Natural Hazards (2007) 40:43–70
DOI 10.1007/s11069-006-0004-z

Vulnerability of Hampton Roads, Virginia to Storm-Surge Flooding and Sea-Level Rise

LISA R. KLEINOSKY, BRENT YARNAL[★] and ANN FISHER
Center for Integrated Regional Assessment, The Pennsylvania State University, University Park, PA, 16802, USA

(Received: 1 February 2005; accepted: 8 January 2006)

Abstract. Sea-level rise will increase the area covered by hurricane storm surges in coastal zones. This research assesses how patterns of vulnerability to storm-surge flooding could change in Hampton Roads, Virginia as a result of sea-level rise. Physical exposure to storm-surge flooding is mapped for all categories of hurricane, both for present sea level and for future sea-level rise. The locations of vulnerable sub-populations are determined through an analysis and mapping of socioeconomic characteristics commonly associated with vulnerability to environmental hazards and are compared to the flood-risk exposure zones. Scenarios are also developed that address uncertainties regarding future population growth and distribution. The results show that hurricane storm surge presents a significant hazard to Hampton Roads today, especially to the most vulnerable inhabitants of the region. In addition, future sea-level rise, population growth, and poorly planned development will increase the risk of storm-surge flooding, especially for vulnerable people, thus suggesting that planning should steer development away from low-lying coastal and near-coastal zones.

Key words: storm-surge flooding, hurricanes, sea-level rise, climate change, coastal hazards, coastal development, vulnerability

1. Introduction

Global sea-level rise is a major impact of human-induced climate change. The Intergovernmental Panel on Climate Change (IPCC) projects a global sea-level rise of 48 cm over the next century, with an uncertainty range of 9–88 cm, resulting from thermal expansion of the oceans and glacial melt (Church and Gregory, 2001). Sea-level rise will be worse in regions experiencing subsidence. For example, Najjar *et al.* (2000) estimated that the coastline of the United States Mid-Atlantic region is sinking at the rate of about 2 mm per year due to crustal warping (Walker and Coleman, 1987), sediment compaction (Psuty, 1992; Nicholls and Leatherman, 1996), and groundwater withdrawal (Leatherman *et al.*, 1995). Because shorelines with

---

[★] Author for correspondence: Phone: + 1-814-863-4894; Fax: + 1-814-863-7943; E-mail: alibar@eesi.psu.edu

shallow slopes, such as those found in the mid-Atlantic region, can be dramatically affected by even small increases in sea level, low-lying coastal areas such as deltas, coastal plains, and barrier islands are especially vulnerable to sea-level rise (McLean and Tsyban, 2001).

Although sea-level rise will affect coastal areas in many ways (McLean and Tsyban, 2001), this study investigates one particular impact: more-severe storm-surge flooding (Flather and Khandker, 1993). When a hurricane passes over or near a coastal margin, it generates a storm surge that causes flooding in low-lying areas. Hurricane storm surge results from the interaction of atmospheric pressure depression and wind shear stress on the water's surface. That is, the intense low-pressure center of a hurricane lifts the water beneath it, forming a dome of water that the storm's winds push onshore. The advancing surge combines with the normal tide to create the hurricane storm tide. In addition, superimposed on the storm tide are wind-driven waves. Together, storm tide and wind-driven waves can cause severe flooding in coastal regions (National Hurricane Center, 2005a).

The degree of flooding depends on hurricane intensity, fluctuations in astronomically generated tides, slope of the continental shelf, and rainfall amounts over land. More intense storms produce higher storm surges, and flooding is worst when surges coincide with high tides. Flood severity is also a function of water depth offshore and of location relative to the eye of the hurricane. When shallow water is present offshore, the mound of water that builds as the storm approaches cannot disperse. In the Northern Hemisphere, locations in the right-front quadrant of a hurricane experience strong onshore winds and consequently the highest surge heights (National Hurricane Center, 2005a). It is important to note that tropical cyclones can generate intense rainfall ahead of the storm, which can sometimes cause more flooding than the surge. Worst-case flood scenarios occur when a river storm wave flowing downslope combines with a storm tide moving onshore.

The effect of a higher sea level is to move the effective shoreline landward, closer to existing structures and settlements. In addition, Tsyban *et al.* (1990) stress that sea-level rise, by increasing the mean sea-level height upon which surges build, could by itself allow storm surges to increase in height and thus penetrate farther inland (see also Wu *et al.*, 2002; McInnes *et al.*, 2003; Gönnert, 2004). Thus, holding all other factors constant, a hurricane occurring at a higher sea level would cause more damage than a hurricane of equal intensity at present sea level simply because the shoreline would be further inland than today and storm surge would build from a higher base. Nicholls *et al.* (1999) estimate that an addition of 50 cm to global sea level would cause a sixfold increase in the number of people flooded in a typical year by hurricane storm surges.

Because coastal zones are at risk of greater storm surges with sea-level rise, it is important to analyze the vulnerability of crucial coastal zones to the increased storm-surge flooding associated with sea-level rise. Vulnerability is a much-discussed concept in research on the human dimensions of global environmental change (e.g., Clark *et al.*, 2000; IHDP, 2001; Kasperson and Kasperson, 2001). The IPCC defines vulnerability as "the extent to which a natural or social system is susceptible to sustaining damage from climate change" (Schneider and Sarukhan, 2001). It is a function of the *exposure* of the system to climatic hazards, the *sensitivity* of the system to changes in climate, and the *adaptive capacity* of the system to moderate or offset the potential damages of climate change. The focus on vulnerability shifts attention from simple assessments of stressors (e.g., sea-level rise and hurricanes) and their impacts to an examination of the system under stress and its ability to respond to the stress (Luers *et al.*, 2003).

This paper uses Hampton Roads, a ten-city, sixteen-county area in southeastern Virginia, as a case study to understand how sea-level rise will increase the vulnerability of people and infrastructure to hurricane storm-surge flooding over the next century. It builds on vulnerability assessment methods developed by NOAA Coastal Services Center (1999), Cutter *et al.* (2000), and especially Wu *et al.* (2002). The study area of Hampton Roads is described in Section 2. Section 3 assesses the overall vulnerability of Hampton Roads to present-day storm-surge flooding by determining its exposure to storm surges from hurricanes of various intensities and by mapping social vulnerability throughout the region. In Section 4, the paper describes how exposure could change by mapping the expansion of storm-surge flood-risk zones with various sea-level rise scenarios. Section 5 addresses uncertainty in future population growth and in population distribution patterns and provides credible future impact scenarios for the year 2100. The paper concludes with the implications of this research for local planners.

2. Study Area

2.1. REGIONAL CONTEXT

The metropolitan region of Hampton Roads consists of 10 cities and six counties in southeastern Virginia (Figure 1). The area covers approximately 7500 km^2 of low-lying coastal land at the confluence of the James, Nansemond, and Elizabeth Rivers with the Chesapeake Bay. It is home to more than 1.5 million people and has intensely developed, densely populated coastal frontages, making it an appropriate case study for understanding the potential impacts of storm-surge flooding and sea-level rise. Understanding the vulnerability of the region to storm-surge flooding is

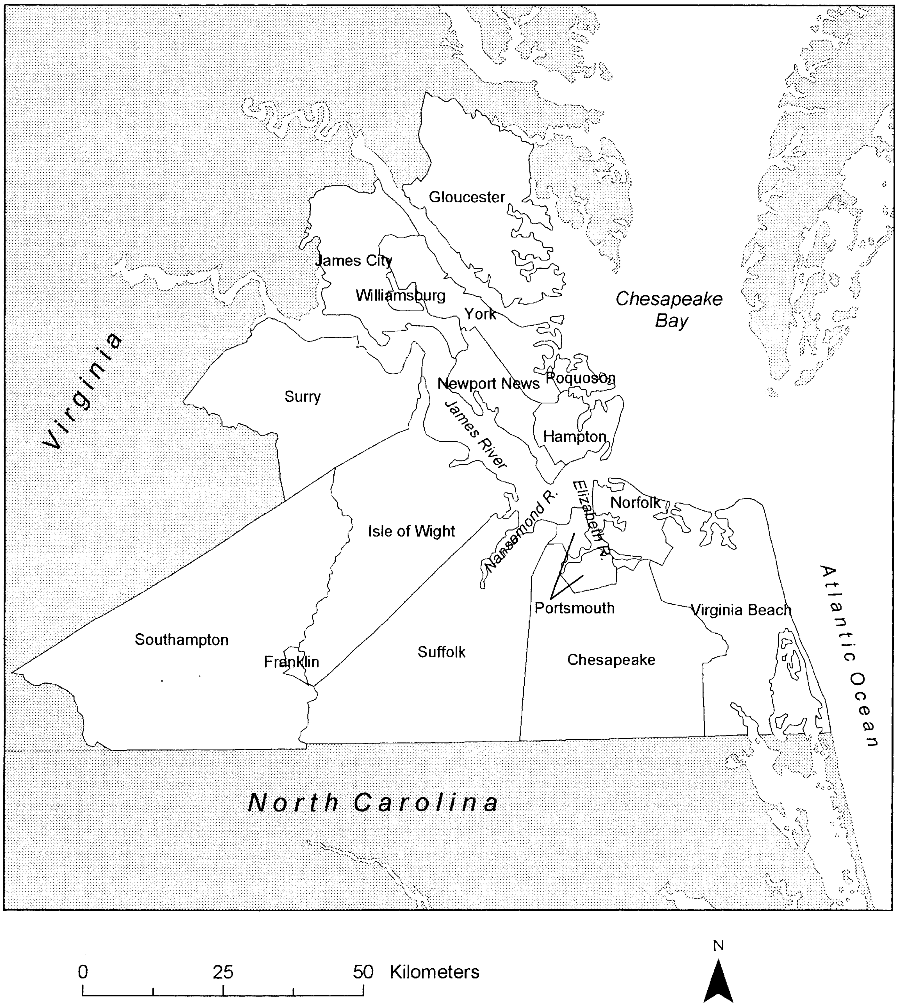

Figure 1. Location of Hampton Roads, Virginia.

also crucial for economic and national security reasons. Hampton Roads is not only the second largest port on the East Coast and the center of Virginia's tourism industry, but also the location of the largest naval base in the world.

Hampton Roads is composed of three geographic subdivisions (Hampton Roads Planning District Commission, 2003). South Hampton Roads contains the cities of Chesapeake, Norfolk, Portsmouth, Suffolk, and Virginia Beach. The Rural Southeastern Virginia region consists of the city of Franklin and the counties of Isle of Wight, Southampton, and Surry. The subdivision known as the Peninsula is comprised of the cities of Hampton, Newport News, Poquoson, and Williamsburg as well as the counties of

James City, York, and Gloucester. The northeastern quarter of South Hampton Roads and the southern portion of the Peninsula are overwhelmingly urban, while the rest of the study area is dominated by forested and agricultural land. A few hundred square kilometers of wetlands are also present, as well as a small amount of open water and barren land (Figure 2).

Hampton Roads is located entirely within the low-lying physiographic region known as the Atlantic Coastal Plain (Bingham, 1991). Elevation rises slightly across the study area from east to west (Figure 3). Hampton

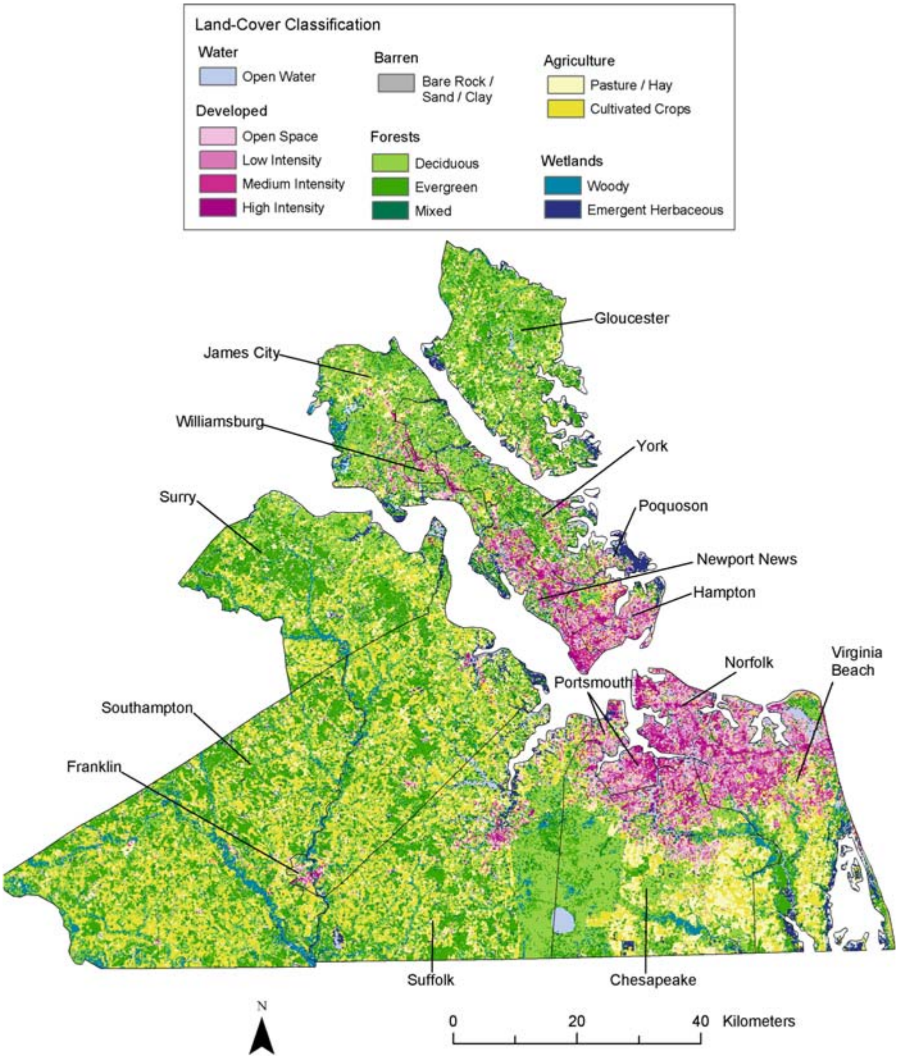

Figure 2. Land-cover distribution of Hampton Roads.

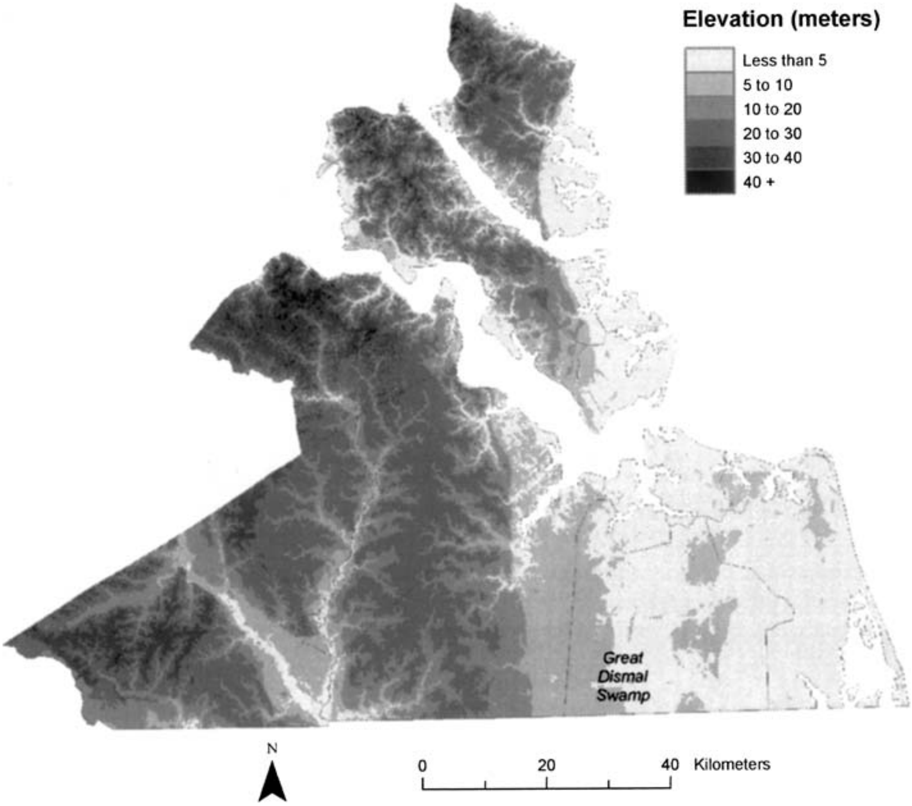

Figure 3. Elevation of study area above sea level.

Roads reaches a maximum elevation of about 54 m above sea level along its western edge, while most of the eastern half of the study area is less than ten meters above sea level. Nearly all of South Hampton Roads is at elevations of less than 5 m, including heavily developed sections of Norfolk, Portsmouth, Virginia Beach, and Chesapeake. The Great Dismal Swamp, which occupies about 1500 km^2 of southern Virginia and northern North Carolina, is also less than 5 m above sea level. Additionally, the eastern edge of the Peninsula is characterized by a bowl-shaped depression known as the Chesapeake Bay Impact Crater. The crater was created about 35 million years ago by a comet or meteorite (Powars, 2000). Today it encompasses most of the cities of Poquoson and Hampton, as well as the eastern portions of Gloucester and York counties.

The cities of South Hampton Roads have a very shallow slope and therefore are particularly vulnerable to sea-level rise. It is important to note Hampton Roads is still experiencing subsidence in reaction to the unloading of the Laurentide ice sheet from the North American continent, which exacerbates local sea-level rise. Data from the Sewells Point tide monitoring station indicates that sea level has risen by 41 cm in Hampton Roads between 1933 and 2003 (Boon, 2004).

2.2. HURRICANE HISTORY

The Virginia Department of Emergency Management (2005) reports that 25 hurricanes affected Hampton Roads in the 20th century, including a hurricane in 1933 that set the record high storm tide and storm surge for Norfolk (Table I). Most recently, in September 2003, Hurricane Isabel produced an equal storm tide of approximately 2.4 m and a storm surge of roughly 1.5 m (Boon, 2004).

The Chesapeake Bay-Potomac Hurricane of 1933 is an example of how even a moderate hurricane can produce major storm-surge flooding. Although the storm was only a weakening Category 2 hurricane when it made landfall, storm surge was particularly devastating due to an unusual storm trajectory and associated pressure pattern (Cobb, 1991). A high-pressure system over Maine prevented the storm from curving to the northeast; after making landfall near Nags Head, North Carolina, the storm continued to move northwest directly over the Hampton Roads area. As the storm moved north of Norfolk, it encouraged the development of a high-breaking wave, known as a tidal bore, which moved up the Chesapeake Bay. In Norfolk, bay and ocean waters combined to produce a storm tide of 2.4 m above mean low water, but storm tides may have been as much as 3.7 m above mean low water in some narrow estuaries.

Although incomplete records exist, at least 15 hurricanes affected the area in the 17th, 18th, and 19th centuries. Intensity and tide height for some of those hurricanes might have far surpassed those of recent record. A hurricane in September 1667 might have had a storm tide that was 1.7 m higher than that of the record 1933 hurricane. Moreover, a particularly violent hurricane in October 1749 may have had a storm tide approximately 2.3 m higher than the record storm tide (Virginia Department of Emergency Management, 2005). Thus, storm-surge flooding is a significant hazard in Hampton Roads.

Table I. Hurricanes striking Hampton Roads with significant storm tides and storm surges.

Date	Name	Estimated storm tide (m)	Estimated storm surge (m)
1667	Unnamed	4.1	?
1749	Unnamed	4.7	?
1933	"Chesapeake Bay-Potomac"	2.4	1.8
2003	Isabel	2.4	1.5

3. Present Vulnerability to Storm-Surge Flooding

3.1. EXPOSURE

3.1.1. *Methods*

The study used output from the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model of the National Hurricane Center to evaluate the possible exposure of Hampton Roads to storm-surge flooding. The SLOSH model was originally meant to make real-time forecasts for surge heights of approaching hurricanes (Jelesnianski *et al.*, 1992). When the model is used to estimate surge from an actual hurricane, results are generally accurate within plus or minus 20% (National Hurricane Center, 2005a). In recent years, the SLOSH model also has been used to determine which coastal areas are at risk of storm-surge flooding (Jelesnianski *et al.*, 1992; see Wu *et al.*, 2002). SLOSH model output has become important to the development of coastal hurricane evacuation plans (National Hurricane Center, 2005a).

For SLOSH modeling, the National Hurricane Center has divided the United States coasts into a series of 38 elliptical basins, and each basin is divided into hundreds of grid cells. To determine at-risk areas for storm surge, the National Hurricane Center runs a series of hundreds of hypothetical hurricanes of various Saffir–Simpson categories, forward speeds, landfall directions, and landfall locations for each basin. At the end of each model run, an envelope of water is generated, reflecting the maximum surge height obtained by each grid cell (National Weather Service, 2005). After all of the model runs, a composite called the Maximum Envelopes of Water (MEOW) is formed. The MEOW contains the maximum surge height in a cell for a given hurricane category and storm track. A further composite called a MOM (Maximum of MEOWs) represents the maximum surge height in each cell for hurricanes of a particular Saffir–Simpson category, regardless of storm track or direction (National Hurricane Center, 2005a). Surge height values from a model run or composite can then be compared to elevation values.

This study used output for the Pamlico Sound SLOSH basin, which covers the entire study area. The model output contains five grided layers that correspond to storm-surge heights for hurricanes of intensities 1 through 5 on the Saffir–Simpson scale (Table II). The MOM composites were used, which were calculated using high-tide model runs.

The SLOSH model output was compared to a digital elevation model (DEM) obtained from the United States Geological Survey (2004). Immediately along the coast, the DEM has cells that are 10 m per side with contour intervals of 0.1 m. Cells further inland are 30 m per side with contour intervals of 1 m.

To compare the SLOSH model output to the DEM, the vertical datum of the DEM was matched to that of the SLOSH model. For each hurricane category, those areas where storm-surge heights were greater than elevation values were mapped. Because high-elevation barriers can prevent the propagation of floodwaters, any low-lying area appearing to be at risk of flooding but surrounded by higher, non-flooded land was excluded from the at-risk zone.

3.1.2. *Results*

The present-day storm-surge flood-risk zones are shown in Figure 4 and the size of each flood-risk zone is shown in Table III. Nearly one-third of the study area is currently at risk of storm-surge flooding from Category 5 hurricanes. Storm-surge flood-risk scores were assigned to each zone as shown in Table IV. Areas at risk of flooding from Category 1 hurricanes were given the highest score, while areas not at risk of flooding from even Category 5 hurricanes were given the lowest score.

The results show that the low-lying eastern portion of the study area is most at risk to storm surges from hurricanes of all categories. South Hampton Roads and the eastern edge of the Peninsula are especially susceptible to storm-surge flooding. In South Hampton Roads, locations along the Elizabeth and Nansemond Rivers are at risk of flooding from storm surges produced by even weak or moderate hurricanes. Because slope in this region is very shallow, storm-surge waters from stronger hurricanes can affect locations much farther inland. For example, in the city of Chesapeake, about 50.15 km^2 (5.5% of the city's total land area) are at risk of flooding from storm surges associated with Category 1 hurricanes. For Category 5 hurricanes, the storm-surge flood-risk zone occupies 707.66 km^2 – about 77.6% of the city.

The low-lying land occupying the Chesapeake Bay Impact Crater is also vulnerable to storm surges from even Category 1 hurricanes. Nearly all of Poquoson and Hampton, as well as the eastern portions of Gloucester and

Table II. Saffir–Simpson hurricane classification scale.

Category	Wind speed (km/h)	Average storm surge (m)
1	119–153	1.2–1.5
2	154–177	1.8–2.4
3	178–209	2.7–3.7
4	210–249	4.0–5.5
5	>249	>5.5

Source: National Hurricane Center (2005b).

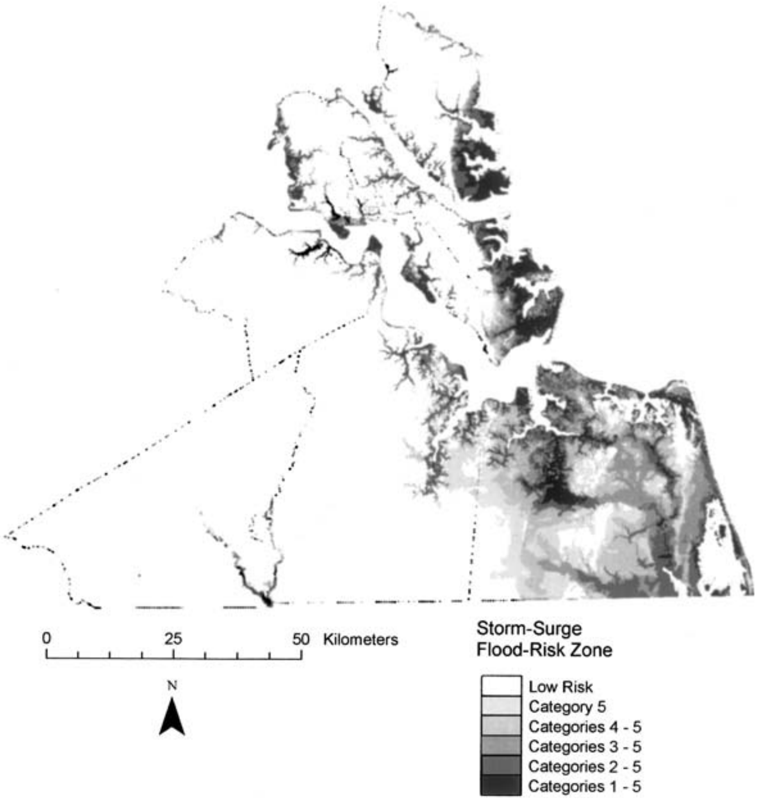

Figure 4. Physical vulnerability of Hampton Roads to storm-surge flooding at high tide.

Table III. Storm-surge flood-risk zones.

Hurricane intensity	Storm-surge flood-risk zone (km^2)
Category 1	484
Category 2	924
Category 3	1385
Category 4	1890
Category 5	2390

York, are at risk. However, slope in this area is steep because elevation increases rapidly inland from the edges of the depression. Thus, increases in hurricane intensity do not make visibly striking changes to the flood-risk zones in the Peninsula. For instance, the Category 1 storm-surge flood-risk zone in Gloucester County is 90.82 km^2, whereas the Category 5 risk zone is 173.12 km^2 – a relatively small absolute increase of 82.3 km^2.

Table IV. Flood-risk scores.

Storm-surge flood-risk zone	Risk score
Low risk	1
Category 5	2
Categories 4–5	3
Categories 3–5	4
Categories 2–5	5
Categories 1–5	6

3.2. SOCIAL VULNERABILITY

Kleinosky *et al.* (2006) cover the background material on and analysis of social vulnerability in the Hampton Roads metropolitan area. This section summarizes elements of that work relevant to this paper.

3.2.1. *Background*

Previous vulnerability analyses for the coastal United States have used census data at the block group level to build social vulnerability indices (Cutter *et al.*, 2000; Wu *et al.*, 2002). This approach requires the selection of variables that indicate vulnerability; for example, Cutter *et al.* (2000) used numbers of children and elderly to represent greater susceptibility to hazards due to physical weakness and number of mobile homes to represent the level of structural vulnerability. Typically, the value of each variable is standardized on a scale from zero to one by comparing the value in each block group to the maximum value in the county or study area. Higher index values indicate higher vulnerability. A composite social vulnerability score for each block group can be constructed by combining the index scores for each variable. As in Wu *et al.* (2002), when specific weights are not attached to each variable, the composite index uses a simple average of the scores of all variable.

In addition to deciding which indicators to include and choosing how to devise an index or scale from the variable list, the size and composition of each indicator must be considered. Previous vulnerability analyses have used either size or composition, but not both. For example, Cutter *et al.* (2000) used size – absolute numbers for each variable – to indicate vulnerability. The logic for using absolute numbers is based on the assumption that a block group with more people, households, and housing units has a higher potential for damage than one with fewer people and structures. In contrast, Clark *et al.* (1998) used percentage values for each variable to indicate vulnerability. Using this method, the composition of block groups is more important than size. This approach allows block groups with high percentages of vulnerable people, but relatively small populations, to have high vulnerability scores.

This paper considers both size and composition to be important when determining vulnerability. However, it is risky to use raw numbers of vulnerable people without taking into account the areal extent of each block group. For example, a hypothetical block group may have twice as many vulnerable people as its neighbor. When raw numbers are used to indicate vulnerability, the second block group appears to be half as vulnerable as the first. If, however, the first block group is twice the size of the first, the density of vulnerable people is the same, and in that respect the block groups could be considered equally vulnerable. Therefore, this study uses both percentages and areal densities of vulnerable people and households.

3.2.2. *Analysis*

Some broad indicators appear repeatedly in vulnerability analyses, although different variables may be chosen to represent each indicator. Kleinosky *et al.* (2005) used the vulnerability indicators of poverty, gender, race and ethnicity, age, and disabilities. To capture these indicators, they chose 57 variables for inclusion in a principal components analysis of social vulnerability. All variables were derived from the 2000 United States Census and were analyzed at the block-group level. Densities were calculated by clipping the census block-group files to county boundaries and calculating the area of each block group in square kilometers. The number of people, households, or housing units in a particular category was then divided by the area of the block group. The use of both percentages and densities did not pose a problem to the analysis because the basic aim of a principal components analysis is to reduce a complex set of many correlated variables into a set of fewer, uncorrelated components.

The variables were entered into a correlation matrix and a Varimax orthogonal rotation with Kaiser normalization to the solution was applied (George and Mallery, 2003). This approach generated 13 components with eigenvalues greater than 1.0. These 13 components explained 81.01% of the variance in the dataset; however, with such a large number of components, each component was difficult to describe. After examining a scree plot, only three components were extracted for analysis. Together, the three components explained 50.83% of the variance in the dataset. Each component seemed to have clear explanatory power; the loadings of the individual variables made each component easy to describe.

Descriptions of the three components are shown in Table V. Although general names – "poverty," "immigrants," and "old age/disabilities" – are used to describe the three components, more individual variables load highly onto those components than the names can express. For example,

Table V. Groupings of social vulnerability components.

Component name	Census variables	Variance explained	Cumulative variance explained
Poverty	High percentages and densities of Young people Old people Adults without high school diplomas People living in poverty People dependent on public transit Single-mother households Renters Housing units without telephones Housing units without vehicles Low values of Per capita incomes Median earnings Median household incomes Median housing values	24.03%	24.03%
Immigrants	High percentages and densities of New immigrants Asians People of two or more races People of some “other” race Non-English speakers	14.45%	38.47%
Old age/ disabilities	High percentages and densities of Old people People with disabilities (all types)	12.36%	50.83%

although the first component is called “poverty” because it represents low incomes and many people living in poverty, this component also includes high percentages and densities of black people and single-mother households. It is important to note that no major disparities were found between the results using percentages and densities. Thus, regardless of the chosen method of representation, the same key variables emerged as central indicators of social vulnerability.

3.2.3. *Results*

Understanding the distribution of the individual social vulnerability components can be useful to emergency managers. For example, Figure 5

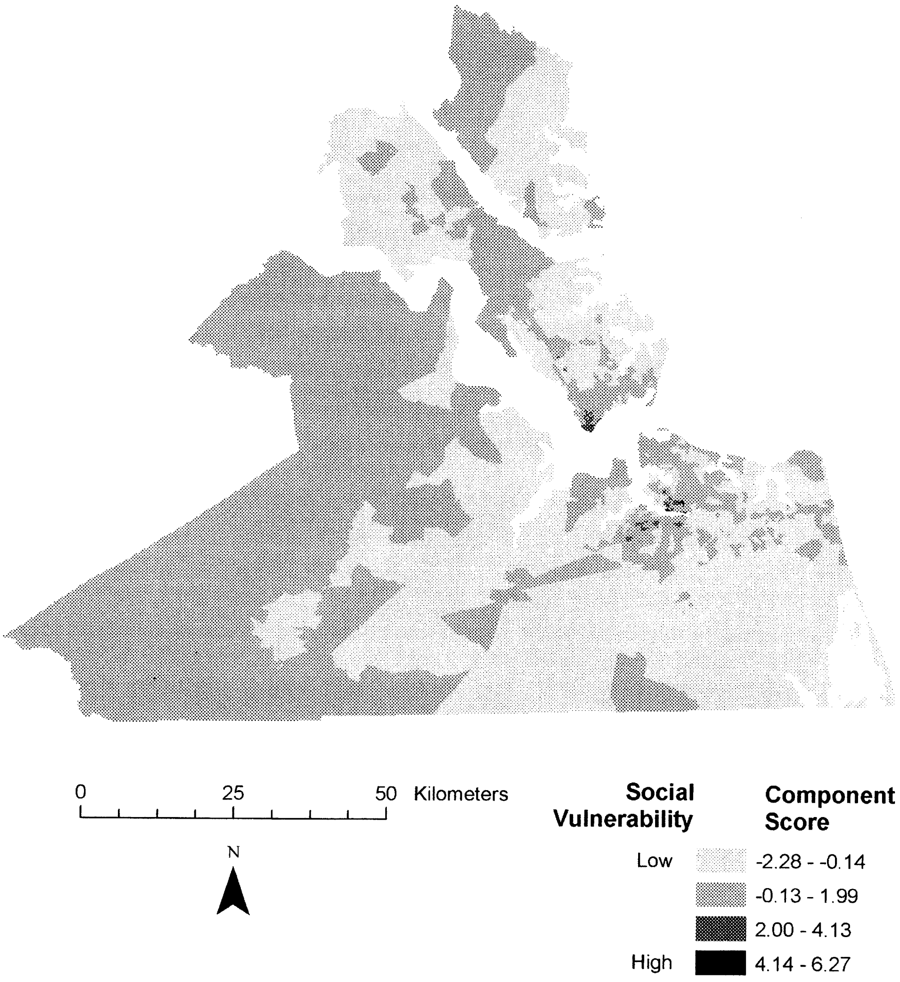

Figure 5. "Poverty" component scores.

depicts block-group scores for the "poverty" component. The 1027 block groups in the study area are sorted into four equal-interval classes.

For this component, the most vulnerable block groups occupy intensely developed land along the northern coast of South Hampton Roads and at the southern tip of the Peninsula. Only a few block groups show exceptionally high component scores. Five block groups – four in Norfolk and one in Newport News – have component scores in the highest class. The next highest class contains 21 block groups, all within the cities of Newport News, Norfolk, and Portsmouth. Component scores in the third-highest class are associated with most of Rural Southeastern Virginia and with heavily developed block groups in the cities of Suffolk, Chesapeake, and Virginia Beach.

Scores for the "poverty" component are lowest in block groups that occupy forested or agricultural land in southern South Hampton Roads and some sections of the Peninsula. Fourteen of the 20 lowest scores can be found in Virginia Beach. Large portions of James City County, York County, Suffolk County, and the city of Chesapeake also possess low scores for the first component.

Although maps of individual component scores are useful, it is easiest to assess overall social vulnerability throughout a region if the multidimensional components can be combined into a single measure (Clark *et al.*, 1998). The simplest way to combine component scores into a single measure is to average the three component scores for each block group. However, averaging component scores poses two significant problems. The first problem concerns the construction of a weighted average. Simple averages can be used if all components are assumed to contribute equally to vulnerability, but if a researcher decides that certain components contribute more to overall social vulnerability, he or she must make subjective decisions to create a weighting scheme. The second problem with using averages is that they may obscure high scores on one component when they are averaged with low scores on the other components. However, extreme values on even one component may indicate areas particularly in need of attention from emergency managers. To avoid the problems created by using component score averages to measure absolute overall social vulnerability, this study used Pareto ranking to organize the block groups into a series of ranks. See Kleinosky *et al.* (2006) for details of this technique and its application to the vulnerability data.

In this study, with 1027 block groups and three component scores, block groups are sorted into 19 ranks (Figure 6). Block-group rank membership shows a normal bell-curve distribution. The middle ranks each contain approximately 100 block groups, while the very highest and very lowest ranks contain only a dozen block groups or less.

3.3. OVERALL VULNERABILITY

3.3.1. *Methods*

To assess overall vulnerability, flood-risk scores shown in Table IV were multiplied by social vulnerability scores. The 19 Pareto ranks were reassigned such that the most vulnerable block groups had a score of 19 and the least vulnerable block groups had a score of 1. The social vulnerability score of each block group was then defined as its Pareto rank. Final results were rescaled from 0 to 1 to increase interpretability, and overall vulnerability zones were established by sorting the scores into four equal-interval classes (Figure 7).

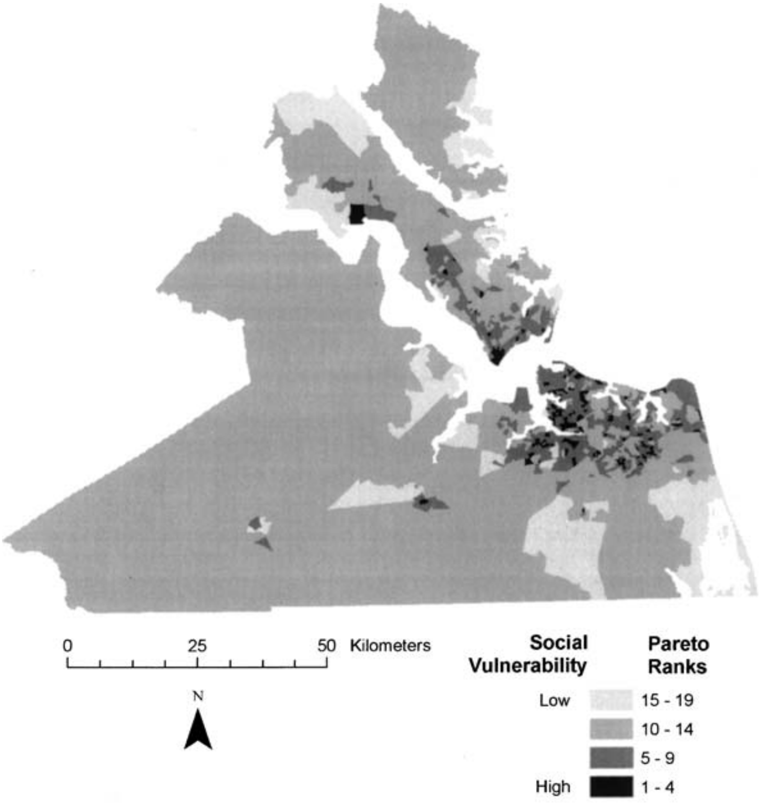

Figure 6. Overall social vulnerability in Hampton Roads, calculated using the Pareto ranking technique.

3.3.2. *Results*

The region's present-day overall vulnerability to storm-surge flooding is shown in Figure 7. Because much of the western portion of the study region has low flood-risk scores and relatively low social vulnerability, nearly 90% of the study area has overall vulnerability scores in the lowest class. However, much intensely developed land within Hampton Roads – including large portions of Hampton, Portsmouth, Norfolk, northern Chesapeake, and northern Virginia Beach – has at least moderate overall vulnerability, and areas of high and very high overall risk are found only in that portion of the study area. Thus, the parts of the study area most likely to experience storm-surge flooding are also home to the most socially vulnerable population segments – those people most likely to be sensitive to exposure to a significant hazard and least likely to cope effectively with the impacts of a disaster.

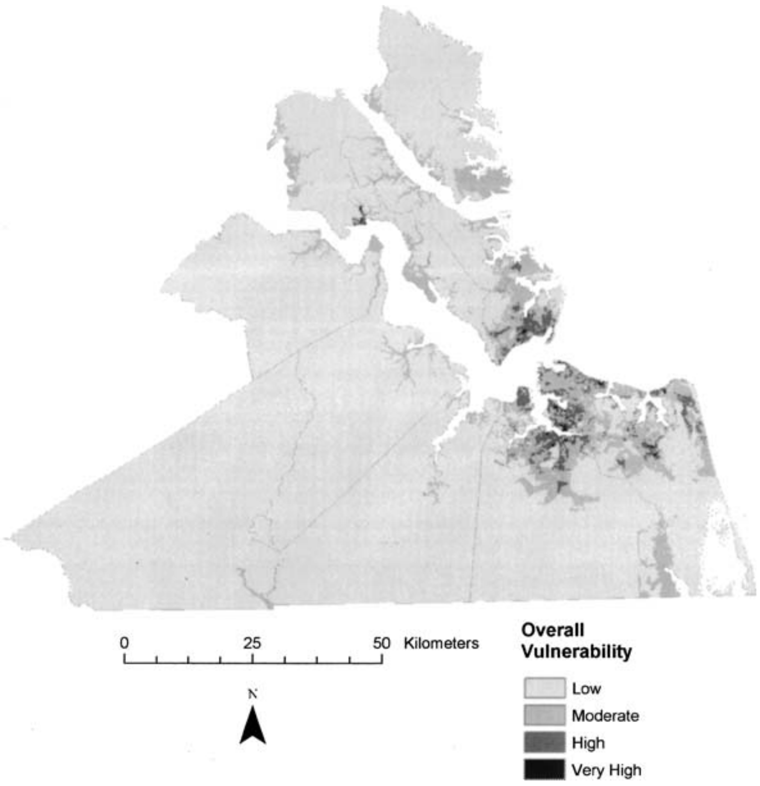

Figure 7. Overall vulnerability to storm-surge flooding.

4. Vulnerability with Sea-Level Rise

4.1. EXPANSION OF FLOOD-RISK ZONES

The IPCC projection of a global sea-level rise of 48 cm over the next century is likely to be accelerated in Hampton Roads because of regional subsidence. Thus, a baseline sea-level rise estimate of 60 cm was chosen for the year 2100, and the storm-surge flooding analysis was repeated by adding 60 cm to surge heights. For purposes of comparison, a low-end estimate of 30 cm and a high-end estimate of 90 cm were also selected.

The size of each flood-risk zone expands considerably with sea-level rise (Table VI). The area of greatest increase is the gently sloping portion of southern South Hampton Roads, as illustrated in Figure 8 using Category 1 hurricanes as an example. Significant percentages of developed land and wetlands are currently at risk, and, assuming an unchanged land-cover distribution, risk to both of these land-cover types increases substantially with sea-level rise (Table VII).

Table VI. Expansion of storm-surge flood-risk zones with sea-level rise.

Hurricane intensity	Sea-level rise scenario					
	30 cm		60 cm		90 cm	
	Risk zone (km^2)	% Increase	Risk zone (km^2)	% Increase	Risk zone (km^2)	% Increase
Category 1	590	21.98	730	50.74	936	93.37
Category 2	1080	16.88	1218	31.79	1340	45.00
Category 3	1532	10.64	1646	18.89	1773	28.04
Category 4	2042	8.01	2174	15.03	2297	21.50
Category 5	2560	7.13	2687	12.44	2756	15.33

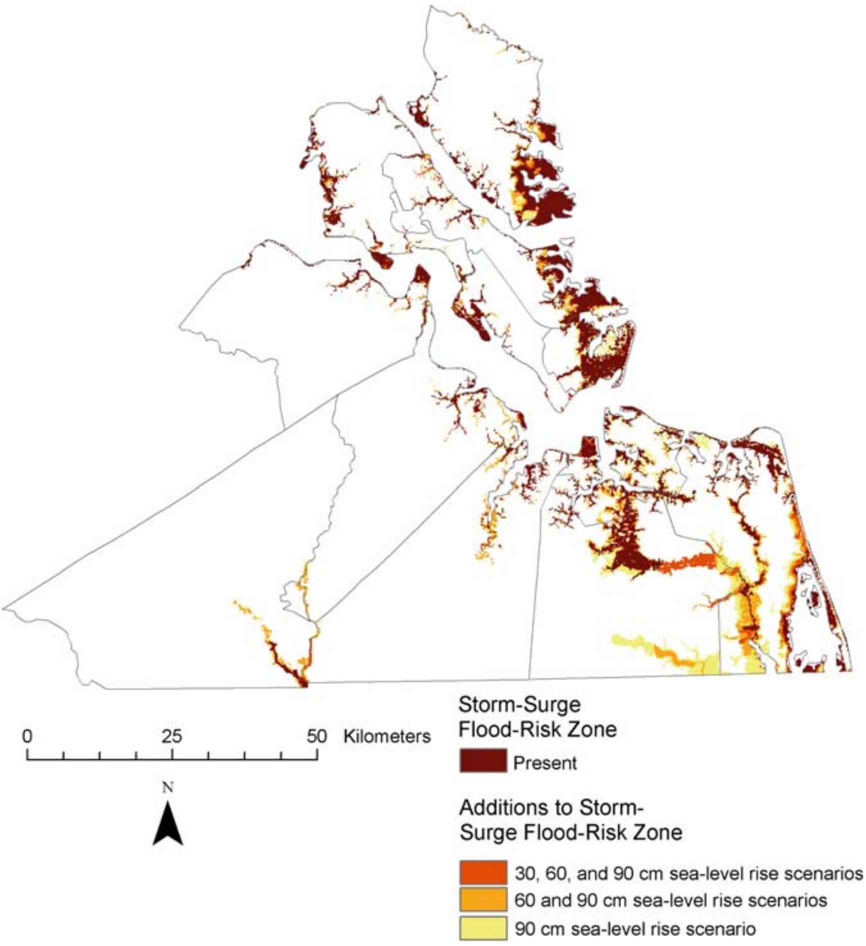

Figure 8. Storm surge flood-risk zone with post sea-level rise increases, Category 1 hurricanes at high tide.

Table VII. Land-cover distribution of storm-surge flood-risk zones, Category 1 hurricanes.

Land-cover class	Storm-surge flood-risk zone (km^2)	% of class affected	Post-sea-level rise increase (km^2)
Present day			
Open water	68	50.40	–
Developed	106	12.32	–
Barren	24	11.69	–
Forests	100	2.82	–
Agriculture	59	2.67	–
Wetlands	127	20.45	–
Total	484	6.39	–
30 cm sea-level rise			
Open water	73	54.03	5
Developed	123	14.36	18
Barren	27	13.17	3
Forests	137	3.85	37
Agriculture	71	3.25	13
Wetlands	159	25.53	32
Total	590	7.80	106
60 cm sea-level rise			
Open water	77	57.11	9
Developed	143	16.64	37
Barren	31	15.04	7
Forests	184	5.19	84
Agriculture	91	4.12	32
Wetlands	204	32.77	77
Total	730	9.63	246
90 cm sea-level rise			
Open water	81	59.75	13
Developed	191	22.22	85
Barren	36	17.67	12
Forests	255	7.17	154
Agriculture	132	6.01	73
Wetlands	241	38.81	114
Total	936	12.36	452

4.2. VULNERABILITY OF CRITICAL FACILITIES

Increases in vulnerability with sea-level rise can also be assessed by observing changes in the flood-risk exposure of critical facilities (Wu *et al.*, 2002) such as schools, hospitals, and fire and rescue departments that are crucial to the everyday functioning of a community. They also supply essential services during emergencies and often provide special care to vulnerable populations such as children or the disabled. The total number of these facilities within each flood-risk zone is a useful indicator of the overall vulnerability of Hampton Roads to storm-surge flooding.

Data from the Virginia Economic Development partnership (2004) were used to inventory the following critical facilities: public schools, hospitals, fire and rescue stations, solid waste facilities, water treatment facilities, and sewer treatment facilities. Hampton Roads is home to 744 of these facilities in all. Although the location of critical facilities will certainly change over the next century as older facilities deteriorate and new facilities replace them, Table VIII shows the change in the number of presently existing facilities within each flood-risk zone associated with sea-level rise.

Table VIII. Number of critical facilities in various flood-risk zones.

Hurricane intensity/sea-level rise scenario	Facilities in flood-risk zone	Increase (no. of facilities)	Increase (%)
Category 1			
Present day	151	–	–
30 cm sea-level rise	177	26	17.22
60 cm sea-level rise	206	55	36.42
90 cm sea-level rise	248	97	62.58
Category 2			
Present day	253	–	–
30 cm sea-level rise	282	29	11.46
60 cm sea-level rise	317	64	25.30
90 cm sea-level rise	341	88	34.78
Category 3			
Present day	361	–	–
30 cm sea-level rise	385	24	6.65
60 cm sea-level rise	409	48	13.30
90 cm sea-level rise	428	67	18.56
Category 4			
Present day	445	–	–
30 cm sea-level rise	457	12	2.70
60 cm sea-level rise	469	24	5.39
90 cm sea-level rise	477	32	7.19
Category 5			
Present day	487	–	–
30 cm sea-level rise	493	6	1.23
60 cm sea-level rise	495	8	1.64
90 cm sea-level rise	504	17	3.49

Each sea-level rise scenario causes an increase in the number of vulnerable critical facilities. The increase is particularly striking for hurricanes of lesser intensity, as even small increases in sea level put substantial numbers of additional facilities at risk. However, for hurricanes of Category 5, most critical facilities are already included in the storm-surge flood-risk zone before additional sea-level rise takes place. Even the 90 cm sea-level rise scenario does not put many more facilities at risk because the remaining facilities are mostly located inland on much higher terrain.

4.3. SOCIAL AND OVERALL VULNERABILITY

Projections of changes to the population composition of census block groups are unlikely to be accurate or realistic over a timeframe of nearly 100 years. Consequently, this study did not attempt to project changes in the social vulnerability of Hampton Roads over the next century. To analyze changes in overall vulnerability with sea-level rise, the study simply calculated how overall vulnerability would change if the current population composition of Hampton Roads were exposed to expanded storm-surge flood risk zones. Table IX shows increases in mean overall vulnerability scores with sea-level rise, and Table X shows changes to the size of each zone.

Maps depicting changes to overall vulnerability (not shown) appear insignificant at first glance because much of the western part of the study

Table IX. Mean overall vulnerability scores.

Scenario	Mean overall vulnerability score
Present	0.1157
30 cm SLR	0.1210
60 cm SLR	0.1260
90 cm SLR	0.1311

Table X. Changes to overall vulnerability zones with sea-level rise.

Overall vulnerability zone	Scenario						
	Present	30 cm SLR		60 cm SLR		90 cm SLR	
	Size (km^2)	Size (km^2)	% Change	Size(km^2)	% Change	Size (km^2)	% Change
Very high	8	10	21.05	12	51.09	18	115.82
High	148	168	13.57	182	23.12	208	41.15
Moderate	723	788	9.02	859	18.87	926	28.06
Low	6669	6582	−1.30	6494	−2.62	6396	−4.10

area is too far inland and too high in elevation to be at risk of storm-surge flooding. However, the heavily developed southeastern portion of Hampton Roads does exhibit important increases in overall vulnerability with sea-level rise. Any increases in overall vulnerability in South Hampton Roads are of particular concern because this area has high investments in infrastructure and high concentrations of people who are likely to experience difficulty coping with disasters.

5. Addressing Uncertainties and Creating Bounding Scenarios

5.1. POPULATION GROWTH AND DISTRIBUTION

Although a characterization of the composition of future populations was considered to be of dubious accuracy, it was judged possible to estimate the *size* of the at-risk population. To make such an estimate, it was first necessary to consider uncertainty in rates of population growth and in future population distribution patterns. Estimates of absolute population growth for the region were obtained from the National Planning Association (NPA Data Services, 1998). NPA provides county-level population projections; in the Commonwealth of Virginia, independent cities are combined with neighboring counties. Projections go to the year 2050 and are based on factors such as birth rates, death rates, and migration. After considerable exploration of possible projection techniques, this study extrapolated the NPA projections to the year 2100 using a simple linear model; see Table XI for the resulting high-end, baseline, and low-end population projections for Hampton Roads. These estimates assume high, medium, and low growth, respectively, for every county in the study area. However, it is unlikely that growth will be uniform among all counties in Hampton Roads. Because many coastal frontages are already heavily built, it is reasonable to assume that future coastal development may slow while inland development, where flood risk is lower, may increase (Wu *et al.*, 2002).

Given the level of uncertainty about future growth patterns, three population distribution scenarios were constructed (not shown). The high-risk population distribution scenario assumes that the population in 2100 will have the same distribution as today; that is, Hampton Roads will exhibit

Table XI. Population estimates for 2100, extrapolated from NPA projections.

Projection	Population estimate for 2100
High-end	4,086,416
Baseline	3,140,294
Low-end	2,230,004

high rates of growth in heavily developed coastal areas with low or moderate growth elsewhere. Given that cities such as Norfolk and Portsmouth have shown population decline over the last decade, this scenario is the least likely of the three. The medium-risk scenario was loosely constructed around socioeconomic data from the Hampton Road Planning District Commission (Pickard, 2003). Over the next few decades, local authorities expect to see continued population decreases in portions of Norfolk and Portsmouth; they also anticipate population losses in the most heavily developed coastal portions of Newport News and Hampton. Population increases are still expected in the coastal cities of Chesapeake, Virginia Beach, and Suffolk, but also in some inland areas where flood risks are lower. The low-risk scenario assumes that all heavily developed coastal areas will show low rates of growth, while areas farther inland will have high or moderate growth. This scenario assumes that development will increase substantially in the rural subdivision.

Given the population distribution scenarios described above, plausible population estimates for Hampton Roads in 2100 were created (Table XII). For each city or county, either the low-end, baseline, or high-end population estimate extrapolated from the NPA dataset was chosen. However, further breakdowns were needed for parts of cities and for independent cities grouped with nearby counties. First, the 2000 population of each NPA geographic unit was found and the percentage of that population currently living in each subdivision was calculated. Then, future population in each subdivision was estimated by calculating that percentage of the chosen population estimate for each NPA unit.

5.2. FUTURE IMPACT SCENARIOS

The various sea-level rise and population distribution scenarios were combined to create three future impact scenarios. Although dozens of possible future impact scenarios could have been used, the goal was to provide a credible medium-risk scenario and realistic upper and lower bounds.

The upper-bound scenario is based on a 90 cm increase in sea-level and the high-risk population distribution pattern. The medium scenario uses

Table XII. Population estimates for 2100, based on various population distribution scenarios.

Population distribution scenario	Population estimate for 2100
High risk	3,888,581
Medium risk	3,238,210
Low risk	2,446,786

the medium-risk population distribution scenario and assumes a 60 cm increase in sea level. The lower bound scenario incorporates the 30 cm sea-level rise scenario and the low-risk population distribution pattern. For each future impact scenario, Table XIII shows the future population estimates within each flood-risk zone. The present-day population of each flood-risk zone is also included for comparison.

For each future impact scenario, the absolute number of people in each flood-risk zone is higher than at present. For the upper-bound scenario, the percentage of the total population in each flood-risk zone increases substantially. Percentage increases for the medium future impact scenario are also significant. However, percentage increases for the lower-bound scenario are not as substantial. For hurricanes of Categories 1 through 3, the percentage of the total population within the storm-surge flood-risk zone is only slightly higher than at present. The percentage of the total population within the flood-risk zone for hurricanes of Categories 4 and 5 is smaller than at present.

6. Conclusions

This paper assessed the vulnerability of the people and infrastructure of Hampton Roads, Virginia to present-day hurricane storm-surge flooding resulting from future sea-level rise. The analysis demonstrated that those areas of the region most likely to experience storm-surge floods today are the same areas where the most socially vulnerable population segments live. The most conservative sea-level rise scenario shows major increases in the population potentially exposed to storm-surge floods; less conservative scenarios show even greater populations exposed to storm surges. Again, the most vulnerable populations would be more likely to experience flooding than less vulnerable populations. In addition, the most conservative sea-level rise scenario reveals that large proportions of the region's critical

Table XIII. Population estimates for each storm-surge flood-risk zone.

Hurricane category	Scenario							
	Present		Upper-bound		Medium		Lower-bound	
	Population	%	Population	%	Population	%	Population	%
1	176,318	11.2	729,798	18.8	408,568	12.6	281,966	11.5
2	386,745	24.6	1,517,397	39.0	944,484	29.2	619,973	25.3
3	683,493	43.4	2,286,038	58.8	1,692,402	52.3	1,116,823	45.6
4	947,452	60.2	2,674,937	68.8	2,055,912	63.5	1,439,950	58.9
5	1,088,217	69.1	2,941,929	75.7	2,362,737	73.0	1,652,042	67.5

facilities are at risk of flooding, even with relatively weak storms. Scenarios that account for future population growth and distribution show that low overall growth rates, especially away from low-lying coastal and near-coastal positions, limits the potential exposure to storm-surge flooding. In contrast, moderate to high growth results in considerable risk to hundreds of thousands of people, especially if development occurs in coastal and near-coastal areas. The problem is compounded by the expansion of each flood-risk zone as a result of sea-level rise.

The messages from this analysis are clear: hurricane storm surge presents a considerable hazard to the inhabitants of Hampton Roads, especially to those people who are likely to be most sensitive to the hazard and least likely to adjust or adapt in the case of disaster. Moreover, future sea-level rise, population growth, and poorly planned development will result in significantly greater risk of storm-surge flooding to more people in this area. Local planners should account for the storm-surge zones identified in this research when considering future development in Hampton Roads, paying special attention to the placement of critical facilities and of housing for poor, elderly, and other vulnerable people.

Acknowledgements

We thank Arthur Taylor of the National Oceanic and Atmospheric Administration, Joseph Gavin of the Army Corps of Engineers, and Andrew Pickard and Eric Walberg of the Hampton Roads Planning District Commission for their help with this research. We also thank Rob Neff and Jason Spangler, Center for Integrated Regional Assessment, for help with some of the analyses and programming. This material is based on work supported by the US Environmental Protection Agency under Cooperative Agreement No. R-830533-01-0 (Ann Fisher, Principal Investigator) and by the National Science Foundation under Grant No. SBE-9978052 (Brent Yarnal, Principal Investigator). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the US Environmental Protection Agency or the National Science Foundation.

References

Bingham, E.: 1991, The physiographic provinces of Virginia, *Virginia Geographer* **23**, 19–32.

Boon, J.: 2004, The three faces of Isabel; storm surge, storm tide, and sea level rise, accessed at http://www.vims.edu/physical/research/isabel/.

Church, J. A. and Gregory, J. M.: 2001, Changes in sea level, In: J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. Linden van der and D. Xiaosu (eds.), *Climate Change 2001: The Scientific Basis*, Cambridge: Contribution of the Working Group I to the Third

Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Pres, pp. 639–693.

Clark, G., Moser, S., Ratick, S., Dow, K., Meyer, W., Emani, S., Jin, W., Kasperson, J., Kasperson, R., and Schwarz, H. E.: 1998, Assessing the vulnerability of coastal communities to extreme storms: The case of Revere, MA, USA, *Mitigation Adapt. Strategies Global Change* **3**, 59–82.

Clark, W. C., Jager, J., Corell, R., Kasperson, R., McCarthy, J. J., Cash, D., Cohen, S. J., Desanker, P., Dickson, N. M., Epstein, P., Guston, D. H., Hall, J. M., Jaeger, C., Janetos, A., Leary, N., Levy, M. A., Luers, A., MacCracken, M., Melillo, J., Moss, R., Nigg, J. M., Parry, M. L., Parson, E. A., Ribot, J. C., Schellnhuber, H.-J., Seielstad, G, A., Shea, E., Vogel, C., Wilbanks, T. J.: 2000, Assessing vulnerability to global environmental risks, *Report of the Workshop on Vulnerability to Global Environmental Change: Challenges for Research, Assessment and Decision Making, Warrenton, VA*, Research and Assessment Systems for Sustainabiiity Program Discussion Paper 2000-12, Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, Cambridge, MA.

Cobb, H.: 1991, The Chesapeake-Potomac hurricane of 1933, *Weatherwise* **44**, 24–29.

Cutter, S. L., Mitchell, J. T., and Scott, M. S.: 2000, Revealing the vulnerability of people and places: A case study of Georgetown county, South Carolina, *Ann. Assoc. Am. Geogr.* **90**, 713–737.

Flather, R. A. and Khandker, H.: 1993, The storm surge problem and possible effects of sea level changes on coastal flooding in the Bay of Bengal, In: R. A. Warrick, E. M. Barrow and T. M. L. Wigley (eds.), *Climate and Sea Level Change: Observations, Projections, and Implications*, Cambridge, UK: Cambridge University Press, pp. 229–245.

George, D. and Mallery, P.: 2003, *SPSS for Windows: Step by Step*, Allyn and Bacon, Boston, MA.

Gönnert, G.: 2004, Maximum storm surge curve due to global warming for the European North Sea region during the 20th–21st century, *Nat. Hazards* **32**, 211–218.

Hampton Roads Planning District Commission: 2003, Hampton Roads 2003 data book, accessed at http://www.hrpdc.org/economics/Databook03.shtml.

IHDP: 2001, Special issue on vulnerability, *IHDP (International Human Dimensions Program) Update* Vol. 2, 1–16, accessed at http://www.ihdp.unibonn.de/html/publications/update/IHDPUpdate01_02.html.

Jelesnianski, C., Chen, J., and Shaffer, W.: 1992, SLOSH: Sea, lake, and overland surges from hurricanes, *NOAA Technical Report NWS 48*, Silver Spring, MD.

Kasperson, J. X. and Kasperson, R. E.: 2001, A workshop summary prepared on behalf of workshop participants, *International Workshop on Vulnerability and Global Environmental Change, 17–19 May 2001*, SEI Risk and Vulnerability Programme Report 2001-01, Stockholm Environment Institute (SEI), Stockholm, Sweden.

Kleinosky, L.R., O'Sullivan, D., and Yarnal, B.: 2005, A method for constructing a social vulnerability index: An application to hurricane storm surges in a developed country, *Mitigation Adaptation Strategies for Global Change* (in press).

Leatherman, S. P., Chalfont, R., Pendelton, E. C., McCandless, T. L., and Funderburk, S.: 1995, *Vanishing Lands, Sea Level, Society, and Chesapeake Bay*, University of Maryland and US Fish and Wildlife Service, Annapolis, MD.

Luers, A. L., Lobell, D. B., Sklar, L. S., Addams, C. L., and Matson, P. A.: 2003, A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico, *Global Environ. Change* **13**, 255–267.

McInnes, K. L., Walsh, J. E., Hubbert, G. D., and Beer, T.: 2003, Impact of sea-level rise and storm surges on a coastal community, *Nat. Hazards* **30**, 187–207.

McLean, R. F. and Tsyban, A.: 2001, Coastal zones and marine ecosystems, In: J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken and K. S. White (eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Cambridge, UK: Cambridge University Press, pp. 343–379, Contribution of the Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change.

Najjar, R. G., Walker, H. A., Anderson, P. J., Barron, E. J., Bord, R. J., Gibson, J. R., Kennedy, V. S., Knight, C. G., Megonigal, J. P., O'Connor, R. E., Polsky, C. D., Psuty, N. P., Richards, B. A., Sorenson, L. C., Steele, E. M., and Swanson, R. S.: 2000, The potential impacts of climate change on the mid-Atlantic coastal region, *Climate Res.* **14**, 219–233.

National Hurricane Center: 2005a, Hurricane awareness: Storm surge, accessed at http://www.nhe.noaa.gov/HAW2/engli.sh/storm_surge.shtml.

National Hurricane Center: 2005b, Saffir–Simpson hurricane scale, accessed at http://ratfish.nhc.noaa.gov/aboutsshs.shtml.

National Weather Services: 2005, Hurricane storm surge forecasting, accessed at http://www.nws.noaa.gov/tdl/marine/hursurge.htm.

Nicholls, R. J. and Leatherman, S. P.: 1996, Adapting to sea-level rise: Relative sea-level trends to 2100 for the United States, *Coastal Manage.* **24**, 301–324.

Nicholls, R. J., Hoozemans, F. M. J., and Marchand, M.: 1999, Increasing flood risk and wetland losses due to sea-level rise: Regional and global analyses, *Global Environ. Change* **9**, S69–S87.

NOAA Coastal Services Center: 1999, Community vulnerability assessment tool: New Hanover County, North Carolina case study, NOAA Coastal Services Center, Charleston, SC, accessed at http://www.csc.noaa.gov/products/nchaz/startup.htm.

NPA Data Services: 1998, *Regional Economic Projections Series*, NPA Data Services, Washington, DC.

Pickard, A.: 2003, *Hampton Roads 2000 and 2026 socioeconomic data by TAZ*, Hampton Roads Planning District Commission, Chesapeake, VA.

Powars, D.: 2000, Vol. 1612, The effects of the Chesapeake Bay impact crater on the geological framework and correlation of hydrogeologic units of the lower York – James Peninsula, Virginia, *U.S. Geological Survey Professional Paper* 1622, U.S. Geological Survey, Washington, DC.

Psuty, N. P.: 1992, Estuaries: Challenges for coastal management, In: P. Fabbri (ed.), *Ocean Management in Global Change*, London: Elsevier Applied Science, pp. 502–518.

Schneider, S. and Sarukhan, J.: 2001, Overview of impacts, adaptation, and Vulnerability to climate change, In: J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken and K. S. White (eds.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, Cambridge, UK: Cambridge University Press, pp. 75–103, Contribution of the Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change.

Tsyban, A. V., Everett, J. T., and Titus, J. G.: 1990, World oceans and coastal zones, In: W. Tegart, G. W. Sheldon and D. C. Griffiths (eds.), *Climate Change: The IPCC Impacts Assessment*, Canberra, Australia: Australian Government Publishing Service, pp. 1–28.

United States Geological Survey: 2004, The national map: Seamless data distribution viewer, accessed at http://seamless.usgs.gov/.

Virginia Department of Emergency Management: 2005, Library: the hurricane history of coastal Virginia, accessed at http://www.vaemergency.com/newsroom/history/hurricane.cfm.

Virginia Economic Development Partnership; 2004, Ally information exchange, geographic information systems, accessed at http;//gis.vedp.org/meta/metadata/html.

Walker, H. J. and Coleman, J. M.: 1987, Atlantic and Gulf coastal province, In: W. Graf (ed.), *Geomorphic Systems of North America, Centennial Special Vol. 2*, Boulder, CO: Geological Society of America, pp. 51–l00.

Wu, S. Y., Yarnal, B., and Fisher, A.: 2002, Vulnerability of coastal communities to sea-level rise: A case study of Cape May County, New Jersey, USA, *Climate Res.* **22**, 255–270.