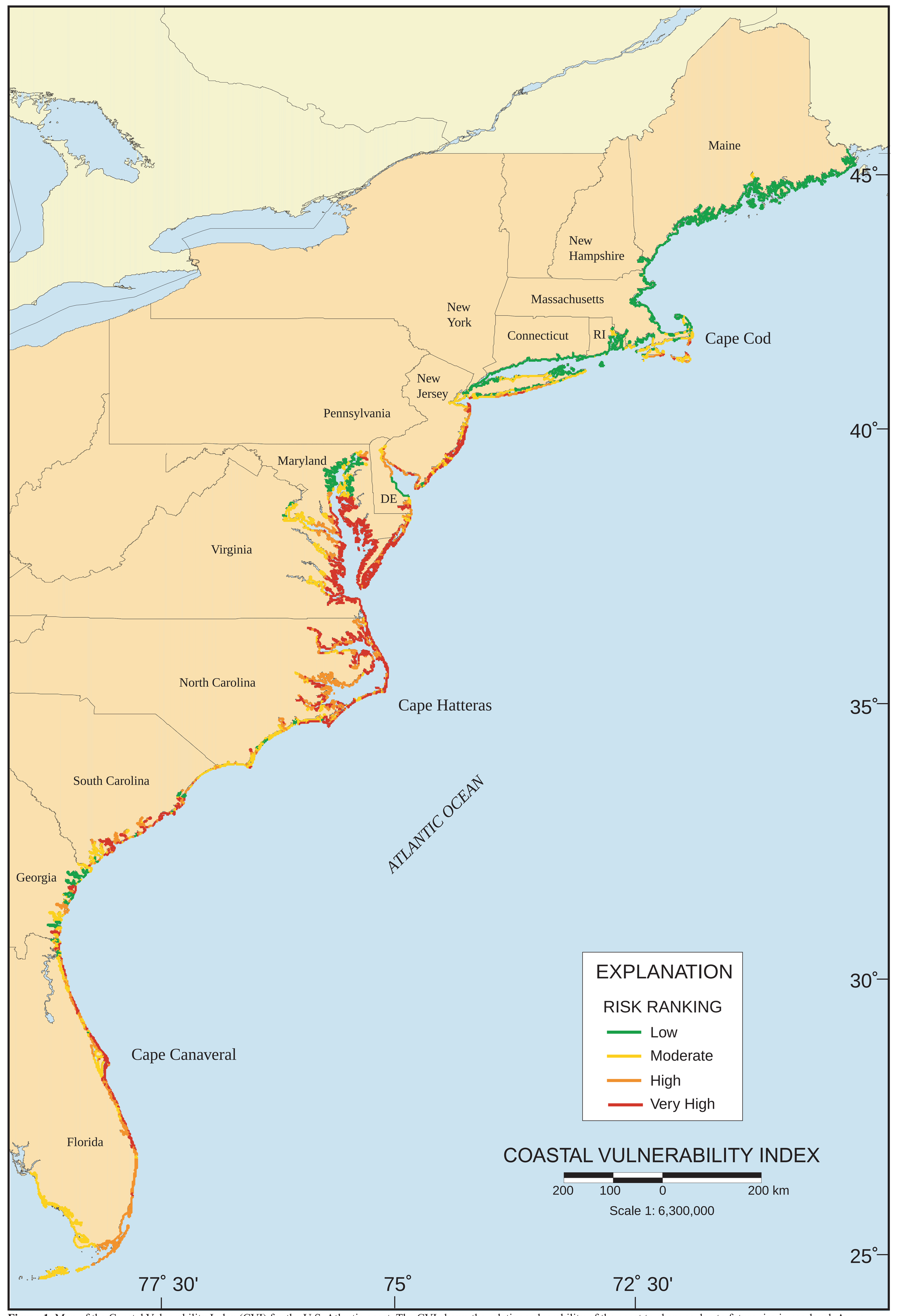

Figure 1. Map of the Coastal Vulnerability Index (CVI) for the U.S. Atlantic coast. The CVI shows the relative vulnerability of the coast to changes due to future rise in sea-level. Areas along the coast are assigned a ranking from low to high risk, based on the analysis of physical variables that contribute to coastal change.

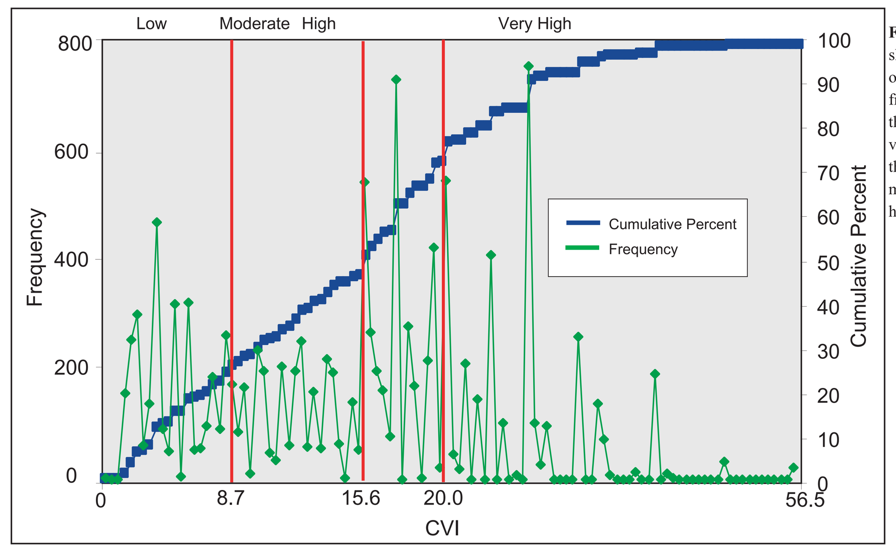

Figure 2. Histograms showing the frequency of occurrence and cumulative frequency of CVI values for the U.S. Atlantic coast. The vertical red lines delineate the chosen ranges for low, moderate, high, and very high risk areas.

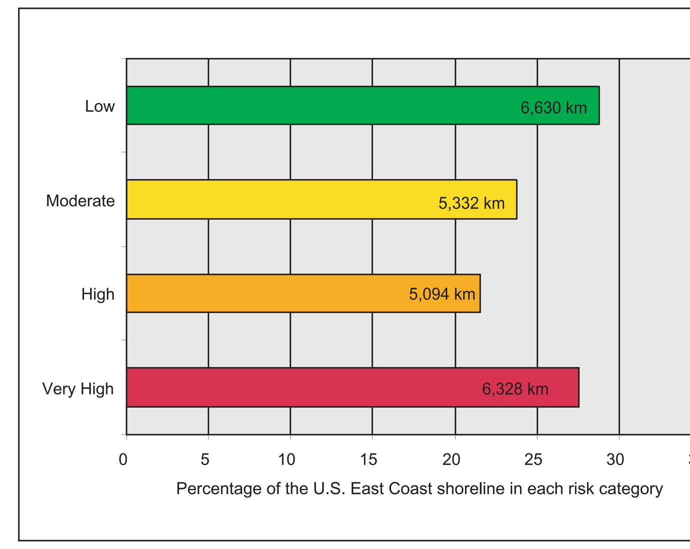

Figure 3. Bar graph showing the percentage of shoreline along the U.S. Atlantic coast in each risk category. The graph also shows the total length of shoreline (in kilometers) in each risk category. The total length of mapped shoreline in this study is 23,384 km.

Ranking of coastal vulnerability index					
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	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
Coastal Slope (%)	>0.115	0.115 – 0.055	0.055 – 0.035	0.035 –0.022	< 0.022
Relative sea-level change (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 3.0	3.0 – 3.4	> 3.4
Shoreline erosion/ accretion (m/yr)	>2.0	1.0 –2.0 Accretion	-1.0 – +1.0 Stable	-1.1– -2.0	< - 2.0 Erosion
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 –1.9	< 1.0
Mean wave height (m)	<0.55	0.55 – 0.85	0.85 – 1.05	1.05 –1.25	>1.25

Table 1. Ranking of coastal vulnerability index variables.

New York to New Jersey example

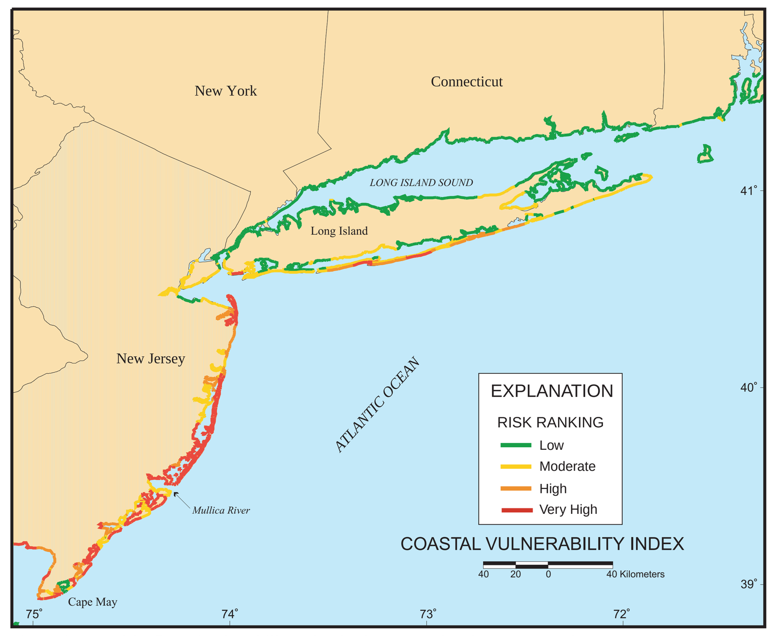

Figure 4. Map of the Coastal Vulnerability Index for the New York to New Jersey region.

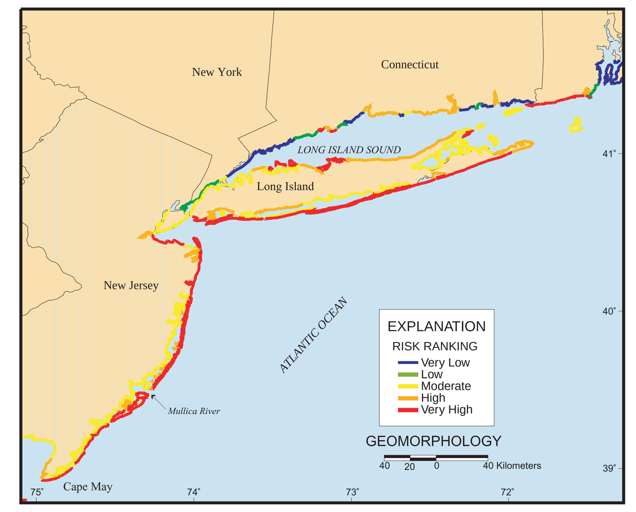

Figure 5. Map of the geomorphology variable for the New York to New Jersey region. The open-ocean shoreline is composed primarily of high-risk sandy barrier islands, while risk due to geomorphology is lower for lagoons and along the bluffs of northern Long Island.

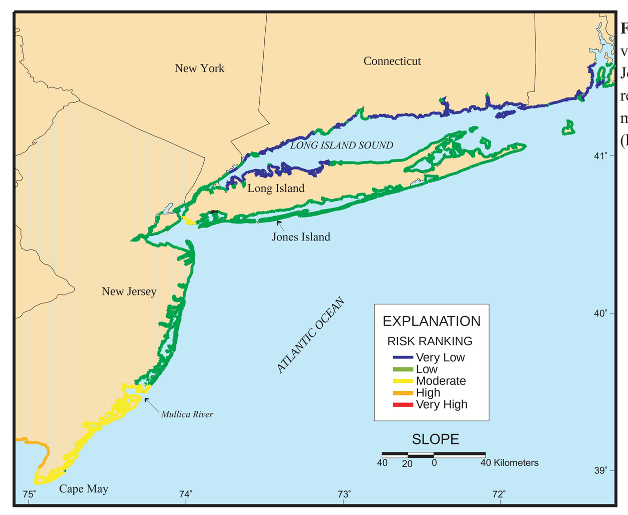

Figure 6. Map of the coastal slope variable for the New York to New Jersey region. The coastal slope is relatively steep (low risk) throughout much of this area, but is quite low (high risk) in southern New Jersey.

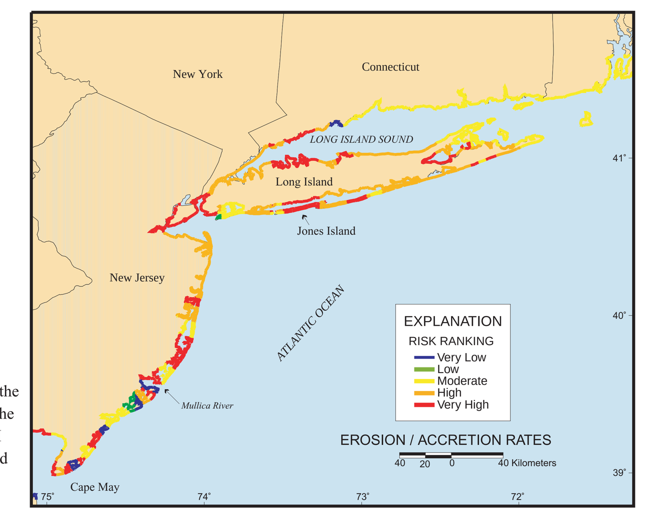

Figure 7. Map of the shoreline erosion/accretion rate variable for the New York to New Jersey region. The smaller-scale variations in the CVI values (see Figure 4) are influenced primarily by changes in shoreline erosion rate.

North Carolina to Georgia example

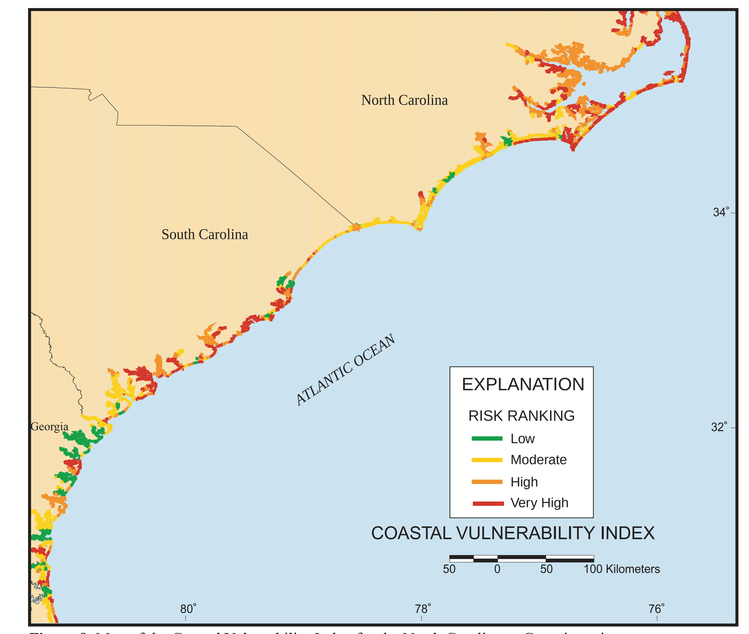

Figure 8. Map of the Coastal Vulnerability Index for the North Carolina to Georgia region.

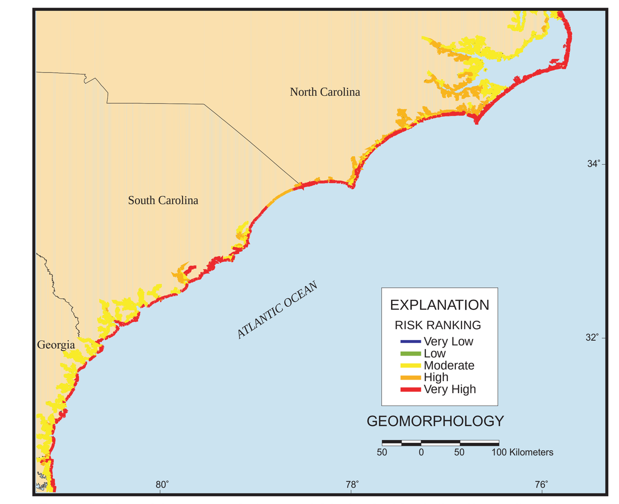

Figure 9. Map of the geomorphology variable for the North Carolina to Georgia region. Like the New York to New Jersey region, geomorphology is still the dominant variable influencing the CVI values (see Figure 8).

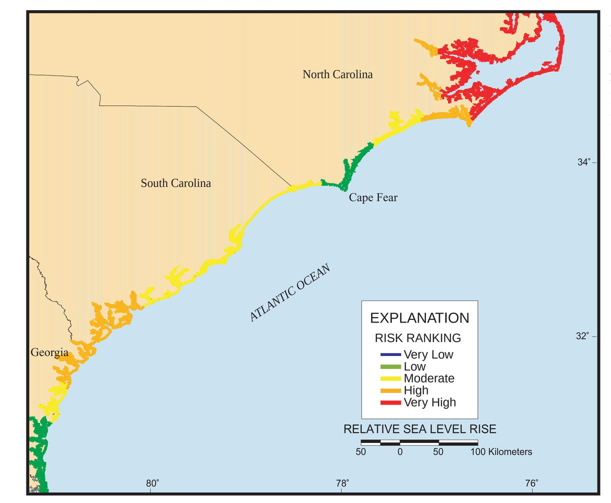

Figure 10. Map of the relative sea-level rise variable for the North Carolina to Georgia region. The rate of sea-level change is lowest at Cape Fear, North Carolina, due to long-term tectonic uplift of the mid-Carolina Platform High.

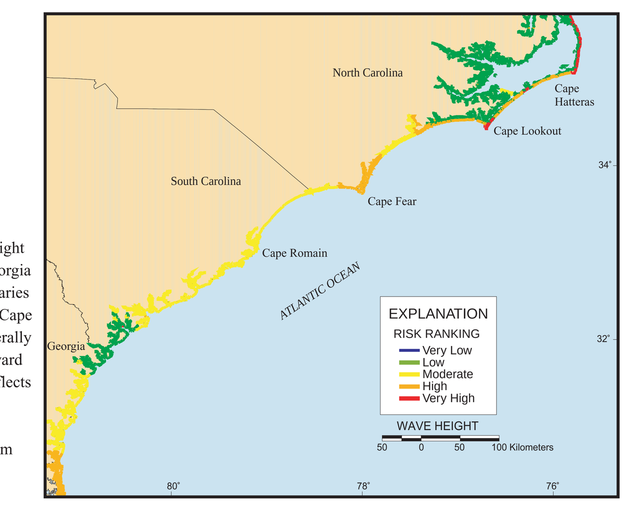

Figure 11. Map of the mean wave height variable for the North Carolina to Georgia region. The risk due to wave height varies between the north and south sides of Cape Hatteras and Cape Lookout, and generally decreases from Cape Hatteras southward into the Georgia embayment. This reflects differences in wave exposure due to shoreline orientation, as well as the increasing continental shelf width from North Carolina to Georgia.

National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the U.S. Atlantic Coast

By

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1999

INTRODUCTION

One of the most important applied problems in coastal geology today is determining the physical response of the coastline to sea-level rise. Prediction of shoreline retreat and land loss rates is critical to the planning of future coastal zone management strategies, and assessing biological impacts due to habitat changes or destruction. Presently, long-term (≥ 50 years) coastal planning and decision-making has been done piecemeal, if at all, for the nation's shoreline (National Research Council, 1990; 1995). Consequently, facilities are being located and entire communities are being developed without adequate consideration of the potential costs of protecting or relocating them from sea level rise-related erosion, flooding and storm damage.

Recent estimates of future sea-level rise based on climate model output (Wigley and Raper, 1992) suggest an increase in global eustatic sea-level of between 15-95 cm by 2100, with a "best estimate" of 50 cm (IPCC, 1995). This is more than double the rate of eustatic rise for the past century (Douglas, 1997; Peltier and Jiang, 1997). Thus, sea-level rise will have the largest sustained impact on coastal evolution at the societally-important decadal time scale. For example, Zhang et al. (1997) showed that sea-level rise over the past 80 years at two locations on the U.S. East Coast contributed directly to significant increases in the amount of time the coast is subjected to extreme storm surges. From 1910-1920, the coast near Atlantic City, New Jersey was exposed to anomalously high water levels from extreme storms less than 200 hours per year, whereas during the early 1990's the coast was exposed to high water from storms of the same magnitude 700 to 1200 hours per year. Interestingly, the authors found that although storm surge varied a great deal on annual to decadal scales, there was no long-term trend showing increases in storm intensity or frequency that might account for the increasing anomalously high water levels. Zhang et al. (1997) concluded that the increase in storm surge exposure of the coast was due to sea-level rise of about 30 cm over the 80-year period. This finding suggests that the historical record of sea-level change can be combined with other variables (e.g., elevation, geomorphology, wave characteristics) to assess the relative coastal vulnerability to future sea-level change.

The prediction of future coastal evolution is not straightforward. There is no standard methodology, and even the kinds of data required to make such predictions are the subject of much scientific debate. A number of predictive approaches have been used (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. Each of these approaches, however, has its shortcomings or can be shown to be invalid for certain applications (National Research Council, 1990). Similarly, the types of input data required vary widely and for a given approach (e.g. sediment budget), existing data may be indeterminate or simply not exist. Furthermore, human manipulation of the coastal environment in the form of beach nourishment, construction of seawalls, groins, and jetties, as well as coastal development itself, may drive federal, state and local priorities for coastal management without regard for geologic processes. Thus, the long-term decision to renourish or otherwise engineer a coastline may be the sole determining factor in how that coastal segment evolves.

Although a viable, quantitative predictive approach is not available, the relative vulnerability of different coastal environments to sea-level rise may be quantified at a regional to national scale using basic information on coastal geomorphology, rate of sea-level rise, past shoreline evolution, and other factors. The overall goal of this study is to develop and utilize a relatively simple, objective method to identify those portions of the U.S. coastal regions at risk and the nature of that risk (e.g., inundation, erosion, etc.). The long-term goal of this study is to predict future coastal changes with a degree of certainty useful for coastal management, following an approach similar to that used to map national seismic and volcanic hazards (e.g., Miller, 1989; Frankel et al., 1996; Hoblitt et al. 1998). This information has immediate application to many of the decisions our society will be making regarding coastal development in both the short- and long-term.

This study involves two phases. The first phase, presented in this report for the U.S. East Coast, involves updating and refining existing databases of geologic and environmental variables, such as that compiled by Gornitz and White (1992). For all of the variables in this data set, updated or new data exist and are presented here. The second phase of the project has two components. The first component entails integrating model output such as eustatic, isostatic, and short-term climatic sea-level change estimates in order to assess the potential impacts on the shoreline due to these changes. The second component involves developing other databases of environmental information, such as relative coastal sediment supply, as well as including episodic events (hurricane intensity, track, and landfall location, Nor'easter storm intensity data, and El Niño-related climate data such as short-term sea-level rise).

In this preliminary report, the relative vulnerability of different coastal environments to sea-level rise is quantified for the U.S. East Coast. This initial classification is based upon variables such as geomorphology, regional coastal slope, and shoreline erosion and accretion rates. The combination of these variables and the association of these variables to each other furnishes a broad overview of regions where physical changes will occur due to sea-level rise.

RISK VARIABLES

In order to develop a database for a national-scale assessment of coastal vulnerability, relevant data have been gathered from local, state and federal agencies, as well as academic institutions. The compilation of this data set is integral to accurately mapping potential coastal changes due to sea-level rise. This database is based loosely on an earlier database developed by Gornitz and White (1992). A comparable assessment of the sensitivity of the Canadian coast to sea-level rise is furnished by Shaw et al. (1998).

Table 1 summarizes the six physical variables used here: 1) geomorphology, 2) shoreline erosion and accretion rates (m/yr), 3) coastal slope (percent), 4) rate of relative sea-level rise (mm/yr), 5) mean tidal range (m), and 6) mean wave height (m). As described below, each variable is assigned a relative risk value based on the potential magnitude of its contribution to physical changes on the coast as sea-level rises.

The geomorphology variable expresses the relative erodibility of different landform types (Table 1). These data were derived from state geologic maps and USGS 1:250,000 scale topographic maps.

Shoreline erosion and accretion rates for the U.S. have been compiled by May and others (1983) and Dolan and others (1985) into the Coastal Erosion Information System (CEIS) (May and others, 1982). CEIS includes shoreline change data for the Atlantic, Gulf of Mexico, Pacific and Great Lakes coasts, as well as major bays and estuaries. The data in CEIS are drawn from a wide variety of sources, including published reports, historical shoreline change maps, field surveys and aerial photo analyses. However, the lack of a standard method among coastal scientists for analyzing shoreline changes has resulted in the inclusion of data utilizing a variety of reference features, measurement techniques, and rate-of-change calculations. Thus, while CEIS represents the best available data for the U.S. as a whole, much work is needed to accurately document regional and local erosion rates. The CEIS data are being augmented by and updated with shoreline change data obtained from states and local agencies, in addition to new analyses being conducted as part of this study.

The regional slope of the coastal zone was calculated from a grid of topographic and bathymetric elevations extending approximately 50 km landward and seaward of the shoreline. The regional slope permits an evaluation of not only the relative risk of inundation, but also the potential rapidity of shoreline retreat, since low-sloping coastal regions should retreat faster than steeper regions (Pilkey and Davis, 1987). In order to compute the slope from the subaerial coastal plain to the submerged continental shelf, the slope for each grid cell was calculated by defining elevation extremes within a 10 km radius for each individual grid cell. In areas where the shelf/slope break was less than 10 km offshore, the slope was recalculated with a more appropriate radius. For the U.S. East coast, north of Florida, elevation data were obtained from the National Geophysical Data Center (NGDC) as gridded topographic and bathymetric elevations to the nearest 0.1 meter for 3 arc-second (~90 m) grid cells. These data were subsampled to 3-minute (approximately 5 km) resolution. For the Florida coast, the U.S. Navy ETOPO5 digital topographic and bathymetric elevation database was used. This gridded data set has a vertical resolution of one meter, and a horizontal resolution of approximately 8 km, which we resampled to a horizontal resolution of approximately 5 km.

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 (e.g., Emery and Aubrey, 1991). Relative sea-level change data were obtained for 28 National Ocean Service (NOS) data stations and contoured along the coastline. This variable inherently includes both the global eustatic sea-level rise as well as local isostatic or tectonic land motion. Relative sea-level change data are a historical record, and thus show change for only recent time scales (past 50-100 yr).

Tide range data were obtained from the NOS. Tide range is linked to both permanent and episodic inundation hazards. Tidal data were obtained for 657 tide stations along the U.S. coast and their values contoured along the coastline.

Wave height is used here as an indicator of wave energy, which drives the coastal sediment budget. Wave energy increases as the square of the wave height; thus the ability to mobilize and transport beach/coastal materials is a function of wave height. In this report we use hindcast nearshore mean wave height data for the period 1976-1995 obtained from the U.S. Army Corps of Engineers Wave Information Study (WIS) (see references in Hubertz et al., 1996). The model wave heights were compared to historical measured wave height data obtained from the NOAA National Data Buoy Center. Wave height data for 151 WIS stations along the U.S. coast were contoured along the coastline.

DATA RANKING

Table 1 shows the six physical variables described above, ranked on a linear scale from 1-5 in order of increasing vulnerability due to sea-level rise. In other words, a value of 1 represents the lowest risk and 5 represents the highest risk. The database includes both quantitative and qualitative information. Thus, numerical variables are assigned a risk ranking based on data value ranges, while the non-numerical geomorphology variable is ranked according to the relative resistance of a given landform to erosion. Regional coastal slopes are considered to be very low risk at values >0.2 percent; very high risk consists of regional slopes <0.025 percent. The rate of relative sea-level rise is ranked using the modern rate of eustatic rise (1.8 mm/yr) as very low risk. Since this is a global or "background" rate common to all shorelines, the sea-level rise ranking reflects primarily regional to local isostatic or tectonic effects. 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 risk. Tidal range is ranked such that microtidal coasts are high risk and macrotidal coasts are low risk. Mean wave height rankings range from very low (<0.55 m) m to very high (>1.25 m).

In previous and related studies (Gornitz, 1990; Shaw et al., 1998), large tidal range (macrotidal; tide range > 4m) coastlines were assigned a high risk classification, and microtidal coasts (tide range <2.0 m) received a low risk rating. This decision was based on the concept that large tide range is associated with strong tidal currents that influence coastal behavior. We have chosen to invert this ranking such that a macrotidal coastline is at a low risk. Our reasoning is based primarily on the potential influence of storms on coastal evolution, and their impact relative to the tide range. For example, on a tidal coastline, there is only a 50 percent chance of a storm occurring at high tide. Thus, for a region with a 4 m tide range, a storm having a 3 m surge height is still up to 1 m below the elevation of high tide for half a tidal cycle. A microtidal coastline, on the other hand, is essentially always "near" high tide and therefore always at the greatest risk of inundation from storms.

COASTAL VULNERABILITY INDEX

The coastal vulnerability index (CVI) presented here is similar to that used by Gornitz et al. (1994), as well as to the sensitivity index employed by Shaw et al. (1998). The index allows the six physical variables to be related in a quantifiable manner. This method yields numerical data that cannot be directly equated with particular physical effects. It does, however, highlight those regions where the various effects of sea-level rise may be the greatest.

Once each section of coastline is assigned a risk value based on each specific data variable, the coastal vulnerability index is calculated as the square root of the geometric mean, or the square root of the product of the ranked variables divided by the total number of variables as

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

where, a = geomorphology, b = coastal slope, c = relative sea-level rise rate, d = shoreline erosion/accretion rate, e = mean tide range, and f = mean wave height.

RESULTS

A map of the coastal vulnerability index for the U.S. East Coast is shown in Figure 1. The calculated CVI values range from 1.22 to 39.52. The mean CVI value is 14.75; the mode is 24.49; and the median is 15.49. The standard deviation is 7.7. The 25th, 50th, and 75th percentiles are 8.7, 15.6 and 20.0, respectively.

Histograms of the CVI values are shown in Figure 2. The CVI scores are divided into low, moderate, high, and very high-risk categories based on the quartile ranges and visual inspection of the data (Figure 2). CVI values below 8.7 are assigned to the low risk category. Values from 8.7-15.6 are considered moderate risk. High-risk values lie between 15.6-20.0. CVI values above 20.0 are classified as very high risk.

Figure 3 shows a bar graph of the percentage of shoreline in each risk category. A total of 23,384 km of shoreline is ranked in the study area. Of this total, 27 percent of the mapped shoreline is classified as being at very high risk due to future sea-level rise. Twenty-two percent is classified as high risk, 23 percent as moderate risk, and 28 percent as low risk.

The mapped CVI values (Figure 1) show numerous areas of very high vulnerability along the coast, particularly along the mid-Atlantic coast (Maryland to North Carolina) and northern Florida. The highest vulnerability areas are typically high-energy coastlines where the regional coastal slope is low and where the major landform type is a barrier island. A significant exception to this is found in the lower Chesapeake Bay. Here, the low coastal slope, vulnerable landform type (salt marsh) and high rate of relative sea-level rise combine for a high CVI value.

The coastline of northern New England, particularly Maine, shows a relatively low vulnerability to future sea-level rise. This is primarily due to the steep coastal slopes and rocky shoreline characteristic of the region, as well as the large tidal range.

DISCUSSION

The data underlying the CVI show variability at several spatial scales. The rate of sea-level rise, and tide range vary over a spatial scale of >100 km. In the case of sea-level rise, this represents the large-scale patterns of isostasy and tectonism present along the Atlantic continental margin of North America (Peltier, 1996; Braatz and Aubrey, 1987). Changes in tide range generally reflect changes in the configuration of the continental shelf as a whole (e.g., shelf width).

A second group of variables, consisting of geomorphology and wave height, vary on a ~10 km scale that reflects primarily the landward changes in environments and energy in the coastal system. For example, there is a nearly continuous chain of barrier islands backed by estuaries and lagoons along the open-ocean coast from eastern Long Island, New York to the Florida Keys.

The shoreline erosion/accretion rates vary on a spatial scale equal to the minimum size of our grid, which is 3 minutes or ~6 km. It is this variable which adds the greatest variation to the CVI values. As described above, this is also the variable in our data set that is the least well-documented.

Regional Examples

To highlight the nature of the CVI and its underlying data, different index variables from two geographic regions are presented below.

New York to New Jersey

The CVI values for this region (Figure 4) correlate best with the geomorphology (Figure 5) variable. The open-ocean shoreline, for example, is composed primarily of high-risk sandy barrier islands, while risk due to geomorphology is lower for the lagoons and along the bluffs of northern Long Island. The coastal slope (Figure 6) is relatively steep (low risk) throughout much of this area, but becomes lower (relatively higher risk) in southern New Jersey.

The smaller-scale variations in the CVI values are influenced primarily by changes in shoreline erosion rate (Figure 7). Two ways in which the erosion rate impacts upon the CVI are evident. First, the lack of data for lagoon shorelines along southern Long Island and southern New Jersey causes erosion rates there to default to the values for the open-ocean shoreline (e.g., Jones Island). This is partially an artifact of the original CEIS data set, but also the coarse grid size (0.25 degrees) used by Gornitz and White (1992) from which these data were obtained for this study. Second, where other variables are essentially equal (e.g., southern New Jersey), the erosion rate data dominate the CVI. The combined effect of these two problems is particularly visible just north of Cape May, where a short reach of shoreline, extending from the barrier island coast to the lagoon, has an anomalously low CVI ranking. This is in contrast to the reach of shoreline just south of the Mullica River that has a similar physiographic setting. As described above, updated and higher-accuracy shoreline change data are needed to rectify such problems.

North Carolina to Georgia

Along the North Carolina, South Carolina, and Georgia coasts the variability in the CVI ranking (Figure 8) is more strongly influenced by different variables than the New York - New Jersey coast. Here, geomorphology is still the dominant variable (Figure 9). Variations in the CVI, however, are apparent due to the rate of relative sea-level change and wave height. The rate of sea-level change (Figure 10) is lowest at Cape Fear, North Carolina, due to long-term tectonic uplift of the mid-Carolina Platform High, also known as the Cape Fear Arch (Gohn, 1988). This factor places the risk due to sea-level rise for Cape Fear into the moderate category when other risk variables would give it a higher risk.

The risk due to wave height varies between the north and south sides of Cape Hatteras and Cape Lookout (Figure 11), and generally decreases from Cape Hatteras southward into the Georgia embayment. This reflects differences in wave energy at two spatial scales. At the scale of each cape, there is a substantial difference in wave energy between the east-facing (high energy) and south-facing (lower energy) cape flanks. This is due in part to the orientation of the shoreline relative to the open Atlantic Ocean, and in part to the sheltering effect of the large sand shoals that extend several kilometers southeast from each cape (Heron et al., 1984). The decrease in wave energy from Cape Hatteras to Georgia is due primarily to the increasing continental shelf width in this region.

SUMMARY

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 a base for developing a more complete inventory of variables influencing the coastal vulnerability to future sea-level rise to which other elements can be added as they become available; and 2) as an example of the potential for assessing coastal vulnerability to future sea-level rise using objective criteria.

As ranked in this study, coastal geomorphology is the most important variable in determining the CVI. Coastal slope, wave height, relative sea-level rise, and tide range provide large-scale variability to the coastal vulnerability index. Erosion and accretion rates contribute the greatest variability to the CVI at short (~3 km) spatial scales. The rates of shoreline change, however, are the most complex and poorly documented variable in this data set. The rates used here are based on a dated, low-resolution data set and thus far corrections have been made only on a preliminary level. To best understand where physical changes may occur, large-scale variables must be clearly and accurately mapped, and small-scale variables must be understood on a scale that takes into account their geologic, environmental, and anthropogenic influences.

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