INTRODUCTION

One of the most important applied problems in coastal geology today is determining the physical response of the coastline to sea-level rise. Predicting shoreline retreat and land loss rates is critical to planning 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 sea-level of between 15-95 cm by 2100, with a "best estimate" of 50 cm (IPCC, 1995). This rate 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 a large, 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 increase in 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, and 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 may simply not exist (Klein and Nicholls, 1999). 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. This approach combines the coastal system's susceptibility to change with its natural ability to adapt to changing environmental conditions, and yields a relative measure of the system's natural vulnerability to the effects of sea-level rise (Klein and Nicholls, 1999). 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. Gulf of Mexico coast and previous reports for the U.S. Atlantic and Pacific coasts (Thieler and Hammar-Klose, 1999; 2000), involves updating and refining existing databases of geologic and environmental variables, such as that compiled by Gornitz and White (1992). The variables included in this database are geomorphology, regional coastal slope, rate of relative sea-level rise, shoreline erosion and accretion rates, mean tide range and mean wave height. 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 Nino-related climate data such as short-term sea-level rise) and human influences (e.g. coastal engineering).

In this preliminary report, the relative vulnerability of different coastal environments to sea-level rise is quantified for the U.S. Gulf of Mexico Coast. This initial classification is based upon variables such as coastal geomorphology, regional coastal slope, rate of sea-level rise, wave and tide characteristics, and historical shoreline change rates. The combination of these variables and the association of these variables to each other furnishes a broad overview of regions where physical changes are likely to 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 mapping potential coastal changes due to sea-level rise. This database 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 et al. (1998).

The input data for this database of coastal vulnerability have been assembled using their original, sometimes variable horizontal resolution and resampled to a 3-minute grid cell resolution. A data set for each variable is then stored within the 3-minute grid. For mapping purposes, data stored in the 3-minute grid is transferred to a 1:2,000,000 vector shoreline with each segment of shoreline lying within a single grid cell.

Table 1 summarizes the six physical variables used here: 1) geomorphology, 2) coastal slope (percent), 3) rate of relative sea-level rise (mm/yr), 4) shoreline erosion and accretion rates (m/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, as well as correlated with descriptive information found in the Living with the Shore book series (Morton et al., 1983; Kelley et al., 1984; Canis et al., 1985 and Doyle et al., 1985).

The regional coastal slope provides an evaluation not only of the relative risk of inundation, but also 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 landward and seaward of the shoreline. 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. Gulf of Mexico coast, elevation data were obtained from the U.S. Navy ETOPO5 digital topographic and bathymetric elevation database with elevations to the nearest 1 meter for 5-minute grid cells. These data were subsampled to 3-minute (approximately 5 km) resolution to be consistent with our other coastal databases (Thieler and Hammar-Klose, 1999; 2000).

The relative sea-level change variable is derived from the increase (or decrease) in 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 seven National Ocean Service (NOS) data stations and contoured along the coastline. This variable inherently includes 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).

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 sources and 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.

Where higher-quality data are available, we replace and augment the CEIS data with shoreline change data obtained from states and local agencies. In this report, for example, the updated erosion rates for the Gulf of Mexico are from a regional study in the Northern Gulf of Mexico (Westphal et al., 1991), as well as an Alabama coastal hazards assessment study (NOAA Coastal Services Center, 1997). The long-term erosion rates for Alabama were calculated using a linear regression approach (Dolan et al., 1991) using data derived from aerial photographs spanning the years 1970-1997. These data were correlated with beach profile survey data from 92 points covering the Alabama coastline (NOAA Coastal Services Center, 1997).

Tide range is linked to both permanent and episodic inundation hazards. Tide range data were obtained from the NOS for 117 tide stations along the U.S. Gulf of Mexico coast; the values were 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 122 WIS stations along the U.S. Gulf of Mexico 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, whereas the non-numerical geomorphology variable is ranked according to the relative resistance of a given landform to erosion. For the U.S. Gulf of Mexico coast, regional coastal slopes are considered to be very low risk at values >0.115 percent; very high risk consists of regional slopes <0.022 percent. The rate of relative sea-level rise is ranked to reflect the regional to local isostatic or tectonic effects, taking into account that these data also reflect the modern rate of eustatic rise (1.8 mm/yr). 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) 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 a 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 classified as low risk. Our reasoning is based primarily on the potential influence of storms on coastal evolution, and their impact relative to the tidal 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 significant storm impact.

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 that expresses the relative vulnerability of the coast to physical changes due to sea-level rise. This method yields numerical data that cannot be equated directly 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.

The CVI values reported here apply specifically to the U.S. Gulf of Mexico coast, but are also comparable to the values for the U.S. Atlantic coast since the data ranges for the Gulf of Mexico are categorized using overall values for both coasts. Absolute CVI values given for the Pacific coast, however, (e.g., Thieler and Hammar-Klose, 2000) are not directly comparable to the data presented here. We feel this approach best describes and highlights the vulnerability for each of the different continental margin types that make up the U.S. coast.

RESULTS

The calculated CVI values range from 1.2 to 39.5. The mean CVI value is 15.25; the mode is 7.3; and the median is 15.5. The standard deviation is 7.89. The 25th, 50th, and 75th percentiles are 8.7, 15.6, and 20.0, respectively.

Figure 1 shows a map of the coastal vulnerability index for the U.S. Gulf of Mexico coast. 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. 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 and 20.0. CVI values above 20.0 are classified as very high risk. Histograms of the CVI values are shown in Figure 2.

Figure 3 shows a bar graph of the percentage of shoreline in each risk category. A total of 8058 km of shoreline is evaluated in the study area. Of this total, 42 percent of the mapped shoreline is classified as being at very high risk due to future sea-level rise. Thirteen percent is classified as high risk, 37 percent as moderate risk, and 8 percent as low risk.

In the calculation of the Coastal Vulnerability Index, certain variables add more weight to the index than others. For example, in a region where most variables score low in the risk ranking (1-3), but one variable scores high (4 or 5), the high variable adds the most weight to the index. This variable is said to dominate the index. In most cases along the U.S. Gulf of Mexico coast, two or three variables dominate the index, while the other, lower-ranking variables have little impact on the index value.

The mapped CVI values show large areas of very high vulnerability, particularly along the Louisiana - Texas coast. The highest-vulnerability areas are typically lower-lying beach and marsh areas; their susceptibility is primarily a function of geomorphology, coastal slope and rate of relative sea-level rise. On the Gulf of Mexico coast, much of the vulnerability is due to geomorphology and tide range; two variables which are ranked as generally high for the entire Gulf of Mexico region. The western Gulf of Mexico is ranked as more vulnerable than the eastern Gulf of Mexico when described in terms of relative sea-level rise. Wave energy is highest along sections of the Texas coast and on the southern tip of the Mississippi delta. The slope variable has the highest risk ranking along the Louisiana coast, the Texas coast north of Corpus Christi and the southwest Florida coast. The erosion rates within the study area range from low risk to very high risk. In contrast to the Pacific and Atlantic coasts (see Thieler and Hammar-Klose, 1999; 2000), the erosion rates in the Gulf of Mexico do not vary consistently on very short spatial scales. Instead, there are reaches of coastline as long as 150 km with the same risk ranking.

DISCUSSION

The data variables underlying the CVI show variability at several spatial scales. The geomorphology and tide range vary over a spatial scale of >500 km. For geomorphology, this lack of variability represents the large-scale, rather uniform patterns of landform type along the Gulf coast (Figure 4). Barrier islands, lagoons, marshes and deltas dominate the coast, which are landforms that have a very high risk ranking (see Table 1). In addition, the entire coast is microtidal; thus, this variable yields a very high risk ranking (Figure 5).

A second group of variables, consisting of relative sea-level rise and wave height, vary on a ~200 km spatial scale. For example, the low-energy Gulf of Mexico coast has mean wave heights that on average are ~0.5 m (Figure 6), and vary between only 0.07 m and 1.04 m.

Changes in relative sea-level rise are greatest around New Orleans, Louisiana, where the rates can be as much as 10 mm/yr (Figure 7). East of Louisiana, the rate of relative sea-level rise is ~ 2 mm/yr. This lower value, however, is still higher than the modern rate of eustatic rise (1.8 mm/yr), which reflects the ongoing recent subsidence of this region. To the west of Louisiana, rates of relative sea-level rise are also lower, decreasing to the 3-5 mm/yr range, which again is well above the modern eustatic rate and still within the very high risk range of our rating system. These high rates of relative sea-level rise within and surrounding Louisiana are primarily due to the natural compaction of the Holocene deltaic sediments in the Gulf of Mexico (Penland and Ramsey, 1990; Turner, 1991).

The coastal slope variable changes on a ~ 50 km spatial scale (Figure 8). The areas with the lowest slope are those surrounding the Mississippi delta. These data show slopes of less than 0.02%. The highest slopes along the Gulf of Mexico coast are found south of Corpus Christi, Texas, along the Florida panhandle, and in the greater Tampa-St. Petersburg, Florida region. While these values of slope yield a moderate to low susceptibility ranking, they are only in the 0.5% range, and thus are not steep slopes in an absolute sense.

In some cases, the data describing erosion and accretion rates vary on a small spatial scales of about 5 km, but most of the variation in erosion rates varies on the ~20 km scale. There are long sections of coastline (~150 km), however, that show little to no variation in erosion rates (Figure 9), both because of an actual lack of change as well as an absence of comprehensive erosion rate data.

The CVI rankings for the Gulf of Mexico coast are governed by the large-scale variations of its variables (Figure 1). The CVI shows a regional distinction centered on the New Orleans region. From the very high vulnerability New Orleans region to the west, the CVI rankings remain as high vulnerability along the coast with lower vulnerability in the inland bays. To the east of New Orleans, the CVI values decrease to moderate. The one exception to this trend is Apalachicola Bay, Florida, which due to its high erosion rates, low slope, and moderate rate of sea-level rise receives a very high susceptibility ranking. The regional variation of higher vulnerability to the west and lower vulnerability to the east is controlled by the mean wave height, the relative sea-level rise and to some extent the coastal slope.

The CVI shows that the region around New Orleans is the most vulnerable of all areas along the Gulf of Mexico coast. The Florida panhandle, as well as the West Florida coast, are considered to be at low to moderate risk, primarily because of the lower rates of relative sea-level rise, lower mean wave heights, and a relatively higher coastal slope in this region. The Texas coast is considered to be at a high to very high risk because of the relatively high mean wave height and relative sea-level rise vulnerabilities.

SUMMARY

The coastal vulnerability index (CVI) for the Gulf of Mexico coast 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 and tide range are the most important variables in determining the CVI for the Gulf of Mexico coast since both variables reflect very high vulnerabilities along nearly the entire shoreline. Wave height, relative sea-level rise, and coastal slope provide large-scale (50-200 km alongshore) variability to the coastal vulnerability index. Erosion and accretion rates, where complete, contribute the greatest variability to the CVI at short 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 and environmental influences.

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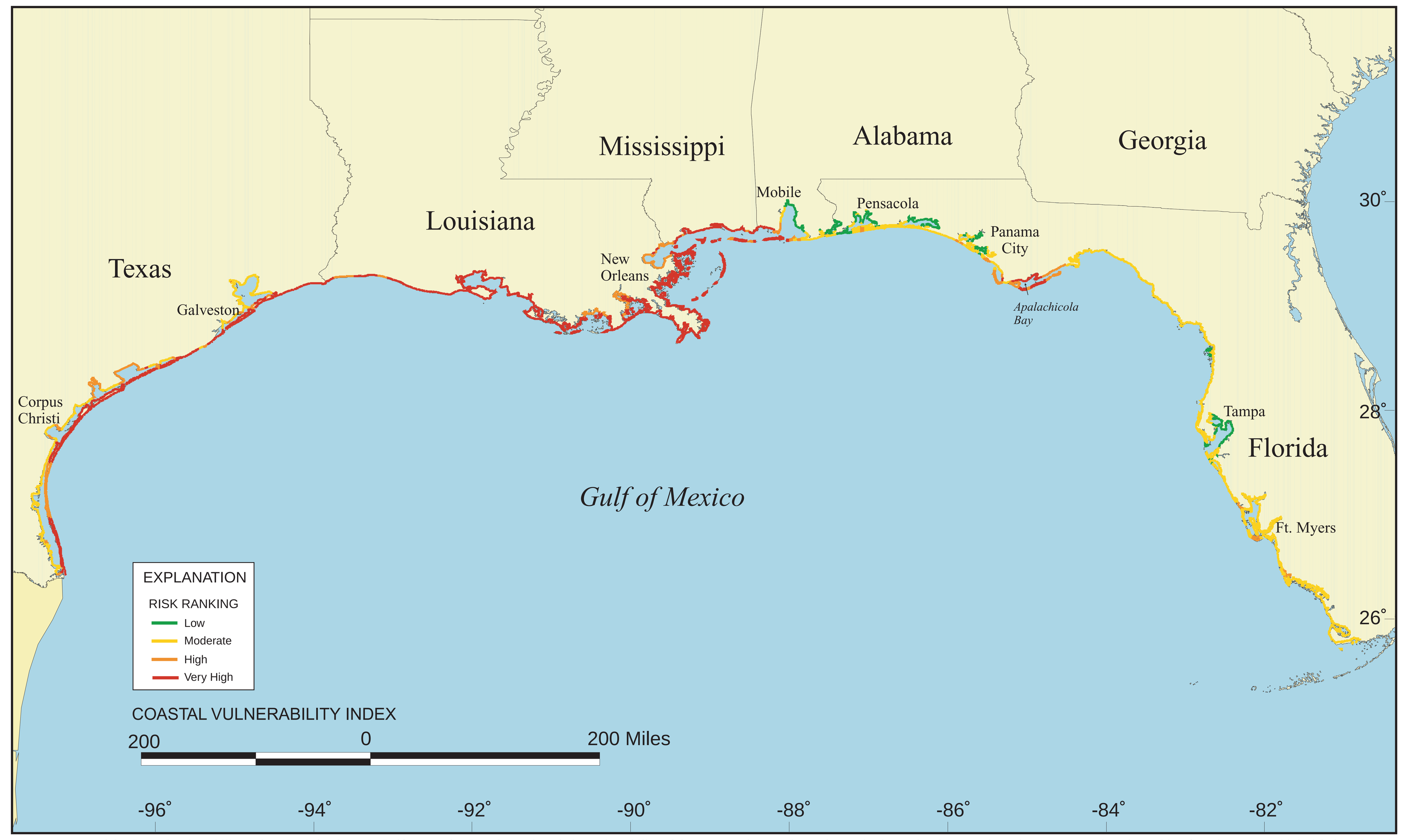

Figure 1. Map of the Coastal Vulnerability Index (CVI) for the U.S. Gulf coast. The CVI shows the relative vulnerability of the coast to changes due to future rise in sea-level. Areas along the coast are assigned a ranking from low to very high risk, based on the analysis of physical variables that contribute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

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 Accretion	1.0 –2.0	-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 for the U.S. Gulf of Mexico.

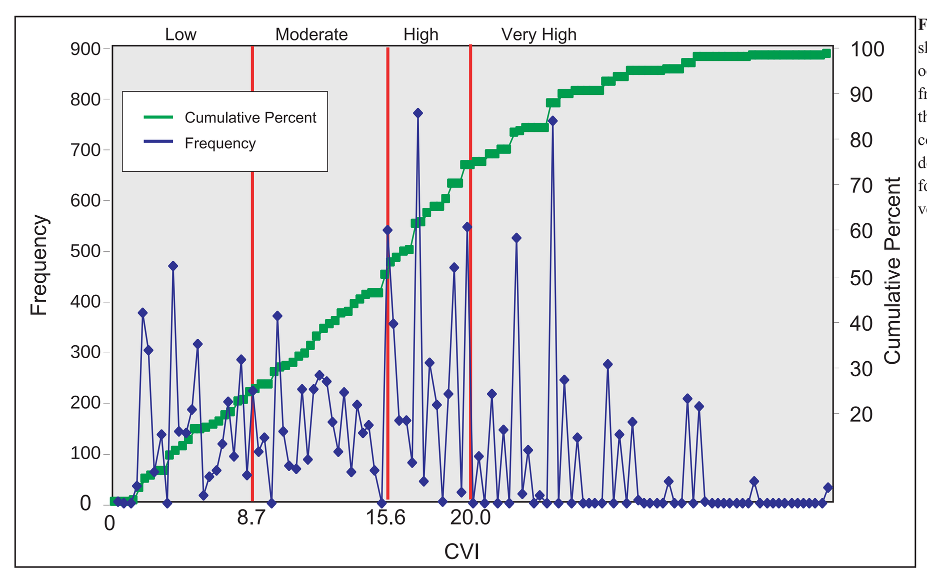

Figure 2. Histograms showing the frequency of occurrence and cumulative frequency of CVI values for the U.S. Gulf of Mexico coast. The vertical red lines delineate the chosen ranges for low, moderate, high, and very high risk areas.

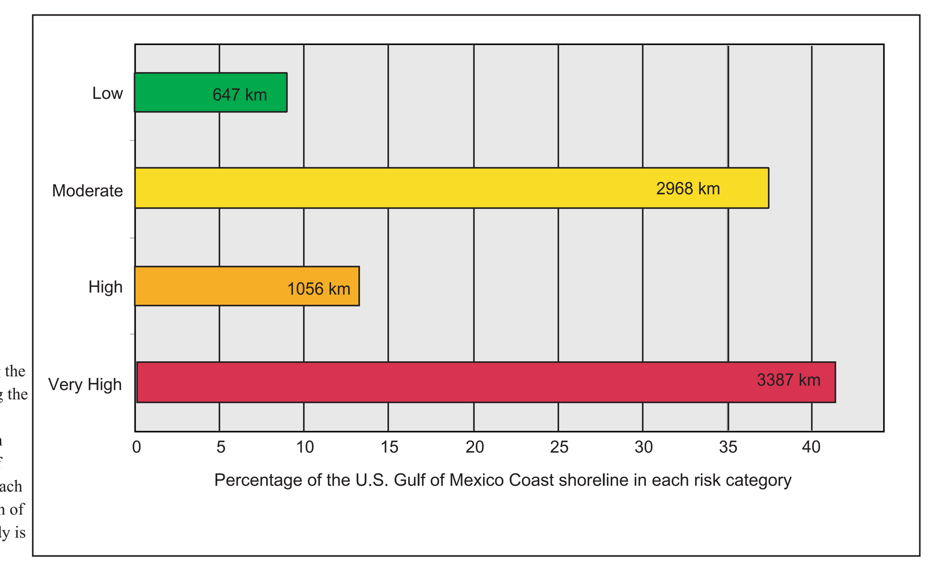

Figure 3. Bar graph showing the percentage of shoreline along the U.S. Gulf of Mexico coast in each risk category. The graph also shows the total length of shoreline (in kilometers) in each risk category. The total length of mapped shoreline in this study is 8058 km.

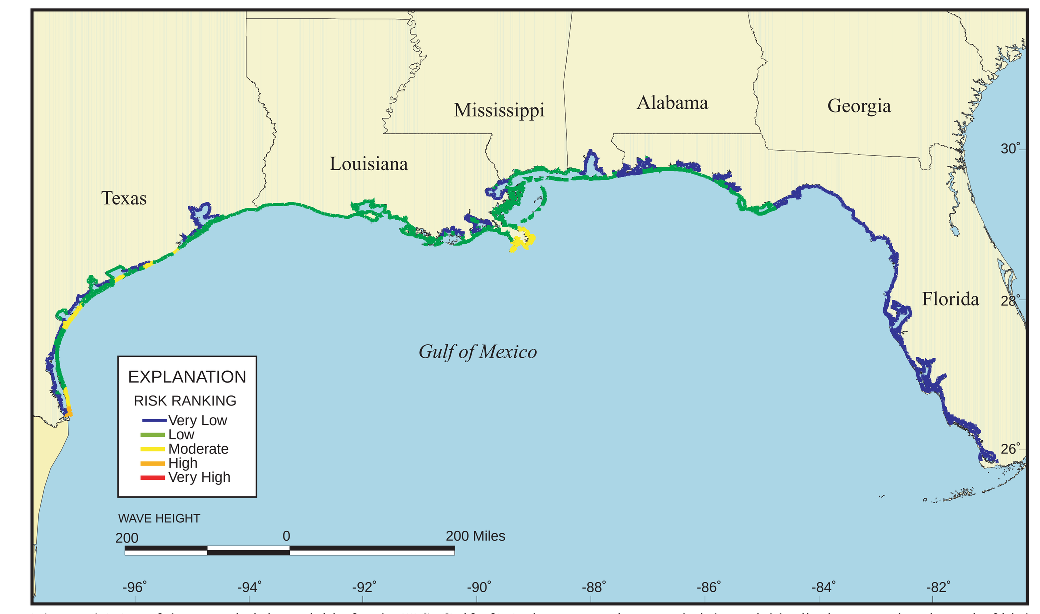

Figure 6. Map of the wave height variable for the U.S. Gulf of Mexico coast. The wave height variable displays a regional trend of high wave heights (>.8 m) to the west and lower wave heights (< .4 m) to the east.

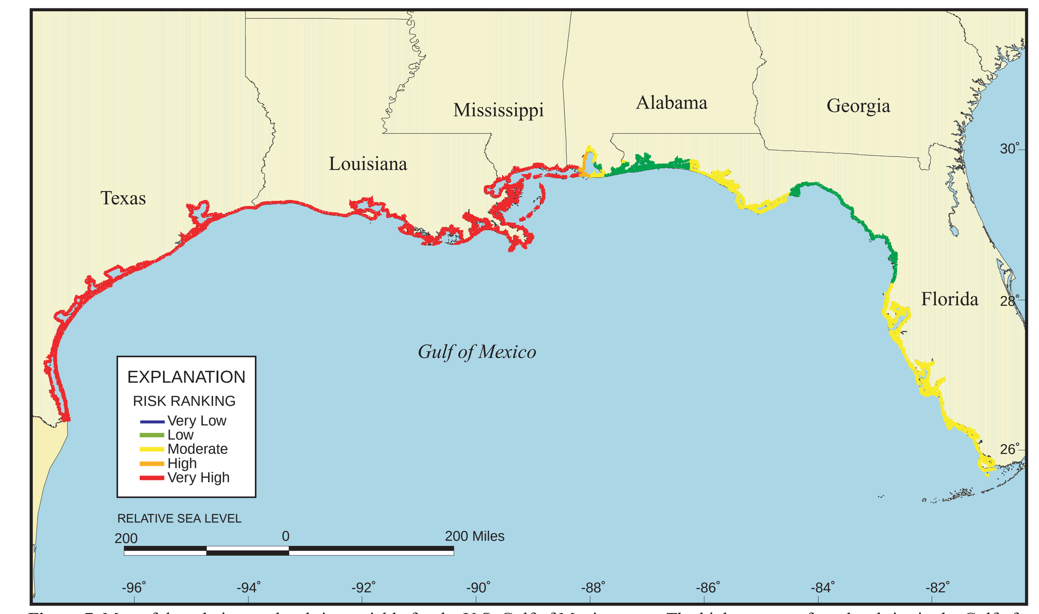

Figure 7. Map of the relative sea level rise variable for the U.S. Gulf of Mexico coast. The highest rates of sea-level rise in the Gulf of Mexico (and in the United States) are in the Mississippi delta region (>10 mm/yr).

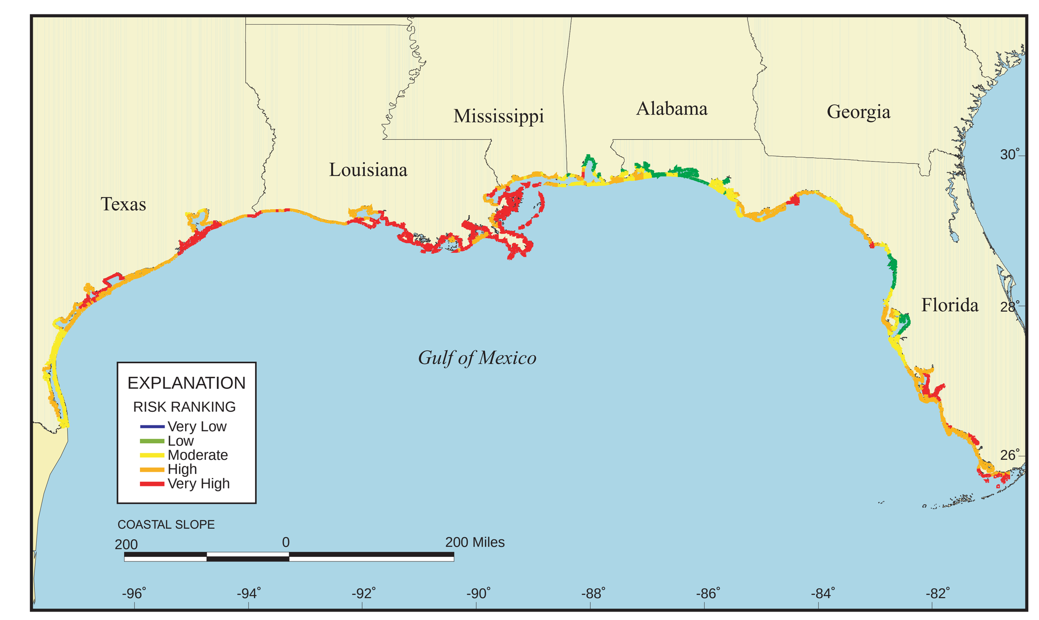

Figure 8. Map of the coastal slope of the U.S. Gulf of Mexico coast. The slope is the least, <0.02%, in the region of the Mississippi delta. The slope is the highest (>.0435 %) south of Corpus Christi, along the western panhandle of Florida, and in the greater Tampa - St.Petersburg region.

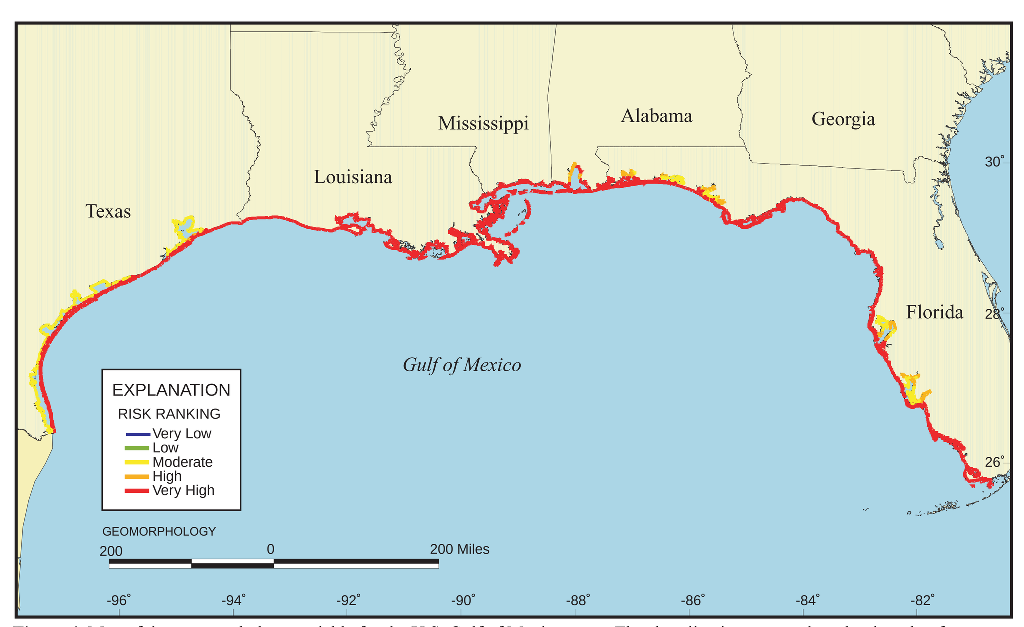

Figure 4. Map of the geomorphology variable for the U.S. Gulf of Mexico coast. The shoreline is composed predominantly of very high-risk barrier island complexes, lagoons, marshes and deltas.

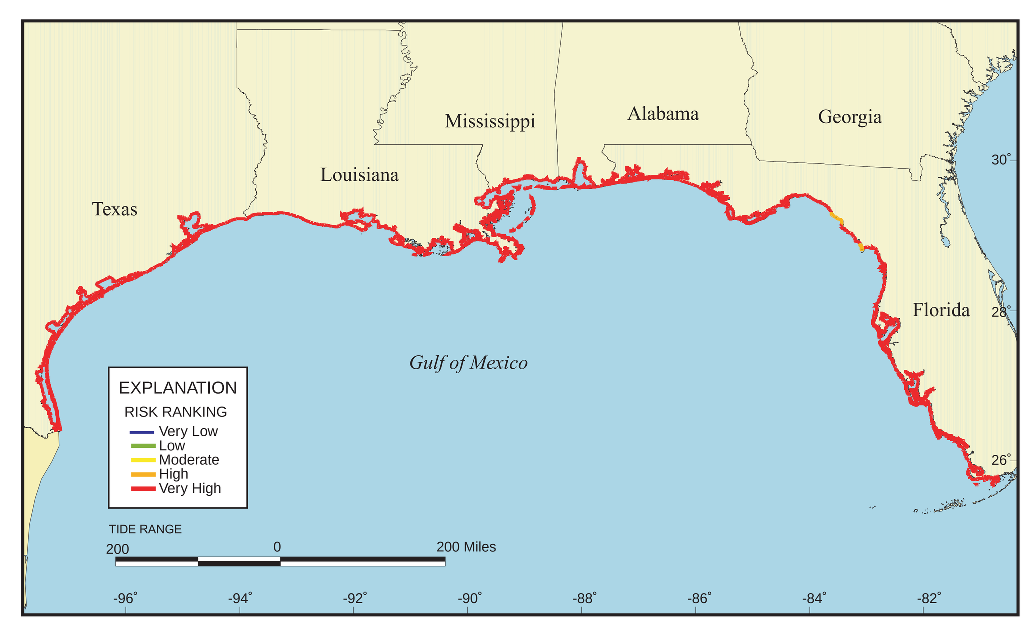

Figure 5. Map of the tide range variable for the U.S. Gulf of Mexico coast. The tide ranges are less than 1.0 m over the open-ocean coast, thus, the entire coast has a very high risk ranking.

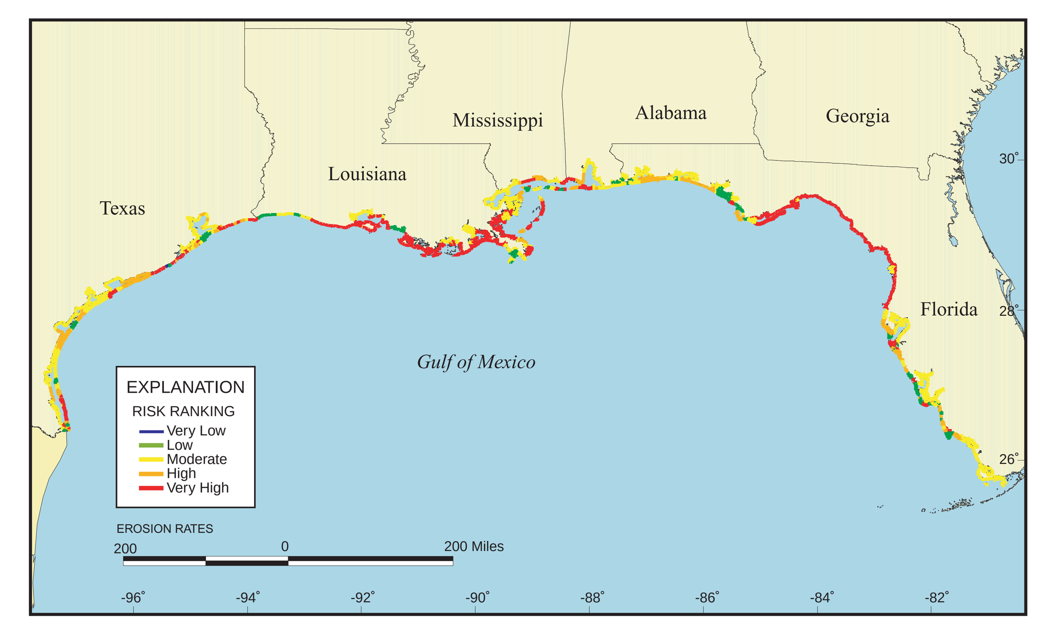

Figure 9. Map of the erosion rate variable for the U.S. Gulf of Mexico coast. Most of the Gulf of Mexico coast receives a moderate to very high risk ranking, meaning the coastline is either stable or is eroding. There are few accreting areas.

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