Coastal Vulnerability Assessment of Cape Hatteras National Seashore (CAHA) to Sea-Level Rise

By Elizabeth A. Pendleton, E. Robert Thieler, and S. Jeffress Williams

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the National Coastal Vulnerability study at http://woodshole.er.usgs.gov/project-pages/cvi/,
or view the USGS online fact sheet for this project in PDF format at http://pubs.usgs.gov/fs/fs095-02/.
To visit Cape Hatteras National Seashore go to http://www.nps.gov/caha/index.htm.

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Abstract

A coastal vulnerability index (CVI) was used to map the relative vulnerability of the coast to future sea-level rise within Cape Hatteras National Seashore (CAHA) in North Carolina. The CVI ranks the following in terms of their physical contribution to sea-level rise-related coastal change: geomorphology, regional coastal slope, rate of relative sea-level rise, historical shoreline change rates, mean tidal range, and mean significant wave height. The rankings for each variable were combined and an index value was calculated for 1-minute grid cells covering the park. The CVI highlights those regions where the physical effects of sea-level rise might be the greatest. This approach combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, yielding a quantitative, although relative, measure of the park's natural vulnerability to the effects of sea-level rise. The CVI provides an objective technique for evaluation and long-term planning by scientists and park managers. Cape Hatteras National Seashore consists of stable and washover dominated segments of barrier beach backed by wetland and marsh. The areas within Cape Hatteras that are likely to be most vulnerable to sea-level rise are those with the highest occurrence of overwash and the highest rates of shoreline change.

Introduction

The National Park Service (NPS) is responsible for managing nearly 12,000 km (7,500 miles) of shoreline along oceans and lakes. In 2001, the U.S. Geological Survey (USGS), in partnership with the NPS Geologic Resources Division, began conducting hazard assessments of future sea-level change by creating maps to assist NPS in managing its valuable coastal resources. This report presents the results of a vulnerability assessment for Cape Hatteras National Seashore (CAHA), highlighting areas that are likely to be most affected by future sea-level rise.

Global sea level has risen approximately 18 centimeters (7.1 inches) in the past century (Douglas, 1997). Climate models predict an additional rise of 48 cm (18.9 in.) by 2100 (IPCC, 2001), which is more than double the rate of rise for the 20th century. Potential coastal impacts of sea-level rise include shoreline erosion, saltwater intrusion into groundwater aquifers, inundation of wetlands and estuaries, and threats to cultural and historic resources as well as infrastructure. Predicted accelerated global sea-level rise has generated a need in coastal geology to determine the response of a coastline to sea-level rise. However, an accurate and quantitative approach to predicting coastal change is difficult to establish. Even the kinds of data necessary to make shoreline response predictions are the subject of scientific debate. A number of predictive approaches have been proposed (National Research Council, 1990), including: 1) extrapolation of historical data (e.g., coastal erosion rates), 2) static inundation modeling, 3) application of a simple geometric model (e.g., the Bruun Rule), 4) application of a sediment dynamics/budget model, or 5) Monte Carlo (probabilistic) simulation based on parameterized physical forcing variables. However, each of these approaches has inadequacies or can be invalid for certain applications (National Research Council, 1990; 1995). Additionally, shoreline response to sea-level change is further complicated by human modifications of the natural coast such as beach nourishment projects, and engineered structures such as seawalls, revetments, groins, and jetties. Understanding how a natural or modified coast will respond to sea-level change is essential to preserving vulnerable coastal resources.

The primary challenge in predicting shoreline response to sea-level rise is identifying and quantifying the important variables that contribute to coastal evolution in a given area. In order to address the multi-faceted task of predicting sea-level rise impact, the USGS has implemented a methodology to identify areas that may be most vulnerable to impacts of future sea-level rise (see Hammar-Klose and Thieler, 2001). This approach combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, yielding a quantitative, although relative, measure of the shoreline's natural vulnerability to the effects of sea-level rise. The methodology focuses on six variables which strongly influence coastal evolution:

1) Geomorphology

2) Historical shoreline change rate

3) Regional coastal slope

4) Relative sea-level change

5) Mean significant wave height

6) Mean tidal range

These variables can be divided into two groups: 1) geologic variables and 2) physical process variables. The geologic variables are geomorphology, historic shoreline change rate, and coastal slope; they account for a shoreline's relative resistance to erosion, long-term erosion/accretion trend, and its susceptibility to flooding, respectively. The physical process variables include sea-level change, significant wave height, and tidal range, all of which contribute to the inundation hazards of a particular section of coastline over time scales from hours to centuries. A relatively simple vulnerability ranking system (Table 1) allows the six variables to be incorporated into an equation that produces a coastal vulnerability index (CVI). The CVI can be used by scientists and park managers to evaluate the likelihood that physical change may occur along a particular shoreline as sea level continues to rise. Additionally, NPS staff will be able to incorporate information provided by this vulnerability assessment technique into general management plans.

Data Ranking

Table 1 shows the six variables described in the Introduction, which include both quantitative and qualitative information. Numeric variable values are assigned a vulnerability ranking based on value ranges, whereas the non-numerical geomorphology variable is ranked qualitatively according to the relative resistance of a given landform to erosion. Shorelines with historical erosion/accretion rates between -1.0 and +1.0 m/yr are ranked as moderate. Increasingly higher erosion or accretion rates are ranked as correspondingly higher or lower vulnerability. Regional coastal slopes range from very high risk, <0.3 percent to very low risk at values >1.2 percent. The rate of relative sea-level change is ranked using the modern rate of eustatic rise (1.8 mm/yr) as very low vulnerability. Since this is a global or "background" rate common to all shorelines, the sea-level rise ranking reflects primarily local to regional isostatic or tectonic adjustment. Mean wave height rankings range from very low (<0.55 m) to very high (>1.25 m). Tidal range is ranked such that microtidal (<1 m) coasts are very high vulnerability and macrotidal (>6 m) coasts are very low vulnerability.

Cape Hatteras National Seashore

Cape Hatteras National Seashore is part of the Outer Banks of North Carolina, which stretch more than 280 kilometers (175 miles) from Virginia to Shackleford Banks, along the Atlantic coast of North Carolina (Figure 1). The National Seashore extends 115 km (70 mi) over portions of three barriers islands, Bodie, Hatteras, and Ocracoke. These narrow barriers are separated from the North Carolina mainland by wide, shallow Pamlico Sound. Most of the barriers within the National Seashore are only a few hundred (<400 m) meters in width and they lie entirely within the 100-year flood zone (Wolverton and Wolverton, 1988). The widest part of Cape Hatteras National Seashore is near Cape Point between Buxton and Frisco; here the barrier reaches a maximum width of about 4 km.

Nor'easters, hurricanes, and tropical storms all pass over the Outer Banks allowing storms to potentially play a role in coastal evolution throughout the year. The combination of intense storms and shallow shoals near Cape Hatteras has led to this area being named the Graveyard of the Atlantic. Historians estimate that over 1000

shipwrecks have occurred along the North Carolina coast since the 1600s (for more information see http://coastalguide.com/packet/
shipwrecks01.htm or http://www.nps.gov/caha/shipwreck.htm).

Storm impacts on coastal evolution along the Outer Banks are too numerous to detail here, but for a comprehensive overview of storms and storm tracks along the coast of North Carolina since 1933 see: http://www.erh.noaa.gov/er/akq/hist.htm. Also a summary of the recent impacts of Hurricane Isabel (September 2003) is hosted by USGS at: http://coastal.er.usgs.gov/hurricanes/Isabel/.

Six locations in and around the national seashore have been identified by the Outer Banks Task Force (http://www.obtf.org/) as erosional hot spots, or sections of coast where the dunes are frequently destroyed by storms. Sections of North Carolina highway 12 have been relocated in these hot spot areas, and when breaks form in the dunes they are immediately filled, which may interfere with natural barrier overwash processes. Some scientists suggest that storms and overwash processes are essential to the evolution of these barriers, and human interference through dune building, road maintenance, and breach filling only ensures an increase in vulnerability of these islands (Dolan and Lins, 1986; Pilkey and others, 1998). Park managers, charged with resource preservation for future generations, are faced with a difficult task along the Outer Banks.

This report does not directly address the vulnerability of the bay side shoreline of Cape Hatteras National Seashore to future sea-level rise, because the methodology presented here does not apply well to quieter water or estuarine wetland environments; however, the authors acknowledge the important issues impacting the Pamlico and Albemarle Sound shoreline and direct interested readers to investigations on sea-level rise and estuarine shoreline erosion along the North Carolina Coast produced by Riggs (2001) and Riggs and Ames (2003).

Methodology

In order to develop a database for a park-wide assessment of coastal vulnerability, data for each of the six variables mentioned above were gathered from state and federal agencies (Table 2). The database is based on that used by Thieler and Hammar-Klose (1999) and loosely follows an earlier database developed by Gornitz and White (1992). A comparable assessment of the sensitivity of the Canadian coast to sea-level rise is presented by Shaw and others (1998). The database was constructed using a 1:70,000-scale shoreline for Cape Hatteras that was produced from the medium resolution digital vector U.S. shoreline provided by the Strategic Environmental Assessments Division of the National Oceanic and Atmospheric Administration's Office of Ocean Resources Conservation and Assessment (http://spo.nos.noaa.gov/projects/shoreline/shoreline.html). Data for each of the six variables (geomorphology, shoreline change, coastal slope, relative sea-level rise, significant wave height, and tidal range) were added to the shoreline attribute table using a 1-minute (approximately 1.5 km) grid (Figure 2). Next each variable in each grid cell were assigned a relative vulnerability value from 1-5 (1 is very low vulnerability, 5 is very high vulnerability) based on the potential magnitude of its contribution to physical changes on the coast as sea level rises (Table 1).

Geologic Variables

The **geomorphology** variable expresses the relative erodibility of different landform types (Table1). These data were derived from 1998 1-meter resolution digital aerial orthophotographs of Cape Hatteras (Tabale 2). In addition, field visits were made within the park to ground-truth the geomorphologic classifications. The geomorphology of Cape Hatteras varies from high vulnerability barrier island with dunes to very high vulnerability washover-dominated barrier shoreline (Figure 3-10). A Hurricane Isabel impact study shows the barrier breach that formed between Frisco and Hatteras Village on September 18, 2003 (Figure 11) (USGS, 2003). This breach occurred in a washover-dominated very high vulnerability area. The U.S. Army Corps of Engineers and the NCDOT closed the inlet and reconstructed Highway 12 during October and November of 2003.

Shoreline erosion and accretion rates for Cape Hatteras were calculated from existing shoreline data provided by USGS (Table 2). Shoreline rates of change (m/yr) were calculated at 200 m intervals (transects) along the coast using Digital Shoreline Analysis System software to derive the rate of shoreline change over time (Thieler and others, 2003). The rates for each transect within a 1-minute grid cell were averaged to determine the shoreline change value used here, with positive numbers indicating accretion and negative numbers indicating erosion. Shoreline change rates on Cape Hatteras range from greater than 2 m/yr of accretion (very low vulnerability) to greater than 2 m/yr of erosion (very high vulnerability) (Figure 12 A-D).

The determination of **regional coastal slope** identifies the relative vulnerability of inundation and the potential rapidity of shoreline retreat because low-sloping coastal regions should retreat faster than steeper regions (Pilkey and Davis, 1987). The regional slope of the coastal zone was calculated from a grid of topographic and bathymetric elevations extending 10 km landward and seaward of the present-day shoreline. Elevation data were obtained from the National Geophysical Data Center (NGDC) as gridded topographic and bathymetric elevations at 0.1 meter vertical resolution for 3 arc-second (~90 m) grid cells (Table 2). Regional coastal slopes for Cape Hatteras fall within the high vulnerability (4) to very high vulnerability (5) category (Table 1).

Physical Process Variables

The **relative sea-level change** variable is derived from the increase or decrease in annual mean water elevation over time as measured at tide gage stations along the coast. The rate of sea-level rise in Beaufort, NC (about 75 km SW of Ocracoke Island) is 3.71 +/- 0.64 mm/yr based on 27 years of data (Zervas, 2001) (Table 2). This variable inherently includes both global sea-level rise as well as regional sea-level rise due to isostatic and tectonic adjustments of the land surface. Relative sea-level change data are a historical record, and thus only portray the recent sea-level trend (<150 years). The rate of relative sea-level rise for Cape Hatteras is very high (5), approximately 2 times the global average, based on water elevation data at Beaufort, NC (Table 1).

Mean significant wave height is used here as a proxy for wave energy which drives the coastal sediment budget. Wave energy is directly related to the square of wave height;

$$E = 1/8\ \rho g H^2$$

where E is energy density, H is wave height, ρ is water density and g is acceleration due to gravity. Thus, the ability to mobilize and transport coastal sediments is a function of wave height squared. In this report, we use hindcast nearshore mean significant wave height data for the period 1976-95 obtained from the U.S. Army Corps of Engineers Wave Information Study (WIS) (see references in Hubertz and others, 1996). The model wave heights were compared to historical measured wave height data obtained from the NOAA National Data Buoy Center to ensure that model values were representative of the study area ((Table 2). For Cape Hatteras, mean significant wave heights are between 1.2 and 1.3 m, which is categorized as high (4) and very high vulnerability (5), respectively (Table 1).

Tidal range is linked to both permanent and episodic inundation hazards. Tide range data were obtained from NOAA/NOS for ocean tide gauges at Cape Hatteras fishing pier and the Duck, NC Field Research Facility pier (Table 1). All of Cape Hatteras is classified as very high vulnerability (< 1 m) with respect to tidal range (Table 1).

Coastal Vulnerability Index

The coastal vulnerability index presented here is the same as that used in Thieler and Hammar-Klose (1999) and is similar to that used in Gornitz and others (1994), as well as to the sensitivity index employed by Shaw and others (1998). The CVI allows the six variables to be related in a quantifiable manner that expresses the relative vulnerability of the coast to physical changes due to future sea-level rise. This method yields numerical data that cannot be equated directly with particular physical effects. It does, however, highlight areas where the various effects of sea-level rise may be the greatest. Once each section of coastline is assigned a vulnerability value for each specific data variable, the coastal vulnerability index is calculated as the square root of the product of the ranked variables divided by the total number of variables;

$$\text{CVI} = \sqrt{\frac{(a*b*c*d*e*f)}{6}}$$

where, a = geomorphology, b = shoreline erosion/accretion rate, c = coastal slope, d =relative sea-level rise rate, e = mean significant wave height, and f = mean tide range. The calculated CVI value is then divided into quartile ranges to highlight different vulnerabilities within the park. The numeric CVI values that correspond to a specific vulnerability index (low - very high) are unique to Cape Hatteras National Seashore, and are not comparable to CVI ranges in other parks where the CVI has been employed (i.e., very high vulnerability means the same among parks; it's the numeric values that differ, such that a numeric value that equals very high vulnerability in one park may equal moderate vulnerability in another). To compare vulnerability among coastal parks, the national-scale studies should be used (Thieler and Hammar-Klose, 1999, 2000a, and 2000b). This approach best describes and highlights the vulnerability specific to each park.

Results

The calculated CVI values for Cape Hatteras range from 18.26 to 51.03. The mean CVI value is 37.64; the mode is 45.64 and the median 36.5. The standard deviation is 7.5. The 25th, 50th, and 75th percentiles are 32.0, 36.0, and 42.0, respectively.

Figure 14 shows a map of the CVI (vulnerability ranges) for Cape Hatteras National Seashore. The CVI scores are divided into low, moderate, high, and very high-vulnerability categories based on the quartile ranges and visual inspection of the data. CVI values below 32.0 are assigned to the low vulnerability category. Values from 32.0-36.0 are considered moderate vulnerability. High-vulnerability values lie between 36.01 and 42.0.

CVI values above 42.0 are classified as very high vulnerability. Figure 14 shows a histogram of the percentage of CAHA shoreline in each vulnerability category. Nearly 195 km (120 miles) of shoreline is evaluated along the Outer Banks. Of this total, 27 percent of the mapped shoreline is classified as being at very high vulnerability due to future sea-level rise. Another 27 percent is classified as high vulnerability, 30 percent as moderate vulnerability, and sixteen percent as low vulnerability.

Discussion

The data within the CVI show variability at different spatial scales (Figure 13). However, the ranked values for the physical process variables vary little over the extent of the shoreline. The value of the relative sea-level rise variable is constant at very high vulnerability for the entire study area. The significant wave height vulnerability is very high to high, and the tidal range is very high vulnerability.

The geologic variables show greater variability and thus have the most influence on the CVI value and ranges (Figure 13). Geomorphology in the park includes high vulnerability barrier island shoreline with dune ridges separated by very high vulnerability washover-dominated low areas. Vulnerability assessment based on historical shoreline change trends varies from very low to very high (Figure 12 A -D). Regional coastal slope is mostly in the very high vulnerability range with a few high vulnerability slope areas.

The most influential variables in the CVI are geomorphology, shoreline change, regional coastal slope and significant wave height; therefore they may be considered the dominant factors controlling how Cape Hatteras will evolve as sea level rises. Geomorphology, coastal slope, and significant wave height only vary between high and very high vulnerability, whereas shoreline change ranges from very low to very high.

Because of the importance of habitat and the dynamic nature of the Outer Banks, concern about erosion, storm surge breaching of the barriers, future sea-level rise, and mainland flooding, planning is underway by private, federal, and state agencies to address these issues. Alternatives such as large-scale nourishment of the beach and dunes along Cape Hatteras are being considered. Implementation of future beach nourishment could alter the CVI results presented here.

Conclusions

The coastal vulnerability index (CVI) provides insight into the relative potential of coastal change due to future sea-level rise. The maps and data presented here can be viewed in at least two ways:

1) as an example of where physical changes are most likely to occur as sea-level rises; and

2) as a planning tool for the Cape Hatteras National Seashore.

As ranked in this study, geomorphology, shoreline change, coastal slope, and significant wave height are the most important variables in determining the CVI for Cape Hatteras National Seashore. Tide range and sea-level rise do not contribute to the spatial variability in the CVI.

Cape Hatteras National Seashore preserves a dynamic natural environment, which must be understood in order to be managed properly. The CVI is one way that a park can assess objectively the natural factors that contribute to the evolution of the coastal zone, and thus how the park may evolve in the future.

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List of Figures and Tables

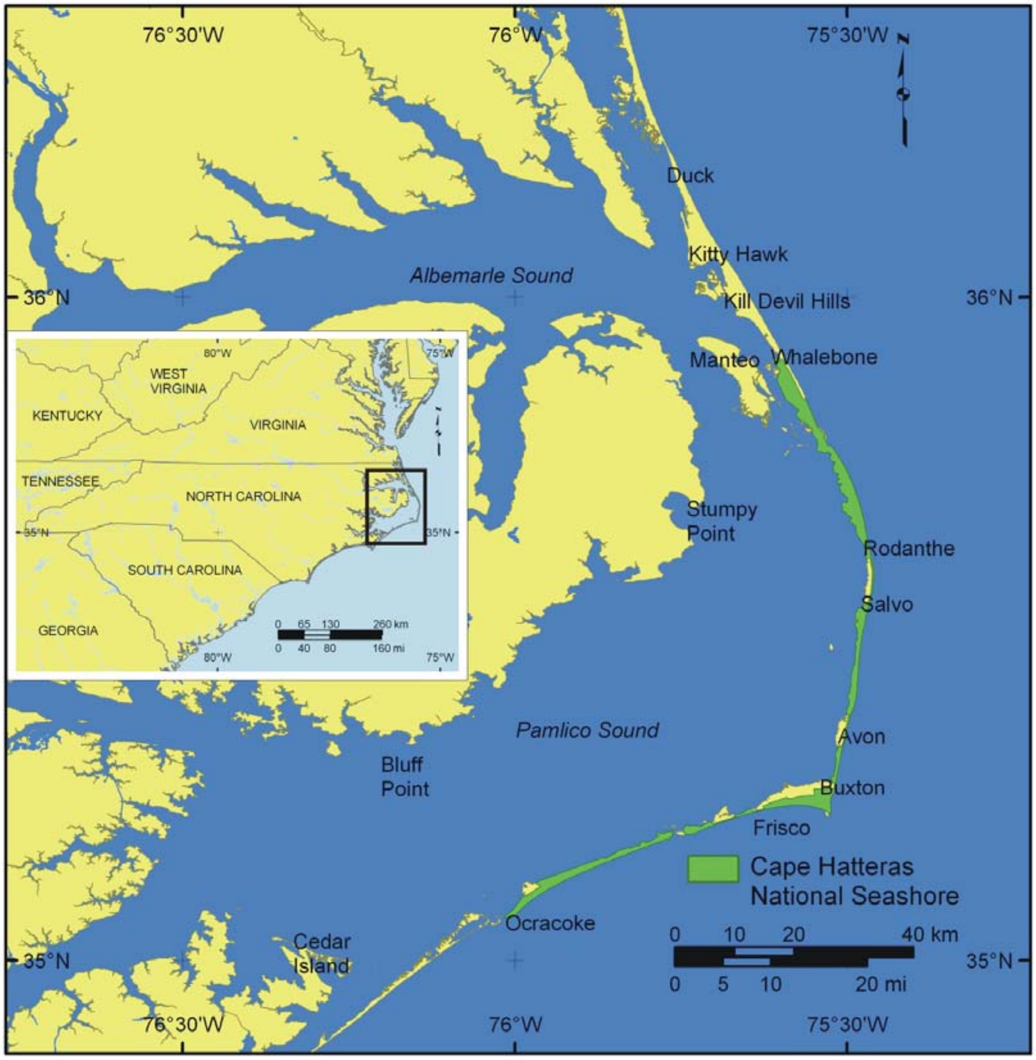

Figure 1. Location of Cape Hatteras National Seashore in North Carolina.

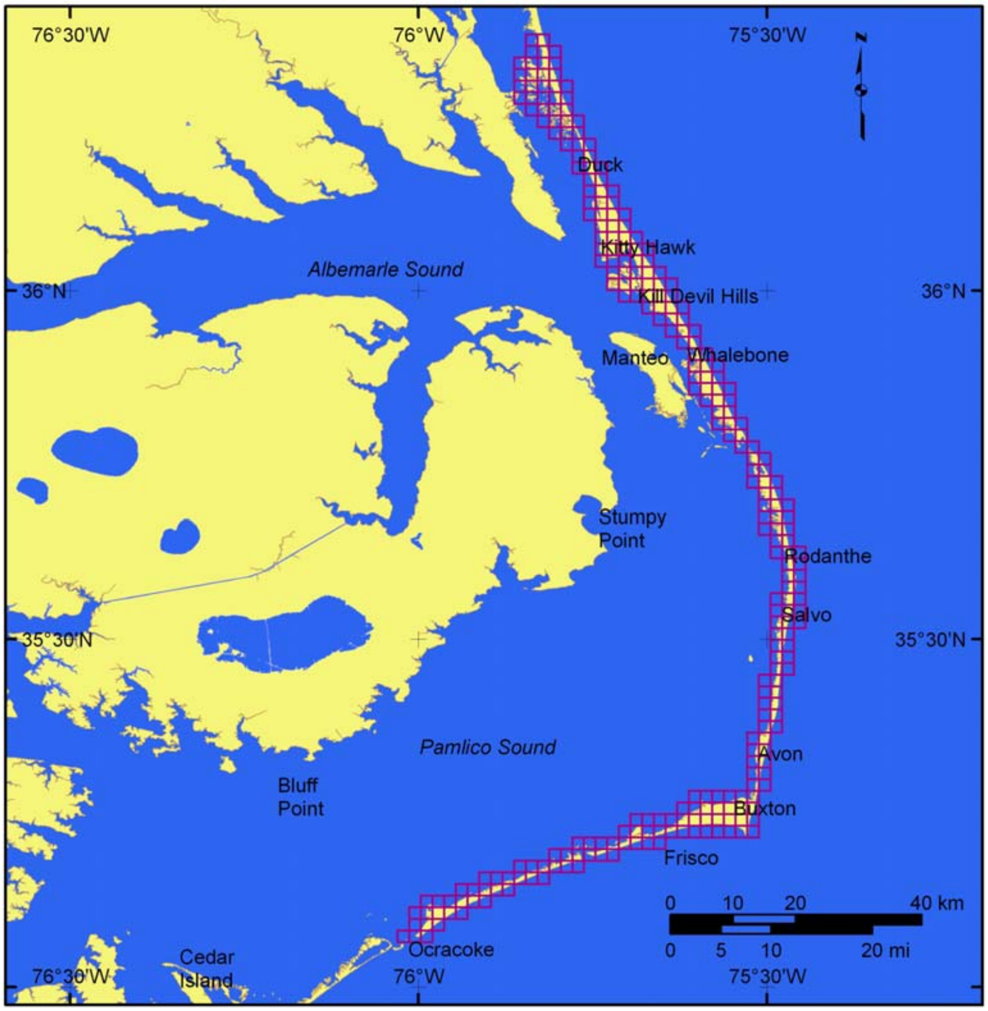

Figure 2. Shoreline grid for Cape Hatteras National Seashore.

Figures 3-10. Photos taken along Cape Hatteras National Seashore in August 2003; the numbers on the inset location map correspond to the Figure numbers.

Figure 3. Coquina Beach with Bodie Island Lighthouse in the background. Coquina Beach is ranked as very high vulnerability based on geomorphology.

Figure 4. A) http://10.0.40.33/project-pages/glacier_studies/html/chapters.html. B) Sand dredged from Oregon Inlet is being pumped onto the beach within Pea Island NWR. Pea Island is ranked as a very high vulnerability area.

Figure 5. A) Vast wildlife habitat especially for shorebirds on the landward side of Pea Island NWR. B) The bridge that was constructed in the 1940's to bypass a breach that occurred across Pea Island during a hurricane.

Figure 6. Area just north of Rodanthe known as the S-curves. Road relocations caused by erosion hotspots have result in such turns in the road (very high vulnerability).

Figure 7. Road relocation between Avon and Buxton. The former location of the road is denoted by the break in vegetation. The barrier is so narrow that there is no room left to move the road landward (very high vulnerability).

Figure 8. Oblique view of the narrow part of the island shown in Figure 7. The NC Department of Transportation has planted dune-colonizing grass, which shows up in a gridded pattern (very high vulnerability).

Figure 9. The new location of Cape Hatteras Lighthouse. The old location was behind the groin in the foreground. The groin in the photo is one of three that were built to protect the lighthouse prior to its relocation in 1999-2000 (very high to high vulnerability).

Figure 10. Numerous overwashes have occurred on the eastern end of Ocracoke Island. Deposits from washover events are visible on the landward side of the island (very high vulnerability).

Figure 11: Photo from Hurricane Isabel impact study (USGS, 2003) showing the location of inlet formation between Frisco and Hatteras Village (http://coastal.er.usgs.gov/hurricanes/Isabel/). The inlet was 600 meters wide with 3 distinct channels.

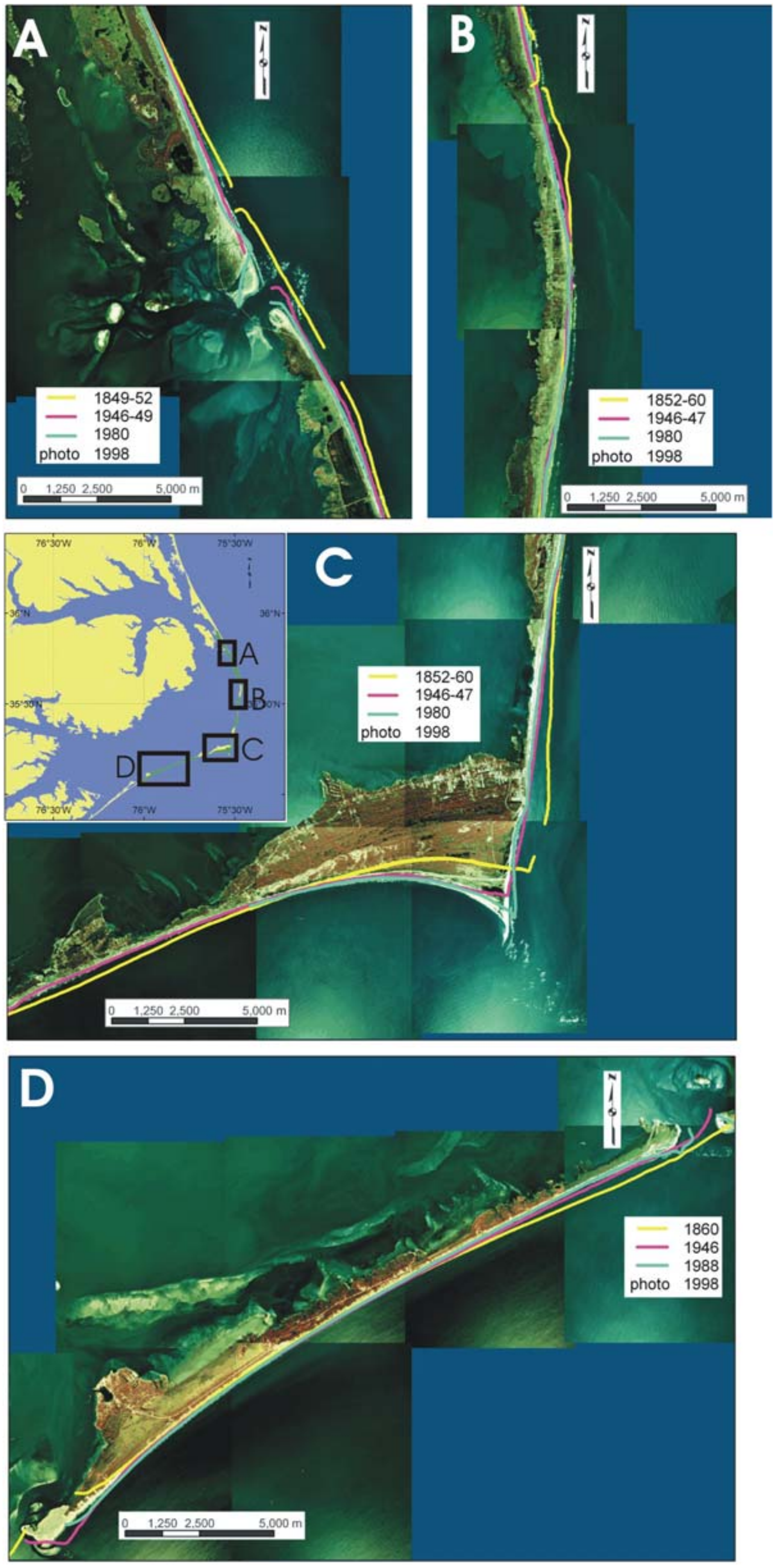

Figure 12: Historic shoreline positions for A) Bodie Island and Pea Island NWR near Oregon Inlett, B) Rodanthe, C) Cape Point, Buxton, Frisco, Hatteras Village and D) Ocracoke Island. The figure locations are shown on inset map.

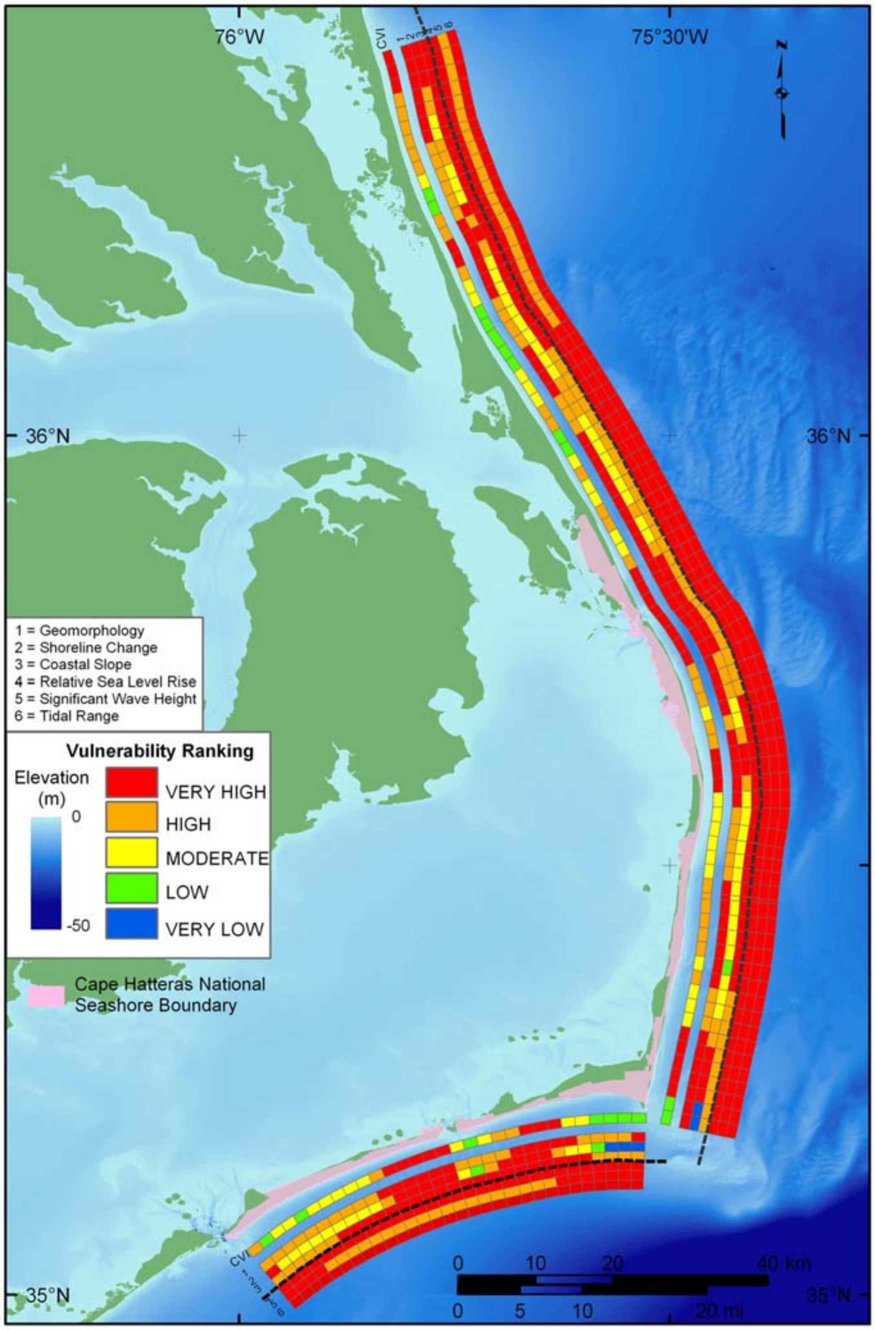

Figure 13. Shows a map of the CVI (vulnerability ranges) for Cape Hatteras National Seashore. The CVI scores are divided into low, moderate, high, and very high-vulnerability categories based on the quartile ranges and visual inspection of the data. CVI values below 13.9 are assigned to the low vulnerability category. Values from 13.91-15.7 are considered moderate vulnerability. High-vulnerability values lie between 15.71 and 18.6. CVI values above 18.6 are classified as very high vulnerability

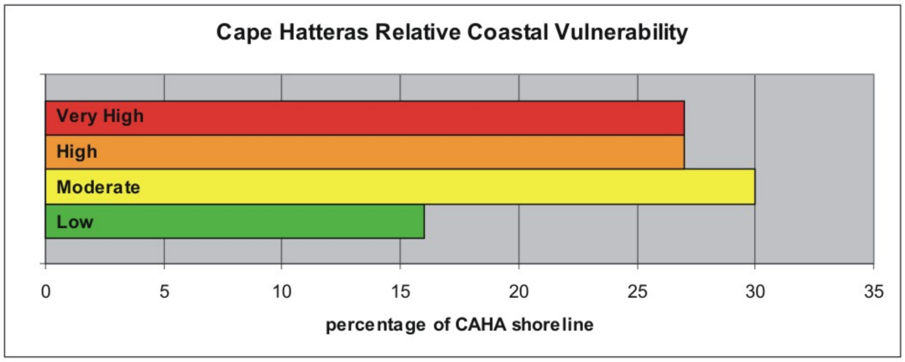

Figure 14. Shows a histogram of the percentage of CAHA shoreline in each vulnerability category. Over 115 km (70 miles) of shoreline is evaluated along the Cape Hatteras National Seashore. Of this total, 26 percent of the mapped shoreline is classified as being at very high vulnerability due to future sea-level rise. Another 24 percent is classified as high vulnerability, 26 percent as moderate vulnerability, and 24 percent as low vulnerability.

Table 1. Ranges for Vulnerability Ranking of Variables on the Atlantic Coast.					
Variables	**Very Low** **1**	**Low** **2**	**Moderate** **3**	**High** **4**	**Very High** **5**
GEOMORPHOLOGY	Rocky cliffed coasts, Fjords	Medium cliffs, Indented coasts	Low cliffs, Glacial drift, Alluvial plains	Cobble Beaches, Estuary, Lagoon	Barrier beaches, Sand beaches, Salt marsh, Mud flats, Deltas, Mangrove, Coral reefs
SHORELINE EROSION(-) /ACCRETION(+) (m/yr)	> + 2.0	1.0 to 2.0	-1.0 to 1.0	-2.0 to -1.0	< -2.0
COASTAL SLOPE (%)	> 1.20	1.20 - 0.90	0.90 - 0.60	0.60 - 0.30	< 0.30
RELATIVE SEA-LEVEL CHANGE (mm/yr)	< 1.8	1.8 2.5	2.5 - 3.0	3.0 - 3.4	> 3.4
MEAN WAVE HEIGHT (m)	< 0.55	0.55 - 0.85	0.86 - 1.05	1.06 - 1.25	> 1.25
MEAN TIDE RANGE (m)	> 6.0	4.0 - 6.0	2.0 - 4.0	1.0 - 2.0	< 1.0

Table 2. Sources for Variable Data		
Variables	**Source**	**URL**
GEOMORPHOLOGY	1998 Color-infrared DOQQ's from the North Carolina Corporate Geographic Database (CGIA)	http://www.cgia.state.nc.us/cir98status/index.html
SHORELINE EROSION/ACCRETION (m/yr)	Hisotical Shorelines for North Carolina coast (1866 –2001) from the US Geological Survey.	http://coastal.er.usgs.gov/national-assessment/
COASTAL SLOPE (%)	NGDC Coastal Relief Model Vol 02	http://www.ngdc.noaa.gov/mgg/coastal/coastal.html
RELATIVE SEA-LEVEL CHANGE (mm/yr)	NOAA Technical Report NOS CO-OPS 36 SEA LEVEL VARIATIONS OF THE UNITED STATES 1854-1999 (Zervas, 2001)	http://www.co-ops.nos.noaa.gov/publications/techrpt36doc.pdf
MEAN WAVE HEIGHT (m)	North Atlantic Region WIS Data (Phase II) and NOAA National Data Buoy Center	http://frf.usace.army.mil/wis/wis_main.html http://seaboard.ndbc.noaa.gov/
MEAN TIDE RANGE (m)	NOAA/NOS CO-OPS Historical Water Level Station Index	http://www.co-ops.nos.noaa.gov/usmap.html