Coastal Vulnerability Assessment of Virgin Islands National Park (VIIS) to Sea-Level Rise

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

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Contents

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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 Virgin Islands National Park on St. John in the US Virgin Islands. 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 input variable were combined and an index value calculated for 500-meter grid cells covering coastal areas of 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. Virgin Islands National Park coast consists of carbonate sand beaches, rock cliffs, fringing reefs, and mangrove wetlands. The areas within Virgin Islands National Park that are likely to be most vulnerable to sea-level rise are areas of unconsolidated sediment where coastal slope is low, and wave energy is high.

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 Virgin Islands National Park, 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, 2002), 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 likely 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 predict shoreline response are the subject of scientific debate. A number of predictive approaches have been proposed (National Research Council, 1990 and 1995), 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 uses different ranges of vulnerability (low to very high) to describe a coast's susceptibility to physical change as sea level rises. The vulnerability index determined here focuses on six variables that 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 significant wave height, tidal range, and sea-level change, 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. The five quantitative variables are assigned a vulnerability ranking based on their actual values, 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 being of moderate vulnerability in terms of that particular variable. Increasingly higher erosion or accretion rates are ranked as correspondingly higher or lower vulnerability. Regional coastal slopes range from very high vulnerability, <4.59 percent, to very low vulnerability at values >14.7 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 contributions to vulnerability 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.

The Virgin Islands National Park

The beautiful tropical coast of Virgin Islands National Park encompasses most of the island of St. John in the US Virgin Islands (Figure 1). The Virgin Islands are part of an arcuate chain of islands that form the northern and eastern boundaries of the Caribbean Sea, separating it from the Atlantic Ocean. The Puerto Rico - Virgin Island microplate, believed to be derived from oceanic crust of the Caribbean plate, stretches from eastern Hispaniola to the Virgin Islands, and lies along the boundary of the Caribbean plate and the North American plate (Rankin, 2002).

Cretaceous volcanism produced most of the rocks seem on St. John including basalts, andesite, and keratophyre. Lesser amounts of calcareous rocks and cherts contribute to the complex geology of this rugged 49 km^2 island (Rankin, 2002). St. John has a maximum height of 390 m (1280 ft) above sea level, and slopes steeply to beaches and headlands along the coast (Figure 2). Much of the coastline of St. John is paralleled by shallow fringing reefs which are vulnerable not only to expected sea-level rise acceleration, but also to hurricane damage, increased water temperature, runoff and sedimentation from adjacent land, boat anchoring, coral disease, and bottom fishing (for more information on coral reefs in the US Virgin Islands see http://biology.usgs.gov/s+t/SNT/noframe/cr134.htm). In addition to the many natural and biologic resources on St. John, there are also a number of cultural resources within the park including ancient petroglyphs and Danish sugar plantation ruins.

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 others (1994). 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 1:48,000-scale shoreline for Virgin Islands that was obtained from the National Oceanic and Atmospheric Administration's Biogeography Program (http://biogeo.nos.noaa.gov/products/benthic/). 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 500-meter grid (Figure 3). For segments of shoreline that experienced geomorphologic changes within one grid cell, smaller shoreline segments were created. Next each variable in each grid cell or shoreline segment was assigned a 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 1999 vertical aerial photography provided by NOAA's biogeography program. In addition, field visits were made within accessible locations of the park to verify the geomorphologic classification (Figure 5 A-H). Virgin Islands National Park contains several geomorphology types, including low vulnerability rock cliffs, moderate vulnerability alluvium and cliffs with fringing reefs, high vulnerability gravel beaches or cliff backed beaches, and very high vulnerability mangrove wetlands and sand beaches (Figure 4 and Figure 5 A-H).

Shoreline erosion and accretion rates for Virgin Islands National Park were calculated using digitized shorelines from 1971 and 1983 NOAA Coastal Survey Charts and 1999 aerial photography (Table 2). Shoreline rates of change (m/yr) were calculated at 50 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. The change rates for each transect within each 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 for St. John fall almost completely within the moderate vulnerability category, which is between -1 m/yr and +1 m/yr. Consolidated sections of the shoreline have not changed. There has been some erosion/accretion within bays and sandy areas such as Cinnamon Bay and Coral Bay. However, most of the rates still lie within +/- 1 m/yr (Figure 6).

Regional coastal slope is an indication of the relative vulnerability to 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 5 km 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 90-meter cells. Regional coastal slopes for Virgin Islands National Park fall within the very low to very high vulnerability category (< 4.55% - > 14.7%) (Figure 7).

Physical Process Variables

The **relative sea-level change** variable is derived from the change in annual mean water elevation over time as measured at tide gauge stations along the coast. The rate of sea-level rise for the US Virgin Islands is 0.5 +/- 0.74 mm/yr based on 25 years of data at Charlotte Amalie, St. Thomas (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 portray only the recent sea-level trend (< 150 years). Relative sea-level rise for Virgin Islands falls within very low vulnerability based on water elevation data on St. Thomas (Figure 8).

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 1990-1999 obtained from the USACE 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 the Virgin Islands, wave heights ranged from 1.0 m (moderate vulnerability) to 1.9 m (very high vulnerability) (Figure 9).

Tidal range is linked to both permanent and episodic inundation hazards. Tide range data were obtained from a NOAA/NOS published benchmark on St. John Island in Coral Harbor. Mean tidal range here is 0.262 m; therefore Virgin Islands National Park is classified as very high vulnerability (> 1meter) with respect to tidal range (Figure 10).

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 Virgin Islands National Park, 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 CVI values calculated for Virgin Islands range from 4.47 to 12.25. The mean CVI value is 8.01; the mode and the median are 7.75. The standard deviation is 1.86. The 25th, 50th, and 75th percentiles are 6.5, 7.8 and 9.0, respectively.

Figure 11 shows a map of the coastal vulnerability index for Virgin Islands National Park. 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 6.5 are assigned to the low vulnerability category. Values from 6.51 to 7.8 are considered moderate vulnerability. High-vulnerability values lie between 7.81 and 9.0. CVI values above 9.0 are classified as very high vulnerability. Figure 12 shows the percentage of Virgin Islands shoreline in each vulnerability category. Nearly all of the shoreline of St. John is evaluated for the Virgin Islands National Park. Thirteen percent of the mapped shoreline is classified as being at very high vulnerability due to future sea-level rise. Twenty-nine percent is classified as high vulnerability, twenty-eight percent as moderate vulnerability, and twenty-nine percent as low vulnerability.

Discussion

The data within the coastal vulnerability index (CVI) show variability at different spatial scales. However, the ranked values for the physical process variables vary less over the extent of the shoreline. The value of the relative sea-level rise variable is constant at very low vulnerability for the entire study area. The significant wave height vulnerability is moderate to very high. The tidal range is very high vulnerability (< 1m) for all of St. John.

The geologic variables show the most spatial variability and thus have the most influence on CVI variability (Figure 11). Geomorphology in the park includes very high vulnerability sandy beach shoreline, high vulnerability gravel beaches, moderate vulnerability alluvium or cliffs with fringing reefs, and low vulnerability rock and cliff features (Figure 4 and Figure 5 A-H). Vulnerability assessment based on shoreline change remains constant at moderate vulnerability for all of Virgin Islands NP (Figure 6). Regional coastal slope is in the very low to very high vulnerability range for Virgin Islands.

The most influential variables in the CVI are geomorphology, coastal slope, and wave energy; therefore they may be considered the dominant factors controlling how Virgin Islands National Park will evolve as sea level rises.

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 indication of where physical changes are most likely to occur as sea level continues to rise; and

2. as a planning tool for the Virgin Islands National Park.

As ranked in this study, geomorphology, regional coastal slope, and wave energy are the most important variables in determining the spatial variability of the CVI for Virgin Islands. Shoreline change rate, tidal range, and sea-level rise rate do not contribute to the spatial variability in the coastal vulnerability index. Virgin Islands National Park preserves a dynamic natural environment, which must be understood in order to be managed properly. The CVI is one way that park managers 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

pocket beaches where coastal slope is low and significant wave heights are high. The low vulnerability shoreline is generally located along rock cliffs or in sheltered areas such as in Hurricane Hole.

Figure 12. Percentage of Virgin Islands shoreline in each CVI category.

List of Tables

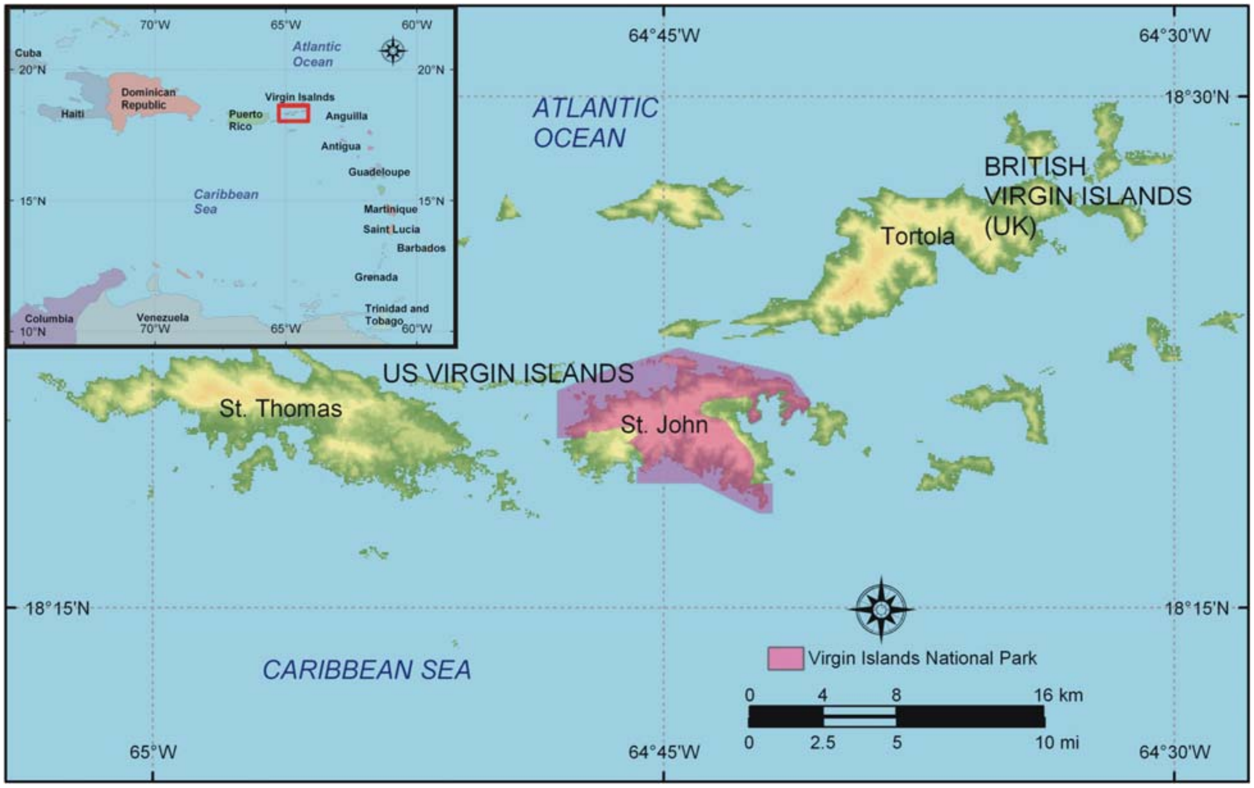


Figure 1. Location of Virgin Islands National Park, St. John, U.S. Virgin Islands.

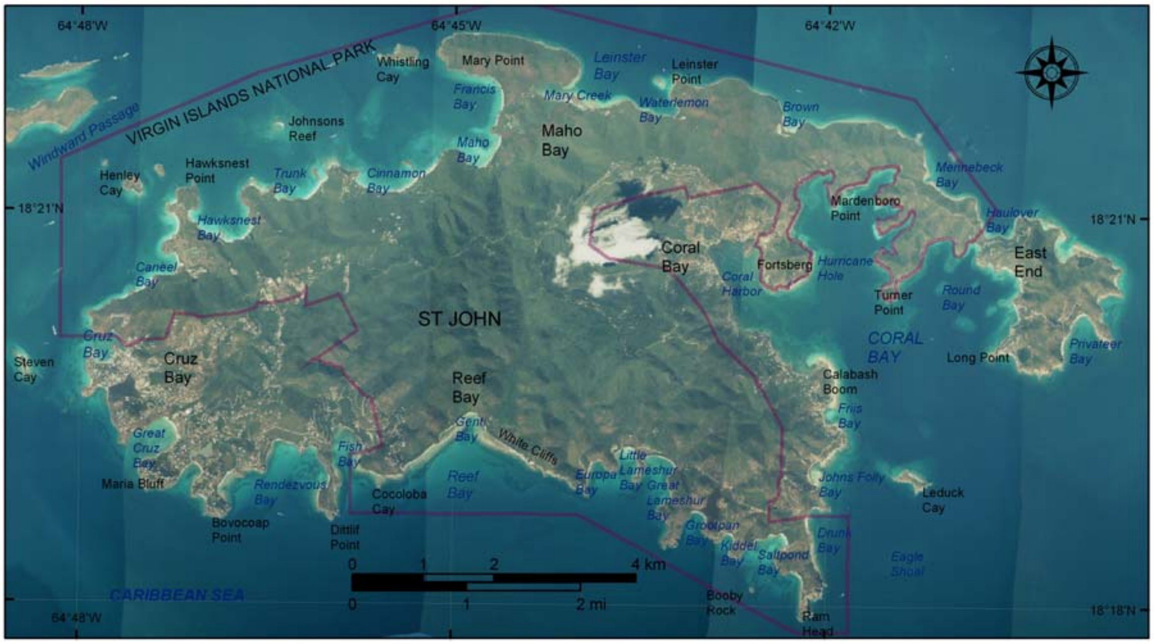
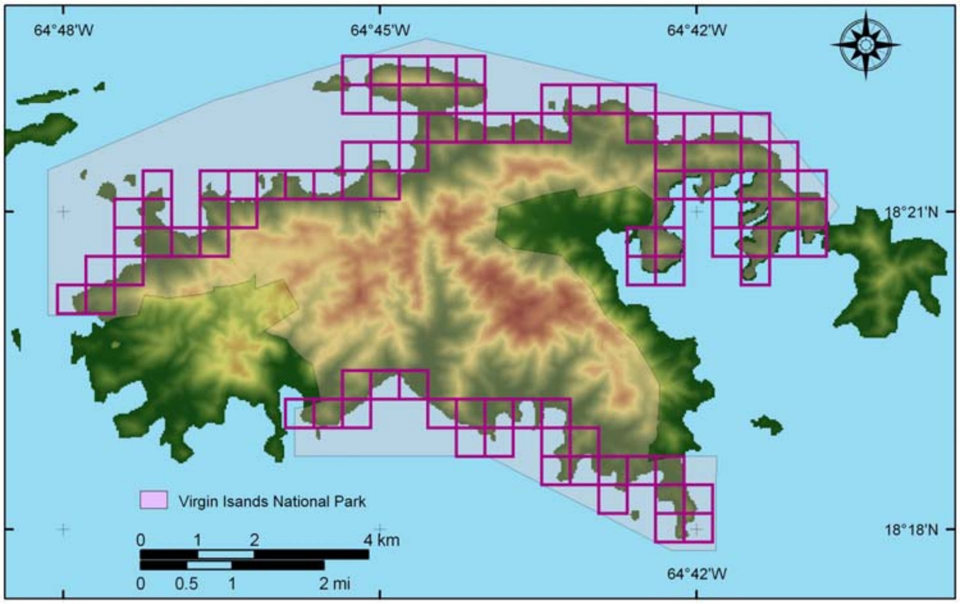


Figure 2. Virgin Islands National Park on St. John Island. Aerial photo mosaic produced from NOAA/NOS photos (http://biogeo.nos.noaa.gov/projects/mapping/caribbean/) showing physiography and location labels. The red line is the boundary of Virgin Islands National Park.



Figures 3. Shoreline grid for Virgin Islands National Park. Each cell is approximately 500 meters of shoreline and represents a shoreline segment for which each variable is defined.

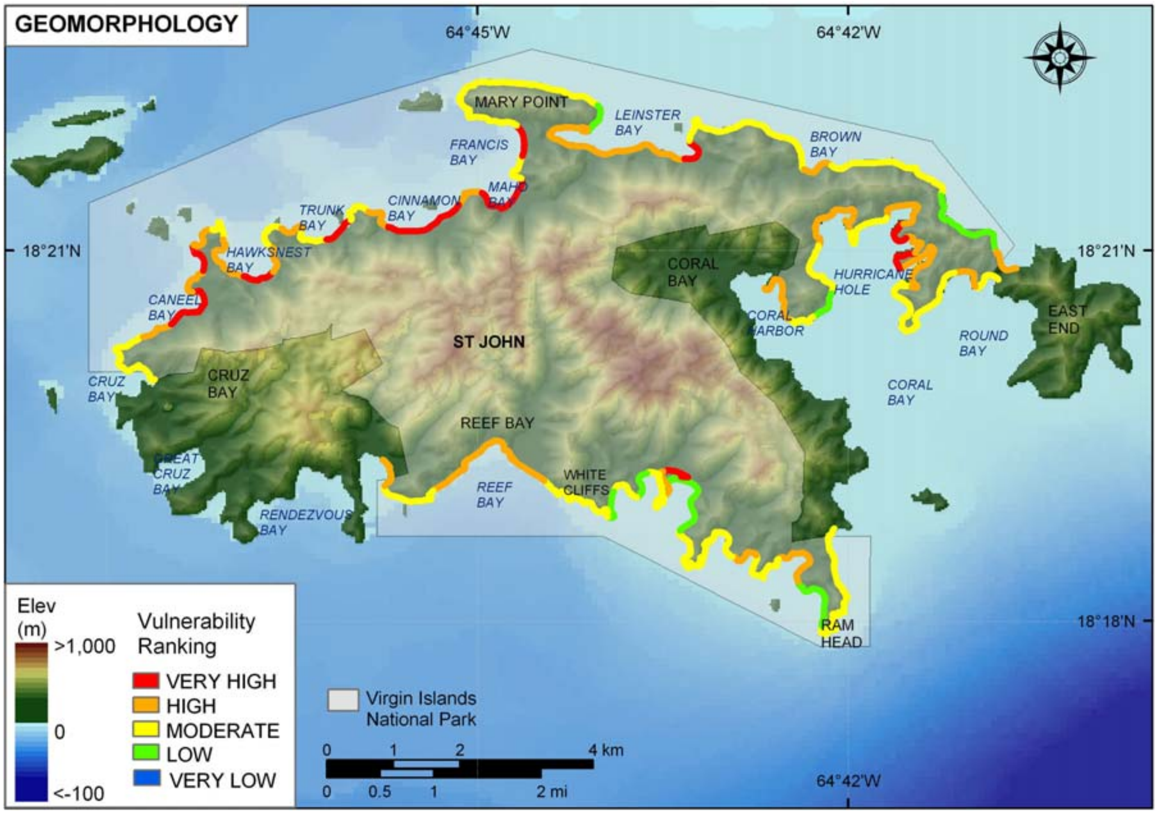


Figure 4. Coastal Geomorphology of Virgin Islands National Park. The colored shoreline represents the variations in coastal geomorphology within the park. The very high vulnerability geomorphology is mostly sand beaches or mangrove wetlands. High vulnerability geomorphology includes gravel or cobble-sized beaches or cliff-backed beaches. Moderate vulnerability geomorphology consists of alluvium or fringing reefs fronting low cliffs. Low vulnerability geomorphology includes medium cliffs and rock headlands.

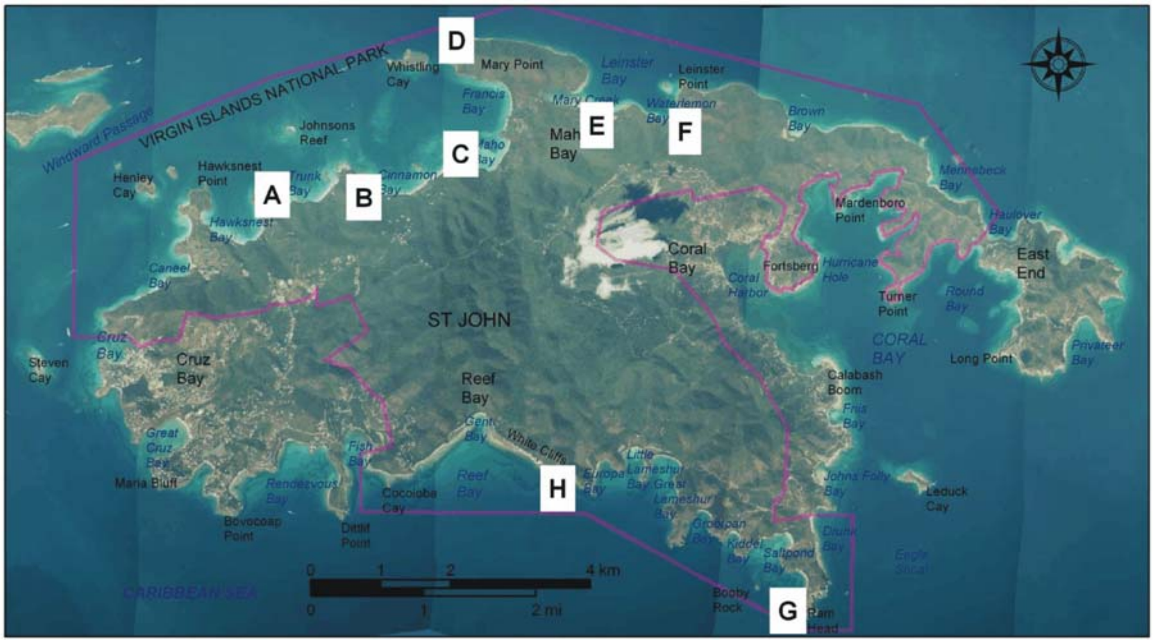


Figure 5. Photos of different geomorphologic types within Virgin Islands National Park. *Click on a letter to see a photo near that location*.

A) A view of Trunk Bay from the east, very high vulnerability.
B) The shoreline at Cinnamon Bay is experiencing erosion, very high vulnerability.
C) A view of Maho Bay from the east, very high vulnerability.
D) Mary Point was ranked as low vulnerability (photo by Rebecca Beavers).
E) The Annaberg Mill ruins are in an area ranked as high vulnerability with respect to geomorphology (photo by Rebecca Beavers).
F) The shoreline surrounding Waterlemon Bay is a cobble beach, high vulnerability
G) Ram Head is a rocky headland, low vulnerability (photo by Rebecca Beavers). H) The white cliffs near Reef Bay were ranked as low vulnerability (photo by Rebecca Beavers).

Figure 5. A) A view of Trunk Bay from the east, very high vulnerability.

Figure 5. B) The shoreline at Cinnamon Bay is experiencing erosion, very high vulnerability.

Figure 5. C) A view of Maho Bay from the east, very high vulnerability.

Figure 5. D) Mary Point was ranked as low vulnerability (photo by Rebecca Beavers).

Figure 5. E) The Annaberg Mill ruins are in an area ranked as high vulnerability with respect to geomorphology (photo by Rebecca Beavers).

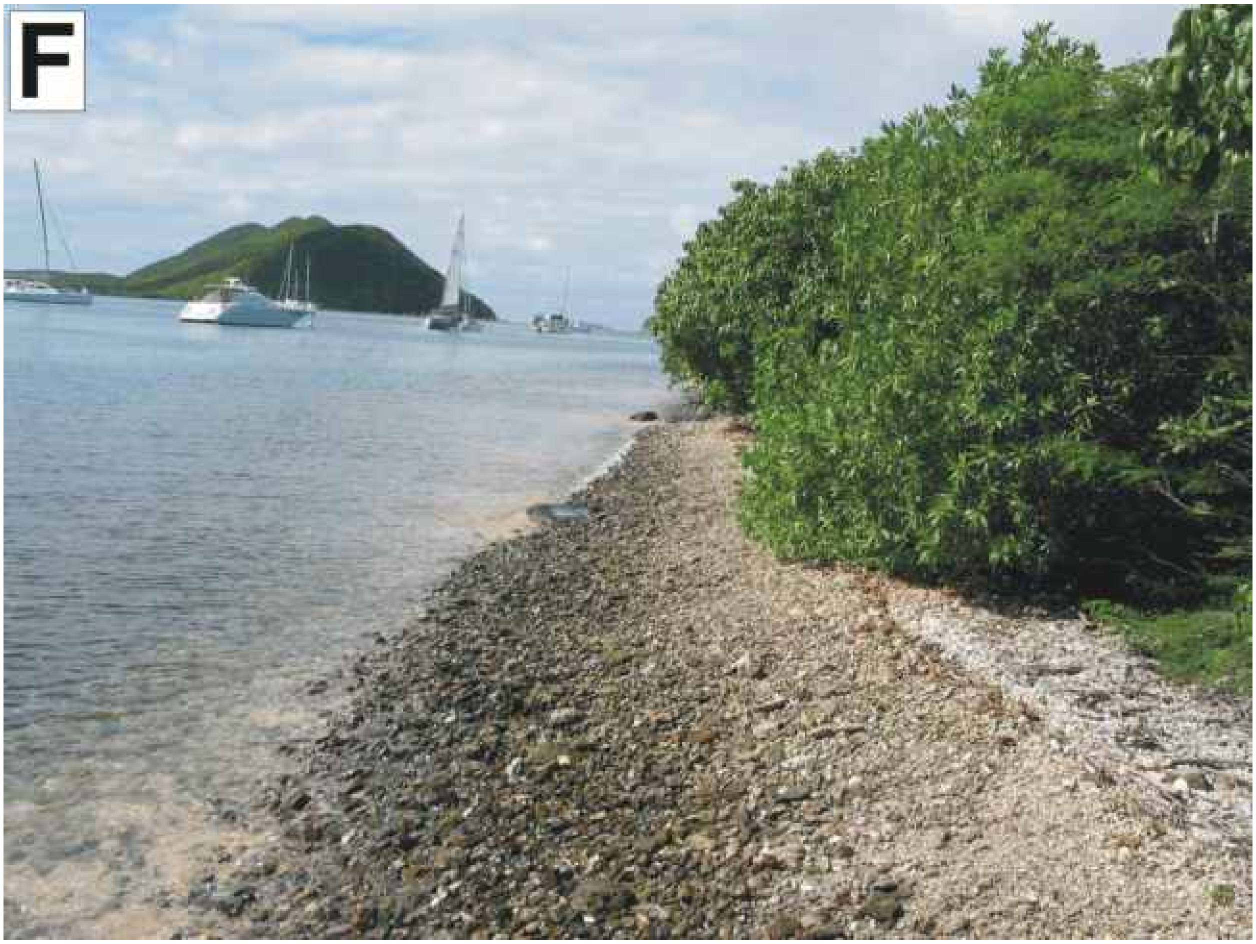


Figure 5. F) The shoreline surrounding Waterlemon Bay is a cobble beach, high vulnerability

Figure 5. G) Ram Head is a rocky headland, low vulnerability (photo by Rebecca Beavers). H) The white cliffs near Reef Bay were ranked as low vulnerability (photo by Rebecca Beavers).

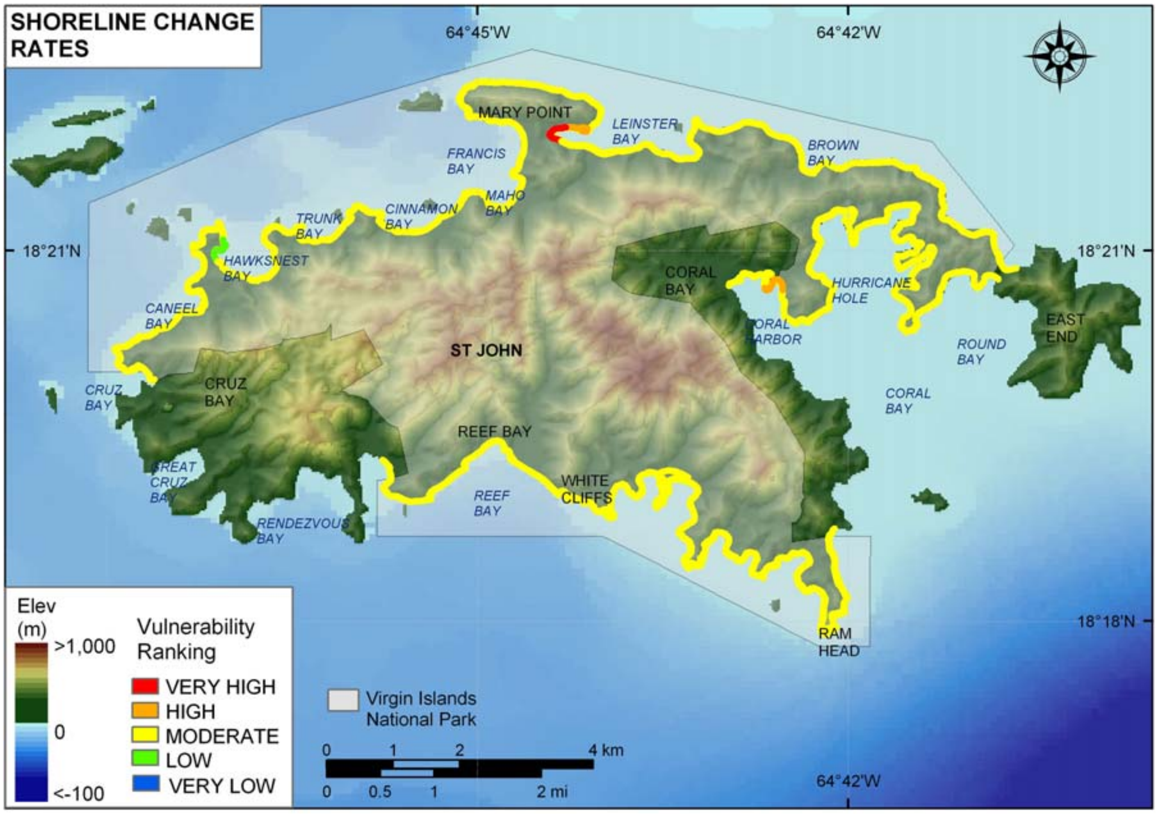


Figure 6. Shoreline change rates for Virgin Islands National Park. The colored shoreline represents the rate of shoreline erosion or accretion. Most of Virgin Islands National Park is moderate vulnerability (-1m/yr - +1m/yr) with respect to shoreline change, there are a few small sandy areas of locally higher erosion rates.

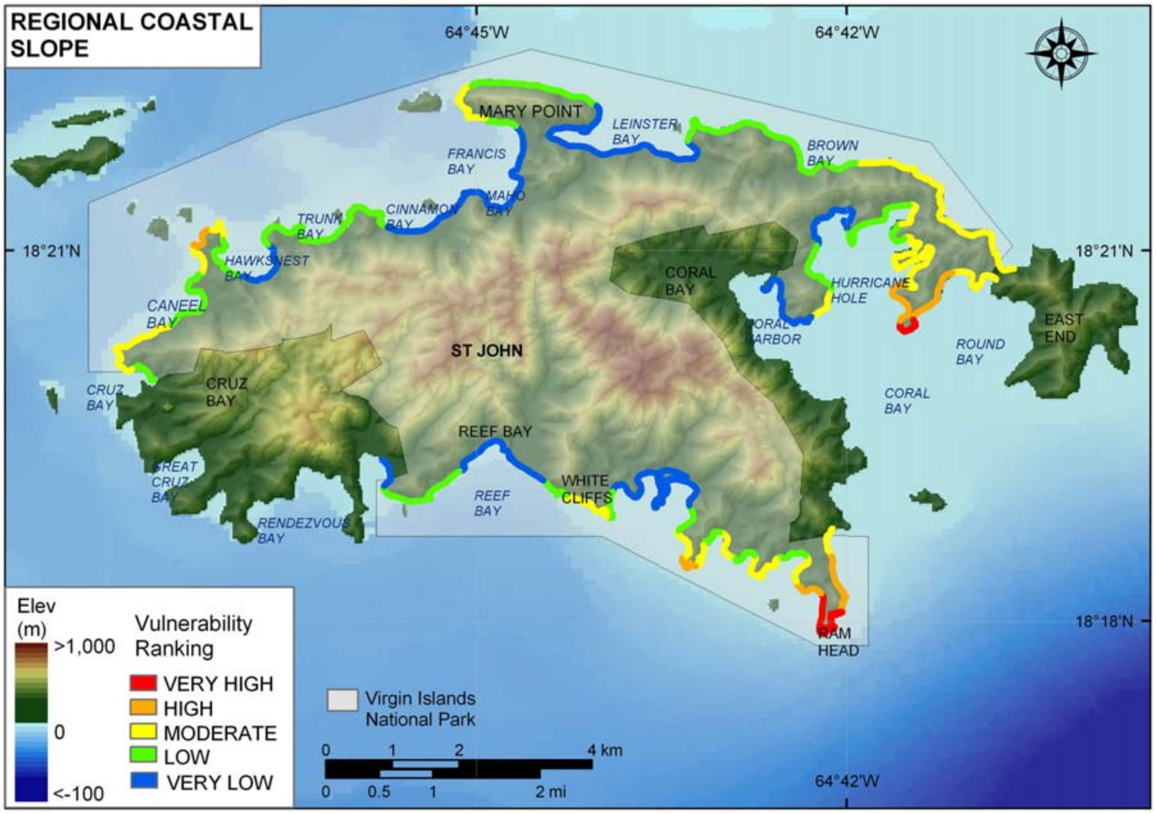


Figure 7. Regional coastal slope for Virgin Islands National Park. The colored shoreline represents the regional slope of the land, 5 km landward and seaward of the shoreline. Very low vulnerability coastal slope areas are where high mountains are adjacent to the coast. High vulnerability slopes are generally around the shallow bay areas or less mountainous regions towards East End.

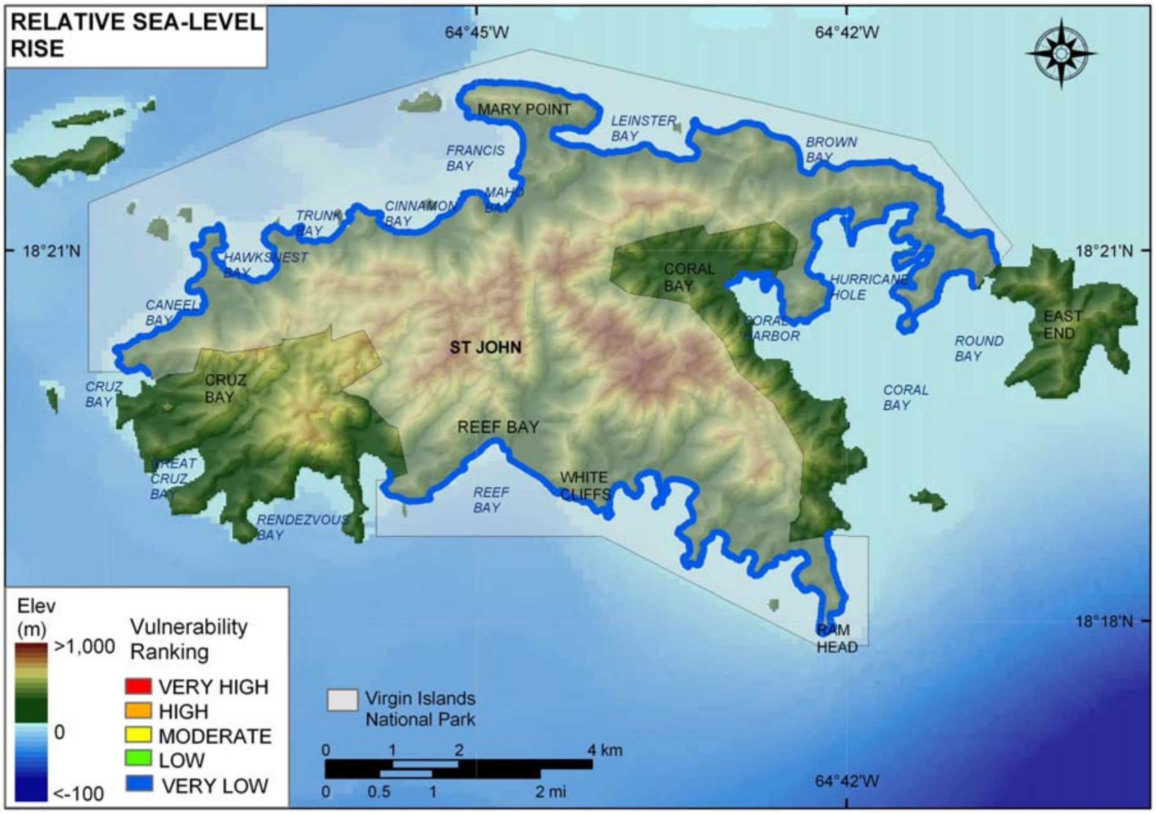


Figure 8. Rate of relative sea-level rise for Virgin Islands National Park. The colored shoreline represents the ranked rate of rise for Charlotte Amalie, St. Thomas. All of Virgin Islands National Park is ranked as very low vulnerability with respect to relative sea-level rise.

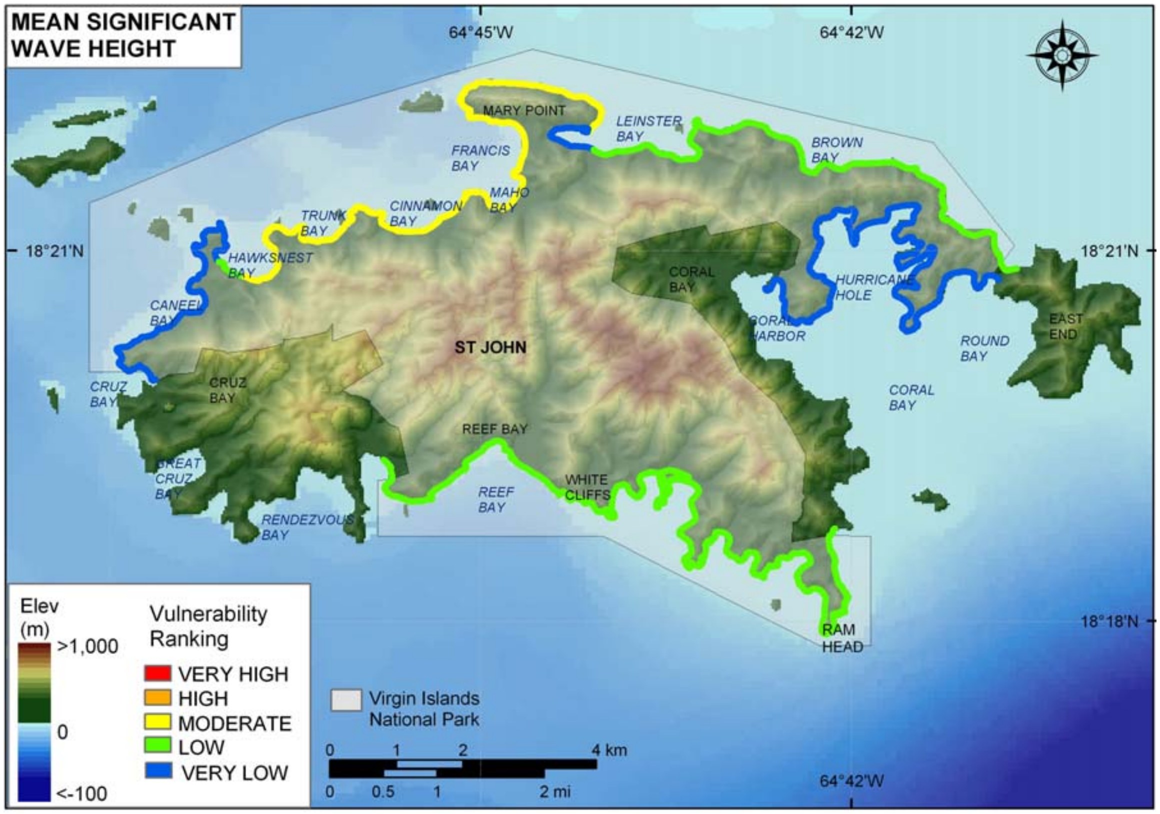


Figure 9. Mean significant wave heights for Virgin Islands National Park based on WIS data. The colored shoreline represents the significant wave heights within the park. Very high wave energy areas are located along the open Atlantic Coast. Significant wave heights are lower along the Caribbean Sea shoreline and vulnerability is moderate where the shoreline is protected from direct wave approach.

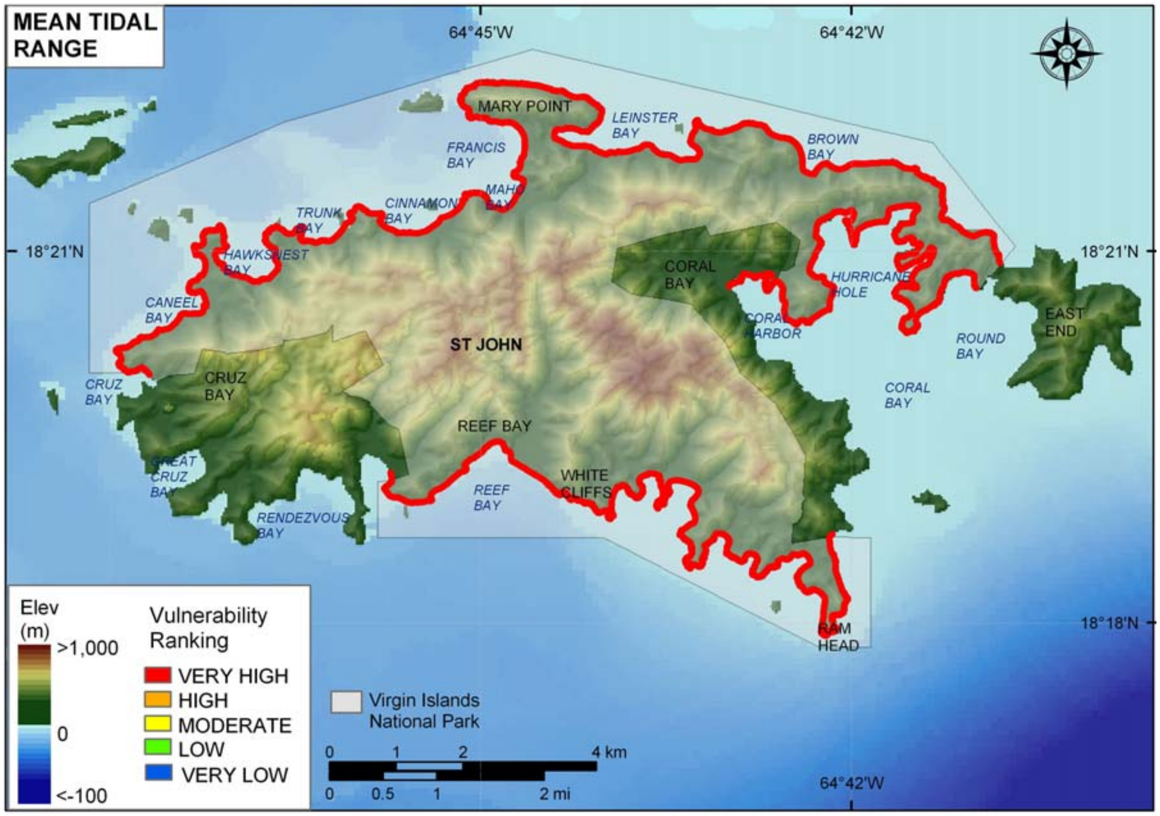


Figure 10. Mean Tidal Range for Virgin Islands National Park. The colored shoreline represents the ranked mean tidal range for Virgin Islands. All of Virgin Islands National Park is ranked as very high vulnerability with respect to tidal range.

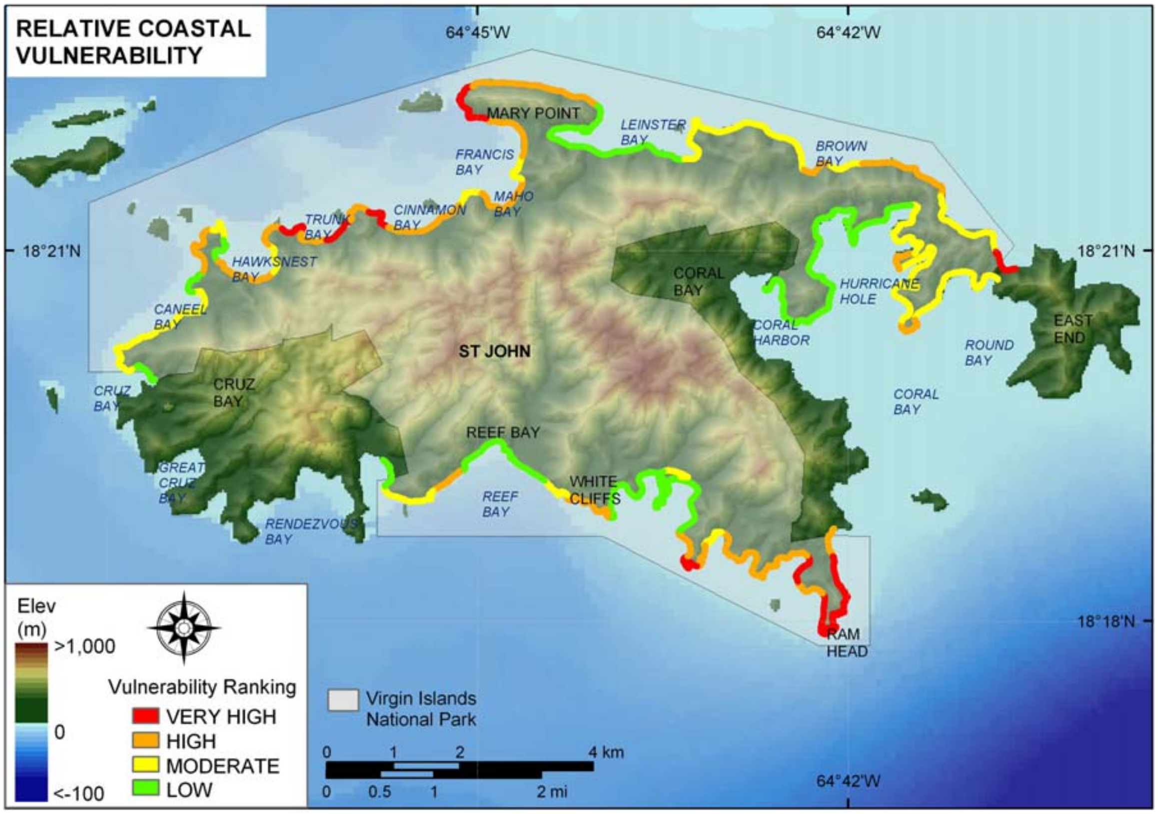


Figure 11. Relative Coastal Vulnerability for Virgin Islands National Park. The colored shoreline represents the relative coastal vulnerability index (CVI) determined from the six variables. The very high vulnerability shoreline is located along sandy pocket beaches where coastal slope is low and significant wave heights are high. The low vulnerability shoreline is generally located along rock cliffs or in sheltered areas such as in Hurricane Hole.

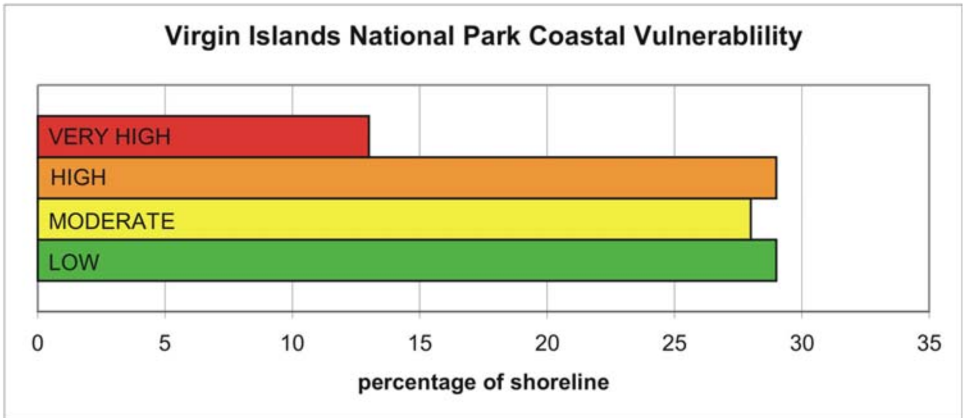


Figure 12. Percentage of Virgin Islands shoreline in each CVI category.

Table 1. Ranges for Vulnerability Ranking of Variables on the Atlantic/Caribbean 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 (%)	> 14.70	10.90 - 14.69	7.75 - 10.89	4.60 - 7.74	< 4.59
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)	< 1.1	1.1 -2.0	2.01 - 2.25	2.26 - 2.6	> 2.6
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 (Not all sources are downloadable)**
GEOMORPHOLOGY	Mosaiced aerial photography from the Benthic Habitats of Puerto Rico and the US Virgin Islands NOS/NOAA Biogeography Program	http://biogeo.nos.noaa.gov/products/benthic/
SHORELINE EROSION/ACCRETION (m/yr)	St. John shoreline change data were derived by digitizing shorelines of 1971 and 1983 NOAA Coastal Survey Charts, and from a 1999 shoreline from NOS/NOAA Biogeography program	http://historicals.ncd.noaa.gov/historicals/histmap.asp http://biogeo.nos.noaa.gov/products/benthic/
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)	WIS Hindcast Wave Data for US Coasts and NOAA National Data Buoy Center	http://frf.usace.army.mil/wis/ 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