that it totally buries the eroding marsh shoreline, forming beautiful small-scale depositional and erosional structures, including berms, channels, tidal deltas, collapsed scarps, etc.

Underlying the surface marsh is a pure Holocene peat substrate that ranges from 5 to 7 feet thick. The peat overlays a tight clay of late Pleistocene age. The erosional scarp along the shoreline is cut 1 to 3 feet into the peat causing the floor of the inner estuarine area to be composed of soft in situ peat. The peat floor continues soundward for several hundred yards, thinning to zero thickness in about 5- to 7-foot water depths where tight Pleistocene clay forms the estuarine floor.

The 1998 DOQQ (Fig. 8-3-11) shows the location of digitized estuarine shorelines for 1969 and 1998. During this period, the Point Peter site had an average rate of shoreline recession of –7.5 ft/yr (Table 8-3-1). Recession rates were laterally very uniform with recession rates ranging from only a low of –7.1 to a high of –8.3 ft/yr.

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

FIGURE 8-3-13. *Photographs of the North Bluff Point site.* ***PANELS A and B****. Summer photographs looking northeast (A) across the Outfall Canal to the upland vegetation on the far spoil bank and looking southwest (B) along the outer edge of the marsh platform. The outer zone of this platform marsh consists of* Spartina alterniflora *that grades landward into a dense growth of* Spartina cynosuroides*. The latter grass is growing on a slightly elevated zone of spoil that was deposited along the outside of the impoundment ditch as indicated on Figure 8-3-14. Notice the highly irregular shoreline geometry of the rapidly eroding marsh peat shoreline. Photographs are by M. Murphy.* ***PANELS C and D.*** *Close-up photographs of the irregular marsh peat shoreline. The peat is about 6 to 7 feet thick at this point, with the wave-cut scarp eroded to depths of 2 to 4 feet below the water surface. Thus, the bottom of the estuary is still in the soft peat. The estuarine floor gently slopes away from the land to 6- to 7-feet water depth where the peat has been totally eroded away and the underlying tight clay forms the estuarine floor. Notice the dark coffee color of the water.*

8.3.F. North Bluff Point Site

(Figures 8-3-13, 8-3-14 and 8-3-15)

North Bluff Point is located in Carolina Gull Rock Game Land in Hyde County. The study site occurs at the end of the Outfall Canal Road and the ditch draining Lake Mattamuskeet. The road turns off of U.S. Hwy. 264 at Holland and runs southeast about 6.7 miles to the shores of southern Pamlico Sound. The all-weather road is built on dredged material derived from the adjacent large canal and rises significantly above the surrounding land. Thus, the canal road itself is surrounded by scrub-shrub and upland forest. However, traveling southeast from U.S. Hwy. 264, the Outfall Canal Road transects through an extensively ditched and drained agricultural area and freshwater pocosin swamp forest. The outer 0.7 miles grades into a transition zone characterized by stressed and dead trees with transition zone vegetation and a broad marsh zone. Remnants of old freshwater impoundments along the west side of the road have severely modified the natural marsh zonation that can be seen along the east of the canal in the 1983, 1995 and 1998 aerial photographs.

The inner marsh zone is a low brackish-water system dominated by *Juncus roemerianus* with large patches of *Distichlis spicata* and variable amounts of *Spartina patens* and *Scirpus*.

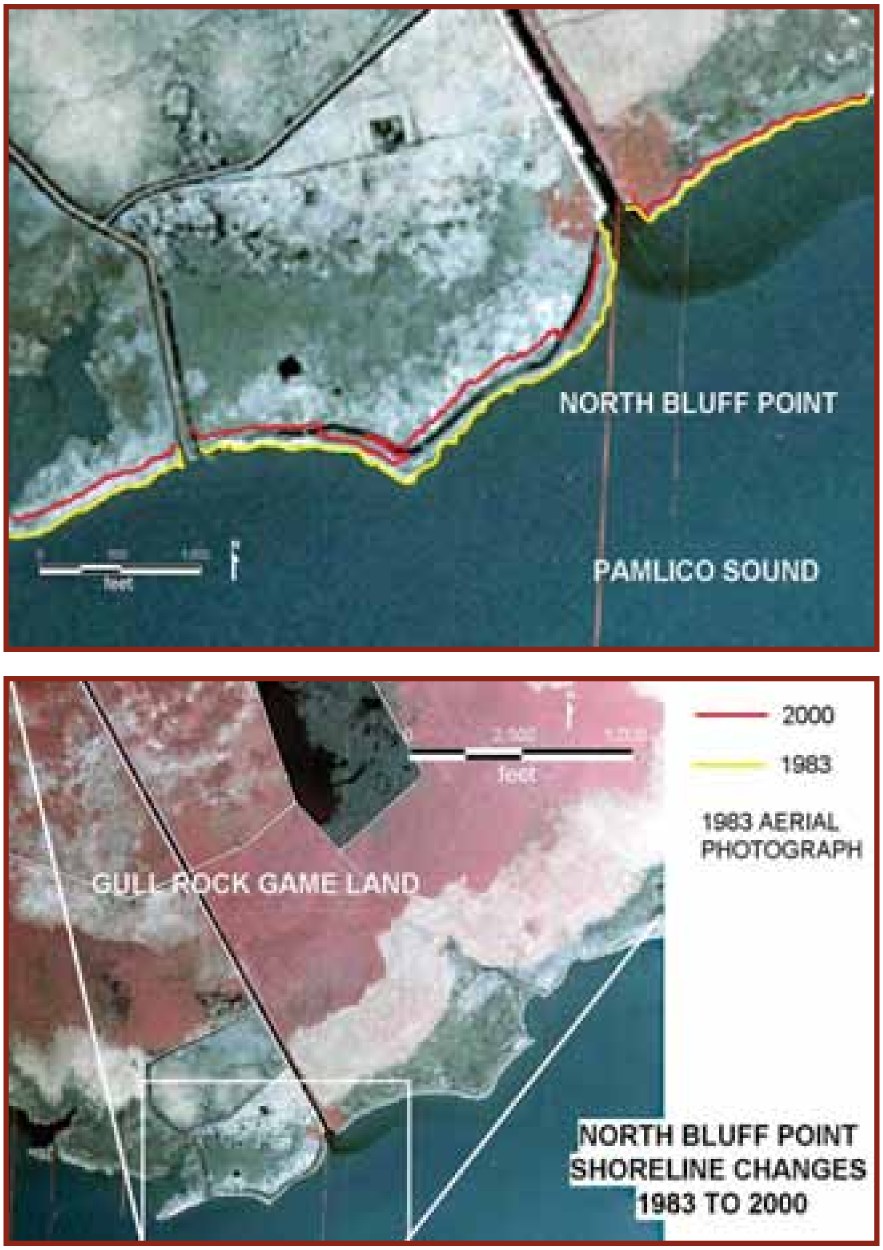

FIGURE 8-3-14. *The North Bluff Point site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ), with digitized shorelines for 1983 and 2000.*

The outer marsh, along the Pamlico Sound shore, is an intermediate brackish-water system composed primarily of *Spartina alterniflora* and *Spartina patens* with minor *Juncus roemerianus*. A thick zone of *Spartina cynosuroides* occurs along the shoreline and grows on the berm created by the dredge spoils from the old impoundment ditch. Each of these zones display strikingly different color patterns on the aerial photos. Along the shoreline, the Holocene peat is about 6 to 7 feet thick and occurs on top of a light, gray-blue silty clay that can be seen at the road end where it is being eroded. This clay was dredged from the canal and used to build the elevated road bed in 1914 to drain Lake Mattamuskeet for agricultural development (Forrest, 1999). The shallow waters adjacent to the canal mouth are floored in soft, in situ peat that slopes gently offshore for several hundred yards to water depths of about 5 to 6 feet, where the underlying tight clay crops out and forms the estuarine floor. The peat bed thins gradually northwards towards the swamp forest.

The eroding peat bank drops off into 2 to 4 feet of water littered with large eroded peat blocks. The peat banks are severely undercut below the dense modern root mass. With undercutting, the large overhanging peat blocks move with the waves and ultimately break off and fall to the estuarine floor. The extent of erosion between 1983 and 1995 is obvious in the aerial photographs by comparing the amount of land lost relative to the outermost ditch.

The 1998 DOQQ (Fig. 8-3-14) shows the location of digitized estuarine shorelines for 1983 and 2000. During this period, the average shoreline recession rate for the entire reach considered was –5.7 ft/yr with a range from a low of –1.1 to a high of –11.5 ft/yr. However, the marsh shoreline on the southwest side of the canal eroded at an average rate of –6.9 ft/yr, while the northeast side eroded at an average rate of only –2.2 ft/yr (Table 8-3-1). It is not clear why these different rates occur.

8.3.G. Swan Quarter Site

(Figure 8-3-16)

The Swan Quarter site occurs within the Swan Quarter National Wildlife Refuge of the U.S. Fish and Wildlife Service. The site is located in Hyde County and along the northern shore of southern Pamlico Sound at the confluence with the Pamlico River estuary. The portion of shoreline analyzed for this study includes Swan Quarter Island and East Judith Island, occurring between Rose Bay on the west and Swan Quarter Bay on the east. Due to the vast size and limits concerning accessibility and control stations, this site was only analyzed via aerial photography utilizing the 1956 and 1998 end-member photographs.

The study area consists of two different platform marsh shoreline segments on Swan Quarter and East Judith islands. The southern side of Swan Quarter Island is an open shoreline with a 20- to 25-mile fetch from the south and southeast across southern Pamlico Sound. The second segment of marsh shoreline includes the north shore of Swan Quarter Island and the outer perimeter of East Judith Island. This latter segment is a semiprotected platform marsh shoreline occurring along the shorelines of Swan Quarter and Rose bays with fetches that range from 0.5 to 5 miles. Analyzing these two segments provides important data concerning the role of fetch in shoreline erosion, as well as data for the many miles of semiprotected marsh that occur in coastal North Carolina.

The marsh islands within the Swan Quarter National Wildlife Refuge are world-class platform marshes composed of an interior marsh dominated by *Juncus roemerianus*. A low berm occurs slightly inland of and parallels the shoreline and consists of transition zone vegetation, including *Spartina cynosuroides*, *Iva* (marsh elder) and *Baccharis* (cotton bush). Soundward of the berm, the *Juncus* has largely been stripped off the peat surface and now consists primarily of a narrow zone of *Spartina patens*, which is capable of more rapid recruitment after storms than is the *Juncus*. The marsh is growing on a very thick bed of Holocene peat that forms the eroding banks around the island perimeters. This peat is up to 8 to 10 feet thick. Due to the high-energy environment, water depths right up to the edge of the eroding peat banks are generally 2 to 6 feet deep and often up to 6 to 10 feet deep. Strandplain beaches occur locally within some coves, primarily on the southern shore of Swan Quarter Island, where short-term erosion rates may decrease to 0 ft/yr.

The 1998 DOQQ (Fig. 8-3-16) shows the location of digitized estuarine shorelines for 1956 and 1998. During this time period, the open marsh shoreline receded at an average rate of –2.9 ft/yr with ranges from low rates of 0 ft/yr to high rates of –10.9 ft/yr (Table 8-3-1). In contrast, the semiprotected shorelines within Rose and Swan Quarter bays and associated embayments receded at an average rate of –1.2 ft/yr with a range from 0 to –6.4 ft/yr.

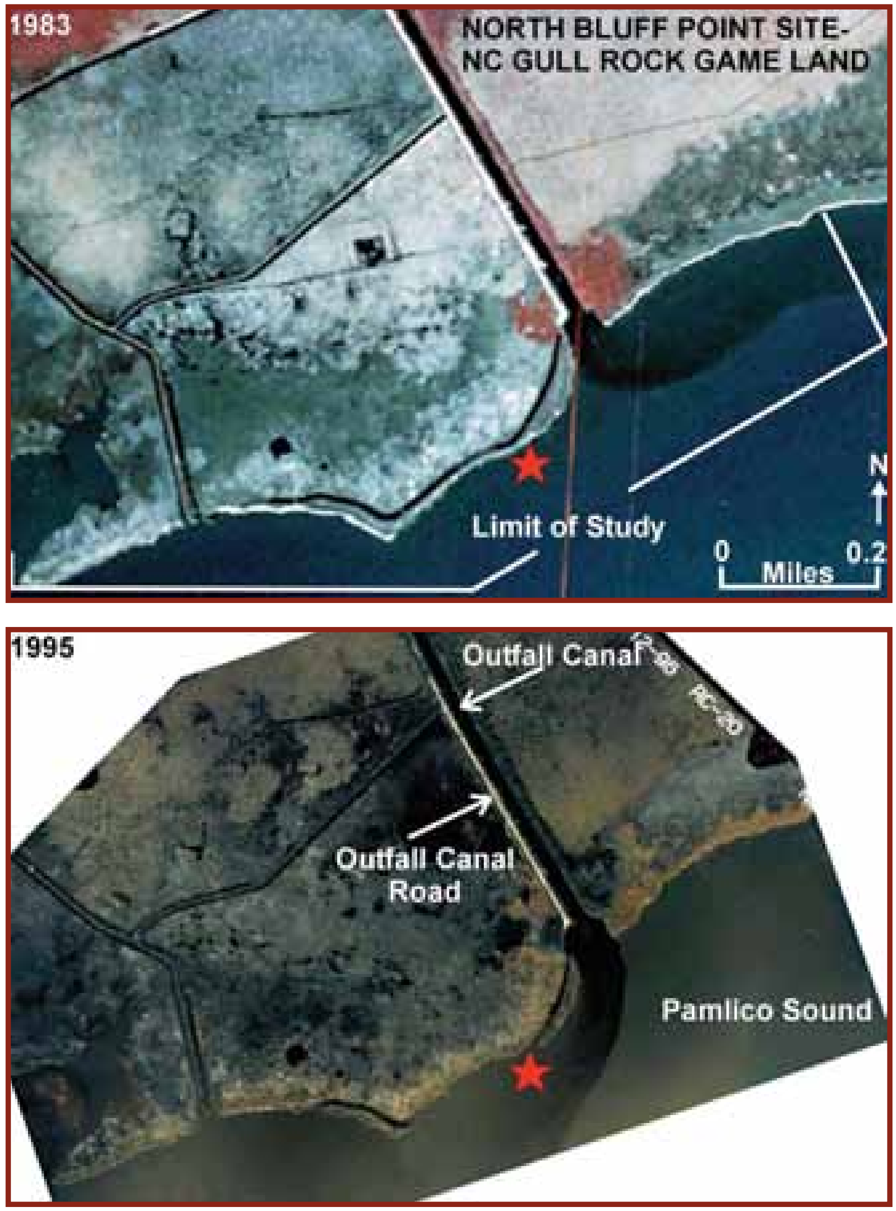

FIGURE 8-3-15. *The North Bluff Point site aerial photograph time slices from 1983 and 1995. The rapid rate of shoreline recession is indicated by the red star. An entire segment of the marsh between Pamlico Sound and the outer ditch of the impoundment, southwest of Outfall Canal Road, has largely disappeared in this 12-year period.*

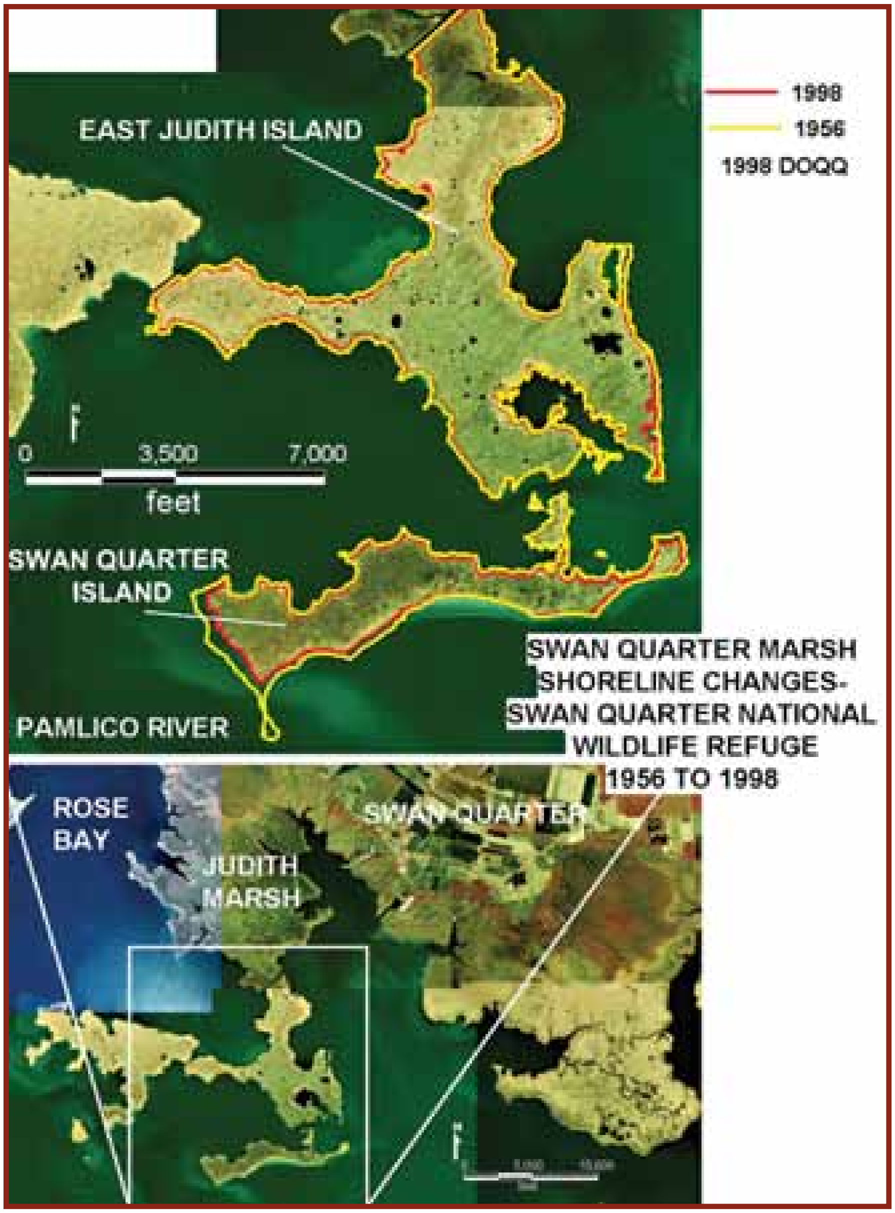

FIGURE 8-3-16. *The Swan Quarter site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ), with digitized shorelines for 1956 and 1998.*

8.3.H. Lowland Site

(Figures 8-3-17, 8-3-18 and 8-3-19)

The Lowland site is located along the southern shore of the Pamlico River estuary on Goose Creek Island in Pamlico County. The site occurs at the north end of a 0.5-mile fair weather track through the swamp. The track occurs at a major west turn in the Fulford Point Road located 1.2 miles north of Lowland Road and 1.5 miles east of Goose Creek.

The geometry and erosion at this site is complex and controlled by the paleotopography of the Pleistocene clay surface. At the large-scale, the entire Oyster Creek drainage system is incised into the underlying Pleistocene clay during the last sea-level low stand. The subsequent rise in sea level systematically flooded up the drainage system to produce the marshes and resulting peat deposits. The initial drowning and first peat development took place in the Oyster Creek stream bottom and sequentially migrated upward and outward across the clay slopes through time. Today, all of the headwater and tributary creeks feeding the main stem of Oyster Creek are surrounded by broad marshes that lap onto the adjoining clay uplands.

On a smaller scale, the upland Pleistocene clay surface is slightly undulating. The east-west oriented shoreline generally consists of low sediment banks with a platform marsh fringe that has been largely eroded away. The marsh is completely gone in the coves, which today are dominated by low sediment bank shorelines, with marsh persisting along the headlands. Within the coves, the 1- to 2.5-foot high-low sediment bank and associated land are composed of tight gray clay substrate that holds surface water. This results in poorly drained land containing a mixed growth of scrub-shrub, pond pine and hardwoods with abundant bay trees. As the clay surface declines in elevation, a marsh occurs with a thin layer of organic peat lapping onto the clay surface. The peat thickens to 3 to 4 feet into the drainages or soundward into the headlands as the clay surface topography declines.

Along the headlands, the outer portion of the marshes are dominated by *Juncus roemerianus*. A narrow zone of *Spartina patens* occurs around the outermost estuarine perimeter where *Juncus* has been stripped off by storms. Extensive growths of *Spartina cynosuroides* and *Phragmites australis*, along with variable amounts of the shrubs *Iva* and *Baccharis*, occur primarily on the wrack storm berm and landward into the inner portion of the marsh. The marsh grades landward into a freshwater swamp dominated by saw grass, pond pine and abundant wax myrtle and bay shrubs. This habitat produces a fine-grained organic peat that is about 0.5 foot

Continued on page 121

FIGURE 8-3-17. *Photographs of the Lowland site.* ***PANEL A.*** *Winter photograph looking northeast within the cove and along a low sediment bank shoreline with* Spartina patens, *scrub-shrub and pond pine growing on the upper surface. Notice the small strandplain beach that occurs only within the apex of the cove.* ***PANEL B.*** *Close-up of the wave-cut scarp eroded into the low sediment bank overlain by a thin pocosin peat containing a cover of* Spartina patens *in the foreground and pond pine with transition zone scrub-shrub in the background. The sediment bank is composed of a Pleistocene, tight, slightly sandy clay. This is the source of the limited sand forming the small strandplain beach in Panel A.* ***PANEL C.*** *Summer photograph looking east along the narrow marsh platform in front of the mineral soils, with their wetland woods consisting predominantly of scrub-shrub, bay trees and pond pine. The marsh platform is composed of organic peat that is forming on top of and pinches out onto the mineral soil that forms the shoreline in Panel B. Photograph is by M. Murphy.* ***PANEL D.*** *Summer close-up of the marsh platform dominated by a narrow outer zone of* Spartina patens *adjacent to the water and an inner zone of* Spartina cynosuroides *that is growing on a very thin and slightly raised sand and wrack berm. Photograph is by M. Murphy.* ***PANEL E.*** *Winter photograph looking northwest along the marsh platform shoreline within the cove. Notice the thick roots of* Spartina cynosuroides *that extend out to edge of the eroding marsh peat where the plants have been stripped off by wave action.* ***PANEL F.*** *Close-up of the wave-cut scarp and wave-cut platform eroded into the marsh peat. In the foreground, the tight, root-bound, upper surface has been eroded off in a stair-step fashion. Whereas, in the background, this root-bound surface is being undercut forming an overhang.*

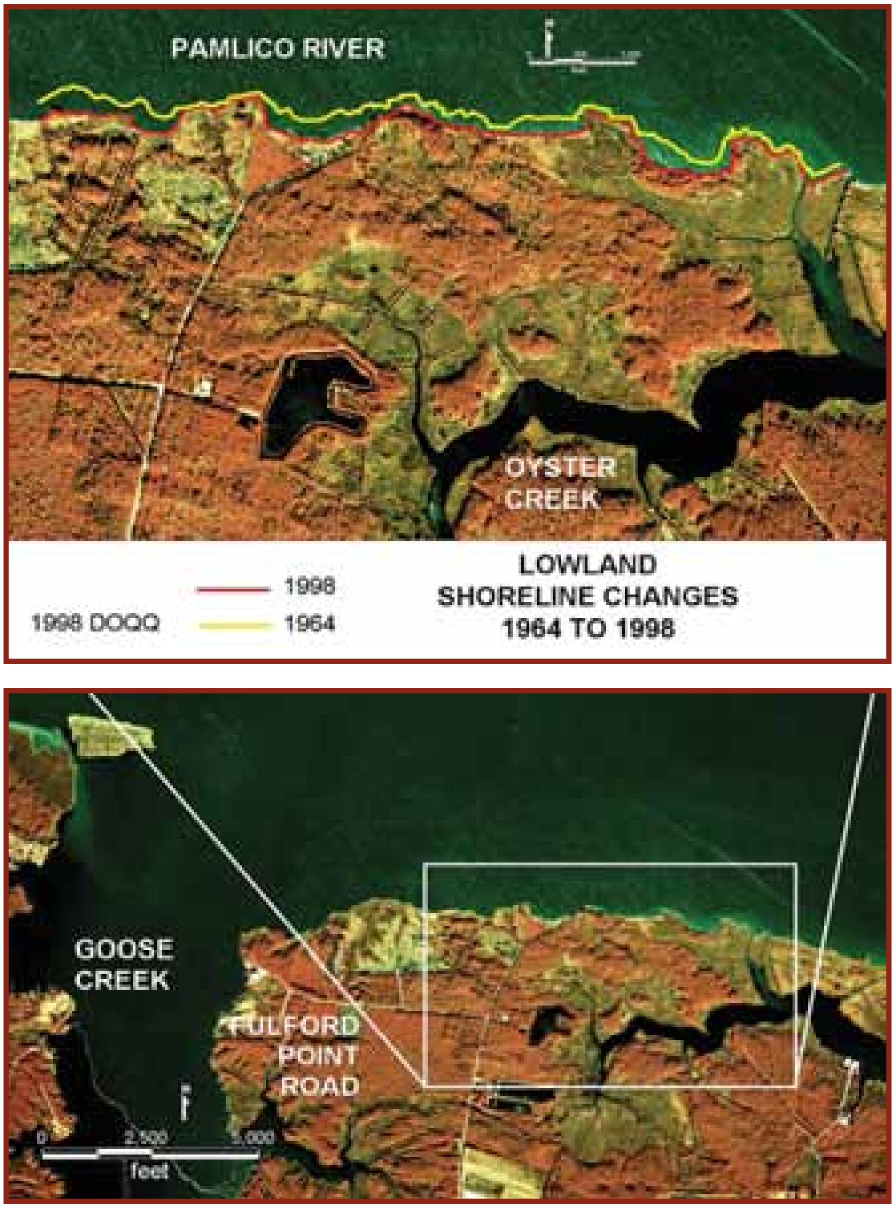

FIGURE 8-3-18. *The Lowland site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1964 and 1998.*

thick on top of the clay throughout the upland area.

Within the coves, erosion of the low-sediment banks leaves a trail of pine stumps standing in the shallow water on lone tap roots with a whorled mass of shallow surface roots radiating outward like a lace collar. Low sediment bank shorelines often have thin and local strandplain beaches that form on the clay surfaces. The clay surfaces slope down to about 2 to 3 feet below mean sea level and continue offshore for at least several hundred yards. Scattered across this flat clay surface in the offshore area is a thin and variable layer of sand with local sand bars. Frequently, a small sand berm occurs on top of the clay scarp and in front of the freshwater swamp on the landward side as previously described.

On the 1964 aerial photograph of the Lowland site, the shoreline consisted entirely of marsh and was more regular and significantly further soundward than today. By 1970, the irregular erosion of marsh began to develop coves that intersected upland vegetation and formed the initial low sediment bank shorelines. The abundance and distribution of low sediment banks continued to expand since 1970. Today, the shoreline consists of a mixed, low sediment bank with remnants of the former marsh platform.

The 1998 DOQQ (Fig. 8-3-18) shows the location of digitized estuarine shorelines for 1964 and 1998. During this period, the combined low sediment bank and marsh platform at the Lowland site eroded at an average rate of –4.0 ft/yr, with a range from –0.8 to –8.1 ft/yr (Table 8-3-1). It appears that the marsh platform on the headlands is eroding at the average rate of –1.7 ft/yr, while the low sediment banks within the coves are eroding at an average rate of –4.9 ft/yr. The rate of recession for a marsh platform with a significant fetch is quite low. However, this shoreline consisted of 100% marsh platform during the early portion of the study interval, while the latter portion was characterized by decreased amounts of marsh and increased low sediment banks. Consequently, the overall low recession number probably reflects a complexly mixed shoreline that is changing an abundance of shoreline types through time.

8.4. PAMLICO RIVER SHORELINE EROSION SITES

8.4.A. Summary: Pamlico River Shorelines

At the time Hardaway (1980) determined the shoreline erosion rates for sites along the Pamlico River estuary, the efforts to stabilize the shoreline with hard structures were minimal. Only portions of Hickory Point and segments of the

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

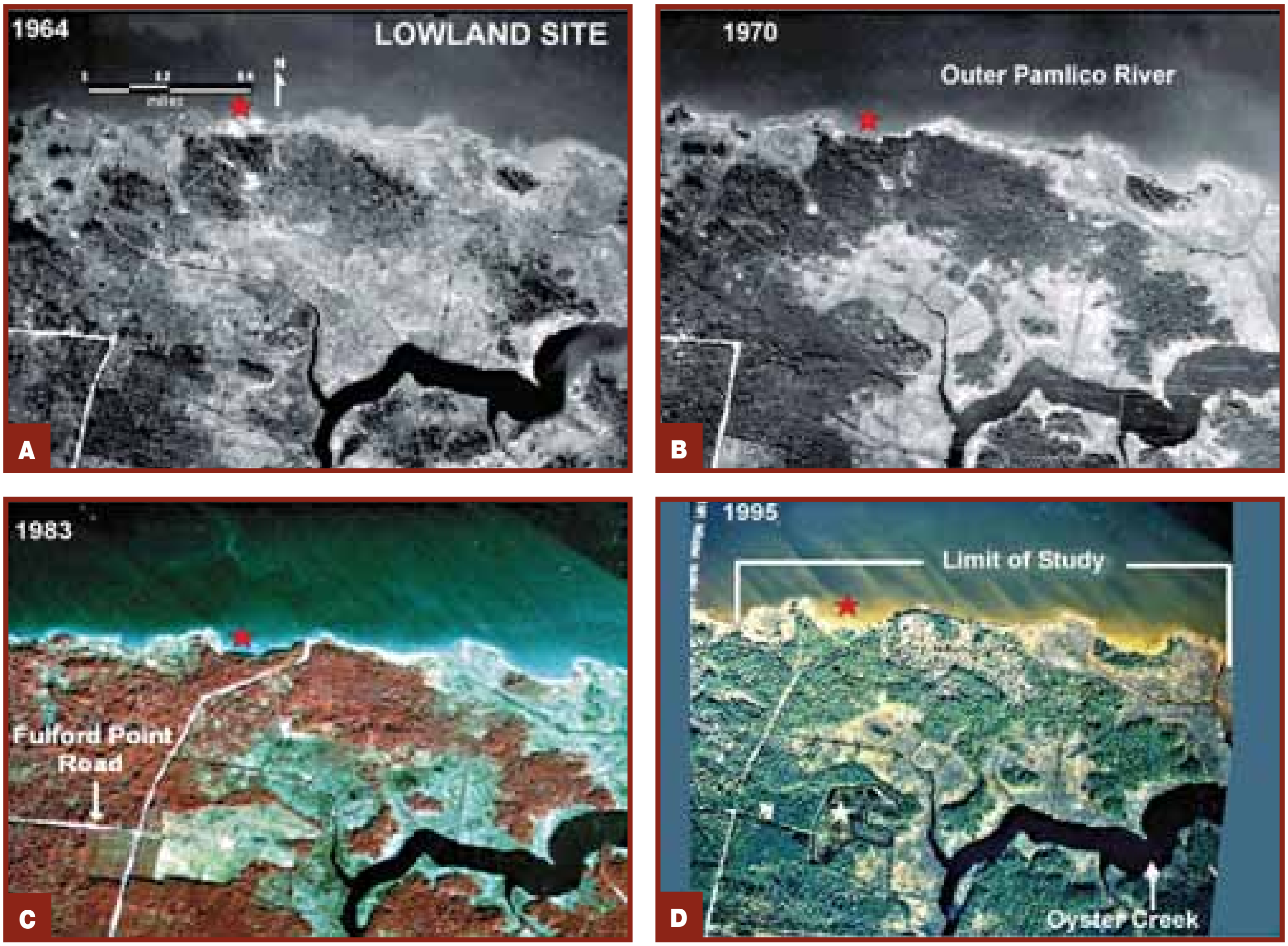

FIGURE 8-3-19. *The Lowland site aerial photograph time slices from 1964, 1970, 1983 and 1995. The entire region within the area of the photograph is wetland. Dense scrub-shrub, swampforest vegetation (red color in the 1983 photograph) lives in standing water on top of the tight clay soils much of the year. The slightly lower area surrounding and adjacent to the Oyster Creek drainage system is dominated by marsh grasses (light blue-green color in the 1983 photograph) living on a marsh peat substrate that thickens into the drainages. The time series suggests an expansion of the scrub-shrub, swampforest vegetation through time (excluding the logged areas indicated with white stars) and loss of associated marsh along the Outer Pamlico River shoreline due to erosion (red stars).*

Pamlico shore at Wades Point were hardened. However, since the Hardaway study, six Pamlico River sites were largely developed and included major shoreline erosion protection procedures. These six sites include Bay Hills, Mauls Point, Camp Leach, Pamlico Marine Lab, Hickory Point and the Pamlico side of Wades Point. Thus, the potential for obtaining high quality shoreline erosion data requires knowing when each structure was built or rebuilt, as well as knowing the specific history of which shoreline segments were eroded and structures rebuilt following specific high storm tides such as the 1996-1999 hurricanes. To carry out a study evaluating the response of stabilized shorelines during major storm events, good historical documentation and permit records are required, along with high quality post-storm aerial photographs. This type of information does not presently exist. Such an effort was beyond the scope of the present study. Consequently, the six modified sites are revisited in a general mode in the present study, while the unmodified sites are analyzed in more detail. Table 8-4-1 summarizes the long-term shoreline erosion data developed by the present study.

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Table 8-4-1 Short-Term Erosion Rates for the Pamlico River Sites

Summation of the short-term estuarine shoreline erosion rates for the mainland Albemarle-Pamlico Sound estuarine sites based upon the present study. See Figure 8-1-1 for locations of study sites.

SITE AND SHORELINE TYPE	TIME PERIOD (YEARS)	DISTANCE ANALYZED (FEET)	AVERAGE LONG-TERM EROSION RATE DATA — PRESENT STUDY NET (FT/YR)	RANGE (FT/YR)
15. **Wades Point — Confluence of Pungo and Pamlico Rivers:**				
Marsh-Platform—NET	1970-1998	5,105	–3.2	–0.8 to –7.0
Marsh-Platform	1970-1984	5,275	–3.4	–0.9 to –7.0
Marsh-Platform	1984-1998	4,936	–2.9	–0.8 to –6.1
Low Sediment Bank—NET	1970-1998	3,308	–4.1	–0.6 to –8.9
Low Sediment Bank	1970-1984	3,407	–3.3	–1.2 to –6.1
Low Sediment Bank	1984-1998	3,208	–5.2	–0.6 to –8.9
Modified Low Bank—NET	1970-1998	3,252	–0.6	+1.9 to –2.6
Modified Low Bank	1970-1984	2,308	–0.3	+1.9 to –1.9
Modified Low Bank	1984-1998	4,196	–0.9	–0.6 to –2.6
16. **Hickory Point — Pamlico River and South Creek:**				
Marsh-Platform—NET	1970-1998	1,928	–3.6	–1.8 to –4.9
Low Sediment Bank—NET	1970-1998	2,992	–4.3	–2.2 to –6.6
Modified Low Bank—NET	1970-1998	4,866	–1.4	0.0 to –6.6
Modified Low Bank	1970-1984	4,866	–2.4	0.0 to –5.1
Modified Low Bank	1984-1998	4,866	–0.4	0.0 to –6.6
17. **Pamlico Marine Labs — South Creek:**				
Low Sediment Bank-E and W sides—NET	1970-1989	1,430	–4.9	–3.3 to –6.3
Low Sediment Bank-E Side—NET	1989-1998	570	–2.5	–0.6 to –3.4
Modified Low Bank-W Side	1989-1998	860	Negligible	
Modified Low Bank-All	1998-2003	1,430	Negligible	
18. **Bayview — Bath Creek and Inner Pamlico River:**				
High Sediment Bank—NET	1970-1998	930	–0.2	+0.8 to –1.0
Low Sediment Bank—NET	1970-1998	1,050	–1.4	–0.7 to –2.4
19. **Camp Leach — Inner Pamlico River:**				
Marsh-Platform—NET	1970-1998	315	–1.3	–0.9 to –2.0
Marsh-Fringing—NET	1970-~1986	2,255	–0.3	+2.1 to –0.8
Modified Marsh	~1986-1998	2,255	Negligible	
Low Sediment Bank—NET	1970-~1986	1,940	–0.6	0.0 to –1.1
Modified Low Bank	~1986-1998	1,940	Negligible	
20. **Mauls Point — Blounts Bay and Inner Pamlico River:**				
Bluff—NET	1970-1984	803	–2.9	–0.6 to –3.1
Modified Bluff	1984-1998	803	–0.2	+2.6 to –2.6
Modified Low Bank	1970-1998	344	+0.8	+1.2 to –0.4
Modified Bank-All	1998-2003	1,147	Negligible	
21. **Bay Hills — Chocowinity Bay and Inner Pamlico River:**				
Bluff—NET	1970-1998	750	< –1.0	
Modified Bluff	1970-1998	2,990	< –0.5	

C O N T I N U E D :

Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

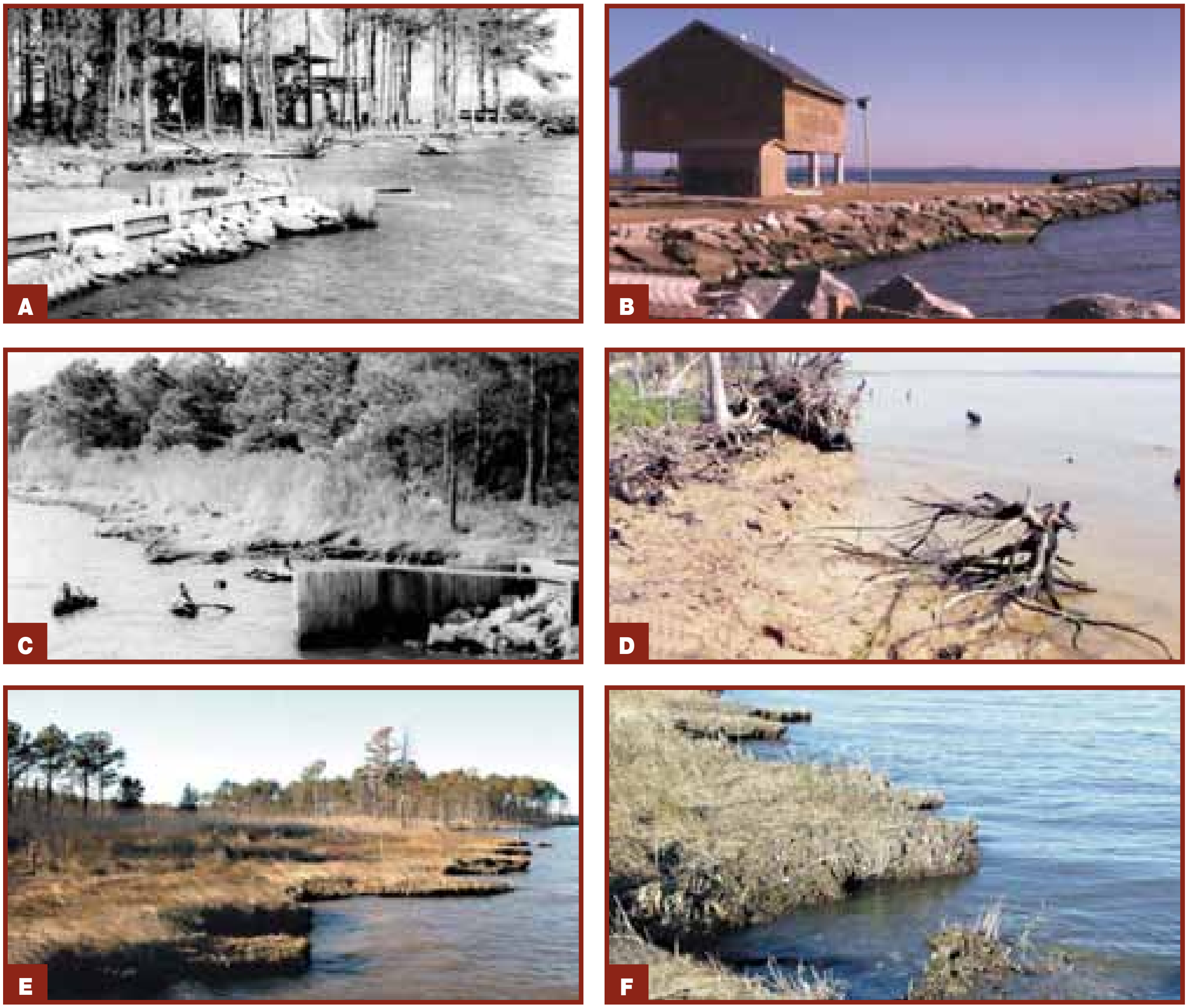

FIGURE 8-4-1. *Photographs of the Wades Point site.* ***PANEL A.*** *September 1979 photograph looking east towards the eroding Wades Point and a former beach cottage located on the nonhardened low sediment bank shoreline with upland pine vegetation. Photo is from Hardaway (1980).* ***PANEL B.*** *A January 2001 photograph from about the same location as Panel A. Notice the hardened shoreline, lack of upland vegetation, and a relatively new beach cottage.* ***PANEL C.*** *September 1979 photograph looking west along the low sediment bank shoreline of the Pamlico River. Photo is from Hardaway (1980).* ***PANEL D.*** *Close-up of the wave-cut platform eroded into the low sediment bank shoreline indicated in Panel E. The shoreline is composed of tight Pleistocene clay, with the absence of a strandplain beach due to lack of sand in the eroding clay sediment. Also, the shallow root systems of the upland vegetation are totally excavated as demonstrated by the trees along the shoreline.* ***PANEL E.*** *January 2003 photograph looking north along the platform marsh shoreline of the Pungo River from Wades Point. The marsh interior is dominated by* Juncus roemerianus*, with a narrow outer perimeter marsh dominated by* Spartina patens*. Locally, there is a narrow and mixed zone of* Phragmites australis *and* Spartina cynosuroides *growing on a thin sand and wrack berm that parallels the shoreline. Notice the highly irregular erosion pattern of the marsh peat in the foreground and the upland area and associated low sediment bank shoreline in the distance (see Panel D).* ***PANEL F.*** *January 2003 close-up photograph of the eroding platform marsh shoreline. Notice the large peat block in the near-shore that has recently broken off the shoreline.*

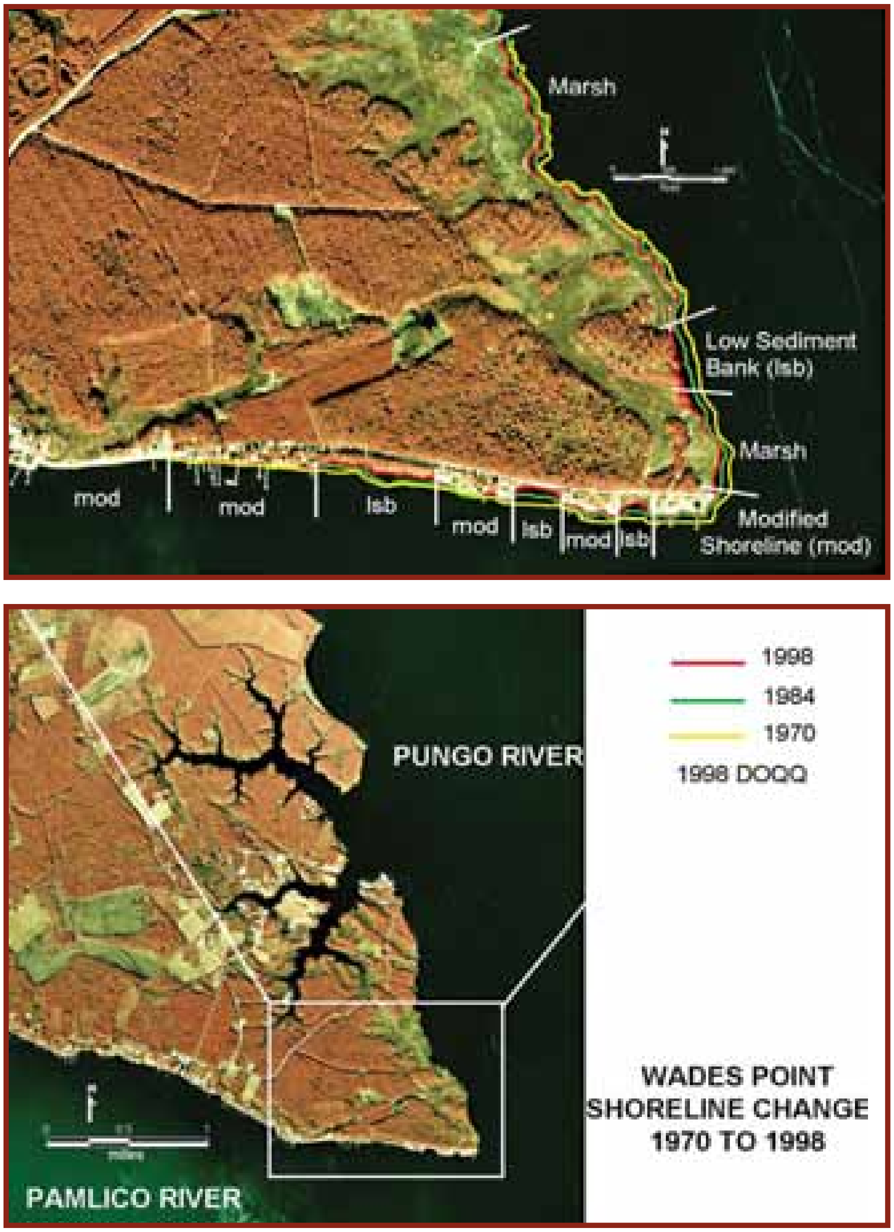

FIGURE 8-4-2. *The Wades Point site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1970, 1984, and 1998.*

8.4.B. Wades Point Site

(Figures 8-4-1, 8-4-2 and 8-4-3)

Wades Point is the northwest point at the confluence of the Pungo and Pamlico river estuaries. It is located 1.4 miles east of Pamlico Beach in Beaufort County and at the southeast end of Pamlico Beach Road, a classic "going-to-sea" road. The site consists of two very different shorelines. The east-west trending shoreline is a low sediment bank along the north shore of the Pamlico River that has been largely modified through the years. The northwest-southeast trending Pungo River shoreline remains totally undeveloped and dominated by a marsh with a small segment of a low sediment bank.

The interior of the marsh is irregularly flooded and dominated by *Juncus roemerianus*. Locally, a thin sand and wrack berm parallels the shoreline with a narrow 10- to 20-foot wide fringe along the shoreline dominated by *Spartina patens*. The berm contains mixed patches of *Phragmites australis* and *Spartina cynosuroides* with scattered *Iva* and *Baccharis* shrubs. The shoreline zone consists of *Juncus* peat in which the *Juncus* has been stripped off by wave activity and is rapidly recolonized by the *Spartina patens*. In addition, wave action tends to strip off upper plates of the peat, producing a stair-step erosion pattern, as well as undercutting the modern root mass zone. The peat is underlain by a tight clay. The peat pinches out where the clay surface rises above mean sea level, producing pine-dominated islands or hammocks in the marsh. Away from the pine islands, the clay surface drops below sea level, and the peat thickens to 2 to 3 feet or more into these topographic lows.

Erosion of the marsh produces small-scale, irregular shorelines characterized by alternating headlands and embayments with 5- to 20-foot amplitudes. The marsh is generally characterized by a 1- to 3-foot high eroding scarp in approximately 2 feet of water and a tight clayey sand bottom in the nearshore area. The low sediment bank shorelines tend to be fairly straight, are composed of tight clayey sand and rise up to two feet above mean sea level. Sand derived from the eroded sediment bank forms a 10- to 20-foot wide strandplain beach containing many pine stumps in front of the eroding sediment bank.

The 1998 DOQQ (Fig. 8-4-2) shows the location of digitized estuarine shorelines for 1970, 1984 and 1998. The aerial photographs demonstrate both the human and natural ecologic evolution of the Wades Point site through time. The Pamlico River shoreline is primarily a low sediment bank, where all

FIGURE 8-4-3. *The Wades Point site aerial photograph time slices from 1970, 1984, 1989 and 2000. The rate of shoreline recession is obvious along the Pamlico River shoreline through time. Compare the fairly straight and unmodified shoreline and shore parallel to Pamlico Beach Road in 1970 with the 2000 aerial photograph. Notice the sequence and effect of shoreline hardening upon the erosion process.*

development and shoreline modifications have taken place. The 1970 aerial photograph displays a fairly straight, low sediment bank that was eroding uniformly at the average rate of –3.3 ft/yr except for a couple of small hardened segments that displayed almost negligible recession rates of –0.3 ft/yr (Table 8-4-1). Three additional segments of this shoreline were hardened sometime between 1970 and 1984, which essentially slowed the average erosion rate down to –0.9 ft/yr for the period between 1984 and 1998. However, the three small unprotected low sediment bank segments experienced increased rates of erosion from 1984 to 1998, receding at an average rate of –5.2 ft/yr. Today, these three eroding sites almost intersect the road.

In 1970, the Pungo River shoreline was entirely marsh and eroding at an average rate of –3.4 ft/yr. By 1984, the receding shoreline intersected a pine upland, resulting in a low sediment bank shoreline segment. From 1984 to 1998, the marsh eroded at an average rate of –2.9 ft/yr (Table 8-4-1), while the low sediment bank portion receded at an average rate of –5.2 ft/yr. Notice that the higher portions of land along the shoreline, labeled low sediment bank in the 1998 photo, developed a fairly heavy growth of pine trees between 1970 and 1998. This is seen as dark gray on the 1970 aerial photo, dark green on the 1984, 1989 and 2000 aerials and red color on the 1998 infrared aerial photograph. This demonstrates both shoreline recession and changing patterns of shoreline types through time.

8.4.C. Hickory Point and Pamlico Marine Lab Sites

(Figures 8-4-4, 8-4-5, 8-4-6 and 8-4-7)

Hickory Point and the Pamlico Marine Lab are on the narrow peninsula that extends east between the Pamlico River south shore and South Creek north shore in Beaufort County. Hickory Point is about 3 miles east of the N.C.

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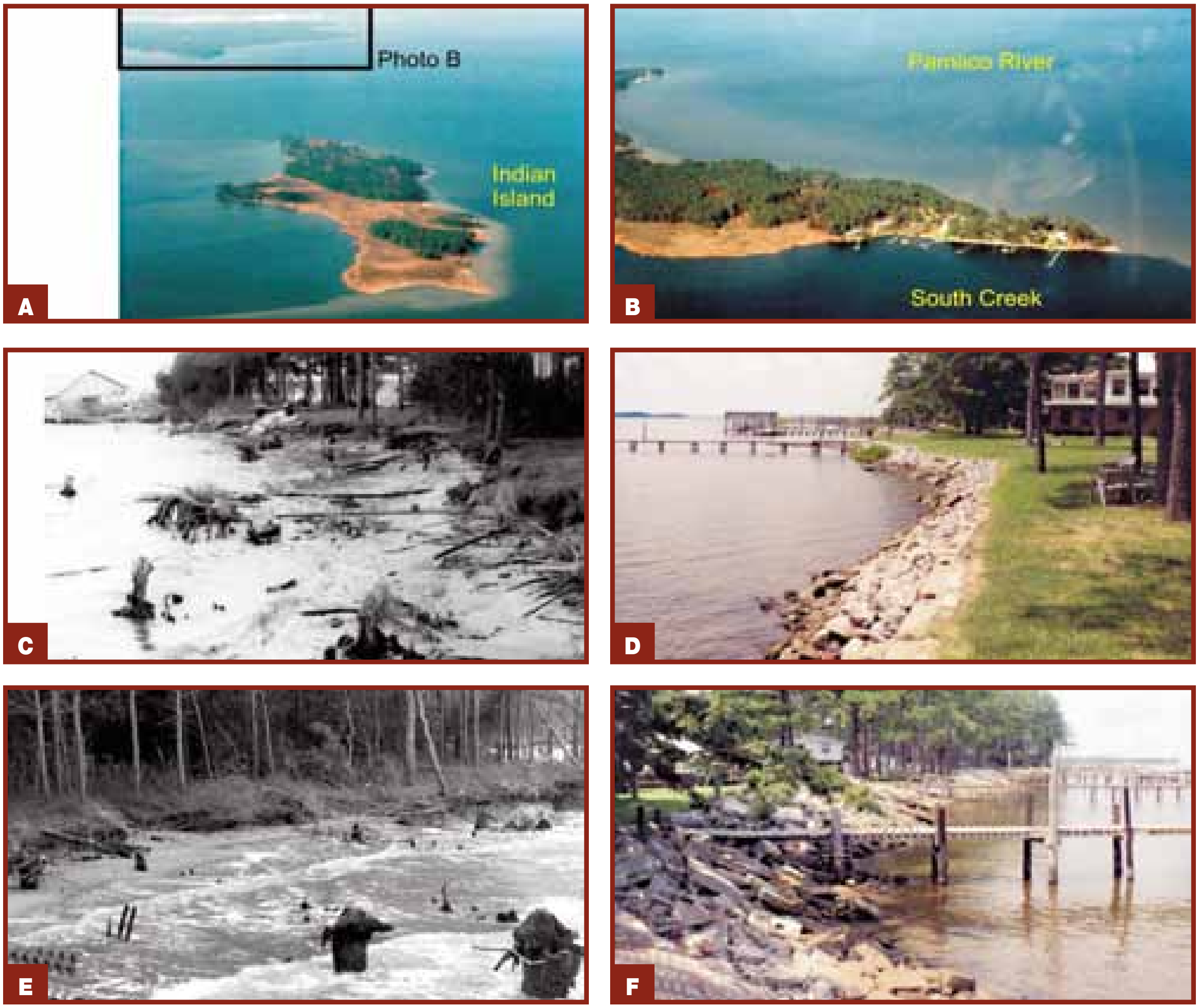

FIGURE 8-4-4. *Photographs of the Hickory Point site.* ***PANEL A.*** *Oblique aerial photograph (December 1991) looking west across Indian Island and Hickory Point with Pamlico River to the right and South Creek to the left. Indian Island and Hickory Point are high areas along the interstream divide between the two water bodies. Indian Island has become separated from Hickory Point by rising sea level and associated shoreline erosion.* ***PANEL B.*** *Oblique aerial photograph (December 1991) of the study area at Hickory Point showing the marsh shoreline in the left foreground, modified low sediment bank shoreline along both sides of the Point, and unmodified low sediment bank shoreline along the wooded, curved coast in the upper left.* ***PANEL C.*** *A 1979 photograph along the South Creek low sediment bank shoreline prior to human modification. Notice the small pine stumps left in the near shore as the shoreline recedes and the beach cottage in the upper left corner that is collapsing into South Creek. Photograph is from Hardaway (1980).* ***PANEL D.*** *A 2001 photograph in approximately the same location as Panel C, showing the human-modified, low sediment bank shoreline. Notice that the rock and rubble revetment along the South Creek shoreline is slightly smaller scale than along the Pamlico River shoreline in Panel F. Photograph is from Murphy (2002).* ***PANEL E.*** *A 1979 photograph of a typical low sediment bank shoreline with a dense growth of small pine trees. The long pine tap root holds the stumps in place in the near-shore as the shoreline recedes. Minor sand derived from the erosion of the Pleistocene, slightly sandy clay bank results in a thin and ephemeral strandplain beach. Photograph is from Hardaway (1980).* ***PANEL F.*** *A 2001 photograph looking west along the human-modified, low sediment bank shoreline of the Pamlico River. Photograph is from Murphy (2002).*

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Department of Transportation ferry terminal at Aurora. The Hickory Point site is at the end of N.C. Hwy. 306. Whereas, the Pamlico Marine Lab site is about 2.4 miles east of the ferry terminal down an access road south of N.C. Hwy. 306.

The Hickory Point peninsula used to be connected to Indian Island. They are part of the interstream divide between the Pamlico River and South Creek. However, rising sea level and long-term shoreline erosion processes have systematically eroded the upland, resulting in a shallow, underwater ridge that extends from Hickory Point east to Indian Island. Today, both Indian Island and Hickory Point continue to slowly disappear due to the systematic erosion of their shorelines.

The Hickory Point site is divided into three shoreline segments. Both sides of the outer portion of the point, Segment 2, consist of severely modified low sediment banks. To the west along the Pamlico River is Segment 1, a natural low sediment bank. To the west along South Creek is Segment 3, an extensive platform marsh. The natural low sediment bank along Segment 1 is characterized by a 2- to 3-foot-high erosional scarp, abundant eroded stumps and roots occurring along the shoreline as well as downed shrubs and logs on the shoreface. The bank is composed of a tight clayey sand substrate that continues onto the estuarine floor. A thin and narrow, 5- to 20-feet-wide strandplain beach occurs along most of the shoreline. The low sediment banks within Segment 2 are mostly modified with little to no strandplain beach. Segment 3 marsh consists dominantly of *Juncus roemerianus*, with a fringe of *Spartina cynosuroides* and *Phragmites australis* forming an inner zone in front of the transition zone vegetation.

Development at Hickory Point began many decades ago and consisted initially of small, low-cost beach cottages. Shoreline protection measures consisted of cement debris, broken bricks, cinder blocks and miscellaneous junk. Through time, storms repeatedly tore up these makeshift shoreline protection structures, as well as many of the small cottages. The size

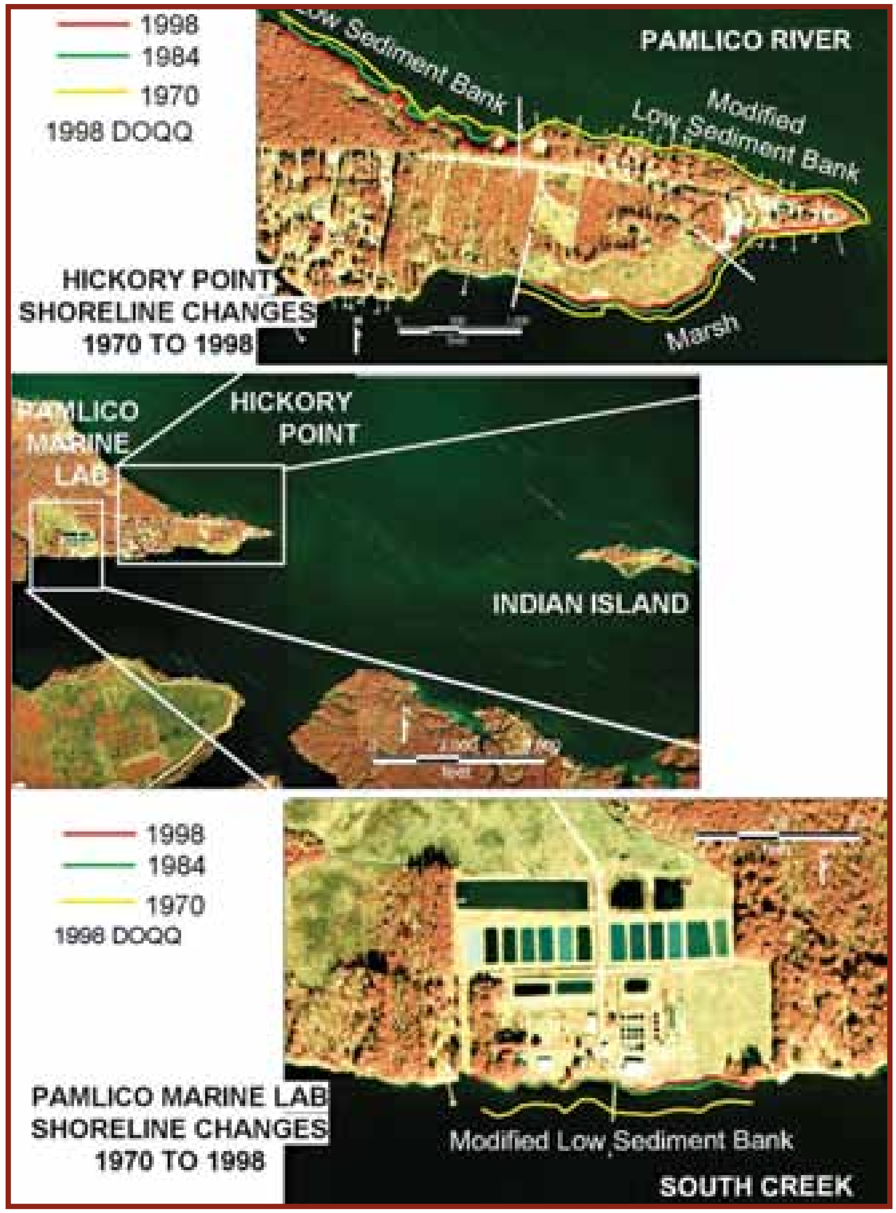

FIGURE 8-4-5. *The Hickory Point and Pamlico Marine Lab sites 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1970, 1984, and 1998.*

and value of replacement dwellings have increased through time, as well as an increased effort to protect the shoreline with wooden bulkheads, rock revetments and groins.

The 1998 DOQQ (Fig. 8-4-5) shows the location of digitized estuarine shorelines for 1970, 1984, and 1998. Between 1970 and 1998, the natural low-sediment bank eroded at an average rate of –4.3 ft/yr with a range from –2.2 to –6.6 ft/yr (Table 8-4-1). The eastern and highly modified portion along both the Pamlico River and South Creek shorelines eroded during

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the same time period at an average rate of –1.4 ft/yr. Between 1970 and 1984, dumped rubble along the shoreline slightly moderated the average erosion rates to –2.4 ft/yr. However, since 1984 many shoreline structures were either rebuilt or upgraded with an overall decrease in the average erosion rate to –0.4 ft/yr. No significant difference occurred in the erosion rates between the north- and south-facing, modified low sediment bank shorelines. The Segment 3 marsh platform along the western portion of South Creek eroded at an average rate of –3.7 ft/yr between 1970 and 1998.

Pamlico Marine Lab is located on South Creek, about 1.2 miles west of the point at Hickory Point. The entire shoreline is a low sediment bank that ranges from 3 to 4 feet high, with abundant tree stumps and root masses. The vertical bank is composed of a lower, very clayey sand overlain by an upper one foot of sandy soil. The erosion of this upper unit supplied sand for a strandplain beach that existed prior to shoreline modification. Due to high erosion rates, the shoreline was hardened with rock riprap, starting in about 1989.

The 1998 DOQQ (Fig. 8-4-5) shows the location of digitized estuarine shorelines for 1970, 1984 and 1998. Prior to modification (from 1970 to 1989), the entire natural low sediment bank shoreline in front of Pamlico

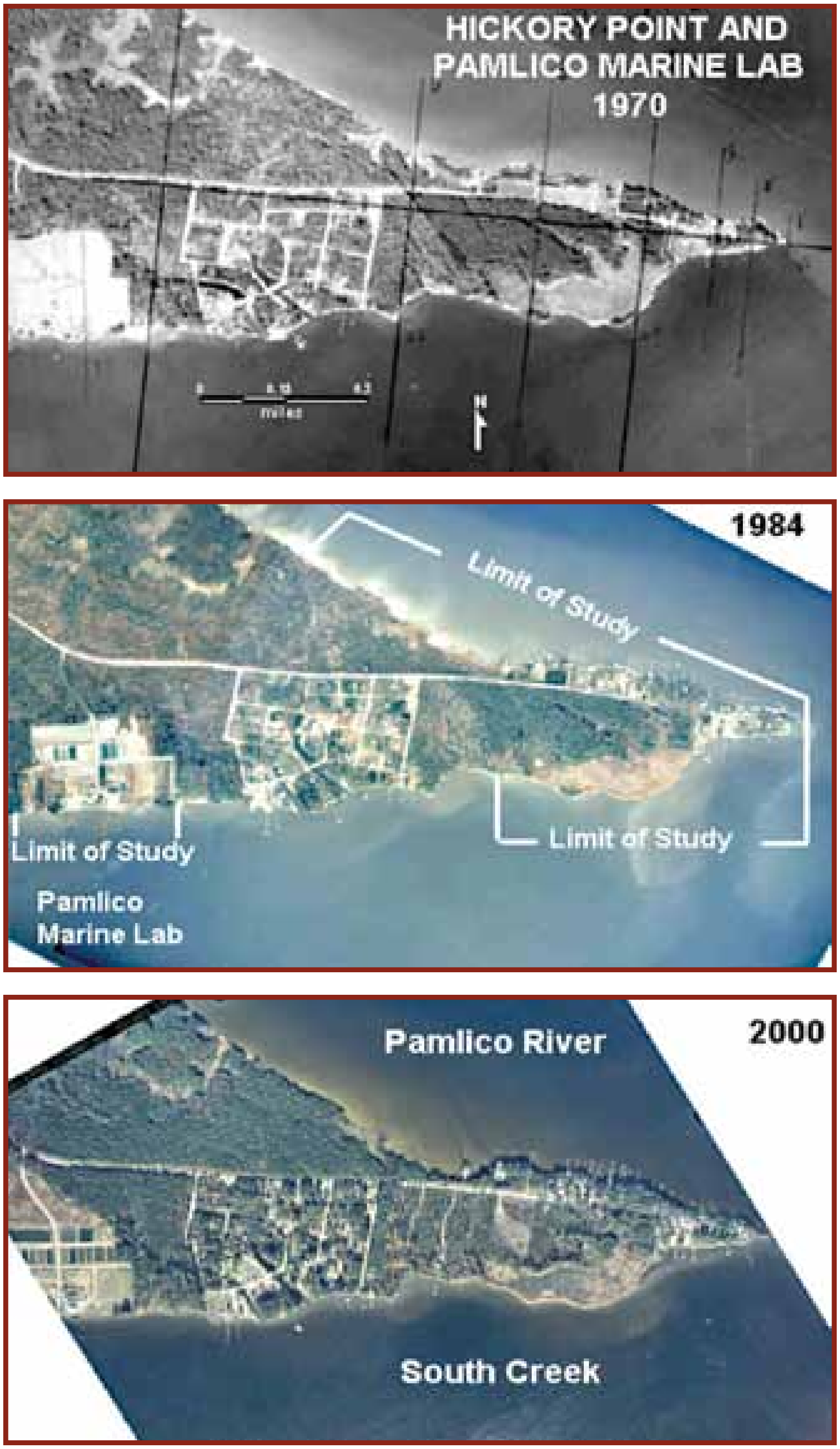

FIGURE 8-4-6. *The Hickory Point and Pamlico Marine Lab site aerial photograph time slices for 1970, 1984 and 2000. The marsh shoreline on the South Creek side of Hickory Point has two small clumps of upland trees (dark zones) forming small headlands on the south side of the marsh in the 1970 aerial photograph. In the 2000 photograph, these two areas of upland vegetation are completely eroded away, and the shoreline is beginning to straighten out in response to the erosion processes. Notice the increased rate of shoreline hardening from 1970 to 1984, in concert with a significant recession of the unmodified low sediment bank shoreline west of Hickory Point along the Pamlico River shore (see Fig. 8-4-5).*

FIGURE 8-4-7. *Photographs of the Pamlico Marine Lab site.* ***PANELS A and B.*** *March 1978 close-up photographs of the unmodified and eroding, low sediment bank shoreline of the Pamlico Marine Lab site. Panel A is on the western side, and Panel B is on the eastern side of the lab. Notice the large trees lying along the bank and the stumps in the near shore, reflecting the receding shoreline. The area has been generally cleared for the lab, leaving only a few trees along the bank.* ***PANELS C and D.*** *August 2001 photographs of the modified low sediment bank shorelines of the Pamlico Marine Lab site. Panel C is on the western side, and Panel D is on the eastern side of the lab. The rock revetment has temporarily stopped the shoreline recession. Photographs are from the pier by M. Murphy.*

Marine Lab receded at an average rate of –4.9 ft/yr. During the period from 1989 to 1998, the stabilized western 860 feet showed negligible shoreline erosion. However, the nonhardened eastern 570 feet continued to recede at an average rate of –2.5 ft/yr. As a result of this erosion at the east end, a new section of rock riprap was added along that shoreline in 1999. There has been no further shoreline erosion along the modified shoreline, but the strandplain beach has disappeared.

8.4.D. Bayview Site

(Figures 8-4-8 and 8-4-9)

The Bayview site is in Beaufort County along the eastern shore of outer Bath Creek near the confluence with the Pamlico River estuary. The site is east of Bath and south off of N.C. Hwy. 92 about 1.6 miles at the southwest end of Breezy Shore Road and northwest end of Bayview Road, respectively. At the end of the paved road, walk northwest through the woods to the shore and continue north past a marsh and low sediment bank to the high sediment bank shoreline.

According to Hardaway (1980), this shoreline is a mixed low and high sediment bank, with the low bank in front of the high bank everywhere except in the northern segment. Here the low bank disappears, and the high bank intersects the shoreline. The high bank rises about 10 to 15 feet above mean sea level with a hardwood forest on top. The high bank consists of a lower 7-foot-thick unit of interbedded clean sands and thin tight clay laminae, overlain by a 5-foot thick unit of iron-stained sandy clay, and a

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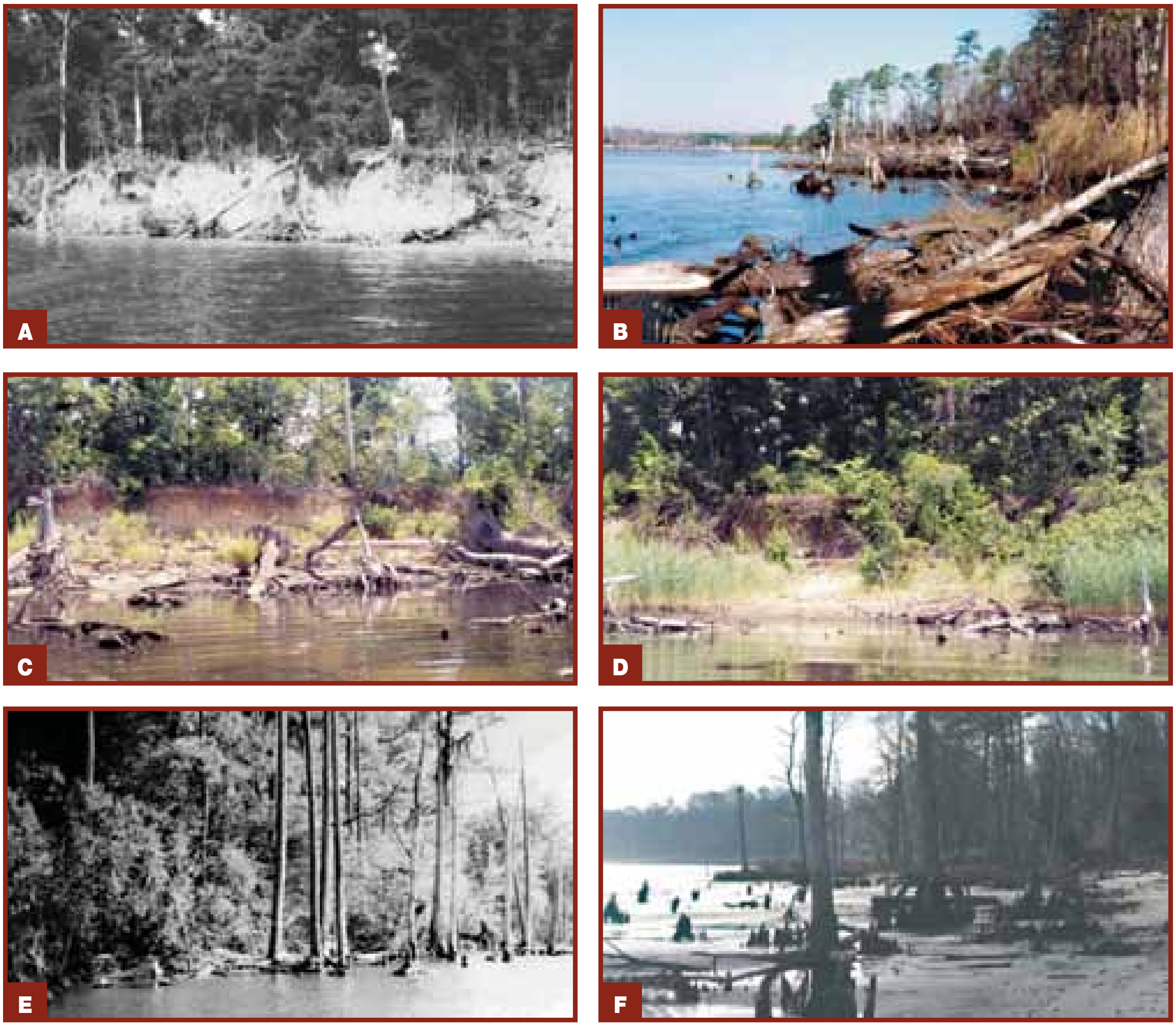

FIGURE 8-4-8. *Photographs of the Bayview site.* ***PANEL A.*** *A September 1979 photograph looking at the eroding high sediment bank shoreline on the north side of the study site along outer Bath Creek. Notice the small strandplain beach due to the low sand content in the eroding bank, the overhanging modern root mass and tree roots, and the slumped trees. Photograph is from Hardaway (1980).* ***PANEL B.*** *A January 2001 photograph looking north along the same eroding high sediment bank as Panel A. It appears that there are far more stumps in the water and tree debris along the shoreline.* ***PANEL C.*** *An August 2001 photograph looking at the last remnants of the low sediment bank in front of an eroding high sediment bank shoreline in the middle of the study site. Photograph is by M. Murphy.* ***PANEL D.*** *An August 2001 close-up view of the eroding low sediment bank shoreline, with a strandplain beach and fringing marsh in front of a stable high sediment bank with a heavy vegetative cover. Photograph is by M. Murphy.* ***PANEL E.*** *A September 1979 photograph looking south at the low sediment bank shoreline on the south side of the study site along outer Bath Creek. Notice the large number of trees standing in the near shore area with exposed roots. Photograph is from Hardaway (1980).* ***PANEL F.*** *A 2003 typical eroding low sediment bank along the open Pamlico River that is experiencing a more severe state of shoreline recession than the shoreline in Panel E. The sand strandplain beach is only a few inches thick and is on top of a Pleistocene, tight sandy clay substrate.*

1- to 2-foot-thick upper unit of sandy soil (Hardaway, 1980). The abundance of sand in the high banks results in a major strandplain beach littered with fallen trees and logs. The low bank rises 2 to 4 feet above mean sea level with a dense growth of shrubs and pine trees on top. It consists of 1 to 2 feet of dense clayey sand overlain by 1 to 2 feet of a sandy soil horizon. The shore is littered with shrubby debris, logs and stumps.

The 1998 DOQQ (Fig. 8-4-9) shows the location of digitized 1970 and 1998 estuarine shorelines. The long-term average erosion rate developed by the present study for the low sediment bank is –1.4 ft/yr, and for the high sediment bank is –0.2 ft/yr. The low erosion rates are attributed to the semiprotected character of the site within the mouth of Bath Creek, resulting in a small southwest fetch. In addition, abundant tree and stump litter occurs on the strandplain beach, and the nearshore area that tends to break down incoming wave energy.

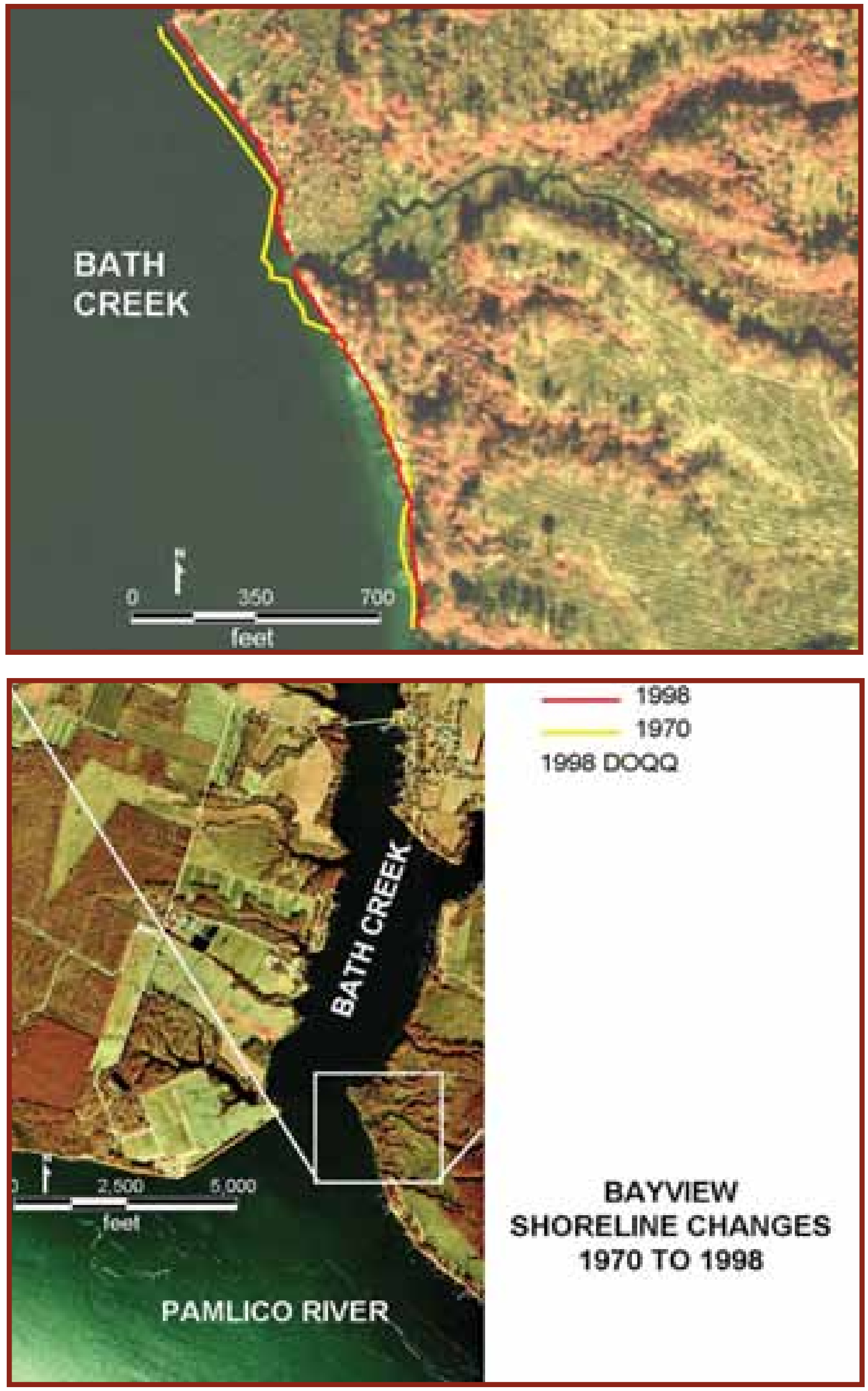

FIGURE 8-4-9. *The Bayview site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1970 and 1998. Notice the small drainage system that flows west off the upland to form a small cypress headland in the middle of the study area.*

8.4.E. Camp Leach Site

(Figures 8-4-10 and 8-4-11)

Camp Leach is located in Beaufort County, along the northern shore of the inner Pamlico River and immediately east and across an unnamed creek from Goose Creek State Park. It is about 3.8 miles south along the Camp Leach Road from Midway Crossroads on U.S. Hwy. 64.

Throughout the time, this site was occupied by Camp Leach, and the shoreline consisted of a narrow marsh with abundant cypress trees in front of a natural low-sediment bank. The remnant marsh occurring along much of the shoreline was quite irregular, about 3 to 15 feet wide, and composed of *Juncus roemerianus* growing on a peat substrate up to 2 feet thick. The presence of a marsh, associated peat and cypress suggest that the stream valley occurring along the western boundary formerly flowed southeast and east in front of Camp Leach. A major section of marsh shoreline still exists across most of the stream mouth on the western side of the site.

The marsh pinched out landward onto the upland sandy surface of the forested low

FIGURE 8-4-10. *Photographs of the Camp Leach site.* ***PANEL A****. A July 1977 photograph looking east along the undeveloped eastern portion of the study site on the Pamlico River north shore. The low sediment bank occurs behind a narrow zone of dense* Juncus roemerianus *and cypress growing on a peat substrate up to 2 feet thick. Photo is from Hardaway (1980).* ***PANEL B****. A January 1977 photograph looking west along a portion of the study site utilized by Camp Leach. Notice the* Juncus roemerianus *headlands with small coves containing thin strandplain beaches lapping up onto the low sediment banks.* ***PANEL C****. A January 1977 photograph of the low sediment bank shoreline in front of Camp Leach. Notice that the root system of the large shoreline trees have been severely exposed by the slow erosion processes. No marsh grass occurs within this high-use area. However, there are local strandplain beaches scattered in the small coves along the shoreline.* ***PANEL D****. A January 2001 photograph in approximately the same area as Panel C. The low sediment bank in this development has now been extensively bulkheaded with the elimination of marsh headlands and shoreline trees. Notice that no strandplain beaches exist in front of bulkheads.*

sediment bank. Within high-use areas of the camp, the marsh was largely gone, and the low sediment bank and associated trees were exposed to the water with local strandplain beaches. The low sediment bank consists of 1 to 2 feet of sandy soil overlying a clayey sand substrate. The housing development began sometime between 1984 and 1995, after much of the marsh had eroded away. With development came clearing of remaining vegetation, extensive bulkheading and loss of strandplain beaches in front of the bulkheads.

The 1998 DOQQ (Fig. 8-4-11) shows the location of digitized estuarine shorelines for 1970 and 1998. Notice that the 1970 purple shoreline almost coincides with the red 1998 shoreline. Since development and bulkheading did not take place until sometime between 1984 and 1995, whatever shoreline was eroded during the time prior to bulkheading was gained back through the bulkheading process. The average erosion rates in Table 8-4-1 represent only the net change between 1970 and 1998. Consequently, the western marsh across the stream mouth has eroded at about –1.3 ft/yr between 1970 and 1998, while the middle segment shows no net change. The eastern low

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sediment bank/modified low sediment bank displays a –0.6 ft/yr net loss over the same time period. Prior to modification, the Camp Leach shoreline was characterized by minor rates of local shoreline erosion that were storm dependent. In response to a major storm in 1978, Hardaway (1980) obtained a –2.3 ft/yr average erosion rate for this low sediment bank shoreline.

8.4.F. Mauls Point Site

(Figures 8-4-12, 8-4-13 and 8-4-14)

Mauls Point is located in Beaufort County, along the south shore of the inner Pamlico River estuary. It is a southwest-northeast oriented bluff shoreline situated at the northeastern end of Blounts Bay and about 5.4 miles north of N.C. Hwy. 33 at Coxs Crossroads. This entire northwest-facing Blounts Bay shoreline consists of bluff sediment banks that are occasionally dissected by small stream valleys. Within these valleys are narrow shoreline segments of low sediment banks and floodplain swamp forests that form small cypress headlands. Two such cypress headlands occur at either end of the site. On the southwestern part of the site, a small floodplain delta forms a sediment bank shoreline. This low sediment bank has been bulkheaded with an older beach cottage located on the delta lobe. The northeastern stream valley runs generally parallel to the northeast-facing shore, resulting in an extensive cypress fringe and headland located in front of the highly vegetated bluff to the southwest. In 1977, this cypress headland consisted of very dense swampforest vegetation. However, by 1998 much of this swamp forest had been either closed or severely thinned.

The photographs show the bluff before development, as well as the severely modified shoreline during and after development. The 30-foot-high bluff is a Pleistocene sequence of

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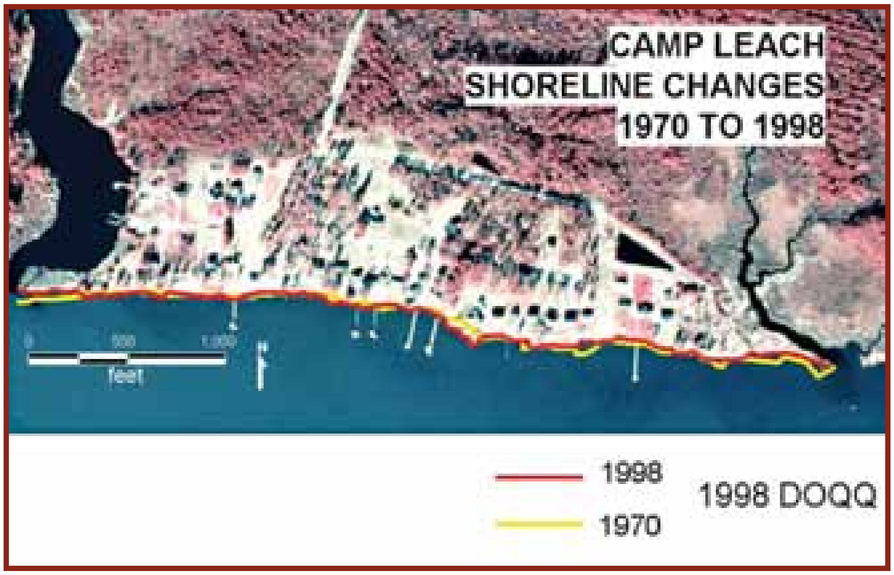

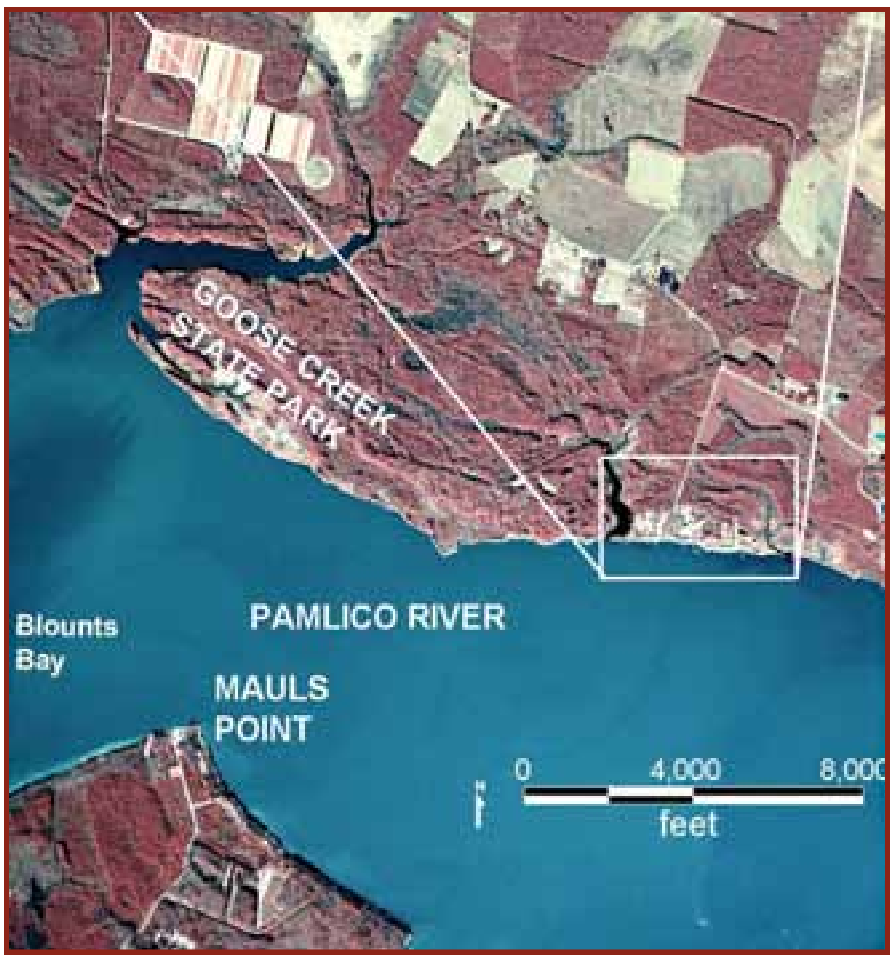

FIGURE 8-4-11. *The Camp Leach site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1970 and 1998.*

FIGURE 8-4-12. *Photographs of the Mauls Point site.* ***PANEL A****. A July 1977 photograph looking southwest along the unmodified bluff at Mauls Point. Notice the overhanging modern root mass, the tree debris along the shoreline, and the strandplain beach in front of the wave-cut bluff. Photograph is from Hardaway (1980).* ***PANEL B****. An August 1998 photograph of the bulldozed and bulkheaded bluff that occurs in Panel A. A portion of the modified bluff has been seeded and covered with landscape fabric.* ***PANEL C****. An August 2001 close-up photograph of the modified bluff pictured in both Panels A and B. Notice the lack of a strandplain beach in front of the steel bulkhead and rock revetment. Photograph is from Murphy (2002).* ***PANEL D****. A January 2003 photograph of the modified cypress headland that occurs off of a small creek dissecting the upland and associated bluff on the southwest side of the study site (see Fig. 8-4-14). The local occurrence of sand in front of the bulkhead that formed in response to a bulkhead failure and associated gullying just below the bottom of the photograph.* ***PANEL E****. A 1979 photograph of the swampforest shoreline along the cypress headland that occurs at Mauls Point, on the northeast side of the study site. Photograph is by S. Hardaway.* ***PANEL F****. An August 2001 photograph of the same location as Panel E. The rock is the northeast end of the revetment in Panel C. Notice how the swamp forest has been thinned and the occurrence of a small strandplain beach. Photograph is from Murphy (2002).*

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interbedded gray clay and crossbedded quartz sand with several zones of iron oxide cemented sandstone. The bluff base is undercut during high storm tides, causing the unstable upper blocks to slump onto the beach. With time, the slump blocks are reworked by wave energy into strandplain beaches up to 25 feet wide. Abundant trees and shrubbery debris from the slump blocks end up on the beach and act as natural breakwaters and groins that trap and hold sand. Longshore currents transport some of the abundant sand supplies to the northeast, producing a major sand berm that buries the outer cypress and pine and develops a major spit at the Point. Prior to development, mixed hardwood and pine forests dominated the bluff top.

A portion of the bluff between the two cypress headlands was initially bulldozed prior to the Hardaway study (1980) with no vegetation planted on the raw bank. Consequently, the bank severely eroded and gullied. Subsequently, the entire bluff within the site was bulldozed to produce a grassed ramp with multiple rock, wood and steel bulkheads. The bulldozing processes put a lot of sediment into the nearshore area with redevelopment of a major strandplain beach. The strandplain beach is slowly being lost due to stabilization of the bluff, except where bulkheads temporarily fail. Local bank erosion results in deposition of small sediment lobes in front of the bulkhead.

The 1998 DOQQ (Fig. 8-4-13) shows the location of digitized estuarine shorelines for the period between 1970 and 1998. This site was a natural bluff shoreline for the period from 1970 to 1984 with an average rate of shoreline recession of –2.9 ft/yr (Table 8-4-1) and a range in erosion rates from –0.6 to –3.1 ft/yr. The period from 1984 to 1998 represented mixed conditions when the natural bluff was severely modified by bulldozing and bulkheading. This resulted in a slight net shoreline loss for this period of –0.2 ft/yr with an average range from –2.6 to +2.6 ft/yr (Table 8-4-1). Due to the amount of sediment bulldozed onto the bluff shoreline, the adjacent modified low sediment bank to the southwest displayed average accretion rates of +0.8 ft/yr.

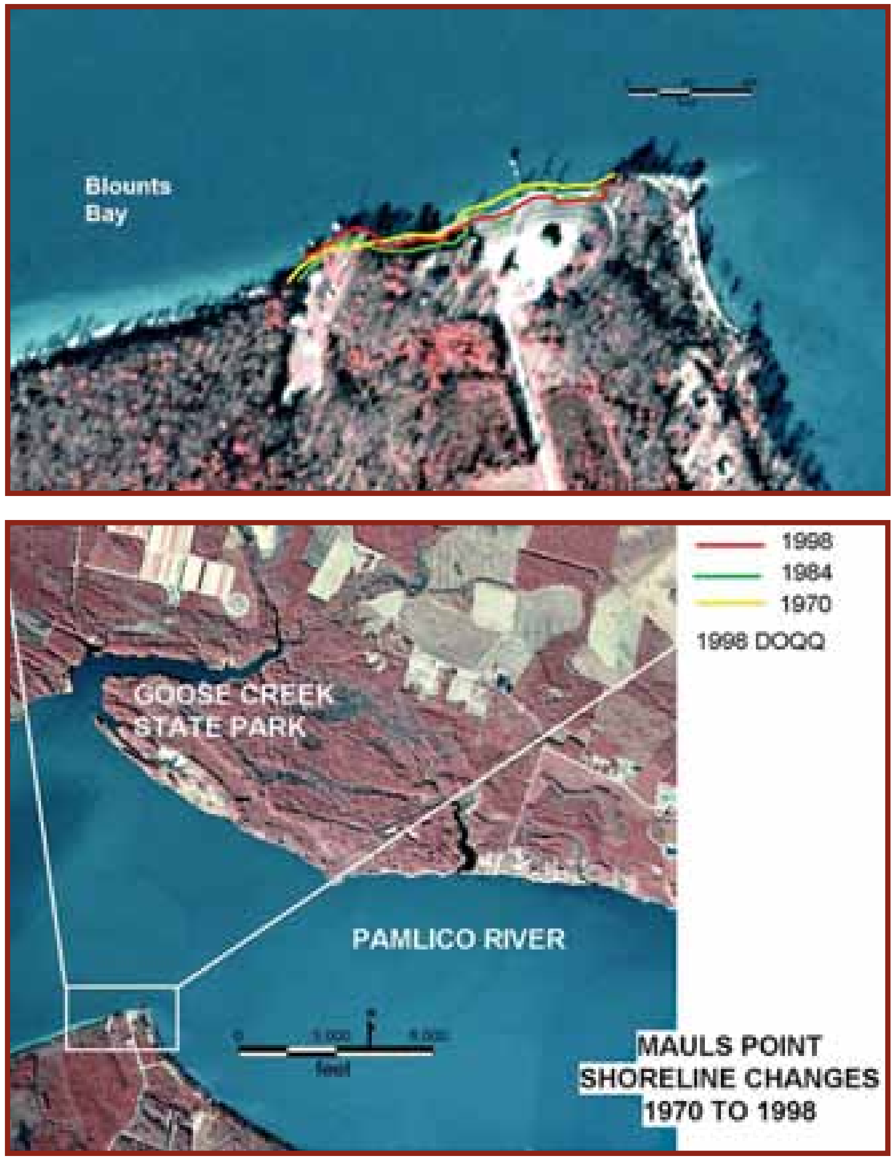

FIGURE 8-4-13. *The Mauls Point site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1970, 1984, and 1998.*

8.4.G. Bay Hills Site

(Figures 8-4-15, 8-4-16 and 8-4-17)

The Bay Hills site is located on the south shore of Chocowinity Bay at the western end of the inner Pamlico River estuary in Beaufort County. The site occurs one mile north of Old Blounts Creek Road at the end of Bay Hills Drive and River Hills Road. The area extends for about 2,440 feet to the west and 1,300 feet to the east of Bay Hills Drive. About 2,990 feet of this shoreline is generally a bluff that has been extensively developed and modified by bulldozing and bulkheading. Whereas, 750 feet of bluff shoreline located east of the developed bluff remains in its natural condition. The 1970 aerial photograph shows a small stream

FIGURE 8-4-14. *The Mauls Point site aerial photograph time slices from 1984 and 2000. Mauls Point Road runs north along an interstream high between two small drainages that parallel the road. The drainage on the northeast side of the road has been intersected by the Pamlico River, creating a wide swampforest shoreline along the Pamlico River side and forms a cypress headland at Mauls Point (Fig. 8-4-12, Panels E and F). The bluff shoreline occurs where Blounts Bay intersects the interstream divide at the end of the road (Fig. 8-4-12, Panels A, B, and C). Another small swampforest shoreline forms a cypress headland that extends into the water where the drainage on the southwest side of the road flows into Blounts Bay (Fig. 8-4-12, Panel D).*

dissecting the bluff and flowing into Chocowinity Bay west of Bay Hills Drive. A nice example of a cypress headland occurs where this stream floodplain enters the bay.

The natural bluff rises 25 to 30 feet above mean sea level with a very tight blue Pleistocene clay cropping out in the lower 15 feet of the bluff. The basal clay grades upward into a 5- to 10-foot-thick unit of muddy fine sand and an upper 7-foot-thick unit of iron-stained clayey sand and soil. The vegetative cover above the bluff is hardwood forest. The upper sandy portion of the natural bluff slumps onto the beach and is reworked by waves to produce a 20- to 30-foot-wide strandplain beach littered with logs and stumps. The shoreline itself is eroded into the lower clay unit, forming an erosional clay platform that continues riverward under the strandplain beach and onto the estuarine floor.

The entire shoreline within this portion of Chocowinity Bay was undeveloped in 1970. The developed portion of Bay Hills was initially bulldozed in 1975 to a 1:1 sloped ramp with a low sediment bank shoreline located in front of the bluff slope (Hardaway, 1980). The graded slope was vegetated, but seriously eroded until it was stabilized in 1978. The resulting low sediment bank was pushed riverward about 10 to 20 feet further than along the natural bluff shoreline. Today, most of this shoreline has been either bulkheaded or armored with rock revetments.

The 1998 DOQQ (Fig. 8-4-16) shows the location of digitized shorelines for 1970 and 1998. Comparison of these shorelines suggest that the amount of change is < 1.0 ft/yr. This low erosion rate occurs within the error associated with the analytical procedures. The larger error bar at this site results from analyzing photographs taken at different times of day and along different flight paths relative to the shadow created by the north-facing bluff, as well as the poor quality of the older aerial photographs. Consequently, the errors associated with georeferencing, digitizing and measuring the individual photographs are

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Short-Term Estuarine Shoreline Evolution in the North Carolina Coastal System

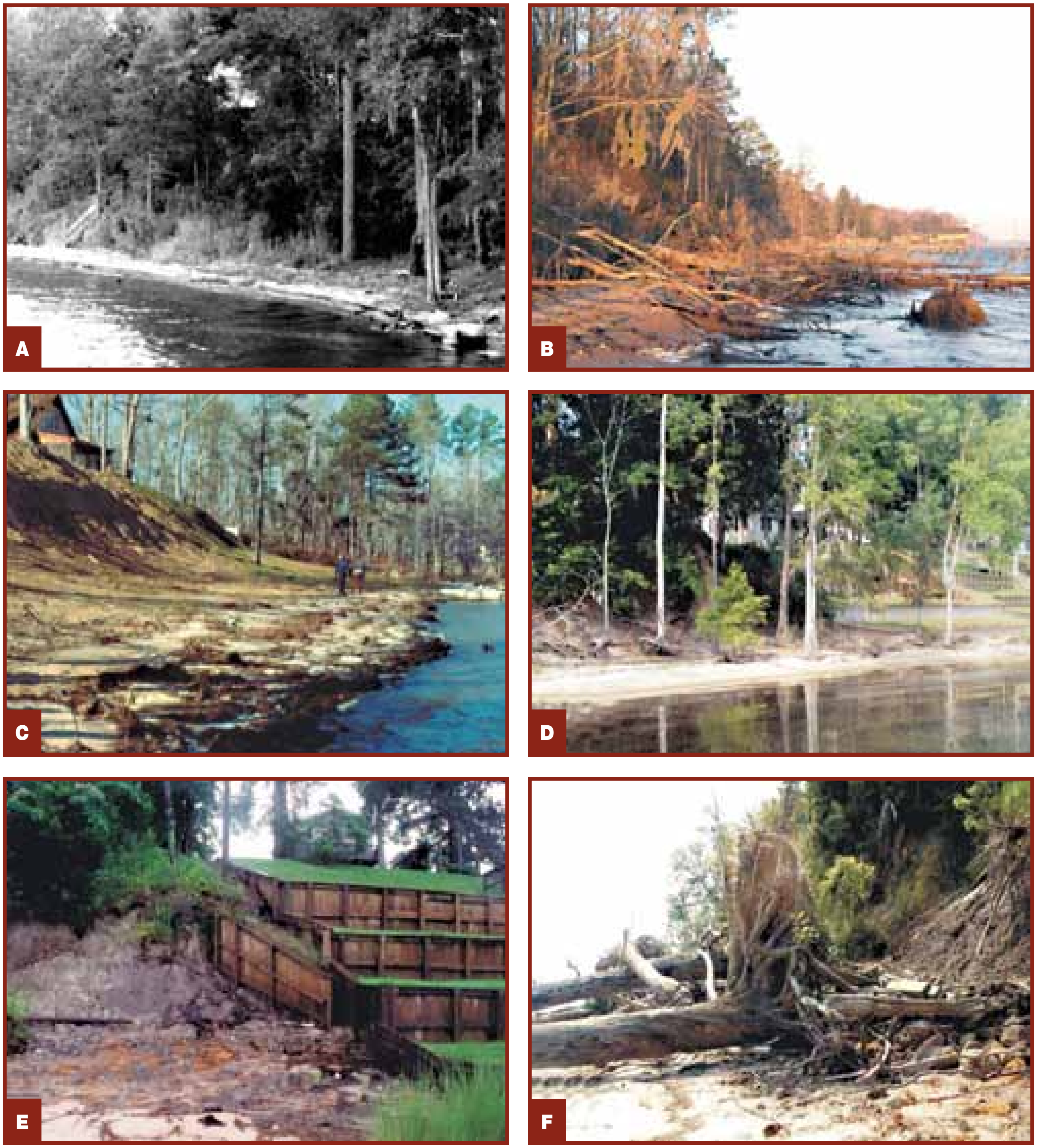

FIGURE 8-4-15. *(PAGE 138) Photographs of the Bay Hills site.* ***PANEL A.*** *A July 1977 photograph looking east along a highly vegetated, natural bluff shoreline. The lack of an erosional cut-bank, slump blocks and tree and shrub debris indicate that this bluff is not eroding on a year-to-year scale. This moderately stable bluff shoreline has a modest slope that can develop a significant vegetative cover to protect the bluff through small storms and the short term. Photograph is by S. Hardaway.* ***PANEL B.*** *A January 2003 photograph along the same portion of Bay Hills that locally displays steeper erosional bluff segments and wider strandplain beaches with abundant tree debris. Portions of this shoreline were destabilized by a series of very high storm tides (up to +10 feet above mean sea level) that impacted the upper Pamlico River area between 1996 and 1999. Thus, normally stable shorelines in semiprotected areas with small fetches do erode. This happens during extreme storm events when the shoreline recedes in large pulses.* ***PANELS C, D and E.*** *Panel C is a January 1977 photograph looking west along a modified bluff shoreline. The bluff was bulldozed in 1975 to form a 1:1 sloped ramp behind a low sediment bank shoreline. Both the bulldozed bluff and low sediment bank have, in most cases, been extensively bulkheaded as demonstrated in the 2001 photographs in Panels D and E. Much of this extreme bulkheading was done since the high storm tides of the 1996-1999 hurricanes destabilized and severely eroded the bluffs. Notice that the natural bluff shoreline in Panel D still has a strandplain beach. Photograph in Panel D is from Murphy (2002), and Panel E is by Murphy.* ***PANELS E and F.*** *Panel E is a close-up view of the Pleistocene, tight blue clay that crops out along the lower 15 feet of the bluff shoreline. An easily erodable, unconsolidated sand bed overlies the clay bed. The former readily slumps onto the beach carrying the vegetative cover with it, as demonstrated in Panel F. This stratigraphic combination produces bluffs with an overall lower slope that can generally develop more stable vegetative covers. Panel F is from Murphy (2002).*

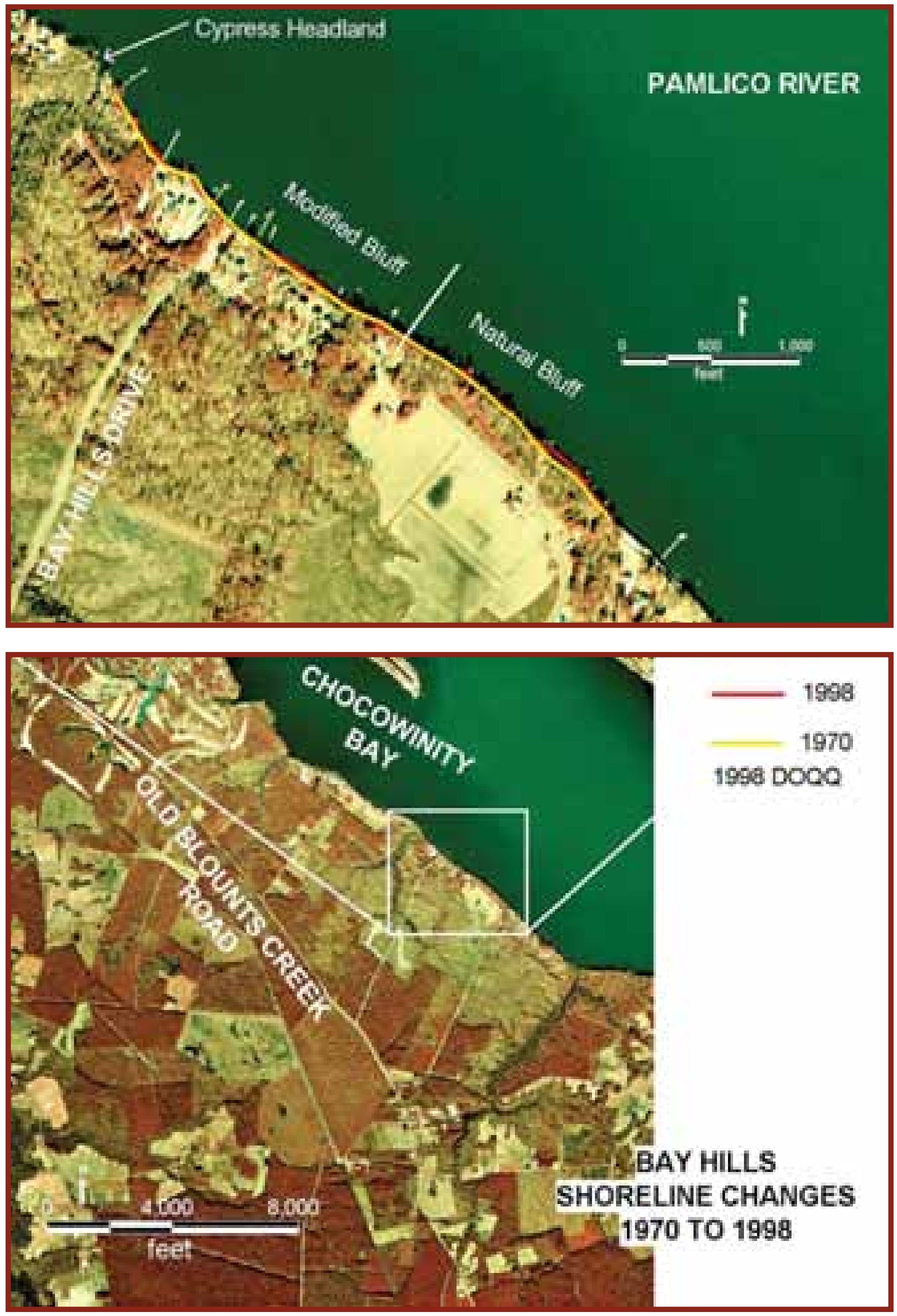

FIGURE 8-4-16. *The Bay Hills site 1998 Digital Orthophoto Quarter Quadrangle (DOQQ) with digitized shorelines for 1970 and 1998.*

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greater than the erosion rate at this site. Long-term shoreline erosion is taking place along the natural bluff in direct response to major storm events, such as the series of hurricanes during the late 1990s. However, most structures along the modified shorelines were quickly rebuilt to their prestorm locations.

The overall low erosion rates at Bay Hills result from several major factors. First, the semiprotected character of the south shore of Chocowinity Bay results in fetches less than 4 miles in all directions. Second, the presence of a thick, tight clay bed along the bluff base protects the bluff from direct wave erosion by small storms. Third, through time, the shoreline has eroded a shallow water, nearshore platform into the clay bed that breaks incoming wave energy, except during the high storm tides associated with major hurricanes. Fourth, the bluff consists of a dense clay bed overlain by a sand bed. This geometry results in preliminary retreat of the upper sandy bluff, creating a sloped surface that develops a significant vegetative cover. The lower bluff, composed of dense clay, tends to resist erosion and generally holds the overall bank in place.

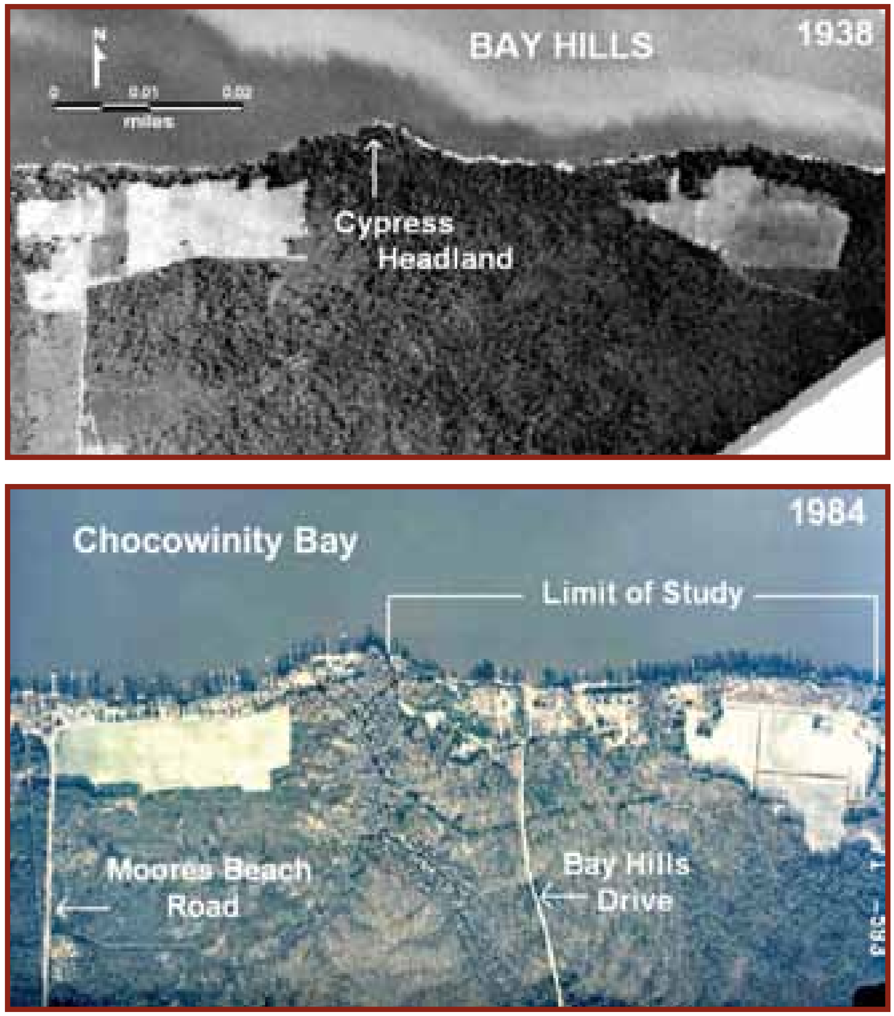

FIGURE 8-4-17. *The Bay Hills site aerial photograph time slices from 1938 and 1984. Compare the absence of waterfront cottages in the 1938 aerial photograph with the high density of homes and associated piers extending into Chocowinity Bay in the 1984 photograph. Notice the small drainage system just west of Bay Hills Drive in the 1984 photo. The cypress tress in the floodplain swamp forest form a cypress headland where this stream enters Chocowinity Bay. Cypress headlands are more resistant to shoreline erosion than adjacent sediment banks and therefore, protrude out into the bay, while the sediment banks erode slightly faster and form shallow coves.*

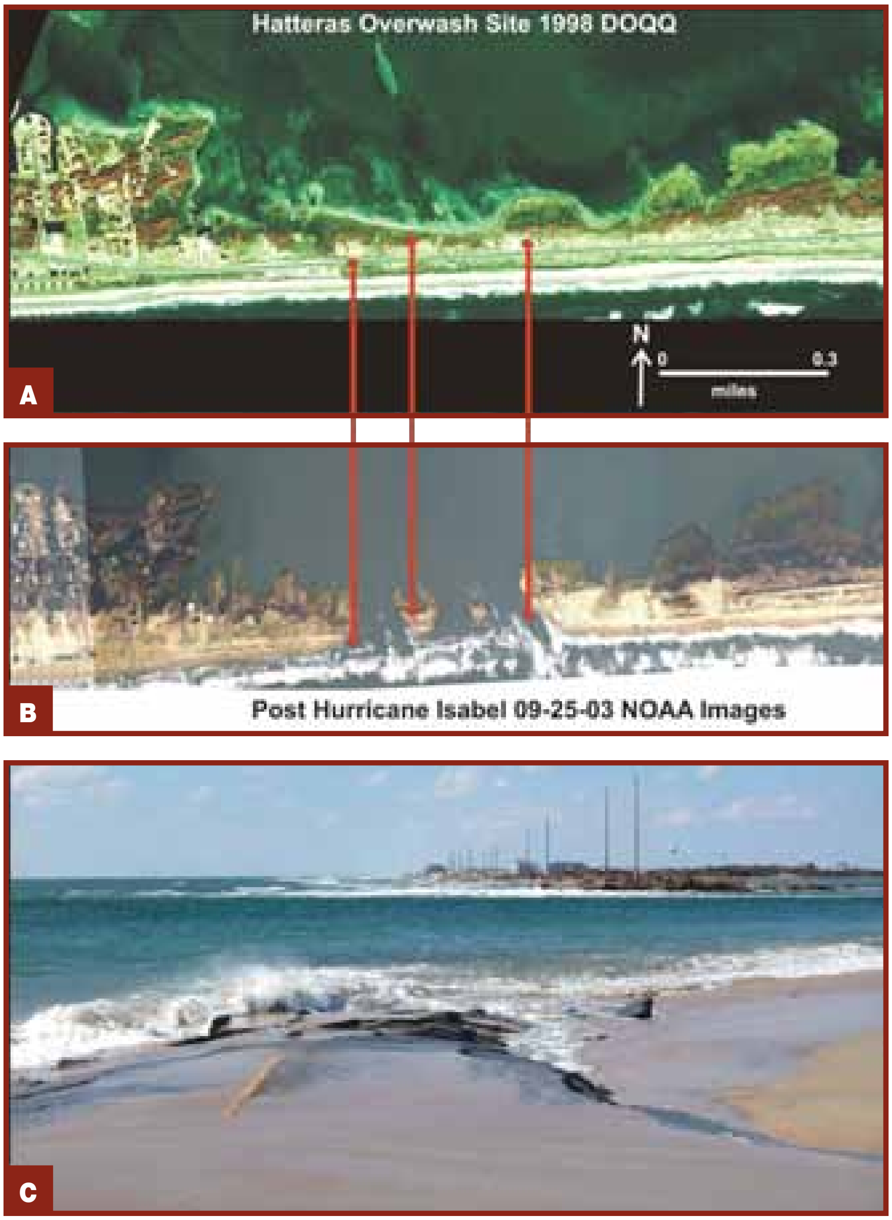

FIGURE 8-4-18. ***PANEL A.*** *A 1998 DOQQ shows the location of the Hatteras Overwash site and location of the future Isabel Inlet (red stars). The inlet opened in the western portion of the shoreline erosion site (Figure 8-2-3) and through the narrowest island segment. After the inlet opened, it eroded eastward into the edge of the back-barrier marsh platform as indicated by the easternmost red line.* ***PANEL B.*** *Post-Hurricane Isabel aerial photograph taken on 9/25/03, 7 days after the Inlet formed, by the U.S. National Oceanographic and Atmospheric Administration.* ***PANEL C.*** *Photograph of Isabel Inlet taken on 9/29/03 shows NC Hwy. 12 "going-to-sea" with Hatteras Village in the distance.*

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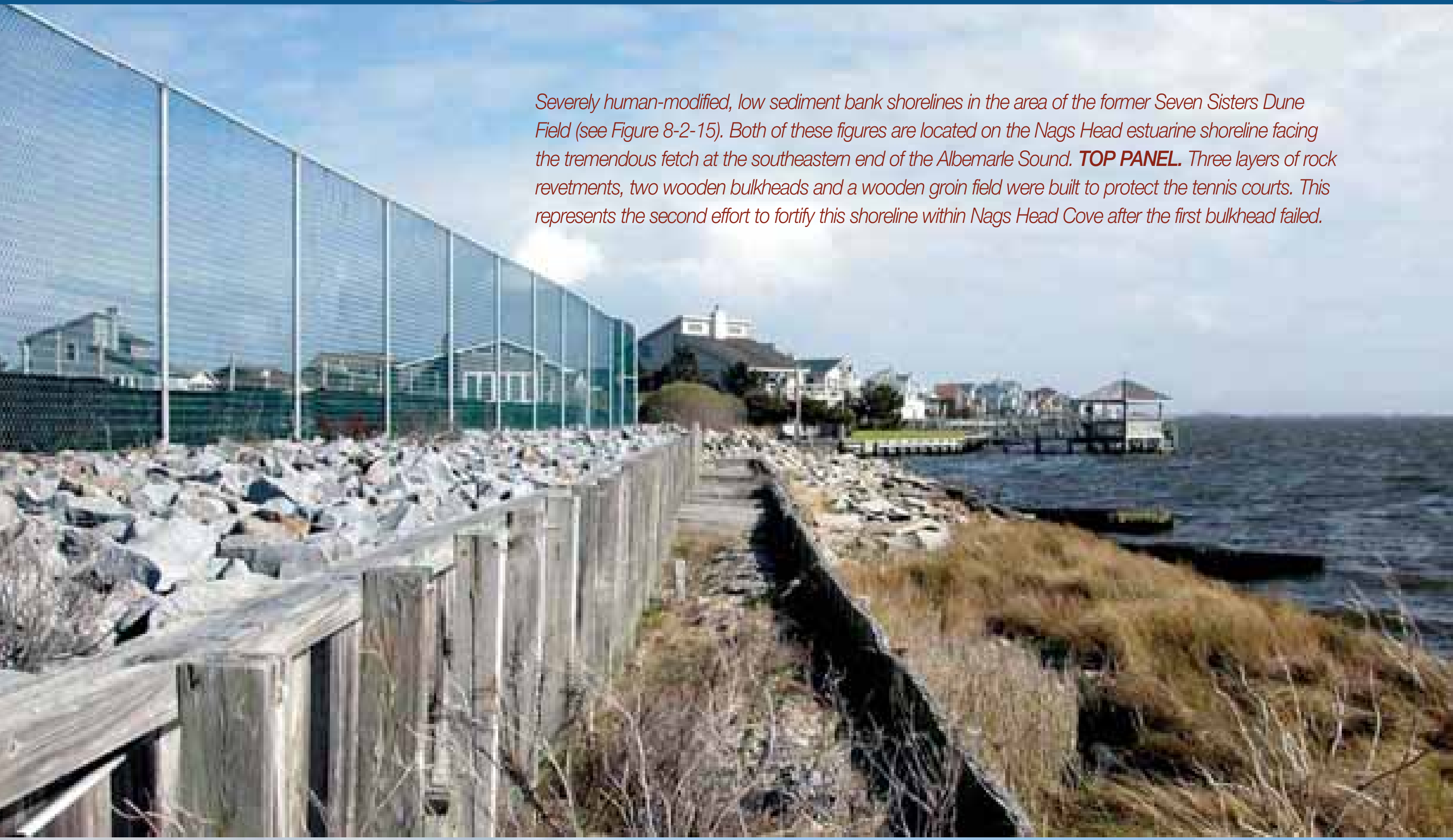
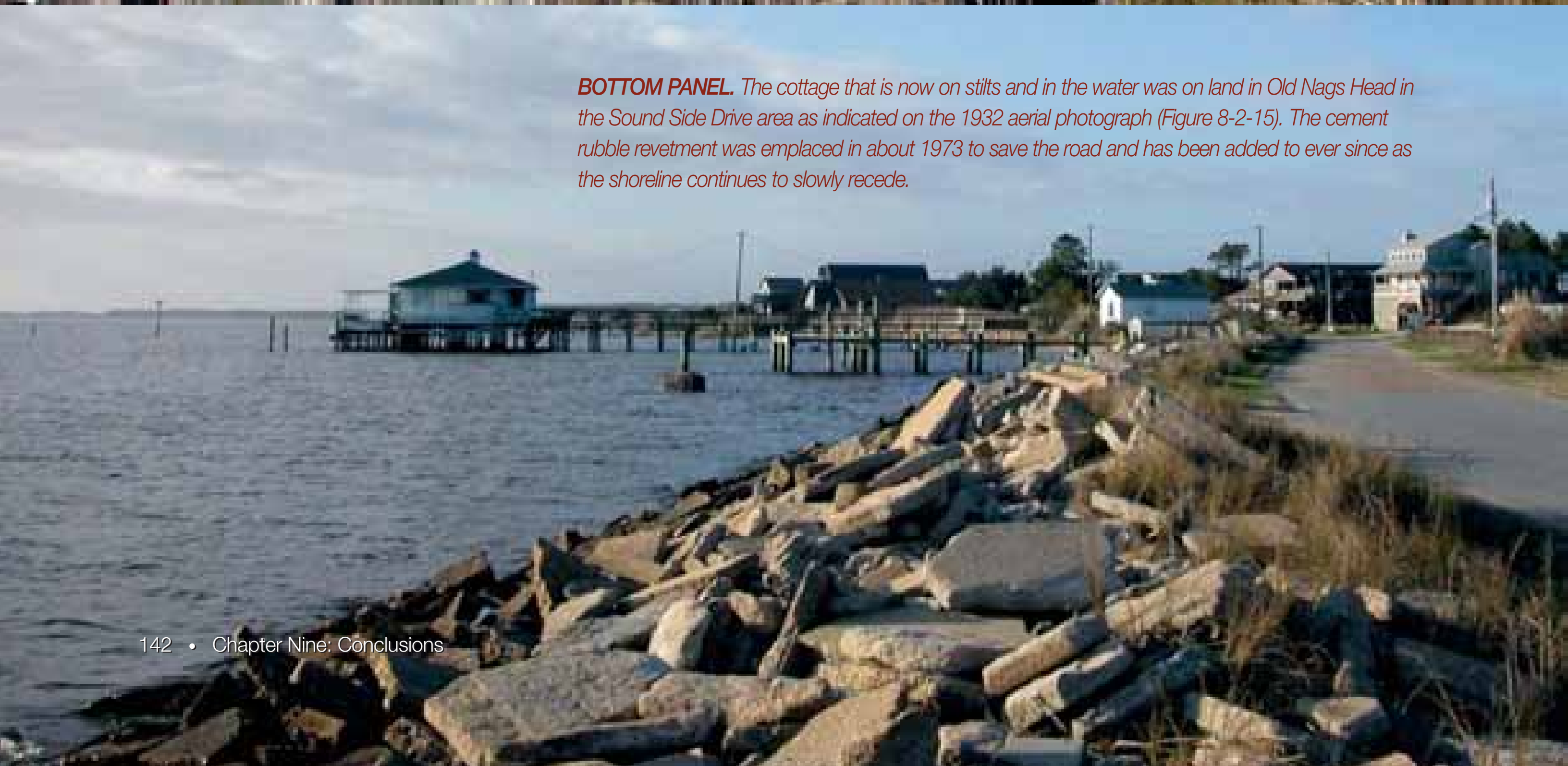
CHAPTER NINE:

Conclusions



*Severely human-modified, low sediment bank shorelines in the area of the former Seven Sisters Dune Field (see Figure 8-2-15). Both of these figures are located on the Nags Head estuarine shoreline facing the tremendous fetch at the southeastern end of the Albemarle Sound. **TOP PANEL.** Three layers of rock revetments, two wooden bulkheads and a wooden groin field were built to protect the tennis courts. This represents the second effort to fortify this shoreline within Nags Head Cove after the first bulkhead failed.*



***BOTTOM PANEL.** The cottage that is now on stilts and in the water was on land in Old Nags Head in the Sound Side Drive area as indicated on the 1932 aerial photograph (Figure 8-2-15). The cement rubble revetment was emplaced in about 1973 to save the road and has been added to ever since as the shoreline continues to slowly recede.*

Conclusions

9.1. SYNTHESIS OF ESTUARINE SHORELINE EROSION DATA

Tables 9-1-1, 9-1-2 and 9-1-3 summarize the range and mean shoreline erosion rates for each study site within the back-barrier island, mainland Albemarle-Pamlico sounds and Pamlico River areas, respectively. It is clear that the processes of estuarine shoreline erosion are extremely variable from site to site with large ranges within most sites. The actual rates are dependent upon the numerous variables previously summarized in Chapters Five and Six. The site with the highest average rate of recession is the marsh platform at Point Peter Road, with an average recession rate of –7.5 ft/yr in contrast to the lowest average recession rate of < –1.0 ft/yr along the bluff shoreline at Bay Hills. Locally, erosion rates varied from 0 ft/yr during periods of low storm activity to a high of –26.3 ft/yr along the sand bluffs at the north end of Roanoke Island during periods of high storm activity.

Several important patterns concerning average annual erosion rates for major shoreline types and estuarine regions are obvious from these data and are summarized in Tables 9-1-4 and 9-1-5, respectively. Table 9-1-4 demonstrates the relationship between erosion rates and shoreline type. Low sediment bank (–3.2 ft/yr) and mainland marsh (–3.0 ft/yr) have the overall highest average rates of estuarine shoreline erosion. They are also the most abundant shoreline types, constituting 85% of the coastal system in northeastern North Carolina. Bluffs and high sediment banks are less abundant (8%) and generally erode more slowly (–2.5 ft/yr) compared to low sediment banks (-3.2 ft/yr). This is largely due to the higher volume of sand available from eroding bluffs and high banks to build large strandplain beaches, as well as the availability of abundant wood debris and growth of fringing vegetation. Swampforest shorelines are the least abundant (7%) and erode the slowest (–2.2 ft/yr) due to their extremely low profile in concert with the role of trees in abating wave energy.

Strandplain beaches, associated with all shoreline types, effectively absorb wave energy under normal storm conditions and generally tend to slow relative rates of shoreline recession. Also, shorelines with major strandplain beaches are the only shorelines that are either holding their own or locally accreting (Table 9-1-4). Strandplain beaches can form adjacent to any shoreline type if a source of "new sand" exists and if the adjacent water is not too deep. If strandplain beaches form and maintain themselves, they are critical substrates available for vegetative growth, including formation of fringing marsh and fringing cypress. Strandplain beaches break wave energy, trap sand and are important natural shoreline protection agents in most physical settings.

Most shoreline modification is designed to stop shoreline recession and consists of some form of hardening or hardening in concert with vegetative plantings (Rogers and Skrabel, 2001). However, most shoreline modifications are short-term controls that only temporarily slow or stop shoreline erosion. Since terminating sediment-bank erosion results in the loss of "new sediment" necessary for either building or maintaining a strandplain beach, the ultimate consequence is generally the total loss of strandplain beaches and their function. Also, most structures deteriorate with time, and large storms take their toll resulting in a net long-term recession of most hardened shorelines (Table 9-1-4).

Table 9-1-1 Summary of Estuarine Shoreline Erosion Rates for Back-Barrier Sites

STUDY SITES	SHORELINE TYPE	EROSION RATES RANGE FT/YR	EROSION RATES MEAN FT/YR
1. Seven Sisters Site	Low Sediment Bank	0 to –8	–5.2
2. Jockey's Ridge Site	Low Sediment Bank	–1 to –8	–3.5
	Strandplain Beach	+6 to –2	+1.7
3. Buxton Inlet Site	Marsh	+5 to –19	–2.6
4. Nags Head Woods Site	Open Marsh	0 to –4	–1.7
	Embayed Marsh	+1 to –1	+0.6
5. Salvo Day-Use Site	Marsh	0 to –2	–0.9
6. Duck Field Research Facility	Low Sediment Bank	+8 to –5	–0.7
	Marsh with Strandplain Beach	+16 to –24	–0.3
7. Hatteras Overwash Site	Marsh	0 to –1	–0.5
	Strandplain Beach	+3 to –1	+0.8

Conclusions

Table 9-1-5 summarizes the shoreline erosion rate data by region. These data demonstrate a clear and strong relationship between actual rates of recession and the physical setting, including the size of adjacent estuarine water body or fetch. The lowest average erosion rate occurs in the inner Pamlico River with an average of –1.1 ft/yr. Within the Pamlico River, there is a general increase in erosion rates from the innermost site (Bay Hills) to the outermost sites (Wades and Hickory Points) as indicated by the arrow on Table 9-1-3. These data are equally applicable to the small, inner portions of major drowned rivers, as well as small lateral tributaries. This includes the inner Neuse River and lateral tributaries such as the Broad and Clubfoot creeks, Bath and Durham creeks adjacent to the Pamlico River and Yeopim and Scuppernong rivers that flow into Albemarle Sound.

Erosion rates increase dramatically to an average of –3.8 ft/yr within the outer Pamlico River estuary and the mainland Pamlico-Albemarle Sound region (Table 9-1-5). Most of

Table 9-1-2 Summary of Estuarine Shoreline Erosion Rates for the Mainland Albemarle-Pamlico Sound Sites

STUDY SITES	SHORELINE TYPE	EROSION RATES RANGE FT/YR	EROSION RATES MEAN FT/YR
1. Point Peter Road Site	Marsh	–7 to –8	–7.5
2. North Roanoke Island Site	Bluff	–1 to –25	–6.0
3. North Bluff Point Site	Marsh	–1 to –12	–5.7
4. Lowland Site	Low Sediment Bank	–3 to –8	–4.9
	Marsh	–1 to –3	–1.7
5. Swan Quarter Site	Open Marsh	0 to –11	–2.9
	Embayed Marsh	0 to –6	–1.2
6. Woodards Marina Site.	Swamp Forest	–2 to –4	–2.4
7. Grapevine Landing Site.	Swamp Forest	–1 to –6	–1.8

Table 9-1-3 Summary of Estuarine Shoreline Erosion Rates for the Pamlico River Sites

STUDY SITES	SHORELINE TYPE	EROSION RATES RANGE FT/YR	EROSION RATES MEAN FT/YR
1. Wades Point Site	Marsh	–1 to –8	–3.2
	Low Sediment Bank	–1 to –9	–4.1
2. Hickory Point Site	Marsh	–2 to –5	–3.6
	Low Sediment Bank	–2 to –7	–4.3
3. Pamlico Marine Lab Site	Low Sediment Bank	–1 to –6	–4.9/–2.5
4. Bayview Site	High Sediment Bank	+1 to –1	–0.2
	Low Sediment Bank	–1 to –2	–1.4
5. Camp Leach Site	Marsh (Platform/Fringing)	+2 to –2	–1.3/–0.3
	Low Sediment Bank	0 to –1	–0.6
6. Mauls Point Site	Bluff	–1 to –3	–2.9
7. Bay Hills Site	Bluff	–1 to –2	<–1.0

these sites have low elevations with extremely large fetches across vast expanses of estuarine water. If shorelines within this outer region are regular and openly exposed to the large estuarine bodies (i.e., the bluff at north Roanoke Island, swamp forest at Woodard's Marina or marsh platform at Point Peter Road), erosion rates tend to be very regular (Table 9-1-2). However, if extensive embayments and irregularities occur along the shoreline (i.e., the Swan Quarter marsh platform), erosion rates within the semiprotected areas are significantly less than those that are openly exposed (Table 9-1-2).

The back-barrier estuarine shorelines are generally adjacent to major water bodies with extremely large fetches. However, the average erosion rate of –2.2 ft/yr is significantly less than either the outer Pamlico River or the mainland Albemarle-Pamlico sound region, both with average erosion rates of –3.8 ft/yr (Table 9-1-5). The generally lower rates are attributable to the very shallow water character of the nearshore systems. The three southern sites are situated on the broad and shallow water feature known as the Hatteras Flats. The sites at Duck, Jockey's Ridge and Seven Sisters dune fields are located within the very shallow waters of Currituck and Roanoke sounds, respectively. The Nags Head Woods site occurs behind the shallow waters of Colington and Buzzards Bay shoals that occur on the eastern end of Albemarle Sound. Thus, all of these sites tend to be semiprotected by the presence of broad, shallow-water systems occurring in front of them.

Overwash processes on low and narrow barrier-island segments and erosional processes

Table 9-1-4 Erosion Rates for Different Shoreline Types

SHORELINE TYPE (% OF SHORELINES)		MAXIMUM RATE FT/YR	AVERAGE RATE FT/YR
• Sediment Bank	(38%)		
Low Bank	(30%)	–8.9	–3.2
Bluff/High Bank	(8%)	–26.3	–2.5
Back-Barrier Strandplain Beach		–2.0	+0.7
• Organic Shoreline	(62%)		
Mainland Marsh	(55%)	–18.3	–3.0
Back-Barrier Marsh		–19.0	–1.4
Swamp Forest	(7%)	–5.8	–2.2
• Overall Weighted Average*			–2.7
Human Modified	(?%)	–6.6	–0.5

** Includes all types except strandplain beaches and modified shorelines*

Table 9-1-5 Summary of Estuarine Shoreline Erosion in Northeastern North Carolina by Region

ESTUARINE REGIONS*	AVERAGE EROSION RATES FT/YR
1. Inner Pamlico River	–1.1
2. Outer Pamlico River	–3.8
3. Albemarle-Pamllico Sounds	–3.8
4. Back Barrier-Northern Outer Banks	–2.2
NE NC Estuarine System Weighted Average*	–2.7

** Includes all types except strandplain beaches and modified shorelines*

Conclusions

of back-barrier dune fields on high and wide complex barrier segments normally feed critical sand to the back-barrier coastal system. These sources of "new" sand are necessary to build and maintain overwash fans, marsh platforms and associated strandplain beaches in front of eroding back-barrier shorelines. The resulting strandplain shorelines consist of shallow beaches that ramp up onto and protect the eroding scarp on the adjacent land and marsh. Also, during low storm activity periods, fringing marshes commonly form on broad strandplains beaches. These factors tend to minimize rates of shoreline recession, as indicated by the low-average, back-barrier erosion rate (ave. = –2.2 ft/yr), while some sand-rich, back-barrier shorelines actually have accretion rates that average +0.7 ft/yr (Table 9-1-4).

However, human activity on the barriers has critically impacted sand supplies to the back-barrier coastal system during the past decades. Dune-ridge building, urban growth, highway construction and maintenance have led to increased barrier island elevation and the expansive growth of upland vegetative. Vegetative stabilization and development of back-barrier dune fields on complex barriers (i.e., Jockey's Ridge and Seven Sisters dune fields) have had a tremendous negative effect upon the adjacent estuarine shoreline systems. Additionally, increased rates of hardening back-barrier shorelines, along with dredging projects for sand and navigation in the immediate back-barrier system, have major impacts upon shoreline erosion processes and resulting recession rates. Thus, increased human activities through time have dramatically diminished major sand sources, resulting in either the total loss of or more ephemeral character of strandplain beaches. As the occurrence and size of strandplain beaches are diminished through time, erosion rates increase.

All estuarine shorelines in northeastern North Carolina are eroding in response to the ongoing long-term rise in sea level. As indicated in Table 9-1-5, the weighted average for the recession of all shoreline types within the highly variable regional setting is –2.7 ft/yr. Erosion, largely driven by storm processes, results in the systematic loss of both uplands and wetlands through time. The approximate rate of land loss to estuarine shoreline erosion can be estimated from the data developed in this study (Tables 9-1-1 through 9-1-4).

Table 9-1-6 approximates the total amount of land lost to erosion at the sites studied in this report and during the time intervals analyzed for each site (Tables 8-2-1, 8-3-1, and 8-4-1). At the 21 sites studied, approximately 119 acres of upland and 246 acres of wetlands were lost during the time intervals analyzed. If the assumption is made that the average annual recession rates for each shoreline type are applicable to the entire 1,593 miles of estuarine shoreline mapped by Riggs et al. (1978), then approximately 629 acres of land are lost each year within the 1,593 miles.

However, Riggs et al. only mapped about 50% of the estuarine shoreline in northeastern North Carolina. If it is assumed that the remaining 50% of unmapped shoreline has the same relative distribution of shoreline types defined by Riggs et al., the total annual shoreline loss for northeastern North Carolina can be estimated (Table 9-1-6). This results in a loss of about 478 acres of uplands per year and about 780 acres of wetlands per year. Spread over a year within the tremendous size of the North Carolina coastal system, these amounts would probably not be noticeable. However, the cumulative effects of the loss rate through time represent an inevitable and significant change to both North Carolina's coastal system and individual property owners.

We do not advocate trying to stop the ongoing and natural process of drowning the North Carolina coastal system — after all, change is the only constant within our coastal system. However, we do advocate learning to live with the evolutionary processes by changing the way shorelines are utilized. And more importantly, the natural upward and landward migration of wetlands in response to slowly rising sea level, must not be hindered. The continued modification of wetlands with drainage networks, highway road dams and

Table 9-1-6 Measured and Estimated Land Loss Due to Estuarine Shoreline Erosion in Northeastern North Carolina

1. Total land lost for 21 field sites measured for the time between the oldest and newest aerial photos used at each study site = 365 acres (0.57mi^2), including 246 acres of marsh.
2. Land lost for 1,593 miles of mapped estuarine shoreline (Riggs et al., 1978) = 629 acrea/year or~1 mi^2/yr.
3. If Riggs et al, (1978) mapped 50% of mainland estuarine shorelines in NE NC, the total mainland shoreline = ~3,186 miles.
4. Assuming the same proportions of shoreline types and same erosion rates of this study, the annual land loss = ~1,258 acres/yr or ~2mi^2/yr.
5. If wetlands = 62% of the estuarine shorelines, the annual wetland loss = 780 acres/yr or ~1.2 mi^2/yr.
6. Total land loss for the 25-year period between 1975-2000 = ~49mi^2.

bulkheads will lead to a one-way net loss of wetlands. However, if the natural migration processes are recognized and honored with continued rise in sea level, the net expansion of new wetlands along the inner zone should equal the loss of wetlands on the outer shoreline zone. Wetland habitats of the North Carolina coastal system must be allowed to expand into the future, or there will be ever decreasing amounts of this critical coastal habitat.

9.2. LIVING WITH ESTUARINE SHORELINE EROSION

North Carolina's estuaries represent a geologically young and dynamic portion of the coastal system. As the last great Pleistocene ice sheet began to melt in response to global climate warming, the present coastal system began to develop. As the glaciers melted and receded, the melt waters raised the ocean level. This rising sea level caused the coastal system to migrate across the continental shelf, flooding over the land and up the topographically low river valleys to form our present estuarine system. After 10,000 years, 425 feet of sea-level rise, and a lateral migration of 15 to 60 miles westward, the North Carolina coast began to develop a familiar look.

The glaciers are still melting today, sea level continues to rise, and the ocean slowly, but relentlessly continues to flood the coastal lands of North Carolina. This results in the continuing upward and landward migration of the shoreline. The process of coastal migration is better known as ***shoreline erosion***. The fact that sea level is rising worldwide means that erosion is ubiquitous to all of North Carolina's thousands of miles of shoreline. The only differences between shorelines are the rates of erosion that are dependent upon specific shoreline variables and varying storm conditions. Locally, a shoreline may appear stable or actually accrete sediments. However, such a situation is anomalous and is usually ephemeral in nature.

Because change is a constant within dynamic coastal zones, natural and human-induced hazards to normal styles of development abound in the coastal region. For those who live and work in the coastal zone, there is an extremely high level of property loss that results from flooding, shoreline erosion and other storm-induced factors. The burgeoning population and exploding development demands stability that results in negative impacts upon the coast and a cumulative toll on the health of the entire natural system. The dynamic character of the coastal resources makes this an Earth habitat that truly does have "limits to growth."

Another serious effect of rapid population growth and development is habitat modification within our coastal system. Some of the greatest population growth rates in North Carolina occur within the coastal counties, leading to unprecedented urban explosion within the coastal zone. New four-lane roads and bridges are being constructed at unparalleled rates, new water supplies are being developed, and pressures are increasing upon severely overloaded sewage systems. This growth is intimately intertwined with a booming tourist industry, causing major cumulative wetland losses and habitat modifications. Maritime forests are cleared, shorelines are bulkheaded, shallow waters are dredged, wetlands are channelized, dune fields are bulldozed, and the surface is paved for parking lots. All of these activities modify the land surface, alter the drainage, and result in increased contaminants moving into the adjacent coastal waters.

The coastal system — a high-energy, dependent system that is characterized by environmental extremes and reliant upon storm events to maintain the overall health of the natural system — is not fragile. Rather, it is the fixed human superstructure superimposed upon this dynamic system that is fragile. There is no guaranteed permanency to any characteristic or feature within the North Carolina coastal system. Early settlers of the coastal system understood this. However, modern society has forgotten these environmental constraints in the headlong rush to transpose "Raleigh-style" developments and lifestyles upon this dynamic and changeable coastal environment.

FIGURE 9-1-1. *The fate of sand castles built on a beach in a rising tide is clearly evident. But what happens to low-lying shoreline development, as well as the short- and long-term evolution of the coastal system, with a rising sea level?*

DROWNING

CHAPTER TEN:

References Cited

Like the sea itself, the shore ... is a strange and beautiful place. All through the long history of earth it has been an area of unrest where waves have broken heavily against the land, where the tides have pressed forward over the continents, receded, and then returned. For no two successive days is the shore line precisely the same ... the level of the sea itself is never at rest. It rises or falls as the glaciers melt or grow, as the floor of the ocean basins shift under its increasing load of sediments, or as the earth's crust along the continental margins warps up or down in adjustment to strain and tension. Today a little more land may belong to the sea, tomorrow a little less. Always the edge of the sea remains an elusive and indefinable boundary.

— *RACHEL CARSON,* THE EDGE OF THE SEA, *1955*

An actively "going-to-sea" state road at Wades Point, the high-energy confluence of the Pungo and Pamlico river estuaries.

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Hurricane Isabel

AT RIGHT. *A post-Hurricane Isabel MODIS Level-1B satellite image taken on September 19, 2003 of northeastern North Carolina showing the Albemarle and Pamlico sounds coastal system. The eye of the storm came ashore in the vicinity of Ocracoke Inlet and traveled northwest to the mouth of the Albemarle Sound and west of the Chowan River estuary. The eastern portions of all estuaries are slightly muddy. However, the lower Chowan River and Albemarle Sound are extremely muddy. The bright tan color is due to an incredibly large volume of suspended clay sediment in the water column. This sediment load is the direct consequence of severe erosion of sediment bank shorelines that are extensive in the upper Albemarle Sound and lower Chowan River (Riggs, 2001). Sand from the eroded shorelines formed beaches while the mud sediment components remained suspended in the water column. Slightly muddy waters within Pamlico Sound reflect the vast areas dominated by organic shorelines that are composed dominantly of marsh and swampforest peat with only minor low sediment bank shorelines. Notice that there is no suspended sediment in the Neuse and Pamlico river estuaries due to the northeasterly location of the storm track. See the front and back covers for the pre- and post-Hurricane Isabel photographs of the shoreline site indicated by the red star on this satellite image. Satellite image is from MODIS Image Gallery, Liam Gumley, Space Science and Engineering Center, University of Wisconsin-Madison.*

ON THE BACK COVER. *Post-Hurricane Isabel photograph taken from about the same location along the bluff shoreline as the front cover photograph. The red dotted line is the approximate location of the pre-Hurricane Isabel shoreline. Hurricane Isabel, a small category 2 storm, came ashore on September 18, 2003, with the eye of the storm on a northwest path that was located just west of the Chowan River estuary. Quiet water flood marks in the vicinity of the photograph suggest about a 5- to 8-foot storm surge occurred in the Chowan River with estimated 80 mph sustained winds and gusts up to 95 mph. The consequence was an average bluff shoreline recession of about –50 feet (range from about –30 to –80 feet) for the several segments of accessible bluff shoreline (person for scale = 5 feet tall). Notice that the clay bed on the front cover thinned dramatically into the bluff and changed to a more erodable sandy clay (large eroded blue blocks on the beach). As the waves eroded the basal clay bed, great volumes of rain saturated sands cascaded down the scarp as great slumps. Slumping of the overlying sands was accentuated by winds that blew out the overhanging trees. The slumped sediments were subsequently reworked by waves into a broad sand beach. Photograph was taken on October 6, 2003. See the front cover for the pre-Hurricane Isabel photograph of the same site and page152 for a satellite image showing the site location and post-Hurricane Isabel, sediment-laden, estuarine water conditions.*

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NC State University • Box 8605 • Raleigh, NC 27695-8605
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