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Impact of Sea Level Rise on Roadway Flooding in the Hampton Roads Region of Virginia

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Abstract: The objective of this study was to determine the most critically vulnerable major roadways in Norfolk and Virginia Beach, Virginia. Sea level rise predictions were combined with the mean higher high water and 99% tidal datums and storm surge predictions to project flood water surface elevations through the year 2100. LiDAR data were used to compare major roadway elevations to the projected flood water elevations to determine which roadway segments would be flooded under different scenarios. Traffic data were used to determine critical road segments in the region (heavily-traveled and low elevation). Results suggest that, by the year 2100, and assuming intermediate sea level predictions, nearly than 10% of major roadways will regularly flood at high tide and 15% at the 99% tide; this increases to more than 65% given a 100-year storm surge event. Five critical road segments were identified that would recurrently flood at high tide by 2100. These road segments should be the focus of infrastructure investments to improve the resiliency of the transportation network within the cities.

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Introduction

Recent flooding events in the United States have caused significant social and economic damage to coastal cities. Hurricanes Katrina and Sandy collectively resulted in more than 1,500 fatalities and $100 billion in damage in the Gulf Coast region and Eastern Seaboard of the United States, respectively (Kates et al., 2006; Galarneau et al., 2013). As sea levels rise and intense storms occur more frequently, flooding events in coastal cities are likely to occur more often and with greater severity (Nicholls and Cazenave, 2010). While the destruction caused by major storm events is well known, more frequent, but less severe floods that are tidally-driven and sometimes called "nuisance floods," are also causing disruptions in coastal cities (Ezer and Atkinson, 2014). These flood events have a high, and increasing, cumulative economic and social cost to coastal cities (Suarez et al., 2005; Sweet et al., 2014).

Flooding due to climate change and resulting sea level rise is likely to have significant impacts on valuable transportation infrastructure systems (Kates et al., 2006; Meyer and Weigel, 2011). In the United States alone, transportation assets were valued at over $7 trillion in 2012, with over half of these assets being publically owned (U.S. Department of Transportation, 2013). An important first step in adapting to increased flood risk is to identify infrastructure most vulnerable to flooding so that physical and economic resource spending can be prioritized (El Raey et al., 1999; Lambert et al., 2013; Roberts, 2010). Roads and bridges that are a) susceptible to flooding due to low elevations and b) have high traffic volumes are of special concern. In this paper, such roads and bridges are referred to as critical road segments.

Prior studies have begun to address the vulnerability of transportation networks to sea level rise. Oswald and Treat (2013) developed and applied a framework for modeling transit flooding using GIS data. Bloetscher et al. (2014) used down-scaled elevation data, including high-resolution

LiDAR data, to identify vulnerable transportation infrastructure. Bloetscher et al. (2012) studied the effect of a rising groundwater table in their flooding model. Instead of focusing on the physical infrastructure itself, Suarez et al. (2005) modeled flood impacts on a transportation system's performance using lost trips and delay times as measures of disruption.

This study adds to the current literature by combining high resolution elevation data with traffic data to estimate vulnerability of critical roadways in the Hampton Roads region of Virginia in terms of both flood risk and travel impacts. Mitchell et al. (2013) and Kleinosky et al. (2006) performed studies of potential flooding effects on this same region with a more general focus, rather than specifically considering transportation. Wu et al. (2013) examined the effects of sea level rise and storm surge on transportation infrastructure, however they only investigated the effects of extreme weather events, namely hurricanes, and not more frequent, tidally-driven (or nuisance) flooding impacts. In contrast, Bloetscher et al. (2014) only investigated non-extreme flooding. Neither Wu et al. (2013) nor Bloetscher et al. (2014) took traffic volumes into consideration in their analyses. The novel contributions of this study are the focus on the effect of flooding on roadways in particular, the inclusion of traffic volumes in the analysis, and the consideration of recurrent, tidal flooding of roadways.

This study aims to estimate the impact of sea level rise on flooding of Virginia Department of Transportation (VDOT) roadways in Norfolk and Virginia Beach from the year 2000 to 2100. Vulnerability of the roadways are assessed in terms of flood risk and traffic volumes impacted. Both an extreme (100-yr storm surge event) and non-extreme (mean higher high water (MHHW) and the 99% annual exceedance probability tide, also known as the "king tide") flooding scenarios are considered. The effect of projected sea level rise over time on estimated roadway flooding is examined.

Methodology

Study Area

Due to the its low-lying geography and land subsidence, the Hampton Roads region of Virginia is considered to be the second most vulnerable area to sea level rise in the United States for its population and size, behind New Orleans (Fears, 2012). This region is the 34th most populous metropolitan area with the 38th largest economy in the United States (Hampton Roads Planning District Commission, 2009). It is home to valuable military, historic, and educational assets including the world's largest naval base, multiple universities, and the NASA Langley Research center. These assets make the region valuable to a wide range of stakeholders, from its 1.7 million inhabitants to the U.S. Department of Defense (Kleinosky et al., 2006). Due to their population, important military interests, tourist attractions, and vulnerability to rising sea levels, Norfolk and Virginia Beach were selected for the study area as a subset of the larger Hampton Roads region.

Descriptions of Analyzed Data

To evaluate future sea level rise risks on transportation infrastructure in Virginia Beach and Norfolk, a geographic information system (GIS) was used to perform quantitative spatial analysis. The input data used in the analysis consisted of roadway geospatial data, topographic data, tidal data, storm surge data, and sea level rise projections.

<u>Roadway Geospatial Data:</u>

A geospatial dataset for Virginia roadways was obtained from the Virginia Department of Transportation (VDOT) (VDOT, 2015). These data include interstate highway, arterial and primary routes data, and Average Annual Weekday Traffic (AAWDT) for the entire state from the years 1985 to 2014. The dataset was clipped to only include Norfolk and Virginia Beach. Figures 1 and 2 show the AAWDT for Norfolk and Virginia Beach, respectively. Both cities have highly trafficked roads located near the coast, many of which serve over 100,000 travelers daily.

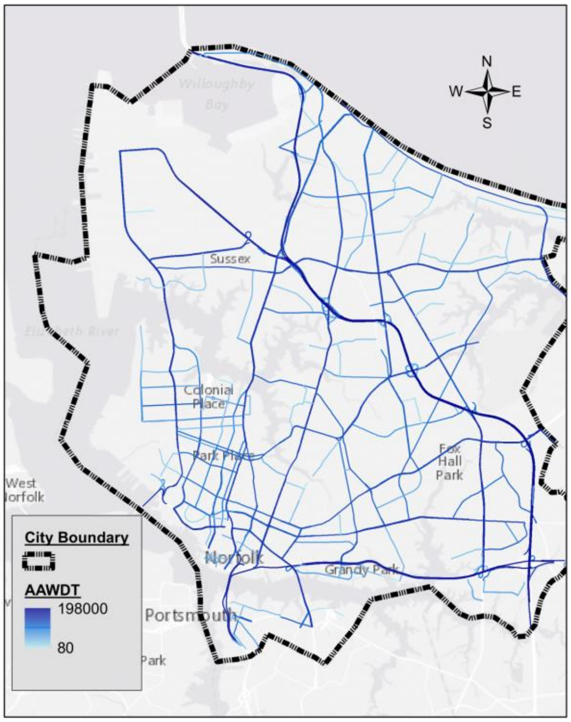

Figure 1. AAWDT values for roadways in Norfolk. Data provided by VDOT (VDOT 2015)

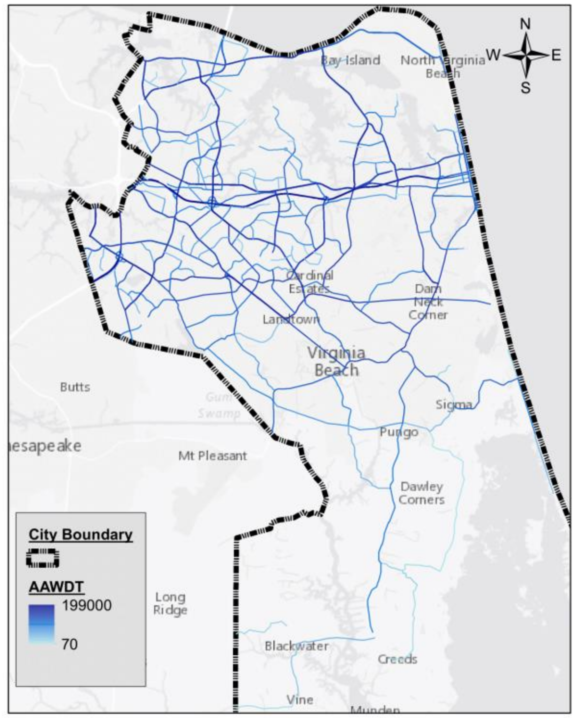

Figure 2. AAWDT values for roadways in Virginia Beach. Data provided by VDOT (VDOT 2015)

<u>Topographic Data:</u>

A LiDAR-derived digital elevation model (DEM), with a horizontal resolution of 0.76 meters (2.5 feet) and a vertical accuracy of 0.2 meters, was obtained from the Virginia LiDAR (Virginia Lidar, 2015). It is a bare earth DEM, meaning that algorithms were used to automatically detect and remove objects such as trees, buildings, and bridges. As a result of this, the reported elevation values for many of the bridge decks were negative. To account for this, all negative values from the DEM were excluded from the analysis.

The DEM was used to estimate the elevation of VDOT roadway centerlines throughout the study area. This was done by using a mask operation in ArcGIS where the DEM raster cells that intersected the roadway centerline feature dataset (described above) retained their value but all raster cells not intersecting a roadway centerline were set to NoData. The resulting raster dataset included elevation values only along the roadway centerlines at the resolution of the LiDAR DEM (0.76 m).

Tide Data:

Annual exceedance probability levels and tidal datums from Sewells Point Station, a station that began collecting sea level data in 1927 and has been continuously operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). shows statistical data made available for the station by NOAA (National Oceanic and Atmospheric Administration, 2016). This study considered two tidal statistics from these data: mean higher high water (MHHW) and the 99% exceedance probability value. NOAA defines the mean higher high water tide as the average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch. The 99% exceedance probability value is expected to be exceeded almost every year (technically all but one year in a century) (National Oceanic and Atmospheric Administration, 2016). In short, the mean higher high water event can be thought of as a typical daily high tide while the 99% exceedance probability event can be thought of as a yearly “king tide.” These levels were adjusted to reference the North American Vertical Datum of 1988 (NAVD88) to be consistent with the DEM data.

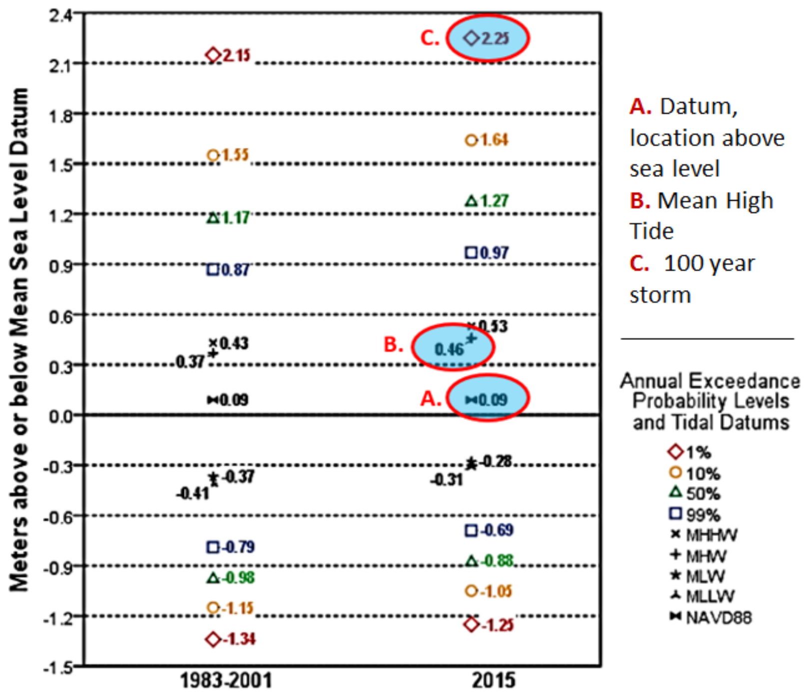

Figure 3. Annual exceedance probability levels and tidal data from Sewells Point Station (National Oceanic and Atmospheric Administration, 2016)

<u>Storm Surge Data:</u>

Storm surge estimates produced in the Region III Federal Emergency Management Administration (FEMA) storm surge study were used in the analysis. The estimates were provided as a number of georeferenced (x, y) points within the study area, each with several storm surge levels corresponding to different return periods (500-year, 100-year, 50-year, etc.). The points have an approximate horizontal spacing of 100 meters. The 100-year storm surge event was considered in this study as representing an extreme storm surge event associated with a hurricane. Inverse distance weighting was used to interpolate a 100-year storm surge surface from the provided point locations.

Sea Level Rise Projections:

Low, intermediate, and high sea level rise scenarios for the years 1992 through 2100 were used in the analysis (Figure 4). The low scenario represents historic rates of sea level rise and projections with no acceleration. This scenario was based on the International Panel on Climate Change 4th Assessment Model, which used conservative assumptions about future emissions and sea level rise. The intermediate scenario represents upper-end projections from semi-empirical models. The high scenario represents upper-end projections as well as sea level rise contributions from ice-sheet loss and glacial melting.

These scenarios were based on the National Climate Assessment and adapted by the Virginia Institute of Marine Sciences to Southeastern Virginia by accounting for local land subsidence (Mitchell et al., 2013). Therefore, the seal level rise estimates are in fact relative sea level rise estimates because they include local land subsidence in addition to sea level rise. The differences in estimates across the three scenarios highlight the uncertainty in sea level rise and climate change predictions. The historic model predicts only 0.49 meters of sea level rise by 2100, while the high scenario predicts 2.3. The low, medium, and high scenarios are included in the analysis to communicate a range of feasible scenarios. It is noted that at a global scale, a sea level rise of 2.3 meters may be unlikely, however, given the land subsidence in the study area, this value is not implausible.

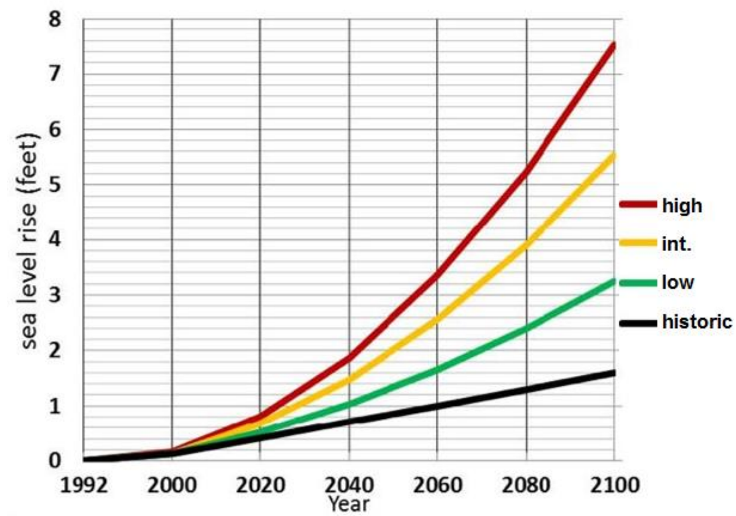

Figure 3. Sea level rise scenarios for Southeastern Virginia (Mitchell et al., 2013)

Prediction of Percent Flooded Roadways Over Time

Three different flooding scenarios were considered in the study. The first flooding scenario was flooding due to a typical daily high tide. For this scenario the mean higher high water value, 0.53 m, from Figure 4 was used. For the second flooding scenario a "king tide" even was considered. For this scenario, the 99% annual exceedance probability tide value 0.97 m was used. The third flooding scenario represents flooding due to storm surge from a 100-year storm surge event occurring coincidentally with the 99% tide level. Low, intermediate, and high sea level rise projections were added to the flooding scenarios to account for the effects of long-term sea level rise on flood water elevations.

Equation 1 shows how the water surface elevations, *WSE*, are calculated for the various scenarios considered in the analysis. The flood water elevation, *FWE*, is the water elevation for flood scenario i (where i can be either the mean higher high water, 99% tide level, or 99% tide level plus 100-yr storm surge) at the geographic location (x, y). The change in the relative sea level, ΔRSL, is a function of the emissions scenario j (where j can be either low, medium, or high) and time t (where t is one of the 20 year periods between 2000-2100). Note that the flood water elevation is a function of location for only the third flooding scenario, which includes the 100-year storm surge values that vary spatially.

$$WSE(i,j,k,x,y) = FWE_i(x,y) + \Delta RSL_{j,t} \quad \textbf{(1)}$$

The water surface elevations estimated with Equation 1 were compared to the elevations of the VDOT roadways taken from the LiDAR DEM. If the elevation of a roadway, z, at location (x, y), was less than or equal to the water surface elevation at that location, that portion of the roadway (meaning a stretch of the roadway equal in size to one of the DEM cells) was considered to be flooded. This is shown in Equation 2 where *flooded* is a variable with a Boolean data type representing whether or not the roadway at location (x, y) will be flooded for a given flood scenario, i, a sea level scenario, j, at a time, t. The sum of the flooded roadway area divided by the sum of total roadway area in the study area was used to determine the percent of roadway flooded.

$$flooded(i,j,t,x,y,z) = \begin{cases} true, WSE(i,j,t,x,y) \geq z \\ false, WSE(i,j,t,x,y) < z \end{cases} \quad \textbf{(2)}$$

Critical Roadway Identification

Critical roadways (i.e. roadways with high traffic volumes and low elevations), were identified using VDOT AAWDT (Figures 1 and 2) values in conjunction with roadway elevations. Three vulnerability levels were considered: (i) roads with low elevation (< 3 m) and low traffic (<30,000 AAWDT), (ii) roads with low elevation (< 3 m) and medium traffic (30,000<AAWDT<75,000), and (iii) roads with low elevation (< 3 m) and high traffic (>75,000 AAWDT). A threshold of 3 m was chosen because approximately 25% of the lowest roadways in the study area were below this elevation and because it represents a feasible high tide water surface elevation in 2100.

The top ten vulnerable locations in terms of AAWDT were examined further to predict the time when these locations would be flooded assuming the high sea level rise scenario and under the three flooding scenarios. The predicted time of flooding was taken as the year at which sea level rise plus the flood water elevation of the given flood scenario would be greater than the roadway elevation. Note that only the sea level rise values are a function of time and the flood water elevations do not vary with time; the tides and storm surge vlues were assumed to be constant over the study period.

Results and Discussion

Predicted Percentage of Flooded Roadways Over Time

Figure 5 shows the elevations of the study roadways taken from the DEM as described above. The figure shows the large amount of low-lying VDOT roadways in Virginia Beach and especially Norfolk. Using spatial analysis tools within ArcGIS, it was determined that approximately 10% of the roadway length in the study area are below 2.1 feet in elevation. The resulting estimated water surface elevations for the analyzed scenarios are summarized in Table 1. Referring to Table 1, by the year 2100 tides reaching MHHW are predicted to flood these roadways. By the year 2080, these roadways are predicted to flood from a 99% level tide.

Table 1. Predicted water surface elevations (m) given intermediate sea level rise

Year	SLR + MHHW	SLR + 99% tide	SLR+99% Tide + Ave 100-yr SS	SLR Range (High SLR – Low SLR)
2000	0.50	0.94	2.9	0
2020	0.65	1.1	3.1	0.091
2040	0.90	1.3	3.3	0.24
2060	1.2	1.6	3.6	0.55
2080	1.6	2.1	4.0	0.85
2100	2.1	2.6	4.5	1.3

Figure 6 shows the predicted effect that these water surface elevations will have on roadway flooding in the study region over time. By 2100, results suggest that approximately 10 to 20% of VDOT roadway length will be flooded when high tide reaches mean higher high water under the intermediate and high sea level rise projections, respectively. This very frequent flooding of 10-20% of the roadways would be an extreme economic and societal burden. Similarly, results suggest that given the 99% tide, approximately 15 to 30% of VDOT roadway length would be flooded in 2100 under intermediate and high sea level rise predictions, respectively.

Figure 6 also shows the impact of the third flooding scenario, a 100-year storm surge along with a 99% tide. Given this flooding scenario, close to 80% of VDOT roadway length is projected to be flooded in 2100 under the high sea level rise scenario. Under an intermediate sea level rise scenario, still more than 65% of VDOT roadway length will be flooded. By 2060, projections suggest that between 40% and 60% of VDOT roadways will be flooded due to the 99% tide, and a 100-year storm surge.

The results suggest that sea level rise will cause a large increase in flooded roadways when considering each of the three flooding scenarios. The percent of roadway length flooded increases from practically zero to nearly 10% and to more than 15% for the mean higher high water and 99% tide scenarios due to intermediate predicted sea level rise; for the 100-year storm surge scenario, the increase of predicted flooded roadway length is from 20% to more than 65% due to intermediate predicted sea level rise. These increases in predicted flooded roadways highlight the increase in vulnerability of roadway infrastructure in the study area due to sea level rise.

Critical Roadways Vulnerable to Flooding

Figure 7 shows road segments identified as having low elevation (< 3 m) and either low (0-30,000), medium (30 – 75,000), or high (> 75,000) AAWDT. Many of these areas are known for flooding concerns including those on Shore Drive in Virginia Beach and portions of Downtown Norfolk. The ten roadway segments with low elevation and the highest AAWDT are highlighted in the figure as notable locations in order from highest to lowest AAWDT. The Figure shows that Norfolk has a higher concentration of critical roadways compared to Virginia Beach. Eight of the ten notable locations shown in the Figure, which again are low elevation roads with high traffic, are in Norfolk. Six of these eight locations are in the southern portion of the city along the Elizabeth River.

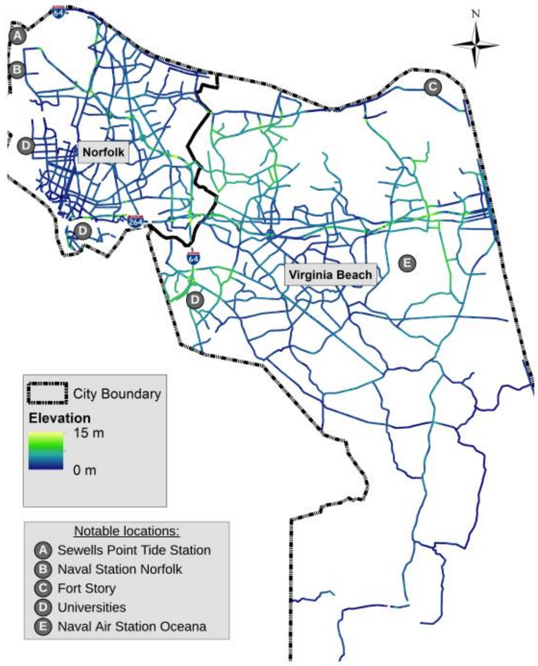

Figure 5. VDOT roadway elevations for Norfolk and Virginia Beach.

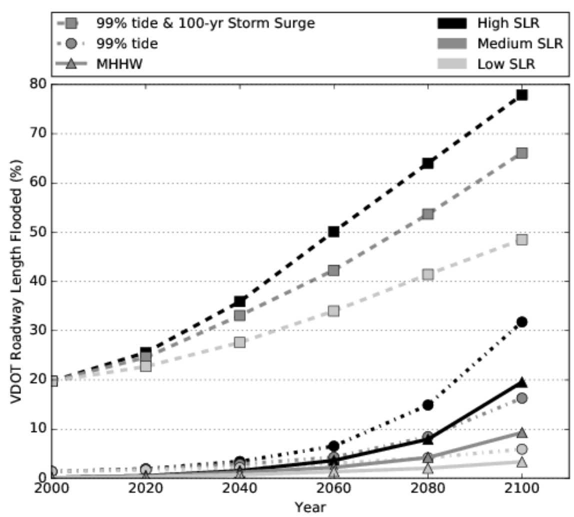

Figure 6. Prediction of flooded roadway length over time

Table 2 gives the years in which the ten notable locations shown in Figure 7 are expected to be flooded given high sea level rise predictions and the three flooding scenarios. The results suggest that five of the ten locations are predicted to recurrently flood when from a typical daily high tide by the end of the century, with the second and third locations by 2080. All ten locations are predicted to flood when high tide reaches the 99% level by 2100, with locations two and three predicted to flood by 2080. Finally, all ten locations are predicted to be flooded from the 99%-tide and a 100-year storm surge under current sea level conditions. Flooding of these roadway sections, given their high traffic volumes, could cause significant challenges for the region. Efforts to raise these and similar roadways with low elevation and high traffic in coming years will be important to avoid travel disruptions due to recurrent, tidally-driven flooding.

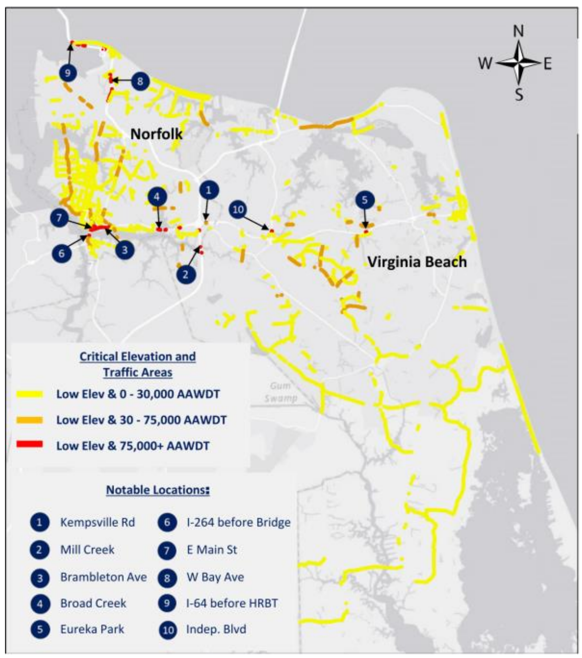

Figure 7. Critical roadways: high traffic, low elevation roadways

Assumptions and Limitations

This study assumes that all roads within the study area whose elevations are below the estimated flood water surface elevations will be flooded. In reality, lack of hydrologic connectivity inland may mean that those roads further inland may be protected against the coastal flooding scenarios examined in this paper. That said, the inland roads not hydrologically connected to the sea through surface water, may still be impacted by rising sea levels due to the associated rise in

Table 2. Water surface and roadway elevation for roadways with high AAWDT and low elevations (i.e., critical and vulnerable locations in the study area)

					Year of Predicted Flooding			
Point	**Location**	**City**	**Roadway Elevation (m)**	**Storm Surge Elevation (m)**	**SLR + MHHW**	**SLR + 99%-Tide**	**SLR + 99%-Tide + SS**	**AAWDT**
1	Intersection of I-264 and Kempsville Road	Norfolk	2.9	2.4	> 2100	2080-2100	Present	198,000
2	I-64 near Mill Creek	Norfolk	2.0	2.4	2080	2060-2080	Present	146,000
3	Intersection of I-264 and Brambleton Avenue	Norfolk	2.0	2.4	2080	2060-2080	Present	131,000
4	Intersection of I-264 and Broad Creek	Norfolk	2.8	2.4	> 2100	2080-2100	Present	123,000
5	I-264 near Eureka Park	Virginia Beach	3.0	2.2	> 2100	2080-2100	Present	111,000
6	I-264 Connection South of Berkley Bridge	Norfolk	3.0	2.4	> 2100	2080-2100	Present	107,000
7	Intersection of I-264 and E Main Street	Norfolk	3.0	2.4	> 2100	2080-2100	Present	105,000
8	Intersection of I-64 and W Bay Avenue	Norfolk	2.3	2.2	2080-2100	2060-2080	Present	93,000
9	I-64 W before Hampton Roads Bridge Tunnel	Norfolk	2.7	2.2	2080-2100	2080-2100	Present	88,000
10	Intersection of Independence Boulevard and Garrett Drive	Virginia Beach	2.6	2.3	2080-2100	2080-2100	Present	76,000

groundwater tables (Bloetscher 2012). The incorporation of rising groundwater levels in the surficial aquifer into the modeling of roadway flooding would be an important enhancement to the analysis as a more comprehensive picture of sea level rise effects. Future research should investigate the complex surface and subsurface hydrologic connectivity in the region and its role in coastal flooding of transportation infrastructure.

The study assumes that tide levels and storm surge from a 100-year storm surge event will be constant over time as sea levels rise, which may not hold true. Future research should explore the non-stationarity in storm surge and tides due to climate change and resulting sea level rise. More sophisticated approaches using hydrodynamic models capable of projecting how inland flooding due to storm surge will impact transportation infrastructure would also provide more accurate assessments of transportation vulnerability due to extreme events. The hydrodynamics of flooding due to storm surge are complex and this work is meant as a first approximation of vulnerable road infrastructure.

There is significant uncertainty in the sea level rise predictions themselves. Three different sea level rise scenarios (low, intermediate and high) were used in this study to account for this uncertainty. More recent literature on sea level rise has suggested that the actual sea level rise may be much higher than previously thought due to various factors, including instability of the Antarctic ice sheet. These factors may cause an additional meter of sea level rise by the end of the century and up to 15 meters by 2500, nearly doubling prior sea level rise projections (DeConto and Pollard, 2016). The uncertainty about sea level rise is a challenging problem for long-term planning. Researchers are still advancing knowledge of sea level rise, and it will be critical for planners to adjust to new predictions, as the science continues to advance. For this reason, simple elevation-based data of transportation assets may be an effective way for planning for future sea-level rise vulnerability given these uncertainties.

It is important to note that these flooding scenarios only consider flooding from tides and storm surge and not from rainfall. Rainfall-driven flooding is also a concern in coastal communities and can be exacerbated by rising sea levels. Stormwater infrastructure designed in part to mitigate flooding risks caused by development and increased impervious surfaces are typically gravity-driven systems. In coastal communities where these systems drain to tidally influenced water bodies, changes in the sea level conditions will have (and area already beginning to have) significant impacts on the functioning of the stormwater systems. As the sea level rises, tailwater pipes can be inundated during high tide, causing sea water to back up into the stormwater system. As a result, if a heavy rain occurs at high tide in these systems, it can result in flooding due to poorly functioning stormwater infrastructure. Accounting for these complex relationships between sea level change, tides, rainfall, and other hydrologic variables like soil moisture and groundwater table variations are ultimately needed to fully capture flooding risks in coastal regions.

Conclusions

The objectives of this research were to (i) quantify the impacts of sea level rise on roadway flooding in Virginia Beach and Norfolk given tidal (mean higher high water and 99% tide, or “king tide”) and storm surge (99% tide plus 100-year storm surge) flooding scenarios and (ii) identify critical roadway sections within Norfolk and Virginia Beach. Under the intermediate sea level rise scenario, by 2100 nearly 10% of major roads in Virginia Beach and Norfolk are predicted to regularly flood due at tides reaching mean higher high water. This increases to over 15% of major roads with a 99% tide and to over 65% of major roads with the addition of a 100-year storm surge.

Using average annual weekday traffic (AAWDT) data from VDOT, the most critical roadway sections, meaning those with both low elevations and high traffic volumes, were identified. The top ten critical roadway sections in Virginia Beach and Norfolk were identified. These had the highest traffic volumes (AAWDT > 75,000) and were low-lying (elevation < 3 m). Results suggest that all of these road segments are vulnerable to flooding now from a 99% tide plus 100-year storm surge event. With high sea level rise, by 2100, half of the locations are vulnerable to flooding when tides reach mean higher high water and all will be flooded when tides reach the 99% tide. These results suggest that these locations should be high priority areas for infrastructure investments to minimize traffic disruptions due to recurrent, tidally-driven flooding.

Although this study focused on the two cities in the Hampton Roads region of Virginia, in a similar way, the methodology could be applied to other coastal areas to identify vulnerable roadway sections. This study could also be integrated into a method like the Climate Change Adaptation Tool for Transportation: Mid-Atlantic framework (Oswald and McNeil, 2013) to provide municipalities with not only a list of at-risk areas of roadway, but also a path forward to plan for future adaptation efforts.

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