



In Cooperation with the National Park Service, Fire Island National Seashore

Coastal Vulnerability Assessment of Fire Island National Seashore (FIS) to Sea-Level Rise

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

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Contents

Abstract.....	1
Indroduction	1
Data Ranking System	2
Coastal Geology of Fire Island National Seashore.....	3
Methodology.....	3
Geologic Variables	4
Physical Process Variables	4
Calculating the Coastal Vulnerability Index.....	5
Results	6
Discussion.....	6
Conclusions	7
References.....	7

Figures

1. A) Location of Fire Island National Seashore on Long Island in NY	9
1. B) Fire Island National Seashore.....	9
2. Shoreline grid for FIIS.....	10
3. Historical Inlet locations along Fire Island (after Leatherman and Joneja, 1980)	10
4. A number of historic inlets are recorded along Fire Island, especially east of Watch Hill. This is a view of Old Inlet, which was open until 1857. See Figure 3 for other former inlet locations.....	10
5. A large sand bar welding to the beach at Robert Moses State Park. This is a high vulnerability area	10
6. The groin at Robins Rest has resulted in downdrift erosion of the beach. Notice the change in elevation from the updrift side of the groin to the downdrift	10
7. Blue Point Beach is in the high vulnerability portion of Fire Island, however, the beach is very narrow and the dunes are heavily scarped in this area.....	10
8. Frontal dune at Watch Hill Visitor Center. The beach is relatively narrow, but the dune is well vegetated and is migrating naturally. This area is located near the transition from high geomorphologic vulnerability to very high.....	10
9. Artificial frontal dune created after a renourishment project at Fire Island Pines. Notice the location of the natural dune versus the artificial dune. Property owners are trying to maintain an older shoreline location.....	10
10. Scarped dunes at Davis Park. Notice the staircases that were left in during the winter	10
11. Large dune scarp within Otis Pike Wilderness area (very high geomorphologic vulnerability).....	10
12. Dune built with dredged material in front of the pavilion at Smith Point County Park. This area has been experiencing severe erosion (very high geomorphologic vulnerability).....	10
13. Very low elevation dunes behind a narrow beach at Smith Point County Park (very high geomorphologic vulnerability)	10

14. Historic shoreline positions from 1830, 1870, 1962, 1979, 1983, and 2001 at *A*) Fire Island Lighthouse and Visitors Center, *B*) Sailors Haven Visitors Center, *C*) Talisman/Barrett Beach, *D*) Otis Pike Wilderness Area (Old Inlet sections), and *E*) Smith Point County Park..... 12

15. Relative Coastal Vulnerability for Fire Island National Seashore. The innermost color bar is the relative coastal vulnerability index (CVI). The remaining color bars are separated into the geologic variables (1-3) and physical process variables (4-6). The very high vulnerability shoreline is near Moriches inlet and the Fire Island lighthouse where the shoreline change rates are highest. High vulnerability shoreline is concentrated east of Watch Hill where overwash occurrence is most frequent. Moderate vulnerability shoreline is along the community section of Fire Island, and the low vulnerability portion of the shore lies within Robert Moses State Park where shoreline accretion rates are high because of spit progradation. Large-scale (10-15 km) coastal vulnerability is controlled by the geologic framework differences that exist east and west of Watch Hill. Smaller-scale (2-5 km) variations in vulnerability reflect the rates of historic shoreline change in the area. 13

16. Percentage of Fire Island shoreline in each CVI vulnerability category..... 13

Tables

1. Ranges for Vulnerability Ranking of Variables on the Atlantic Coast..... 14

2. Sources for Variable Data..... 15

Coastal Vulnerability Assessment of Fire Island National Seashore to Sea-Level Rise

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

Abstract

A coastal vulnerability index (CVI) was used to map the relative vulnerability of the coast to future sea-level rise within Fire Island National Seashore (FIIS), New York. 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, shoreline change rates, mean tidal range and mean wave height. The rankings for each variable were combined and an index value 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. Fire Island consists of stable and washover dominated portions of barrier beach backed by lagoons, tidal wetlands and marsh. The areas most vulnerable to sea-level rise are those with the highest historic occurrence of overwash and the highest rates of shoreline change. Implementation of large-scale beach nourishment and other coastal engineering alternatives being considered for Fire Island could alter the CVI computed here. The CVI provides an objective technique for evaluation and long-term planning by scientists and park managers.

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 Fire Island National Seashore (FIIS), 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). Additionally, shoreline response to sea-level change is further complicated by human modification 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 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 future sea-level rise (see Hammar-Klose and Thieler, 2001). This technique focuses on six variables which strongly influence coastal evolution:

- 1) Geomorphology
- 2) Shoreline change rate
- 3) 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 significant wave height, tidal range, and sea-level, 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 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. Actual 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 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) 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.

Coastal Geology of Fire Island National Seashore

Fire Island and the other barrier islands comprising about two-thirds of the south shore of Long Island, NY began to form about 8,000 years ago, well seaward of their present locations, as the rate of sea-level rise began to slow, and waves and currents began reworking glacial-fluvial sediments deposited by the Laurentide Ice Sheet (21,000-10,000 years before present). Today, the sandy south shore barriers extend from the western end of Long Island to Southampton and are broken by six tidal inlets. Historically, the inlets of the south shore migrate to the west in response to the dominant southeast waves, resulting in a net westerly longshore sediment transport current (Williams, 1976).

Fire Island National Seashore is located on one of the central barriers of Long Island's south shore (figure 1A). Fire Island is a long narrow barrier island about 50 km (32 miles) in length and varies in width from 200 m to 1 km (~0.1 and 0.6 miles). Twenty-six miles of Fire Island were designated as National Seashore in 1964 in an effort to preserve "unspoiled areas of great natural beauty..." (figure 1B). Much of the western half of the Long Island coastal region including western Fire Island has a complex offshore geologic framework that is controlled by outcrops of semi-consolidated Cretaceous coastal plain strata offshore the Watch Hill region of Fire Island. This more stable portion of Fire Island is thought to be supplied with sediment being transported onshore from sand ridges associated with Cretaceous and Quaternary sediment outcrops (Williams and Meisburger, 1987). In contrast, east of Watch Hill the shoreline is experiencing a more rapid rate of shoreline retreat which is attributed to the lack of an inner shelf source of sand-size sediment (Schwab and others, 2000).

Three major storms in the 20th century severely impacted the south shore of Long Island. One such storm was the Hurricane of 1938, which cost an estimated \$6.2 million (\$15 billion --1998 adjusted) and opened 12 new inlets across the barrier islands of the south shore (Francis, 1988). A major extratropical nor'easter storm (the "Ash Wednesday" storm) in March, 1962 resulted in 50 washovers and a new inlet in Westhampton (<http://chl.wes.army.mil/shore/ashwednesday.htm>). Another major nor'easter in December 1992 created two breaches east of Moriches Inlet and destroyed more than 100 homes. Storm impacts compounded by sea-level rise are not directly addressed in this report because the long-term effects of storms on coastal change are uncertain. However, it is important to acknowledge major events that have and will continue to contribute to geomorphologic change along the south shore.

Methodology

In order to develop a GIS database for a park-wide assessment of coastal vulnerability, data for each of the six variables described 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 Fire Island shoreline that was produced from the medium resolution digital vector U.S. shoreline provided by the Strategic Environmental Assessments (SEA) Division of NOAA's Office of Ocean Resources Conservation and Assessment (*ORCA*). Data for each of the six variables (geomorphology, shoreline change, coastal slope, relative sea-level rise, significant wave height, and tidal range) were joined to the shoreline using a 1 minute (approximately 1.5 km) grid (figure 2). The data were next 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 (Table 1). These data were derived from 1-meter resolution digital orthophotos (table 2), historic washover distribution (Leatherman and Joneja, 1980), and nearshore geology (Williams, 1976; Schwab and others, 1999). In addition, field visits were made within the park to ground-truth the geomorphologic classification. The geomorphology of Fire Island varies from high vulnerability stable barrier island to very high vulnerability washover-dominated barrier shoreline (figures 3-13).

Shoreline **erosion and accretion rates** for Fire Island were calculated from existing shoreline data provided by the US Army Corps of Engineers and the USGS. Shoreline rates of change (m/yr) were calculated at 20 m intervals (transects) along the coast using Digital Shoreline Analysis System (DSAS) software (<http://woodshole.er.usgs.gov/project-pages/dsas/>) to derive the rate of shoreline change over time. The rates for each transect within a 1-minute grid cell were averaged to determine the shoreline change value used here, with positive numbers indication accretion and negative numbers indicating erosion. Shoreline change rates on Fire Island range from greater than 2 m/yr accretion (very low vulnerability) to greater than 2 m/yr erosion (very high vulnerability) (figure 14 A-E).

The determination of **regional coastal slope** identifies the relative vulnerability of inundation and the potential rapidity (rate) 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 landward and seaward of the 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. Regional coastal slopes for Fire Island are high vulnerability between 0.30 - 0.60 percent.

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 gauge stations along the coast. The rate of sea-level rise in the Battery in NY is 2.77 +/- 0.05 mm/yr and 2.58 +/- 0.19 mm/yr in Montauk, NY, based on 144 and 53 years of data, respectively (Zervas, 2001). This variable inherently includes both eustatic 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). Relative sea-level rise for Fire Island falls within moderate vulnerability.

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. For Fire Island, mean significant wave heights are between 1.3 and 1.4 m, which represents very high vulnerability.

Tidal range is linked to both permanent and episodic inundation hazards. Tide range data were obtained from NOAA/NOS for three ocean tide stations along the Atlantic Coast of Long Island; the values were contoured along the park shoreline and mapped to the 1-minute grid cells. All of Fire Island has a microtidal tide range (< 1 m) suggesting very high vulnerability.

Calculating the Coastal Vulnerability Index

The coastal vulnerability index (CVI) 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 (CVI) is calculated as the square root of the product of the ranked variables divided by the total number of variables;

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

where, a = geomorphology, b = shoreline erosion/accretion rate, c = coastal slope, d = relative sea-level rise rate, e = mean wave height, and f = mean tide range. The CVI values reported here apply specifically to Fire Island National Seashore. Thus, absolute CVI values given for other coasts and parks are not directly comparable to the data presented here. To compare different coastal parks, the national-scale studies should be used (Thieler and Hammar-Klose, 1999, 2000a, 2000b). In addition to the CVI values, the data ranges are also subdivided using values different from other studies so that the values used here reflect only the relative vulnerability along this coast. We feel this approach best describes and highlights the vulnerability specific to each park.

Results

The calculated CVI values for Fire Island range from 14.17 to 31.62. The mean CVI value is 26.5; the mode and the median are 27.38. The standard deviation is 3.58. The 25th, 50th, and 75th percentiles are 20.0, 24.5, and 28.0, respectively.

Figure 15 shows a map of the coastal vulnerability index for the Fire Island 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 20.0 are assigned to the low vulnerability category. Values from 20.0 to 24.5 are considered moderate vulnerability. High-vulnerability values lie between 24.6 and 28.0. CVI values above 28.0 are classified as very high vulnerability. Figure 16 shows a histogram of the percentage of FIIS shoreline in each vulnerability category. A total of 55 km (32 miles) of shoreline is evaluated along the national seashore. Of this total, 22 percent of the mapped shoreline is classified as being at very high vulnerability due to future sea-level rise. Thirty-six percent is classified as high vulnerability, thirty-four percent as moderate vulnerability, and eight percent as low vulnerability.

Discussion

The data within the coastal vulnerability index (CVI) show variability at different spatial scales (figure 15). However, the ranked values for the physical process variables are constant over the extent of the shoreline. The value of the relative sea-level rise variable is constant at moderate vulnerability for the entire study area. The significant wave height vulnerability is very high, and the tidal range is microtidal for all of Fire Island, making it very high vulnerability.

The geologic variables show the most variability and thus have the most influence on the CVI value (figure 15). Geomorphology in the park includes high vulnerability stable barrier island shoreline with dune ridges in the west, and very high vulnerability washover-dominated barrier beaches to the east. Vulnerability assessment based on historical shoreline change trends varies from very low to very high (figure 14 A-E). Regional coastal slope is in the high vulnerability range for the extent of Fire Island.

The most influential variables in the CVI are geomorphology and shoreline change; therefore they may be considered the dominant factors controlling how Fire Island will evolve as sea level rises. Geomorphology varies at a greater spatial scale (20 km) than shoreline change (> 2 km). This spatial variation is apparent in the CVI where geomorphology divides Fire Island into the slightly higher vulnerability east and the slightly lower vulnerability west; the shoreline change variable resolves vulnerability within the larger geomorphologic framework.

Because of the development and high economic value of property along the coast and mainland of Long Island and concern about erosion, storm surge breaching of the barriers, future sea level rise, and mainland flooding, planning is underway by Federal and State agencies to address these issues. Alternatives such as large-scale nourishment of the beach and dunes along Fire Island are being considered. Implementation of 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 Fire Island National Seashore as well as other parts of the Long Island Atlantic coast.

As ranked in this study, geomorphology and shoreline change are the most important variables in determining the CVI for Fire Island. Wave height, tide range, coastal slope, and sea-level rise do not contribute to the spatial variability in the coastal vulnerability index.

FIIS 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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Figures



Figure 1. A) Location of Fire Island National Seashore on Long Island in NY. B) Fire Island National Seashore.

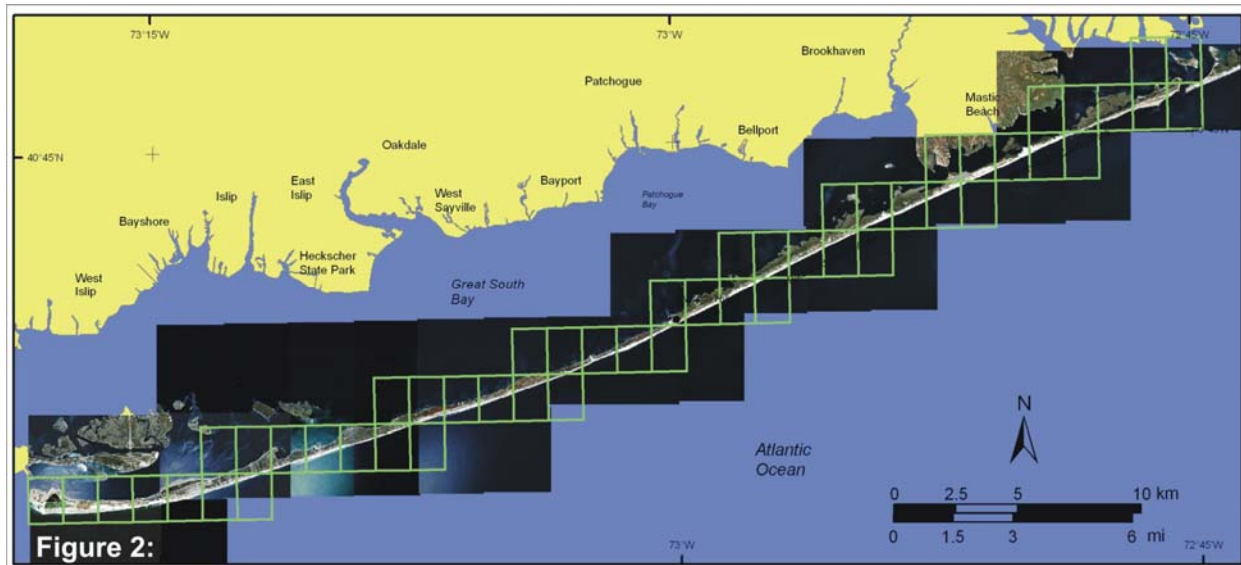


Figure 2. Shoreline grid for FIIS.



Figure 3. Historical Inlet locations along Fire Island (after Leatherman and Joneja, 1980).

Figure 4. A number of historic inlets are recorded along Fire Island, especially east of Watch Hill. This is a view of Old Inlet, which was open until 1857. See figure 3 for other former inlet locations.

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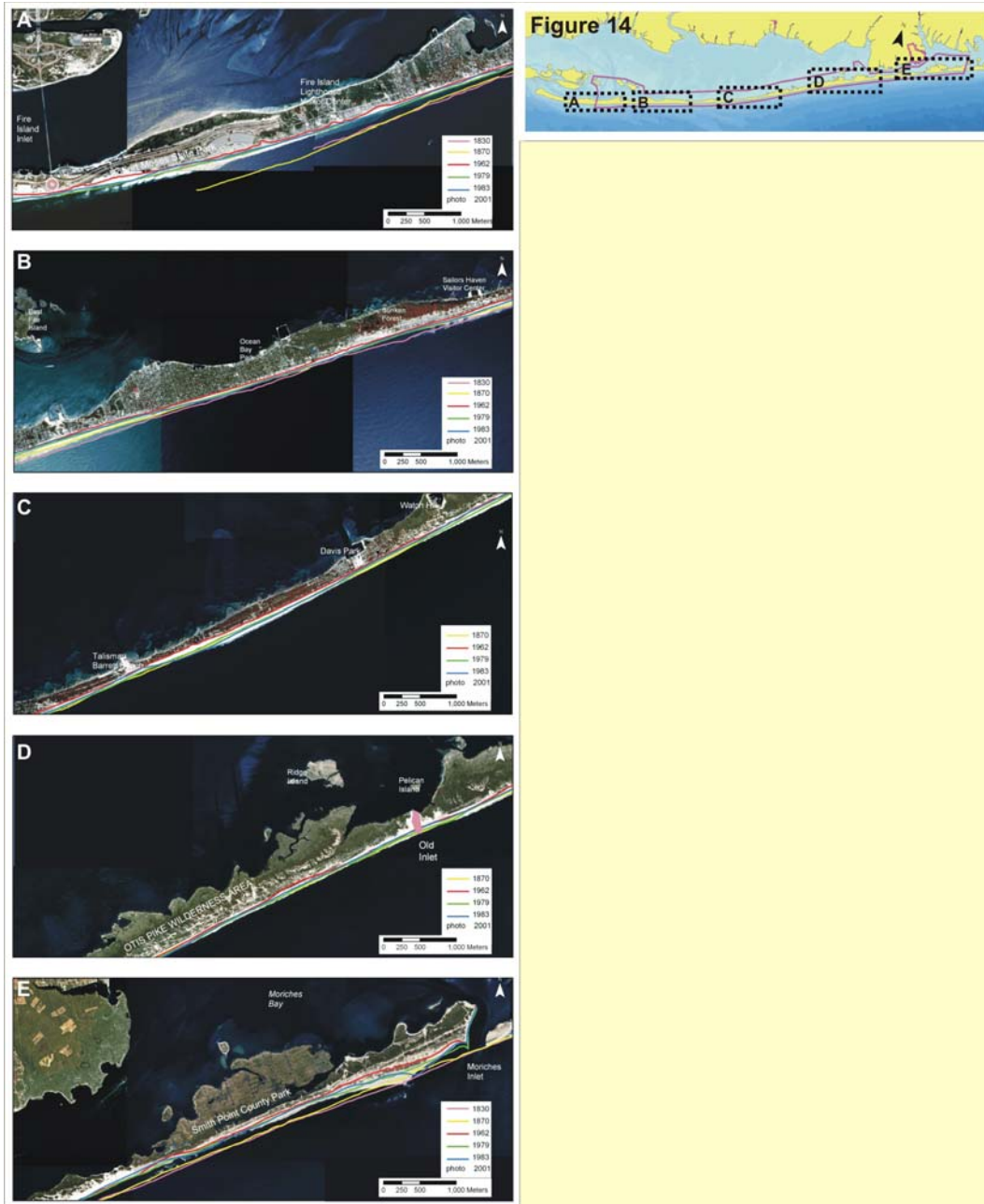


Figure 14. Historic shoreline positions from 1830, 1870, 1962, 1979, 1983, and 2001 at A) Fire Island Lighthouse and Visitors Center, B) Sailors Haven Visitors Center, C) Talisman/Barrett Beach, D) Otis Pike Wilderness Area (Old Inlet sections), and E) Smith Point County Park.

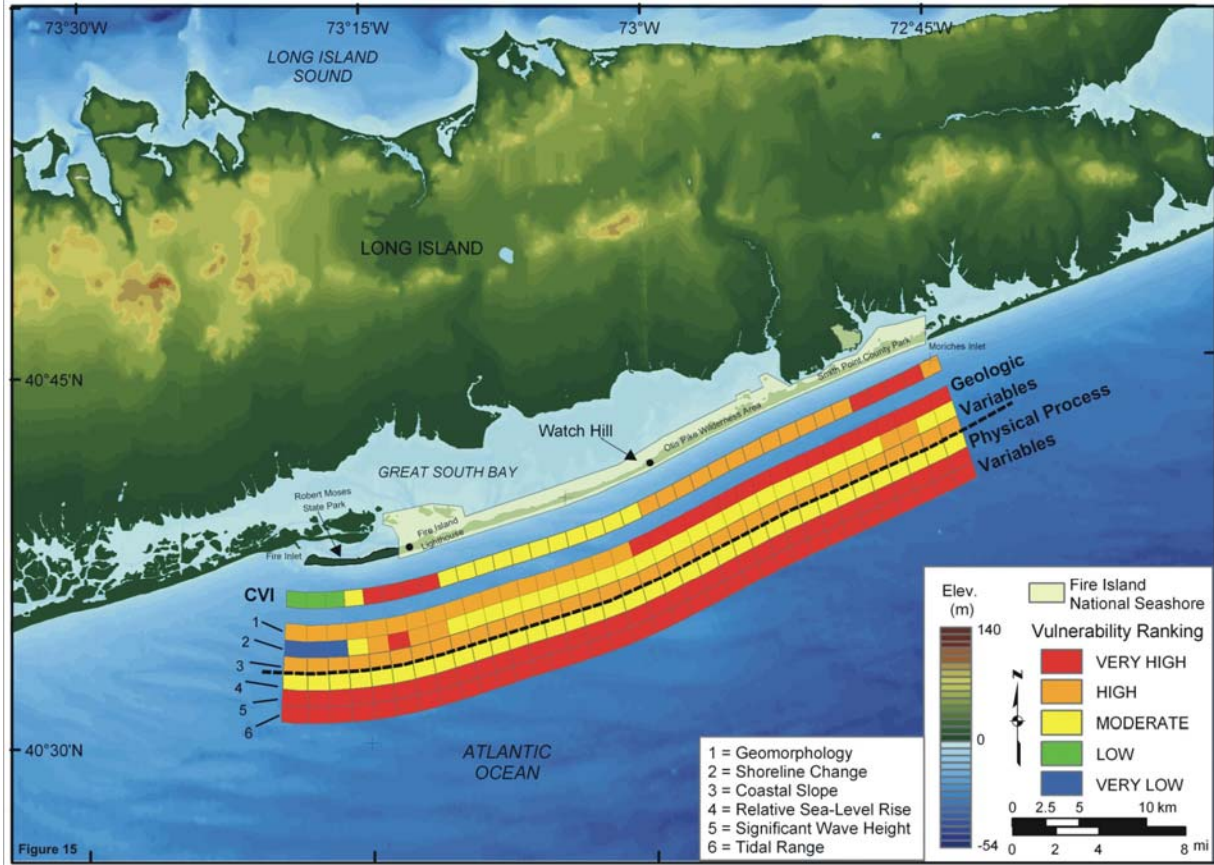


Figure 15. Relative Coastal Vulnerability for Fire Island National Seashore. The innermost color bar is the relative coastal vulnerability index (CVI). The remaining color bars are separated into the geologic variables (1-3) and physical process variables (4-6). The very high vulnerability shoreline is near Moriches inlet and the Fire Island lighthouse where the shoreline change rates are highest. High vulnerability shoreline is concentrated east of Watch Hill where overwash occurrence is most frequent. Moderate vulnerability shoreline is along the community section of Fire Island, and the low vulnerability portion of the shore lies within Robert Moses State Park where shoreline accretion rates are high because of spit progradation. Large-scale (10-15 km) coastal vulnerability is controlled by the geologic framework differences that exist east and west of Watch Hill. Smaller-scale (2-5 km) variations in vulnerability reflect the rates of historic shoreline change in the area.

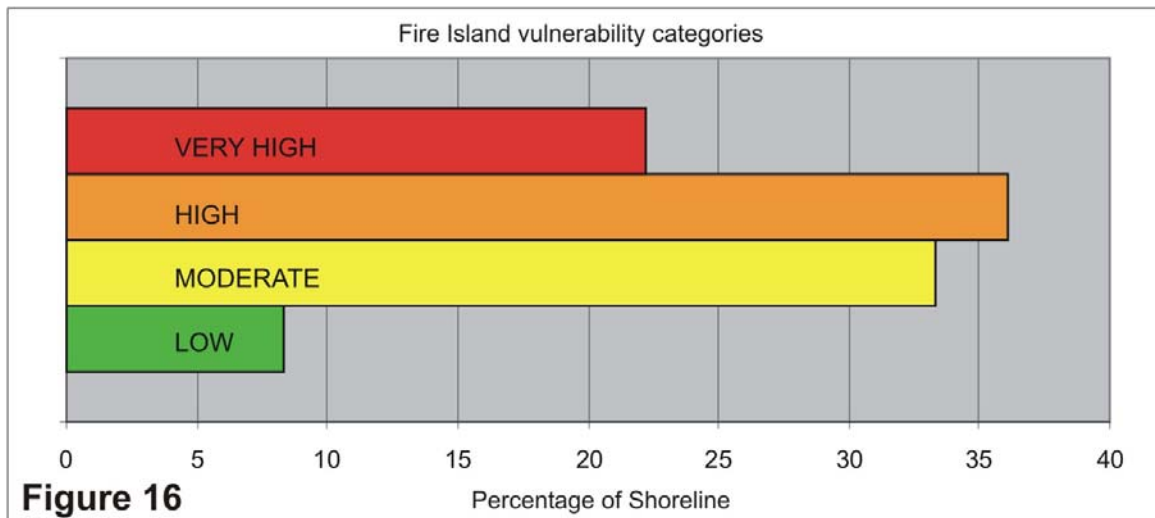


Figure 16. Percentage of Fire Island shoreline in each CVI vulnerability category.

Tables

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 - 2.0	-1.0 - 1.0	-2.0 - -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	0.85 - 1.05	1.05 - 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	New York State Statewide Digital Orthoimagery Program	http://www.nysgis.state.ny.us/index.html
SHORELINE EROSION/ACCRETION (m/yr)	Compilation of Existing Fire Island Shoreline Data (1830-1995) from US Army Corps of Engineers and US Geological Survey	http://pubs.usgs.gov/fs/fs136-01/fs136-01.pdf
COASTAL SLOPE (%)	NGDC Coastal Relief Model Vol 01 12/17/1998	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://bigfoot.wes.army.mil/ 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