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Relative Risk Assessment for Cape Hatteras National Seashore

John Cary Buie
College of William and Mary - Virginia Institute of Marine Science

RELATIVE RISK ASSESSMENT
FOR CAPE HATTERAS NATIONAL SEASHORE

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APPROVAL SHEET

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John C. Buie

Approved, August 1996

Carl H. Hershner, Ph.D.
Committee Chairman/ Advisor

Robert J. Byrne, Ph.D.

Gene M. Silberhorn, Ph.D.

Carl H. Hobbs, III, M.S.

Thomas A. Barnard, Jr., M.A.

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ABSTRACT

This study estimates the potential risks posed to various cultural and natural resources within Cape Hatteras National Seashore (CAHA) due to the physical processes associated with barrier island transgression. These processes include shoreline retreat, inlet formation, and overwash. The risk estimates used in this analysis are derived from readily available historical data and from data gathered in the field. The risk assessment was carried out using the Geographic Information System (GIS) Arc/INFO.

Areas within Cape Hatteras National Seashore were evaluated for the relative magnitude or probability of occurrence of shoreline retreat, inlet formation, and overwash. This information was used to estimate the overall risk to National Seashore cultural and natural resources. The northern section of the National Seashore, including both Bodie Island and Pea Island National Wildlife Refuge, and the resources contained in these regions, were found to be at high risk due to all three modeled processes. A small section of the park between the enclave of Avon and Cape Hatteras was also found to be at high risk. Potential management strategies that the National Park Service might adopt to deal with the risk to park resources were evaluated as part of this project.

RELATIVE RISK ASSESSMENT

FOR CAPE HATTERAS NATIONAL SEASHORE

1. INTRODUCTION

Coastal barrier islands are found in chains in many places of the world; among the most familiar examples in the U.S. Atlantic Southeast are the Outer Banks of North Carolina and Assateague-Chincoteague on the Delmarva Peninsula. Barrier island systems are characterized as fragile ecosystems, yet many are among the most heavily developed of all natural shorelines.

Barrier islands exhibit a wide range of morphologic features. This diversity in form is a function of the variations in sediment supply, tidal range, geographic orientation/exposure, and wave energy. Barrier islands along the central Atlantic coast of North America (e.g., the Outer Banks of North Carolina) are termed microtidal because the tide range in this region is less than 2 meters. Microtidal barrier islands which are not in equilibrium are either regressive (prograding) or transgressive (eroding). The majority of the mid-Atlantic barrier islands are transgressive. They are storm-dominated and possess few inlets and many washovers. In some local areas, the rates of shoreline retreat exceed 8 meters per year (Inman and Dolan, 1989).

The dynamics of mid-Atlantic barrier island systems are driven primarily by climatological forces (Dolan and Lins, 1987; Dolan et al., 1980). Storm events, particularly northeast storms, are responsible for the landward translation of the islands as sea level rises. This migration is effected most significantly through overwash and inlet formation.

In order to deal effectively with the projected impacts of global climate change on barrier island systems, the National Park Service has contracted the Department of Resource Management and Policy at the Virginia Institute of Marine Science to analyze the potential risk to cultural and natural resources within the coastal national parks of the U.S. Atlantic southeast. This thesis examines the potential risk posed to various cultural and natural resources within Cape Hatteras National Seashore (CAHA) due to the physical processes associated with barrier island transgression.

2. STUDY AREA

Cape Hatteras National Seashore (Figure 1) was authorized by Congress in 1937, but funds were not made available for land acquisition (Schoenbaum, 1982). Private monetary donations and matching North Carolina state funds enabled the physical creation of the national park in 1952. Cape Hatteras National Seashore extends approximately one hundred twenty kilometers from Whalebone Junction (just south of Nags Head) to Ocracoke Inlet. Within the boundaries of the National Seashore, the federal government has ownership of all lands from ocean to sound, except for those lands within U.S. Coast Guard jurisdiction and the village enclaves of Rodanthe, Waves, Salvo, Avon, Buxton, Frisco, Hatteras, and Ocracoke. On the oceanside of the enclaves, federal ownership is limited to 500 feet landward from mean low water. Federal and state lands on the Outer Banks thus exist in close proximity to private commercial and residential lands. This close association leads to predictable conflicts between private landowners, developers, and resource protection agencies.

Several use conflict issues exist within Cape Hatteras National Seashore. These use conflicts drive the management practices of the National Park Service. Table 1 summarizes the major management issues facing CAHA (NPS, 1993) and Table 2 outlines the National Park Service's goals for CAHA.

The extreme northern end of CAHA consists of Bodie Island. Bodie Island is separated from Hatteras Island by Oregon Inlet, a large, active inlet that is maintained through dredging by the U.S. Army Corps of Engineers as the only shipping channel into and out of Pamlico Sound. Oregon Inlet was opened during a hurricane in 1846 (Fisher, 1962); the Herbert C. Bonner Bridge crosses the inlet and connects Bodie Island with Pea Island. The only "permanent" inlet other than Oregon Inlet that exists in CAHA is Hatteras Inlet, which separates Hatteras Island from Ocracoke Island.

South of the Bonner Bridge is Pea Island National Wildlife Refuge (PINWR), which is maintained by the U.S. Fish and Wildlife Service (USFWS). PINWR is an important nesting and wintering ground for numerous species of waterfowl. The boundary between PINWR and CAHA is just north of Rodanthe. Historically, an inlet (New Inlet) near Rodanthe separated Pea Island from Hatteras Island (Figure 2). The inlet has been known to reopen temporarily during severe storms (Inman and Dolan, 1989).

Historically, the Outer Banks were thought to have been heavily forested (Birkmeier et al., 1984). The National Park Service presumed logging and livestock grazing to be responsible for the denudation of the islands, and that an elevated, vegetated, stable dune line was necessary to prevent the permanent erosion of the islands by wave action and storm activity. Thus, artificial dunes were constructed under the direction of the National Park Service along the Outer Banks beginning in the 1930's (Birkmeier et al., 1984; DeKimpe et al., 1991). The intent of this project was to "return" the Outer Banks to their "normal" forested state.

Studies by Godfrey (1972) and Dolan (1972) conclude that the Outer Banks were not forested historically as had been assumed by the NPS and that therefore the "normal" state of the Outer Banks was not actually known. These studies, plus the inability of shoreline stabilization efforts to bring erosion under control, reinforced the growing view of barrier islands as systems in dynamic equilibrium. In the early 1970's, the National Park Service decided to abandon its efforts to maintain the artificially constructed dune line. This decision to allow the Outer Banks to return to their natural condition of dynamic equilibrium, while consistent with general NPS policies, has resulted in a management dilemma. Storm damage to property and highways has increased in recent years (DeKimpe et al., 1991). The ability of the National Park Service to plan for changes in morphology within CAHA boundaries requires information regarding rates of shoreline retreat and projections of risk to resources within the park.

The National Park Service maintains numerous man–made structures within CAHA as unique cultural or historic sites (Figures 3a–3c). These structures are reflective of human history on the Outer Banks. The cultural site inventory for CAHA can be found in Table 3.

Several structures that were part of the United States Life Saving Service stand in Cape Hatteras National Seashore. The NPS owns structures at the Bodie Island Station, the Little Kinnakeet Station, and the Chicamacomico Station. Many of the existing structures are in need of refurbishment; however funds have not been identified for this purpose. Nevertheless, the NPS is committed to preserving these historic sites. The Little Kinnakeet Lifesaving and Coast Guard Station was built in 1874, and was moved back from the beach to its present location in 1904 (NPS, 1993).

The Chicamacomico boathouse was built in 1874, and the garage was constructed in 1911. The NPS does not own the land where these structures stand.

The most well–known historic site within Cape Hatteras National Seashore is the Cape Hatteras Lighthouse complex, which originally was sited some 500 meters from the shoreline. This complex includes Cape Hatteras Lighthouse, a small brick oil house, the principle keeper's quarters and the double keeper's quarters. The lighthouse began operation in 1870. The oil house was built in 1894, the double keeper's quarters were built in 1854, and the principle keeper's quarters were built in 1871. The complex is currently located approximately 50 meters from the high water line. The NPS has determined that the Cape Hatteras Lighthouse would be relocated when "the threat of loss of the structure to the sea equaled or exceeded the threat of possible loss by a move" (NPS, 1993). Four Civilian Conservation Corps cabins are located near the lighthouse complex in Buxton. The other lighthouse complex located on the Outer Banks, the Bodie Island Lighthouse, is owned and maintained by the U.S. Coast Guard.

Natural resources in Cape Hatteras National Seashore are typical of a mid–Atlantic barrier island environment. The eco–physiographic zones that are found in CAHA are beach, dune, back–dune meadow and scrub–shrub, maritime forest, freshwater wetland, and back barrier salt marsh. Management practices within the park have tremendous impact on the ecological make–up of these habitats. For example, the maintenance of an artificially high foredune line reduced overwash frequencies and allowed increased scrub–shrub distribution. The park service discontinued maintenance of the artificial dune line in the 1970s; as a result, one would expect increasing overwash with a return to dominance of more salt–tolerant species.

Cape Hatteras National Seashore serves as critical habitat for numerous threatened and endangered species, most of which are birds. Bird species which utilize CAHA on either a temporary or permanent basis include bald eagles, peregrine falcons, and piping plovers. Numerous species thrive in the barrier island environment of CAHA but are not endangered. These include a variety of terns, black ducks, brown pelicans, herons, ibis, and egrets. Cape Hatteras National Seashore also is the northern limit of loggerhead turtle nesting; the loggerhead is a threatened species.

Several natural resource management issues are presently unresolved within Cape Hatteras National Seashore. One is the effect that private development adjacent to the park has on park water quality. Another is the effect of the use of off–road vehicles on the beach and related shorebird habitat.

3. LITERATURE REVIEW

3.1 Storms and Barrier Island Processes

3.1.1 **Sea Level Rise**

The gradual rise in sea level over the past hundred years or so has been well-documented (Dolan and Lins, 1987; Leatherman, 1988). The response of barrier islands to the overall rise was debated in the literature in the 1960's and 1970's. Recent research has focused more on the magnitude of response to sea–level–rise compared to other processes. Sanders (1963) proposed that sea–level–rise most often resulted in the "drowning" of barrier islands rather than landward migration. Migration of barriers was simply a function of overwash and inlet activity.

In a landmark paper, Bruun (1962) calculated the theoretical response of a beach to a given rise in sea level; this proposed link between sea–level–rise and landward migration of barrier islands was termed "the Bruun Rule." The Bruun Rule was substantiated over the ensuing couple of decades (Leatherman, 1988a). Dubois (1990) constructed a model of beach erosion as a function of sea-level rise that he referred to as the "transgressive shoreface model." Dubois' model generally supported Bruun's theory linking shoreline retreat to sea–level rise, but contradicted Bruun's Rule on one important point. Bruun's Rule required that material eroded from a shoreface be deposited offshore on the continental shelf; the transgressive shoreface model predicted most sediment would be deposited on the island itself or in lagoons (i.e., overwash). Dubois' model yielded results close to the observed erosion rates for U.S. east coast.

At the northern end of the Mid–Atlantic barrier island chain, Leatherman (1983, 1988a) found similar patterns at Assateague Island and Ocean City. He calculated the shoreline retreat at Ocean City to be on the order of 75 meters over the past century, which he attributed largely to sea–level–rise.

3.1.2 Overwash Processes

Overwash is the process by which storm waves push sand across the barrier island and through breaches in dune lines (if dunes are present) (Leatherman, 1988a). Overwash is viewed by some as highly destructive; however, continuing over long periods of time, overwash is a geologic process that is necessary for maintaining the barrier island. The frequency of overwash is highly variable and depends on such factors as storm frequency, island exposure and topographic relief, tidal range, wave energy, and dune dimensions (Leatherman, 1988a). Overwash contributes to the landward migration of barrier islands by providing sand for vertical growth of dune fields and by moving volumes of sand toward the back barrier or sound side of the island.

There has been a fair amount of controversy and debate regarding the relative roles of overwash and aeolian transport in the landward displacement of barrier islands (Leatherman, 1988a). A 1977 study by Fisher and Stauble examined washover fans created by Hurricane Belle (1976) at Assateague Island. They concluded that only major storms (either tropical or extratropical) moved enough sediment via overwash to result in measurable landward migration of the island. In addition, in the six months following the storm's passage, much of the sand deposited in the overwash fans was transported back to the shoreface through aeolian transport.

Several studies by Leatherman (Leatherman et al., 1977; Leatherman, 1979; Leatherman and Zaremba, 1987) support the findings by Fisher and Stauble (1977) and concluded that except in unusually severe cases, overwash is not a significant factor in barrier migration due to aeolian deflation of the washover fans (i.e., return of sediment to the shoreface by the wind).

Kochel and Dolan (1986) examined the sediment budgets for four washover sites on Assateague Island and found that a significant portion of the annual sediment transport for the island could be traced to a single storm event. Kochel and Dolan also found minimal aeolian deflation of the fans, contradicting the previous studies by Leatherman and others (e.g., Leatherman, 1979). They attributed the observed differences in aeolian redistribution to Leatherman's site selection in the 1979 Assateague Island study. Kochel and Dolan pointed out that Leatherman's sites were in the low-profile region of the island (the north end), whereas most of the island was dominated by the presence of dunes. Leatherman's sites therefore were unrepresentative of Assateague Island as a whole.

Kochel and Wampler (1989) suggested that both the Leatherman and the Kochel and Dolan studies were of limited value because they were of such short duration (two years in each case). They suggested that the importance of overwash versus deflation was linked to the variability of climatic factors; Leatherman's data were collected during an unusually non-stormy period.

The timing of the study plus Leatherman's sites' location in a low-lying region may have accounted for the discrepancy in results between the studies. Kochel and Wampler encouraged completion of long-term (ten years or more) examinations of sediment budgets to better determine the relative influence of climate variability on overwash and aeolian transport.

Inman and Dolan (1989) calculated the sediment budget for the Outer Banks of North Carolina and found the average rate of shoreline recession to be 1.4 m yr^{-1} between False Cape, Virginia and Cape Hatteras, North Carolina. Inman and Dolan also calculated that Oregon Inlet is migrating landward at an average rate of 5 m yr^{-1} and southward at an average rate of 23 m yr^{-1}. Inman and Dolan estimated that sea–level–rise was responsible for 21% of the average landward migration of the Outer Banks, overwash processes (31%), longshore transport out of the system (17%), aeolian transport (14%), inlet deposition (8%), and removal by dredging at Oregon Inlet (9%).

3.1.3 Inlet Dynamics

Inlets are critical to a barrier island's ability to migrate landward. The presence of both permanent and ephemeral inlets usually results in the construction of flood tidal deltas on the sound side of the inlet (some sediment is deposited on the ocean side in the form of an ebb tidal delta, but the net movement of sediment is almost always toward the sound (Leatherman, 1988). Flood tidal deltas provide a platform for the development of salt marshes after the inlet closes or migrates downdrift in response to littoral currents (Leatherman, 1988a). Effectively, this results in a wider island.

Island rollover may occur if overwash deposits sand on the flood tidal delta salt marshes, moving the entire island landward over time.

Pierce (1969, 1970) examined the formation of inlets and their role in barrier island migration. In his earlier paper, which focused on the North Carolina Outer Banks, Pierce found inlet activity to be responsible for up to 70% of the island's landward retreat (a much larger contribution than in Inman and Dolan's 1989 sediment budget). In the second paper, he described several mechanisms by which inlets could be created, the most spectacular of which was the breakout of water from the sound side of the island during hurricanes. Northeast storms produced many overwash areas but few inlets, largely due to the lower storm surges and wind velocities compared to those of tropical systems.

Temporary inlets were found by Armon (1979) and Armon and McCann (1979) to account for up to 90% of the landward transport of sediment along the Malpeque barrier in the Gulf of St. Lawrence, Canada. These barriers have fairly high dune relief, with exceptions occurring near the sites of relict inlets. Overwash and aeolian transport therefore were found to be relatively inconsequential in terms of barrier migration.

A series of papers by Leatherman (1979, 1985, 1989) deals with the role of inlets in transgressive barrier retreat. He concluded that inlet dynamics was the major force behind barrier retreat at Assateague Island and Fire Island, while overwash served primarily to increase the islands' elevation.

A study by the U.S. Army Corps of Engineers (Everts et al., 1983) suggests that there is a general relationship between island width and the potential of inlet formation: the narrower the island, the greater the chance of inlet formation. According to this study, relict inlet sites often are indicated by anomalously wide sections of the island. These areas are generally not considered to be good candidates for new inlet formation. However, the authors point out that the general physical characteristics of the region that allowed for inlet formation probably have not changed significantly, particularly if an inlet was present relatively recently. For this reason, Everts et al. consider the general areas surrounding historical inlets as potential sites for new inlets.

3.2 Coastal Storm Climatology

Without a doubt, hurricanes and tropical storms are the most studied coastal storms (Davis and Dolan, 1993). On the mid–Atlantic coast, tropical storms are infrequent events. The Outer Banks experience a tropical storm once every year or two (Davis et al., 1992). In comparison, the Outer Banks experience the effects of an average of thirty or more extratropical storms (or northeasters) per calendar year. With the exception of major hurricanes, coastal damage due to tropical weather systems is generally restricted to a small extent of the coastline. Northeasters, on the other hand, can affect large stretches of the Atlantic coast. For example, the so-called "Ash Wednesday Storm" of 1962 produced significant changes in the coastal landscape along the entire Atlantic coast (Dolan, 1987). Yet northeasters remain poorly studied; little research has been published on the climatology of extratropical storms and even less published specifically dealing with the storm climatology of a particular region of the Atlantic coast. Most climatological research either focuses on the macro-scale (or synoptic scale) or the micro-scale, as opposed to the meso-, or regional, scale.

3.2.1 Northeast Storms versus Tropical Storms

Tropical storms and hurricanes are low pressure systems (cyclones) that form over the tropical Atlantic ocean. They typically have a maximum diameter of 650 kilometers or so, although this is variable. The central pressure of hurricanes is usually around 950 mb, although rare storms may have a central pressure of below 900 mb. Hurricane force winds are defined as 74 miles per hour or greater sustained, while tropical storm force winds are defined as 40–74 miles per hour sustained. Most people are familiar with the appearance of a hurricane: a tight counterclockwise spiral of cloud bands and thunderstorms. The cloud tops in hurricanes may reach heights of 12,000 meters or more; this illustrates the convective nature of tropical storms. This convection is fed by warm, tropical water. For this reason, hurricanes form primarily during the summer and autumn months in the North Atlantic.

Hurricanes generally are steered by upper level wind patterns. They may track into the Gulf of Mexico or they may veer northward and threaten the eastern seaboard. Hurricanes require an extensive area of ocean water with surface temperature greater than 26° C for formation. In addition, the presence of wind shear in the atmosphere will preclude development of tropical storms (the convection cells get sheared apart). Tropical storms may persist for 4-5 days, and hurricanes for 2-3 days. However, the storm usually moves the entire time it is in existence; it rarely threatens a single area for more than 12 hours (Barry and Chorley, 1987).

Northeasters also are low pressure systems, but with more variability than hurricanes. Northeasters are "cold core" systems while hurricanes and tropical storms are "warm core" systems. Northeasters therefore do not generate the massive convective cells seen in hurricanes. Northeasters actually intensify with increasing wind shear in the upper atmosphere, and are therefore linked to a strong jet stream. They often form along fronts (or baroclinic zones) where two air masses of different temperatures meet. When a surface baroclinic zone coincides with strong winds aloft, conditions are favorable for cyclogenesis. The stronger the temperature differential between the air masses and the stronger the winds aloft, the stronger the resulting northeaster. There appears to be a relationship between jet stream position and northeaster formation. The primary northeaster season is from October through April. This is typically the time of year when the jet stream follows a more southerly track.

Northeasters do not necessarily develop over water. Some of the strongest northeasters on record developed in the lee of the Rocky Mountains in the middle of North America (Davis et al., 1992).

Although northeasters can develop high winds, most coastal damage is caused by high surf. Northeasters are much larger weather systems than hurricanes; the "Storm of the Century" in March of 1993 covered almost the entire east coast of the United States, from Maine to Georgia. These large low pressure systems can create winds that blow unimpeded across several hundred kilometers. Northeasters also may persist for several days, often without changing their position by more than a few dozen kilometers. The long fetch of Atlantic coast northeasters, the sustained hurricane or near–hurricane force wind speeds and the extended duration of these storms combine to generate large deep water waves, which can exceed 10 meters in height (Davis and Dolan, 1993 and Davis et al., 1992). Davis et al. (1992)

classified northeasters according to their synoptic characteristics. These characteristics are summarized in Table 4.

3.2.2 Implications for Cape Hatteras

Due to the geometry of the Outer Banks, specifically Cape Hatteras, they receive wave energy from virtually all coastal storms that develop along the Atlantic coast. Onshore winds from any offshore direction will create wave conditions that impact this coast. For Cape Hatteras, winds from approximately 340° to 190° produce waves (Wayland, 1985). North of the Cape, critical wind directions are approximately 340° to 160°. Wayland (1985) analyzed the relationship between storm track and wave climate at Cape Hatteras and found that extra-tropical storms which produce the largest waves have an average track of southwest to northeast, or roughly parallel to the Atlantic coastline. Storms that track further east generate larger waves. Wayland also found that tropical storms producing the largest waves track fairly close to Cape Hatteras from the southeast and then veer to the northeast just after passing Hatteras. No reliable east-west variability in the tracks as they relate to wave climate could be discerned from Wayland's study due to the small number of tropical storms associated with the largest wave height category.

The offshore topography of Cape Hatteras significantly contributes to the wave climate. Here the continental shelf is only about 40 km wide, compared to over 120 km wide off Cape Henry, to the north. The Gulf Stream therefore approaches within 30 to 60 km of Cape Hatteras. Strong currents like the Gulf Stream (up to 4 knots) can cause an increase in overall wave height (Bascom, 1980). Offshore shoals are common along the length of the

Outer Banks, and the infamous Diamond Shoals extend over 20 km seaward from Cape Hatteras. The shoals cause local wave refraction that has a significant impact on the velocities of littoral drift along the Outer Banks.

3.3 Shoreline Change Analysis

Typical sources of data for the analysis of patterns of shoreline change through time include maps, nautical charts, and aerial photographs. The methods used to quantify shoreline change are extensive and varied. All have limitations and drawbacks (Crowell et al., 1991). Numerous authors have documented the difficulties associated with determining rates of change along dynamic shorelines (e.g., Smith and Zarillo, 1990; Crowell et al., 1991; Fenster and Dolan, 1993; Fenster et al., 1993; Thieler and Danforth, 1994). A study by Dolan et al. (1991) based on data for Hatteras Island examined the methods most often used by researchers to gauge shoreline rates of change. A follow–up paper (Dolan et al., 1992) examined the influence of spatial sampling on shoreline rate of change values. These reports are summarized below.

The most common method of shoreline change analysis is the so-called *end-point-rate* or EPR method (Dolan et al., 1991). This method uses two shoreline surveys only, with the rate of change calculated as the total distance of shoreline movement divided by the time difference between survey years. The primary advantage of this method is its ease of computation. However, data available between the two survey years are frequently not used in the analysis. The omission of this information may result in important shoreline trends going undetected.

The *average-of-rates*, or AOR method was first described by Foster and Savage (1989). It is a variation of the EPR method. but uses a minimum time criterion to reject data of questionable accuracy. The minimum time criterion is defined as:

$$T_{\min} = \frac{\sqrt{(E_1)^2 + (E_2)^2}}{R_1}$$

where E_1 and E_2 are the measurement errors for the two points (e.g., ± 10 m for USGS topographic maps), and R_1 is the EPR of the longest time span for a particular transect. According to this method, all data that survive this criterion are considered long-term rates. All long-term rates are then averaged. According to the Dolan et al. (1992) review, the advantages of this method are that all "good" data are used, short-term variability is filtered out, and the method allows for calculations of time-dependent variance from the average of rates.

Linear regression is used to calculate a best fit line through the data points available, with the slope of the line being an estimate of the mean shoreline rate of change. Linear regression is advantageous because it uses all available data points. It is a straightforward statistical computation, and is in widespread use within the scientific community. However, linear regression does not deal well with clumped data.

Jackknifing is a modification of the above method of linear regression. This method uses all possible combinations of regressions by omitting one data point for each iteration. A family of regression lines is generated, with the average slope being the estimate of long-term shoreline change rate. The advantages to this method are similar to those of linear regression, without being adversely affected by clumpiness. The primary disadvantage is the time and effort required to perform the computations.

The study by Dolan et al. (1991) found the AOR method to be the most variable of the four methods in terms of the spatial distribution of calculated rates. For Hatteras Island, linear regression and jackknifing produced similar results. The greatest differences in calculated rates were between linear regression and AOR and between jackknifing and AOR.

The second study by Dolan et al. (1992) used standard statistical methods (geostatistics) to determine the optimal sample size for shoreline rate of change calculations along Hatteras Island. The authors found that their original transect spacing of 50 m could be increased to 265–625 meter intervals with 95% confidence of the rate of change estimates being within ± 1 m yr^{-1}, or 160–315 meter intervals with 99% confidence of the estimates being within ± 1 m yr^{-1}.

Error analysis is an important part of shoreline change analysis. Numerous attempts have been made to quantify error associated with shoreline rate of change predictions. Crowell et al. (1991) summarized worst-case error estimates of historical shoreline maps and air photos:

T-sheets (1:10,000 scale) mapped prior to use of aerial photography (1844–1880):
error estimate of digitized position of HWL = 8.9 m + sketching error
T-sheets (1:10,000 scale) mapped prior to use of aerial photography (1880–1930:
error estimate of digitized position of HWL = 8.4 m + sketching error
Recent NOS maps compiled from aerial photography:
error estimate = 6.1 m + inaccurate interpretation of HWL

Smith and Zarillo (1990) estimated the potential error associated with locating the HWL could be as high as ± 40 meters. NOS maps and USGS 1:24,000 topographic maps have a stated error of ±10 meters.

3.4 Risk Assessment

Historically, the term "risk assessment" has been applied to the examination of potential risk to human health as a result of exposure to some introduced environmental toxicant. As an intellectual discipline, risk assessment is in its infancy. Within the past couple of decades, considerable research has been accomplished in the fields of toxicology, industrial hygiene, environmental impact assessment, engineering, and epidemiology. The vast majority of the accessible literature deals with such risk events as radiation exposure as a result of an industrial accident, impact of hazardous material on human health, impact of pesticides on human health, and oil spills. In recent years, a branch of risk analysis has formed that deals primarily with risks posed to the environment as a result of human activity; this type of analysis generally is referred to as "ecological risk analysis."

Traditional risk analysis deals primarily with the human health concerns of various anthropogenic activities. Numerous protocols exist for estimating the human health risk associated with various environmental toxins (e.g., Lilienfeld and Lilienfeld, 1980; Cohrssen and Covello, 1989; Tennant et al., 1987; Davis and Gusman, 1982; Travis and Hattermeyer–Frey, 1988). Traditional risk assessments are characterized by discrete events (e.g., an oil spill or the accidental release of a carcinogen into the environment) which result in a recognizable end–point (e.g., human death). Conversely, environmental stresses most often involve multiple stresses that affect a diversity of organisms or a number of ecosystems. For this reason, many researchers find the methods and assumptions of traditional risk analysis inappropriate to environmental science (Harwell et al., 1992).

3.4.1 Ecological Risk Assessment

In contrast to traditional risk analysis, ecological risk analysis attempts to resolve risks to the environment as a result of human activity. It is a developing field with few (if any) standardized approaches. Most ecological risk analyses performed place emphasis on activities that have broad scale consequences (e.g., global climate change) rather than activities which introduce an environmental contaminant into a relatively limited area. Conclusions based on ecological risk assessments are often in direct conflict with public perception of environmental risk and with the focus of the federal government's own agencies (Table 5). It seems likely that ecological risk analysis will become a key element in the future development of environmental policy at all levels of government.

The paradigm of traditional risk analysis (single stress→single endpoint) has limited application in the field of ecology. Situations which involve the release of a toxin or pollutant into the environment might be well-suited to traditional approaches; however many environmental problems involve multiple stresses that affect many components of an ecosystem. For example, an oil spill poses quantifiable risks to human populations, but the problem is more complex with respect to the risks faced by the affected ecosystem. The task of hazard identification takes on a whole new meaning when dealing with global climate change; an increase in average global temperature might favor some species, but adversely affect others.

Only the most general of paradigms are available for those interested in quantifying ecological risk. Harwell et al. (1992) described this paradigm as a three–step approach: 1) characterize the stress regime experienced by various components of the ecosystem; 2) characterize how ecosystems respond to stress; and 3) characterize how ecosystems recover from or adapt to stress.

The definition of stress includes chemical and physical exposure, and must consider the occurrence of nonchemical stress, spatial extent, frequency, intensity, and duration of the stress event. Differential intensities of the stress within the ecosystem, occurrence of other simultaneous anthropogenic stresses, and the background naturally–occurring stresses must also be integrated. Harwell et al. (1992) listed factors which limit researchers' ability to predict ecosystem response to stress events. These include:

- diversity of ecosystem type
- diversity of disturbance type
- differential response of ecosystems to stresses
- diversity in response according to scale
- lack of baseline information on ecosystem function
- fundamental limitations in ecological theory
- environmental variability and stochasticity

One method of dealing with ecological risk is a prioritization methodology described by Harwell et al. (1992). The authors began with a list of predominantly environmental human health risks found in EPA publications (EPA, 1987a and 1987b). They expanded this list to include a broad range of environmental risks. Harwell et al. then created a matrix of environmental stresses (e.g., acid deposition) and fundamental ecosystem types (e.g., estuaries). This matrix was intended to include projections of recovery potential and magnitude of ecological effects for each ecosystem as a function of a particular stress. A second matrix distinguishes between risks which can be differentiated by scale (global, regional, or local) and risks differentiated by transport mechanism (air, water, or terrestrial). A third matrix relates environmental stresses to recovery time frames. The result of this is an "ecological risk prioritization matrix (Table 6)".

Gornitz et al. (1994) developed a coastal risk assessment database for the southeast coast of the U.S. based on coastal vulnerability to sea-level rise. Their coastal vulnerability index is based on thirteen geophysical and climatological variables including lithology, elevation, subsidence, erosion/accretion, tropical storm probabilities of occurrence, and maximum storm surge. The thirteen variables were grouped into three clusters using factor analysis: permanent inundation, episodic inundation, and erosion potential. The permanent inundation factor incorporated elevation and relative sea level variables. The episodic inundation factor included climatic variables such as tropical storm and hurricane probabilities, extratropical storm frequencies, and storm surge height. The erosion potential factor consisted of geology, shoreline displacement, and wave height variables. These three factors were used to calculate a coastal vulnerability index. The data were presented in grid form, with the grid cells equal to 7.5' latitude by 7.5' longitude. Each cell was classified as being at low, moderate, high, or very-high risk due to sea level rise. Gornitz et al.'s (1994) study represents the cutting edge in terms of application of risk assessment techniques to coastal management strategies. Its major drawback is the relatively large scale (7.5' latitude by 7.5' longitude). However, future risk assessment protocols developed for CAHA could certainly incorporate some elements of Gornitz et al.'s method.

4. METHODS

The goal of this project is to develop a protocol to apply a coastal risk assessment model of physical processes influencing Cape Hatteras National Seashore. This section outlines the methodology used to estimate the spatial variation in magnitude of three components of barrier island transgression for Cape Hatteras National Seashore: shoreline translation, probability of inlet formation, and overwash frequency. These processes were chosen as the basis for the protocol because of their significant historic impact upon the Outer Banks as well as the availability of historic data. Other processes (e.g., littoral sediment transport or sediment removal via human activity) are key components of barrier island dynamics but either could not be modeled within the scope of this project or had no historic data available.

4.1 General Overview of Protocol:

Using the geographic information system (GIS) software ARC/INFO (v. 7.0.2), 338 shore–normal reference transects 250 meters apart were identified from Bodie Island to southwest of Cape Hatteras (Figure 4). Each transect was evaluated for the relative magnitude or probability that each of the 3 risk components would occur at that site. Based on the evaluation, a score of 1, 3, or 5 was assigned to each transect for each risk component, with 1 defined as low risk, 3 defined as moderate risk, and 5 defined as high risk. The potential risk to park resources was subsequently evaluated according to the nature of the resource. A variety of historical data were used to develop the risk assessment.

4.2 Generation of Reference Transects:

The transects were generated using a macro program within ARC/INFO (`transects.aml`). The macro allowed for detailed spatial placement of the transects. The transects were placed approximately perpendicular to the most recent shoreline while still considering their orientation relative to the historic shorelines (see below) which would be analyzed as part of this study. Transects spaced 250 meters apart were within the optimal distance of 160–315 meters used for conducting shoreline change analysis along the Outer Banks (Dolan et al., 1992). The transects were numbered sequentially from north to south (Figure 4). The northern limit of the transects was the park boundary on Bodie Island (Figures 1 and 4). The southern terminus was limited by the availability of reliable data for a shoreline change analysis. The GIS coverage of the reference transects is superimposed on the shoreline retreat coverage, inlet formation coverage, and finally the historic overwash coverage. The transects then were coded for each risk parameter according to the protocol outlined below.

4.3 Historical Shoreline Analysis and Retreat Risk Determination:

Historical shoreline surveys for Cape Hatteras National Seashore exist for 1852, 1917, 1946/1947 and 1980 (Figure 5). The source for these surveys is a series of 1:24000 scale maps published by the NOAA/NOS–CERC Cooperative Shoreline Movement Study (Everts et al., 1983). A 1993 shoreline was surveyed by Harold Berquist of the VIMS Coastal Inventory

Program using a high–precision GPS unit *in situ* and traveling along the high water line on a falling tide.

The analysis of shoreline trends was performed using ARC/INFO. Each historic shoreline survey was digitized as a separate ARC/INFO coverage (Figure 5). Temporally sequential shoreline coverages were joined together (e.g., 1980 and 1993) to form single unioned coverages. Each of these coverages was then joined with a copy of the coverage containing the transects. The distance along each transect between the two sequential shorelines was divided by the time difference in years between surveys, yielding approximate rates of change in shoreline position (m yr^{-1}) at 250 meter intervals along the shore. Each transect was characterized by four rates of change corresponding to a specific time interval (1852–1917, 1917–1946/1947, 1946/1947–1980, and 1980–1993). An overall mean rate of change at each transect location was calculated over the study period (1852–1993) by averaging the interval rates computed above. These rates were applied in the risk assessment score (Appendix 1).

For computational purposes, transects were grouped according to their geographic location (e.g., Bodie Island, Pea Island, Hatteras Island; Figure 4). The median retreat rate (shoreline rate of change ≤ 0 m yr^{-1}) for each island was calculated for the interval 1852–1993 (Appendix 2). The risk of shoreline retreat at each location was defined relative to the median retreat rate for that region.

The risk of shoreline retreat is defined as being either high, moderate, or low. A transect is assigned a high risk score (risk = 5) if the mean rate of change is greater than or equal to the appropriate median retreat rate.

Transects are defined as having a moderate risk of retreat (risk = 3) if the mean rate of change is between 0 meters per year (inclusive) and the median retreat rate. All transects with positive mean shoreline rates of change (i.e., prograding over time) are considered to have a low risk of shoreline retreat, and receive a risk score of 1.

4.4 Relative Risk of Inlet Formation:

Relative risk of inlet formation is based on two sources of data: present island width and historic inlet positions. Historical inlet data are available from Fisher (1962). Everts et al. (1983) provides an accounting of historic inlet activity along the Outer Banks based on Fisher's study. The authors suggest a relationship between previous inlet activity and potential for new inlet formation. Historic inlet locations (from Fisher, 1962 and Everts et al., 1983) plus associated position error (±5" of latitude) were digitized into an ARC/INFO coverage (Figure 2). The Everts et al. study also suggests a relationship between island width and the probability of inlet formation; the narrower the barrier, the higher the probability of inlet formation. The critical width was defined as 1 kilometer. Figure 6 shows areas of Cape Hatteras National Seashore which are narrower than 1 kilometer.

Areas that are defined as having a high relative risk of inlet formation (risk = 5) are those that are narrower than 1 kilometer and have experienced inlet activity in the past. Areas that are defined as having moderate risk of inlet formation (risk = 3) are those that are either narrower than 1 kilometer or have experienced inlet activity in the past. Sections of the Outer Banks that are wider than one kilometer and have not experienced inlet activity within the time period covered by the historic record are defined as having a low relative risk of inlet formation (risk = 1).

4.5 Relative Risk of Overwash:

Risk of overwash for any particular storm event is difficult to quantify. Factors including local relief, wave height and storm surge magnitude determine where and whether overwash or dune breach occur during storm events. Some authors (e.g., Pierce, 1969) suggest that over a 20 to 50 year time span the risk of overwash is roughly equal all along the Outer Banks. Overwash risk can generally be assessed by analyzing the spatial distribution of past overwash events and the topography of the region. Fly-over video was available for conditions in the park immediately following two storm events: the Christmas Northeaster of 1992 and Hurricane Emily of 1993. Analysis of these videos allowed for a general assessment of those park areas that are susceptible to overwash. Figures 7a–7d show the approximate extent and geographic distribution of overwash for each of the two storm events. Information on historic overwash frequency is found in a report by Boc and Langfelder (1977; Figure 8). Detailed topographic data specific to the study region is not currently available; as a consequence, the relative risk of overwash is characterized solely on the basis of historic information.

High risk of overwash (risk = 5) is defined as those sections of the Outer Banks which have experienced total overwash at any point according to the historic and observational data. Moderate risk of overwash (risk = 3) is defined as those sections of the Outer Banks which have experienced only partial overwash according to the historic and observational data. Low risk of overwash is defined as those sections which have not experienced overwash in any capacity according to the available data. With respect to the observational data, "total overwash" is defined as overwash events which crossed Highway 12. "Partial overwash" is defined as overwash events which breached the dune line but did not cross Highway 12.

4.6 Combined Risk Determination:

The risk scores were averaged at each location to produce a mean, or combined, risk. For example, transect 70 received risk scores of 5, 3, and 3 for shoreline retreat, inlet formation, and overwash respectively (Appendix 1). The combined risk is calculated to be 3.7. This method assumes that each physical process contributes equally to the overall risk at any location.

4.7 Risk Assessment

The second component of this study involves projecting the risk posed by shoreline retreat, inlet formation, and overwash to the various cultural sites and natural resources within Cape Hatteras National Seashore. The risk assessment assumes that both cultural sites and natural resources are differentially susceptible to the three physical processes considered. The risk assessment protocol couples the susceptibility of a site or resource to a process with the magnitude or probability of occurrence of the process. The protocol allows for the determination of relative risk to cultural sites and natural resources within the National Seashore.

Table 3 lists the cultural sites located within Cape Hatteras National Seashore which were evaluated as part of the risk assessment. These sites include such well–known park structures as the Cape Hatteras Lighthouse and the Little Kinnakeet Life Saving Station (Figures 3a–3c). Each cultural site was evaluated for its susceptibility to impacts from shoreline retreat, inlet formation, and overwash. This susceptibility score (Table 7) is a qualitative measure based on factors such as the geographic location and the general physical character of the site.

The risk to resources posed by the three processes is assumed to be a function of both susceptibility and opportunity. That is, a resource may be highly susceptible to a particular process, but if the process does not occur at that location then the risk to the site is attenuated. To incorporate both susceptibility and process into the protocol, the susceptibility scores for a particular site are averaged with the risk rankings of adjacent transects (Table 7) to produce resource risk numbers for each parameter. If the cultural site is located proximal to a single transect, then the risk scores for that transect are used in the calculation. If the site is roughly equidistant from two transects, the mean risk scores for the two transects are used in the calculation. For example, the Little Kinnakeet Coast Guard Station is assigned susceptibility scores of 3 , 5, and 5 for shoreline retreat, inlet formation and overwash respectively. The site is located approximately equidistant from transects 260 and 261. Therefore the mean risk scores of the two transects are used to calculate the risk numbers for this cultural site. The mean retreat risk for both transects is 3.0, which is averaged with the retreat susceptibility score for the station (i.e., 3.0) to yield a retreat resource risk number of 3.0. This process is repeated for inlet formation risk and overwash risk, which yield resource risk numbers of 4.0 The three resource risk scores (3.0, 4.0 and 4.0) are then averaged to yield a combined resource risk score of 3.7.

The final output is four risk scores for each resource: one each for shoreline retreat, inlet formation, overwash and a mean risk score. The utility of these numbers is that one can assess the relative overall risk to a particular resource due to general processes operating on barrier islands. One also can examine the relative contribution of these processes in determining the combined risk (i.e., which risk parameter puts the resource most at risk).

Evaluation of risk to natural resources within the park as a result of barrier island dynamics was performed in essentially the same manner as the cultural resources. This study evaluated the risk to threatened and endangered species and other biota within the park using two species, the least tern and the loggerhead turtle, as examples of how a risk assessment protocol might be applied to biological resources. Figures 9a–9c and Figures 10a–10d show the distribution of the least tern and loggerhead turtle, respectively, within the park. These species were chosen because they rely on different habitats within barrier island environments in order to complete their life cycle. Terns build nests in dune fields, and return to the same nesting sites every year. Loggerhead turtles nest on the beach, and are not known to specifically seek out previous nesting sites (NPS, 1993).

For each species, susceptibility to impacts from the three risk parameters is estimated and used with risk information to generate overall risk estimates (Tables 8 and 9). Both species are judged to be highly susceptible to inlet formation (score = 5) and moderately susceptible to retreat and overwash (score = 3). Inlet formation is the only process that would literally remove available habitat as a discrete event. While overwash and shoreline retreat are potentially damaging to the species' nesting sites, these processes act to move the island system as a whole. The determination of resource risk numbers for the least tern and loggerhead turtle is performed in the same manner as the resource risk numbers for the cultural sites.

This study assumes that park policy would allow changes in natural resources within park boundaries as a result of natural processes only; that is, park officials would strive to eliminate the role of human activity in forcing ecosystem changes within the park. In support of this goal, the risk assessment for the example species was conducted within the framework of existing and stated National Park Service policies (NPS, 1993).

5. RESULTS AND DISCUSSION

5.1 Shoreline Change Analysis:

Appendix 2 summarizes the calculated rates of change at each reference transect over all survey intervals. Figures 11a–11d show the frequency distributions of the rates of change, while Figures 12a–12d graphically represent data in Appendix 2. Table 10 summarizes the rate of change data by geographic region.

The data show an increase in not only the overall magnitude of shoreline retreat in Cape Hatteras National Seashore, but an increase in the amount of shoreline affected by the retreat as well. The initial survey interval, Figure 12a, is characterized by three major areas of shoreline retreat and two major areas of shoreline advance. The areas experiencing recession are found on either side of Oregon Inlet, south of New Inlet (transects 110–130), and immediately north of Cape Hatteras (transects 270–304). Areas experiencing significant progradation are north of Avon (transects 200–240) and south of Cape Hatteras (transects 305–338). The second survey interval, shown in Figure 12b, is characterized by four major retreat areas and only one major advance area. Both sides of Oregon Inlet, the New Inlet region, and the shoreline north of Cape Hatteras are all again characterized by retreat, with another major retreat area just north of Avon. The survey interval 1947–1980 (Figure 12c) is marked by three major retreat areas, one major advance area, and many local variations in shoreline change rates. Here again, the major retreat areas are north and south of Oregon Inlet (although immediately north of the inlet, the shoreline is apparently accreting), the relict New Inlet region, and north of Cape Hatteras. South of the bend at Cape Hatteras, there is shoreline advance. The most recent survey interval, 1980–1993 (Figure 12d), is characterized by shoreline retreat throughout the park. Only the area immediately south of Cape Hatteras and the north shore of Oregon Inlet are experiencing shoreline advance. The rate of shoreline retreat appears to be increasing along the northern shore of Pea Island National Wildlife Refuge (transects 70–110).The highest rates of shoreline retreat presently are found south of the Cape Hatteras Lighthouse; the shoreline here is retreating at approximately 20–25 meters per year (transects 290–304). It is reasonable to relate this rapid loss of shoreline to the construction in 1969 of three 500–foot jetties immediately in front of the lighthouse. The jetties were built by the U.S. Army Corps of Engineers to help stabilize the shoreline and prolong the life of the lighthouse. Many coastal geologists (e.g., Dolan, 1972; Inman and Dolan, 1989; Leatherman, 1988) have testified to the relationship between groin and jetty placement along barrier coasts and accelerated loss of shoreline downdrift.

Figure 13 shows the output shoreline retreat risk by transect for Cape Hatteras National Seashore based on data presented in Appendix 1. Virtually all of CAHA is characterized as being at moderate risk or greater to shoreline retreat. The only areas that are at low risk are those that are on the accreting side of Oregon Inlet, a limited section of shoreline just south of Rodanthe (transects 145–146) and an area just south of Salvo (transects 162–180), and the reach immediately west of Cape Hatteras. Areas that are at high risk of shoreline retreat are north of Oregon Inlet, almost all of Pea Island National Wildlife Refuge, and the entire shoreline from Avon to Cape Hatteras.

5.2 Inlet Formation:

Figure 14 shows the output inlet formation risk by transect for Cape Hatteras National Seashore. Almost all of the park is under a minimum of moderate risk of inlet formation. Local areas of low risk are found in sections of the park that are particularly wide (e.g., near Avon). The greatest risk of inlet formation appears to be in Pea Island National Wildlife Refuge north of Rodanthe and the extremely narrow section of Hatteras Island between Avon and north of the Cape Hatteras Lighthouse complex. Both of these areas are quite narrow (Figure 6) and have been characterized by inlet activity in the past, with New Inlet being located in Pea Island National Wildlife Refuge, and Chacandepeco and Buxton Inlets being located south of Avon.

5.3 Overwash Probability:

Figure 15 shows the output overwash risk by transect for Cape Hatteras National Seashore. Most of the park is under moderate risk of overwash, with the highest risks being found at the northern end of Pea Island National Wildlife Refuge and near Cape Hatteras. PINWR in particular experiences overwash during even relatively minor storms. Some local areas are characterized as having a low overwash risk; these are found almost exclusively near the enclaves of Rodanthe, Waves, and Salvo. Some authors (Pilkey et al., 1980) have suggested that this region of the Outer Banks is topographically higher than other, more overwash–prone areas.

5.4 Combined Risk:

Figure 16 illustrates the combined risk computed for the three parameters. The parameters (shoreline retreat, inlet formation, and overwash) are weighted equally to produce the combined or mean risk value. The values range from 1.0 (low) to 5.0 (high). The only low risk section of the park is immediately south of Rodanthe, although a small stretch of shoreline to the west of Cape Hatteras is low risk as well. The sections of CAHA most at risk are the southern end of Bodie Island, the northern end of Pea Island National Wildlife Refuge between Oregon Inlet and Rodanthe, and the area between Avon and Cape Hatteras.

5.5 Calculated Risk to Cultural Resources:

Risk values were calculated for each cultural resource listed in the CAHA inventory. Each site received four scores: shoreline retreat risk, inlet formation risk, overwash risk, and an overall mean risk to the site. Table 7 summarizes the risk assessment information for the cultural sites within CAHA. The scores reflect a combination of the assumed susceptibility of the site to the risk parameters and the calculated risk at the transect(s) nearest the site in question.

Risks to structures within the Cape Hatteras Lighthouse complex ranged from 2.0 (moderate) to 5.0 (high). The Civilian Conservation Corps cabins received an overall risk score of 3.0, with constituent scores of 4.0 (shoreline retreat), 2.0 (inlet formation), and 3.0 (overwash). The oil house and two keepers' quarters received overall risk scores of 4.0 with constituent scores of 5.0 (shoreline retreat), 3.0 (inlet formation), and 4.0 (overwash). The

Cape Hatteras Lighthouse received an overall score of 3.7, with constituent scores of 5.0 (shoreline retreat) and 3.0 (inlet formation and overwash). These structures are most at risk from shoreline retreat, although overwash does pose a moderate risk.

Cultural sites at the Kinnakeet and Chicamacomico sites received overall scores ranging from 3.0 to 4.0. The Big Kinnakeet Tower Ruins received generally high risk scores (3.0, 5.0 and 4.0 for shoreline retreat, inlet formation, and overwash respectively) with an overall score of 4.0. All of the Little Kinnakeet sites (the Coast Guard Station, Kitchen, and Lifesaving Station) received overall risk scores of 3.7 with moderate constituent scores (3.0, 4.0 and 4.0 for shoreline retreat, inlet formation, and overwash respectively). The Chicamacomico boathouse and garage received a high overall risk score of 4.0, with a moderate shoreline retreat score (3.0) and high scores for inlet formation and overwash (5.0 and 4.0). All of the structures at these sites are under relatively high risk overall, with inlet formation and overwash posing the greatest threats. Retreat of the Atlantic coast shoreline poses only a moderate threat at this time since the cultural sites are located on the sound side of the island.

NPS–owned and operated sites on Bodie Island (the Bodie Island Lifesaving Station and the Bodie Island Coast Guard Station) received high overall risk scores of 4.3 with constituent scores of 5.0 (shoreline retreat), 4.0 (inlet formation) and 4.0 (overwash). Although the facilities at the Bodie Island Lighthouse complex are not managed by the NPS, they were included in the risk assessment. The Bodie Island Lighthouse and associated oil house received overall risk scores of 3.0 with constituent scores of 3.0, 4.0 and 2.0 for shoreline retreat, inlet formation, and overwash respectively. The Bodie

Island Lighthouse Keeper's Quarters and Storehouse had shoreline retreat risk scores of 3.0, inlet formation risk scores of 4.0 and overwash risk scores of 2.0 with an overall risk score of 3.0. The Bodie Island Lifesaving Station and Coast Guard Station are under high overall risk, particularly due to shoreline retreat. The proximity of these structures to the shoreline places them in eminent danger from all three barrier island processes considered in the risk assessment.

Table 11 shows the CAHA cultural sites ranked according to overall risk. The sites at greatest risk are the Bodie Island Lifesaving and Coast Guard Stations, followed closely by the structures at the Cape Hatteras Lighthouse complex. However, the rankings for the Bodie Island structures are probably somewhat overestimated due to their proximity to Oregon Inlet; the method for estimating the likelihood of inlet formation favors locations near existing inlets as well as those locations near relict inlets. In any case, these two sites are under moderately high risk due to barrier island processes, particularly shoreline retreat.

5.5.1 Management Considerations:

It is important to note that the risk assessment protocol does not make any judgments about how the NPS should prioritize its management actions regarding the cultural sites. The consequences of loss or damage as a result of natural processes need to be considered when cultural sites are evaluated for protection. This study makes no assumptions regarding the subjective value of the various cultural sites to the National Park Service. However, it is obvious that some cultural sites are intrinsically more valuable than others, for example one might surmise that NPS would spend a great deal of money to maintain the integrity of Cape Hatteras Lighthouse.

There are a number of policy options the National Park Service might pursue in order to maintain the physical integrity of cultural resources in the face of dynamic geophysical conditions. These options include but are not limited to:

- shoreline stabilization through groin/jetty placement
- sea wall construction
- dune and road maintenance
- beach replenishment
- placement of revetments around structures
- physical relocation of structures to more inland sites

The likelihood that any of these actions will be endorsed by the Park Service is difficult to assess. Given the nation–wide objective of NPS to allow natural conditions to predominate in national parks, one might predict that the construction of physical barriers to island migration (e.g., groins and jetties) is unlikely to occur barring extraordinary circumstances.

While groins were placed along the shoreline in front of Cape Hatteras Lighthouse in 1969, there is no evidence to suggest that the National Park Service desires a solution of that variety elsewhere in the park. The only remaining shoreline engineering solution is beach replenishment, which is by many accounts expensive and has an uncertain success rate (e.g., Leatherman, 1988). In the past, at least, the Park Service has shown a willingness to engage in so–called “soft engineering” efforts at shoreline stabilization. In 1973, the NPS endorsed a shoreline nourishment project that pumped approximately 1.3 million cubic meters of sand from Cape Point to a 3.3 kilometer stretch of beach north of the lighthouse (Pilkey, et al., 1980). The relative success of the $4.3 million project is difficult to assess.

It seems that the National Park Service should prepare for physical relocation of culturally significant structures as the only management option available to them which is consistent with NPS policy. Relocation is an acceptable alternative to loss; the Park Service has endorsed a plan to relocate the Cape Hatteras Lighthouse when it can be shown that the structure is in imminent danger from the sea (NPS, 1993).

5.6 Calculated Risk to Natural Resources

Least tern nesting areas occur in an area south of Avon (Figures 9a–9c) that is covered by reference transects 267–271. Table 9 shows the risk calculation for the least tern. Tern nesting areas were judged to be highly susceptible to inlet formation (susceptibility = 5) and marginally susceptible to shoreline retreat and overwash (susceptibility = 3). Terns build seasonal nests in dune habitat, and thus are likely to be able to find suitable nesting sites even if the island retreats, as long as the dunes reestablish themselves. Inlet formation, on the other hand, would remove all available habitat in the preferred nesting area . The least tern resource risk numbers for shoreline retreat were calculated to be 4.0, 5.0, and 3.0 for retreat, inlet formation, and overwash respectively. The overall resource risk number was calculated to be 4.0. According to Potter et al. (1980), least terns begin nesting in May. Along the Outer Banks, usually a single brood is born, although damage to the nests as a result of storms may result in numerous attempts. Storm activity is typically highest along the Outer Banks during the months of October through March (Davis et al., 1992); least tern nesting generally coincides with the least stormy time of year.

Because the distribution of loggerhead turtle nesting sites encompasses all of Cape Hatteras National Seashore (Figures 10a–10d) south of Oregon Inlet, individual nesting sites cannot be evaluated for potential risk. Therefore, the resource risk number calculation for the loggerhead turtle includes all possible combinations of risk values. Table 9 shows the possible combinations of risk values for the reference transects with corresponding resource risk numbers. While only high retreat and overwash risk scores result in a high resource risk number (4.0), even a moderate inlet formation risk score results in a high resource risk number (4.0), and a high inlet formation risk score produces a very high resource risk number (5.0). Turtle nesting sites experience the greatest risk when retreat risk or overwash risk are high, or in areas of moderate to high risk of inlet formation. Unfortunately, this is virtually the entire park. Figure 17 shows the optimum loggerhead turtle nesting habitat based on the calculated resource risk numbers. Optimal nesting locations are those locations characterized by low or moderate (scores = 1, 3) risks of retreat and overwash, and by low (score = 1) risk of inlet formation. Poor nesting areas are those characterized by moderate or high (score = 3, 5) risk of inlet formation, or by high (score = 5) risk of retreat or overwash. All other areas (the vast majority of the park) are deemed satisfactory nesting area, at least with respect to the three parameters modeled in this study. Optimal nesting areas are limited to Hatteras Bight, west of Cape Hatteras, and beaches in front and south of the Rodanthe–Waves–Salvo enclave (Figure 17). Nesting areas at high risk are those located in southern Bodie Island, northern Pea

Island, and between Avon and the Cape Hatteras Lighthouse. The NPS currently provides for relocation of loggerhead turtle nests found in high hazard areas (NPS, 1993). The NPS should certainly continue to monitor sea turtle nesting activity, particularly in the high risk areas mentioned above. Carr (1952) states that loggerheads typically nest from April to August, with the peak period in June. Like the least terns, the nesting period for the loggerhead thus takes place during the least stormy period of the year.

5.6.1 Management Considerations:

As with the cultural sites, the output resource risk numbers only estimate the potential risk to the natural resource in question; the protocol does not address the attendant management issues. Although the example species were found to be primarily influenced by inlet formation, shoreline retreat and overwash do have risk associated with them. This is significant in light of park management practices. Any park management activity which interferes with the island's ability to maintain itself with rising sea–level could impact the species in question, and presumably others as well.

For example, the National Park Service has committed itself by agreement with the state of North Carolina (NPS, 1993) to allowing maintenance of North Carolina State Highway 12 (Figures 3a–3c), which runs the length of the park and connects the local communities on the island to one another and to the mainland. As a general practice, sand which is deposited on the roadway during storm events is pushed either back into the primary dune line or onto the beach face. Little, if any, sediment is allowed to cross the island onto the marsh via storm overwash. Less sand is thus available for vertical and horizontal adjustment of the barrier's position. The island's ability to maintain itself in the face of rising sea level and potential climate change is thus restricted. The impact on natural resources is potentially devastating. As the shoreline retreats toward Highway 12, the dune and beach area available for colonization by nesting shorebirds and/or sea turtles decreases. An alternative strategy might be to remove the sand from the roadway to the salt marsh area of the backbarrier in such a fashion as to simulate natural washovers.

Another management option that the NPS has enacted in the past is relocating Highway 12. In 1973, a severe storm washed over a section of the island south of Avon. In response, the NPS endorsed the previously mentioned beach nourishment project and allowed re–routing of Highway 12 to a more inland location (Pilkey, 1980). The North Carolina Department of Transportation is currently relocating a section of the highway in Pea Island National Wildlife Refuge.

6. CONCLUSION

In general, the shoreline within Cape Hatteras National Seashore appears to be almost uniformly retreating, except for the area south of Cape Hatteras and a local area south of Salvo. Moreover, the shoreline change frequency distributions show that recession rates are increasing along the shoreline over time. This trend is particularly evident immediately south of the Cape Hatteras Lighthouse: retreat rates here exceed 20 meters per year. The other major area of rapid shoreline retreat is northern Pea Island, where average retreat rates approached 10 meters per year from 1980–1993.

The risk of inlet formation within the park generally is also moderate to high. The only area that appears to be at relatively low risk for inlet formation is immediately north of Cape Hatteras. The method used to estimated inlet formation risk is based on historic information, however, and therefore tends to bias the assessment toward currently open inlets. As was pointed out in the literature review, this is not necessarily always a realistic assumption. However, inlets have tended to open in the same spots repeatedly on the Outer Banks in the past.

The overwash risk most likely is underestimated due to a lack of recent data on the distribution and frequency of overwash events on the Outer Banks. Some authors suggest that all of the Outer Banks is essentially under the same long–term (20 years or greater) risk of overwash (e.g., Pierce, 1969). There is a great need for further observation in this area; further refinement of this part of the risk assessment should be based on a more thorough treatment of overwash patterns within CAHA. Local topography greatly influences the relative magnitude of a given overwash event. Unfortunately the physical nature of the barrier island system hinders any attempt to gather reliable topographic data; the relief simply changes too frequently in the dune and beach area for the data to be of much value.

Future versions of this risk assessment protocol would benefit from the inclusion of a treatment of the seasonality of the processes involved. There is a clear seasonal component to the processes of shoreline retreat, inlet formation, and overwash. Winter northeasters drive much of the physiography of the Outer Banks, and as a result the probability of any single event (e.g., overwash) is not the same throughout the year. The temporal variability also has consequences for the biota of the Outer Banks, as was noted previously.

The risks posed to various cultural and natural resources as a result of the physical process of barrier island rollover are difficult to quantify. This study explores the potential benefits to a particular resource management area of a relative risk assessment, which attempts to gauge the relative risk at any geographic location. Figure 18 shows the combined risk due to all three barrier island processes for Cape Hatteras National Seashore. The northern end of Pea Island is the most dynamic region of the park, with high rates of shoreline retreat, frequent overwash and a high probability of inlet formation.

NPS efforts to prevent storms from depositing sand on Highway 12 through sandbagging the dune line and removal of overwash deposits are likely to make matters worse for the Park Service in the long run by restricting the delivery of sediment across the island. Similar management dilemmas exist north of Cape Hatteras near the lighthouse complex. Although inlet formation essentially is a non–factor, and overwash only a minimal problem, rates of shoreline retreat in excess of 20 meters per year will force park officials into a triage: which cultural sites are most valuable and need to be preserved, and at what expense to the natural resources of the park?

Table 1: Major management issues and practices at Cape Hatteras National Seashore (NPS, 1993)

Water quality and quantity

Issues: degradation of water quality in marsh and pond systems on Bodie Island, Buxton Woods; degradation of water quality in park areas adjacent to village enclaves; increasing groundwater withdrawal to provide potable water for village enclaves

Management response: water quality monitoring program; survey of Buxton Woods topography and hydrology

Global climate change

Issues: changes in species composition; accelerated loss of shoreline, barrier island transgression; human compensation for changes in coastal processes

Management response: none as yet

Toxic waste/Pollution

Issues: toxic materials and pollutants delivered to Seashore through variety of mechanisms; relict dump sites

Management response: NMFS and NPS marine debris survey; annual report of findings; proposed delineation and mitigation of toxic material deposits project

Threatened and endangered species

Issues: dependence of threatened and endangered species (loggerhead sea turtles and piping plovers) on National Seashore natural resources

Management response: Nesting Beach Survey, turtle nest relocation; protection of plover nesting sites, plover production study

Exotic species

Issues: inhibition or supplantation of native species by exotics; feral cats preying upon piping plovers; potential gypsy moth colonization

Management response: direct population reduction measures for predatory exotics; monitoring for presence of gypsy moths; proposed project to monitor invasive species

Visitor impacts

Issues: large number of visitors to park annually (average of 1,890,428 during period 1983–1992) assumed to degrade various natural resources; off-road vehicle (ORV) use on beach

Management response: informal assessment of visitor impacts pending funding of formal study; informal monitoring of ORV impacts

Table 1: Major management issues and practices at Cape Hatteras National Seashore (NPS, 1993)

Development

Issues: degradation of park resources through new construction; changes in vegetation in response to alteration of physical landscape due to new development

Management response: conditional permit issuance for new construction; GIS–based land use/ land cover monitoring

Prescribed fire

Issues: fire used as a tool for habitat manipulation

Management response: CAHA has no formal Fire Plan currently

Coastal processes

Issues: maintenance of shipping channels through dredging; placement of dredged materials; erosion of turtle and bird nesting habitats

Management response: informal monitoring of dredge effects by CAHA staff; NPS–guided disposal of dredged materials for bird area enhancement

Oil and gas

Issues: existence of Outer Continental Shelf oil exploration sites within 30 miles of CAHA shoreline suggests potential adverse impacts to fauna

Management response: review of appropriate NEPA documentation for OCS projects by CAHA staff

Hunting

Issues: waterfowl hunting is a legislatively mandated activity at CAHA

Management response: monitoring and management of waterfowl habitat

Table 2: NPS goals for Cape Hatteras National Seashore (NPS, 1993)

1. Establishment of the National Seashore for the benefit and enjoyment of the public.

2. Preservation and protection of cultural resources.

3. Preservation and protection of natural resources.

4. Provide for residents to be allowed to fish commercially, subject to regulation of DOI, and to protect recreational use.

5. Develop certain areas for recreational use.

6. Management of the Seashore should be compatible with USFWS management on refuge lands.

7. Provision for waterfowl hunting under rules and regulations of the Secretary in designated areas.

8. Provision for reserved rights-of-way to build and/or maintain roads on lands deeded to NPS from the State of North Carolina.

9. Compliance with generic federal legislation and policy.

Table 3: Cultural Sites Inventory for Cape Hatteras National Seashore

Cultural Site	Location
CCCC Houses (4)	Transects 290–291
Cape Hatteras Lighthouse	Transect 289
Small Brick Oil House	Transect 289
Principle Keeper's Quarters	Transect 289
Double Keeper's Quarters	Transect 289
Big Kinnakeet Tower Ruins	Transects 260–261
Little Kinnakeet Coast Guard Station	Transects 221–222
Little Kinnakeet C.G. Station Kitchen	Transects 221–222
Little Kinnakeet Life Saving Station	Transects 221–222
Chicamacomico Boathouse and Garage	Transects 135–136
Bodie Island Life Saving Station	Transects 21–22
Bodie Island Coast Guard Station	Transects 21–22
Bodie Island Lighthouse and Oil House	Transect 29
Bodie Island Lighthouse Keeper's Quarters	Transect 29
Bodie Island Storehouse	Transect 29

Table 4: Synoptic characteristics of northeast storms[a]

Synoptic Type	Characteristics
Bahamas Low	Cyclogenesis in Atlantic between Florida coast and Bahamas. Blocking anticyclone in northeast U.S./southern Canada. Long fetch, slow-moving.
Florida Low	Similar to Bahamas Low. Cyclogenesis over southeastern U.S. or off Florida coast. Blocking anticyclone usually present.
Gulf Low	Cyclogenesis west of Florida along stationary front, usually in Gulf of Mexico. Blocking anticyclone absent. Track rapidly, long fetch.
Coastal Plain Cyclogenesis	Cyclogenesis occurs along cold or stationary front over mid-Atlantic or southeast U.S. Blocking anticyclone absent.
Hatteras Low	Secondary cyclone usually formed along warm or stationary front off coast of North Carolina. Highly variable in formation and intensity.
Continental Low	Cyclogenesis typically in lee of Rocky Mountains. Can develop long fetch if system stalls upon reaching Atlantic coast. Difficult to classify.
Coastal Front	Weak cyclogenesis along stationary front parallel to East Coast. Generally short-lived with short fetches.
Anticyclone	Storm winds and waves generated solely from a high pressure system.

- Bahamas Lows, Florida Lows, Gulf Lows most potent.

- Coastal Fronts, Gulf Lows, Anticyclones most common.

[a]From Davis et al., 1992

Table 5: Ecological risk priorities vs. public perception of environmental risks[b]

Ecological risk priorities	Public perception of environmental risks
Highest ecological risks	•active hazardous waste sites
•global climate change	•abandoned hazardous waste sites
•habitat alteration	•water pollution from industrial sources
•stratospheric ozone depletion	•oil spills
•biological depletion	•stratospheric ozone depletion
Higher ecological risks	•radiation from nuclear power plant accidents
•herbicides and pesticides	•chemicals from industrial accidents
High ecological risks	•radionuclides in nuclear waste
•toxics in surface waters	•industrial air pollution
•acid deposition	•groundwater contamination from leaking tanks
•airborne toxics	•coastal pollution
Medium ecological risks	•solid waste
•nutrients	•water pollution from agricultural runoff
•BOD	•water pollution from sewage plants
•turbidity	•vehicular air pollution
Low ecological risks	•global climate change
•oil and petroleum products	•wetland habitat alteration
•groundwater contamination	•acid deposition
•radionuclides	•water pollution from urban runoff
•acid inputs to surface waters	•nonhazardous waste sites
•solid wastes	•releases of genetically engineered organisms
•thermal pollution	

[b]From Harwell et al., 1992.

Table 6: Ecological risk prioritization matrix[c]

		Extent of stress			Medium			Recovery time		
	Environmental Stress	Biosphere	Regional	Ecosystem	Air	Water	Terrestrial	Short	Medium	Long
1	Global climate	HHH	HHH	HHH	HHH					X
	Habitat alteration	HH	HHH	HHH		HHH	HHH		X	X
	Stratospheric ozone	HHH	HHH	HHH	HHH					X
	Biological depletion		HH	HHH		HH	HH			X
2	Herbicides/pesticides		M	HH	HH	HH			X	
3	Toxics in surface waters		M	HH		HH			X	
	Acid deposition		H	H	H				X	
	Airborne toxics	M	HH	HH	HH				X	
4	Nutrients			H		H		X		
	BOD			M		M		X		
	Turbidity			M		M		X		
5	Oil		L	M		M		X		
	Groundwater		L	L		L				X
6	Radionuclides			L		L			X	
	Acid inputs to surface waters			H		H			X	
	Thermal pollution			L		L				

[c] From Harwell, et al., 1992

Table 7: CAHA Cultural Sites Risk Assessment Matrices

CCCC Houses

	Susceptibility Score	Transect 290	Transect 291	Resource Risk Number
Shoreline Retreat	3	5	5	4.0
Inlet Formation	3	1	1	2.0
Overwash Frequency	3	3	3	3.0
Overall Resource Risk Number		3.0		

Cape Hatteras Lighthouse

	Susceptibility Score	Transect 289	Resource Risk Number
Shoreline Retreat	5	5	5.0
Inlet Formation	5	1	3.0
Overwash Frequency	3	3	3.0
Overall Resource Risk Number		3.7	

Small Brick Oil House

	Susceptibility Score	Transect 289	Resource Risk Number
Shoreline Retreat	5	5	5.0
Inlet Formation	5	1	3.0
Overwash Frequency	5	3	4.0
Overall Resource Risk Number		4.0	

Brick Principle Keeper's Quarters

	Susceptibility Score	Transect 289	Resource Risk Number
Shoreline Retreat	5	5	5.0
Inlet Formation	5	1	3.0
Overwash Frequency	5	3	4.0
Overall Resource Risk Number		4.0	

Double Keeper's Quarters

	Susceptibility Score	Transect 289	Resource Risk Number
Shoreline Retreat	5	5	5.0
Inlet Formation	5	1	3.0
Overwash Frequency	5	3	4.0
Overall Resource Risk Number		4.0	

Big Kinnakeet Tower Ruins

	Susceptibility Score	Transect 260	Transect 261	Resource Risk Number
Shoreline Retreat	1	5	5	3.0
Inlet Formation	5	5	5	5.0
Overwash Frequency	5	3	3	4.0
Overall Resource Risk Number		4.0		

Little Kinnakeet Coast Guard Station

	Susceptibility Score	Transect 221	Transect 222	Resource Risk Number
Shoreline Retreat	3	3	3	3.0
Inlet Formation	5	3	3	4.0
Overwash Frequency	5	3	3	4.0
Overall Resource Risk Number		3.7		

Little Kinnakeet Station Kitchen

	Susceptibility Score	Transect 221	Transect 222	Resource Risk Number
Shoreline Retreat	3	3	3	3.0
Inlet Formation	5	3	3	4.0
Overwash Frequency	5	3	3	4.0
Overall Resource Risk Number		3.7		

Little Kinnakeet Lifesaving Station

	Susceptibility Score	Transect 221	Transect 222	Resource Risk Number
Shoreline Retreat	3	3	3	3.0
Inlet Formation	5	3	3	4.0
Overwash Frequency	5	3	3	4.0
Overall Resource Risk Number		3.7		

Chicamacomico Boathouse and Garage

	Susceptibility Score	Transect 135	Transect 136	Resource Risk Number
Shoreline Retreat	1	5	5	3.0
Inlet Formation	5	5	5	5.0
Overwash Frequency	5	3	3	4.0
Overall Resource Risk Number		4.0		

Bodie Island Life Saving Station

	Susceptibility Score	Transect 21	Transect 22	Resource Risk Number
Shoreline Retreat	5	5	5	5.0
Inlet Formation	5	3	3	4.0
Overwash Frequency	5	3	3	4.0
Overall Resource Risk Number		4.3		

Bodie Island Coast Guard Station

	Susceptibility Score	Transect 21	Transect 22	Resource Risk Number
Shoreline Retreat	5	5	5	5.0
Inlet Formation	5	3	3	4.0
Overwash Frequency	5	3	3	4.0
Overall Resource Risk Number		4.3		

Bodie Island Lighthouse and Brick Oil House

	Susceptibility Score	Transect 29	Resource Risk Number
Shoreline Retreat	1	5	3.0
Inlet Formation	5	3	4.0
Overwash Frequency	1	3	2.0
Overall Resource Risk Number		3.0	

Bodie Island Lighthouse Keeper's Quarters

	Susceptibility Score	Transect 29	Resource Risk Number
Shoreline Retreat	1	5	3.0
Inlet Formation	5	3	4.0
Overwash Frequency	1	3	2.0
Overall Resource Risk Number		3.0	

Bodie Island Storehouse

	Susceptibility Score	Transect 29	Resource Risk Number
Shoreline Retreat	1	5	3.0
Inlet Formation	5	3	4.0
Overwash Frequency	1	3	2.0
Overall Resource Risk Number		3.0	

Table 8: Least tern resource risk number calculation

Least Tern Nesting Sites		Transects 267–271		
Transect	Retreat Risk	Inlet Risk	Overwash Risk	Mean Risk
267	5	5	3	4.3
268	5	5	3	4.3
269	5	5	3	4.3
270	5	5	3	4.3
271	5	5	3	4.3
Mean	5	5	3	4.3

	Retreat Risk	Inlet Risk	Overwash Risk	Overall
Tern Susceptibility Scores	3	5	3	
Tern Resource Risk Number	4	5	3	4.0

Table 9: Possible Risk Numbers for Loggerhead Turtle Nesting Sites

Retreat Risk	Inlet Risk	Overwash Risk	Retreat Risk #	Inlet Risk #	Overwash Risk	Overall Risk #
1	1	1	2	3	2	2.3
1	1	3	2	3	3	2.7
1	1	5	2	3	4	3.0
1	3	1	2	4	2	2.7
1	3	3	2	4	3	3.0
1	3	5	2	4	4	3.3
1	5	1	2	5	2	3.0
1	5	3	2	5	3	3.3
1	5	3	2	5	3	3.3
3	1	1	3	3	2	2.7
3	1	3	3	3	3	3.0
3	1	5	3	3	4	3.3
3	3	1	3	4	2	3.0
3	3	3	3	4	3	3.3
3	3	5	3	4	4	3.7
3	5	1	3	5	2	3.3
3	5	3	3	5	3	3.7
3	5	5	3	5	4	4.0
5	1	1	4	3	2	3.0
5	1	3	4	3	3	3.3
5	1	5	4	3	4	3.7
5	3	1	4	4	2	3.3
5	3	3	4	4	3	3.7
5	3	5	4	4	4	4.0
5	5	1	4	5	2	3.7
5	5	3	4	5	3	4.0
5	5	5	4	5	4	4.3

Loggerhead Turtle Susceptibility Scores

Retreat	3
Inlet Formation	5
Overwash	3

Table 10: CAHA shoreline rate of change data summarized by geographic region

Entire Study Area	mean rate of change (m yr^{-1})	-2.7
	standard deviation	4.0
	median retreat rate (m yr^{-1})	-1.8
Bodie Island (transects 1–51)	mean rate of change (m yr^{-1})	0.1
	standard deviation	7.1
	median retreat rate (m yr^{-1})	-1.7
Pea Island (transects 52–106)	mean rate of change (m yr^{-1})	-3.3
	standard deviation	1.4
	median retreat rate (m yr^{-1})	-3.1
Hatteras Island (transects 107–304)	mean rate of change (m yr^{-1})	-2.1
	standard deviation	2.8
	median retreat rate (m yr^{-1})	-1.5
Hatteras Bight (transects 305–338)	mean rate of change (m yr^{-1})	2.8
	standard deviation	3.5
	median retreat rate (m yr^{-1})	-1.5

Table 11: Ranking of Cape Hatteras National Seashore Cultural Sites by Overall Resource Risk

Cultural Site	Overall Resource Risk Number
Bodie Island Lifesaving Station	4.3
Bodie Island Coast Guard Station	4.3
Cape Hatteras Lighthouse Keepers' Quarters	4.0
Cape Hatteras Lighthouse Brick Oil House	4.0
Big Kinnakeet Tower Ruins	4.0
Chicamacomico Boathouse and Garage	4.0
Cape Hatteras Lighthouse	3.7
Little Kinnakeet Coast Guard Station	3.7
Little Kinnakeet Station Kitchen	3.7
Little Kinnakeet Lifesaving Station	3.7
Bodie Island Lighthouse Keeper's Quarters	3.0
Bodie Island Storehouse	3.0
Bodie Island Lighthouse	3.0
CCCC Houses	3.0

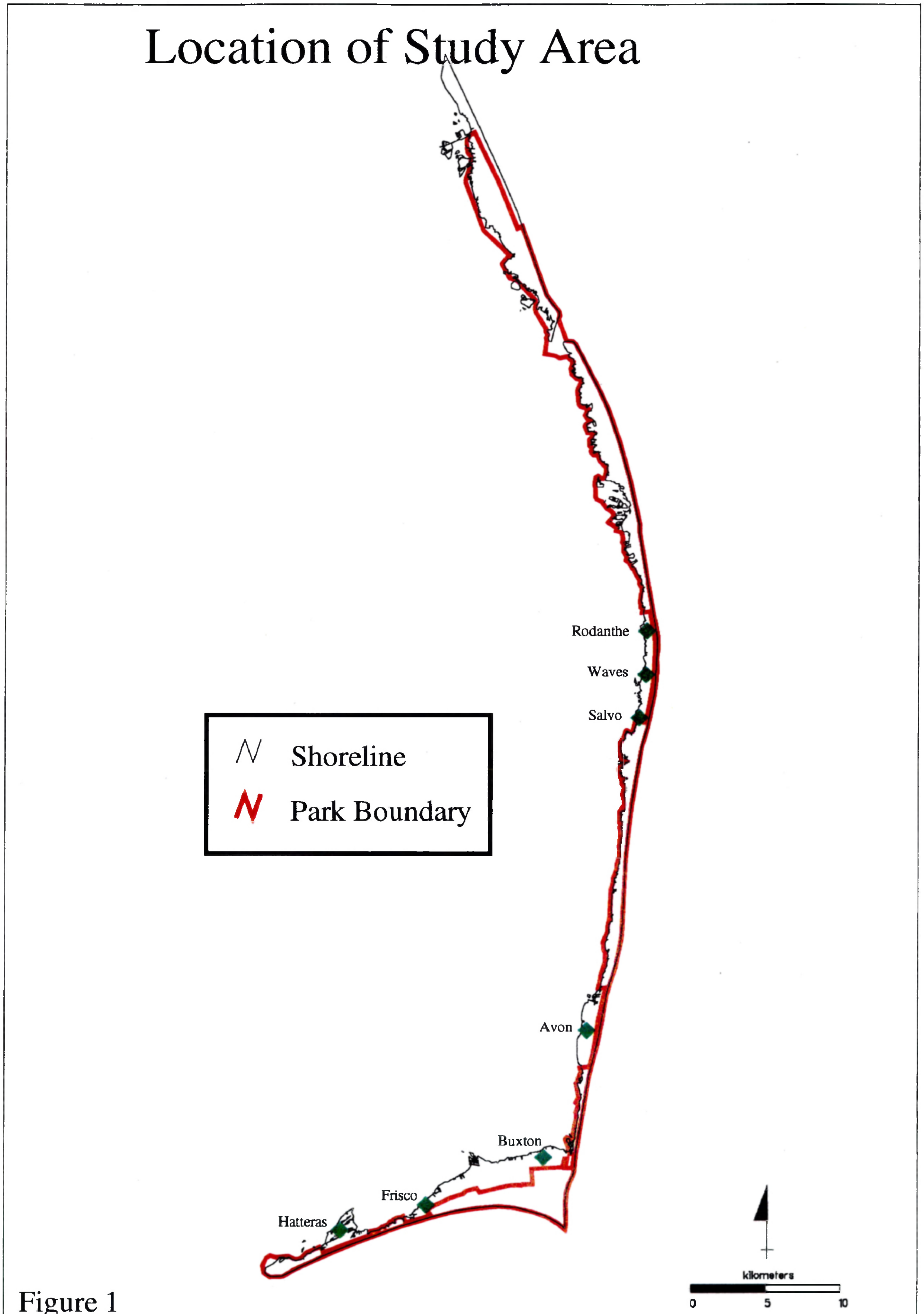

Location of Study Area
Rodanthe
Waves
Salvo
Avon
Buxton
Frisco
Hatteras
Shoreline
Park Boundary
kilometers
0
5
10

Figure 1

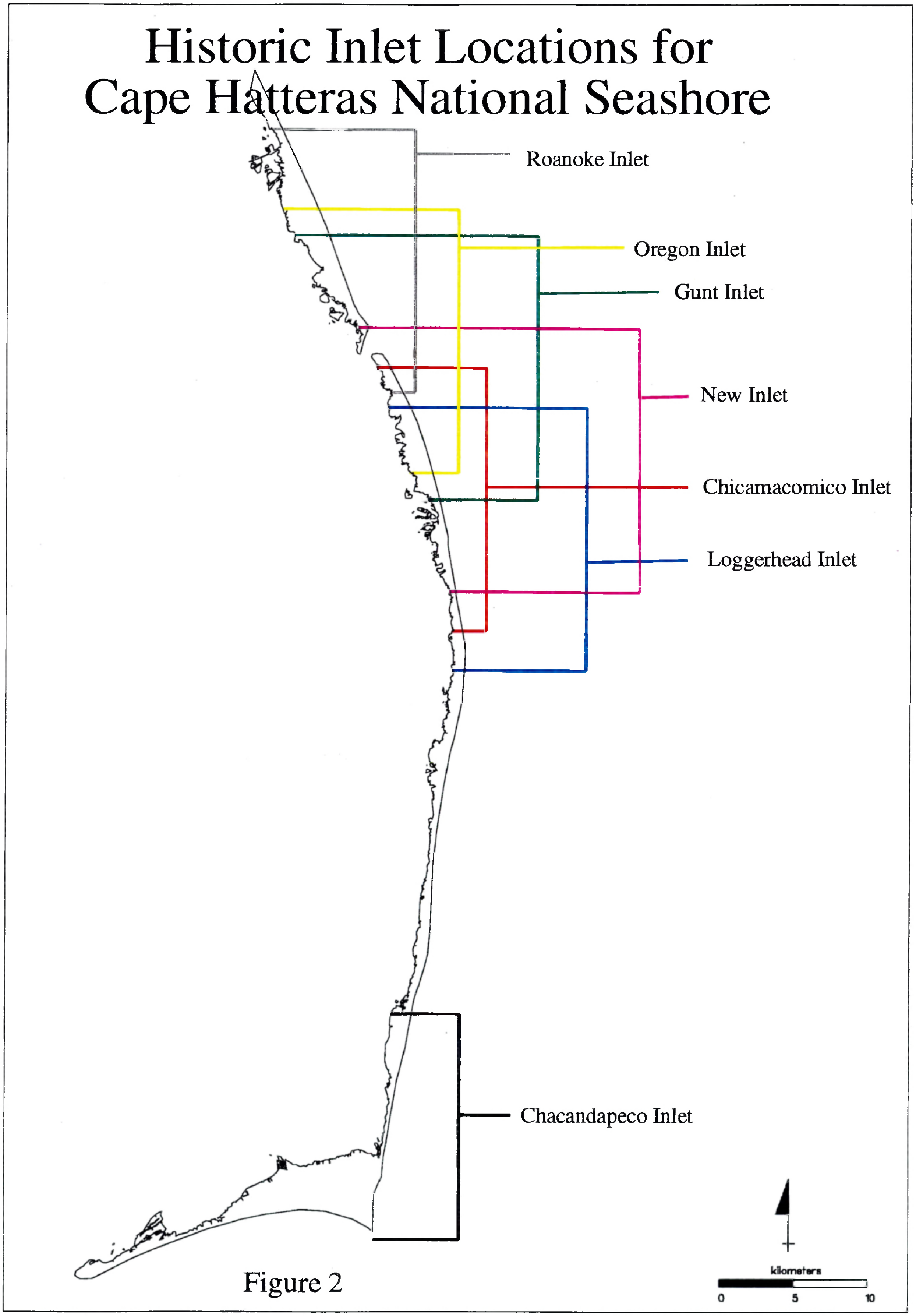


Figure 2

From Everts et al, 1983

Bodie Island Historic Landmarks
Cape Hatteras National Seashore

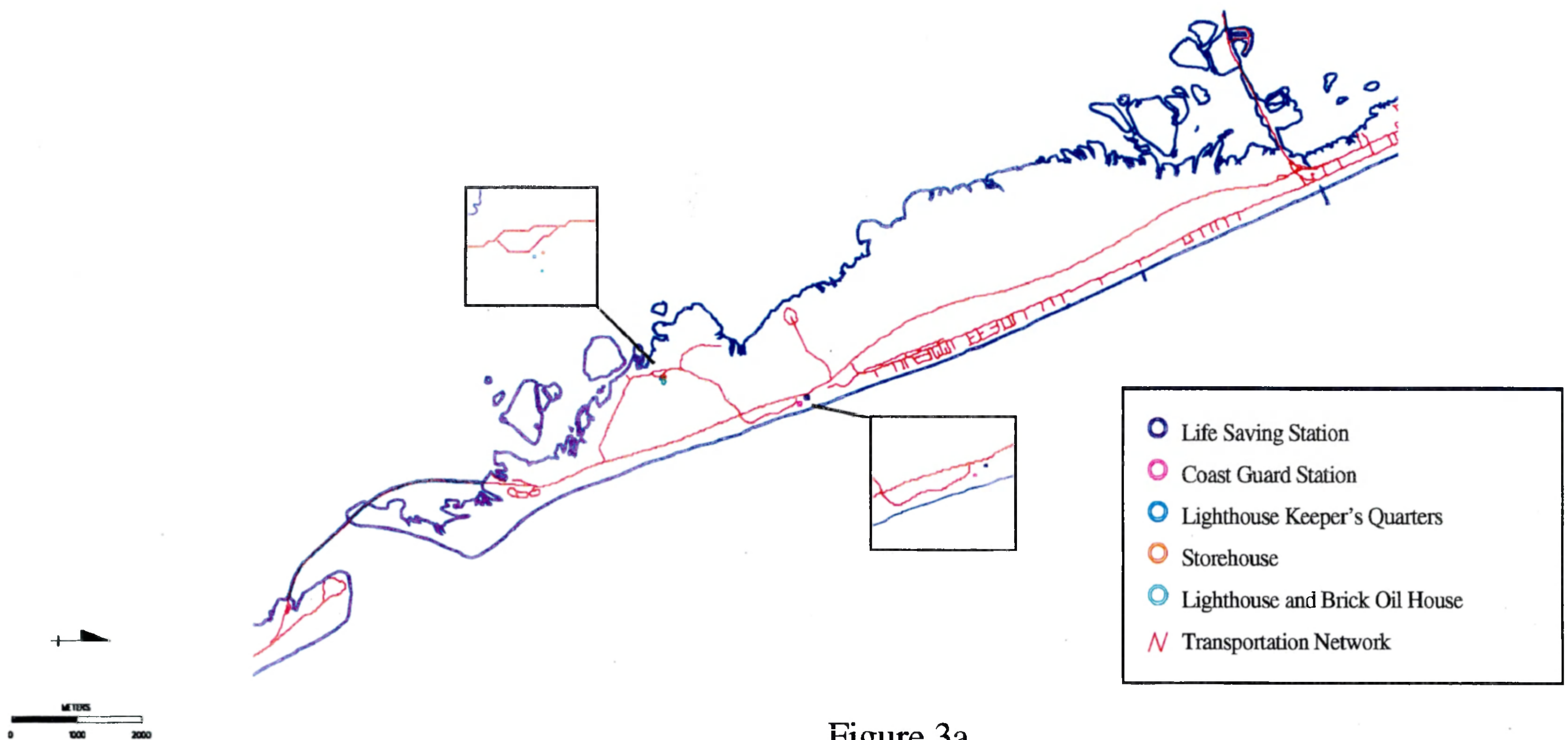


Figure 3a

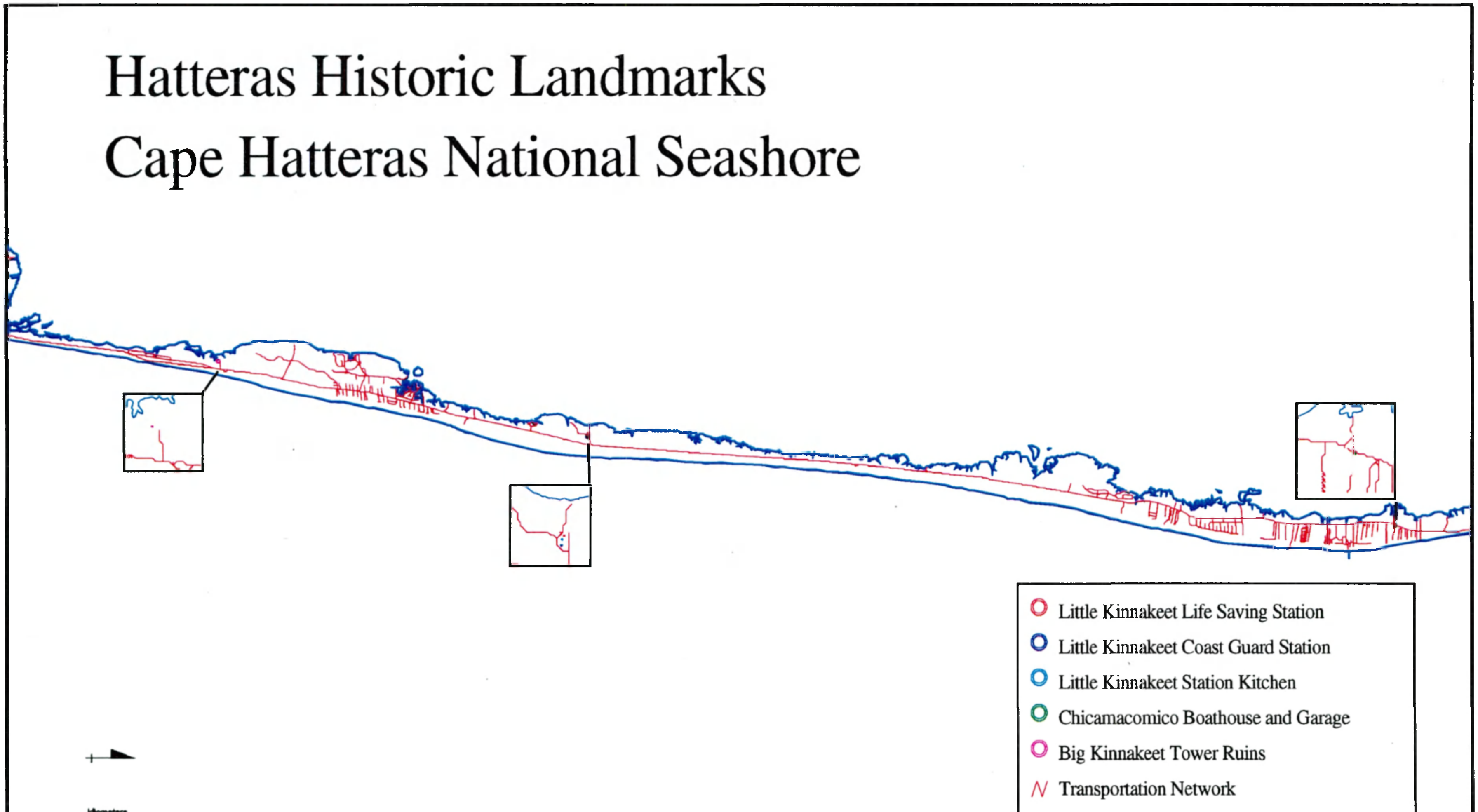

Hatteras Historic Landmarks
Cape Hatteras National Seashore
Little Kinnakeet Life Saving Station
Little Kinnakeet Coast Guard Station
Little Kinnakeet Station Kitchen
Chicamacomico Boathouse and Garage
Big Kinnakeet Tower Ruins
Transportation Network
kilometers
0
1
2
3
4

Figure 3b

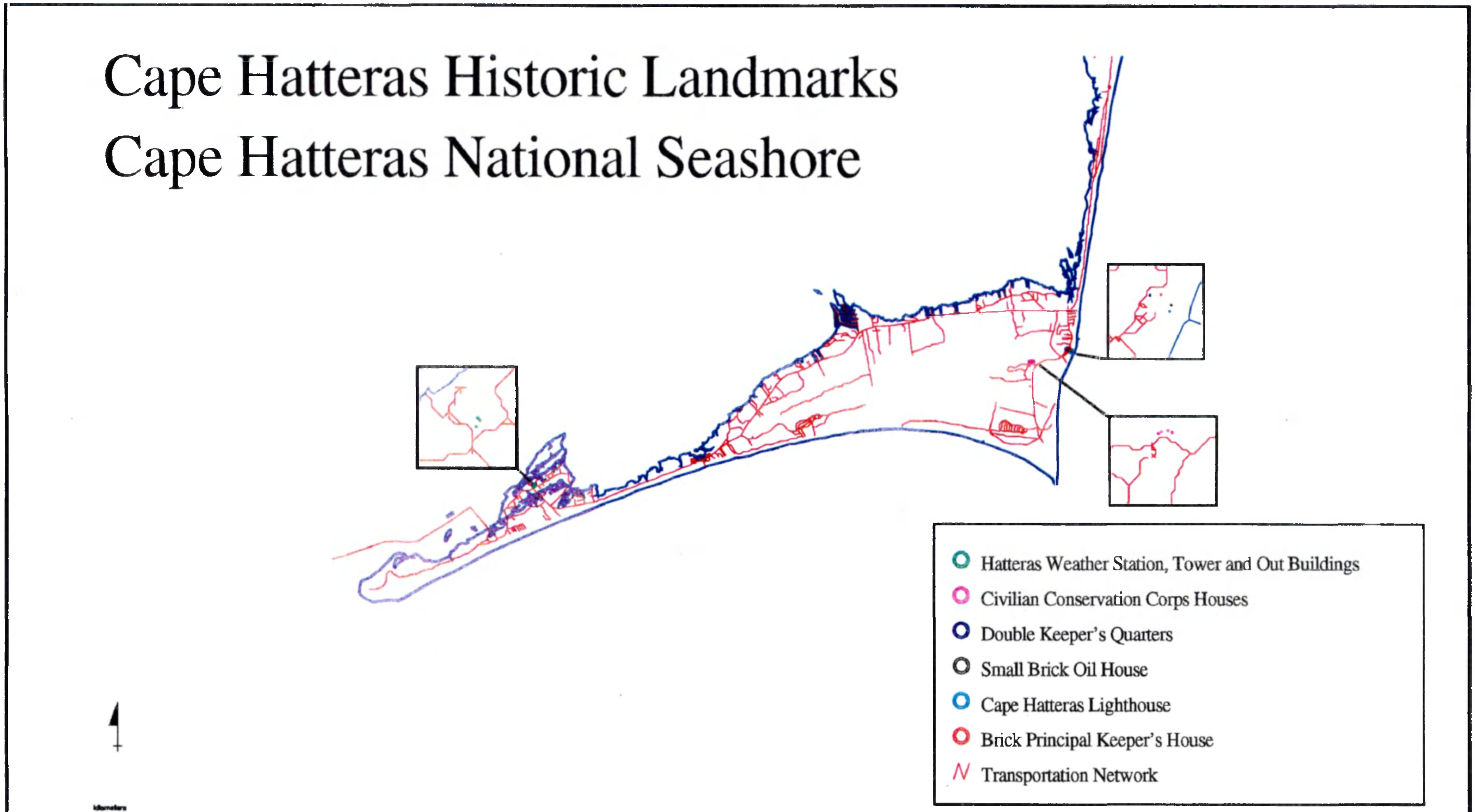

Cape Hatteras Historic Landmarks
Cape Hatteras National Seashore
Hatteras Weather Station, Tower and Out Buildings
Civilian Conservation Corps Houses
Double Keeper's Quarters
Small Brick Oil House
Cape Hatteras Lighthouse
Brick Principal Keeper's House
Transportation Network

Figure 3c

Location and Numbering of Reference Transects

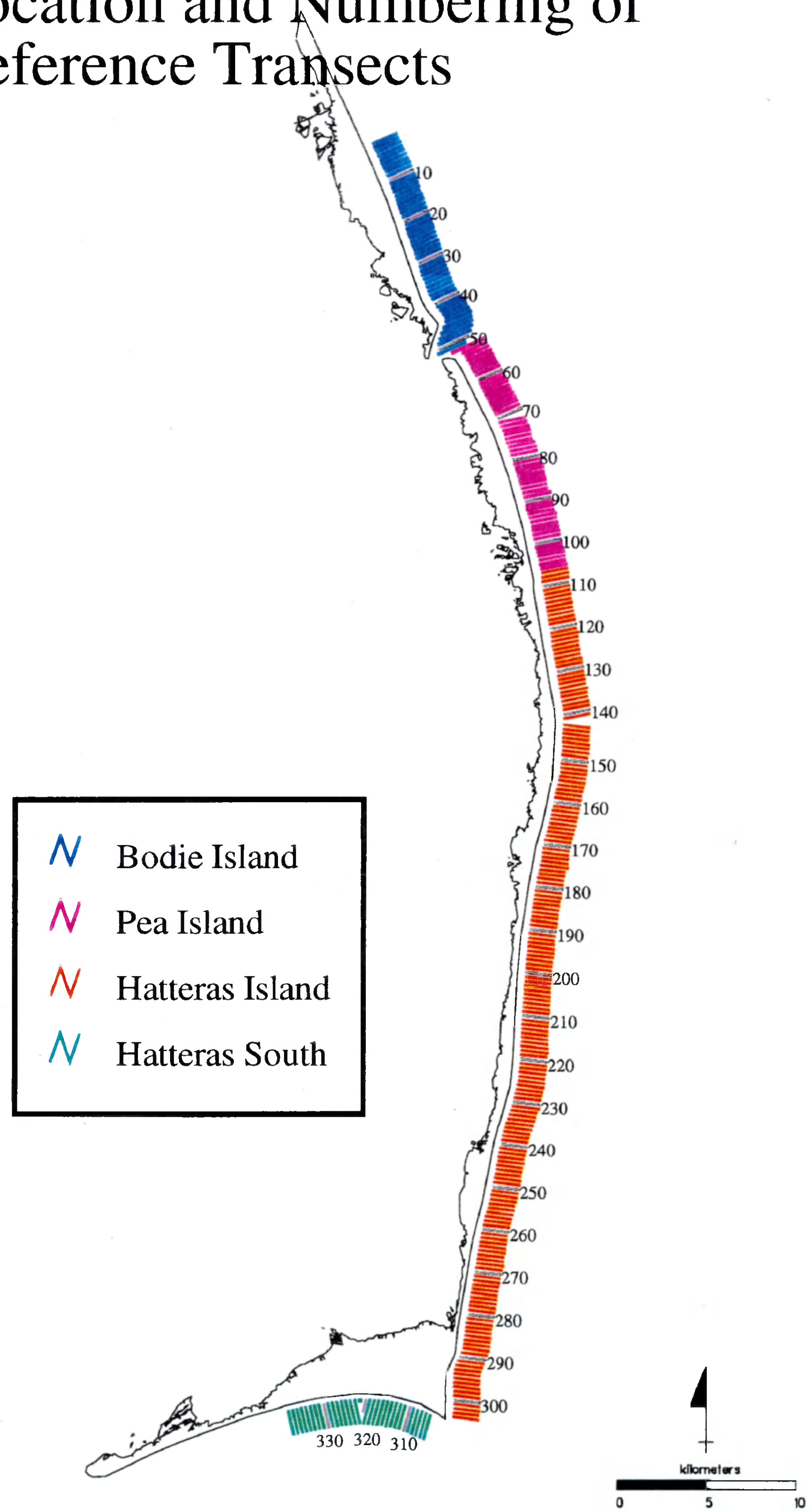


Figure 4

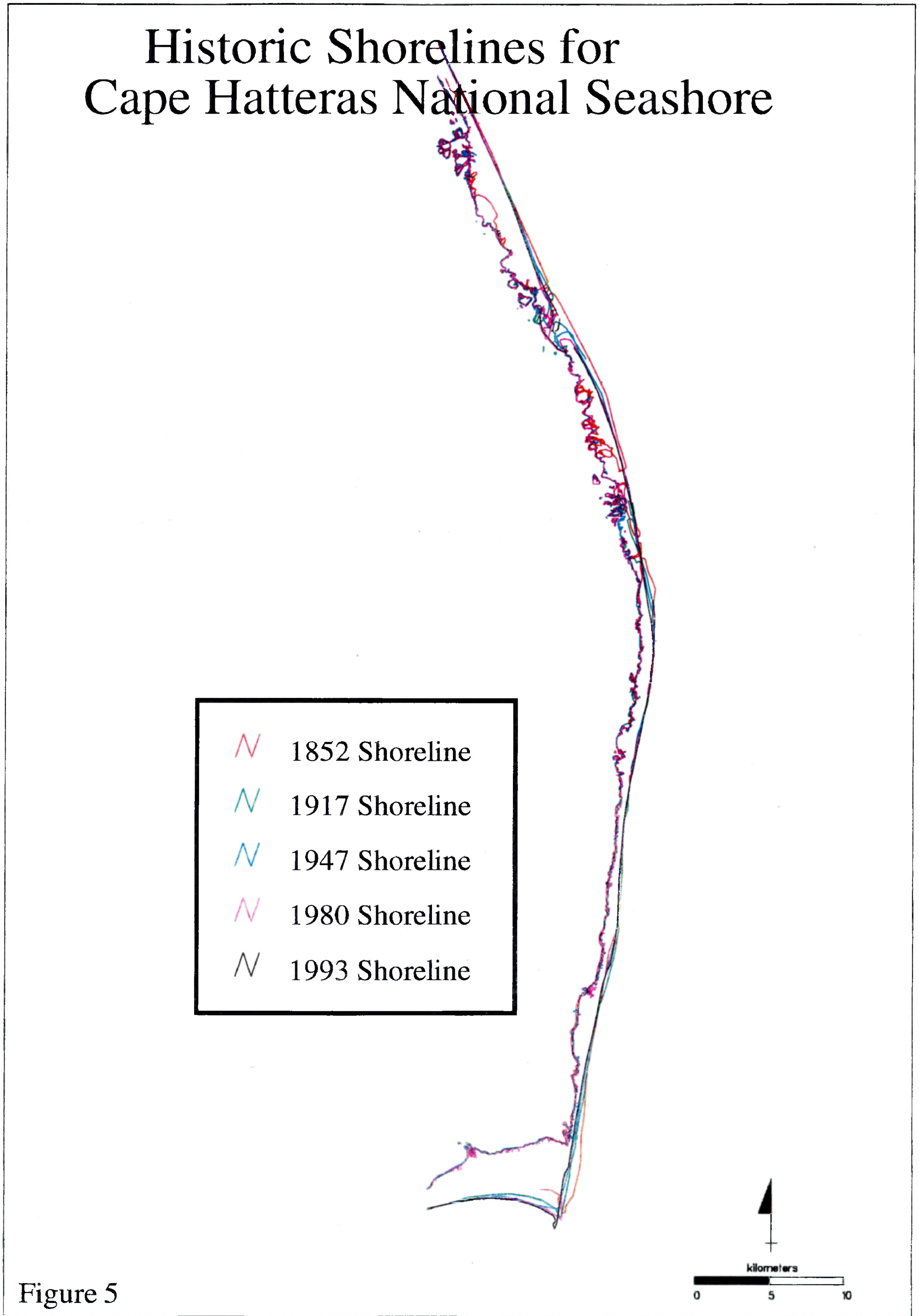

Historic Shorelines for
Cape Hatteras National Seashore
1852 Shoreline
1917 Shoreline
1947 Shoreline
1980 Shoreline
1993 Shoreline
kilometers
0
5
10

Figure 5

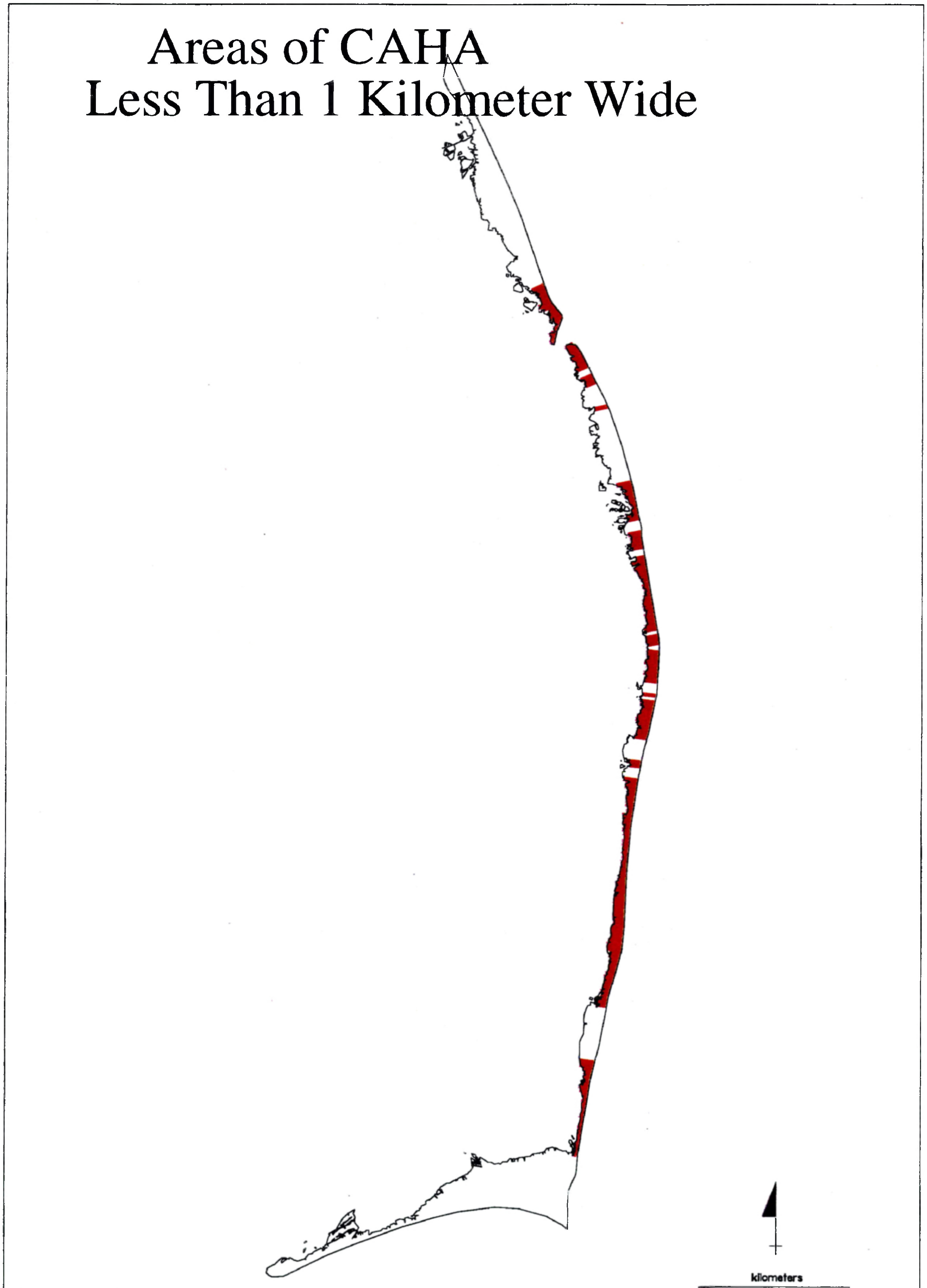


Figure 6

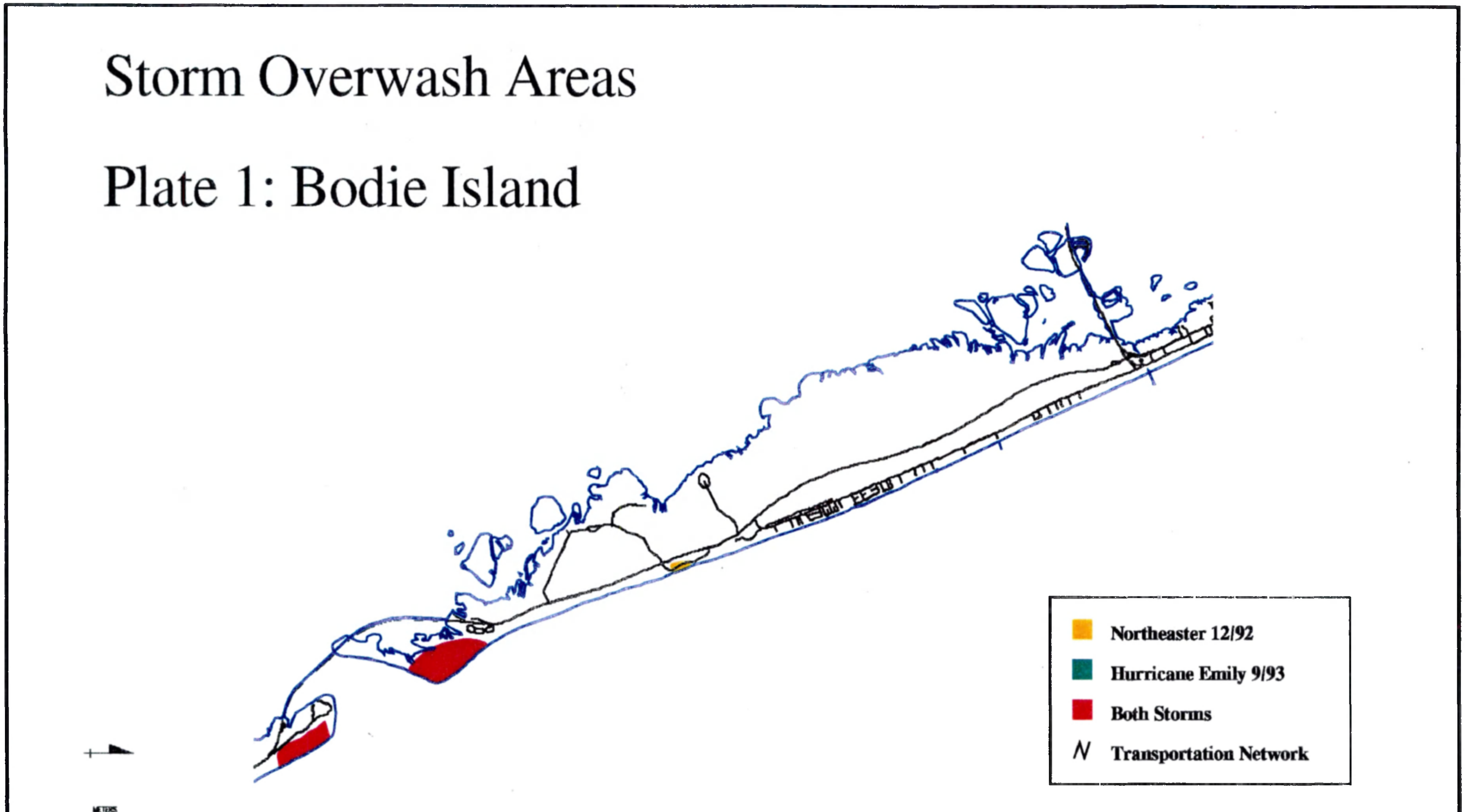

Storm Overwash Areas
Plate 1: Bodie Island
Northeaster 12/92
Hurricane Emily 9/93
Both Storms
Transportation Network
METERS
0
1000
2000

Figure 7a

Storm Overwash Areas

Plate 2: Pea Island

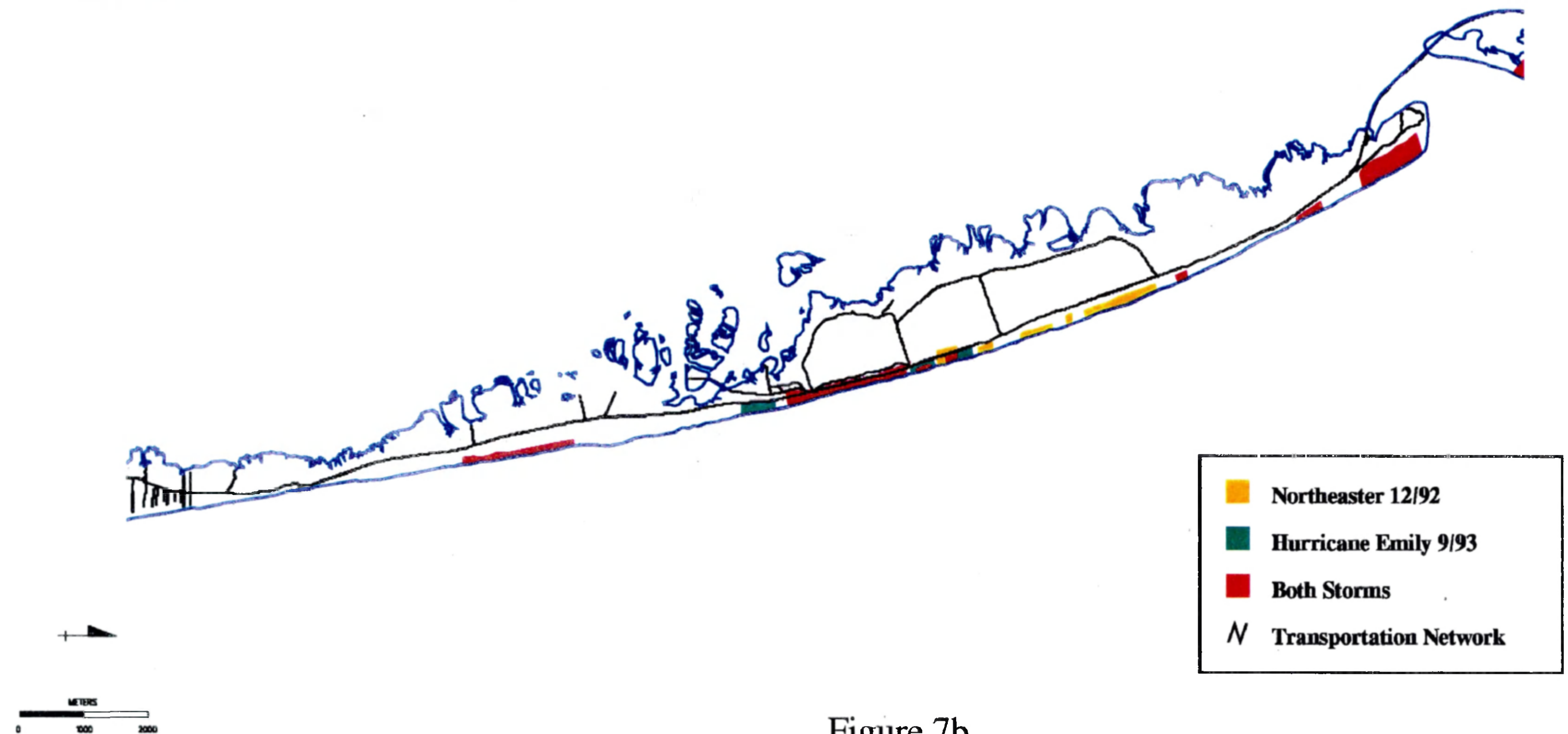


Figure 7b

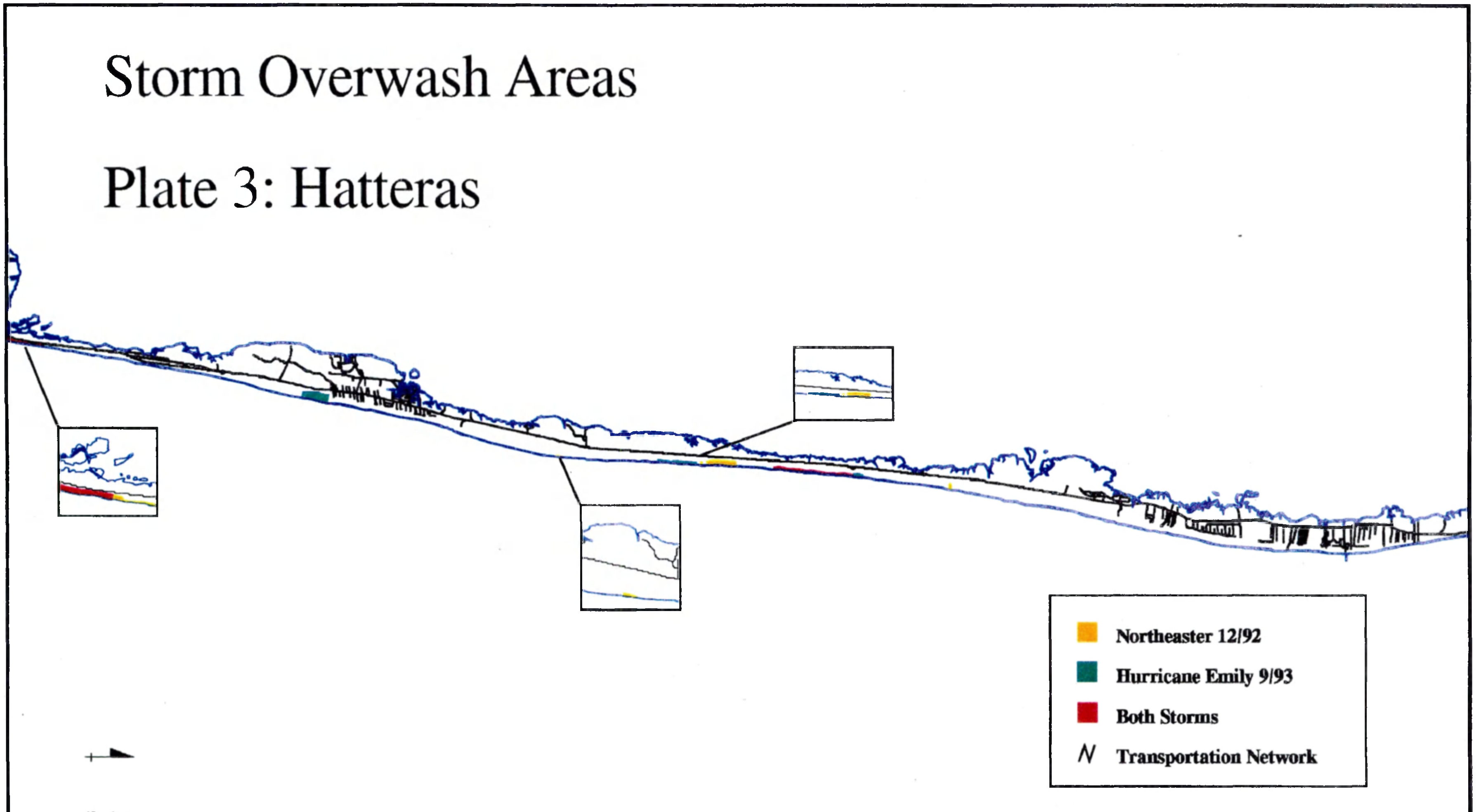

Storm Overwash Areas
Plate 3: Hatteras
Northeaster 12/92
Hurricane Emily 9/93
Both Storms
Transportation Network
kilometers
0
1
2
3
4

Figure 7c

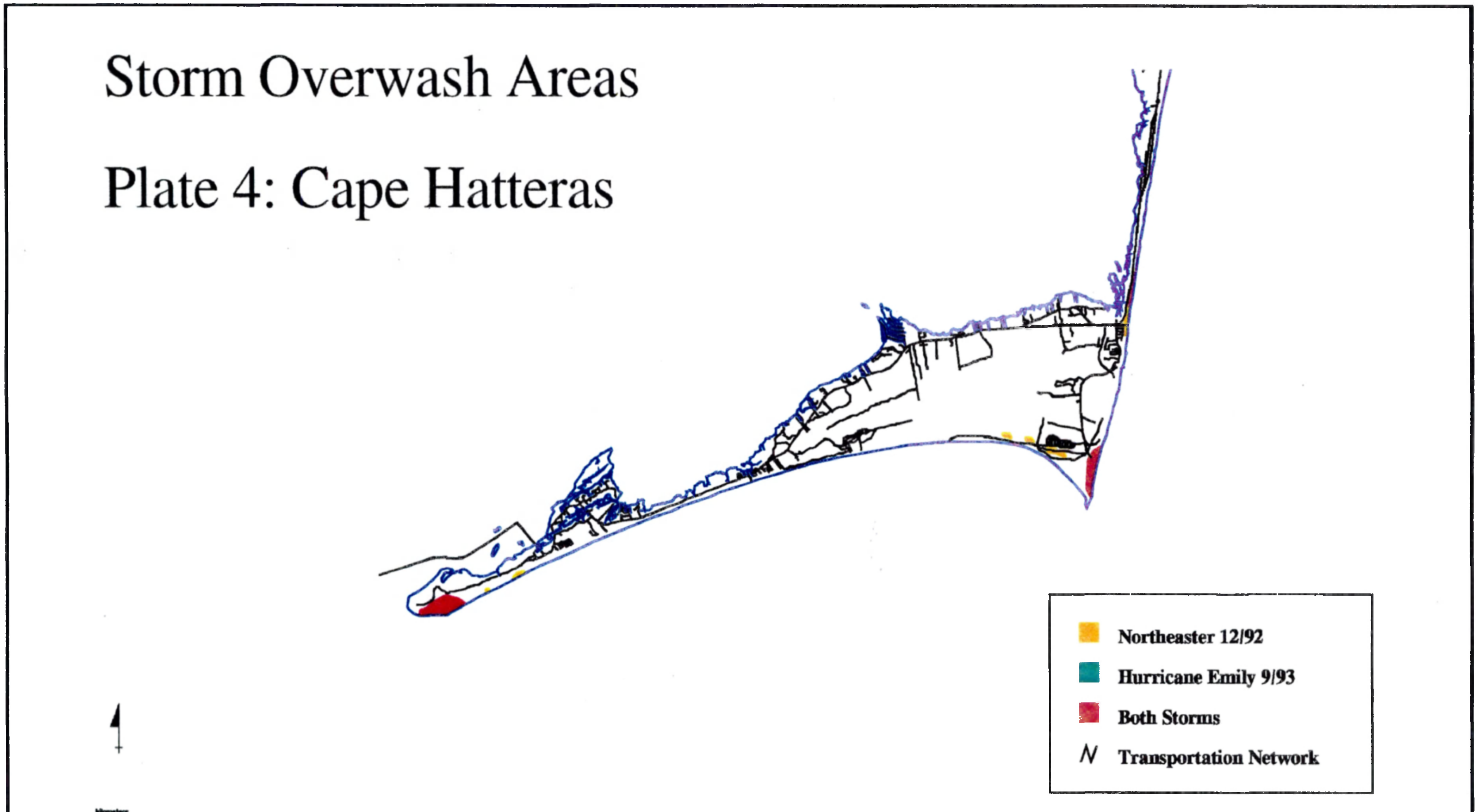

Storm Overwash Areas
Plate 4: Cape Hatteras
Northeaster 12/92
Hurricane Emily 9/93
Both Storms
Transportation Network
0
1
2
3
4

Figure 7d

Historic Overwash Events in Cape Hatteras National Seashore, 1945–1974

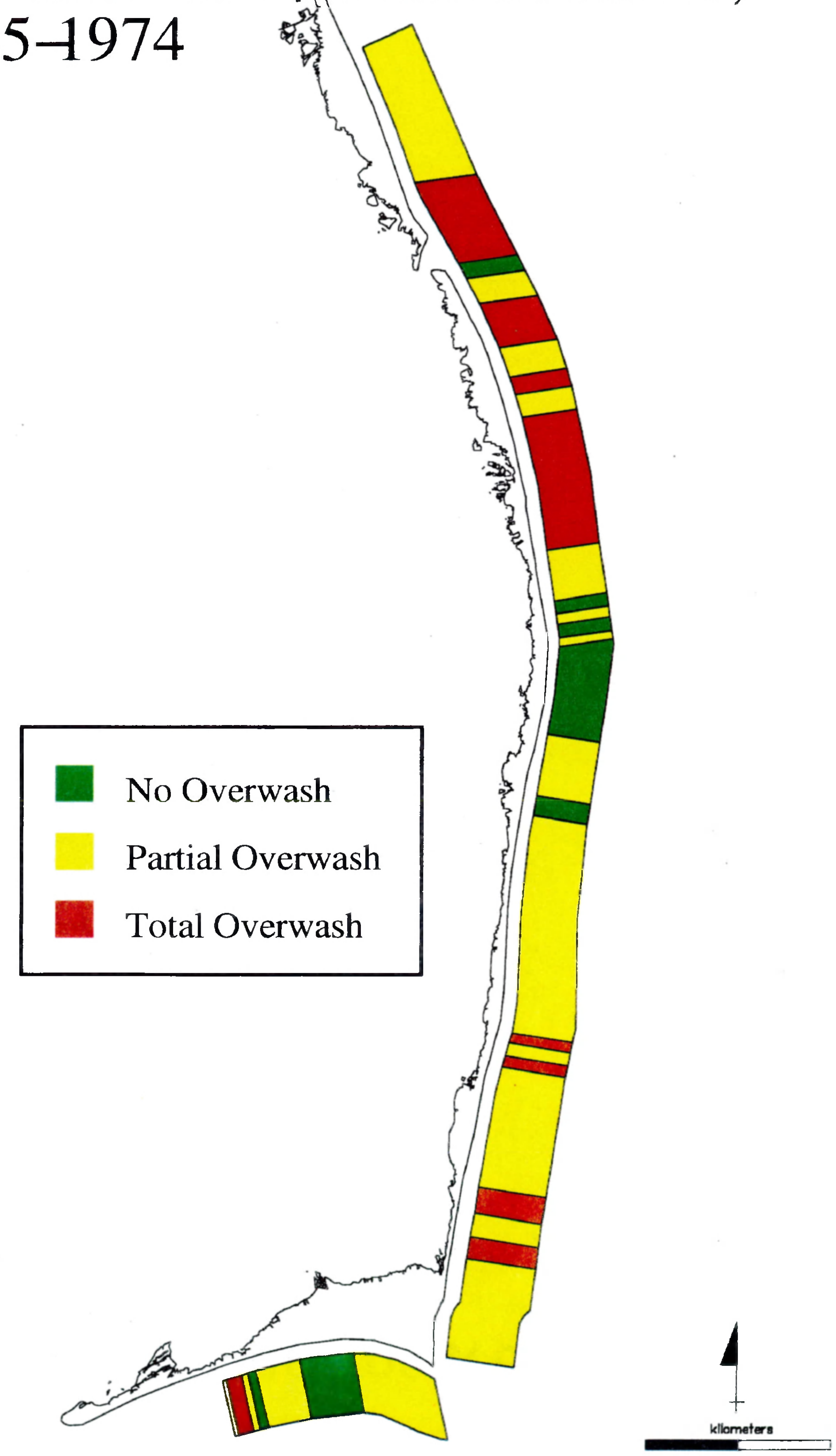


Figure 8

From Boc and Langfelder, 1977

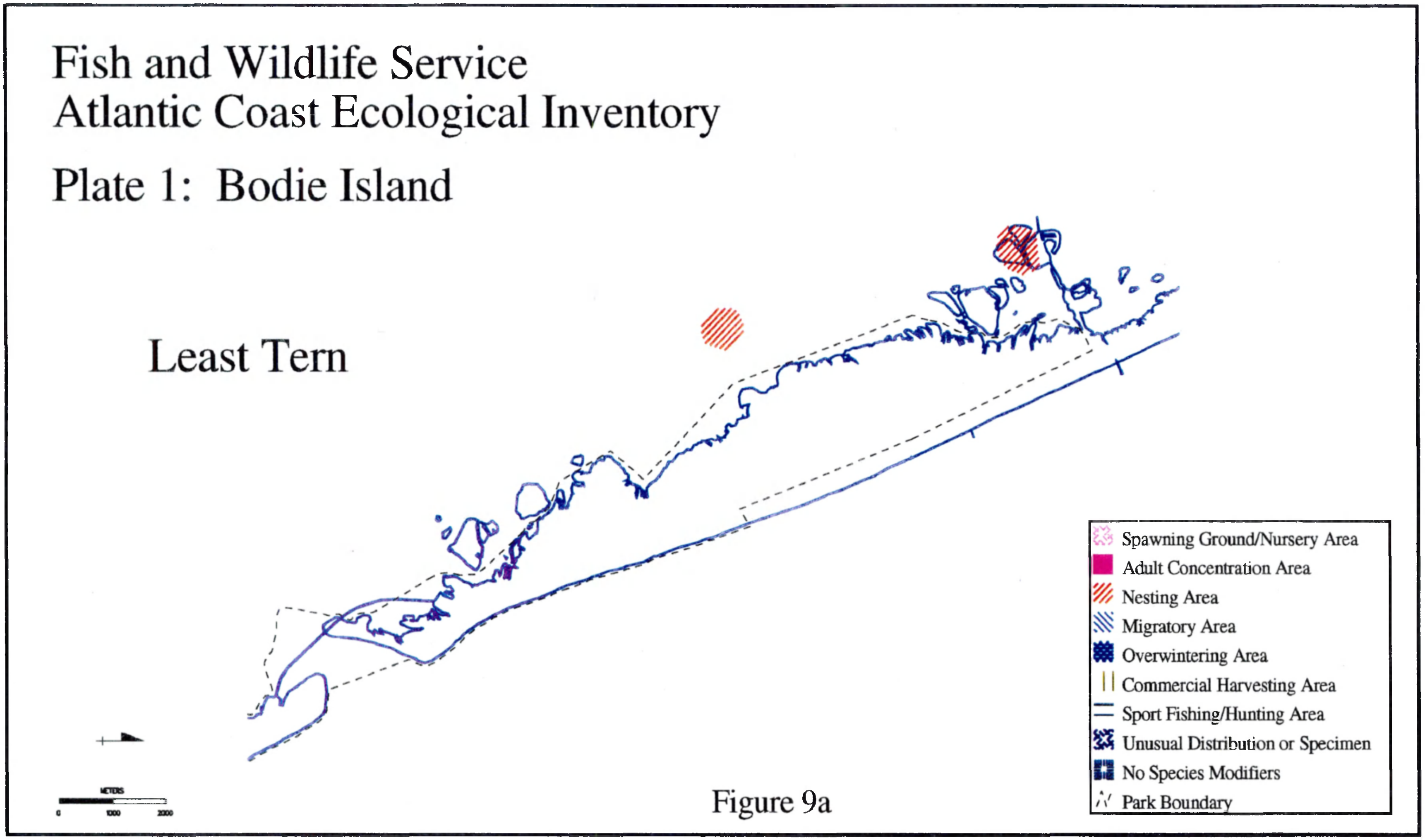

Fish and Wildlife Service
Atlantic Coast Ecological Inventory
Plate 1: Bodie Island
Least Tern
Spawning Ground/Nursery Area
Adult Concentration Area
Nesting Area
Migratory Area
Overwintering Area
Commercial Harvesting Area
Sport Fishing/Hunting Area
Unusual Distribution or Specimen
No Species Modifiers
Park Boundary

Figure 9a

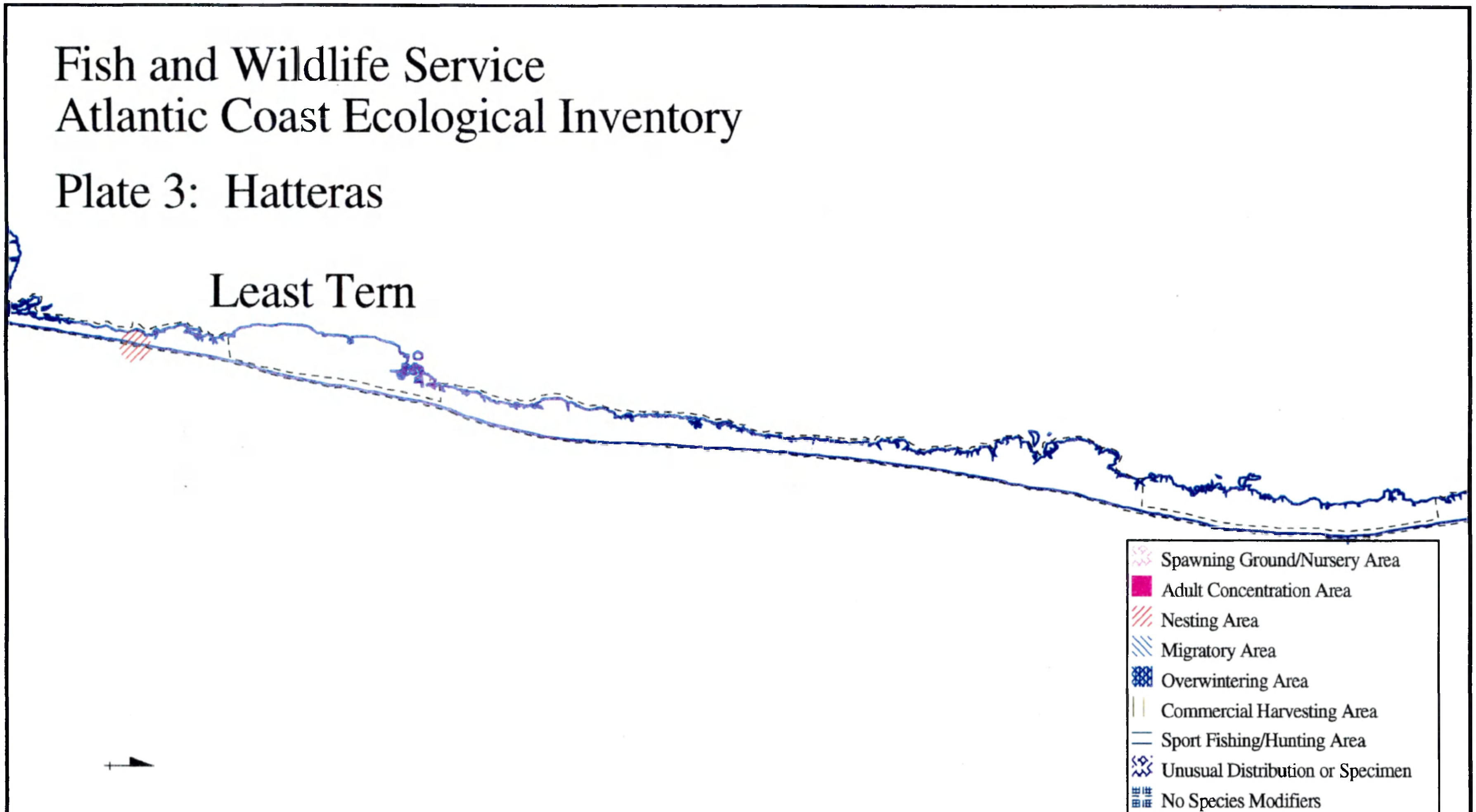

Fish and Wildlife Service
Atlantic Coast Ecological Inventory
Plate 3: Hatteras
Least Tern
Spawning Ground/Nursery Area
Adult Concentration Area
Nesting Area
Migratory Area
Overwintering Area
Commercial Harvesting Area
Sport Fishing/Hunting Area
Unusual Distribution or Specimen
No Species Modifiers
Park Boundary
kilometers
0 1 2 3 4

Figure 9b

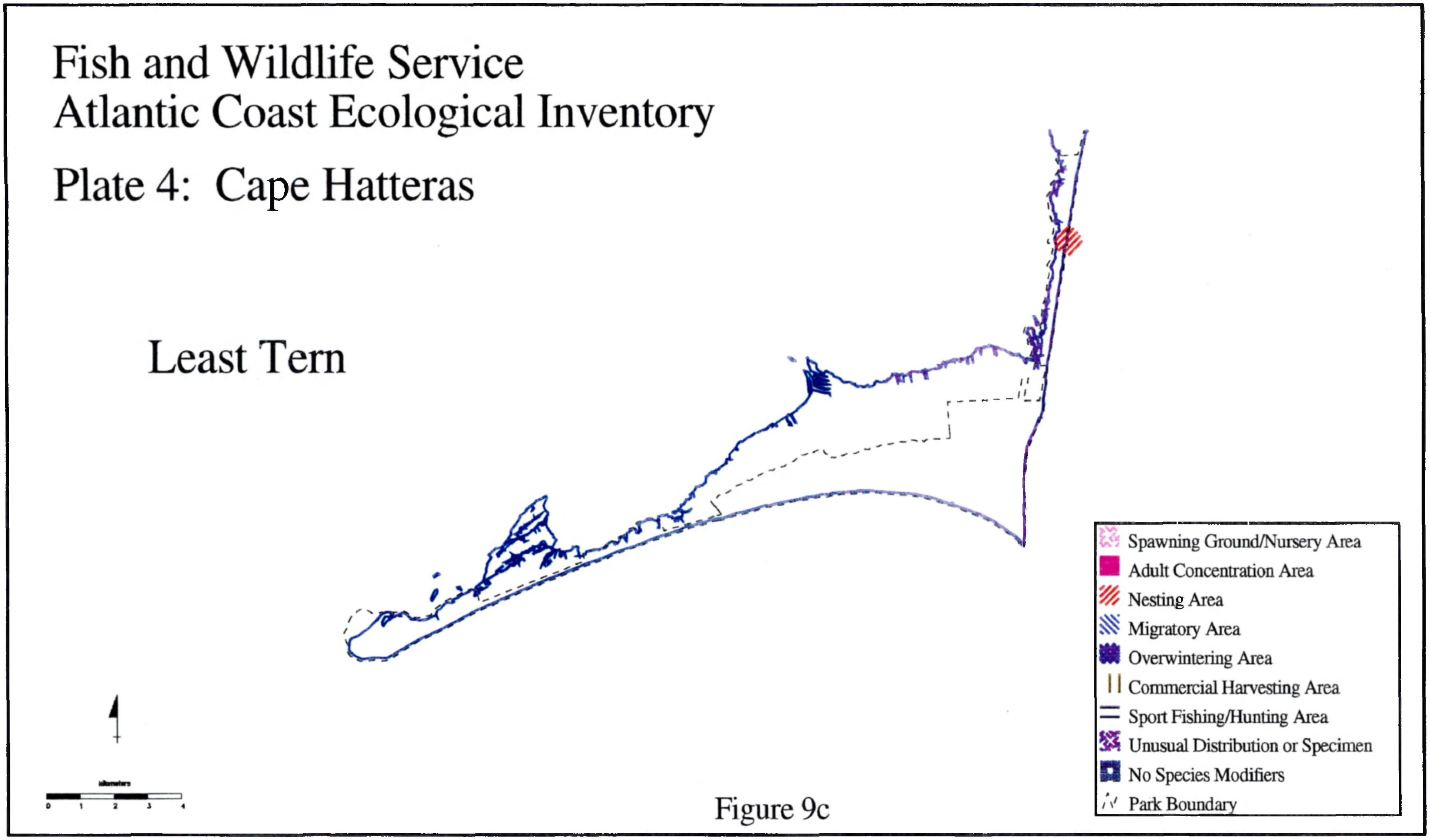

Fish and Wildlife Service
Atlantic Coast Ecological Inventory
Plate 4: Cape Hatteras
Least Tern
Spawning Ground/Nursery Area
Adult Concentration Area
Nesting Area
Migratory Area
Overwintering Area
Commercial Harvesting Area
Sport Fishing/Hunting Area
Unusual Distribution or Specimen
No Species Modifiers
Park Boundary

Figure 9c

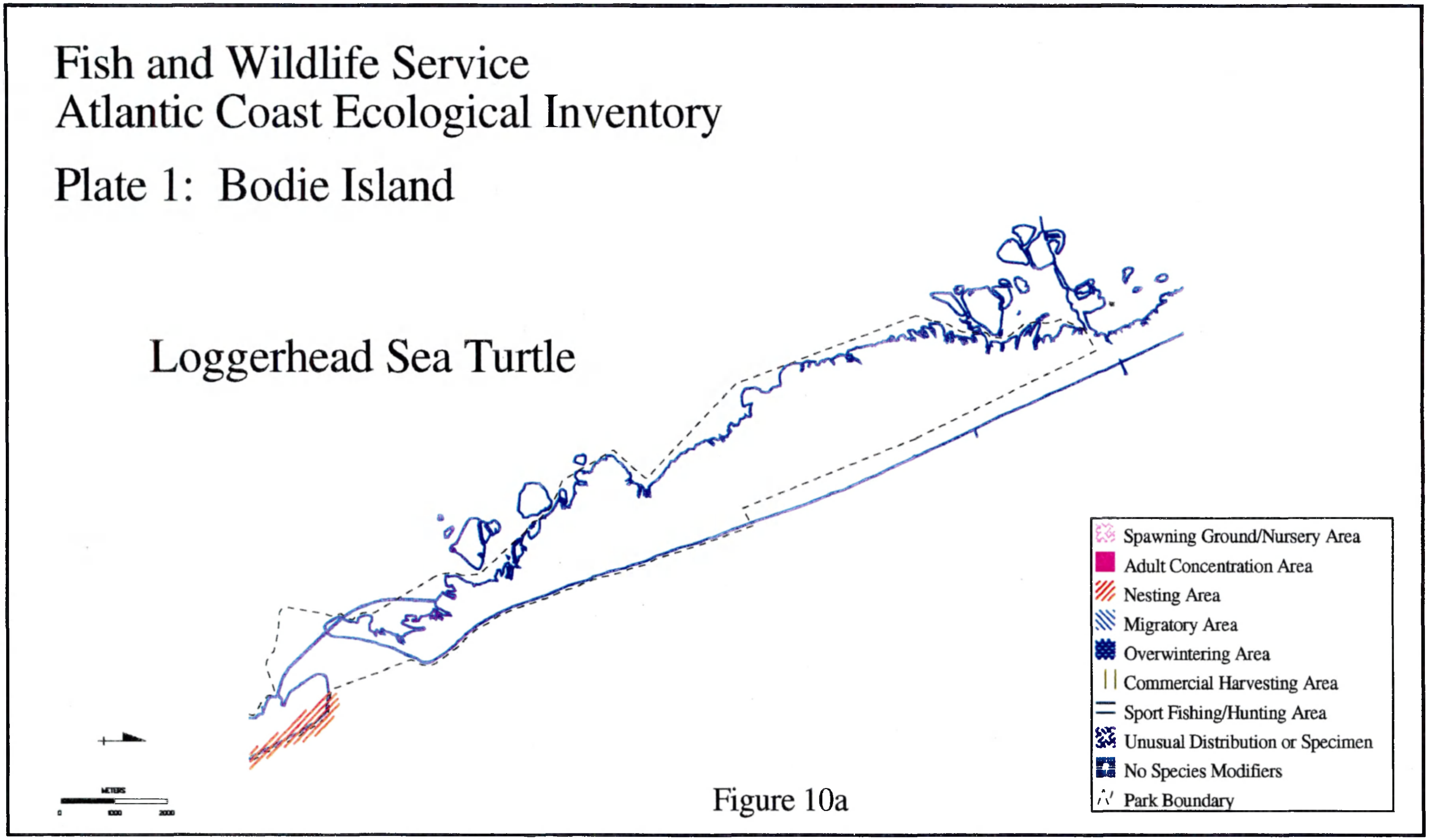
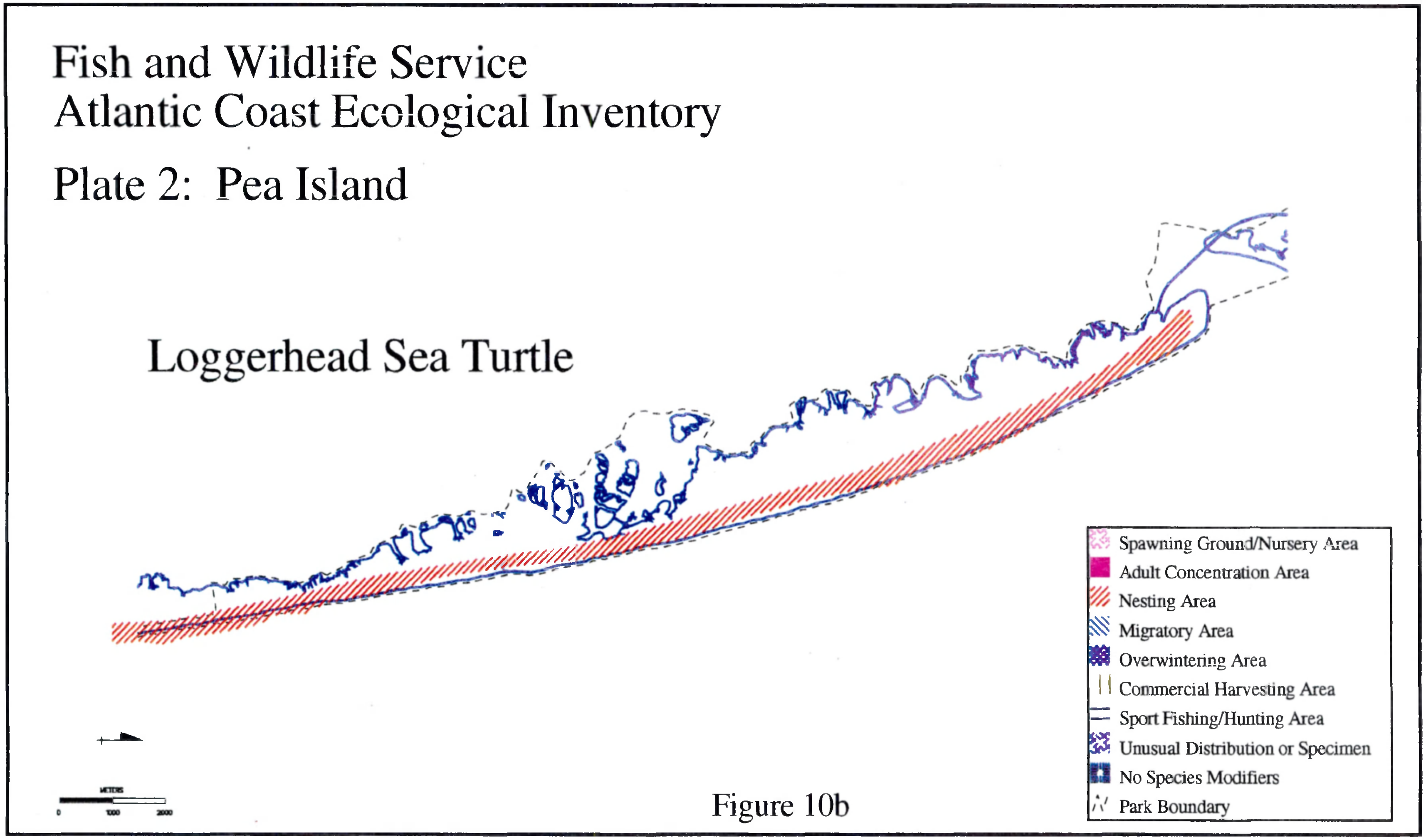
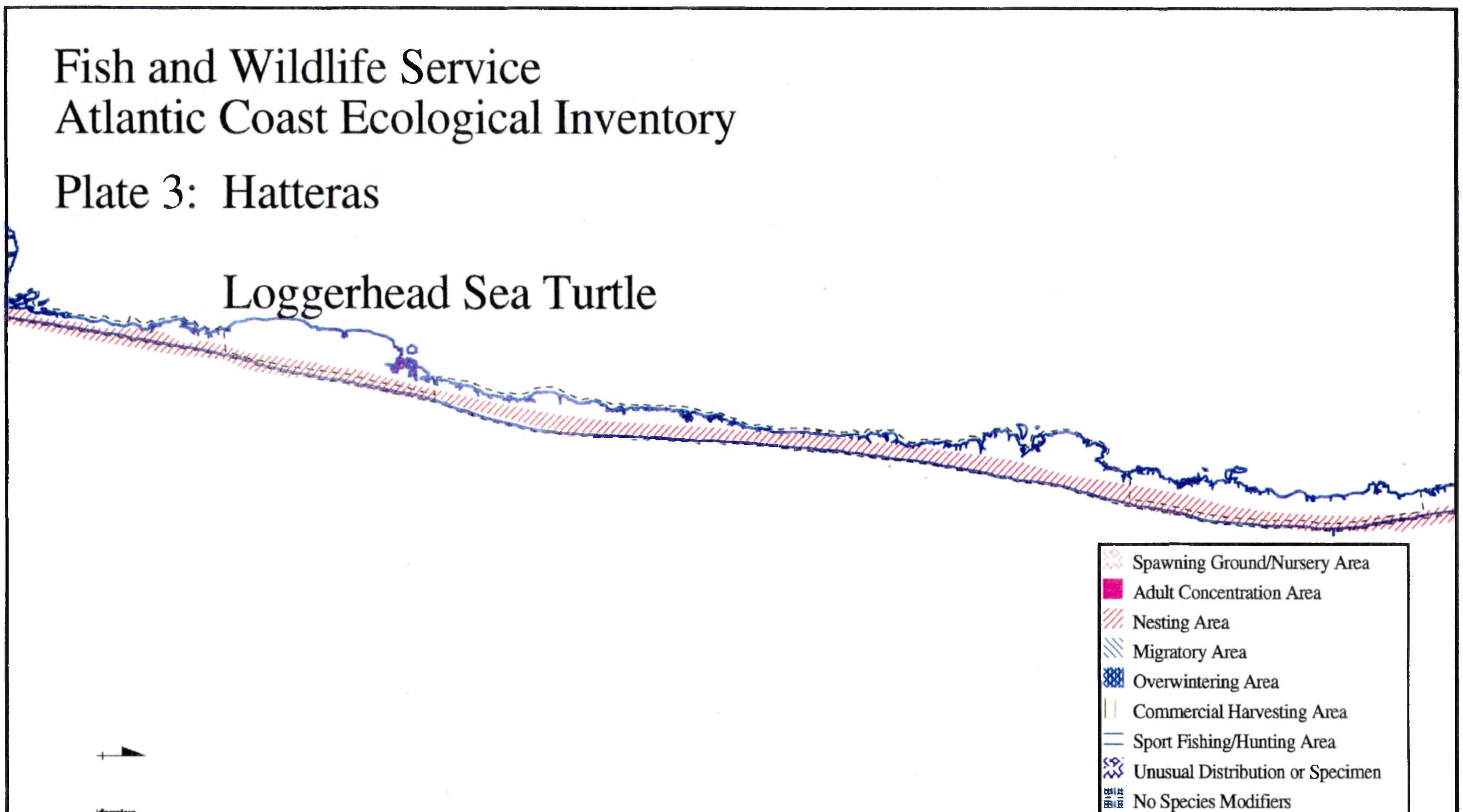

Fish and Wildlife Service
Atlantic Coast Ecological Inventory
Plate 1: Bodie Island
Loggerhead Sea Turtle
METERS
0
1000
2000
Spawning Ground/Nursery Area
Adult Concentration Area
Nesting Area
Migratory Area
Overwintering Area
Commercial Harvesting Area
Sport Fishing/Hunting Area
Unusual Distribution or Specimen
No Species Modifiers
Park Boundary

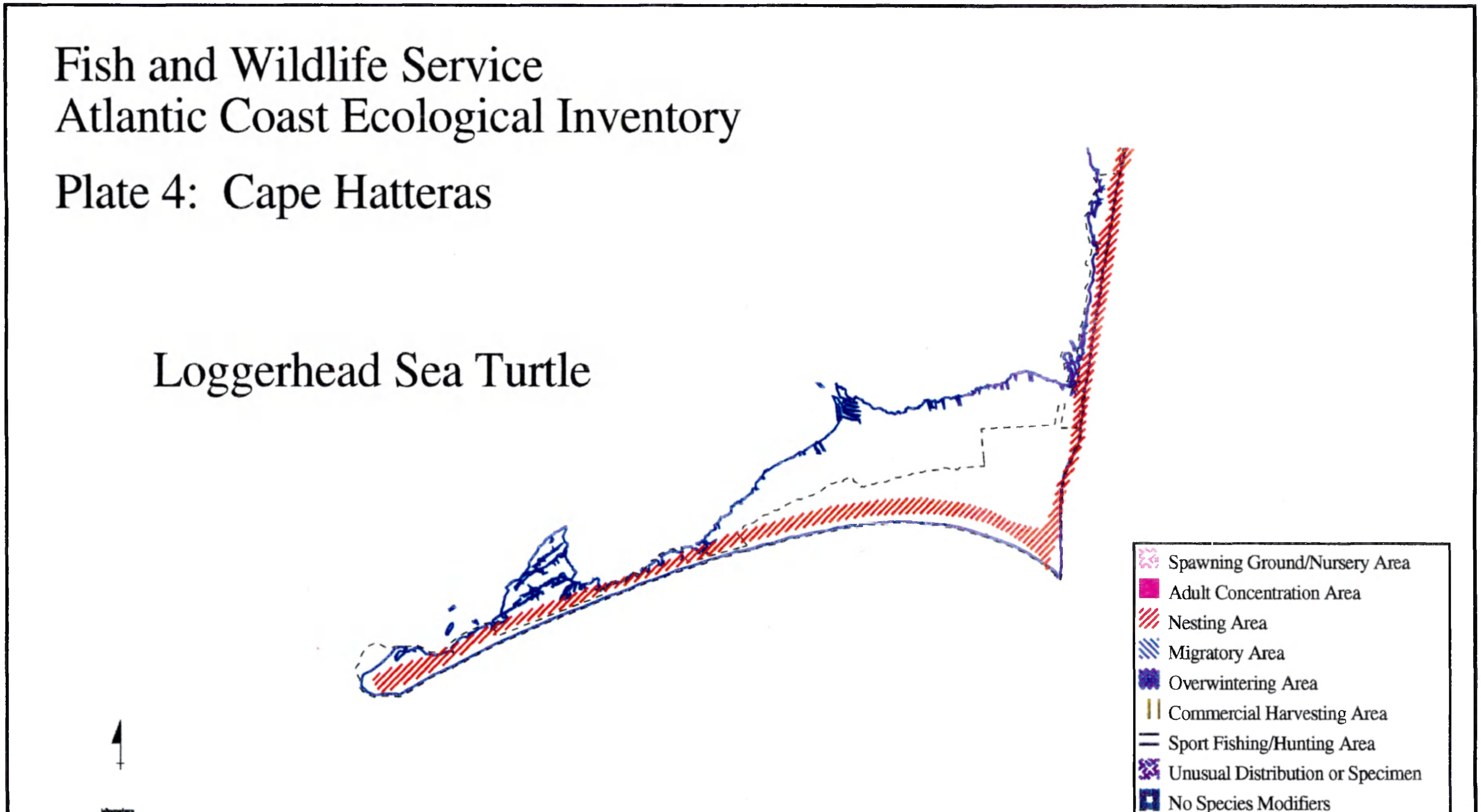
Figure 10a



Fish and Wildlife Service
Atlantic Coast Ecological Inventory
Plate 2: Pea Island
Loggerhead Sea Turtle
Spawning Ground/Nursery Area
Adult Concentration Area
Nesting Area
Migratory Area
Overwintering Area
Commercial Harvesting Area
Sport Fishing/Hunting Area
Unusual Distribution or Specimen
No Species Modifiers
Park Boundary

Figure 10b


Fish and Wildlife Service
Atlantic Coast Ecological Inventory
Plate 3: Hatteras
Loggerhead Sea Turtle
Spawning Ground/Nursery Area
Adult Concentration Area
Nesting Area
Migratory Area
Overwintering Area
Commercial Harvesting Area
Sport Fishing/Hunting Area
Unusual Distribution or Specimen
No Species Modifiers
Park Boundary
kilometers
0
1
2
3
4
Figure 10c



Fish and Wildlife Service
Atlantic Coast Ecological Inventory
Plate 4: Cape Hatteras
Loggerhead Sea Turtle
Spawning Ground/Nursery Area
Adult Concentration Area
Nesting Area
Migratory Area
Overwintering Area
Commercial Harvesting Area
Sport Fishing/Hunting Area
Unusual Distribution or Specimen
No Species Modifiers
Park Boundary
0
1
2
3
4

Figure 10d

Figure 11a: Frequency Distribution of Shoreline Retreat Rates, 1852-1917

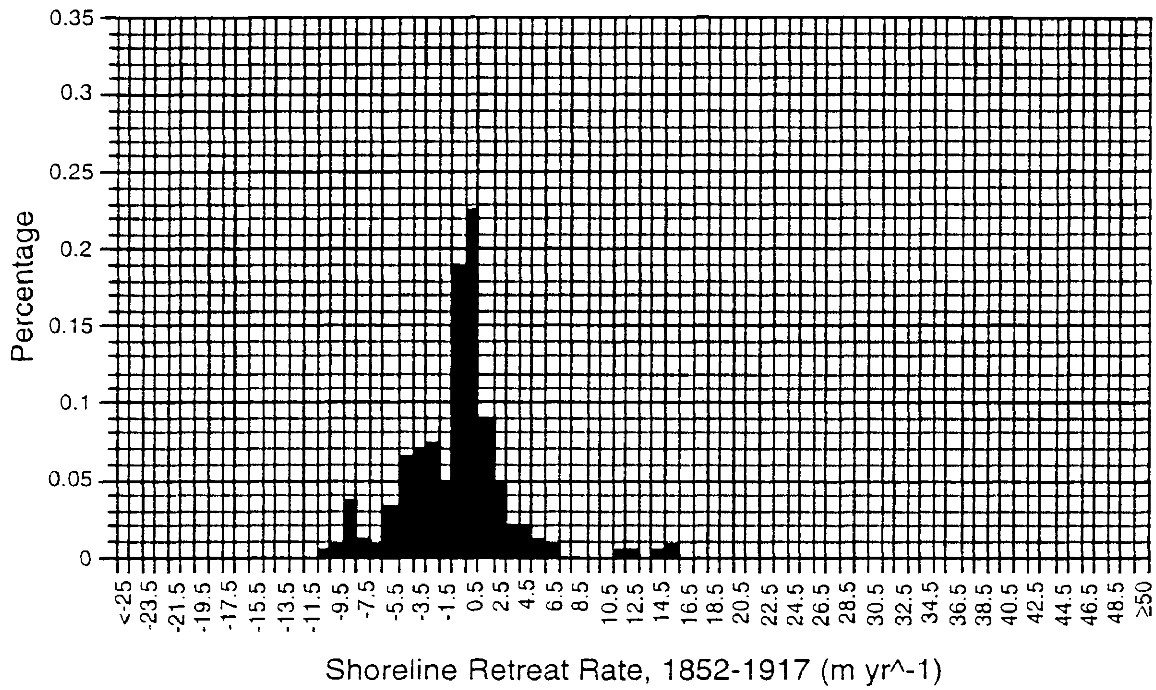


Figure 11b: Frequency Distribution of Shoreline Rates of Change, 1917-1947

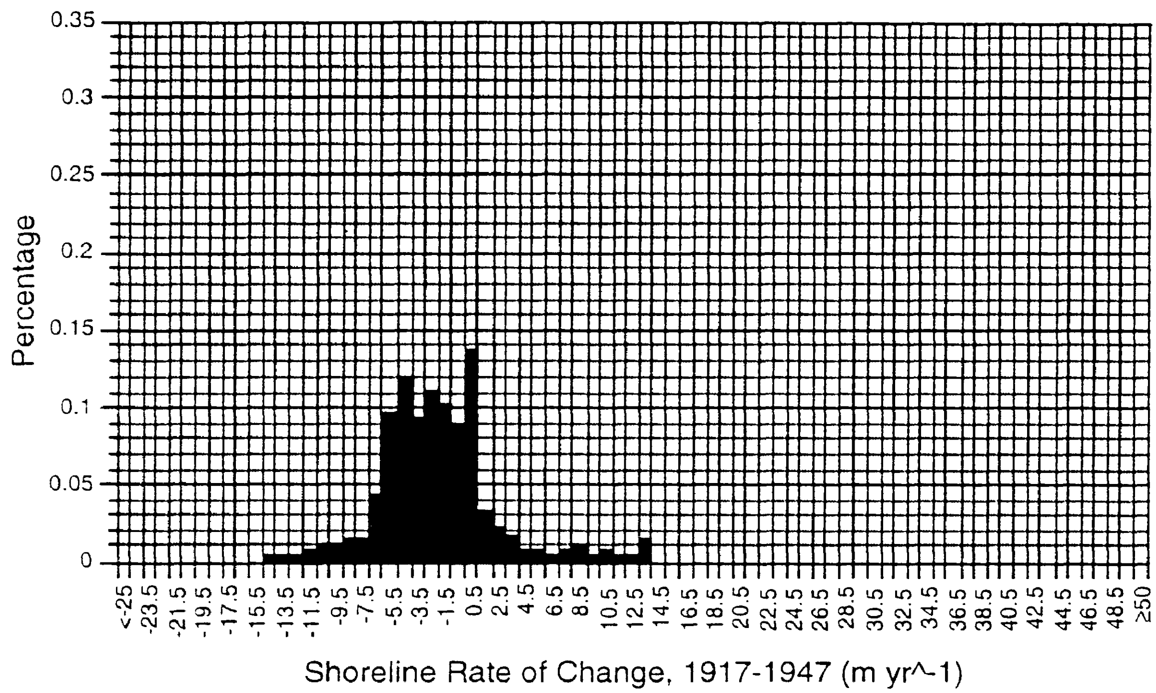


Figure 11c: Frequency Distribution for Shoreline Rates of Change, 1947-1980

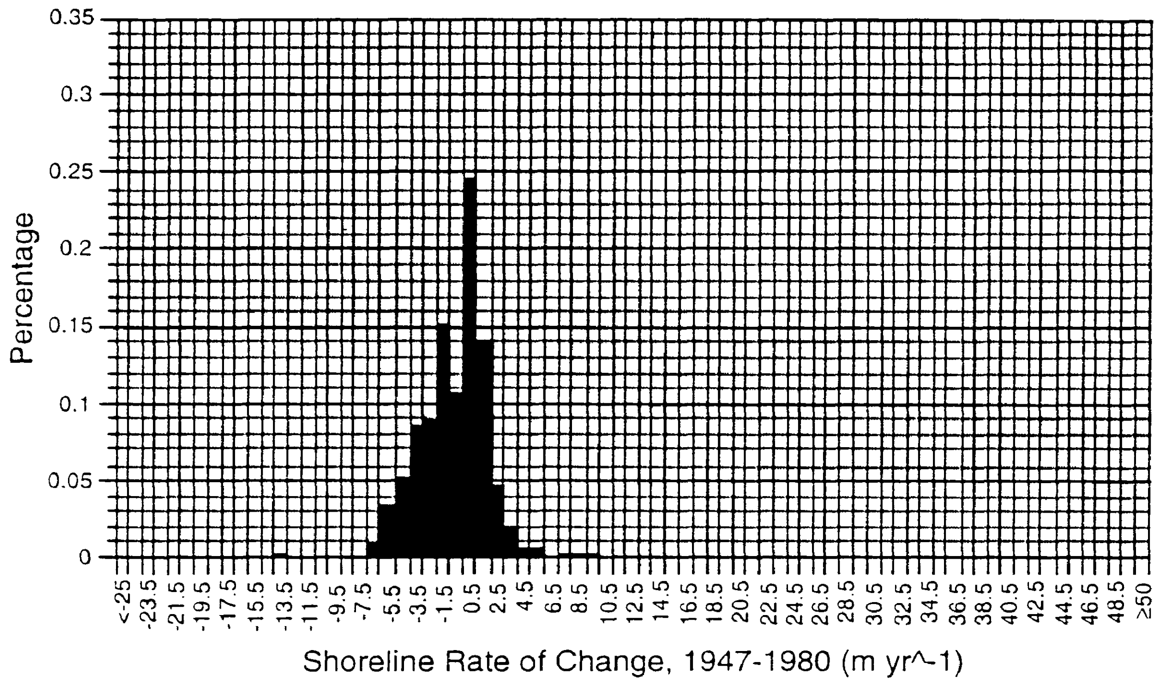


Figure 11d: Frequency Distribution of Shoreline Retreat Rates, 1980-1993

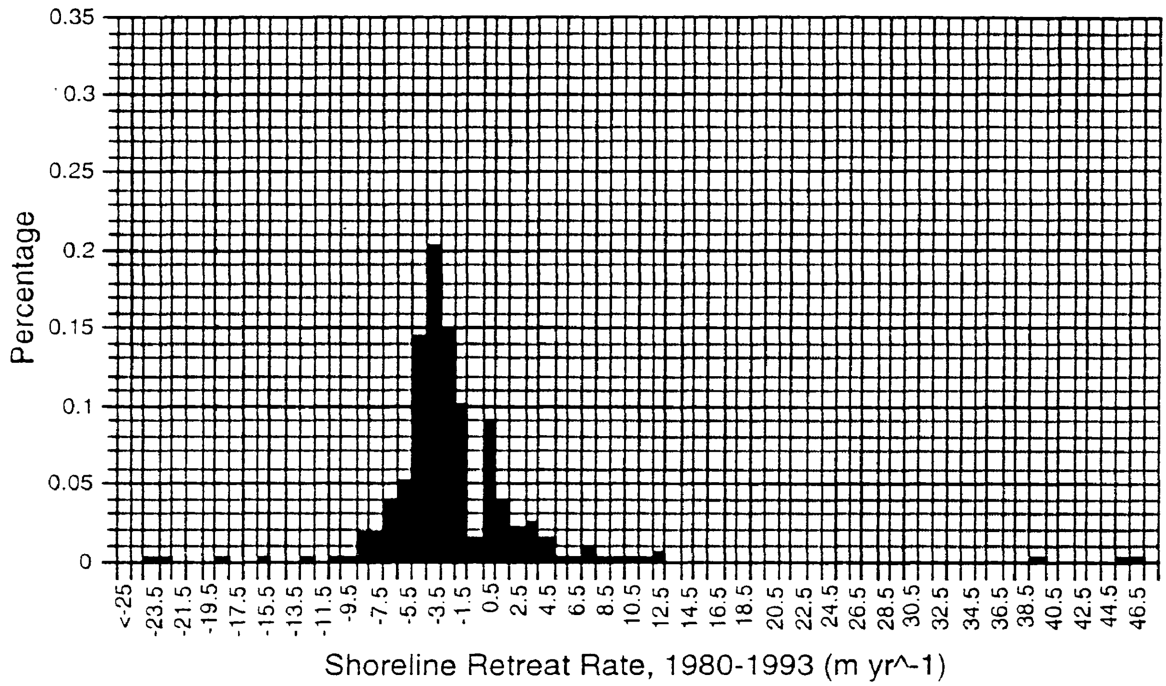


Figure 11e: Frequency Distribution of Shoreline Retreat Rates (1852-1993)

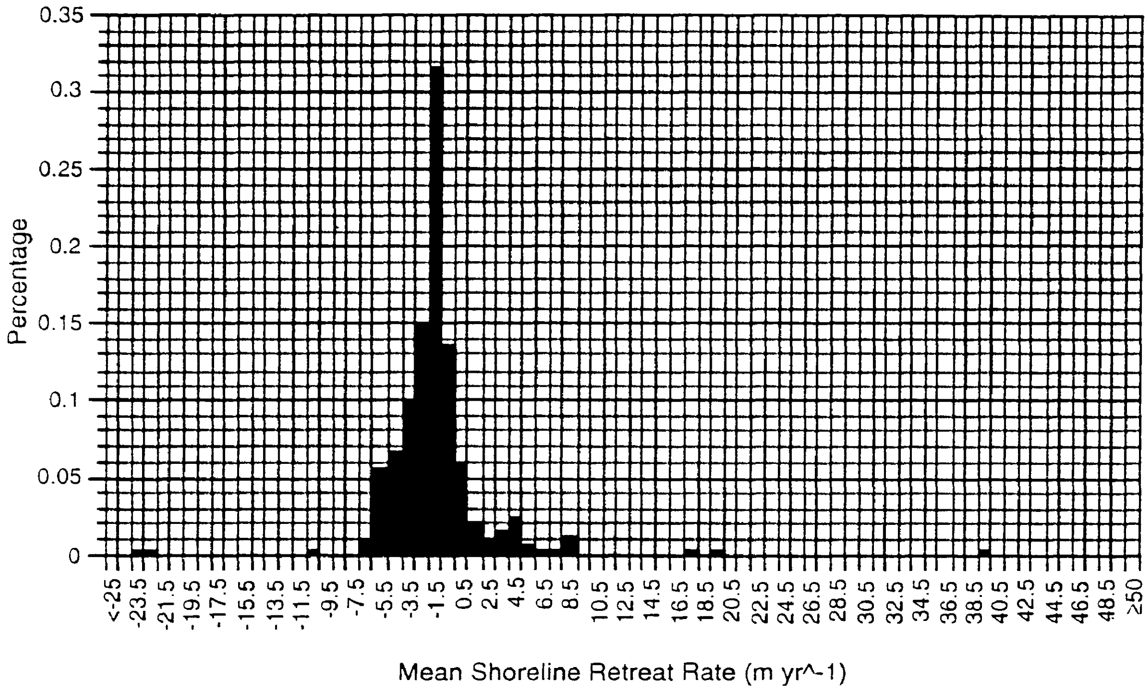


Figure 12a: Shoreline Rates of Change: 1852-1917

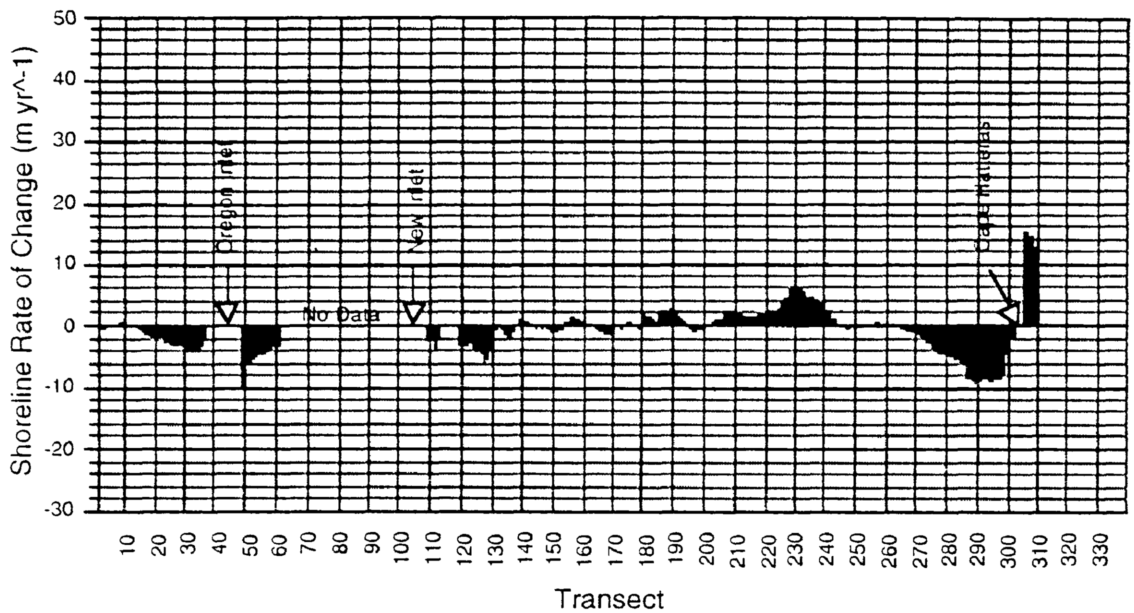


Figure 12b: Shoreline Rates of Change: 1917-1947

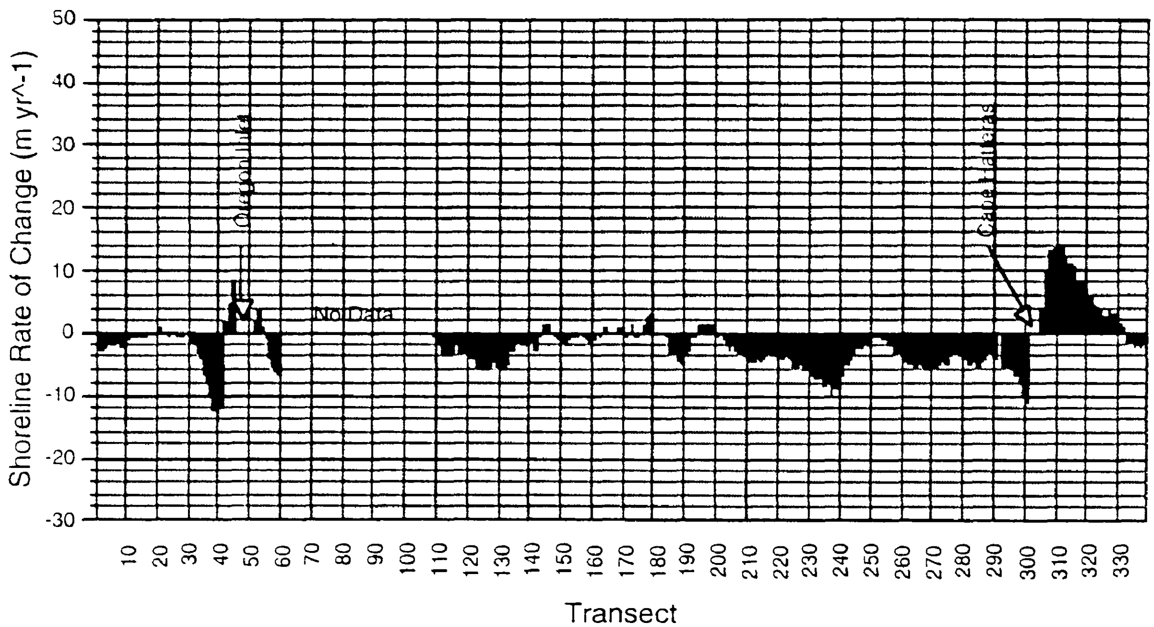


Figure 12c: Shoreline Rates of Change: 1947-1980

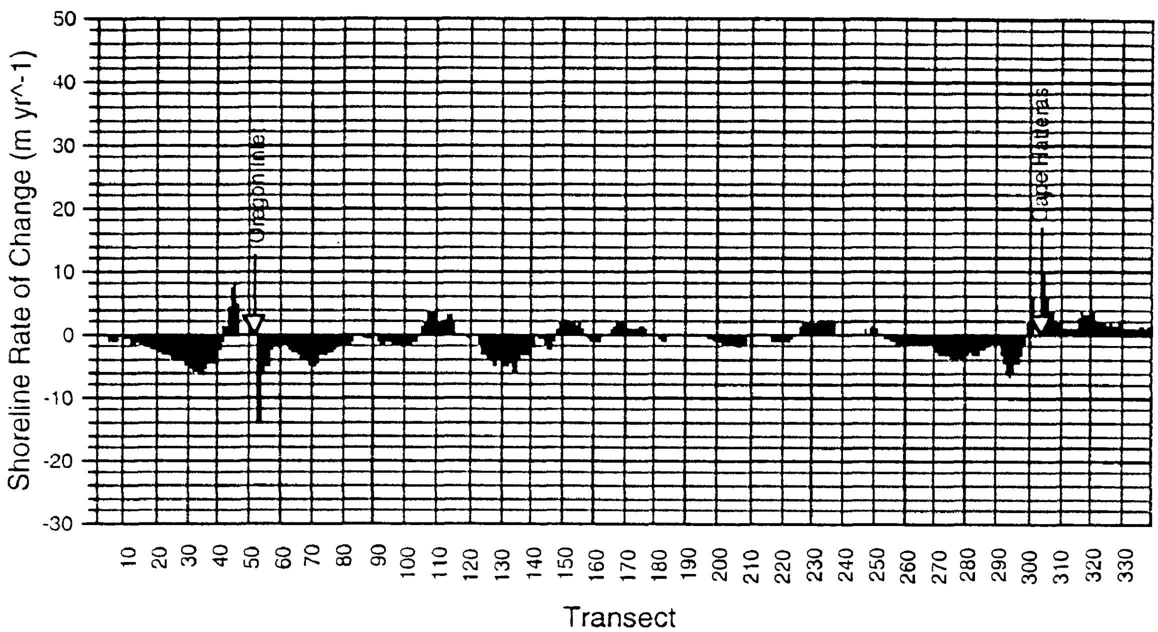


Figure12d: Shoreline Rates of Change:1980-1993

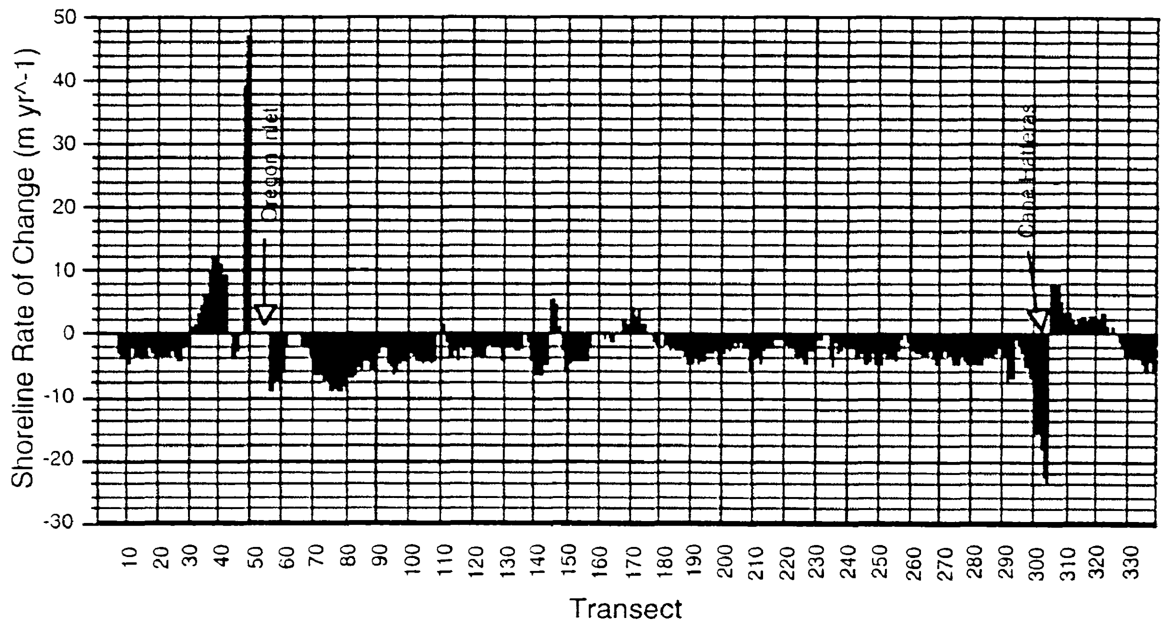
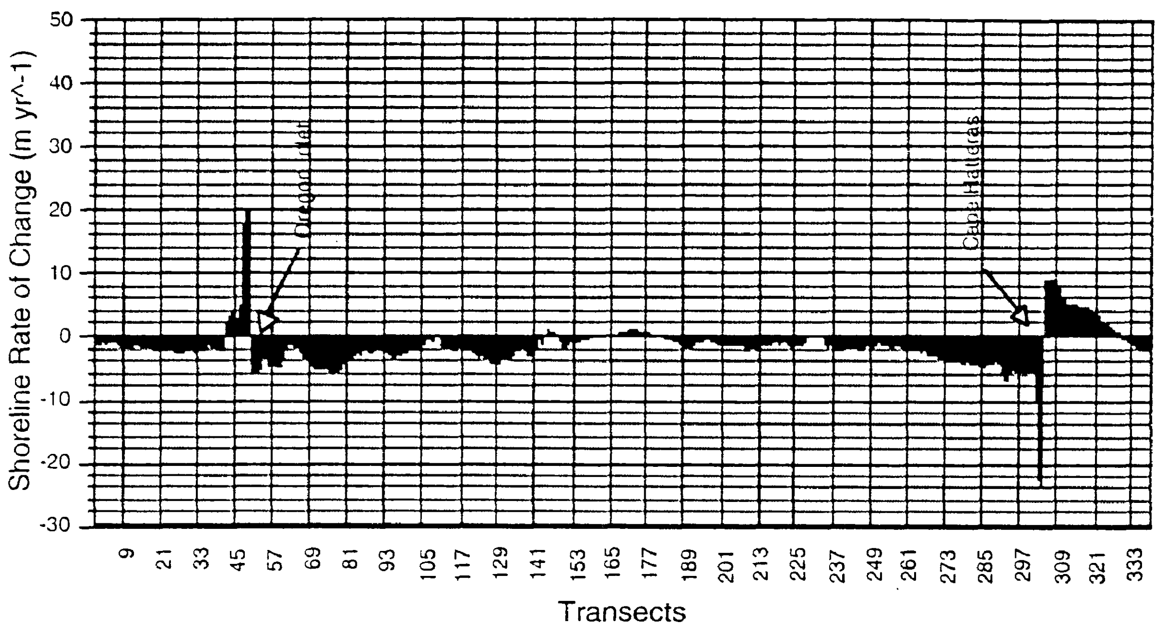


Figure 12e: Shoreline Rates of Change: 1852-1993



Shoreline Retreat Risk for Cape Hatteras National Seashore

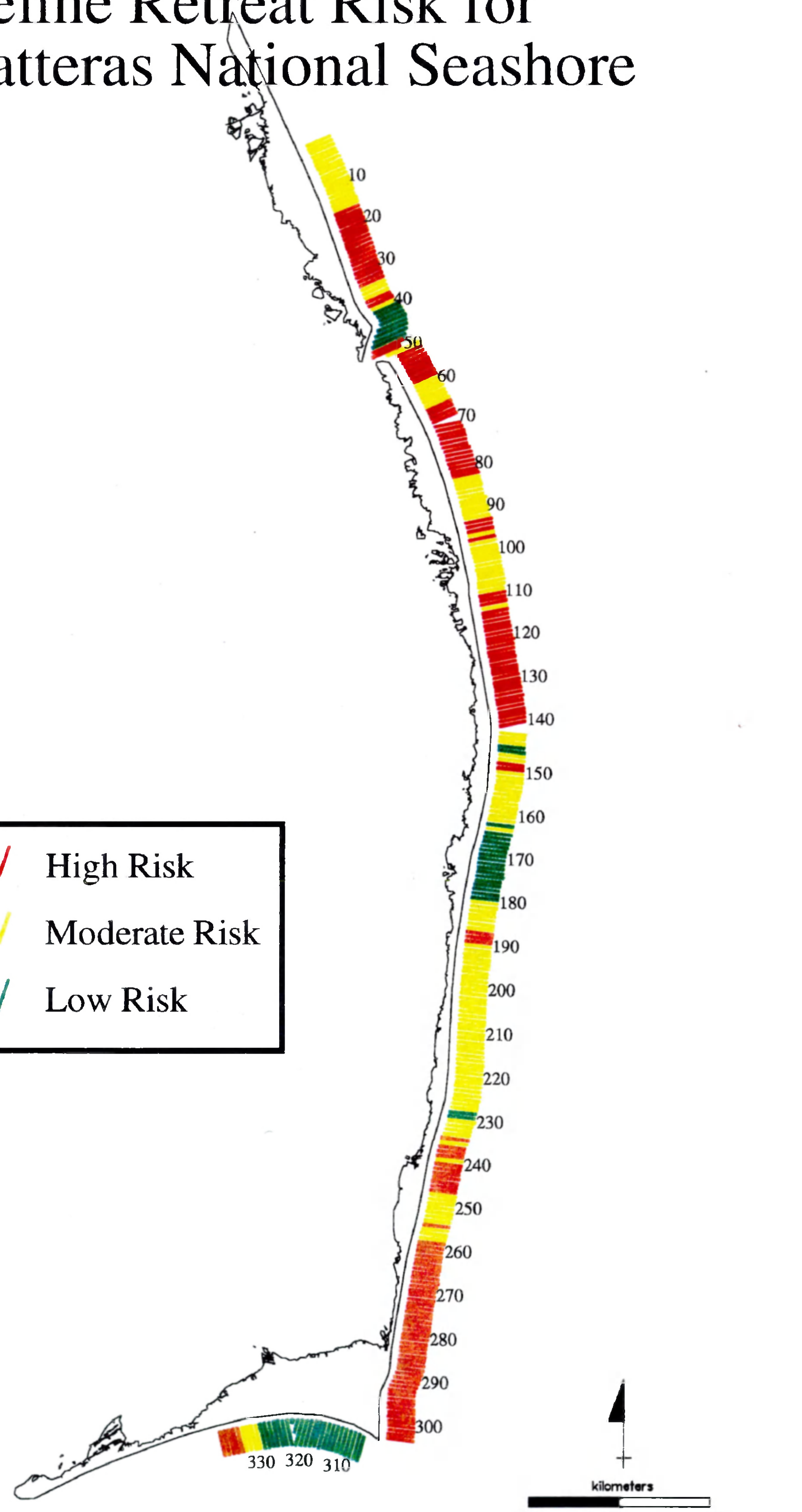


Figure 13

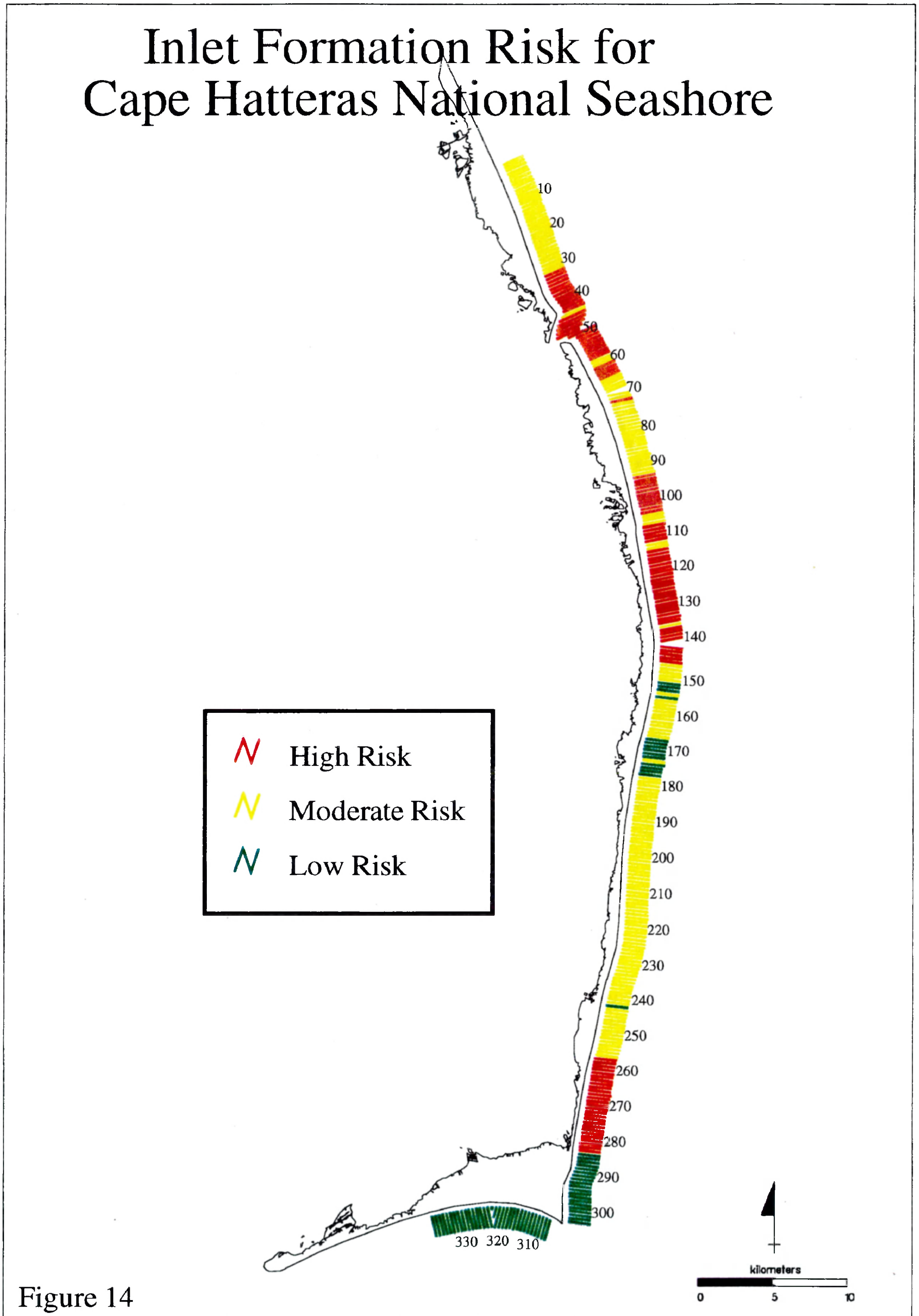

Inlet Formation Risk for
Cape Hatteras National Seashore
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
330
320
310
High Risk
Moderate Risk
Low Risk
kilometers
0
5
10

Figure 14

Overwash Risk for Cape Hatteras National Seashore

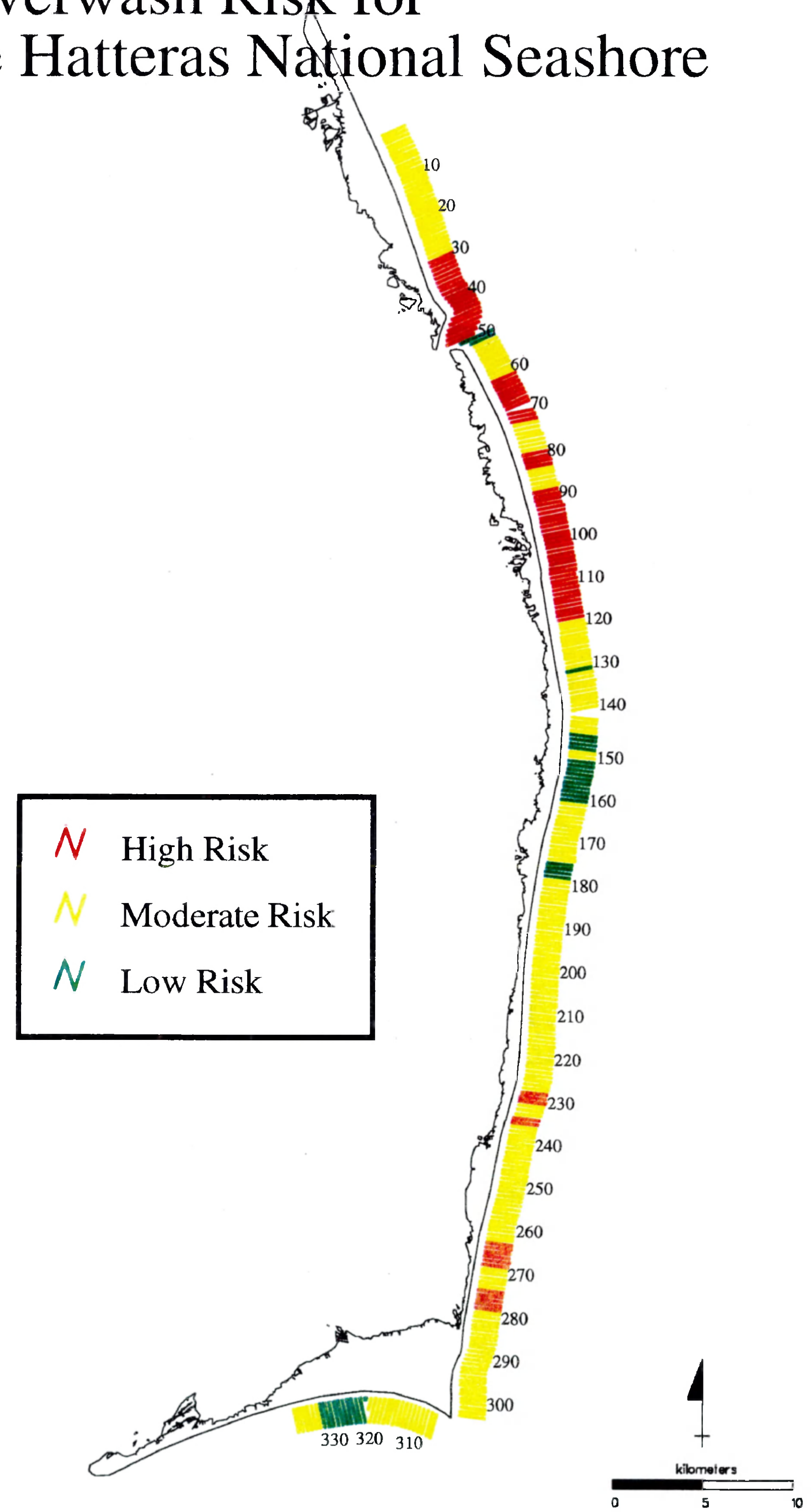


Figure 15

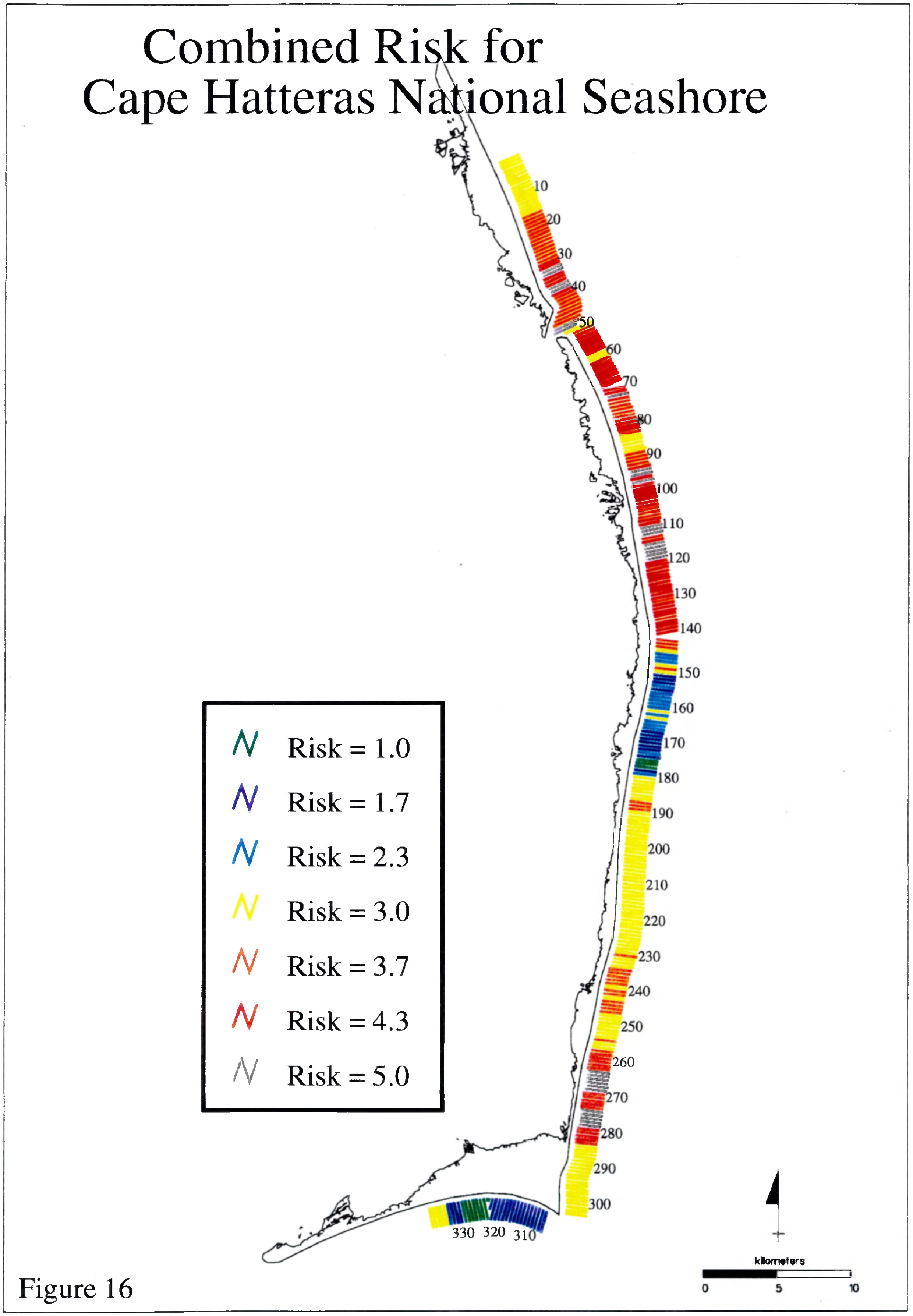

Combined Risk for
Cape Hatteras National Seashore
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
320
330
Risk = 1.0
Risk = 1.7
Risk = 2.3
Risk = 3.0
Risk = 3.7
Risk = 4.3
Risk = 5.0
kilometers
0
5
10

Figure 16

Loggerhead Turtle Management Areas in Cape Hatteras National Seashore

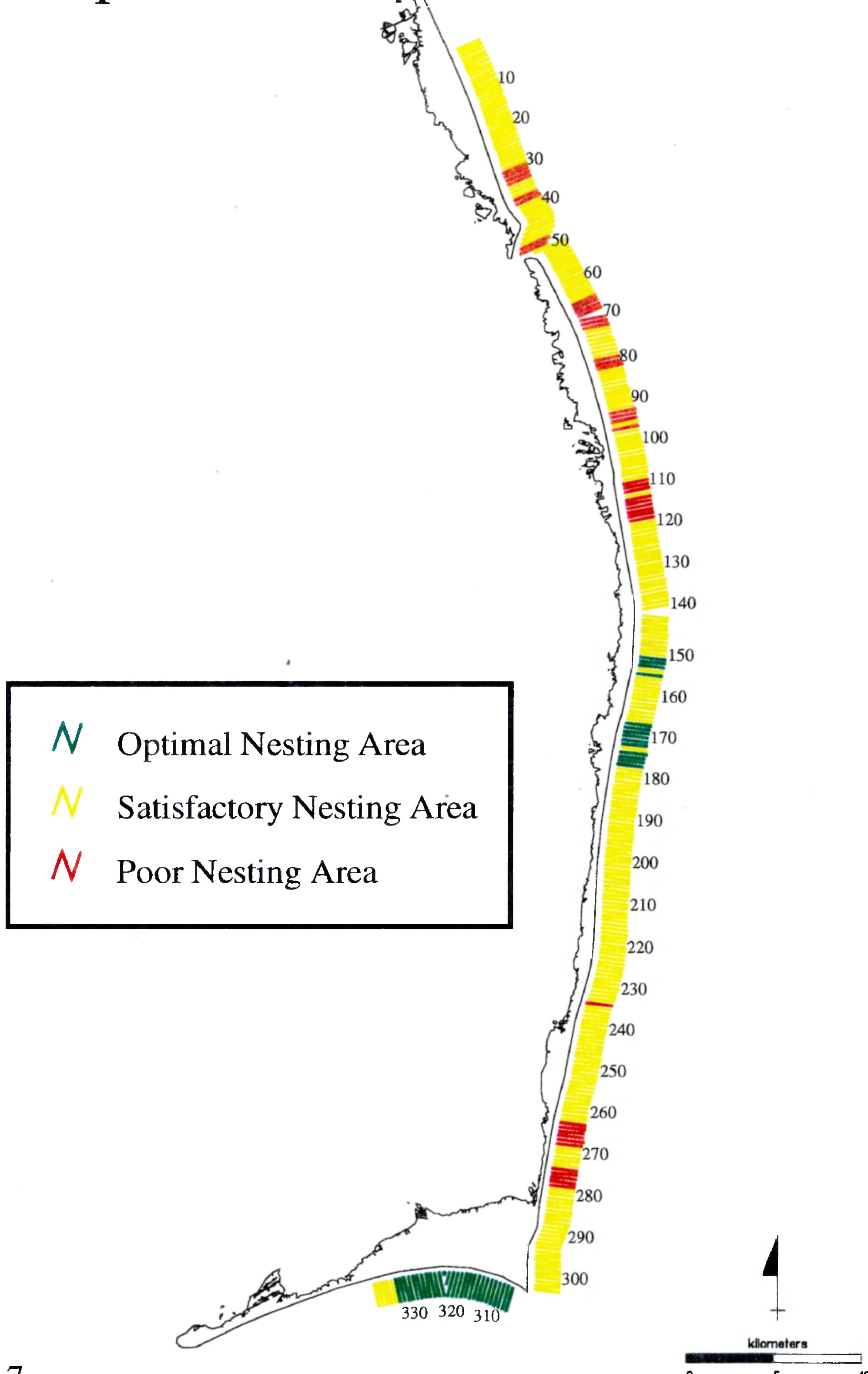


Figure 17

Appendix 1: Summary of risk information for CAHA, 1852-1993

Transect	Retreat	Inlet Formation	Overwash	Combined	Transect	Retreat	Inlet Formation	Overwash	Combined
1	3	3	3	3.0	49	1	5	5	3.7
2	3	3	3	3.0	50	5	5	5	5.0
3	3	3	3	3.0	51	5	5	5	5.0
4	3	3	3	3.0	52	3	5	1	3.0
5	3	3	3	3.0	53	5	5	1	3.7
6	3	3	3	3.0	54	5	5	3	4.3
7	3	3	3	3.0	55	5	5	3	4.3
8	3	3	3	3.0	56	5	5	3	4.3
9	3	3	3	3.0	57	5	5	3	4.3
10	3	3	3	3.0	58	5	5	3	4.3
11	3	3	3	3.0	59	5	5	3	4.3
12	3	3	3	3.0	60	5	5	3	4.3
13	3	3	3	3.0	61	3	3	3	3.0
14	3	3	3	3.0	62	3	3	3	3.0
15	3	3	3	3.0	63	3	5	5	4.3
16	5	3	3	3.7	64	3	5	5	4.3
17	3	3	3	3.0	65	3	5	5	4.3
18	5	3	3	3.7	66	3	5	5	4.3
19	5	3	3	3.7	67	5	3	5	4.3
20	5	3	3	3.7	68	5	3	5	4.3
21	5	3	3	3.7	69	5	3	5	4.3
22	5	3	3	3.7	70	5	3	5	4.3
23	5	3	3	3.7	71	5	3	5	4.3
24	5	3	3	3.7	72	5	3	5	4.3
25	5	3	3	3.7	73	5	5	5	5.0
26	5	3	3	3.7	74	5	3	3	3.7
27	5	3	3	3.7	75	5	3	3	3.7
28	5	3	3	3.7	76	5	3	3	3.7
29	5	3	3	3.7	77	5	3	3	3.7
30	5	3	3	3.7	78	5	3	3	3.7
31	5	3	3	3.7	79	5	3	3	3.7
32	5	3	5	4.3	80	5	3	3	3.7
33	5	3	5	4.3	81	5	3	5	4.3
34	5	5	5	5.0	82	5	3	5	4.3
35	5	5	5	5.0	83	5	3	5	4.3
36	3	5	5	4.3	84	3	3	5	3.7
37	3	5	5	4.3	85	3	3	3	3.0
38	3	5	5	4.3	86	3	3	3	3.0
39	5	5	5	5.0	87	3	3	3	3.0
40	5	5	5	5.0	88	3	3	3	3.0
41	3	5	5	4.3	89	3	3	3	3.0
42	1	5	5	3.7	90	3	3	5	3.7
43	1	5	5	3.7	91	3	3	5	3.7
44	1	5	5	3.7	92	3	3	5	3.7
45	1	5	5	3.7	93	3	3	5	3.7
46	1	5	5	3.7	94	5	3	5	4.3
47	1	5	5	3.7	95	5	5	5	5.0
48	1	5	5	3.7	96	5	5	5	5.0

Appendix 1: Summary of risk information for CAHA, 1852-1993

Transect	Retreat	Inlet Formation	Overwash	Combined
97	3	5	5	4.3
98	5	5	5	5.0
99	3	5	5	4.3
100	3	5	5	4.3
101	3	5	5	4.3
102	3	5	5	4.3
103	3	5	5	4.3
104	3	5	5	4.3
105	3	5	5	4.3
106	3	3	5	3.7
107	3	3	5	3.7
108	3	3	5	3.7
109	3	5	5	4.3
110	3	5	5	4.3
111	5	5	5	5.0
112	5	5	5	5.0
113	5	5	5	5.0
114	3	3	5	3.7
115	5	3	5	4.3
116	5	5	5	5.0
117	5	5	5	5.0
118	5	5	5	5.0
119	5	5	5	5.0
120	5	5	5	5.0
121	5	5	3	4.3
122	5	5	3	4.3
123	5	5	3	4.3
124	5	5	3	4.3
125	5	5	3	4.3
126	5	5	3	4.3
127	5	5	3	4.3
128	5	5	3	4.3
129	5	5	3	4.3
130	5	5	3	4.3
131	5	5	3	4.3
132	5	5	1	3.7
133	5	5	3	4.3
134	5	5	3	4.3
135	5	5	3	4.3
136	5	5	3	4.3
137	5	3	3	3.7
138	5	5	3	4.3
139	5	5	3	4.3
140	5	5	3	4.3
141	5	5	3	4.3
142	3	5	3	3.7
143	3	5	3	3.7
144	3	5	3	3.7

Transect	Retreat	Inlet Formation	Overwash	Combined
145	1	5	3	3.0
146	1	5	1	2.3
147	3	3	1	2.3
148	3	3	1	2.3
149	5	3	1	3.0
150	5	3	3	3.7
151	3	3	3	3.0
152	3	1	1	1.7
153	3	1	1	1.7
154	3	1	1	1.7
155	3	3	1	2.3
156	3	1	1	1.7
157	3	3	1	2.3
158	3	3	1	2.3
159	3	3	1	2.3
160	3	3	1	2.3
161	3	3	1	2.3
162	3	3	3	3.0
163	1	3	3	2.3
164	3	3	3	3.0
165	1	3	3	2.3
166	1	3	3	2.3
167	1	3	3	2.3
168	1	1	3	1.7
169	1	1	3	1.7
170	1	1	3	1.7
171	1	1	3	1.7
172	1	1	3	1.7
173	1	1	3	1.7
174	1	3	3	2.3
175	1	1	3	1.7
176	1	1	1	1.0
177	1	1	1	1.0
178	1	1	1	1.0
179	1	3	1	1.7
180	1	3	3	2.3
181	3	3	3	3.0
182	3	3	3	3.0
183	3	3	3	3.0
184	3	3	3	3.0
185	3	3	3	3.0
186	3	3	3	3.0
187	3	3	3	3.0
188	5	3	3	3.7
189	5	3	3	3.7
190	5	3	3	3.7
191	3	3	3	3.0
192	3	3	3	3.0

Appendix 1: Summary of risk information for CAHA, 1852-1993

Transect	Retreat	Inlet Formation	Overwash	Combined
193	3	3	3	3.0
194	3	3	3	3.0
195	3	3	3	3.0
196	3	3	3	3.0
197	3	3	3	3.0
198	3	3	3	3.0
199	3	3	3	3.0
200	3	3	3	3.0
201	3	3	3	3.0
202	3	3	3	3.0
203	3	3	3	3.0
204	3	3	3	3.0
205	3	3	3	3.0
206	3	3	3	3.0
207	3	3	3	3.0
208	3	3	3	3.0
209	3	3	3	3.0
210	3	3	3	3.0
211	3	3	3	3.0
212	3	3	3	3.0
213	3	3	3	3.0
214	3	3	3	3.0
215	3	3	3	3.0
216	3	3	3	3.0
217	3	3	3	3.0
218	3	3	3	3.0
219	3	3	3	3.0
220	3	3	3	3.0
221	3	3	3	3.0
222	3	3	3	3.0
223	3	3	3	3.0
224	3	3	3	3.0
225	3	3	3	3.0
226	3	3	3	3.0
227	3	3	3	3.0
228	3	3	3	3.0
229	1	3	5	3.0
230	1	3	5	3.0
231	3	3	5	3.7
232	3	3	3	3.0
233	3	3	3	3.0
234	3	3	3	3.0
235	5	3	5	4.3
236	3	3	5	3.7
237	5	3	3	3.7
238	5	3	3	3.7
239	5	3	3	3.7
240	3	3	3	3.0
241	5	3	3	3.7
242	5	3	3	3.7
243	5	1	3	3.0
244	5	3	3	3.7
245	5	3	3	3.7
246	5	3	3	3.7
247	5	3	3	3.7
248	3	3	3	3.0
249	3	3	3	3.0
250	3	3	3	3.0
251	3	3	3	3.0
252	3	3	3	3.0
253	3	3	3	3.0
254	3	3	3	3.0
255	5	3	3	3.7
256	3	3	3	3.0
257	3	3	3	3.0
258	3	5	3	3.7
259	5	5	3	4.3
260	5	5	3	4.3
261	5	5	3	4.3
262	5	5	3	4.3
263	5	5	3	4.3
264	5	5	5	5.0
265	5	5	5	5.0
266	5	5	5	5.0
267	5	5	5	5.0
268	5	5	5	5.0
269	5	5	5	5.0
270	5	5	3	4.3
271	5	5	3	4.3
272	5	5	3	4.3
273	5	5	3	4.3
274	5	5	3	4.3
275	5	5	5	5.0
276	5	5	5	5.0
277	5	5	5	5.0
278	5	5	5	5.0
279	5	5	5	5.0
280	5	5	3	4.3
281	5	5	3	4.3
282	5	5	3	4.3
283	5	5	3	4.3
284	5	5	3	4.3
285	5	1	3	3.0
286	5	1	3	3.0
287	5	1	3	3.0
288	5	1	3	3.0

Appendix 1: Summary of risk information for CAHA, 1852-1993

Transect	Retreat	Inlet Formation	Overwash	Combined
289	5	1	3	3.0
290	5	1	3	3.0
291	5	1	3	3.0
292	5	1	3	3.0
293	5	1	3	3.0
294	5	1	3	3.0
295	5	1	3	3.0
296	5	1	3	3.0
297	5	1	3	3.0
298	5	1	3	3.0
299	5	1	3	3.0
300	5	1	3	3.0
301	5	1	3	3.0
302	5	1	3	3.0
303	5	1	3	3.0
304	5	1	3	3.0
305	1	1	3	1.7
306	1	1	3	1.7
307	1	1	3	1.7
308	1	1	3	1.7
309	1	1	3	1.7
310	1	1	3	1.7
311	1	1	3	1.7
312	1	1	3	1.7
313	1	1	3	1.7
314	1	1	3	1.7
315	1	1	3	1.7
316	1	1	3	1.7
317	1	1	3	1.7
318	1	1	3	1.7
319	1	1	3	1.7
320	1	1	3	1.7
321	1	1	1	1.0
322	1	1	1	1.0
323	1	1	1	1.0
324	1	1	1	1.0
325	1	1	1	1.0
326	1	1	1	1.0
327	1	1	1	1.0
328	1	1	1	1.0
329	1	1	1	1.0
330	3	1	1	1.7
331	3	1	1	1.7
332	3	1	1	1.7
333	3	1	3	2.3
334	5	1	3	3.0
335	5	1	3	3.0
336	5	1	3	3.0
337	5	1	3	3.0
338	5	1	3	3.0

Appendix 2: Shoreline rates of change for CAHA, 1852-1993

Transect	1852-1917	1917-1947	1947-1980	1980-1993	Mean Rate
1	-0.9	-2.3	0.0	No Data	-1.1
2	-0.5	-2.6	0.0	No Data	-1.0
3	-0.4	-2.2	-0.6	No Data	-1.1
4	0.0	-2.3	0.0	No Data	-0.8
5	0.0	-1.8	-1.0	No Data	-0.9
6	0.2	-1.8	-1.0	No Data	-0.9
7	0.3	-1.8	-0.9	-2.9	-1.3
8	0.5	-2.3	0.0	-3.9	-1.4
9	0.6	-2.4	-0.5	-3.0	-1.3
10	0.8	-2.7	-0.5	-3.7	-1.5
11	0.3	-1.2	-0.7	-4.6	-1.5
12	0.0	-0.9	-1.5	-2.2	-1.2
13	-0.4	-0.5	-0.9	-3.3	-1.3
14	-0.5	-0.7	-1.1	-3.7	-1.5
15	-0.6	-0.7	-1.3	-3.7	-1.6
16	-0.7	-0.9	-1.3	-3.8	-1.7
17	-1.2	0.0	-2.1	-2.5	-1.5
18	-1.5	0.0	-2.5	-3.0	-1.7
19	-1.7	0.0	-2.4	-3.7	-1.9
20	-1.8	0.0	-2.9	-3.5	-2.0
21	-2.2	0.8	-2.9	-4.2	-2.1
22	-2.0	0.0	-3.2	-3.6	-2.2
23	-2.6	0.0	-3.1	-3.6	-2.3
24	-2.7	-0.8	-3.2	-2.6	-2.3
25	-3.0	0.0	-3.5	-3.4	-2.5
26	-3.0	0.0	-3.9	-3.8	-2.7
27	-3.0	-0.6	-3.6	-4.2	-2.8
28	-3.2	-0.6	-4.2	-2.3	-2.6
29	-3.7	0.0	-4.8	-1.5	-2.5
30	-4.1	-0.7	-5.2	1.0	-2.2
31	-4.0	-1.5	-5.4	1.0	-2.5
32	-4.0	-2.2	-5.6	1.2	-2.7
33	-4.2	-3.4	-5.7	3.3	-2.5
34	-3.9	-4.2	-5.9	4.2	-2.5
35	-3.2	-6.7	-5.1	6.1	-2.2
36	-2.4	-8.4	-5.2	9.9	-1.5
37	No Data	-10.5	-4.7	11.1	-1.4
38	No Data	-12.3	-4.4	12.2	-1.5
39	No Data	-14.0	-3.9	12.0	-1.9
40	No Data	-14.6	-2.5	10.8	-2.1
41	No Data	-12.0	-0.9	9.0	-1.3
42	No Data	1.6	1.3	4.5	2.5
43	No Data	4.8	4.4	0.0	3.1
44	No Data	8.2	7.3	-4.0	3.8
45	No Data	No Data	8.3	-2.9	2.7
46	No Data	No Data	4.7		4.7
47	No Data	No Data	No Data	39.1	39.1
48	-10.1	No Data	No Data	45.2	17.5
49	-7.6	No Data	No Data	46.9	19.6
50	-6.2	No Data	No Data	No Data	-6.2

Appendix 2: Shoreline rates of change for CAHA, 1852-1993

Transect	1852-1917	1917-1947	1947-1980	1980-1993	Mean Rate
51	-5.8	No Data	No Data	No Data	-5.8
52	-5.2	1.7	No Data	No Data	-1.8
53	-5.1	3.2	-13.9	No Data	-5.3
54	-4.7	0.5	-6.4	No Data	-3.5
55	-4.6	-1.2	-4.8	No Data	-3.6
56	-4.1	-4.1	-2.8	-8.9	-5.0
57	-4.0	-5.4	-2.2	-7.7	-4.8
58	-3.4	-6.4	-2.0	-7.1	-4.7
59	-3.1	-6.7	-2.1	-7.8	-4.9
60	-2.9	No Data	-1.5	-6.2	-3.6
61	No Data	No Data	-1.7	-2.0	-1.8
62	No Data	No Data	-2.2	0.0	-1.1
63	No Data	No Data	-2.3	0.0	-1.2
64	No Data	No Data	-2.9	0.0	-1.5
65	No Data	No Data	-3.2	0.0	-1.6
66	No Data	No Data	-3.8	-1.5	-2.6
67	No Data	No Data	-4.2	-2.4	-3.3
68	No Data	No Data	-3.7	-3.4	-3.5
69	No Data	No Data	-4.8	-3.6	-4.2
70	No Data	No Data	-4.8	-5.0	-4.9
71	No Data	No Data	-4.6	-6.3	-5.5
72	No Data	No Data	-4.0	-6.6	-5.3
73	No Data	No Data	-3.2	-7.1	-5.1
74	No Data	No Data	-3.1	-7.6	-5.4
75	No Data	No Data	-2.6	-9.0	-5.8
76	No Data	No Data	-2.7	-9.2	-5.9
77	No Data	No Data	-2.4	-8.7	-5.6
78	No Data	No Data	-2.1	-8.9	-5.5
79	No Data	No Data	-1.6	-8.3	-4.9
80	No Data	No Data	-1.4	-7.0	-4.2
81	No Data	No Data	-1.3	-6.0	-3.7
82	No Data	No Data	-0.9	-6.7	-3.8
83	No Data	No Data	0.0	-6.5	-3.2
84	No Data	No Data	0.0	-5.5	-2.7
85	No Data	No Data	0.0	-5.8	-2.9
86	No Data	No Data	-0.6	-4.4	-2.5
87	No Data	No Data	-0.6	-4.2	-2.4
88	No Data	No Data	0.0	-5.8	-2.9
89	No Data	No Data	-0.6	-4.0	-2.3
90	No Data	No Data	0.0	-3.2	-1.6
91	No Data	No Data	-0.9	-2.1	-1.5
92	No Data	No Data	-1.3	-2.4	-1.8
93	No Data	No Data	-1.3	-4.5	-2.9
94	No Data	No Data	-0.9	-5.4	-3.1
95	No Data	No Data	-0.8	-6.3	-3.6
96	No Data	No Data	-1.2	-6.0	-3.6
97	No Data	No Data	-1.2	-4.9	-3.0
98	No Data	No Data	-1.9	-4.2	-3.1
99	No Data	No Data	-2.4	-3.1	-2.8
100	No Data	No Data	-1.7	-3.3	-2.5

Appendix 2: Shoreline rates of change for CAHA, 1852-1993

Transect	1852-1917	1917-1947	1947-1980	1980-1993	Mean Rate
101	No Data	No Data	-1.3	-3.4	-2.4
102	No Data	No Data	-0.9	-3.4	-2.1
103	No Data	No Data	0.0	-4.1	-2.1
104	No Data	No Data	1.0	-4.8	-1.9
105	No Data	No Data	1.4	-4.2	-1.4
106	No Data	No Data	1.6	-2.7	-0.5
107	No Data	No Data	3.3	-4.6	-0.6
108	-2.3	No Data	3.7	-4.2	-0.9
109	-2.4	-0.7	2.3	0.0	-0.2
110	-2.3	-2.0	1.8	1.2	-0.3
111	-3.5	-3.2	2.1	-1.2	-1.5
112	-2.5	-3.0	2.0	-2.4	-1.5
113	No Data	-3.7	2.8	-4.0	-1.7
114	No Data	-3.8	2.0	-2.5	-1.4
115	No Data	-3.1	1.7	-4.1	-1.8
116	No Data	-2.1	0.0	-2.5	-1.5
117	No Data	-2.4	0.0	-2.9	-1.8
118	No Data	-3.2	0.0	-2.5	-1.9
119	-3.1	-3.0	-0.5	-1.9	-2.2
120	-3.3	-3.1	0.0	-2.3	-2.2
121	-3.0	-4.0	0.0	-3.4	-2.6
122	-2.5	-5.4	0.0	-3.9	-2.9
123	-2.9	-5.5	-1.4	-3.6	-3.3
124	-3.6	-6.0	-3.0	0.0	-3.2
125	-4.3	-6.0	-2.7	-1.5	-3.6
126	-4.6	-6.0	-3.9	-2.0	-4.1
127	-5.6	-5.5	-3.9	-2.4	-4.3
128	-5.1	-4.8	-4.9	-2.3	-4.3
129	-3.5	-5.5	-4.1	-4.2	-4.3
130	-2.1	-5.3	-4.7	-2.4	-3.6
131	-0.6	-5.9	-4.5	-2.3	-3.3
132	-0.3	-5.6	-5.1	-2.5	-3.4
133	-0.5	-4.9	-4.7	-3.9	-3.5
134	-1.1	-2.9	-5.6	-2.8	-3.1
135	-1.5	-1.4	-5.0	-2.1	-2.5
136	-1.0	-1.6	-4.0	0.0	-1.6
137	-0.7	-2.0	-3.1	-1.4	-1.8
138	0.0	-2.1	-3.0	-4.2	-2.3
139	0.8	-2.1	-2.6	-8.2	-3.0
140	0.6	-1.7	-2.1	-6.4	-2.4
141	0.5	-2.6	0.0	-6.6	-2.2
142	0.3	-2.4	0.0	No Data	-0.7
143	0.0	-0.6	-0.5	-4.5	-1.4
144	-0.5	0.9	-1.4	1.0	0.0
145	0.0	0.9	-2.5	5.6	1.0
146	-0.4	0.0	-1.6	4.4	0.6
147	-0.3	0.0	-1.0	1.0	-0.1
148	-0.6	-0.7	0.6	-2.7	-0.8
149	-0.9	-1.2	1.9	-6.0	-1.5
150	-0.9	-1.8	2.2	-5.3	-1.5

Appendix 2: Shoreline rates of change for CAHA, 1852-1993

Transect	1852-1917	1917-1947	1947-1980	1980-1993	Mean Rate
151	-0.8	-1.9	2.3	-4.9	-1.3
152	-0.4	-1.2	1.7	-4.4	-1.1
153	0.0	-0.8	1.6	-4.4	-0.9
154	0.7	-0.4	1.4	-4.1	-0.6
155	1.0	-0.4	1.7	-5.1	-0.7
156	1.4	0.0	1.0	-4.1	-0.4
157	1.1	-0.8	0.0	-1.9	-0.4
158	0.8	-1.3	-0.5	0.0	-0.2
159	0.5	-1.7	-1.0	0.0	-0.6
160	0.0	-1.2	0.0	0.0	-0.3
161	0.0	0.0	-0.8	0.0	-0.2
162	0.0	-0.6	0.0	-0.9	-0.4
163	0.3	0.0	0.0	0.0	0.1
164	-0.4	0.5	0.0	-1.3	-0.3
165	-0.7	0.0	0.8	0.0	0.0
166	-0.8	0.0	1.2	0.0	0.1
167	-1.1	0.0	2.0	0.0	0.2
168	-1.2	0.6	1.8	1.9	0.8
169	-1.0	0.5	2.3	1.2	0.7
170	-0.4	-0.6	0.9	4.2	1.1
171	-0.3	0.0	0.5	3.9	1.0
172	-0.5	0.9	0.5	2.9	1.0
173	0.0	0.0	0.7	3.5	1.0
174	0.8	-0.7	1.1	1.3	0.6
175	0.7	0.0	1.2	0.0	0.5
176	0.3	1.1	0.6	0.0	0.5
177	-0.2	2.4	0.0	0.0	0.6
178	-0.6	2.7	0.0	-1.3	0.2
179	-0.2	2.2	0.0	-1.7	0.1
180	1.6	0.0	0.0	0.0	0.4
181	1.5	0.0	-0.5	-1.6	-0.1
182	1.0	0.0	-0.8	-1.6	-0.4
183	0.3	0.0	-0.5	-2.6	-0.7
184	0.8	-0.5	0.0	-2.4	-0.5
185	1.9	-2.9	0.0	-2.5	-0.9
186	2.2	-3.5	0.0	-2.7	-1.0
187	2.5	-4.5	0.0	-3.2	-1.3
188	2.6	-5.1	0.0	-3.6	-1.5
189	2.7	-5.4	0.8	-4.6	-1.6
190	2.1	-4.0	0.0	-5.1	-1.7
191	1.2	-2.6	0.0	-3.7	-1.3
192	1.0	-1.0	0.0	-4.5	-1.1
193	0.6	0.0	0.0	-4.2	-0.9
194	0.0	1.1	0.0	-4.1	-0.8
195	-0.5	1.4	0.0	-3.3	-0.6
196	-0.8	1.3	0.0	-2.7	-0.5
197	-0.5	1.4	-0.6	-3.0	-0.7
198	-0.7	1.1	-1.0	-2.6	-0.8
199	-0.5	0.6	-0.8	-4.5	-1.3
200	0.0	-0.5	-0.7	-3.1	-1.1

Appendix 2: Shoreline rates of change for CAHA, 1852-1993

Transect	1852-1917	1917-1947	1947-1980	1980-1993	Mean Rate
201	0.0	0.0	-1.7	-1.9	-0.9
202	0.0	-1.2	-1.1	-2.9	-1.3
203	0.5	-1.8	-1.6	-1.4	-1.1
204	0.9	-2.6	-1.5	-1.4	-1.1
205	1.0	-2.1	-1.7	-1.6	-1.1
206	1.6	-2.6	-2.0	-1.3	-1.1
207	2.0	-3.6	-1.5	-1.8	-1.2
208	2.0	-3.9	-1.3	-2.3	-1.4
209	2.0	-4.3	0.0	-5.5	-1.9
210	1.9	-4.6	0.0	-3.9	-1.6
211	1.8	-4.4	0.0	-3.5	-1.5
212	1.8	-4.6	0.0	-4.5	-1.8
213	1.5	-4.4	0.0	-2.9	-1.5
214	1.4	-4.6	0.0	-1.4	-1.1
215	1.2	-4.3	0.0	-2.3	-1.3
216	1.2	-3.9	0.0	-2.3	-1.2
217	1.3	-3.6	-0.9	-0.9	-1.0
218	1.6	-3.8	-0.8	-0.9	-1.0
219	1.6	-4.1	-0.9	-1.2	-1.1
220	1.6	-3.7	0.0	-2.1	-1.0
221	2.0	-4.1	0.0	-1.7	-0.9
222	2.3	-3.8	-0.9	-2.1	-1.1
223	2.4	-4.4	-0.5	-3.6	-1.5
224	2.9	-4.7	0.0	-4.0	-1.5
225	3.8	-5.6	0.0	-3.3	-1.3
226	4.1	-5.4	1.3	-4.5	-1.1
227	4.6	-4.9	1.7	-4.6	-0.8
228	5.6	-6.1	1.8	-2.8	-0.4
229	6.1	-5.7	1.3	0.0	0.4
230	6.1	-6.2	1.6	0.0	0.4
231	5.6	-7.0	1.6	-0.9	-0.2
232	5.4	-7.2	1.6	0.0	-0.1
233	4.8	-7.3	2.1	0.0	-0.1
234	4.8	-8.0	1.9	-3.7	-1.2
235	4.7	-8.8	2.2	-5.3	-1.8
236	4.0	-8.2	0.0	-1.4	-1.4
237	3.7	-10.3	1.8	-3.0	-2.0
238	3.6	-9.2	0.0	-2.8	-2.1
239	3.4	-9.1	0.0	-1.7	-1.8
240	2.5	-7.8	0.0	0.0	-1.3
241	2.0	-7.0	0.6	-2.0	-1.6
242	0.8	-5.0	0.0	-2.0	-1.5
243	0.9	-4.1	0.0	-3.9	-1.8
244	0.2	-3.3	0.0	-3.2	-1.6
245	0.0	-2.5	0.0	-5.0	-1.9
246	-0.2	-2.5	0.0	-4.7	-1.8
247	-0.6	-2.2	0.5	-4.3	-1.7
248	-0.5	-1.6	0.0	-3.1	-1.3
249	-0.3	-1.9	1.3	-4.8	-1.4
250	-0.3	-1.4	0.7	-4.4	-1.3

Appendix 2: Shoreline rates of change for CAHA, 1852-1993

Transect	1852-1917	1917-1947	1947-1980	1980-1993	Mean Rate
251	-0.2	-1.0	0.0	-3.2	-1.1
252	0.0	-0.9	0.0	-2.9	-1.0
253	0.0	-1.0	0.0	-3.7	-1.2
254	0.2	-1.3	-0.5	-3.8	-1.3
255	0.4	-1.3	-0.9	-4.1	-1.5
256	0.5	-1.9	-1.0	-2.8	-1.3
257	0.2	-2.1	-2.0	-0.9	-1.2
258	0.2	-2.9	-1.9	0.0	-1.2
259	0.3	-3.5	-1.4	-1.4	-1.5
260	0.2	-4.4	-0.9	-2.7	-2.0
261	0.0	-4.5	-1.4	-2.9	-2.2
262	0.0	-5.1	-1.2	-3.1	-2.4
263	0.0	-5.0	-1.6	-3.1	-2.4
264	-0.2	-5.2	-1.3	-3.3	-2.5
265	-0.5	-4.9	-1.3	-3.6	-2.6
266	-1.0	-4.9	-1.3	-2.9	-2.5
267	-0.9	-5.4	-1.3	-3.4	-2.8
268	-0.5	-6.1	-1.6	-3.7	-3.0
269	-0.8	-6.2	-1.4	-4.5	-3.3
270	-1.1	-5.5	-2.8	-3.5	-3.2
271	-1.9	-5.5	-3.1	-2.8	-3.3
272	-2.3	-5.1	-3.2	-3.4	-3.5
273	-2.6	-4.7	-3.4	-3.5	-3.5
274	-2.8	-5.0	-3.0	-4.7	-3.9
275	-3.4	-4.4	-3.4	-4.6	-4.0
276	-4.0	-4.0	-3.7	-3.6	-3.8
277	-4.5	-3.4	-3.6	-4.1	-3.9
278	-4.5	-3.4	-3.7	-4.2	-3.9
279	-4.5	-4.0	-3.0	-4.7	-4.0
280	-5.1	-3.0	-3.0	-4.9	-4.0
281	-4.7	-4.1	-2.9	-5.1	-4.2
282	-4.8	-4.8	-3.0	-4.8	-4.3
283	-5.4	-4.7	-3.0	-4.4	-4.4
284	-5.8	-5.4	-3.0	-3.4	-4.4
285	-6.5	-5.3	-2.3	-3.5	-4.4
286	-7.4	-4.6	-2.0	-3.6	-4.4
287	-8.2	-4.1	-1.4	-3.2	-4.2
288	-8.9	-3.6	-1.3	-2.4	-4.0
289	-9.4	-2.9	-0.6	-3.0	-4.0
290	-9.4	-3.2	-1.3	-3.6	-4.4
291	-9.0	-4.2	-3.2	-7.5	-6.0
292	-8.4	No Data	-4.6	-6.9	-6.7
293	-8.5	-5.6	-6.4	-1.9	-5.6
294	-8.8	-5.7	-6.8	-1.1	-5.6
295	-8.7	-6.0	-5.6	-1.5	-5.4
296	-8.7	-6.0	-4.5	-3.1	-5.6
297	-8.1	-6.8	-3.0	-5.3	-5.8
298	-7.7	-8.4	-1.3	-6.7	-6.0
299	-4.8	-9.6	1.6	-10.2	-5.8
300	-3.5	-10.1	4.0	-12.7	-5.6

Appendix 2: Shoreline rates of change for CAHA, 1852-1993

Transect	1852-1917	1917-1947	1947-1980	1980-1993	Mean Rate
301	-2.1	-11.1	5.8	-15.7	-5.8
302	-2.4	No Data	No Data	-18.1	-10.3
303	No Data	No Data	No Data	-22.6	-22.6
304	No Data	No Data	No Data	-23.5	-23.5
305	15.3	3.8	9.4	7.2	8.9
306	15.5	7.0	5.3	7.9	8.9
307	14.4	9.8	3.3	7.3	8.7
308	12.6	12.9	2.2	4.8	8.1
309	11.2	13.7	1.6	3.0	7.4
310	No Data	13.9	0.7	3.7	6.1
311	No Data	13.7	0.0	3.2	5.6
312	No Data	13.3	0.7	1.5	5.2
313	No Data	11.7	1.0	1.3	4.6
314	No Data	10.8	0.5	2.5	4.6
315	No Data	10.1	1.1	2.8	4.7
316	No Data	8.2	2.5	2.7	4.5
317	No Data	8.2	3.1	1.7	4.3
318	No Data	7.8	2.8	2.7	4.5
319	No Data	7.5	2.5	2.4	4.1
320	No Data	5.3	3.1	2.5	3.6
321	No Data	5.7	2.1	3.0	3.6
322	No Data	4.4	1.7	3.3	3.1
323	No Data	3.6	1.9	0.9	2.1
324	No Data	3.2	1.6	0.0	1.6
325	No Data	2.6	1.3	1.1	1.7
326	No Data	2.6	1.6	0.0	1.4
327	No Data	3.0	1.4	-1.3	1.0
328	No Data	2.7	1.5	-1.8	0.8
329	No Data	1.3	2.1	-3.6	0.0
330	No Data	0.9	1.1	-3.4	-0.5
331	No Data	0.5	1.2	-3.5	-0.6
332	No Data	0.0	1.1	-3.7	-0.8
333	No Data	-1.4	1.0	-3.7	-1.4
334	No Data	-1.4	1.1	-4.5	-1.6
335	No Data	-2.5	1.5	-5.7	-2.2
336	No Data	-2.0	1.2	-5.9	-2.3
337	No Data	-2.5	0.9	-4.4	-2.0
338	No Data	-1.5	1.4	-6.1	-2.1

Appendix 3: CAHA Island Width by Transect (m)

Transect	Island Width (m)	Transect	Island Width (m)
1	1970.182	42	481.928
2	2027.624	43	619.131
3	2133.388	44	805.158
4	2178.519	45	630.371
5	2228.83	46	316.289
6	2273.886	47	284.272
7	2262.39	48	505.118
8	2289.122	49	325.351
9	2283.952	50	352.481
10	2372.965	53	569.662
11	2501.247	54	724.478
12	2304.112	55	719.279
13	2193.121	56	564.066
14	2340.835	57	763.71
15	1977.171	58	622.653
16	1882.561	59	689.602
17	1719.744	60	886.651
18	1649.859	61	1065.018
19	1720.53	62	1036.6
20	1647.653	63	819.504
21	1662.975	64	712.395
22	1572.788	65	735.273
23	1399.374	66	1146.199
24	1287.313	67	1245.42
25	1236.301	68	1353.144
26	2026.497	69	1464.533
27	2024.262	72	1483.767
28	1875.544	73	912.44
29	1697.235	74	1101.139
30	1481.029	75	1507.273
31	1567.921	76	1355.021
32	1386.477	77	1124.614
33	1213.091	78	1119.607
34	1056.041	79	1770.18
35	883.906	80	1369.257
36	683.646	81	1429.974
37	634.765	82	1645.809
38	591.252	83	1670.324
39	632.748	84	1669.631
40	875.156	85	1854.526
41	680.123	86	1399.962

Appendix 3: CAHA Island Width by Transect (m)

Transect	Island Width (m)	Transect	Island Width (m)
87	1509.363	128	596.016
88	1543.414	129	669.776
89	1290.184	130	561.792
90	1148.31	131	564.219
91	1235.361	132	645.811
92	1209.816	133	604.184
93	1435.94	134	585.553
94	1323.112	135	721.662
95	995.603	136	785.917
96	666.767	137	1018.792
97	470.217	138	821.416
98	615.646	139	875.729
99	466.494	140	749.879
100	432.658	143	808.771
101	338.972	144	762.072
102	273.676	145	676.053
103	424.378	146	889.518
104	847.389	147	765.235
105	739.018	148	760.676
106	1006.229	149	946.667
107	1187.36	150	783.685
108	1165.976	151	858.819
109	863.175	152	1019.506
110	663.249	153	1128.038
111	748.573	154	1035.011
112	840.475	155	858.87
113	791.047	156	1068.067
114	1111.724	157	872.06
115	1052.618	158	713.202
116	623.264	159	733.668
117	983.376	160	787.747
118	688.284	161	934.698
119	779.666	162	991.289
120	666.135	163	868.401
121	581.851	164	694.721
122	492.764	165	766.413
123	420.89	166	789.918
124	473.255	167	846.697
125	359.297	168	1277.5
126	369.851	169	1262.959
127	501.473	170	1379.425

Appendix 3: CAHA Island Width by Transect (m)

Transect	Island Width (m)	Transect	Island Width (m)
171	1398.248	212	740.831
172	1292.322	213	749.017
173	1238.181	214	731.931
174	900.216	215	752.521
175	692.643	216	707.9
176	1013.057	217	719.497
177	1109.928	218	659.092
178	1127.51	219	663.805
179	968.807	220	786.817
180	728.078	221	866.943
181	764.925	222	788.057
182	590.841	223	826.353
183	505.474	224	934.574
184	564.701	225	985.831
185	522.87	226	982.854
186	470.496	227	721.698
187	360.26	228	726.97
188	386.276	229	625.819
189	643.494	230	593.291
190	523.087	231	600.113
191	561.724	232	567.771
192	447.922	233	621.354
193	495.148	234	664.146
194	415.145	235	524.917
195	389.502	236	546.53
196	425.502	237	550.561
197	438.34	238	556.825
198	411.518	239	462.527
199	429.13	240	475.489
200	370.245	241	745.203
201	342.368	242	571.926
202	411.487	243	1288.911
203	389.626	244	1312.292
204	404.726	245	1371.456
205	411.393	246	1334.711
206	436.976	247	1293.252
207	569.414	248	1241.498
208	580.174	249	1260.848
209	613.974	250	1223.948
210	707.807	251	1202.799
211	593.911	252	1308.26

Appendix 3: CAHA Island Width by Transect (m)

Transect	Island Width (m)
253	1323.362
254	1283.019
255	1234.986
256	1136.968
257	1080.842
258	959.97
259	872.215
260	642.316
261	504.265
262	425.689
263	447.333
264	485.008
265	667.774
266	558.406
267	418.185
268	295.358
269	337.81
270	310.77
271	239.388
272	236.008
273	308.227
274	239.667
275	269.87
276	273.125
277	256.287
278	257.001
279	240.907
280	231.356
281	314.615
282	256.908
283	248.597
284	289.219
285	2870.762
286	3200.571

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VITA

JOHN CARY BUIE

Born in Lexington, Kentucky, 19 July 1966. Graduated from the North Carolina School of Science and Mathematics in 1984. Earned B.S. in Biology from the University of North Carolina at Chapel Hill in May 1988. Received M.A.T. in Science Education from the University of North Carolina at Chapel Hill in December 1989. Was employed as a Biology Instructor at Central Carolina Community College in Sanford, North Carolina, until returning to graduate school. Entered master's program at the College of William and Mary, School of Marine Science in 1993. Currently employed as a Geographic Information Systems Analyst with Computer Sciences Corporation, Hampton, Virginia.