Climate Change Effects on Transportation Infrastructure

Scenario-Based Risk Analysis Using Geographic Information Systems

Yao-Jan Wu, Tanveer Hayat, Andres Clarens, and Brian L. Smith

The potential effects of climate change on transportation infrastructure have been receiving attention in recent years. An especially useful and increasingly common approach to investigating the potential effects of climate change on infrastructure is the use of geographic information systems (GISs) for risk analysis because climate change effects are likely to occur in conjunction with other geographically specific impacts such as storm surge and traffic operations, whose vulnerability can be most effectively quantified with GIS-based tools. To demonstrate the efficacy of these tools, a scenario-based risk analysis approach is presented: it investigates the effects of climate change on transportation infrastructure in Hampton Roads, Virginia. First, climate change effects in the study site are investigated to develop representative climate change scenarios. Then, a GIS-based evaluation of transportation infrastructure vulnerability to sea level rise and storm surge is formed by combining the GIS data set with results from the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model. Finally, the proposed risk model generates a GIS-based risk map under three scenarios of climate change threat. Results indicate that the city of Virginia Beach, Virginia, is at high risk in all three scenarios because of climate change events, a high level of transportation activity, and density of transportation facilities. The risk map—a visualization of the risk model—can assist transportation planners and decision makers with prioritizing assets to allocate resources for emergency preparation and response.

Climate change is expected to drive hydrologic cycles and extreme weather events in a way that is almost certain to affect transportation infrastructure. Climate is an important factor influencing the construction, operations, and maintenance of the transportation infrastructure system, particularly in coastal regions (*1*). Several key climate change events (e.g., sea level rise, increased precipitation, increased frequency and intensity of hurricanes) already have been identified as crucial variables affecting future transportation planning and operations (*2*). From California (*3*) to London (*4*), people around the world are aware of potential climate change impacts on transportation systems and plan to manage the risks. Understanding the risks allows decision makers to develop adaptations in advance and traffic planners to adjust long-range plans accordingly. Meyer et al. indicate that today's project development process requires risk-oriented analysis to consider potential vulnerabilities for infrastructure assets and suggest incorporating climate-induced change into transportation decision making at the state and local levels (*5*).

Making transportation decisions with climate change considerations is a new concept (*6*). In practice, transportation decision makers commonly use vulnerability, risk, and adaptation assessments to aid the process (*6*). Vulnerability assessment focuses on how climate change would affect transportation systems, whereas risk assessment evaluates the combination of likelihood and consequence of climate change impacts. However, vulnerability and risk could be defined in various ways depending on the context (*7*). For consistency in this study, risk analysis is considered an integral of vulnerability and risk assessment.

Geographic information systems (GISs) provide an effective means of visually delivering the results of the risk analysis process. Thus, GIS-based risk analysis has been widely applied in civil engineering processes such as flood analysis (*8*), hazard material transportation (*9, 10*), seismic bridge analysis (*11*), coastal maritime risk analysis (*12*), and industrial site vulnerability to the surrounding environment (*13*). Recently, research efforts have used GIS to investigate climate change impacts on transportation infrastructure. Jenelius et al. assess critical transportation infrastructure quantitatively, deriving several indices of traffic link importance to evaluate the criticality of the transportation network (*7*). Moser and Tribbia (*3*) adopt a coastal vulnerability index created by Hammar-Klose and Thieler (*14*) to determine the risk of inundation and erosion in California. Gwilliam et al. adopt the concept of the risk map, a combination of vulnerability layer and hazard-exposure layer (*15*). GIS operations are used to generate various types of risk maps, but transportation infrastructure is not the research focus.

Kleinosky et al. consider the impacts of storm surges and sea level rise in Hampton Roads, Virginia, in a vulnerability evaluation that focuses on social vulnerability but lacks an evaluation of transportation vulnerability (*16*). They use the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model to predict storm surge flooding caused by all categories of hurricanes (*17*). Zahran et al. use GIS and statistical techniques to estimate the distribution of climate change risks for metropolitan areas in the United States (*18*). Even though all these research efforts analyze the effects of climate change

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on transportation facilities, the scope is too broad to cover specific climate change impacts on individual transportation facilities, and the climate change scenarios are vague. To address this need, Lu and Peng develop a scenario-based vulnerability analysis to evaluate the impact of sea level rise on transportation network accessibility in Miami, Florida (*19*). The accessibility reduction rate by traffic analysis zone is adopted as a metric to evaluate the vulnerability of the transportation network under two scenarios of sea level rise. Walker et al. identify surface transportation vulnerability for different types of assets and discuss risk management under climate change with Portland, Oregon, as a case study site (*20*).

Results of the literature review indicate that scenario-based analyses can help decision makers understand how climate change would affect transportation assets; however, the construction of representative scenarios is challenging because climate change is uncertain by nature. Moreover, traditional risk analyses tend to lack focus on transportation assets or focus on one type of climate change event (e.g., sea level rise). Therefore, the objectives of this paper are to (*a*) develop reasonable and representative climate change scenarios to facilitate GIS-based risk analysis, (*b*) evaluate the vulnerability of transportation assets to sea level rise and storm surge by combining GIS data sets and the results from the SLOSH model, and (*c*) develop GIS-based risk maps under different climate change risk scenarios to assist decision makers with long-range transportation planning. Hampton Roads is used as a case study site to demonstrate the method.

The paper is organized as follows. First, the geographical and climate characteristics of Hampton Roads are presented. Next, the development procedure for creating representative climate change scenarios for Hampton Roads is described. These scenarios then are used in the GIS-based risk analysis, which focuses on asset vulnerability analysis and spatial risk assessment of the transportation infrastructure. The paper concludes with findings and future work.

STUDY SITE: HAMPTON ROADS

Geographic Description

Located in southeastern Virginia, the Hampton Roads region is surrounded by the Chesapeake Bay, the largest estuary in the United States (Figure 1). The U.S. Census Bureau defines the region as 16 cities and counties in Virginia and North Carolina, with a population of about 1.7 million according to the 2010 U.S. census and a population density of 425.7 people per square mile. The economy of the region is diverse; a strong tourism industry is built around the coastal location, and significant trade ports and military installations make this region critical in terms of politics and national security. The area also is home to several large corporations representing food, health care, transportation, and military contracting.

Because of its location in the low-lying physiographic Atlantic coastal plane with intensive development and dense population, Virginia Beach, Virginia, is ranked the 19th most vulnerable coastal metropolitan area in terms of assets exposed to coastal flooding in the 2070s as a result of climate change and projected socioeconomic change (*21*). The Hampton Roads region is selected as the study site because of its high vulnerability to climate change effects, especially from sea level rise and storm surges.

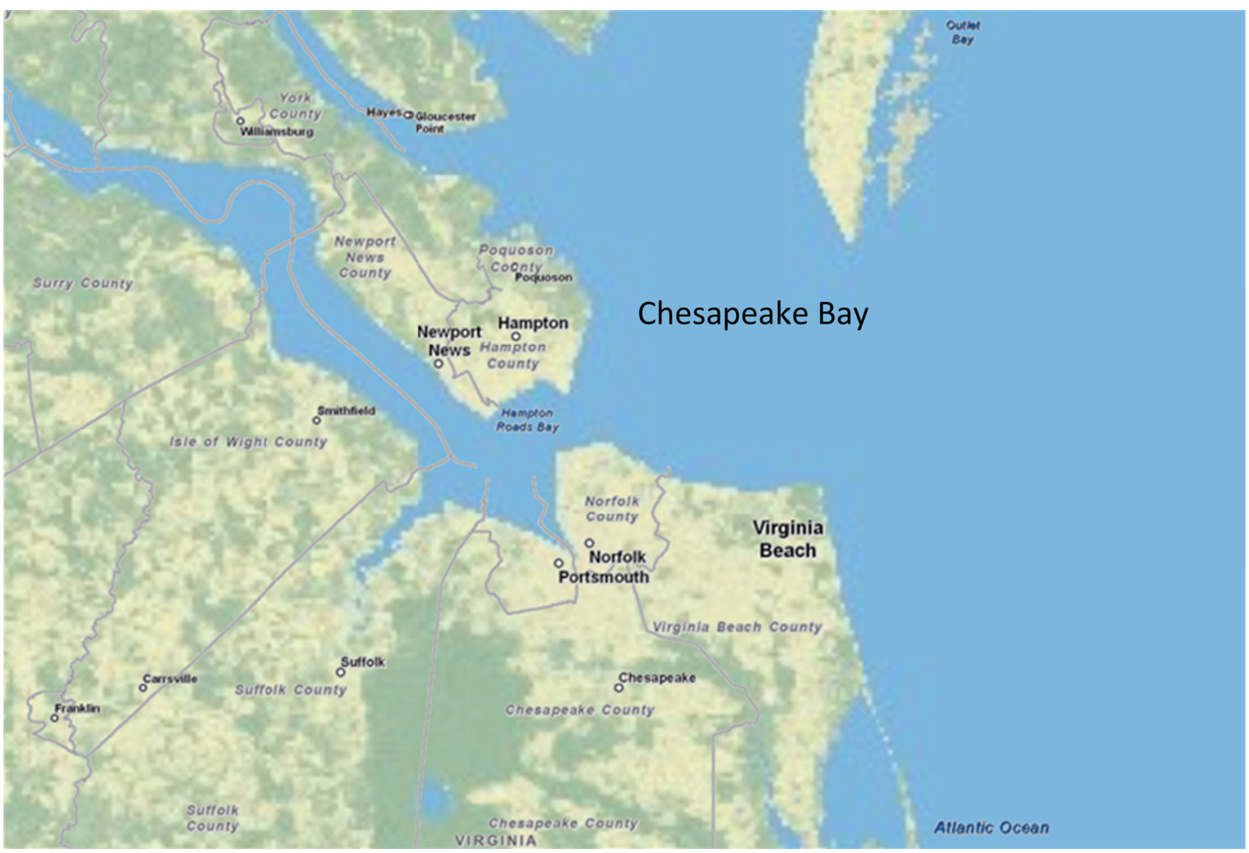


FIGURE 1 Hampton Roads area. (Source: http://resources.arcgis.com/.)

Climate Change

A 2010 report from the Hampton Roads Planning District Commission indicates that many climate change impacts such as inundation, flooding, and severe weather events associated with storm surge are already occurring (*22*). Such impacts are predicted to increase in the next century. Sea level rise is a major concern, and land subsidence increases the vulnerability of low-lying coastal areas. As climate change threats have increased, many listening sessions have been held to increase public attention and involvement (*23*), and climate change studies have assessed the Hampton Roads region's vulnerability to climate change (*22, 24–26*).

CLIMATE CHANGE SCENARIOS

Development

Climate change scenarios are developed to qualitatively and quantitatively identify the impact of different climate change events on the transportation infrastructure. The objectives of scenario development are twofold: scenarios that reflect the reality of the target site provide reliable outcomes for decision makers, and specific scenarios can help decision makers effectively evaluate the effects of climate change with respect to different risk levels.

Cause-and-Effect Analysis

Before scenarios can be created for further risk analysis, the climate change influences and effects in Hampton Roads must be understood. The causes and effects of the Hampton Roads climate scenario are illustrated in Figure 2, which aims to help people who are not climate experts understand the causes and effects of climate-related threats so they can identify the key factors that must be included in the synthetic scenarios. Figure 2 consists of four major sections, each of which contains several climate (or climate change) events:

- Climate change (long-term). Increasing temperature will result in melting glaciers and further raise the sea level but also will increase circulation in the atmosphere as well as the intensity and frequency of precipitation. As indicated by the arrow for relationship flow, climate change would influence the intensity and frequency of the natural disaster component.
- Natural disaster (short-term). Hampton Roads is known for its vulnerability to hurricanes. A snow storm is considered a disaster that brings heavy precipitation and wind. However, hurricanes are a major concern because they bring not only heavy precipitation and wind but also stormwater and storm surge.
- Climate events. The major climate effects are storm surge and stormwater. The severity of these effects would depend on the intensity and frequency of hurricanes.
- Resulting impacts. Inundation and flooding are the major climate change concerns in the Hampton Roads area (*22*). Precipitation would increase the severity of stormwater and the level of inundation and flooding. After inundation or flooding, the level of transportation use would decrease. Heavy precipitation and strong winds would have the same consequences. If the situation becomes more serious, the transportation infrastructure would be destroyed.

Figure 2 is specific to the case study site, but the same concept can be applied to future applications with minor changes (e.g., the natural disaster section might include drought or tornadoes for a different study area). Increasing temperature could have direct impacts on transportation infrastructure (e.g., bridges and pavement). With this diagram, transportation analysts can identify the major climate-related causes and effects in a complicated climate system. This diagram is not designed to fully describe all of the complicated cause-and-effect relationships for all events at the study site; it is

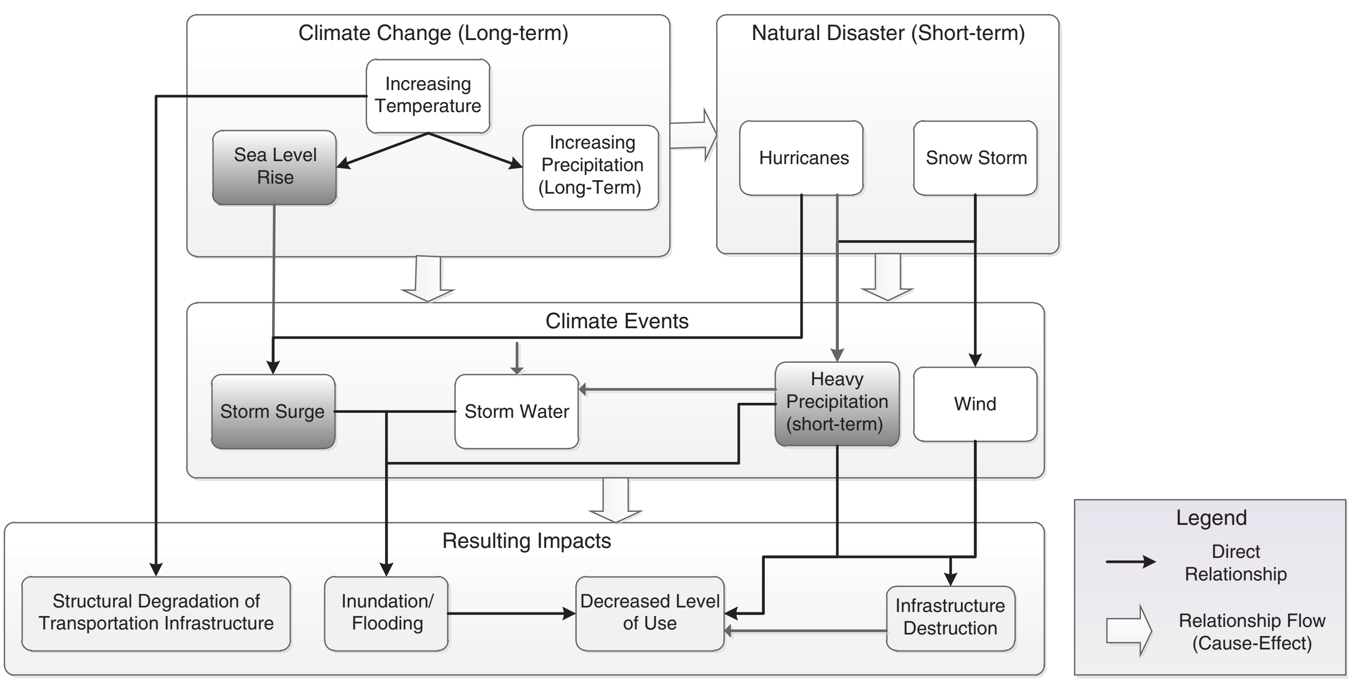


FIGURE 2 Climate change scenario causes and effects in Hampton Roads.

intended to help transportation analysts understand the major causes and effects so they can develop experimental scenarios.

Development Process

After the climate change causes and effects have been explored, the key climate change components can be identified. For the Hampton Roads area, each scenario is assumed to be a combination of different climate-related events, and many events could occur concurrently.

In the present study, a scenario is assumed to combine long- and short-term climate events. The impacts of these events—assumed to be additive—are considered the key events that must be included in the scenario. The reasons are explained as follows:

- Long-term climate change and geologic event. Sea level rise, land subsidence, and precipitation would have additive effects; however, the effects of temperature and sea level rise are difficult to combine. Temperature contributes to sea level rise, as indicated in Figure 2, but long-term precipitation is not an immediate threat to the study site. As a result, only sea level rise is considered for future scenario development.
- Short-term climate change event. Both storm surges and short-term precipitation (precipitation intensity) are additive and considered for future scenario development because storm surges plus precipitation aggravate the effect from a short-term disaster perspective.

Therefore, effective sea level rise, precipitation intensity, and storm surges caused by hurricanes are included in scenario development.

Facts and Projections

Sea Level Rise

Of all climate change events, sea level rise probably is one of the most threatening and noticeable in the Hampton Roads area. According to McFarlane, the observed sea level trends from National Oceanic and Atmospheric Administration (NOAA) tide gauges range from 3.48 ± 0.42 to 6.06 ± 1.14 mm/year (0.137 ± 0.017 to 0.239 ± 0.045 in./year) (*25*). This trend suggests that the sea level would rise about 0.35 to 0.6 m (1.14 to 1.98 ft) over 100 years (*27*) and that sea level rise in the Chesapeake Bay would be 0.7 to 1.6 m (2.3 to 5.2 ft) by 2100 (*26*).

Predicted sea level rise varies by location. Therefore, the accurate prediction of sea level rise for any specific location or region without a tidal station is challenging. Because this study focuses on scenario-based analyses of the outcomes of climate change, precise prediction of sea level is not necessary for scenario generation. Thus, a simplified model for predicting sea level from the U.S. Environmental Protection Agency (EPA) is used in this study to capture a general idea of sea level rise in the Hampton Roads area. This simplified model is formulated as follows (*28*):

$$\text{local}(t) = \text{normalized}(t) + (t - 1990) \times \text{trend} \qquad (1)$$

where

t = sea level projection year,
local(t) = sea level rise by year t at a particular location,
normalized(t) = normalized sea level projections compared with 1990 levels, and
trend = current rate of relative sea level rise at a particular location [a rate of 0.43 cm/year (0.17 in./year) is suggested for Hampton Roads (*28*)].

The normalized projections remove the effects of greenhouse contributions and estimate "the extent to which sea level rise will exceed what would have happened if current trends simply continued" (*28*). The advantage of the EPA method is that it provides a probabilistic view of the future sea level rise prediction without a precise prediction. Sea level rise projections calculated using Equation 1 are presented in Table 1 by year. This cumulative probability-based table can aid practitioners in creating reasonable and representative scenarios for sea level rise.

Precipitation

As indicated in Figure 2, the effects of precipitation can be categorized as short term or long term. Short-term precipitation effects are more likely to have immediate impacts on traffic flow and traffic operations, whereas long-term precipitation effects are more crucial to infrastructure from a transportation planning perspective; the major impacts of long-term precipitation events include inundation, pavement damage, mudslide, and road subsidence (*29*). Therefore, short-term precipitation intensity is considered in the scenario developed.

The GIS-based and estimated statistical precipitation frequency data (with upper and lower bounds of the 90% confidence interval) are collected from the precipitation frequency data server operated by NOAA. The server provides estimated precipitation frequency for precipitation intensity, with the average recurrence interval ranging from 1 to 1,000 years and the duration ranging from 5 min to 60 days. Figure 3 is a GIS map of estimated precipitation frequency that shows precipitation intensity with an average recurrence interval of 2 years with a 60-min duration in the Ohio River and surrounding states (as well as Hampton Roads).

Storm Surge

"Storm surge" is defined as a long wave motion produced by meteorological force that results in a water surface elevation higher than that produced by normal astronomical tides; this abnormal sea level rise is caused mainly by hurricanes or other tropical storms (*31*). The magnitude of storm surge is measured by subtracting the sea level under normal weather conditions from the sea level observed during a hurricane (*32*). A storm surge has the most destructive effect after a hurricane hits a region and is reported to cause 90% of all hurricane-related fatalities (*33*).

To forecast storm surges during a hurricane, NOAA developed the SLOSH model. The estimation is based on simulation results from thousands of historical, hypothetical, or predicted hurricanes (*34*). The SLOSH model predicts flooding caused by a storm surge at a specific location rather than the areas affected by a storm surge during a hurricane. It uses a complex set of equations developed from Newtonian equations of motion and a continuity equation in a predefined geographical region known as a basin by taking the following parameter inputs (*17*):

- Storm position as a function of time,
- Radius of maximum winds, and
- Difference between central pressure and peripheral pressure.

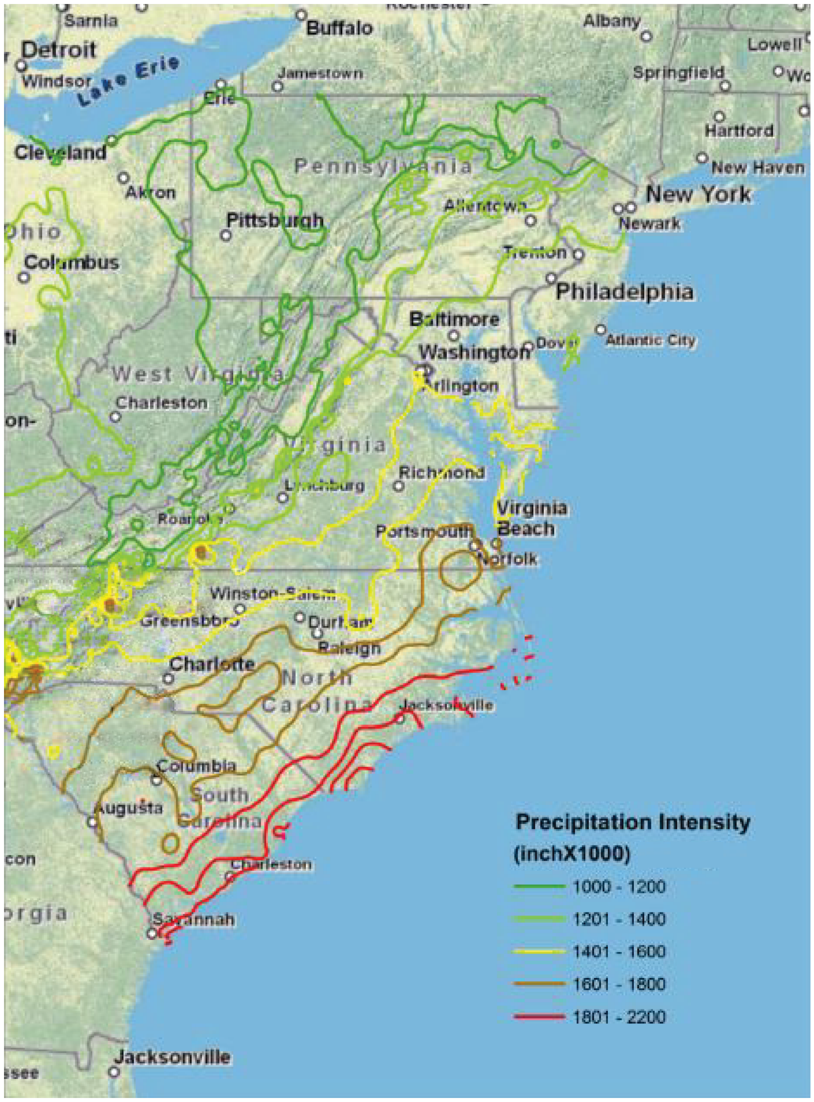


FIGURE 3 Precipitation frequency estimate output: precipitation intensity GIS map (*30*).

For each basin, thousands of hypothetical hurricane iterations are executed, producing two major outputs:

- Maximum envelope of water (MEOW), which is the maximum height of surge at every grid cell in the SLOSH basin, and
- Maximum of the MEOWs, a composite of the maximum storm surge heights for all simulated hurricanes of a given category.

For the purpose of developing a storm surge scenario for GIS analysis, the Chesapeake Bay Basin v2 (Figure 4*a*) was selected because it includes the Hampton Roads area defined in this study. The basin is divided into numerous grid cells, the smallest of which represents an area of about 0.1 mi^2. The SLOSH model contains topographical information for each cell that is combined with storm surge calculations to estimate the water surface elevation for each grid cell. The final output is the combined display of water surface elevation and storm surge for all grid cells in the basin, which was created by applying a color-coded system (Figure 4, *b* and *c*).

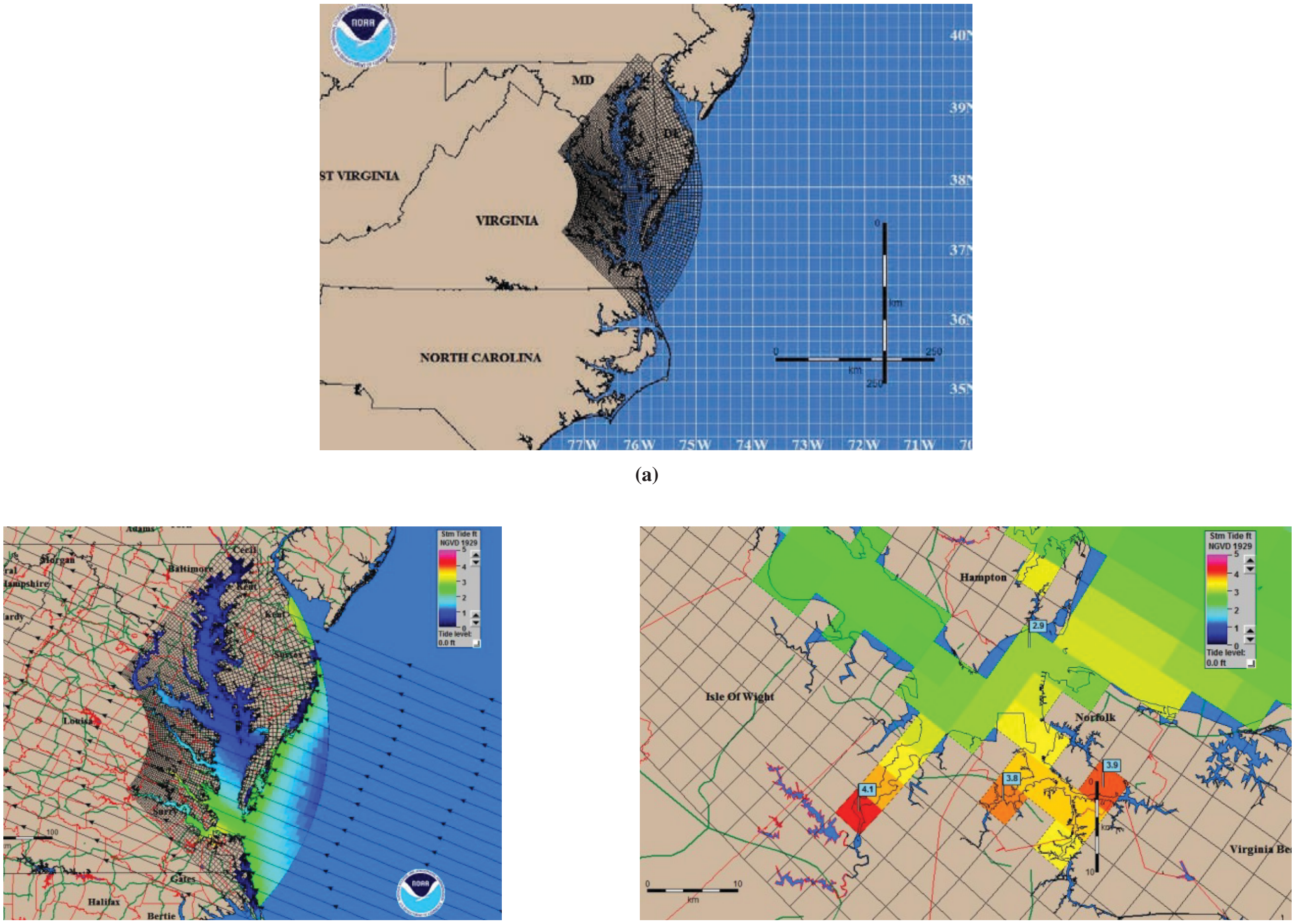
Probability density function curves are created from the SLOSH storm surge database for different hurricanes. The probability density functions of storm surge height for four categories of hurricanes are illustrated in Figure 5. The probability of a high storm surge increases with increased hurricane intensity. These probability density functions are a major resource in determining representative and reasonable storm surge heights for scenario development.

Proposed Scenarios

Even though only the short- and long-term climate events are considered in scenario development, unlimited combinations of events could be used. To assist decision makers, three representative scenarios are proposed with three risk levels: low, medium, and high.

Low-Risk Scenario

- Sea level rise is 1 ft (0.3 m), the lowest bound of the projected value for 100 years in the Hampton Roads area as defined by the Intergovernmental Panel on Climate Change (*25*). Moreover, this



(a)

(b)

(c)

FIGURE 4 SLOSH model: (*a*) Chesapeake Bay Basin v2, (*b*) storm surge simulation, and (*c*) storm surge for each grid cell.

value is close to the 30th-percentile value for the 2050 projection (Table 1).

- A Category 1 hurricane would result in a storm surge of 1 to 5 ft (0.3 to 1.52 m).
- Precipitation is not considered because its contribution is insignificant in this scenario.

Medium-Risk Scenario

- Sea level rise is 1.96 ft (0.6 m), between the lowest and highest bounds of the projected value and close to the 30th-percentile value for the 2100 projection and 70th percentile for the 2075 projection (Table 1).

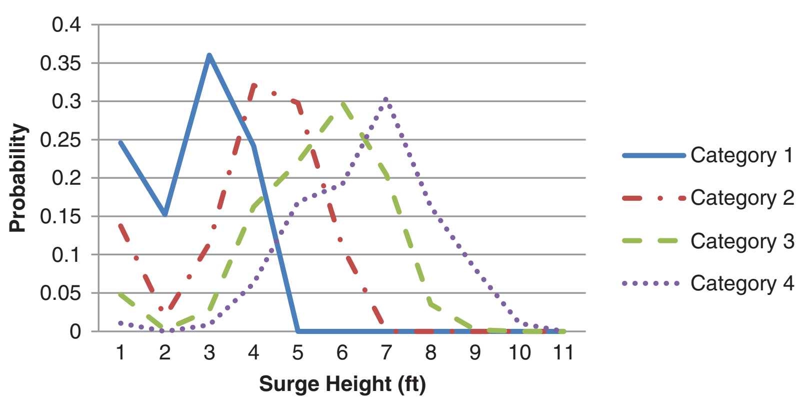


FIGURE 5 Probability density function of storm surge height by storm category.

TABLE 1 Sea Level Projection for Hampton Roads Area, by Year

Cumulative Probability	Sea Level Rise (cm) 2025	2050	2075	2100	2150	2200
1	5.05	9.8	15.55	23.3	36.8	50.3
5	12.05	21.8	31.55	41.3	61.8	82.3
10	14.05	24.8	36.55	48.3	71.8	95.3
20	16.05	28.8	42.55	57.3	84.8	113.3
30	18.05	31.8	46.55	63.3	94.8	127.3
40	19.05	33.8	50.55	67.3	103.8	141.3
50	20.05	35.8	53.55	72.3	111.8	154.3
60	21.05	38.8	57.55	77.3	121.8	168.3
70	23.05	40.8	60.55	83.3	133.8	188.3
80	24.05	43.8	65.55	91.3	148.8	215.3
90	27.05	48.8	73.55	102.3	174.8	264.3
95	29.05	52.8	79.55	113.3	202.8	321.3
97.5	32.05	56.8	86.55	125.3	235.8	386.3
99	34.05	60.8	93.55	139.3	278.8	492.3

- A Category 2 hurricane would result in a storm surge of 2 to 7 ft (0.61 to 2.12 m).
- Precipitation frequency has a 60-min duration and a 2-year recurrence interval, which would result in about 1.7 in./h of rainfall with a 90% confidence interval (*30*).

High-Risk Scenario

- Sea level rise is 3.1 ft (1.0 m), close to the 90th-percentile value for the 2100 projection (Table 1). Sea level rise likely would be 3 to 4 ft (0.92 to 1.22 m) with the effect of high greenhouse gas emissions (*35*).
- A Category 4 hurricane would produce a storm surge of 2 to 11 ft (0.61 to 3.33 m).
- Estimated precipitation frequency has a 60-min duration and a 100-year recurrence interval, which would result in about 3.58 in./h with a 90% confidence interval (*30*).

GIS-BASED RISK ASSESSMENT

To assess the risks to transportation infrastructure under these climate change and weather scenarios, quantitative analyses were conducted and different combinations of data layers were visualized with ArcGIS 10.

Data Description

Several GIS data layers are included in the analyses.

Topographical Data

Obtained from the EPA (published in February 2008), Virginia elevation data with a resolution of 30 m (100 ft) are in raster data class and relative to the spring high water of 2000.

National Highway Data

Obtained from the Virginia Department of Transportation, highway data include information about local, state, and interstate highways as well as annual average daily traffic (AADT).

Transportation Asset Data

Transportation asset data (e.g., freeways, arterials, ports, airports, railroads, and bridges) were collected from the Virginia Department of Transportation and considered in the impact analysis.

Climate Data

Storm surge data were exported from the SLOSH database. The maximum of the MEOWs for each category at high tide was selected from the SLOSH database and then exported as a GIS file for scenario analysis. Precipitation intensity (frequency estimate) data were collected from the Precipitation Frequency Data Server of the Hydrometeorological Design Studies Center (*30*).

Climate Change Impacts on Transportation Infrastructure

The GIS analysis is based on the three proposed scenarios but without considering the effect of precipitation. As mentioned earlier, the effect of precipitation cannot be added to those of sea level rise and storm surge. Risk analysis in the next section can consider the impacts of all data types. Because of the different coverage of each GIS layer, the area of asset impact analysis is confined by the boundary of the SLOSH basin and the elevation data.

Results of analysis for the three scenarios indicate the vulnerability of the transportation infrastructure in the Hampton Roads area. In Table 2, values in parentheses are percentages of transportation infrastructure that would be affected by that particular climate

TABLE 2 Impacts of Different Climate Change Scenarios on Transportation Infrastructure

Scenario	No. of Airports	No. of Limited-Access Highways	No. of Railroads	No. of Ports	No. of Bridges	No. of Highways
No scenario	8	113	2,413	3	2,957	110
Low risk, SLR 0.3 m + Category 1 hurricane	4 (50)	66 (58.4)	1,364 (56.5)	1 (33)	711 (24)	51 (46.3)
Medium risk, SLR 0.6 m + Category 2 hurricane	4 (50)	73 (64.6)	1,478 (60.7)	2 (66)	1,015 (34.3)	58 (52.7)
High risk, SLR 1.0 m + Category 4 hurricane	6 (75)	89 (78.7)	1,875 (78.5)	3 (100)	1,597 (54)	80 (72.7)

NOTE: Values in parentheses are percentages. No. = number; SLR = sea level rise.

change scenario. In the low-risk scenario, all transportation assets have impact percentages greater than 50%, except ports (33%) and highways (46.3%). In the high-risk scenario, all assets have impact percentages greater than 70%, except bridges (54%).

Risk Analysis for Transportation Infrastructure

Because not all the climate (or climate change) events are additive, the analysis of climate change impact in the previous section can investigate only the impact of sea level rise and storm surge. Therefore, the risk map is developed to consider all the effects (risks) caused by all the events. Ma et al. used a similar concept applied to flood disaster (*8*). This study extends the idea to further evaluate the impact of climate change based on the three risk scenarios developed.

Risk Map

To estimate the impact of multiple climate factors in the defined synthetic climate change scenarios, a risk model is proposed. Besides the climate change factors, several risk components were added to the risk model that would influence the vulnerability of the region. Different layers (influential factors) are assumed to have different weights that influence risk. The proposed risk model is formulated as

$$R = \alpha_1 * X_1 + \alpha_2 * X_2 + \alpha_3 * X_3 + \alpha_4 * X_4 + \alpha_5 * X_5 \qquad (2)$$

where

α_i = weights for each factor ($\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 = 1$),
X_i = influence of each factor, and
1 through 5 = factors for sea level rise, storm surge and hurricane, AADT, precipitation intensity, and flood risks, respectively.

An analytic hierarchy process (AHP) was used to determine weights for the influential factors (*36*). A structured technique to organize and analyze complex decision processes (especially useful for group decision making), AHP can help decision makers find the most suitable solution that satisfies their understanding of the problem and the agency's goals. The AHP tool developed by Takahagi was used (*37*). The definitions of and explanations for all influential factors follow:

- Sea level rise (X_1). Land elevation (Z) is a key factor in risk assessment for a region under the threat of sea level rise. The lower the elevation, the higher the risk. Low-lying land not only would be inundated quickly but also would expose people and infrastructure to danger.

$$X_1 = \begin{cases} (Z * (-0.0005) + 1) & \text{for } 0 \le X \le 2{,}000 \text{ (mm)} \\ 0 & \text{for } X > 2{,}000 \text{ (mm)} \end{cases} \qquad (3)$$

- Hurricane category and storm surge heights (X_2). Because tidal movement and precipitation introduce a destructive combination of high-speed winds and water, the associated hurricane risks are assumed to depend on the height of storm surge (H) and hurricane category (C). Weights were assigned for different hurricane categories, with the assumption that the destructive power of a hurricane increases linearly with increasing hurricane intensity.

$$X_2 = C * H \qquad (4)$$

where

$$C = \begin{cases} 0.10 & \text{Category 1} \\ 0.20 & \text{Category 2} \\ 0.30 & \text{Category 3} \\ 0.40 & \text{Category 4} \end{cases} \qquad (5)$$

- AADT (X_3). AADT data for freeways and arterials are included for risk assessment; the higher the volume on a particular roadway, the higher the vulnerability of that roadway.
- Precipitation intensity (X_4). The assigned weights for precipitation intensity (I) are synthetic values to differentiate risk levels for precipitation, which are determined by the partial duration series–based estimates of precipitation frequency (*30*). The 1-h precipitation levels are the lower bounds of 1.41 in. and 4.94 in. (12.54 cm) with 1-year and 1,000-year recurrence intervals, respectively.

$$X_4 = \begin{cases} 0.2 & \text{if } I < 1.41 \text{ in.} \\ 0.3 & \text{if } 1.41 \text{ in.} < I < 4.94 \text{ in.} \\ 0.5 & \text{if } I > 4.94 \text{ in.} \end{cases} \qquad (6)$$

- Flood plain (X_5). The 100-year flood plain (a binary layer in the GIS map) is included because storm surge and heavy precipitation are likely to flood low-lying areas.

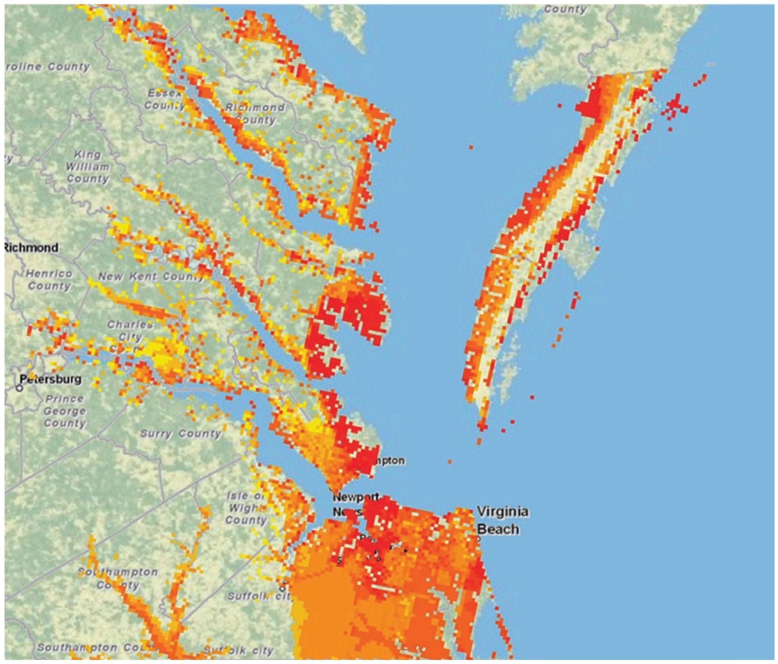
Analysis and Results

The risk formula is applied in the spatial domain with GIS. Because all data layers have different resolutions, Raster Calculator in the Spatial Analyst tools is used to convert all risk contributor layers to raster geographic layers. In this way, Raster Calculator calculates all the individual raster layers by the risk model in Equation 2. The risk maps under the three proposed scenarios (Figure 6) provide a visualization of regional vulnerability in Hampton Roads. The darker the area, the higher the vulnerability of that area. As expected, coastal areas are most vulnerable. Virginia Beach is especially vulnerable; the dark area expands as risk level increases.

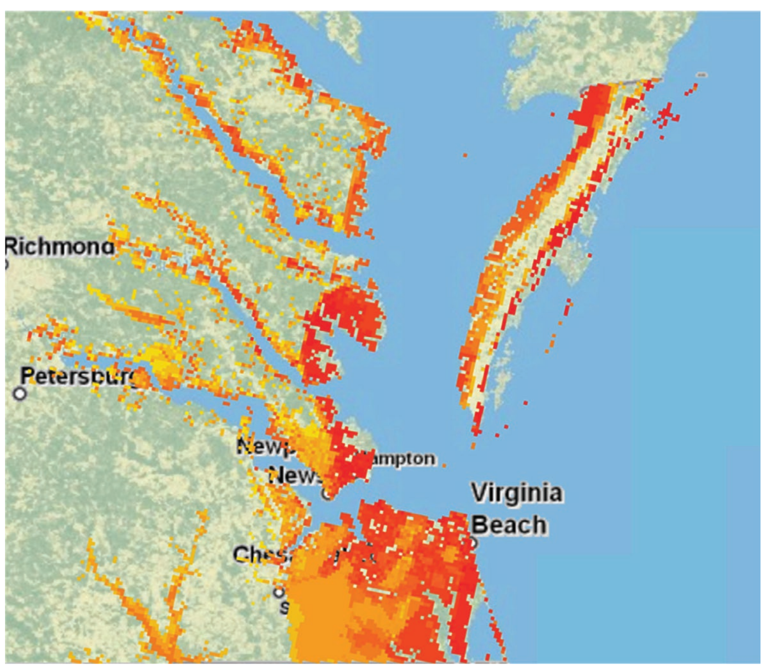
The risk model considers not only climate change and climate effects but also the locations of transportation facilities and activities. Therefore, some inland areas are considered vulnerable. Areas with key transportation infrastructure have increased risk. Visualization of the risk can help transportation planners and decision makers in different agencies prioritize the allocation of resources for emergency preparation and response. Moreover, these maps can provide useful information for the development of better emergency plans. The risk model has higher weights for storm surge and sea level rise in the case study; however, the weights can be adjusted and more data layers (e.g., population data) can be included in future risk calculations.

Discussion of Risk Assessment

Similar scenario-based impact assessment approaches have been taken in the past. A 2009 report from the U.S. Climate Change Science Program focuses on the Mid-Atlantic region, a broader



(a)



(b)

FIGURE 6 GIS-based risk maps: (*a*) low-risk scenario, and (*b*) medium-risk scenario.

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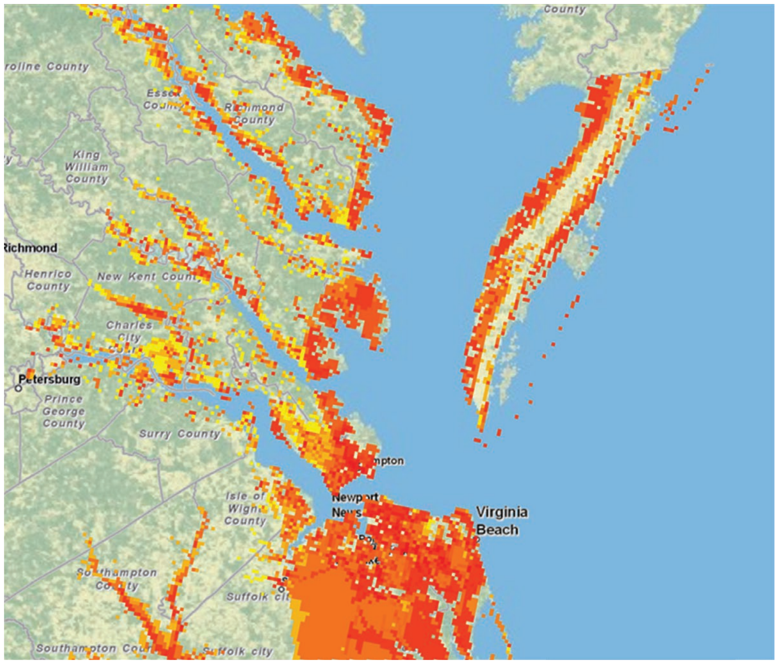

(c)

FIGURE 6 *(continued)* GIS-based risk maps: (*c*) high-risk scenario.

coverage area with a focus on analyzing the effect of sea level rise from a natural environment perspective (*2*). Kleinosky et al. develop similar scenarios but focus their analysis more on socio-economic impacts (*16*). The Hampton Roads Planning District Commission's Phase II report on climate change focuses on the effects of sea level rise and storm surge on specific critical infrastructure and businesses (*25*).

This paper takes a unique approach in combining different levels of sea rise with different categories of hurricane to create scenarios that focus specifically on transportation infrastructure. The major advantage of the proposed risk model is that it is flexible; individual agencies can create their own risk models according to their own priorities and planning policies.

CONCLUSIONS AND RECOMMENDATIONS

Climate change is expected to have a significant effect on transportation infrastructure. GIS-based analysis is a common approach to investigating the effects of climate change. In addition to sea level rise, factors such as storm surge and transportation activities determine the risk level of traffic operations and transportation infrastructure. Risk analysis and vulnerability assessment are fundamental parts of long- and short-term planning.

In an effort to account for the most inclusive set of contributing factors, a scenario-based assessment protocol is adopted here. First, a range of realistic, region-specific climate change effects are developed that consist of primarily sea level rise and storm surge inundation. Next, transportation asset vulnerability to sea level rise and storm surge is evaluated by combining the GIS data set with results from the SLOSH model. Finally, a GIS-based risk map is generated under three developed climate change risk scenarios. Results indicate that coastal areas—especially the city of Virginia Beach—are at high risk due to climate change event trends, dense populations, and complicated and delicate transportation infrastructures.

This paper successfully completed the proposed objectives to (*a*) provide a scenario-based GIS framework for risk analysis, (*b*) demonstrate the analytical procedure for scenario development, and (*c*) demonstrate the feasibility of the GIS-based risk analysis map calculated by the proposed risk model. For future work, scenario development can include different climate and weather events, providing region-specific customization and ongoing trend observation. Furthermore, in the risk model, weights were calibrated by surveying experts on the pilot project team; however, they can be adjusted according to different agency perspectives, and more GIS layers can be included in the risk map analysis. To improve the robustness of the risk model, other complex decision models could be tested in the future.

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