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Erosion Hazard Vulnerability of US Coastal Counties

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ABSTRACT

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This article examines the vulnerability of US coastal counties to erosion by combining a socioeconomic vulnerability index with the US Geological Survey's physically based coastal vulnerability index. The end product is a county-based index of overall coastal place vulnerability. The results indicate that place vulnerability along the coast is highly differentiated and influenced by a range of social, economic, and physical indicators. Regionally, Gulf Coast vulnerability is more of a product of social characteristics rather than physical attributes. The opposite is true of Pacific and Atlantic coastal counties, where physical characteristics are more influential in determining erosion-hazard vulnerability. It is clear that overall vulnerability of coastal counties cannot be determined without the union of social, economic, built-environment, and physical characteristics. Yet the methods for combining these components are not widely used at present by coastal scientists and policy makers, rendering hazards assessments incomplete and mitigation plans untenable for many places.

ADDITIONAL INDEX WORDS: *Erosion hazards, coastal vulnerability, hazard mitigation.*

INTRODUCTION

Coastal counties along the Atlantic and Pacific Oceans and the Gulf of Mexico account for only 11% of the total number of counties in the United States, yet they contain 25% of the nation's population (US CENSUS BUREAU, 2002). From 1990 to 2000, 18% of the nation's economic losses from natural hazards (well over $14 billion dollars) occurred in these same coastal counties (SHELDUS, 2004). While increased densities of people and structures along the US coast certainly account for a portion of these losses, other explanations include increased storm activity and the decreased ability of communities to rebound from disasters. The future loss outlook is bleak as well with the expectations of greater losses as a function of global climate change, sea-level rise, and increased intensity of tropical and extratropical storms (MCCARTHY *et al.,* 2001).

To assess the hazard potential from natural events along the coast, it is important to identify and measure those elements that contribute to it, namely, risk and vulnerability. Risk is the probability of an event occurring, while vulnerability is defined as those factors that magnify or attenuate the effects of an extreme natural, technological, or human-induced event and those factors that decrease a community or individual's ability to rebound after the event has occurred (KASPERSON and KASPERSON, 2001; TOBIN and MONTZ, 1997). The probability or frequency of an event occurrence can be calculated from past events, but determining vulnerability is more complicated, requiring examination of the interacting physical attributes and the socioeconomic characteristics of a locale (CUTTER, 1996; KLEIN and NICHOLLS, 1999; NICHOLLS, 1998; SMALL and NICHOLLS, 2003). Combining physical and socioeconomic characteristics provides a measure of the overall vulnerability of the community and is termed place vulnerability (CUTTER, 1996; CUTTER, MITCHELL, and SCOTT, 2000).

This article examines differences in the place vulnerability of coastal counties in the United States. The goal of this study is to produce a relative ranking of the erosion hazard vulnerability of US coastal counties and determine those underlying factors that increase or decrease it. Three questions are examined: (1) Is there regional variability in the vulnerability of US coastal counties to erosion hazards? (2) What is the greatest contributor to the overall vulnerability of each region, physical or social characteristics? (3) What specific factors explain the differences in physical and social vulnerability among regions? It is hypothesized that regional differences in erosion vulnerability are best explained by socioeconomic rather than physical risk indicators.

VULNERABILITY AT THE COAST

The majority of coastal hazards research has focused on the determination and analysis of the physical characteristics of coastal vulnerability, with little reference to social indicators. There is little integrative work on coastal vulnerability, although such studies are now emerging (CLARK *et al.,* 1998; CUTTER, MITCHELL, and SCOTT, 2000; DAVIDSON and LAMBERT, 2001; GAMBOLATI, TEATINI, and GONELLA, 2002; ODEH, 2002; WOOD, GOOD, and GOODWIN, 2002; WU, YAR-

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NAL, and FISHER, 2002). At present, this body of integrative research remains focused on localized case studies such as Revere, Massachusetts (CLARK *et al.,* 1998), Georgetown, South Carolina (CUTTER, MITCHELL, and SCOTT, 2000), Cape May, New Jersey (WU, YARNAL, and FISHER, 2002), Yaquina Bay, Oregon (WOOD, GOOD, and GOODWIN, 2002), or New Hanover, North Carolina (FLAX, JACKSON, and STEIN, 2002), rather than regional or national comparative assessments.

Physical Risk Indicators

Due to their frequency and high damage potentials, hurricane risks and impacts are at the forefront of coastal vulnerability research, especially hurricane-landfall probabilities in the Atlantic Ocean, Caribbean, and Gulf of Mexico (GRAY, KLOTZBACH, and LANDSEA, 2003). Other risk indicators include the maximum exceedence probabilities for category-1 hurricane winds at the county level (JAGGER, ELSNER, and NIU, 2001) and susceptibility to inundation from hurricane storm surge (MERCADO, 1994; NATIONAL HURRICANE CENTER, 2002). All of these indices are entirely based on the physical characteristics of the natural hazard with little or no attempt to address the human dimension of vulnerability.

While hurricane exposure dominates the coastal vulnerability literature, beach erosion is also important. Monitoring changes in littoral profiles to develop signatures of erosion is one approach used to quantify coastal erosion (KANA, 2003). BRYAN *et al.* (2001) used GIS-based spatial models to determine regional vulnerability to inundation and erosion along portions of the south Australian coast. ZHANG, DOUGLAS, and LEATHERMAN (2001) developed an erosion-potential index based on storm tides, wave energy, and storm duration from Nor'easters for much of the Atlantic Coast. Erosion hazards were the focus for a national study of historic erosion rates along US coastlines (H. JOHN HEINZ III CENTER, 2000a). This Heinz Center study included both physical and social attributes in the spatial delineation of properties, historic erosion rates, and future projections of economic losses. Unfortunately, the study did not consider changes in the built environment or changes in the rate of erosion as it made its forecast, but the report does take an important step toward identifying and measuring human-environment interactions, a necessary prerequisite for understanding place-based vulnerability.

Recently, the US Geological Survey (USGS) produced the *Coastal Classification Atlas,* which identified areas along the southwestern Florida coast that were susceptible to high wave action from coastal storms (MORTON and PETERSON, 2003). This study categorized the shoreline's geomorphic structures and ranked the density of development. Designed as a baseline for future vulnerability assessments, this study was limited in geographic coverage, but it does provide an initial prototype for integrating human and physical systems in the understanding of place-based vulnerability.

Another component of coastal ecosystem vulnerability is based on environmental degradation indicators, such as environmental sensitivity analyses (JENSEN *et al.,* 1993, 1998; NORONHA *et al.,* 2003), GAP analysis, and state Heritage Program rankings of ecological vulnerability (H. JOHN HEINZ III CENTER, 2000b). Gulf Coast states are working with the US Minerals Management Service to determine those on-shore regions most susceptible to degradation from oil pollution (H. JOHN HEINZ III CENTER, 2000b). Unfortunately, these studies are focused entirely on ecosystems and habitat degradation with no linkage to social vulnerability.

Recent interest in the impacts of global climate change resulted in a plethora of research on coastal vulnerability to sea-level rise. Among the first regional analyses of climate-change impacts were those conducted by GORNITZ, BEATY, and DANIELS (1997) and GORNITZ and WHITE (1992, 1994), who developed an index of vulnerability to sea-level rise along US coasts. The original study compared coastal segments based on seven physical parameters, including maximum wave height, shoreline erosion, and accretion rates, and landform susceptibility to inundation. The Geological Survey of Canada (GSC) and the USGS enhanced the initial Gornitz studies, creating an improved Coastal Vulnerability Index (CVI) (HAMMER-KLOSE and THIELER, 2001; SHAW *et al.,* 1998; THIELER and HAMMER-KLOSE, 1999, 2000a, 2000b). The USGS baseline data have far fewer data gaps than its predecessors and provide a better metric of physical vulnerability at the county level.

Social Vulnerability and the Coast

Many of the social and economic characteristics that influence the vulnerability of individuals and communities along the coast are known at a conceptual level. However, this knowledge has not been translated into empirically based assessments of the socioeconomic vulnerability of coastal communities (H. JOHN HEINZ III CENTER, 2000b, 2002). Recently, the social vulnerability index (SoVI) provided a comparative spatial assessment of human-induced vulnerability to environmental hazards (CUTTER, BORUFF, and SHIRLEY, 2003). This index explained around 76% of the variation in socioeconomic vulnerability in US counties. While this method was designed for all counties in the US, a subset of coastal counties (not including those in the Great Lakes, Alaska, and Hawaii) produced comparable results (80% of the variation in social vulnerability explained) (BORUFF, CUTTER, and EMRICH, 2002).

The use of a quantitatively derived social vulnerability index, such as SoVI, is important for two reasons. First, the method provides a useful tool for comparing the spatial variability in socioeconomic vulnerability using a single value derived from multivariate characteristics. Second, SoVI can be linked (statistically and spatially) to more physically based indices in calculating the overall vulnerability of a specific place. Not only does this index make a significant contribution to the methods and metrics used in vulnerability science, but it also provides important comparative information for policy makers and emergency managers.

STUDY AREA AND DESCRIPTION

The focus of this study is on coastal counties in the conterminous United States. The selection of coastal counties was based on the original USGS selection criteria (*e.g.,* counties

Table 1. *Social variable descriptions used in the computation of the coastal social vulnerability index (CSoVI).**

Median age
Per capita income (in dollars)
Median dollar value of owner-occupied housing
Median rent (in dollars) for renter-occupied housing units
Vote cast for president—percent voting for leading party (Republican)
Birth rate (number of births per 1000 population)
Net international migration
Land in farms as a percent of total land
Percent African American
Percent Native American
Percent Asian
Percent Hispanic
Percent of population under 5 years old
Percent of population over 65 years
Percent of civilian labor force that is unemployed
Average number of people per household
Percent of households earning more than $100,000
Percent living in poverty
Percent renter-occupied housing units
Percent rural farm population
General local government debt to revenue ratio
Percent of housing units that are mobile homes
Percent of population 25 years or older with no high school diploma
Number of housing units per square mile
Number of housing permits per new residential construction per square mile
Number of manufacturing establishments per square mile
Earnings (in $1000) in all industries per square mile
Number of commercial establishments per square mile
Value of all property and farm products sold per square mile
Percent of the population participating in the labor force
Percent females participating in civilian labor force
Percent employed in primary extractive industries (farming, fishing, mining, and forestry)
Percent employed in transportation, communications, and other public utilities
Percent employed in service occupations
Percent population change 1990/2000
Percent urban population
Percent females
Percent female headed households, no spouse present
Per capita social security recipients

* There are three missing variables from the original study (Cutter *et al.,* 2003): nursing home residents per capita, number of community hospitals per capita, and number of physicians per 100,000 people. Their omission is deemed insignificant as these three variables had low loadings on the factors used to compute the original social vulnerability index (SoVI).

that had some portion of their land area directly exposed to the Pacific Ocean, Atlantic Ocean, or Gulf of Mexico) in order to compare results. A total of 213 counties met this specification and are used in this analysis.

Demographically, dense populations characterize most of the coastlines of the United States, yet each coastal region has distinct geomorphic, geologic, and oceanographic characteristics (Dean, 1999). The Pacific Coast is characterized by high-energy oceanic patterns (wave and storm action) in the north with relatively low energy patterns in the south (Thieler and Hammer-Klose, 2000a). Offshore subduction, producing raised Quaternary marine terraces, indicates uplift along much of the Pacific Coast (Gornitz, Beaty, and Daniels, 1997). Cliffs dominate much of the shoreline, giving way to river mouths, bays, and estuaries, and occasional pocket beaches (Thieler and Hammer-Klose, 2000a). Population densities and income levels in the Pacific Coast region are quite variable. The region is ethnically diverse, especially within its large coastal cities, San Diego, Los Angeles, and San Francisco.

Table 2. *Factor scores and loadings used to construct the coastal social vulnerability index (CSoVI).*

Factor/label	Scaling Method	Percentage Explained Variance
Factor 1: Poverty	None	15.79
Factor 2: Age	Absolute value	14.83
Factor 3: Development density	None	14.20
Factor 4: Asian and immigrants	None	9.71
Factor 5: Rural/urban dichotomy	Absolute value	7.09
Factor 6: Race ad gender	Absolute value	5.35
Factor 7: Population decline	Inverse	5.04
Factor 8: Ethnicity (Indian) and farming	Abolsute value	3.72
Factor 9: Infrastructure employment reliance	None	3.36
Factor 10: Income	Inverse	3.16

The Atlantic coastline is also characterized by decreasing oceanic energy levels from north to south. Tidal ranges are less dramatic than the Pacific and are affected by changes in the configuration of the continental shelf. Wave energies are generally lower along the Atlantic Coast than along the Pacific. Rocky coastlines in the north turn into barrier islands backed by estuaries and lagoons as the Atlantic coastline heads south to the Florida Keys (Thieler and Hammer-Klose, 1999). The nation's largest coastal cities (New York, Boston, and Miami) are located here. Per capita wealth is concentrated along the Northern Atlantic coastline from Boston to Cape May as well as in South Florida. Significant African American populations are found along the mid-Atlantic coastal region.

The Gulf of Mexico is quite a different environment all together. Low oceanic energy is coupled with a relatively small tidal range. Barrier islands, marshes, and deltas are the most dominant landforms along the coast, which is mainly comprised of fine-grained sediments that are eroded easily in the event of a coastal storm (Thieler and Hammer-Klose, 2000b). Population density is lower along the Gulf Coast, with more African American and Latino populations, less wealth, and more dependence on service- and agricultural-sector employment (Boruff, Cutter, and Emrich, 2002).

METHODS

Index Construction

To create an index of social vulnerability for the 213 US coastal counties, we replicated the methods first developed by Cutter, Boruff, and Shirley (2003). Of the 42 socioeconomic variables used in the original study, only 39 were available in the 2000 US Census (Table 1). The socioeconomic variables were placed in a principal components analysis (PCA). Using the varimax rotation option, 10 factors with eigenvalues greater than 0.95 were extracted. These factors explain 82% of the variance among US coastal counties (Table 2). All factors were scaled so that positive values indicate

Table 3. *Physical variables used to create the coastal physical vulnerability index (CVI).**

Variable	Measurement	Source
Mean tidal range	Meters	Tide gauges
Coastal slope	Percent	Topography, bathymetry
Rate of relative sea-level rise	Δ mean water elevation	Tide gauges
Shoreline erosion and accretion rates	Meters/year	Coastal Erosion Information System (CEIS)
Mean wave height	Meters	Wave Information Study (WIS)
Geomorphology (erodability)	Ordinal value	Geology, topography

* Based on data from Thieler and Hammer-Klose (1999, 2000a, 2000b).

higher levels of vulnerability, while negative values decrease vulnerability. In those instances where the effect was ambiguous (*e.g.,* age where elderly would load positively and younger children negatively), the absolute value was used. Once extracted and scaled, the factors were placed in an additive model (making no *a priori* assumption about the relative importance of each) to produce the overall coastal social vulnerability score (CSoVI).

Determining the physical vulnerability of US coastlines to environmental hazards followed the procedures used by the USGS (Thieler and Hammer-Klose, 1999, 2000a, 2000b). The USGS formulated the spatial representation of data for each coastline through hand-digitized line segments. We utilized the same six variables for each line segment (Table 3). These segments were then broken down to conform to county coastline extents, thus permitting analyses at the county level.

To calculate the CVI, each variable was ranked on an ordinal scale between one and five following the USGS methodology (Thieler and Hammer-Klose, 1999, 2000a, 2000b). CVI was then computed as the square root of the product of all ranked variables for each line segment divided by n (6),

$$CVI = \sqrt{(a \cdot b \cdot c \cdot d \cdot e \cdot f)/n} \quad (1)$$

The USGS data, however, are based on characteristics applicable only to the coastlines for which they were derived. Therefore, each individual variable is not directly comparable with the same variable on another coast. To create a regionally comparable index, the USGS then reranked CVI on an ordinal scale from one to four (Thieler and Hammer-Klose 1999, 2000a, 2000b). The reranked CVI was used in our analysis to test for regional differences in physical vulnerability.

The overall place vulnerability index (or PVI) is an additive model derived by summing the CVI (physical) and CSoVI (social) scores for each county. Due to the range of values for CVI and CSoVI, z scores were first calculated for each index as a means for creating comparable scales. To visually represent the extremes of the data, the PVI for all coastal counties was mapped into three categories (low, medium, and high) using the standard deviations from the mean as the classification scheme. This same procedure was used in mapping the constituent parts, physical vulnerability (CVI) and social vulnerability (CSoVI).

Table 4. *Results of tests for regional differences.**

Index	ANOVA *F*-Statistic (>3.00)	Significance (<0.05)
PVI	12.677	0.000
CVI	9.504	0.000
CSoVI	6.768	0.001

* PVI = place vulnerability index; CVI = coastal vulnerability index; CSoVI = coastal social vulnerability index.

Determining Relative Importance

To determine the dominant influences on coastal vulnerability, socioeconomic or physical characteristics, two procedures were used. First, to test the degree of physical and socioeconomic influences on place vulnerability (PVI), a standard linear regression was performed with PVI as the dependent variable and all physical and socioeconomic variables as independents. Using a dependent variable composed of the independent variables violates statistical assumptions, but in this instance, the independent variables were not used to model the dependent variable, rather, the procedure was used to determine the relative influence of each on the aggregate vulnerability index (PVI) using the standardized beta coefficients.

The second procedure involved the examination of the physical and social characteristics of the least and most vulnerable counties. First, the standardized beta coefficients for all the independent variables were grouped into physical and socioeconomic categories and then summed. The average standardized beta coefficient for each group (physical and socioeconomic) was computed to see which group of variables explained the most variance in the model. The mean standardized beta coefficient was used due to the difference in the total number of variables for each category.

ANALYSIS AND FINDINGS

Regional Variability and Comparisons

An analysis of variance (ANOVA) tested for regional differences in the overall place vulnerability (PVI), social vulnerability (CSoVI), and physical vulnerability (CVI). Using a frequency histogram for each region, the normality of the data (as a whole and for each coast) was examined. Results of the ANOVA show that there are significant differences (at the 95% confidence level) for each of the indices (PVI, CSoVI, and CVI) between the Atlantic, Pacific, and Gulf Coasts (Table 4). These differences are not surprising given the diversity of physical characteristics of the coasts described earlier.

In addition to ethnic and racial disparities, economic differences exist between the regions. The average per capita income of Pacific Coast counties is twice that of both the Atlantic and Gulf coastal counties. Not surprisingly, the median value of owner-occupied homes in Pacific Coast counties is twice that of Gulf Coast counties and one and one half times that of Atlantic Coast counties. The density of commercial establishments on the Atlantic Coast is twice that of the Pacific Coast and 10 times that of the Gulf Coast counties. Finally, the earning density (a measure of county wealth derived from earnings in all industries standardized by square

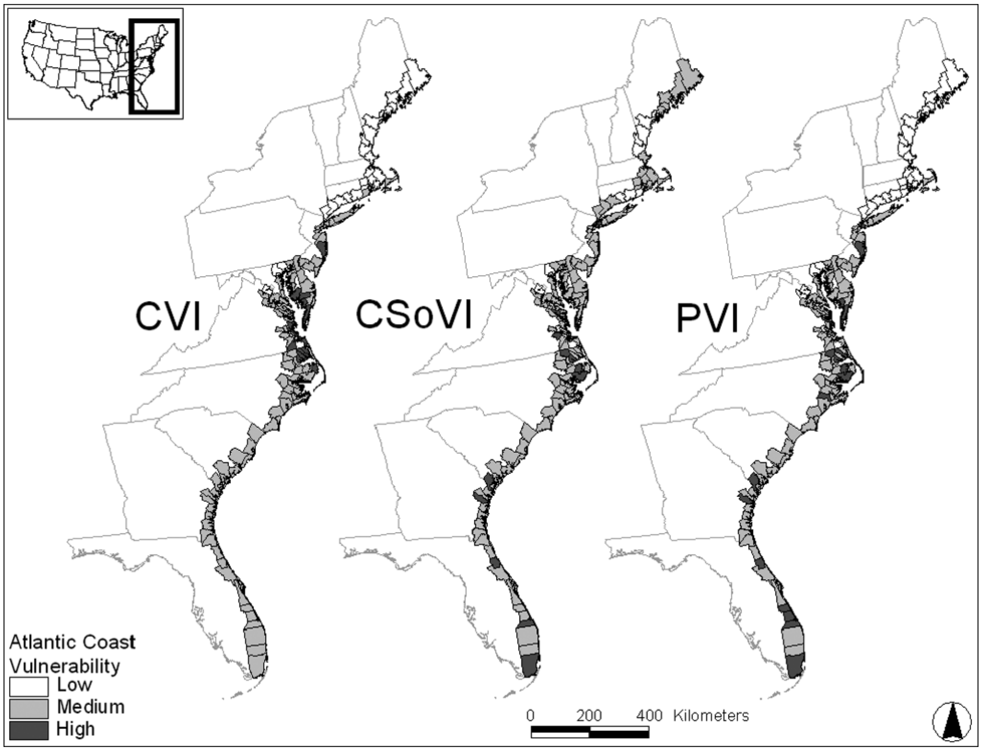

Figure 1. Vulnerability of Atlantic coastal counties based on physical (CVI) and social (CSoVI) indicators and their integration into place vulnerability (PVI).

miles) of Atlantic coastal counties is twice that of Pacific Coast counties and 20 times the earning density of counties along the Gulf Coast.

Atlantic Coast

Mapping the CVI for the Atlantic Coast shows high index values are clustered in the mid-Atlantic counties, particularly in North Carolina and Virginia (Figure 1). For the most part, these counties have a gentle coastal slope, less than a two-foot mean tidal range, are eroding at a rate of more than 1 m per year, and are categorized as a barrier island, sand beach, salt marsh, mud flat, or delta. Mathews County, Virginia, is a good example of a county categorized as highly vulnerable based on physical characteristics (Table 5). Those counties exhibiting low levels of physical vulnerability tend to group along the North Atlantic coastline in the New England states. On average, low physically vulnerable counties experience more accretion than erosion, have steeper slopes, are less affected by sea-level rise, and are categorized as having rocky, cliffed coastlines with glacial and alluvial deposits. Cumberland, Maine, is an example of a coastal county with a low physical vulnerability score.

From a socioeconomic perspective, the same geographic pattern appears, with high levels of social vulnerability clustered in counties along the mid-Atlantic Coast and low levels of social vulnerability along the North Atlantic shoreline (Figure 1). Counties with high levels of socioeconomic vulnerability have large percentages of persons in poverty, those receiving social security benefits, African Americans, and female-headed households. Conversely, those counties with low levels of social vulnerability have little poverty and unemployment, few mobile homes, and low levels of international immigrants. New York (Manhattan borough) has the highest social vulnerability score, while Poquoson County, Virginia, has the lowest (Table 5).

North Atlantic coastal counties have the lowest levels of place vulnerability (Figure 1) of all the regions. The most vulnerable counties again are grouped in the mid-Atlantic region—along the North Carolina, Virginia, and Maryland coastlines. The major exceptions to this are metropolitan New York counties and the south Florida counties of Miami-Dade, Indian River, St. Lucie, and Martin, each having relatively moderate levels of physical vulnerability but high enough levels of socioeconomic vulnerability that, when combined, produce a high PVI value. Northampton, Virginia (on the Delmarva peninsula), and Cumberland, Maine (Portland), have the highest and lowest levels of overall vulnerability, respectively (Table 5).

Gulf Coast

Gulf Coast counties with the highest levels of physical vulnerability are clustered along the Louisiana and Mississippi coasts (Figure 2). These counties are characterized by barrier islands, sand beaches, salt marshes, mud flats, and deltas,

Table 5. *Drivers of regional variations in levels of vulnerability.*

Physical Vulnerability	CVI Score*	Social Vulnerability	CSoVI Score†	Overall Place Vulnerability	PVI Score‡
Atlantic Coast					
Most vulnerable					
Mathews, Virginia	1.977	New York, New York	3.304	Northampton, Virginia	2.992
Northampton, Virginia	1.877	Hudson, New Jersey	3.263	Perquimans, North Carolina	2.383
Dorchester, Maryland	1.787	Bronx, New York	2.652	Hudson, New Jersey	2.212
Least vulnerable					
Westchester, New York	−1.857	Poquoson, Virginia	−3.727	Cumberland, Maine	−3.397
Cumberland, Maine	−1.781	James City, Virginia	−2.348	Sagadahoc, Maine	−3.194
Bronx, New York	−1.712	York, Virginia	−2.247	Strafford, New Hampshire	−3.094
Gulf Coast					
Most vulnerable					
Plaquemines, Louisiana	2.4905	Cameron, Texas	2.798	Cameron, Texas	3.932
Terrebonne, Louisiana	2.1647	Kenedy, Texas	2.745	Plaquemines, Louisiana	2.998
Iberia, Louisiana	2.1229	Willacy, Texas	2.076	Kenedy, Texas	2.973
Least vulnerable					
Hillsborough, Florida	−1.041	Jefferson, Louisiana	−1.103	Hillsborough, Florida	−1.469
Citrus, Florida	−0.873	Jackson, Mississippi	−0.784	Okaloosa, Florida	−1.232
Walton, Florida	−0.835	Jefferson, Texas	−0.731	Baldwin, Alabama	−0.935
Pacific Coast					
Most vulnerable					
San Francisco, California	0.962	San Francisco, California	2.169	San Francisco, California	3.130
Coos, Oregon	0.490	Del Norte, California	0.981	San Mateo, California	0.777
Marin, California	0.299	Monterey, California	0.929	Pacific, Washington	0.415
Least vulnerable					
Clallam, Washington	−0.998	Marin, California	−0.937	San Luis Obispo, California	−1.552
Monterey, California	−0.981	Lane, Oregon	−0.870	Humboldt, California	−1.498
Humboldt, California	−0.928	Sonoma, California	−0.850	Lane, Oregon	−1.397

* Physical vulnerability (erosion hazard) index scores range from −1.857 to 2.490, with a median value of 0.546. The range in values is greatest in the Atlantic and Gulf Coast regions.
† Coastal social vulnerability index values range from a low of −3.727 to 3.304 with a median value of −0.487. The variablity in social vulnerability is greatest in the Atlantic Coast region.
‡ Place vulnerability index scores range from −3.397 (low) to 3.932 (high), with a median value of 0.059. The greatest diversity in index scores is found in the Atlantic Coast region.

with less than a meter tidal range, little slope, and high sea-level rise and erosion rates. Counties with low levels of physical vulnerability have coastlines with greater slopes and lower erosion rates. These counties are concentrated along the western portion of the Florida panhandle. Plaquemines County, Louisiana, has the greatest physical vulnerability, while Hillsborough (Tampa Bay area) has the least (Table 5).

The highest levels of socioeconomic vulnerability are found in counties along the southern Texas coast and along the northwestern portion of Florida's west coast (Figure 2). There was an interesting split among the factors that contributed to high levels of social vulnerability in each of these two areas. In Texas, high CSoVI values are due to large percentages of Hispanic persons, international immigrants, and high levels of poverty and unemployment (*e.g.,* Cameron County, Texas) (Table 5). Along the Florida coast, high CSoVI values are attributed to large elderly populations, numerous mobile homes, and large numbers of Social Security-benefit recipients. For those counties with low levels of socioeconomic vulnerability (found sporadically along the northern coastline of the Gulf of Mexico, such as Jefferson Parish, Louisiana), there is no dominant single indicator.

Mapping place vulnerability results in a different pattern all together (Figure 2). Counties with high PVI values are located along the southern Texas coast and in Louisiana, while counties with low levels of vulnerability are located along the western portion of the Florida panhandle and around the Tampa Bay area. The counties with high PVI values along the Texas coast are due to high levels of socioeconomic vulnerability, while counties along Louisiana have high levels of physical vulnerability. Low PVI values along the western portion of the Florida panhandle are a function of low values on both the physical and social indicators.

Pacific Coast

Pacific Coast counties with high physical vulnerability are located in central Oregon and in the San Francisco Bay area (Figure 3). These counties have low, cliffed coastlines, cobble and sand beaches, alluvial plains, deltas, and estuaries. As expected, counties classified as highly vulnerable based on the physical indicators had a steeper slope and higher erosion rates. San Francisco County, California, is an example of the most physically vulnerable county in the Pacific Coast region, while Clallam, Washington, bordering the Strait of Juan de Fuca, has the lowest physical vulnerability (Table 5).

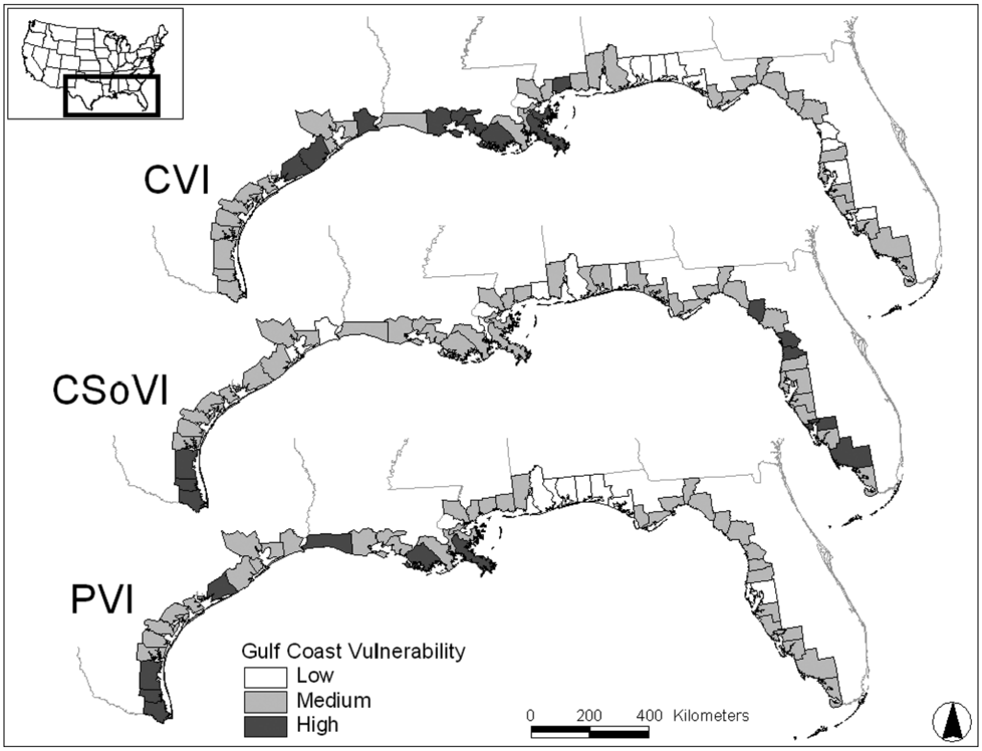

Figure 2. Vulnerability of Gulf coastal counties based on physical (CVI) and social (CSoVI) indicators and their integration into place vulnerability (PVI).

As with the Gulf of Mexico, there was a considerable variability in the social vulnerability of the Pacific Coast (Figure 3). Counties in the San Francisco Bay area with high levels of socioeconomic vulnerability have large percentages of Asian and Hispanic persons and increasing populations coupled with already dense residential and commercial development. Other counties on the Pacific Coast with high CSoVI values, such as Del Norte, California, have large Native American populations, large percentages of female-headed households, and relatively large numbers of Social Security-benefit recipients. Pacific counties with low levels of socioeconomic vulnerability have less ethnic diversity and lower levels of commercial and residential development. A good example is Lane, Oregon (the host county for the Oregon Dunes National Recreation Area).

The overall place vulnerability of Pacific Coast counties is greatest in the San Francisco Bay area (San Francisco and San Mateo counties) and is a function of socioeconomic factors (Figure 3). Counties with low levels of place vulnerability appear in a random geographic pattern (Table 5).

The first question posed in this research asked whether there was regional variation in the place vulnerability of US coastal counties. Results from the ANOVA and the spatial analysis found regional differences not only in place vulnerability but also in physical and socioeconomic vulnerability as well. These findings, especially in the case of physical differences, are consistent with the extant literature. Socioeconomic differences appear between each coast, but there are few studies to either support or refute this finding at the present time.

Social and Physical Influences of Vulnerability

Determining the greatest influence on the overall vulnerability of each region (physical or social characteristics) was the second objective of this article. To assess this, a simple regression analysis was performed using PVI as the dependent variable and the CVI and CSoVI as the independent variables. For all coasts, the average standardized beta coefficient for physical variables was 0.239, while the average standardized beta coefficient for the socioeconomic variables was 0.046 (Table 6), initially suggesting physical characteristics are the greater determinant of overall vulnerability. This conclusion holds for the Atlantic and Pacific Coasts. For Gulf Coast counties, however, the average standardized beta coefficient for socioeconomic variables was larger than the average standardized beta coefficient for physical variables (0.409 and 0.360, respectively). This suggests that, in this region, social vulnerability is the greater driver of place vulnerability (Table 6).

When examining individual counties, the influences are more apparent. For example, it is the combination of both high levels of social and physical vulnerability that produce San Francisco's ranking (Table 7). Yet, in Cameron, Texas, the coastal vulnerability index is quite low but is overwhelmed by the social vulnerability component. In the case

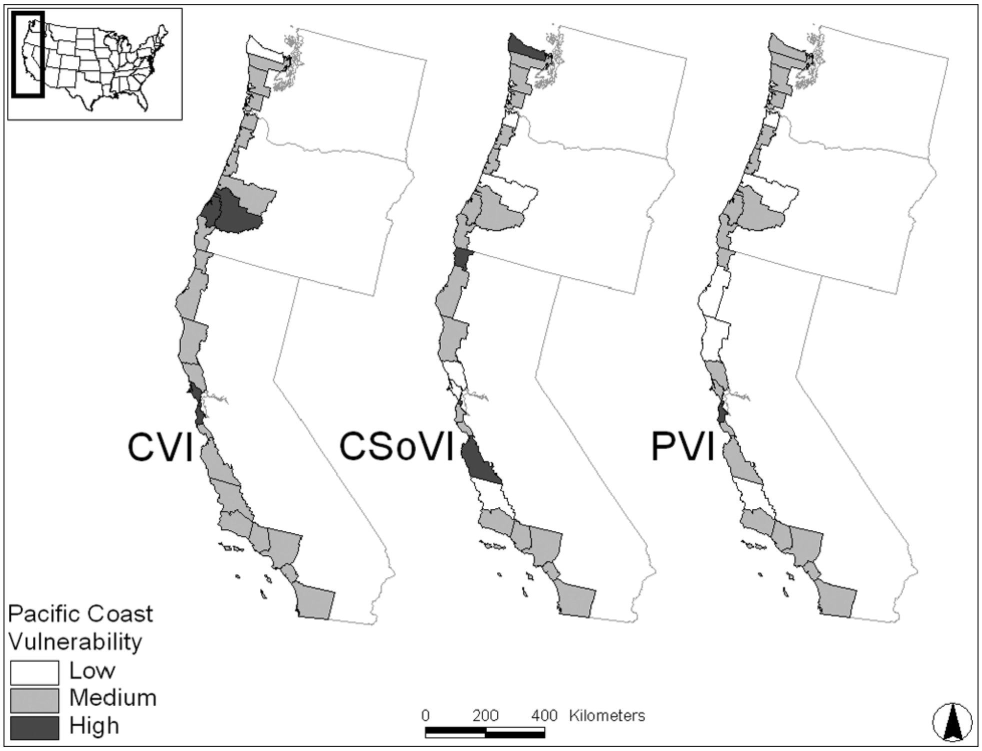

Figure 3. Vulnerability of Pacific coastal counties based on physical (CVI) and social (CSoVI) indicators and their integration into place vulnerability (PVI).

of Cumberland, Maine, low values on both physical and social indicators combine to produce a score representing the least vulnerable county in the United States. If only the top 10 most vulnerable counties are examined, social characteristics are as dominant as physical ones in determining vulnerability.

Individual Indicators of Vulnerability

When aggregated for all coasts, sea-level rise is the most important single indicator of place vulnerability, followed by slope, mean wave height, percent over 65, and the density of commercial development (Table 8). For the Atlantic Coast, density of commercial development is the single most important contributor in the model, with slope, sea-level rise, mean wave height, and percent 65 and over following closely behind (Table 8). In the case of the Gulf Coast, percent 65 and over has the greatest influence on place vulnerability, followed by birth rate, sea-level rise, mean wave height, and median age. For the Pacific Coast, percent Asian explains the greatest variation in the model followed by housing-unit density, erosion/accretion rate, percent renter, percent females in the labor force (Table 8).

Table 6. *Mean standardized beta coefficients for all coasts (regression using PVI as the dependent variable and all socioeconomic and biophysical variables as independents).*

	Attributes	
	Physical	Social
All coasts	0.239	0.046
Atlantic Coast	0.240	0.033
Gulf Coast	0.360	0.409
Pacific Coast	0.179	0.146

DISCUSSION

The previous research on coastal vulnerability primarily focused on the physical aspects of vulnerability such as hurricane exposure, beach erosion, and environmental degradation. This article took issue with that conceptualization of vulnerability as only an exposure measure (*e.g.,* GORNITZ, BEATY, and DANIELS, 1997; H. JOHN HEINZ III CENTER, 2000b; JAGGER, ELSNER, and NIU, 2001; MORTON and PETERSON, 2003) and presented a method for combining physical exposure factors with socioeconomic indicators that, in tandem, more accurately reflect the vulnerability of a specific coastal county to erosion hazards.

It has become clear through this analysis that, when physical and social attributes are compared, there are significant spatial differences between them and their overall influence in the assessment of place vulnerability. This finding is consistent with the existing research (most notably, CLARK *et al.* 1998; CUTTER, MITCHELL, and SCOTT, 2000; WU, YARNAL, and FISHER, 2002). In some regions, especially the Atlantic and Pacific Coasts, the overall place vulnerability scores were

Table 7. *Most and least vulnerable counties according to the place vulnerability index (PVI).*

County	Place Vulnerability (PVI)	Physical Attributes (CVI)	Social Attributes (CSoVI)
Most vulnerable			
Cameron, Texas	3.93	1.13	2.80
San Francisco, California	3.13	0.96	2.17
Plaquemines, Louisiana	3.00	2.49	0.51
Northampton, Virginia	2.99	1.88	1.12
Kenedy, Texas	2.97	0.23	2.75
Willacy, Texas	2.89	0.82	2.08
Matagorda, Texas	2.58	1.51	1.07
Perquimans, North Carolina	2.38	1.34	1.04
Terrebonne, Louisiana	2.37	2.16	0.21
Hudson, New Jersey	2.21	−1.05	3.26
Least vulnerable			
Cumberland, Maine	−3.40	−1.78	−1.62
Sagadahoc, Maine	−3.19	−1.60	−1.60
Strafford, New Hampshire	−3.09	−1.64	−1.46
York, Maine	−3.03	−1.58	−1.45
New London, Connecticut	−2.98	−1.56	−1.42
Newport, Rhode Island	−2.95	−1.53	−1.42
Middlesex, Connecticut	−2.90	−1.43	−1.48
Fairfax, Virginia	−2.89	−1.11	−1.78
Knox, Maine	−2.86	−1.67	−1.19
Baltimore, Maryland	−2.83	−1.31	−1.52

driven by the physical characteristics of the coastline and less so by the social characteristics of the people who reside there. Conversely, in the Gulf Coast, social vulnerability is more of a determining factor in the overall place vulnerability of these counties. In those regions where physical characteristics were the more significant determinants of overall vulnerability, it was tidal range and rate of relative sea-level rise that were most significant. This is consistent with the findings reported in ZHANG, DOUGLAS, and LEATHERMAN (2001).

It is important to understand that, either singularly or collectively, physical and social indicators represent only a portion of the human-environment interaction that amplifies or attenuates the vulnerability of coastal populations to environmental hazards. This article promotes the methodological developments of hazards science to demonstrate the interactive nature of human and physical systems in the production of vulnerability, but the place vulnerability index is not a panacea. For example, there are some important questions of scale—social data were at the county level and physical attributes were at a shoreline-segment scale. Further, the physical data included both longer term conditions (rate of sea-level rise) as well as daily averages (mean tidal range), while the social data represent a snapshot for one census year, 2000. In this regard, the PVI is merely a static indicator of conditions at a single point in time, not a dynamic representation of them.

This article highlights the regional variability in vulnerability and its determinants. This understanding is critically important when designing policy and mitigation initiatives for specific locations. Mitigation and other policy initiatives must be place-specific and flexible in order to adjust to variability in physical parameters and social characteristics. For example, improvements in social conditions (especially housing stock) might have a greater impact in reducing vulnerability in some Gulf Coast counties than physically based mitigation measures such as short-lived erosion control by beach nourishment or hardened structures, such as seawalls. Improved decision making based on an understanding of the underlying dimensions of vulnerability is one tangible contribution of this research.

Future work should be aimed at a more detailed understanding of place vulnerability by downscaling the analysis to the subcounty level. This entails a more detailed analysis

Table 8. *Ranking of socioeconomic and biophysical variables based on standardized beta coefficients (β) for all coasts together.**

All Coastlines	β	Atlantic	β	Gulf	β	Pacific	β
Sea-level rise (mm/y)	0.374	Density of commercial development	0.436	Percent 65 and over	0.696	Percent Asian	0.789
Slope	0.315	**Slope**	0.341	Birth rate	0.604	Housing unit density	0.472
Mean wave height (m)	0.291	**Sea-level rise (mm/y)**	0.322	**Sea-level rise (mm/y)**	0.368	**Erosion/accretion rate (m/y)**	0.184
Percent 65 and over	0.206	**Mean wave height (m)**	0.271	**Mean wave height (m)**	0.353	Percent renter	−0.273
Density of commercial development	0.199	Percent 65 and over	0.215	Median age	0.326	Percent females in the labor force	−0.457

* Significant at $p < 0.05$ or better. Derived from a standardized step-wise regression equation. Bold type indicates physical variables.

of social vulnerability at the block or block-group level (using Census data). It also necessitates more detailed analyses of the physical characteristics of specific coastline segments and the integration of the two data sets using enhanced geographic information systems. Such research should explain in greater detail both the physical and social processes that produce coastal vulnerability. The incorporation of a temporal element (last decade to the present) to track changes in both social and physical vulnerability would be a significant improvement as well. Mitigation indicators (seawalls and other protective measures) are not included in the indices even though they may in fact help reduce the physical vulnerability of places. The development of empirically based mitigation metrics would be a useful addition to our understanding of the vulnerability of places. Finally, it would be instructive to include the Great Lakes, Alaska, and Hawaii in future research on the vulnerability of US coastal counties.

CONCLUSIONS

This article generalized some of the regional variability in vulnerability and highlighted some of the specific physical and socioeconomic factors that have the greatest influence on the vulnerability of coastal communities of the United States. The results can be summarized as follows:

- There are significant differences in the social and physical vulnerability of the Atlantic, Pacific, and Gulf coastal counties.
- Physical factors are the more important determinants of vulnerability on the Atlantic and Pacific Coasts, but social factors dominate vulnerability on the Gulf Coast.

The PVI provides a comparative metric of vulnerability for coastal counties, but it includes much more information than that. For example, two counties could have the same PVI score, but county A might have a very high physical vulnerability score and a much lower social vulnerability score. Meanwhile, when county B (with the same PVI score as county A) is examined, it is clear that county B's place vulnerability is a function of its high social vulnerability score and a lower physical vulnerability one. Not only can we compare different places, but we also can disaggregate the scores to see whether physical or social factors or both tend to be more influential in producing the vulnerability of each county to coastal hazards. These findings paint a picture of regional differences in vulnerability and spatial variability in the drivers behind vulnerability and should prompt policy makers to consider a suite of mitigation alternatives that are tailored to the local situation rather than a one-size fits all approach to hazard vulnerability reduction.

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