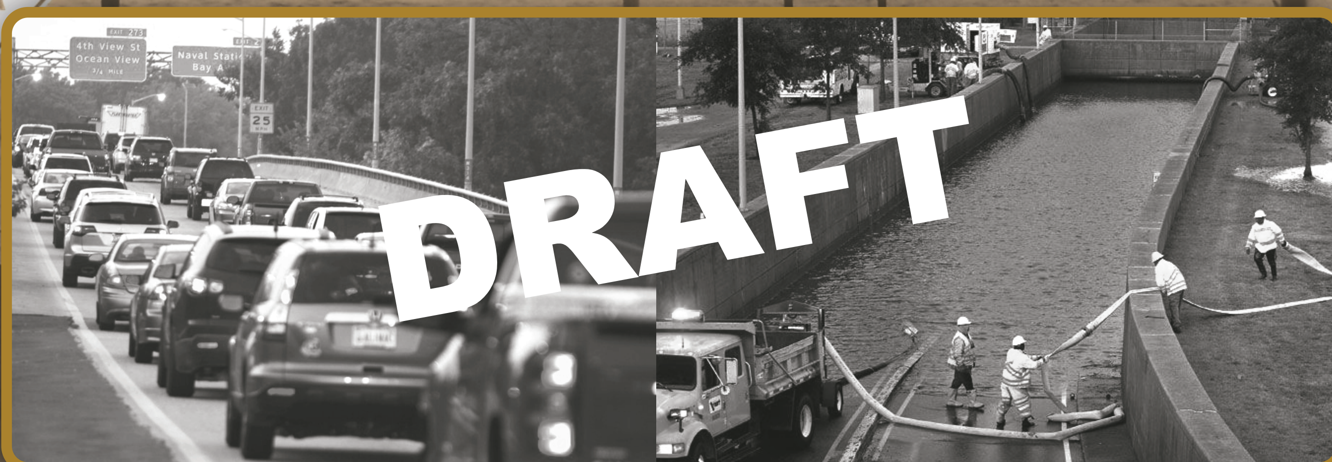
Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads



T16-03

the heartbeat of HAMPTON ROADS TPO
TRANSPORTATION PLANNING ORGANIZATION
January 2016

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DRAFT

PREPARED BY:

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Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads

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ABSTRACT

Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of roadways, bridges/tunnels, and other facilities. Repetitive flooding at critical transportation facilities can severely impact travel and hurt regional and local economies.

HRTPO staff has partnered with HRPDC staff to conduct a GIS-based flooding vulnerability analysis for potential sea level rise and storm surge impacts to regional roadways by 2045 (next Long-Range Transportation Plan horizon year).

This draft report includes a methodology for incorporating sea level rise and storm surge impacts to roadways into the HRTPO Long-Range Transportation Plan Project Prioritization Tool. Furthermore, it contains adaptation strategies, design considerations, best practices, and lessons learned from other coastal regions (e.g. Gulf Coast) that are also vulnerable to sea level rise and storm surge.

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NON-DISCRIMINATION

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Introduction

The impacts from sea level rise and storm surge, extreme weather events, precipitation changes, higher temperatures and heat waves, Arctic warming, and other climatic changes are affecting the reliability and capacity of the U.S. transportation system[1]. Sea level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, rail lines, transit facilities, and roadways and bridges.

Extreme flooding events currently disrupt transportation networks and will likely become more prevalent as sea levels are expected to rise at an accelerated pace for many coastal regions, such as Hampton Roads. Hampton Roads—second only to New Orleans in terms of vulnerability to sea level rise in the United States—is seeing more frequent storm surges and higher tides than before[2]. Based on past storm events, Hampton Roads' east coast location makes it prone to significant storm surges about every four to five years.

The state of Virginia has recently placed emphasis on sea level rise and flooding impacts, especially in Hampton Roads. On March 16, 2015, Governor McAuliffe signed Virginia legislation (SB 1443), amending the Code of Virginia by adding section 15.2-2223.3 for comprehensive plans to incorporate strategies to combat project sea-level rise and recurrent flooding:

> "Beginning July 1, 2015, any locality included in the Hampton Roads Planning District Commission shall incorporate into the next scheduled and all subsequent reviews of its comprehensive plan strategies to combat projected relative sea-level rise and recurrent flooding. Such review shall be coordinated with the other localities in the Hampton Roads Planning District Commission."

Sea level rise will cause significant impacts to coastal regions. Some areas are already experiencing permanent inundation, while other areas are seeing more frequent flooding. As sea levels continue to rise, some areas that have not seen flooding will start to experience it, which will have major infrastructure impacts.

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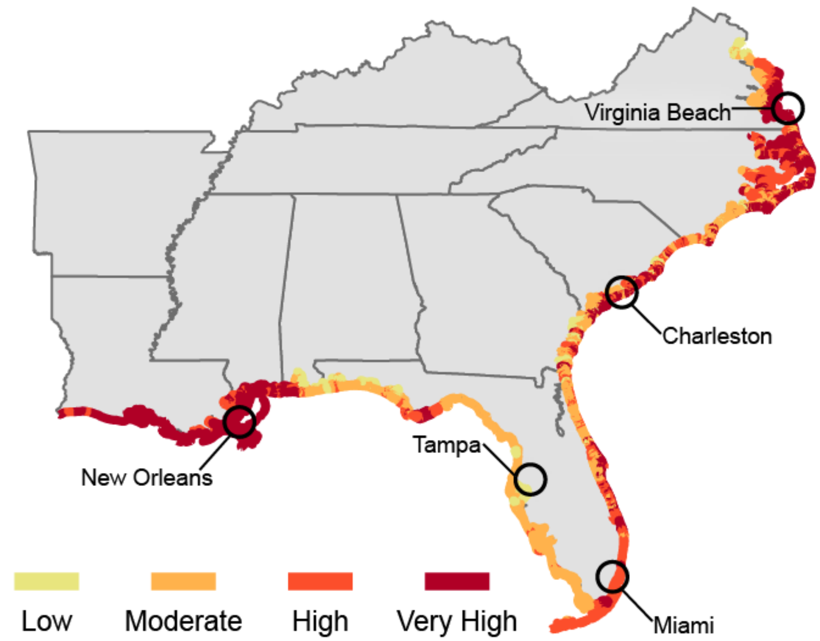
[1] *Climate Change Impacts in the U.S.: The Third National Climate Assessment*, Chapter 5 Transportation, 2014.

[2] *Virginia Conservation Network website*, "Confronting Climate Change" webpage, www.vcnva.org, April 2013.

Vulnerability to Sea Level Rise



Source: National Climate Assessment, data from Hammar-Klose and Thieler, 2001

Colonial Place neighborhood in Norfolk during Nor'easter in November 2009.

What is climate change?

- "any change in climate over time, whether due to natural variability or as a result of human activity"*

How does it relate to relative sea level rise/storm surge?

- Relative sea level rise and changes in storm surge are specific natural occurrences that result from changes in climate over time.

**Intergovernmental Panel on Climate Change (2007)*

Most transportation infrastructure, particularly roadways and bridges, were designed to last 50 years or longer; however, many were constructed without today's knowledge of climate change and the accelerated projections in sea level rise. Several roadways were built along low-lying areas and are now vulnerable to sea level rise and recurrent flooding. Replacing, retrofitting, and/or elevating roadways, bridges, and other critical transportation facilities is expensive and is not an option for many regions due to funding limitations. Therefore, it is important to understand how future climate changes might affect these investments in the coming decades.

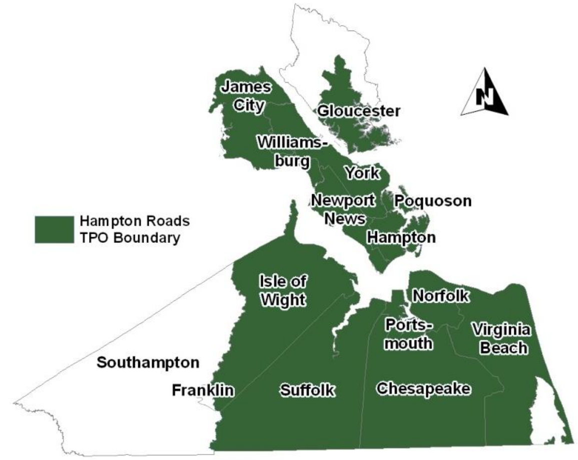
Repetitive flooding at critical transportation facilities can severely impact travel and hurt regional and local economies. When streets are impassable during and after flooding events, it often results in damages to personal property and missed work time, which has a crippling effect on communities.

Study Purpose

While it is important to plan and assess potential climate-based vulnerabilities to all land, air, and marine transportation systems, this study focuses on roadways within the Hampton Roads Metropolitan Planning Area (MPA), including bridges and tunnels. HRTPO staff has partnered with HRPDC staff to conduct a comprehensive GIS-based flooding vulnerability analysis for potential sea level rise and storm surge impacts to regional roadways by 2045—next Long-Range Transportation Plan (LRTP) horizon year.

Prior to the flooding vulnerability analysis, this study provides background information, including sea level rise/storm surge definitions and trends for the Hampton Roads region. Further, it provides a brief description of recent studies and work related to climate change and discusses potential impacts of sea level rise and storm surge on roadway infrastructure.

Hampton Roads Metropolitan Planning Area



The analyses within this study are intended to be a "high level" planning tool to screen regional roadway assets for vulnerability to flooding under three sea level rise and storm surge scenarios for the next long-range transportation planning horizon. The HRTPO Board can use these results by choosing projects for currently vulnerable roads in the HRTPO's Transportation Improvement Program (TIP) and LRTP (2040).

Because of the disconnect between the timeframe of most metropolitan long-range transportation plans (20-25 years) and the 50-80 year timeframe associated with most climate change adaptation planning[3], the results in this study may also be used as a baseline for developing future adaptation strategies beyond 2045. Further comprehensive assessment of individual roadways will be necessary for determining the degree of vulnerability of specific assets in order to set future priorities to protect them.

This report includes a methodology for incorporating sea level rise and storm surge impacts to roadways into the HRTPO Long-Range Transportation Plan Project Prioritization Tool. Furthermore, it contains adaptation strategies, design considerations, best practices, and lessons learned from other coastal regions (e.g. Gulf Coast) that are also vulnerable to sea level rise and storm surge.

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[3] *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2*, Task 3.2: Engineering Assessments of Climate Change Impacts and Adaptation Measures, August 2014.

HRTPO Involvement in Sea Level Rise and Recurrent Flooding

The HRTPO is committed—through facilitating partnerships and performing regional studies—to mitigating the impacts of sea level rise/storm surge on transportation infrastructure in Hampton Roads. Listed below are some recent and ongoing activities related to sea level rise and recurrent flooding that HRTPO staff are engaged in:

- Strong partnership between Hampton Roads Planning District Commission (HRPDC) and HRTPO staff
    - HRPDC performs various planning efforts, including coastal zone management, climate change, sea level rise, and green infrastructure.
- Environmental Sustainability Best Practices for Transportation symposium
    - National symposium which focused specifically on transportation planning and engineering best practices that can enhance the health of the environment.
- Partnerships with other stakeholders
    - HRPDC Sea Level Rise Advisory Committee
        - Major objectives include: (1) develop recommendations for local governments, (2) advocate for federal and state support, and (3) serve as primary regional contact for coordinating efforts with federal agencies and academic institutions.
    - University Efforts (Old Dominion University, University of Virginia, College of William & Mary, Virginia Polytechnic Institute and State University)
    - Virginia Institute of Marine Science (VIMS)
- Hampton Roads SLR Intergovernmental Planning Pilot Project
    - Infrastructure Working Group (HRTPO Staff Membership)
        - The mission of the Pilot Project is to develop a regional "whole of government" and "whole of community" approach to sea level rise preparedness and resilience planning in Hampton Roads that also can be used as a template for other regions.
- Hampton Roads Adaptation Forum
    - A forum to bring together professionals in adaptation including local municipal government staff, scientific experts, private sector engineers, state and federal agency staff, nongovernmental organizations and other stakeholders to facilitate regional coordination, information exchange and share adaptation best practices.

Hampton Roads Dutch Dialogues at the Slover Library in Norfolk in June 2015.

- Hampton Roads Dutch Dialogues
    - A 5-day workshop held in June 2015 where Dutch and American urban designers, engineers, landscape architects, planners, academics, and government officials explored creative solutions and holistic concepts for flood risk reduction, resiliency, and smart redevelopment related to sea level rise and recurrent flooding.
- Hampton Roads Military Transportation Needs Study: Roadways Serving the Military and Sea Level Rise/Storm Surge[4]
    - This study estimates the relative sea level rise and potential storm surge threats to the "Roadways Serving the Military" in Hampton Roads (more details are provided in the Previous Studies and Related Work section on page 15)

[4] *Hampton Roads Military Transportation Needs Study: Roadways Serving the Military and Sea Level Rise/Storm Surge,* Hampton Roads Transportation Planning Organization (HRTPO), July 2013.

VULNERABILITY TO SEA LEVEL RISE/STORM SURGE

The purpose of this section is to define sea level rise/storm surge terminology and trends for Hampton Roads, discuss potential impacts of sea level rise and storm surge on roads systems, and provide a brief description of related recent studies and work.

DEFINING SEA LEVEL RISE AND STORM SURGE

Sea Level Rise

Water is rising and land is sinking—this alarming combination is happening along many coastal regions, including Hampton Roads. The "relative" sea level rise for a given area is the change in sea level relative to the elevation of the land in that same area. This change is affected by three factors:

1) Global Sea Level Rise (change in ocean volume)
2) Land Subsidence
3) Ocean Circulation

"Relative Sea Level Rise" = "Global Sea Level Rise" – "Land Subsidence" + Rise from "Ocean Circulation"

Global Sea Level Rise

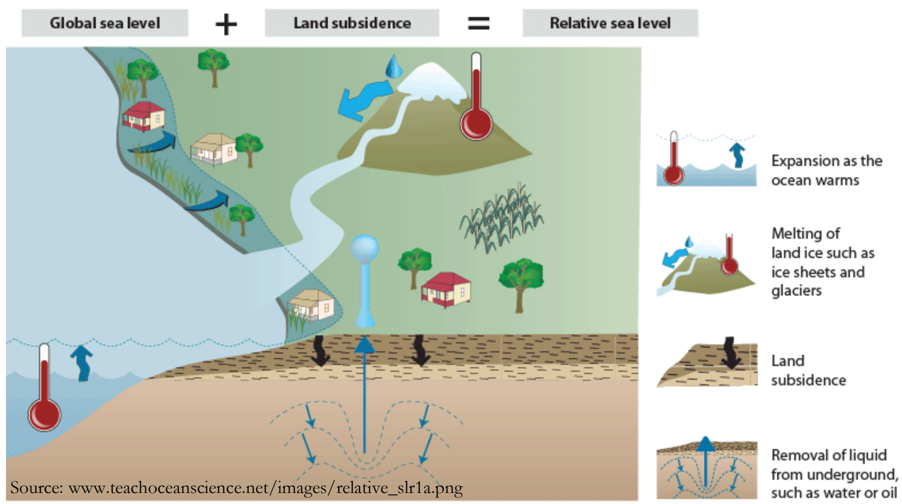
Global sea level is rising due to changes in the density and quantity of water in the world's oceans[5]. The two primary processes that have increased ocean water volume are 1) rising ocean temperatures, which cause the water to expand (thermal expansion), and 2) melting glaciers, ice caps, and ice sheets. These two processes are estimated to have added over six inches to sea levels in the past century. These processes have increased in recent years and are now estimated to be adding water volume at double the prior rate[6].

Land Subsidence

Land subsidence is the sinking of land. Subsidence generally occurs from sediment compaction or extraction of subsurface liquids like water or oil. One of the ongoing causes of land subsidence in the mid-Atlantic coastal region is the result of retreating ice sheets from the last Ice Age. As the ice sheets melted and retreated north, pressure from the weight of the ice was released and the earth's crust is still slowly readjusting. In coastal Virginia, groundwater withdrawals, largely for paper mills, are an additional contributing factor[7]. The region lies above a single aquifer system; removing groundwater results in sediment compaction that causes land subsidence region-wide. Additional localized subsidence occurs in areas where streams and creeks have been filled in to provide developable land. Historically, land subsidence has accounted for more than one-half of the relative sea level rise in the Hampton Roads region[8].

Ocean Circulation

The decreasing rate of movement by the ocean currents that circulate the globe has contributed to the rapid rise in local sea levels discussed below. In the Mid-Atlantic, this appears to be due to a slowing of the Gulf Stream as the polar region continues to warm. Melting freshwater ice reduces the salinity of seawater near the poles, which reduces its density and the speed at which it sinks and circulates. Slower moving water means less pressure is present to move water away from the coast, resulting in higher water levels[9].



Source: www.teachoceanscience.net/images/relative_slr1a.png

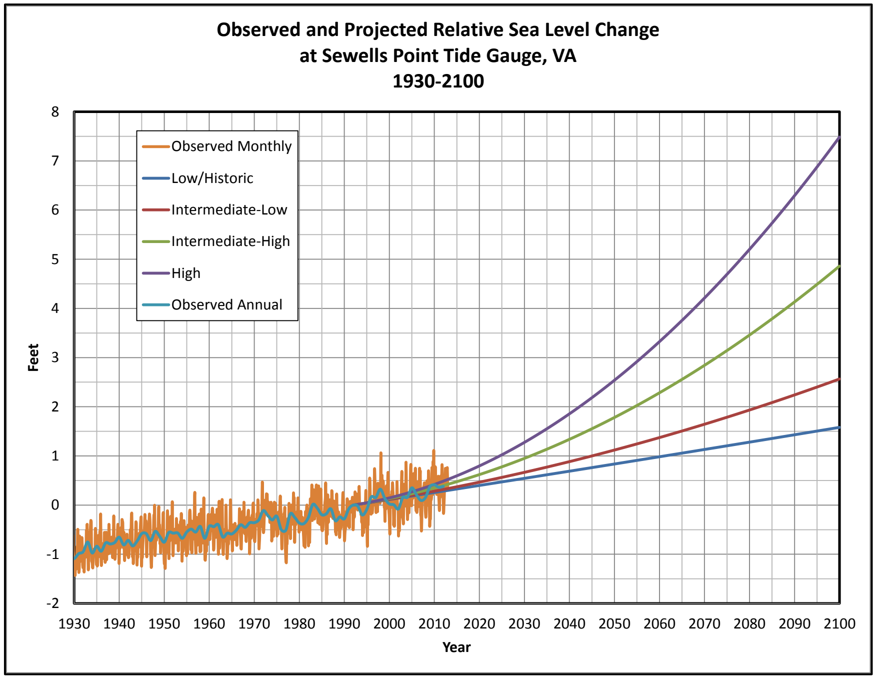
[5] *Climate Change in Hampton Roads – Impacts and Stakeholder Involvement*, Hampton Roads Planning District Commission (HRPDC), February 2010, p. 5.
[6] *Recurrent Flooding Study for Tidewater Virginia (SJR 76, 2012)*, Virginia Institute of Marine Science, January 2013, p. 110.
[7] *Ibid*, p. 110-111.
[8] *Land Subsidence and Relative Sea-Level Rise in the Southern Chesapeake Bay Region*, U.S. Geolocial Survey, 2013, p. 18.
[9] *Recurrent Flooding Study for Tidewater Virginia (SJR 76, 2012)*, Virginia Institute of Marine Science, January 2013, p. 111.

Trends in Relative Sea Level Rise for Hampton Roads

1933 Flooding on Granby Street in Norfolk.

Hampton Roads has experienced a total of 1.29 feet of relative sea level rise since 1927, based on the Sewell's Point tide gauge located on Naval Station Norfolk[10]. According to VIMS, recent analyses and indicators have detected acceleration in the rate of relative sea level rise from the mid-Atlantic to New England[11]. Existing research of global atmospheric processes indicated that temperatures will continue to rise at least until the end of the century. There is significant uncertainty, however, regarding how high and how quickly these temperatures will rise. The rate of land subsidence in Hampton Roads is expected to remain relatively stable.

Hampton Roads Planning District Commission (HRPDC) staff recently projected relative sea level rise based on a combination of global sea level rise scenarios in the 2014 U.S. National Climate Assessment[12] and local land subsidence models. Based on the four scenarios in the National Climate Assessment (low/historic, intermediate-low, intermediate-high, and high), HRPDC staff projected relative sea level rise in the range of 1.6 to 7.5 feet between 1992 and the year 2100 at Sewells Point. Current projections for sea level rise are calculated using a base year of 1992, which is also the midpoint of the most recent National Tidal Datum Epoch (NTDE), which spans 1983 to 2001. Tidal datums such as mean sea level are calculated for each NTDE, which in this case allows for relatively seamless comparisons between established, known local datums and global sea level rise projections. As shown on the graph above, these projections vary significantly due to the uncertainty of future global sea level rise estimates.



Source: HRPDC, October 2015.

According to HRPDC projections (see graph above), a 2.0 foot rise in relative sea level (from a base year of 1992) is estimated to occur sometime between 2043 (high) and 2083 (intermediate-low). Concerning the HRTPO 2045 Long-Range Transportation Plan (LRTP), these two curves show a relative sea level rise of 1.0 to 2.2 feet (between base year 1992 and 2045). Given that the base year is 1992, the approximate amount of rise expected between today (2016) and 2045 would be 1.5 feet, since sea levels have risen about 0.5 feet since 1992.

Planning conservatively, a 2.0 foot relative sea level rise scenario will be used in the 2045 LRTP "flooding vulnerability" analysis in this report.

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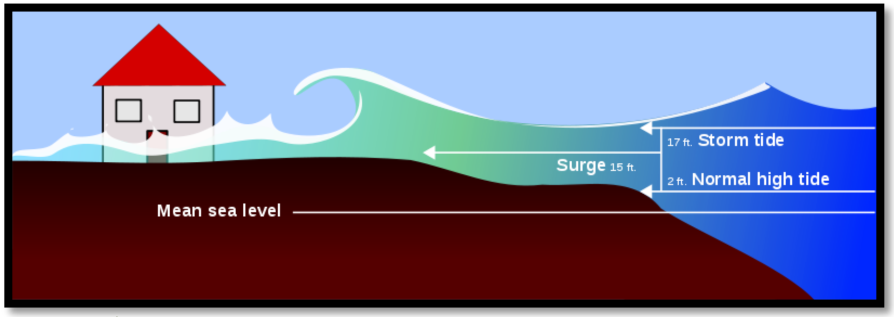
[10] National Oceanic and Atmospheric Administration (NOAA) from *Climate Change in Hampton Roads – Impacts and Stakeholder Involvement*, Hampton Roads Planning District Commission (HRPDC), February 2010, p. 6-7.

[11] Ezer, T., L. P. Atkinson, W. B. Corlett and J. L. Blanco. Gulf Stream's induced sea level rise and variability along the U.S. mid-Atlantic coast. *J. Geophys. Res. Oceans, 118*, 685-697.

[12] *Global Sea Level Rise Scenarios for the United States National Climate Assessment*, National Oceanic and Atmospheric Administration, NOAA Technical Report OAR CPO-1, December 6, 2012.



Impact of a Storm Surge

Source: Wikipedia, Surg big.jpg by Pierre cb, June 2007.

Storm Surge

According to the National Oceanic and Atmospheric Administration (NOAA), storm surge is water that is pushed toward the shore by the force of the winds swirling around the storm. In addition, low atmospheric pressure associated with storms raises sea levels. Severe storms, such as a hurricane, tropical storm, or nor'easter, cause storm surge. This surge combines with the normal tides to create the storm tide, which can increase the mean water level 15 feet or more.

In addition, wind waves are superimposed on the storm tide. The resulting rise in water level can cause severe flooding in coastal areas, particularly when the storm tide coincides with high tide. Storm surges cause many deaths and devastating property losses, such as damaged roads and bridges, destroyed homes and businesses, and wiped out coastal communities. Because many properties in Hampton Roads lie less than 10 feet above mean sea level, the danger from storm tides is tremendous.

In Hampton Roads, storm surges of 4.2 feet were recorded at the Sewells Point tide gauge during Hurricane Irene in 2011 and 4.4 feet during Hurricane Isabel in 2003.

Flood Frequency and Road Design Criteria

According to the Virginia Department of Transportation (VDOT) drainage manual[13], where the primary concern is the maintenance of traffic flow and the convenience of the highway user, roadways are to be designed to accommodate the following minimum flood frequencies:

Roadway Type	Flood Frequency (Annual Risk)
Interstate	50-year (2%)
Primary & Arterial	25-year (4%)
Secondary	10-year (10%)

The above requirements are minimal for the hydraulic design of culverts based on flood flows, upstream and downstream water surface elevations, allowable velocities, and flow routing.

This study analyzes potential flooding impacts to roadways within the HRTPO Congestion Management Process (CMP)—interstates, freeways and other expressways, principal arterials, minor arterials, and a few selected collectors. Given that most roadways within the HRTPO CMP are interstate, primary, and arterial, 25-year and 50-year storm surges are reasonable

25-year and 50-year storm surge scenarios will be used in the 2045 LRTP "flooding vulnerability" analysis in this report.

Photo by National Weather Service

Flooding during Hurricane Isabel in 2003.

[13] *VDOT Drainage Manual*, Virginia Department of Transportation (VDOT), Chapter 8 – Culverts, April 2002, p. 8-7.

Previous Studies and Related Work

The impacts of relative sea level rise and storm surge have been recognized along the southeast coast for many years, particularly for low-lying communities such as Hampton Roads, Virginia. National, state, regional, and local organizations have participated (or are currently participating) in initiatives that address this pressing issue in order to raise awareness and develop potential solutions. This section of the report provides a list and brief description of some recent studies and related work in sea level rise and storm surge:

City of Norfolk – City-Wide Coastal Flooding Study, Fugro Atlantic (Project Lead), Moffatt & Nichol, and Timmons Group, Initiated in 2007.

- This initiative is part of the City of Norfolk's ongoing effort to proactively address flooding. A series of studies have been completed throughout the city to determine vulnerability to sea level rise, high tides, and storm surges. Some recommendations include floodwalls, tide gates, elevated roads, water pumping stations, and upgrades to storm water pipes.

Integrating Climate Change into State and Regional Transportation Plans, Transportation Research Record: Journal of the Transportation Research Board, No. 2119, pp. 1-9, Gallivan, Ang-Olson, and Turchetta, 2009.

- The focus of this paper is on long-range planning documents as tools for climate change planning. Reviews included federal regulations and statutes that govern transportation planning as well as a sample of current planning documents from state departments of transportation and metropolitan planning organizations.
  http://trrjournalonline.trb.org/doi/abs/10.3141/2119-01

Incorporating Climate Change Considerations into Transportation Planning, Transportation Research Record: Journal of the Transportation Research Board, No. 2119, pp. 66-73, Schmidt and Meyer, 2009.

- In this paper, transportation plans and related documentation of metropolitan planning organizations and international cities were reviewed to ascertain whether climate change considerations are being incorporated in the transportation planning process. Recommendations are provided for greenhouse gas (GHG) emission mitigation and climate adaptation strategies.
  http://trrjournalonline.trb.org/doi/abs/10.3141/2119-09

Summary of Natural Resources/Shoreline Adaptation Strategy Recommendations of the Virginia Commission on Climate Change, Wetlands Watch, Skip Stiles, June 2009.

- This document summarizes the specific recommendations taken from the Virginia Commission on Climate Change that outline those adaptation provisions. It also contains a Virginia climate change adaptation strategy flow chart.
  http://www.wetlandswatch.org/Portals/3/WW%20documents/Adap_Strat_adopted_VCCC_062109.pdf

Climate Change in Hampton Roads – Impacts and Stakeholder Involvement, Hampton Roads Planning District Commission (HRPDC), February 2010.

- This report provides an overview of the potential impacts of climate change on the Hampton Roads region and describes various mitigation and adaptation strategies that can be taken to reduce and prevent damage from climate change impacts. A goal of this effort was to provide public outreach and education on these issues.
  http://www.hrpdcva.gov/uploads/docs/Climate_Change_Final_Report_All.pdf

ODU Climate Change and SLR Research Initiative (CC/SLRI), Forum led by Old Dominion University, Initiated Fall 2010.

- The Hampton Roads Adaptation Forum is a regional dialogue among municipalities committed to adopting effective adaptation designs and plans, tailored to meet the needs of our communities in the face of rising sea levels due to climate change. The forum is composed of academic institutions and local, regional, state, and Federal agency officials with authority and responsibility for critical infrastructure and facilities in Hampton Roads (e.g., engineers, planners, facility managers, administrators, etc.). http://www.odu.edu/research/initiatives/ccslri

Climate Change Planning for Military Installations: Findings and Implications, Noblis, October 2010.

- The Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP) tasked Noblis to identify potential climate change effects on military installations and their missions and operations. This report presents the findings portion (collected June 2009 – February 2010) of this study and discusses some implications on policy and practice. Naval Station Norfolk was included as part of this study.
  http://www.dtic.mil/dtic/tr/fulltext/u2/a534204.pdf

Vulnerability Analysis of Transportation Network Under Scenarios of Sea Level Rise, Transportation Research Record: Journal of the Transportation Research Board, No. 2263, pp. 174-181, Lu and Peng, 2011.

- This paper develops an accessibility-based process to analyze transportation network vulnerability to quantify networkwide vulnerability and to identify the most vulnerable regions under different scenarios of sea level rise. http://trrjournalonline.trb.org/doi/abs/10.3141/2263-19

Climate Change in Hampton Roads – Phase II: Storm Surge Vulnerability and Public Outreach, Hampton Roads Planning District Commission (HRPDC), June 2011.

- This report examines the impacts of storm surge flooding on various sectors, such as the built environment and economy, and on engaging the public. This effort was more quantitative and included a vulnerability analysis based on scenario development. http://www.deq.virginia.gov/portals/0/deq/coastalzonemanagement/task12-04-09.pdf

Economic Analysis of Impacts of Sea Level Rise and Adaptation Strategies in Transportation, Transportation Research Record: Journal of the Transportation Research Board, No. 2273, pp. 54-61, Lu, Peng, and Du, 2012.

- This paper attempts to quantify the economic impacts of the SLR as well as the costs and benefits of adaptation strategies by using cost–benefit analysis at the local level. http://trrjournalonline.trb.org/doi/10.3141/2273-07

Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot, University of Virginia, Federal Highway Administration, January 2012.

- This report describes how anticipated impacts of climate change on transportation infrastructure in the Hampton Roads region of Virginia were assessed via a decision to help prioritize elements of the region's Long-Range Transportation Plan. This study was part of a larger effort by the Federal Highway Administration to understand the vulnerability of critical transportation infrastructure in several regions. http://www.virginia.edu/crmes/fhwa_climate/files/finalReport.pdf

Technical Report: Climate Change Sea Level Rise Initiative, Virginia Modeling, Analysis and Simulation Center, January 30, 2012.

- This report provides an initial design (conceptual model) of a Hybrid Simulation with the capability to assist stakeholders in a city or region to make strategic decisions to negate or mitigate the negative impacts of sea level rise.

Climate Change in Hampton Roads – Phase III: Sea Level Rise in Hampton Roads, Virginia, Hampton Roads Planning District Commission (HRPDC), July 2012.

- This report focuses on analyzing the potential future impacts of sea level rise on the region's population, built environment, infrastructure, economy, and natural environment. This was done through the development of a geographic information systems (GIS) tool to model the impacts of sea level rise. http://www.hrpdcva.gov/uploads/docs/HRPDC_ClimateChangeReport2012_Full_Reduced.pdf

Global Sea Level Rise Scenarios for the United States National Climate Assessment, National Oceanic and Atmospheric Administration (NOAA), NOAA Technical Report OAR CPO-1, December 6, 2012.

- This report provides a synthesis of the scientific literature of global sea level rise (SLR) at the request of a federal advisory committee charged with developing the next National Climate Assessment (NCA), which occurs every four years. It also provides a set of four global mean SLR scenarios (as described on page 11 of this report) to describe future conditions for the purpose of assessing potential vulnerabilities and impacts. http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf

Recurrent Flooding Study for Tidewater Virginia (SJR 76, 2012), Virginia Institute of Marine Science, January 2013.

- This purpose of this study was to study strategies for adaptation to prevent recurrent flooding in Tidewater and Eastern Shore Virginia localities. It was passed by the Virginia Senate (February 28, 2012) and the Virginia House of Delegates (February 24, 2012). It is discussed in detail throughout this report. http://ccrm.vims.edu/recurrent_flooding/Recurrent_Flooding_Study_web.pdf

Assessing Impacts of Climate Change on Coastal Military Installations: Policy Implications, Strategic Environmental Research and Development Program (SERDP), US Department of Defense, January 2013.

- This paper discusses the policy context and technical considerations related to climate change impacts, drawing on lessons learned to date from four studies funded by the SERDP. This paper focuses on military coastal installations, but also informs of the DoD's overall approach to climate change. http://www.dtic.mil/dtic/tr/fulltext/u2/a575273.pdf

Risk Quantification for Sustaining Coastal Military Installation Assets and Mission Capabilities, RC-1701, Strategic Environmental Research and Development Program (SERDP), US Department of Defense, June 2014.

- The objective of this project is to develop and demonstrate an integrated, multi-criteria, multi-hazard impact assessment framework that will be suitable for evaluating changes in vulnerability or risk to coastal military installation assets and mission capabilities in the Hampton Roads region due to global climate change effects, with a focus on sea level rise and associated phenomena.
https://www.serdp-estcp.org/Program-Areas/Resource-Conservation-and-Climate-Change/Climate-Change/Vulnerability-and-Impact-Assessment/RC-1701

Quantifying the Influence of Climate Change to Priorities for Infrastructure Projects, IEEE Transactions on Systems, Man and Cybernetics: Part A. You, H., J.H. Lambert, A.F. Clarens, and B.J. McFarlane, 2013.

- This paper identifies and quantifies the influence of climate change combining with other sources of uncertainty to the priority order of projects in a portfolio of infrastructure investments, including a demonstration of the Hampton Roads region.
http://ieeexplore.ieee.org/xpl/articleDetails.jsp?reload=true&arnumber=6495481

Climate Change Influence on Priority Setting for Transportation Infrastructure Assets, ASCE Journal of Infrastructure Systems. Vol. 19, No. 1, pp. 36-46, J.H. Lambert, Y.J. Wu, H. You, A. Clarens, and B. Smith, 2013.

- This paper extends a scenario-based multicriteria decision framework that can assist decision makers in effectively allocating limited resources to adapt transportation assets to a changing climate, including a demonstration of the Hampton Roads region.
http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29IS.1943-555X.0000094

Emergency Operations Plan: Hazard-Specific Annex #3: Hurricane & Tropical Storm Response, Virginia Department of Emergency Management (July 2015).

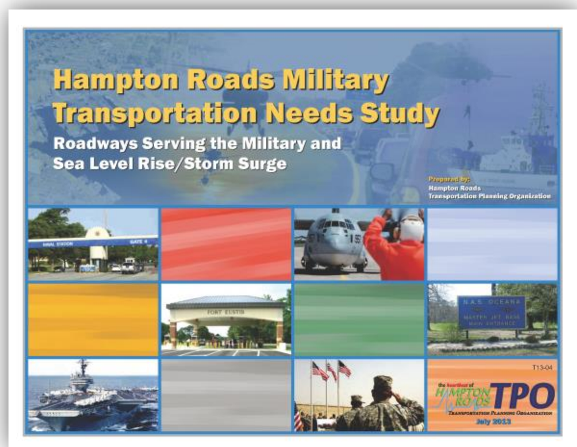
- This document describes how the Commonwealth of Virginia will respond to a Hurricane or Tropical Storm.
http://www.vaemergency.gov/webfm_send/1060/COVEOP_2012_HSA_3_Hurricane_Response_version_2015_July.pdf

Hurricane Lane Reversal Plan, Virginia Department of Transportation, May 2013.

- This document provides "guidelines for an evacuation of Hampton Roads", covering measures to improve traffic flow on Routes 10, 17, 58, 60, 143, 199, and 460, and details for reversing the lanes of I-64 (should the Governor order this reversal).

Hampton Roads Military Transportation Needs Study: Roadways Serving the Military and Sea Level Rise/Storm Surge, Hampton Roads Transportation Planning Organization (HRTPO), July 2013.

- This study (phase three) builds on previous military transportation studies and related work to estimate the relative sea level rise and potential storm surge threats to the "Roadways Serving the Military" network established in phase one of the Hampton Roads Military Transportation Needs Study. This third phase of the study continues the work in phase one by determining flooding-based deficient locations along the roadway network. It expands upon the work and methodologies developed by HRPDC and the Virginia Institute of Marine Science (VIMS) by identifying military roadway segments vulnerable to submergence. Additionally, submergence of other local roadways that provide access to and from the "Roadways Serving the Military" which may be vulnerable to flooding have been identified.
http://www.hrtpo.org/uploads/docs/Roadways%20Serving%20the%20Military%20&%20Sea%20Level%20Rise-Storm%20Surge%20Report.pdf



Impacts of Sea Level rise and Storm Surge on Transportation Systems and Roadway Infrastructure

According to a recent VIMS study, there are three primary threats to roadway networks as a result of relative sea level rise/storm surge[14]:

1) Flooding of evacuation routes
2) Increased hydraulic pressure on tunnels
3) Alteration to drainage capacity

Flooding of Evacuation Routes
As sea levels continue to rise, during storm surge events critical evacuation routes may become unusable. Although most evacuation occurs before storm surge, evacuation decisions will need to be made sooner in order to preserve the safety of citizens within the community.

Increased Hydraulic Pressure on Tunnels
Bridges and tunnels are widely used throughout Hampton Roads to traverse many of the waterways. These facilities are static structures that cannot be easily retrofitted to compensate for rising sea levels. Tunnel entrances that cannot be raised pose potential flooding risks for the tunnel, and a higher water level resulting from surge increases the hydraulic pressures on the tunnel structure[15].

Alteration to Drainage Capacity
Roadway drainage systems rely on the hydraulic gradient to drain water properly. In Hampton Roads, many roadways were constructed in low elevation areas, which makes drainage a challenge. As sea levels rise, hydraulic gradient is reduced, which slows the flow of water and can cause stormwater to back up or pond on the roadway and create a flooding condition.

Other Impacts
Relative sea level rise exacerbates coastal erosion, which may erode roadways in Hampton Roads that are adjacent to waterways. On the other hand, rising sea levels increase channel depths, aiding large containerships traveling to the Port of Virginia. Although clearances under bridges will be reduced[16], this is not expected to be a major problem since many important local bridges are drawbridges. Finally, airport runways or railroad lines located near or adjacent to coastlines may be impacted by rising sea levels and/or storm surge flooding[17].

These issues are dependent upon the rate of relative sea level rise and the anticipated life expectancy of the structures. When a new roadway is constructed or improved, the new and projected sea levels should be considered as part of the design.

Flooding in Virginia Beach on August 1, 2012.

[14] *Recurrent Flooding Study for Tidewater Virginia (SJR 76, 2012)*, Virginia Institute of Marine Science, 2013, p. 93.
[15] *Recurrent Flooding Study for Tidewater Virginia (SJR 76, 2012)*, Virginia Institute of Marine Science, 2013, p. 93.
[16] *Ibid, p. 93.*
[17] *Ibid, p. 93.*

FLOODING VULNERABILITY FOR ROADWAYS IN HAMPTON ROADS

This section analyzes where flooding is expected to occur along regional roadways by 2045 as a result of relative sea level rise and storm surge using HRPDC flooding projections and geographical information systems (GIS) mapping. These maps will serve three primary purposes:

1) Adaptation – Identifying roadway segments that are vulnerable to flooding will enable planners and engineers to develop adaptation strategies for those locations.
2) Road Projects – This analysis will help raise awareness of potential flood locations to consider during design.
3) Scoring of Future Transportation Projects – These results will serve as a basis for scoring future roadway transportation projects for the 2045 LRTP by assigning points based on flooding vulnerability within the Long-Range Transportation Plan (LRTP) Project Prioritization Tool (discussed in further detail on pages 48-49).

It is important to note that flooding is caused by both rising water that submerges the area and inadequate drainage. The analysis within this report estimates flooding only by submergence.

2045 ANALYSIS NETWORK

HRTPO staff is expecting to complete the 2040 Long-Range Transportation Plan (LRTP) in early 2016, and will begin working on the 2045 LRTP thereafter. This study conducts a flooding vulnerability analysis for a **2045 Analysis Network,** consisting of the following roadways:

- **Existing CMP Roadways** – HRTPO Congestion Management Process (CMP)[18]
- **LRTP Roadways** – DRAFT 2040 LRTP List of Fiscally-Constrained Projects[19]
- **Regional Priority Projects** – Roadway projects currently under the purview of the Hampton Roads Transportation Accountability Commission (HRTAC)[20]
- **Unfunded Roadways** – Roadways not included above but are included in the DRAFT 2040 Regional Transportation Vision Plan[21]

This report identifies future flooding impacts for roadways that have the potential to be in place by the year 2045. A map of the 2045 Analysis Network is provided on the following page.

LRTP and Regional Priority Project roadways are planned projects with anticipated funding for construction. Transportation projects within the LRTP and HRTAC that are not roadway-segment related are excluded (e.g. transit, bicycle/pedestrian, and interchanges). Projects included in the DRAFT 2040 Regional Transportation Vision Plan are unfunded prioritized projects that are not included in the fiscally-constrained 2040 LRTP.

It is important to note that this 2045 Analysis Network may not include all future candidate roadways if they are developed between now and the next LRTP. Such candidate roadways will need to be analyzed separately for vulnerability to flooding using the flooding scenario maps developed within this study. The alignments for future candidate roadway projects will need to be overlaid on the projected flooding areas using GIS or subarea maps within this study.

EXISTING LOCAL ROADWAYS

HRTPO staff also conducted a 2045 flooding vulnerability analysis for local roadways within each Hampton Roads jurisdiction using a similar methodology. Local roadways consisted of local and collector streets, ramps, and roads on military installations that were not part of the 2045 Analysis Network. Future local roadways to be constructed between now and 2045 were not included in this analysis.

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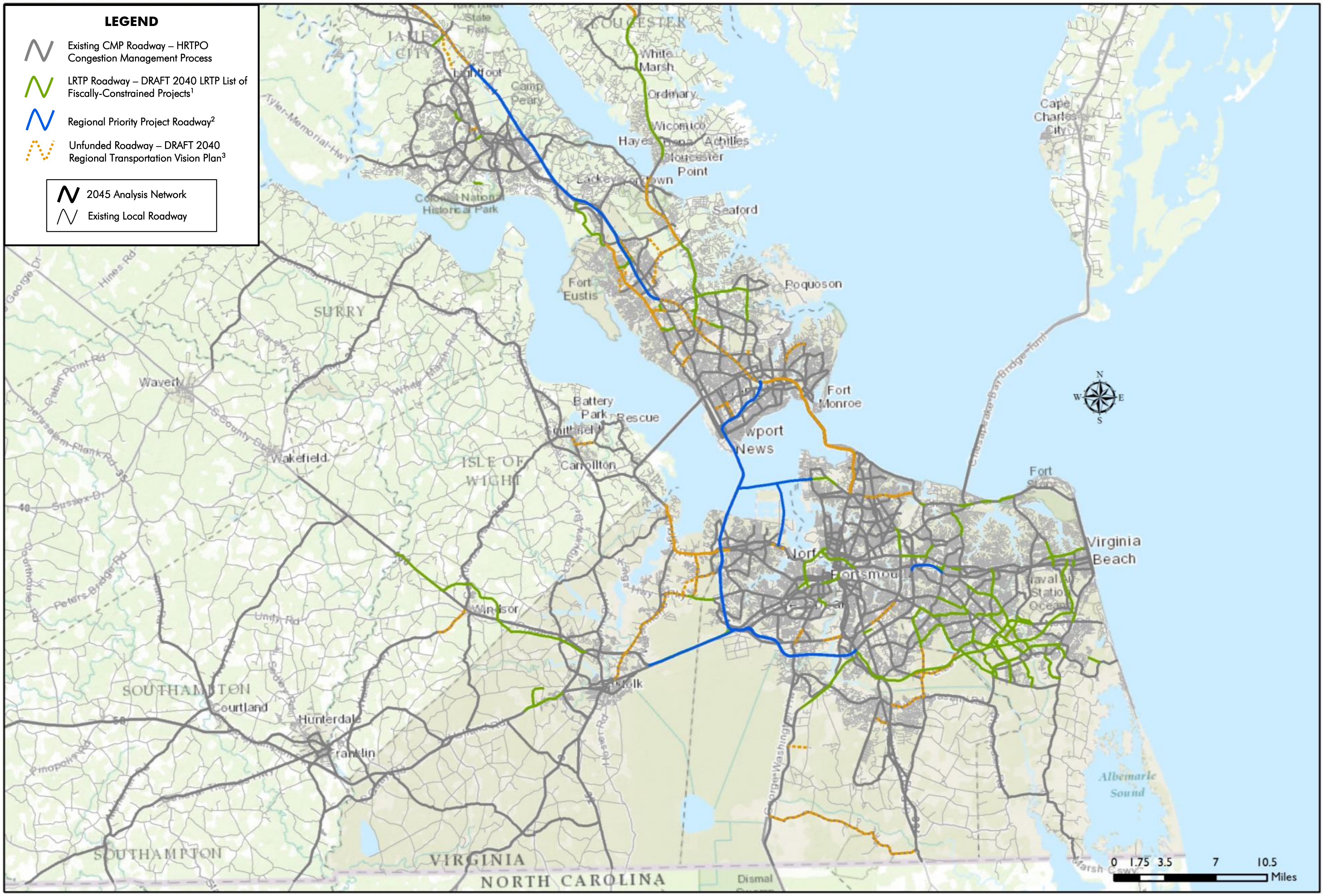
[18] *HRTPO Congestion Management Process (CMP) roadways as of July 2015.*

[19] *Hampton Roads 2040 LRTP: DRAFT Fiscally-Constrained List of Project, HRTPO Retreat Board Meeting, Enclosure 8, May 21, 2015.*

[20] *Regional, high-priority transportation projects adopted by Resolution 2013-9 by the HRTPO Board, October 17, 2013.*

[21] *Hampton Roads DRAFT 2040 Regional Transportation Vision Plan: List of Unfunded Prioritized Projects, HRTPO Transportation Technical Advisory Committee Meeting, Handout 10, June 3, 2015.*

2045 Analysis Network – Hampton Roads



1 Hampton Roads 2040 LRTP: DRAFT Fiscally-Constrained List of Project, HRTPO Retreat Board Meeting, Enclosure 8, May 21, 2015.
2 Regional Priority Projects – Regional, high-priority transportation projects adopted by Resolution 2013-9 by the HRTPO Board, October 17, 2013.
3 Hampton Roads DRAFT 2040 Regional Transportation Vision Plan: List of Unfunded Prioritized Projects, HRTPO Transportation Technical Advisory Committee Meeting, Handout 10, June 3, 2015.

Prepared by: HRTPO Staff, September 2015

Potential Flooding – Three 2045 Scenarios

For this study, maps of potentially submerged areas were developed for three scenarios using the best available elevation data:

1) **2.0 foot relative sea level rise**
2) **2.0 foot relative sea level rise + 25-year storm surge**
3) **2.0 foot relative sea level rise + 50-year storm surge**

Given the uncertainty in how much relative sea level rise will occur and how fast it will accelerate, current research suggests that 2.0 feet of rise could occur in Hampton Roads sometime between 2043 and 2083. With the forecast year of the next HRTPO Long-Range Transportation Plan being 2045, a conservative 2.0 foot relative sea level rise scenario was used in this analysis. HRTPO staff acknowledges that relative sea level rise may be much higher or lower due to the uncertainty of global estimates.

According to the Virginia Department of Transportation (VDOT) drainage manual, culverts for interstate highways are to be designed using a minimum flood frequency of 50 years. A culvert is a structure (e.g. pipe) that allows storm runoff (water) to flow under a road from one side to the other to allow vehicles to travel safely. Culverts for primary and arterial roadways are to be designed using a minimum flood frequency of 25 years. Engineering practice is based on the premise of "acceptable risk"; acceptable risk is addressed by basing design standards on the recurrence probability of storm events (e.g., an interstate highway culvert designed for the 50-year storm has a 2% annual chance of failing). Given that most roadways within the HRTPO CMP are interstate, primary, and arterial, 25-year (4% annual chance) and 50-year (2% annual chance) storm surge scenarios were used on top of the 2.0 foot relative sea level rise to plan for storm events in the 2045 year horizon.

Storm surge varies widely across the region depending on the characteristics of a particular storm and a given area's relationship to the coast. The highest storm surges generally occur along tidal tributaries such as the Elizabeth and Nansemond Rivers. Coastal areas along the Atlantic Ocean, Chesapeake Bay, James River, and York River also experience significant storm surges. Inland areas that drain to the Albemarle Sound, such as those in the Southern Rivers watersheds or near the Back Bay, typically experience smaller storm surges.

What is scenario planning?

- According to FHWA, scenario planning is an analytical tool that can help transportation professionals prepare for what lies ahead. It tests various future alternatives that meet state/regional and community needs.

For Scenario 2 (2.0 feet of sea level rise plus a 25-year storm surge), the water surface elevation ranged from 2.7 feet NAVD (North American Vertical Datum, 1988) to 10 feet NAVD across Hampton Roads. At Sewell's Point in Norfolk, the water surface elevation in this scenario was approximately 8.1 feet NAVD.

For Scenario 3 (2.0 feet of sea level rise plus a 50-year storm surge), the water surface elevation ranged from 3.1 feet NAVD to 11.1 feet NAVD across the region, with a water surface elevation of approximately 8.8 feet NAVD at Sewell's Point. For comparison purposes, during Hurricanes Isabel (September 18, 2003) and Irene (August 27-28, 2011), the water surface elevation was 6.28 feet NAVD and 5.94 feet NAVD at Sewell's Point, respectively.

For more background information on the selection of these scenarios, refer to the previous section of this report—Vulnerability to Sea Level Rise/Storm Surge (pages 11-12).

GIS Mapping Methodology

Analyses for this portion of the study were developed using geographic information system (GIS) elevation data from the Hampton Roads Planning District Commission (HRPDC) for the three scenarios described above. Land elevation surfaces were determined for all Hampton Roads jurisdictions using the most recent and highest resolution LiDAR (Light Detection and Ranging) data[1]. The LiDAR data layers are referenced to North American Vertical Datum 1988 (NAVD), a standard geodetic vertical datum. The LIDAR data used in this analysis was collected over a period of several years, 2011 to 2014.

Tidal datums are calculated based on observations taken and averaged over a period of several years. For most of the United States, the National

[1] For Mulberry Island/Fort Eustis in Newport News and the western shore of Craney Island in Portsmouth, the best available data (1/9 arc-second resolution) from the National Elevation Dataset was used instead.

Vertical Datum – a reference for measuring elevations or depths.

National Tidal Datum Epoch – the specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums. It is necessary for standardization because of periodic and apparent secular trends in sea level. The present NTDE is 1983 through 2001 and is considered for revision every 20-25 years.

Mean Higher High Water* (MHHW) – The average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch.

*Hampton Roads has semidiurnal tides – the tide typically cycles through a high and low twice each day, with one of the two high tides being higher than the other and one of the two low tides being lower than the other.

Source: National Oceanic and Atmospheric Administration (NOAA)

Oceanic and Atmospheric Administration's (NOAA) National Ocean Service averages measurements taken over a specified 19-year period, called a National Tidal Datum Epoch (NTDE), to calculate local tidal datums such as Mean Sea Level (MSL) or Mean Higher High Water (MHHW) for each station (see definitions for NTDE and MHHW above). Since tidal datums are the average of many observations, the mid-point, in this case 1992 (the current NTDE is 1983-2001), is often used for studies involving sea level trends.

In order to determine which areas of land would be submerged, HRPDC staff first identified tidal datums to use as a reference. HRPDC staff chose to use Mean Higher High Water (MHHW) as the reference tidal datum. As defined above, this datum reflects a regularly occurring tidal condition near the top of the normal tidal range. HRPDC staff used a tidal surface layer developed by NOAA's Office for Coastal Management that represents mean higher high water extrapolated landward. HRPDC staff then added 2.0 feet of relative sea level rise to this surface to obtain Scenario 1. For storm surge, the HRPDC staff utilized results from the Region III FEMA storm surge analysis which generated points with various values for periodic storm surges (e.g. the 100-year event or the 500-year event). The HRPDC staff added 2.0 feet to the values for the 25-year and 50-year storm surge events and then interpolated and extrapolated the new point set to create Scenario 2 and Scenario 3. These scenarios were then compared to existing land elevations.

All elevations less than MHHW plus 2.0 feet (or 2.0 feet plus the storm surge scenarios) were analyzed with a dataset representing tidally connected waters to separate those areas that would be flooded or inundated by sea level rise and those that may only be prone to ponding. For all three scenarios, only those areas that were determined to be tidally connected were maintained.

The GIS elevation layer was comprised of 5 feet by 5 feet pixels, with each pixel having a given land elevation. A roadway network shapefile representing the 2045 Analysis Network (described on page 17) was created using multiple HRTPO GIS road layers and was then overlain on the elevation scenarios to test potentially submerged roadway locations. Within GIS, the clip analysis geoprocessing tool was used to identify the specific roadway segments in the potentially submerged areas for all three scenarios. A second GIS roadway network shapefile representing Existing Local Roadways—local and collector streets, ramps, and military installation roads—was also tested using the same methodology for potential submergence and are shown in subarea maps for Hampton Roads jurisdictions later in this section.

For future planned roadways, the GIS analysis used existing land elevations, even though the road may be constructed at higher elevations.

GIS Data Limitations

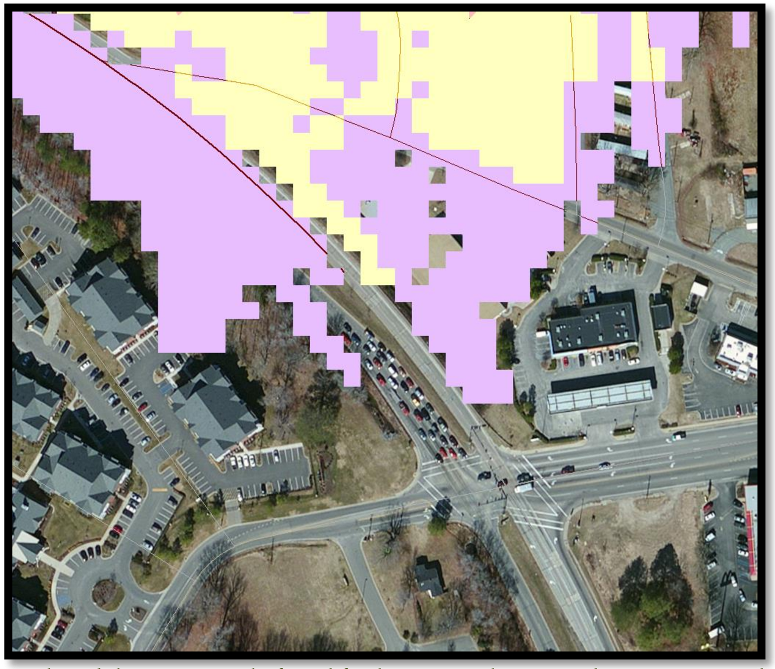
Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography (Google maps and ArcGIS) to remove those submerged locations. Existing Local Roadways,

For the 2045 Analysis Network, potential flooding on elevated roadway structures were removed.
(Location: Shore Dr over Little Creek in Norfolk, Va)

however, were not checked for elevated structures given the large size of that network.

It is important to note that this GIS clip analysis was based only on submergence from relative water level rise. It did not consider flooding due to rainwater that cannot drain fast enough.

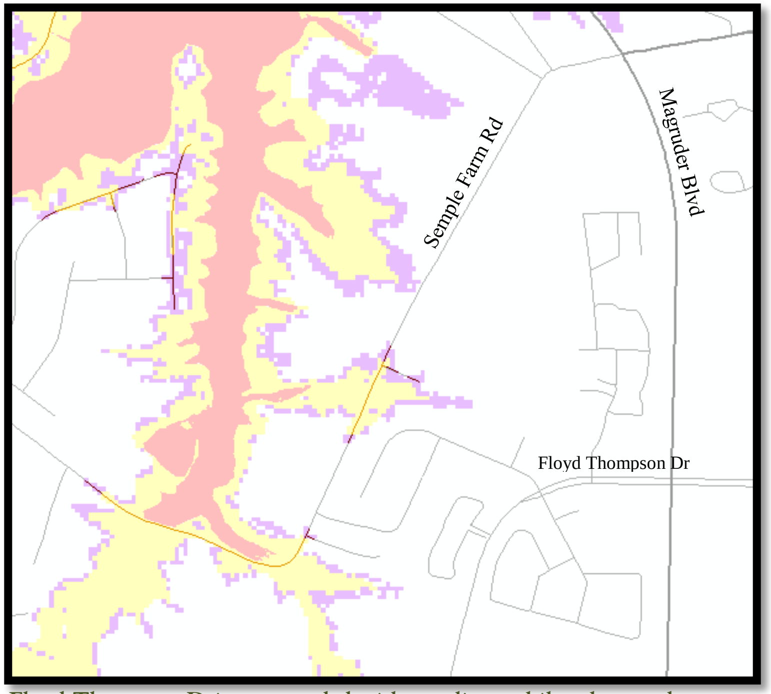
The roadway dataset used in this analysis was a Virginia Geographic Information Network (VGIN) road centerline shapefile/database, obtained from the Virginia Department of Transportation, which includes road names, route numbers, and other information. This analysis did not include the number of lanes, the actual width, or the presence of medians—most roadways were represented by a single line in the center of the roadway location (see GIS screenshot below). A few roadways were represented as two-way with two lines rather than a single line (see GIS screenshot to the right). One weakness of this dataset and analysis is that vulnerabilities were only found for locations where inundation intersected the road centerline. One potential future solution to this problem may be to develop a roadway GIS layer using polygons rather than a single line to determine where potential flooding may occur.



Vulnerabilities were only found for locations where inundation intersected the road centerline. Some roadways may have partial flooding on the edge of the roadway not reflected within the flooding vulnerability analysis. (Location: Magruder Blvd at Semple Farm Rd in Hampton, Va)

In the subsection following the potential submergence maps, a summary of vulnerable roadways by centerline miles by jurisdiction is provided.

This GIS-based flooding analysis shows the locations of potential flooding for three relative sea level rise and storm surge scenarios. It does not, however, provide the depth of water or the anticipated duration of inundation for each location.



Floyd Thompson Drive was coded with two lines while other roadways were represented by a single line. (Location: Hampton, Va)

RESULTS

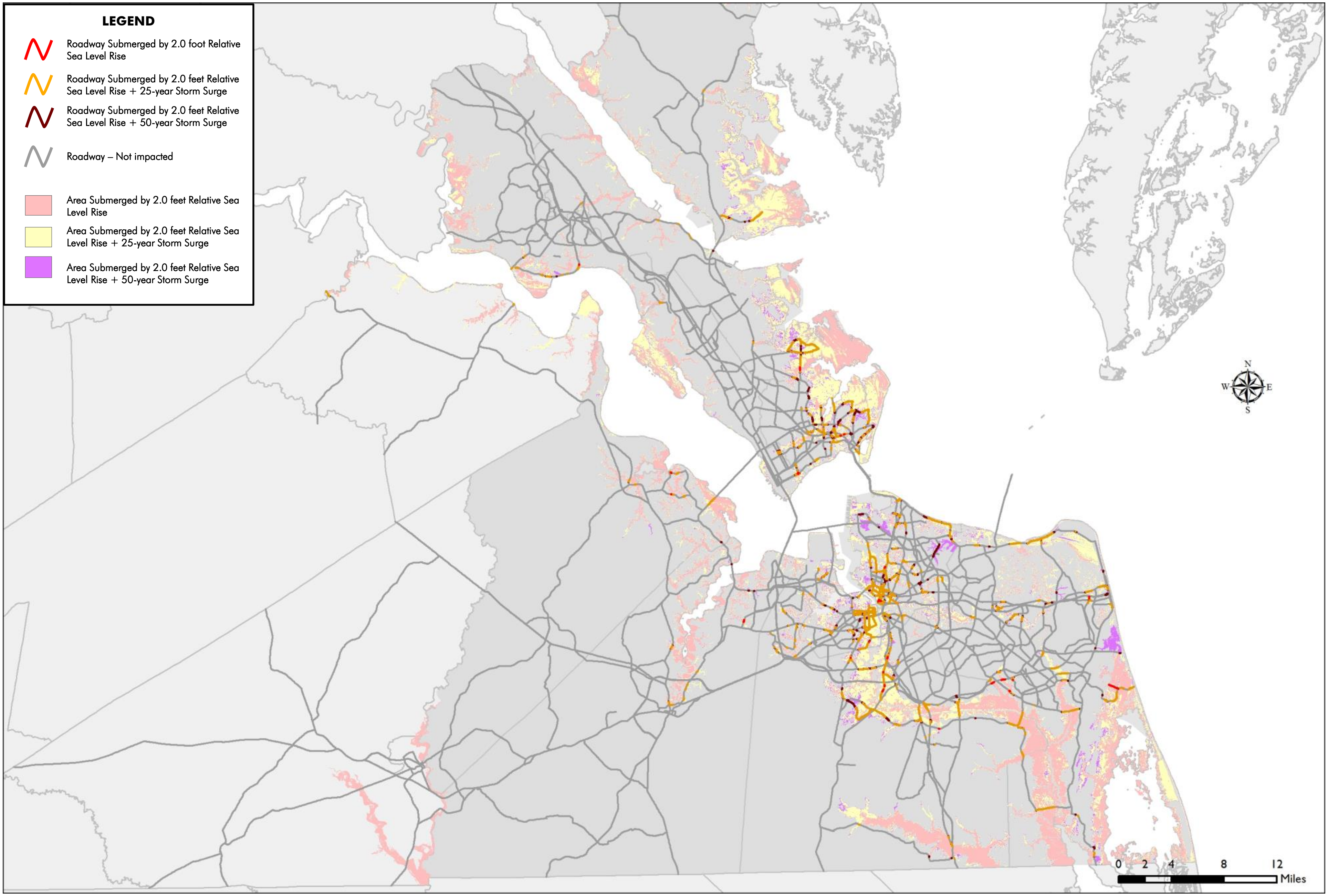
Roadway segments along the "2045 Analysis Network" that are projected to be submerged for the three relative sea level rise and storm surge scenarios are shown in red, orange, and maroon on maps on pages 23-25:

- Potential Submergence of 2045 Analysis Network
  - Hampton Roads (page 23)
  - Hampton Roads Peninsula (page 24)
  - Hampton Roads Southside (page 25)

Additionally, subarea maps that provide a closer view of various Hampton Roads jurisdictions are provided on pages 27-41:

- Potential Submergence of Roadways by 2045
  - James City County and Williamsburg (page 27)
  - Gloucester County (page 28)
  - York County (page 29)
  - Newport News (page 30)
  - Poquoson (page 31)
  - Hampton (page 32)
  - Isle of Wight County (page 33)
  - Suffolk (page 34)
  - Chesapeake (page 35)
  - Northern Chesapeake (page 36)
  - Portsmouth (page 37)
  - Norfolk (page 38)
  - Downtown Norfolk and Portsmouth (page 39)
  - Northern Virginia Beach (page 40)
  - Southern Virginia Beach (page 41)

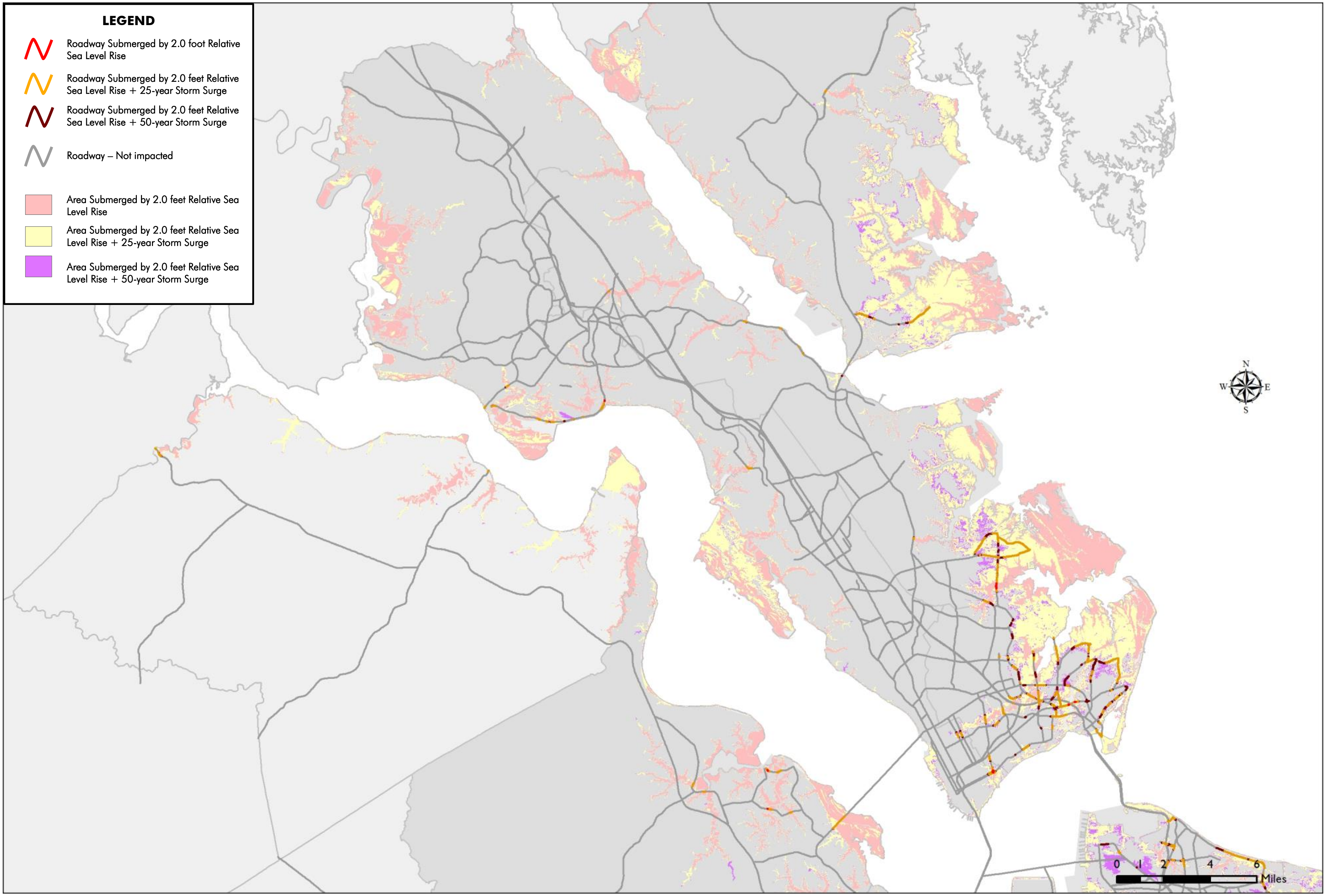
Potential Submergence of 2045 Analysis Network– Hampton Roads



Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

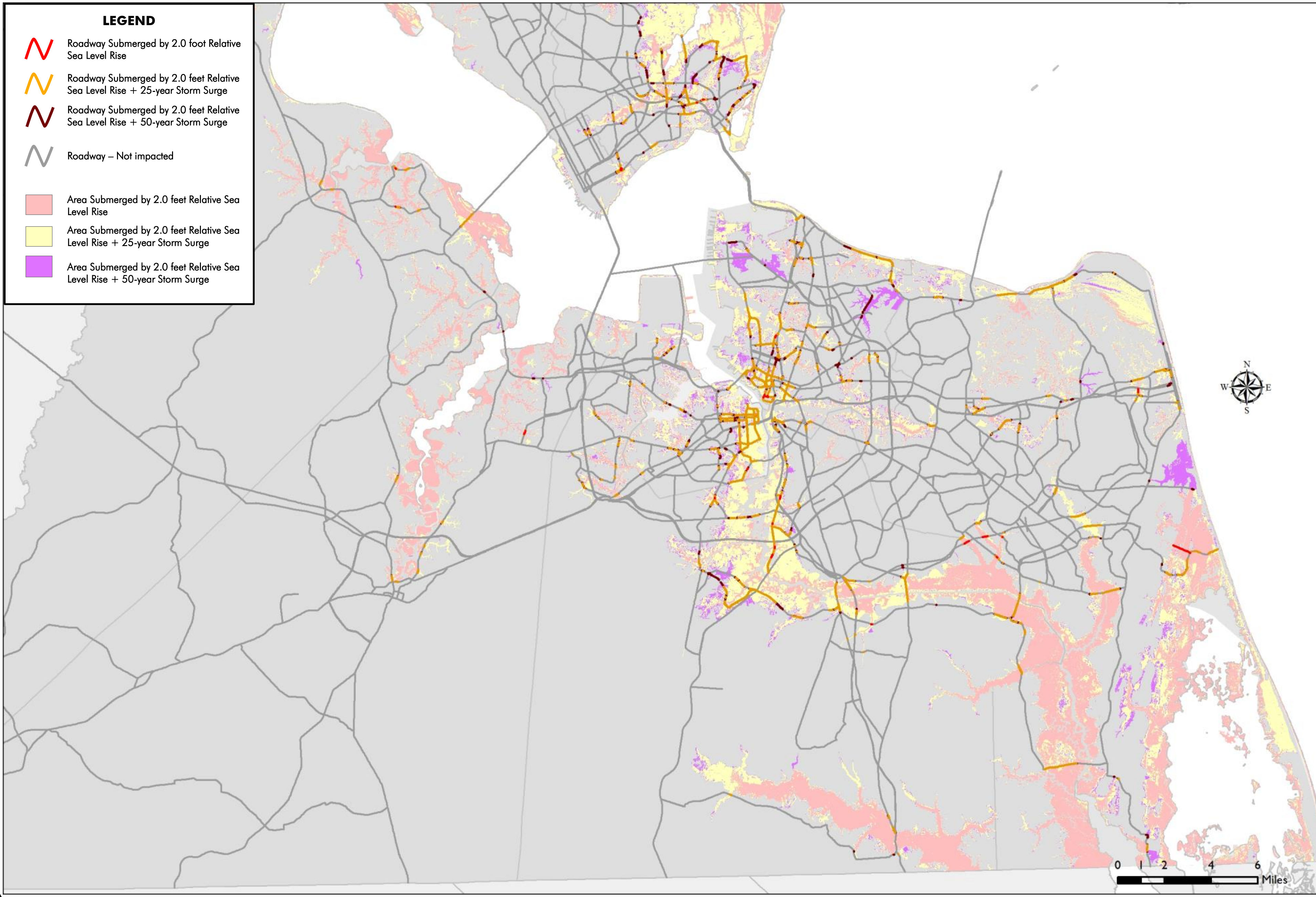
Potential Submergence of 2045 Analysis Network– Hampton Roads Peninsula



Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

Potential Submergence of 2045 Analysis Network– Hampton Roads Southside



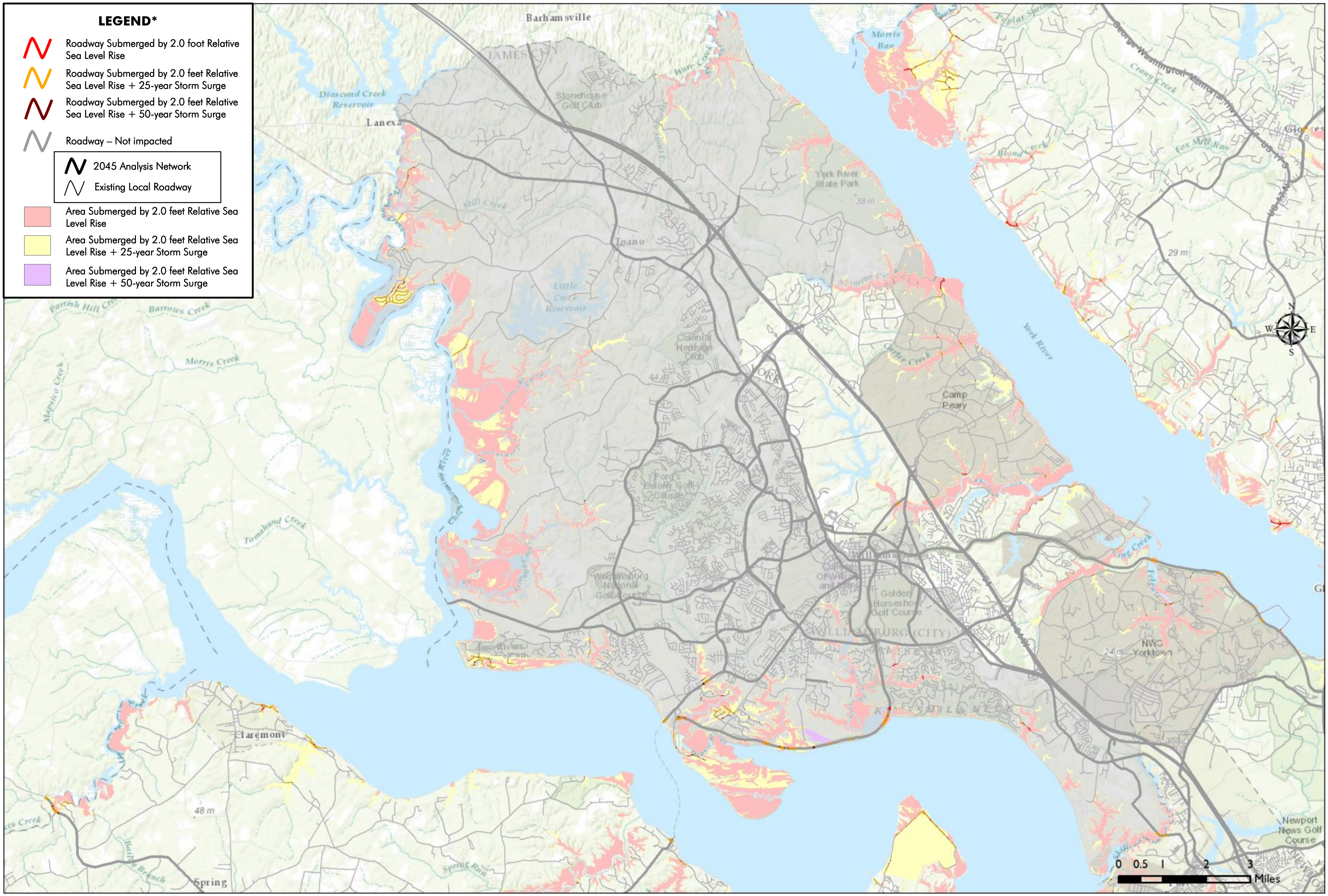
Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

Subarea Maps for Hampton Roads Jurisdictions

Potential Submergence of Roadways

Potential Submergence of Roadways by 2045 – James City County and Williamsburg

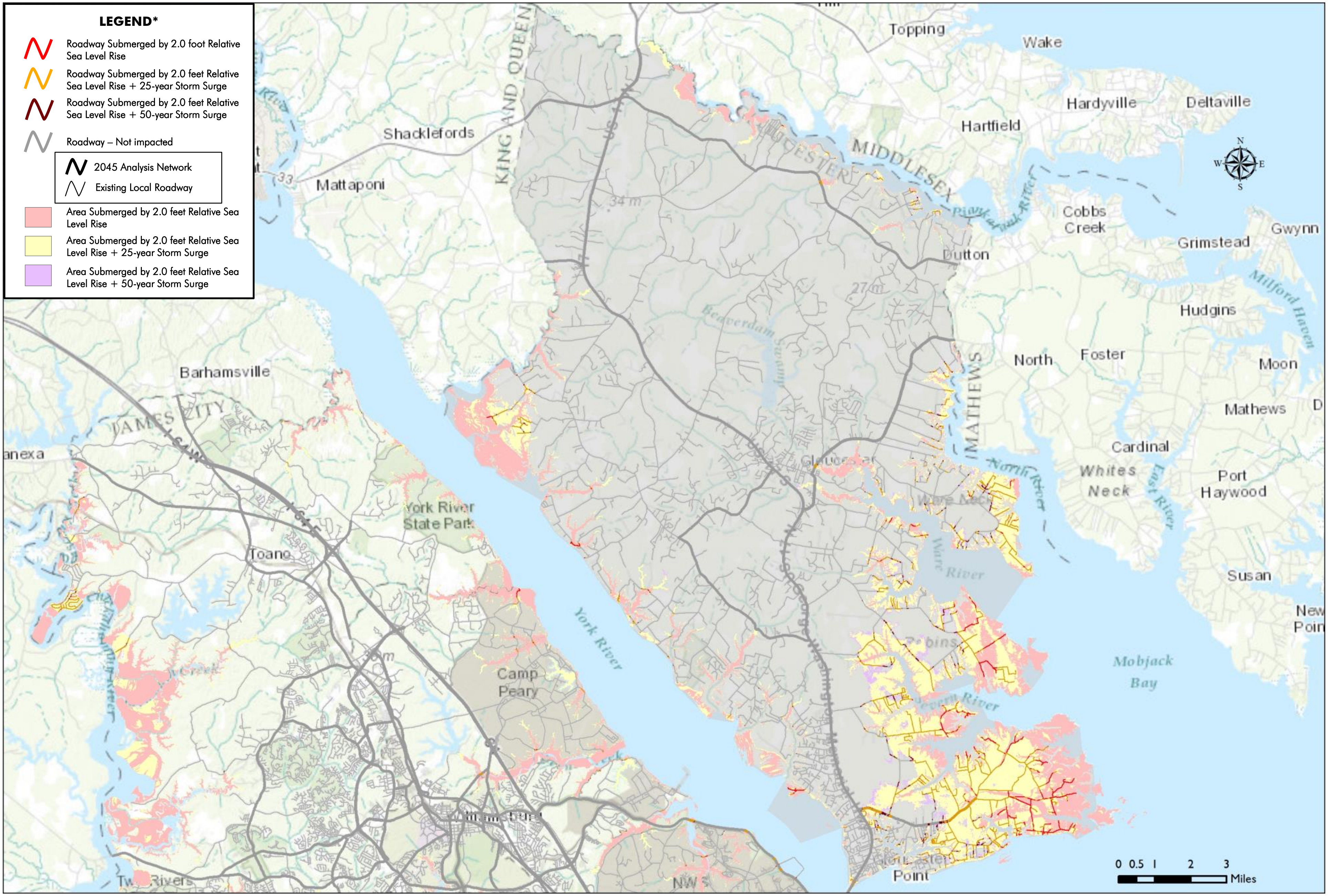


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Gloucester County

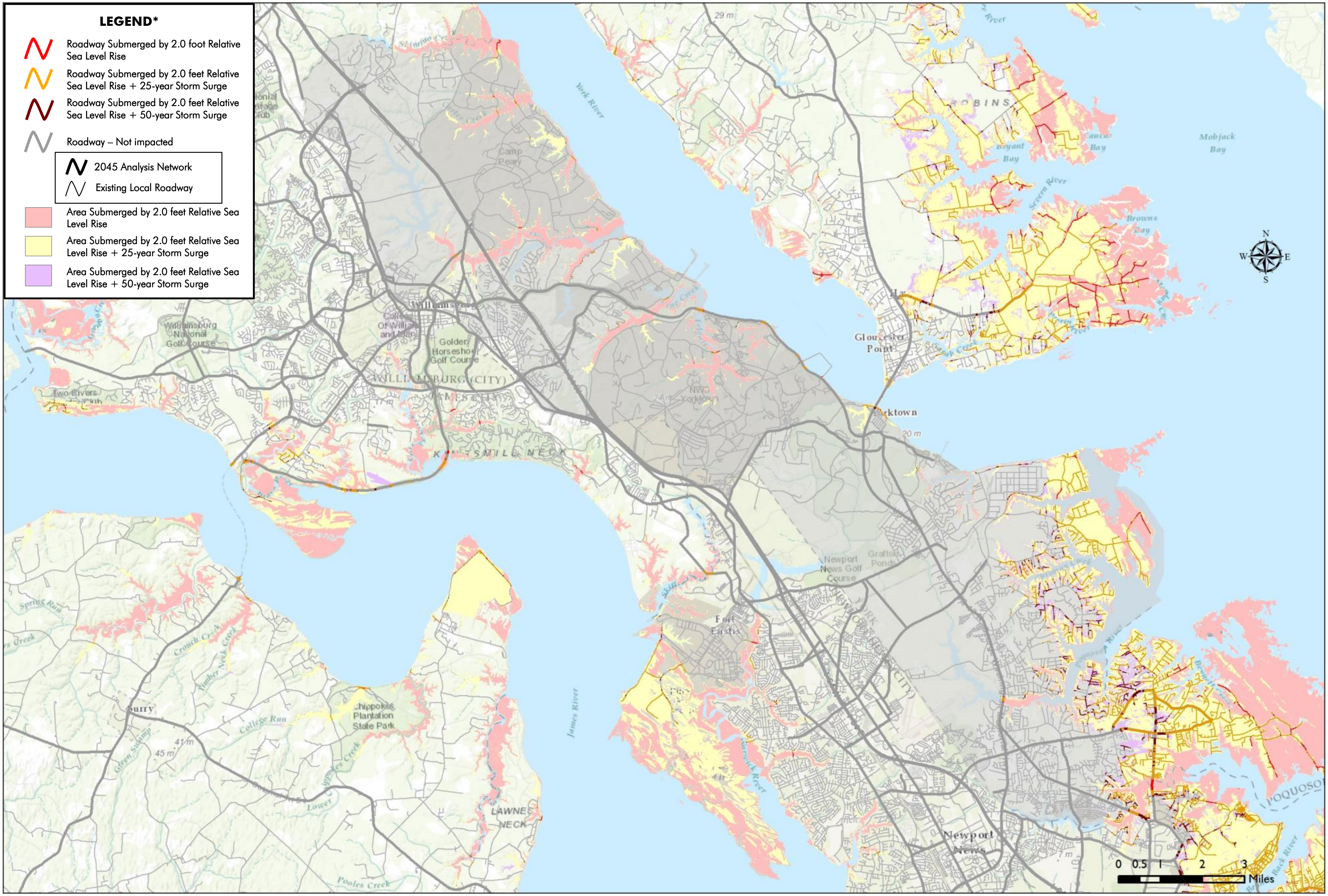


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – York County

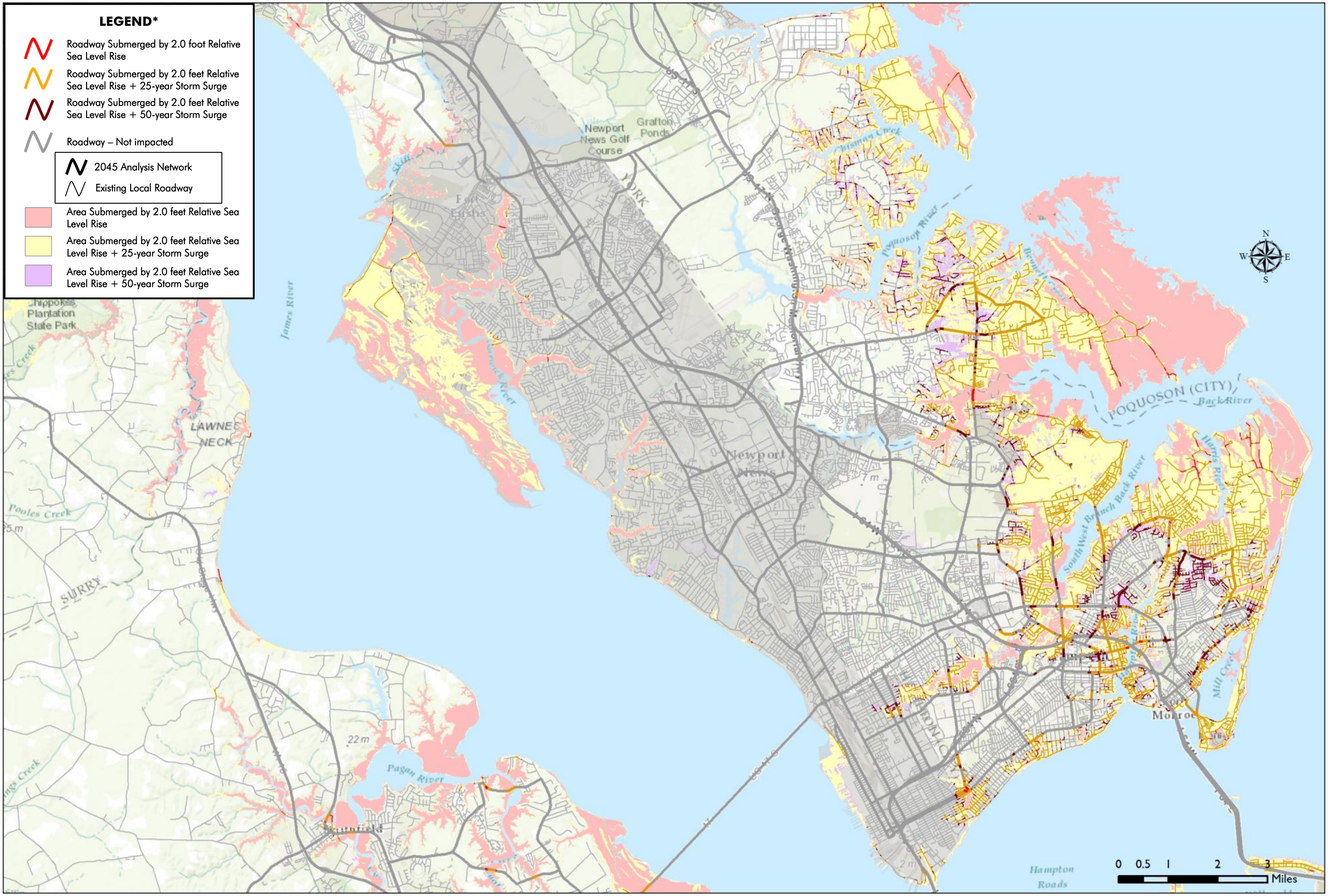


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Newport News

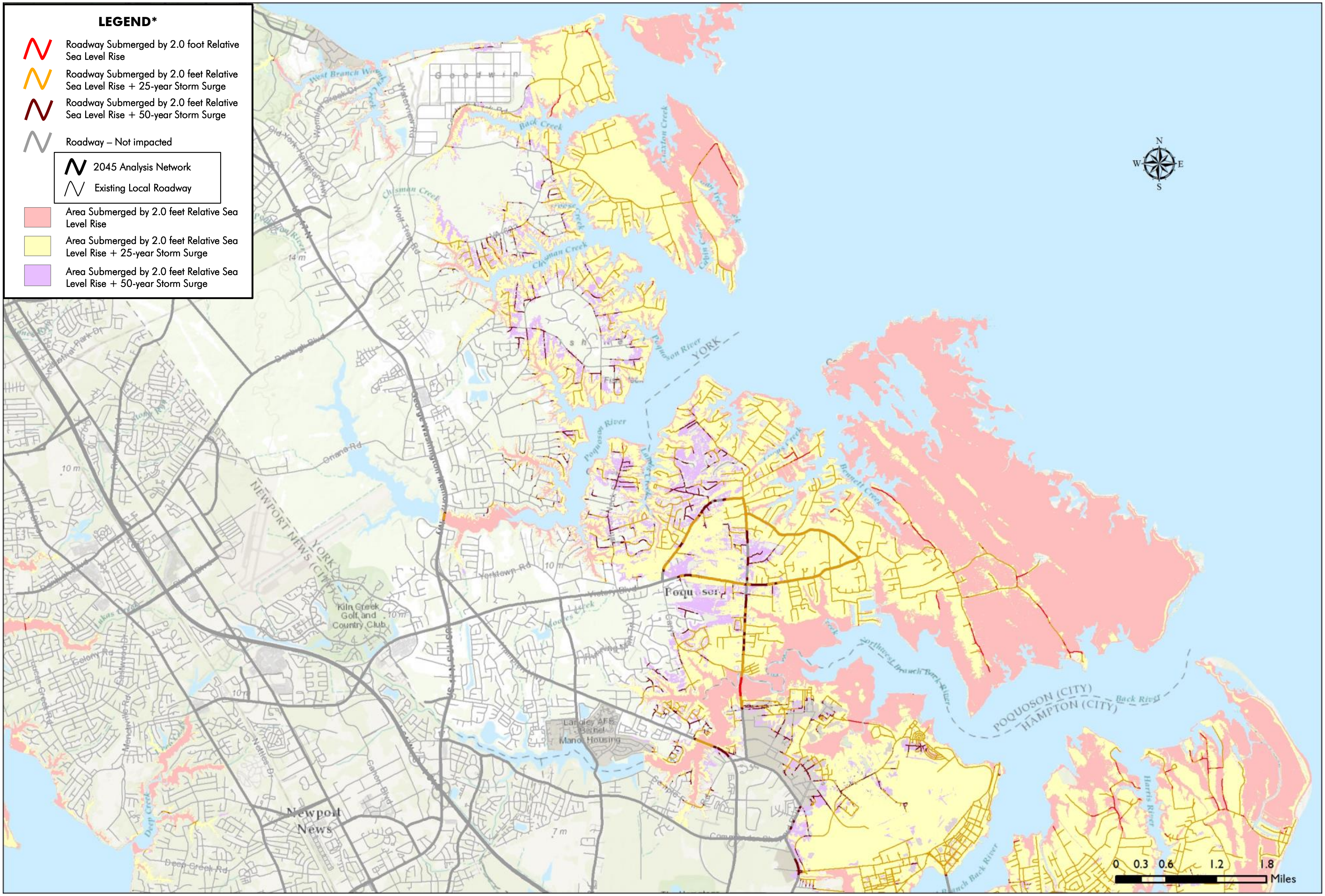


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Poquoson

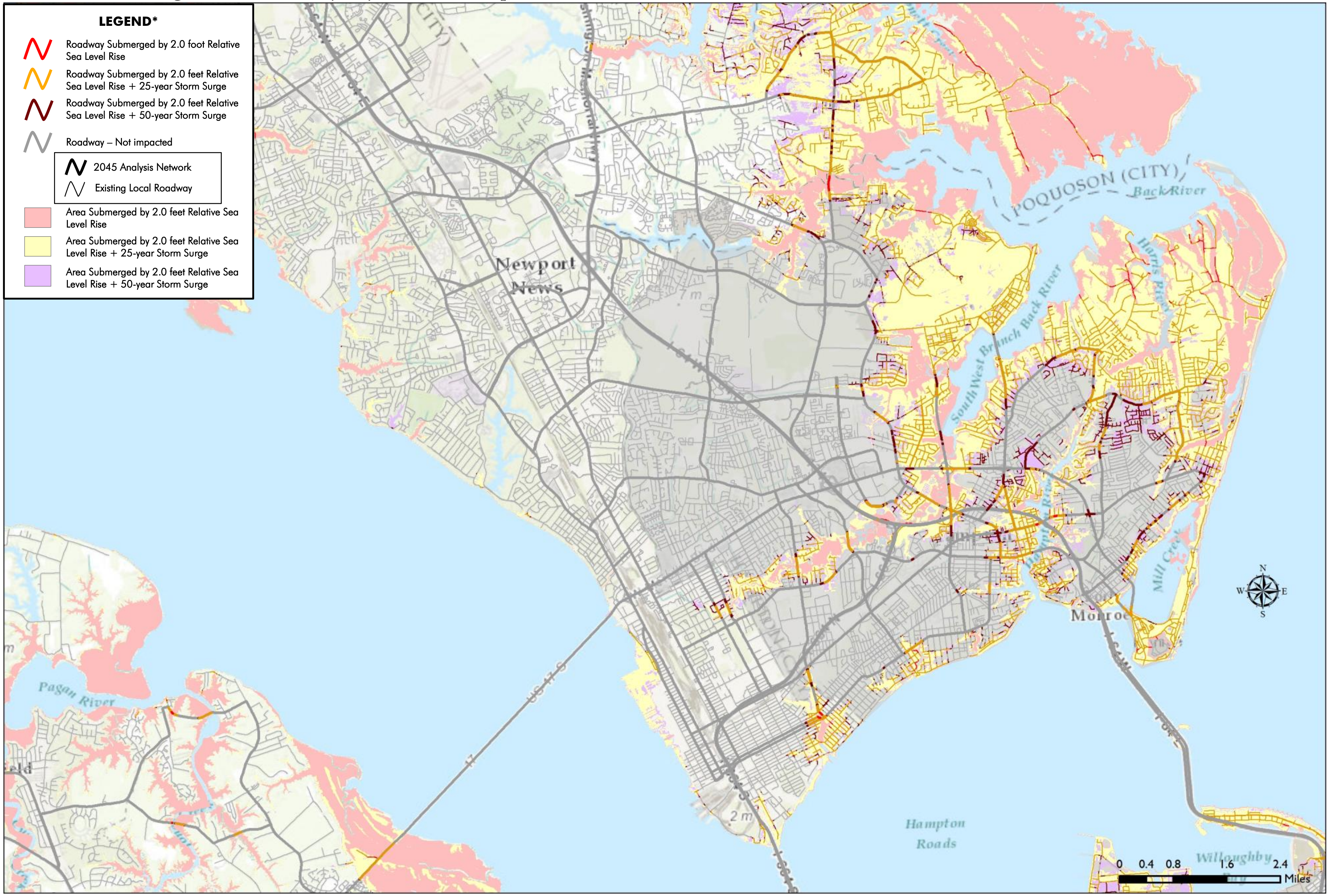


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Hampton

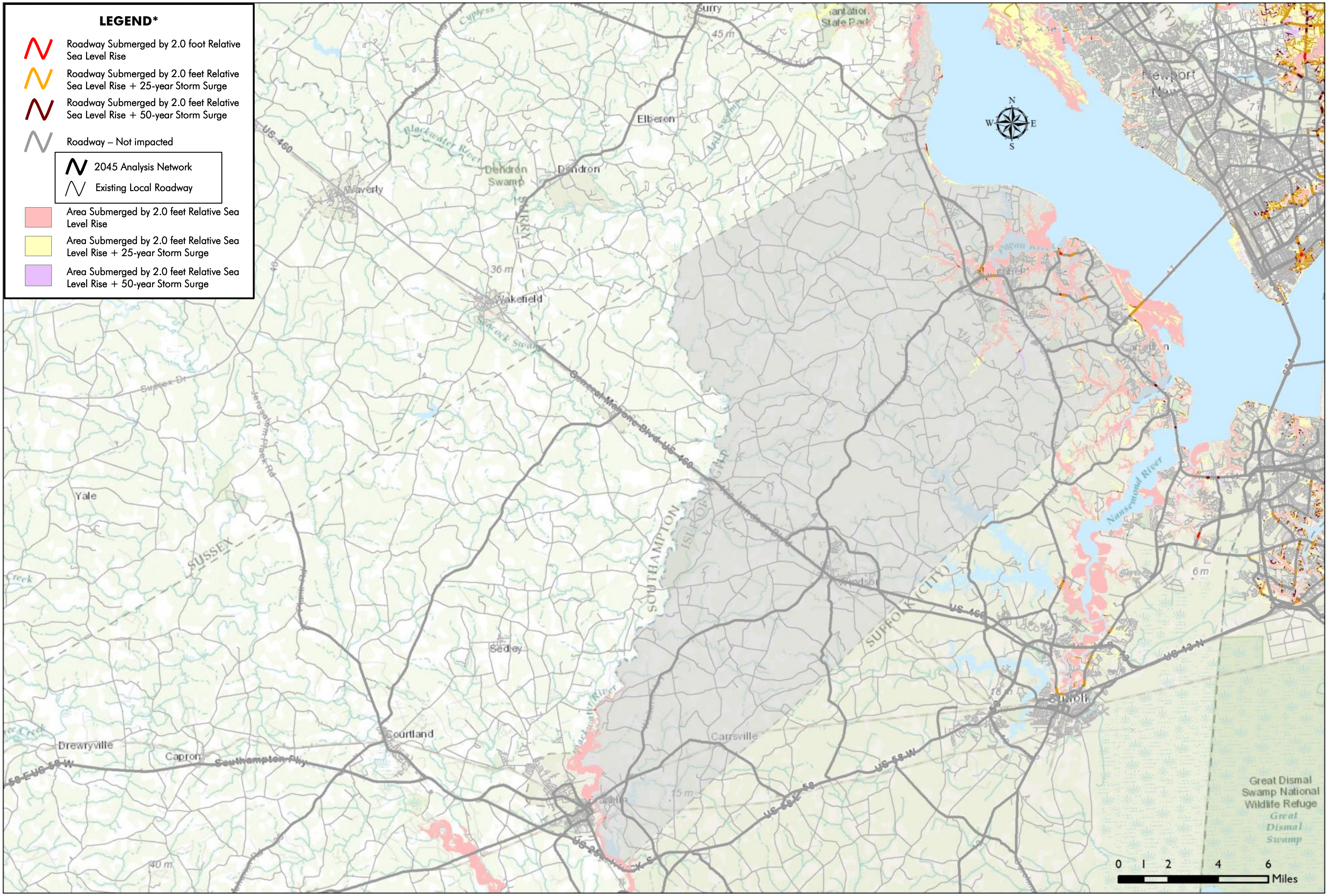


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Isle of Wight County

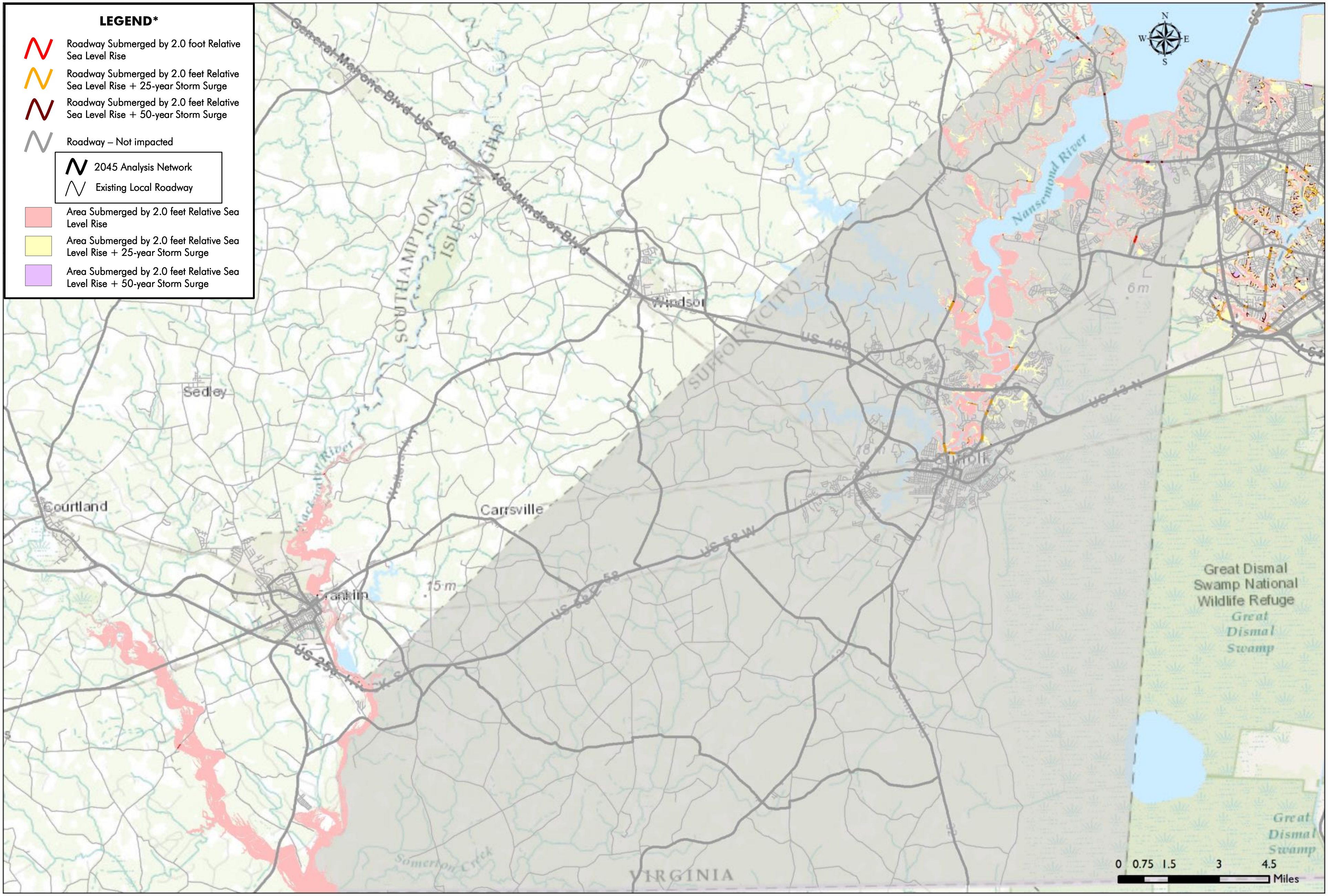


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Suffolk

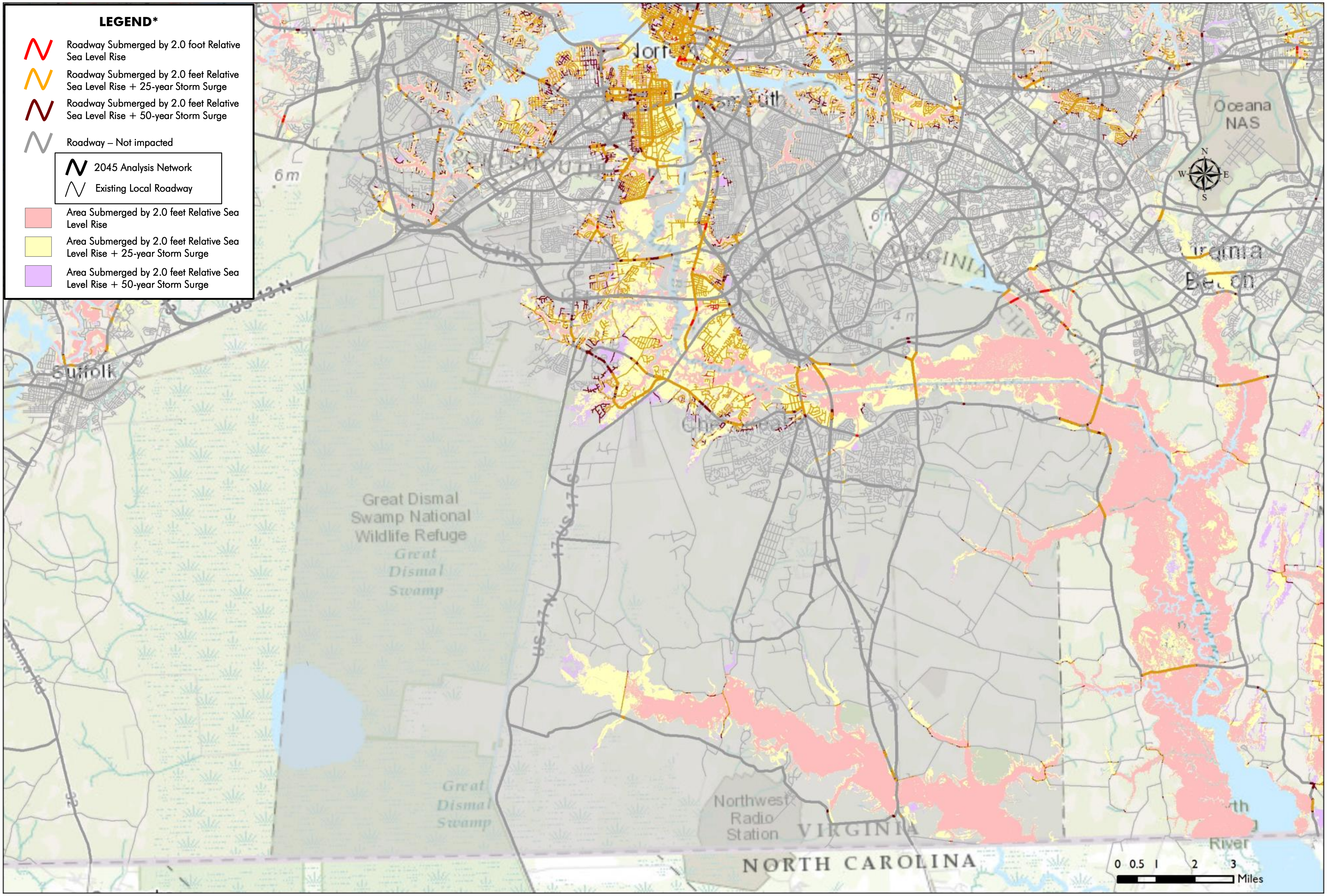


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Chesapeake

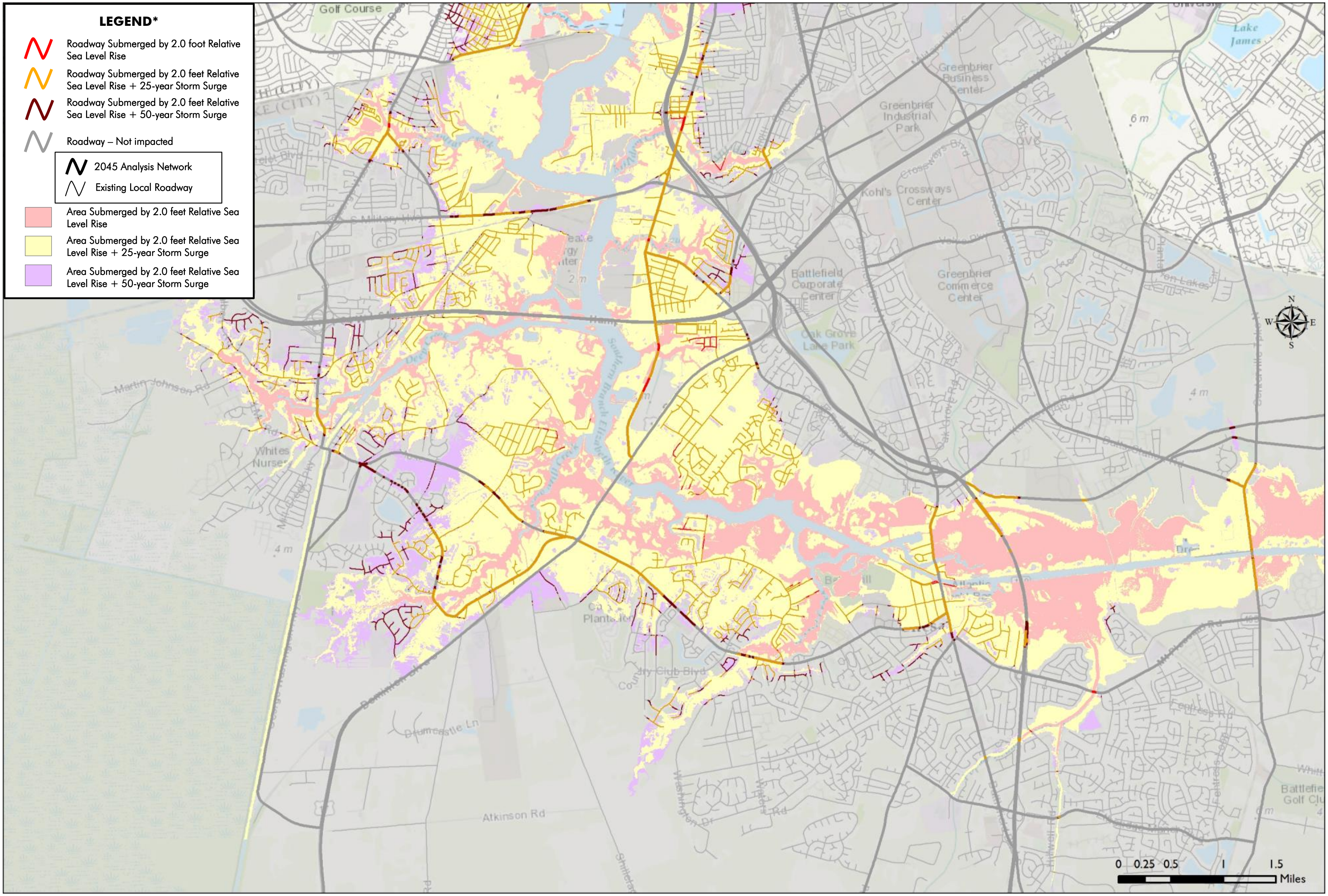


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Northern Chesapeake

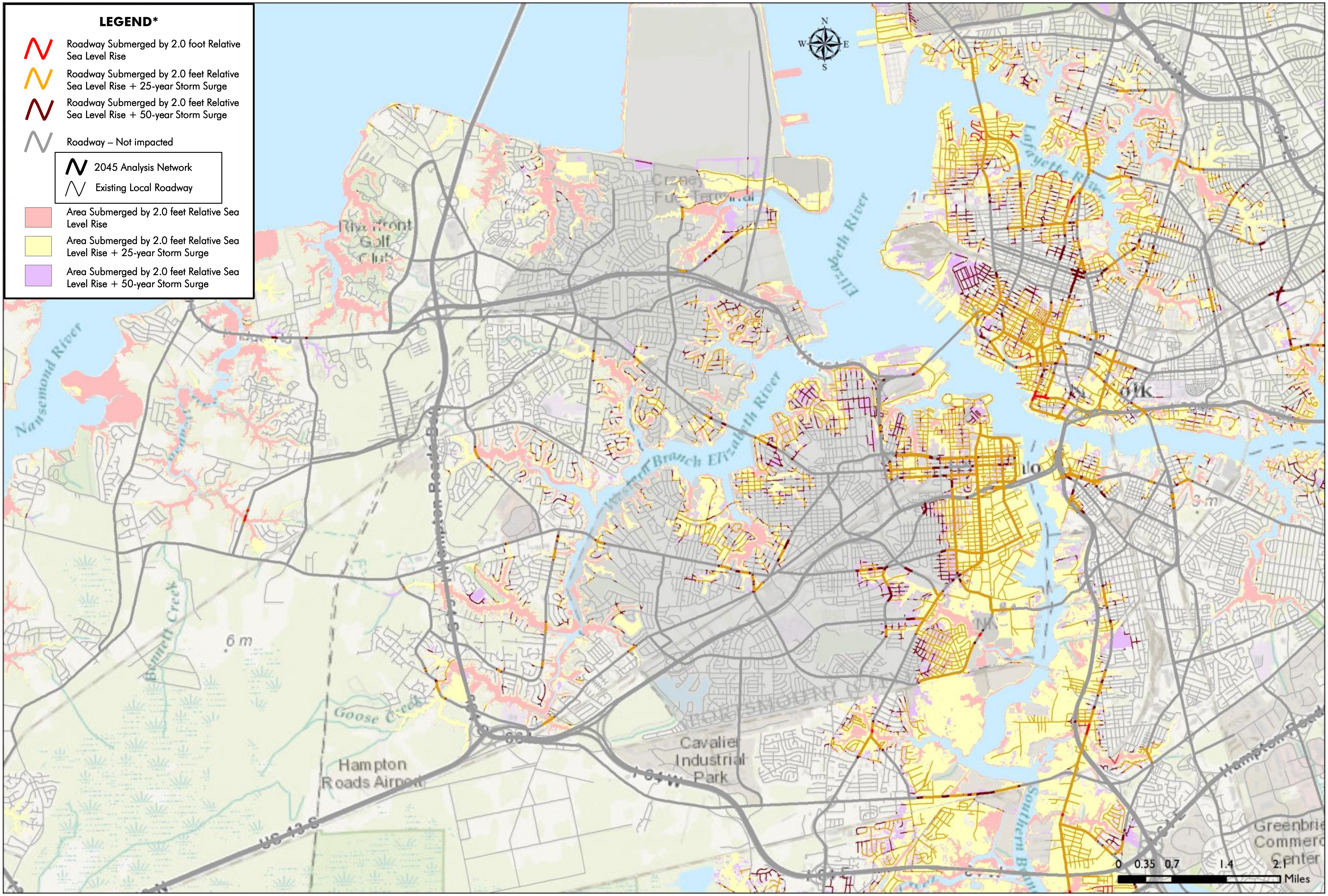


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Portsmouth

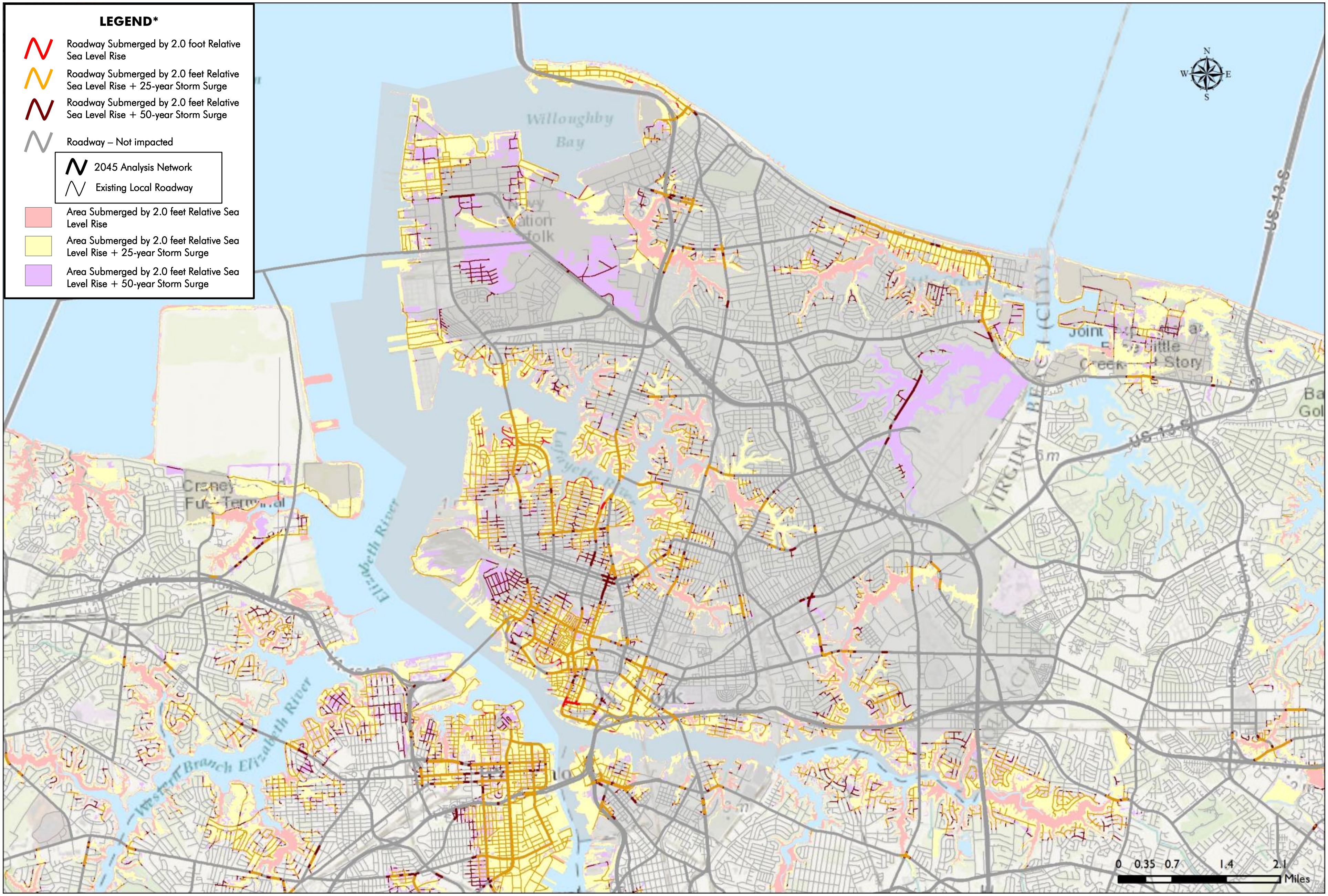


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Norfolk

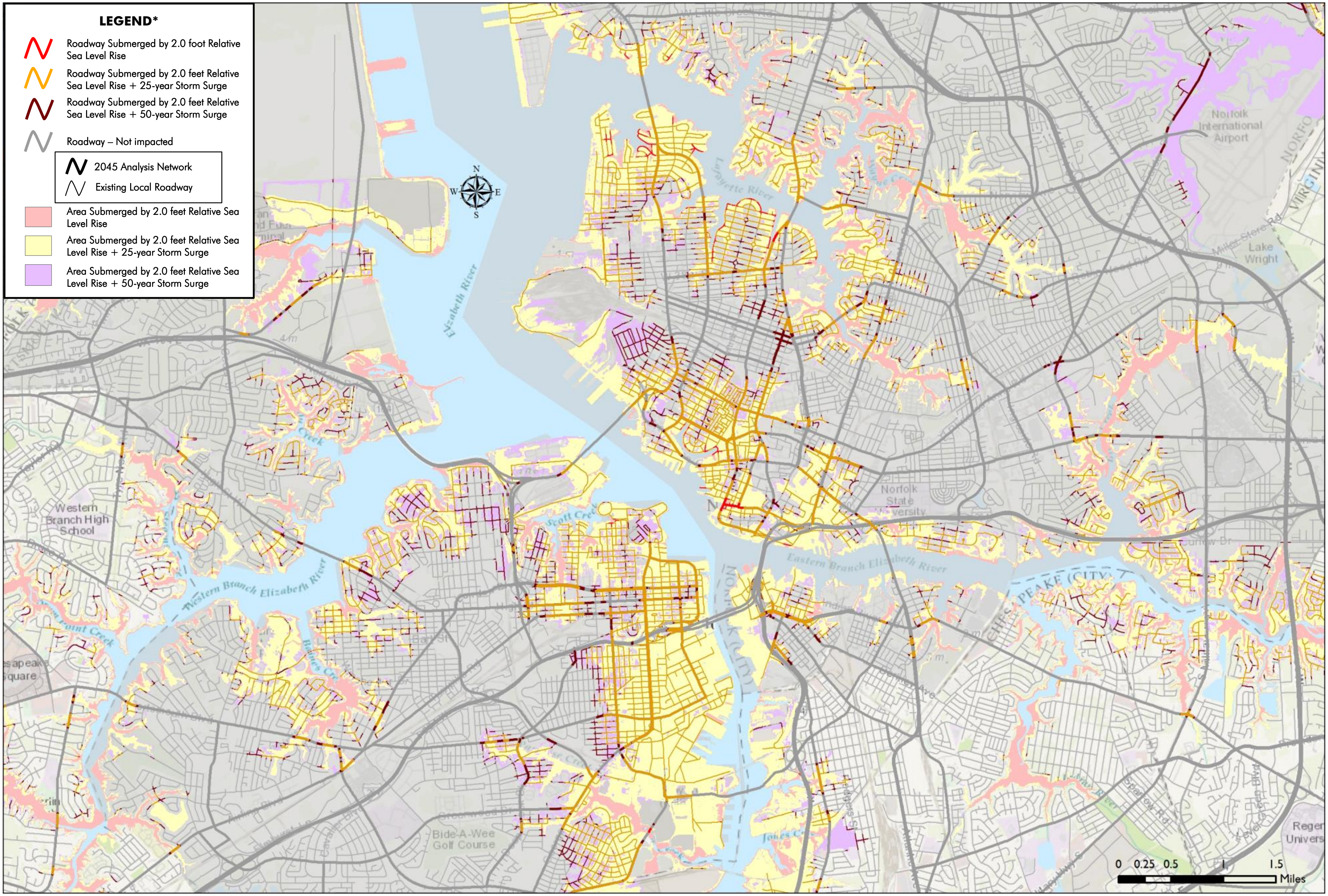


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Downtown Norfolk and Portsmouth

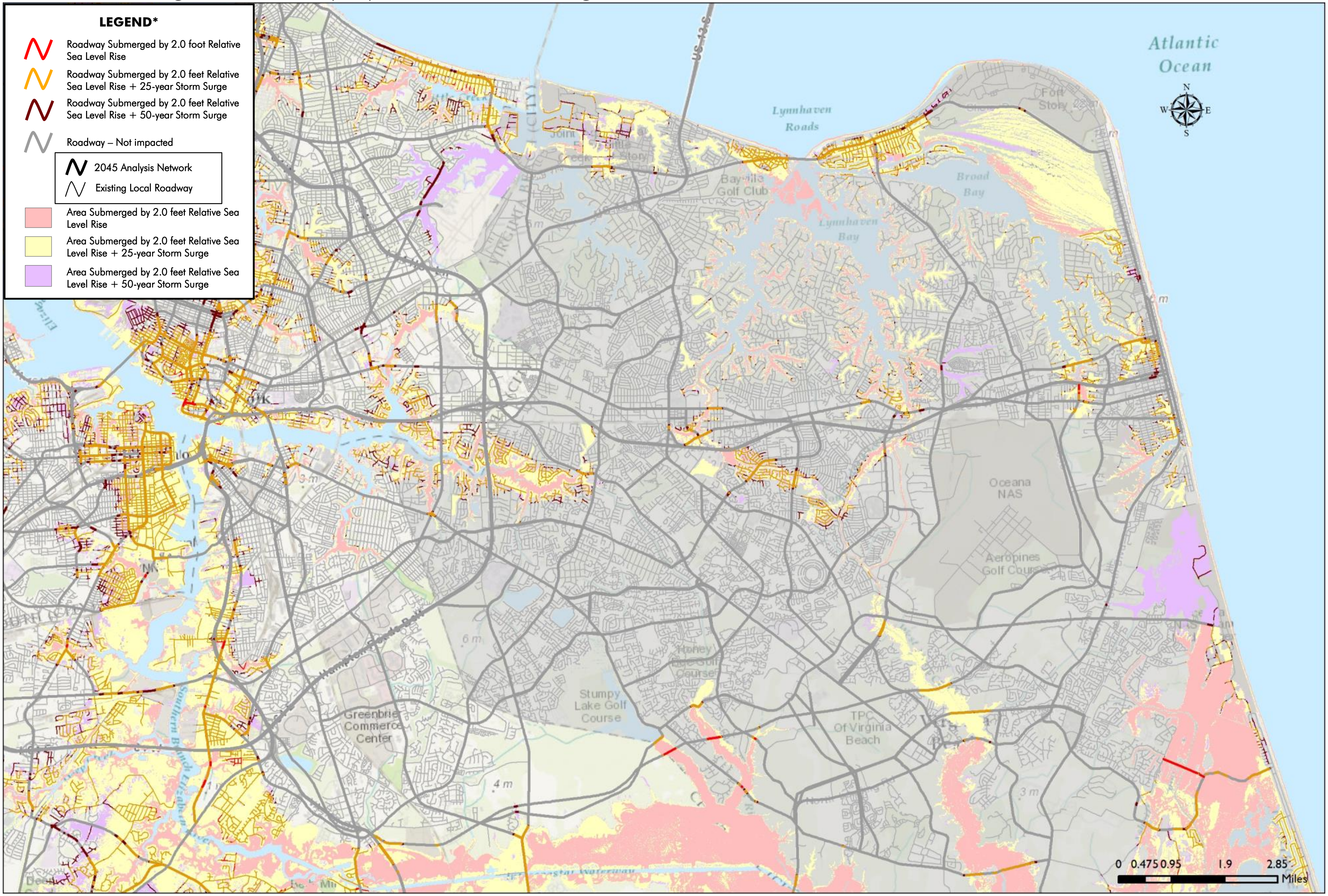


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Northern Virginia Beach

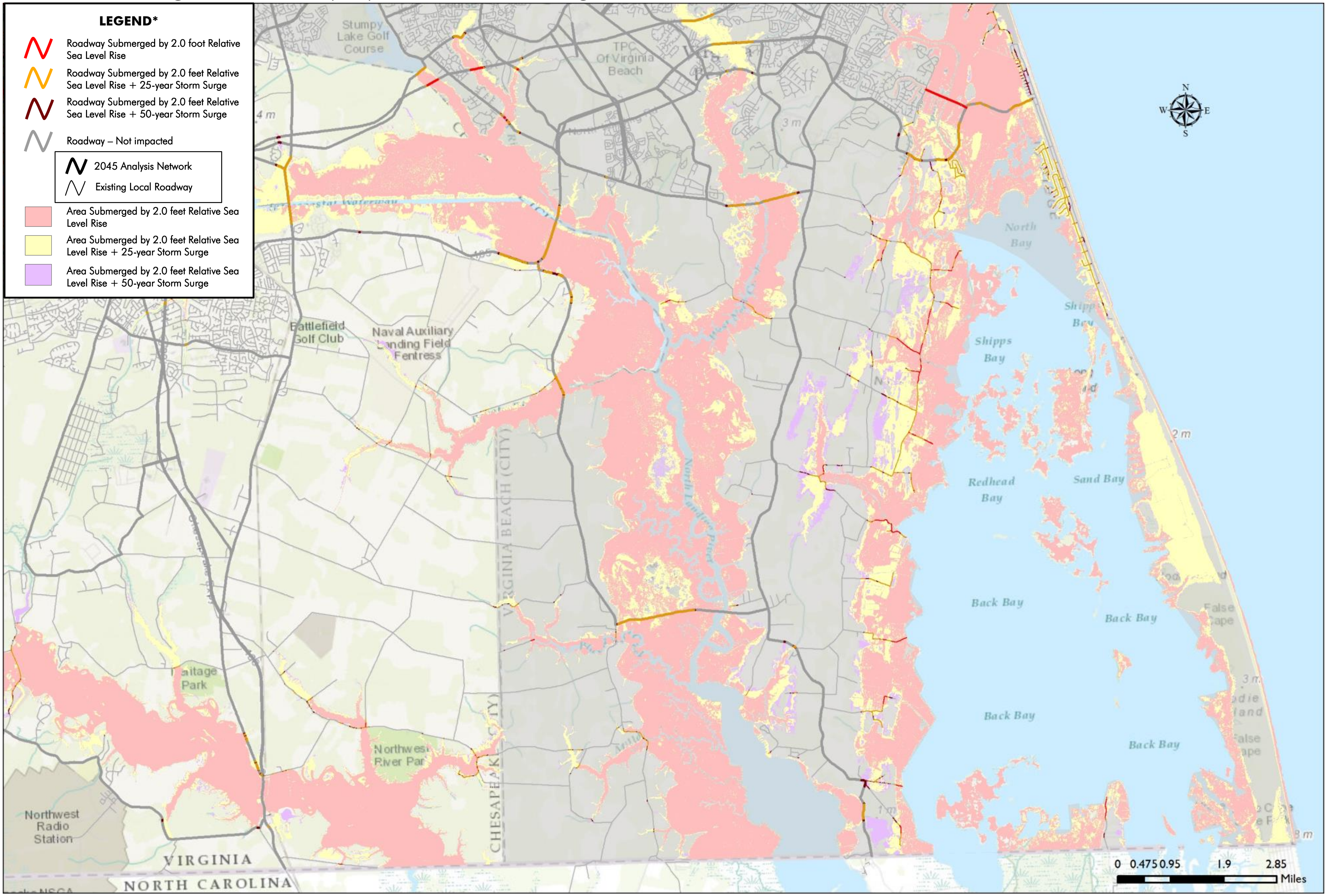


Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

Potential Submergence of Roadways by 2045 – Southern Virginia Beach



Prepared by: HRTPO Staff, October 2015

Data source for projected flooded areas: HRPDC Staff, October 2015

*Within the GIS analysis, some roadways with elevated structures (e.g., bridges and overpasses) were identified to be submerged. At these locations, the land below the roadway structure was expected to flood, not the actual roadway. For the 2045 Analysis Network, HRTPO staff used aerial photography to remove those submerged locations. Existing Local Roadways, however, were not checked for elevated structures given the large size of that network.

SUMMARY BY HAMPTON ROADS JURISDICTION

Jurisdictions within Hampton Roads all have unique land elevations and development patterns. Even though flooding occurs in all Hampton Roads jurisdictions, existing and potential submergence risks from relative sea level rise and storm surges are not uniformly distributed due to this variation in topography and development.

The following tables in this section provide a summary of potential submergence risks of centerline miles flooded by 2045 by jurisdiction for the three relative sea level rise and storm surge scenarios analyzed in this study. The first table summarizes the results for the 2045 Analysis Network (interstate highways, arterials, and some collectors), which includes existing roadway segments, planned roadway segments, and unfunded roadway segments by 2045. The second table on page 43 summarizes the result for Existing Local Roadways, which include all other roadways not included in the 2 045 Roadway Network, such as local and collector streets, ramps, and roads on military installations. The third table on page 44 summarizes the results for all roadways, which includes the 2045 Analysis Network and the Existing Local Roadways.

Within each table, centerline miles are cumulative for Scenarios 2 and 3. For example, Scenario 2 includes roadway segments from Scenarios 1 and 2. Scenario 3 includes roadway segments from Scenarios 1, 2, and 3.

It is important to note that these summaries provide the total number of centerline miles that will be potentially flooded under each scenario, which in many cases are comprised of many small sections of road that are expected to flood. Even though a majority of the road itself may not flood, if a small section is inundated with water, a large portion of that roadway may be unusable.

2045 Analysis Network

Only 0.1% (2.4 centerline miles) of the 2045 Analysis Network is expected to be submerged by 2045 for the 2-foot SLR scenario. However, 5.9% (93.7 centerline miles) and 7.6% (119.8 centerline miles) of the 2045 Analysis Network are expected to be submerged for Scenarios 2 and 3 respectively.

The jurisdictions that have the highest risks of roadway flooding by 2045 for the 2-foot relative sea level rise and 50-year storm (2045 Analysis Network) are:

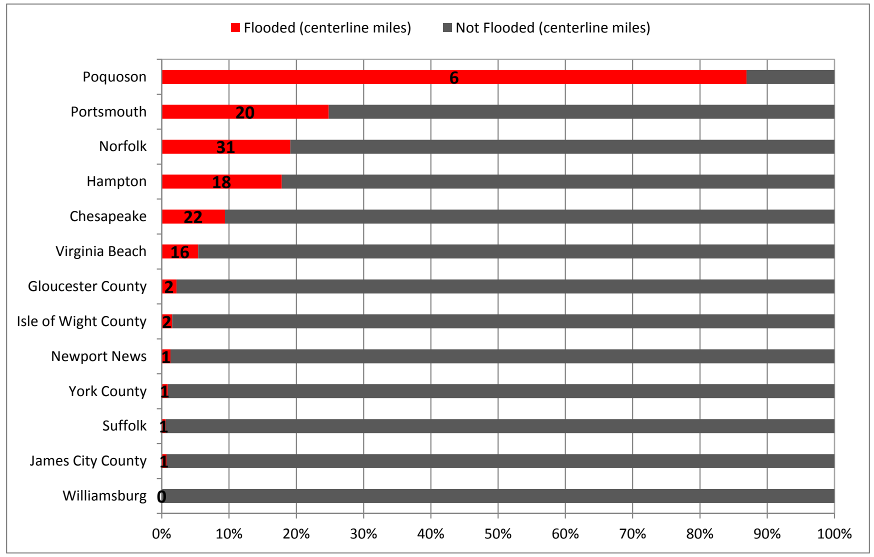
- Poquoson – 86.9% (6.1 centerline miles)
- Portsmouth – 24.8% (20.2 centerline miles)

Potential Submergence of Roadways by 2045 by Jurisdiction – 2045 Analysis Network

		Scenario 1: 2 Ft Sea Level Rise		Scenario 2: 2 Ft Sea Level Rise + 25-Yr Storm Surge*		Scenario 3: 2 Ft Sea Level Rise + 50-Yr Storm Surge*	
Hampton Roads Jurisdiction	Total Centerline Miles	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded
Chesapeake	233	0.3	0.1%	18.0	7.7%	21.9	9.4%
Gloucester County	72	-	0.0%	1.2	1.7%	1.6	2.2%
Hampton	98	0.3	0.3%	11.2	11.4%	17.5	17.8%
Isle of Wight County	106	0.0	0.0%	1.5	1.5%	1.6	1.5%
James City County	102	0.0	0.0%	0.6	0.6%	0.7	0.7%
Newport News	111	0.1	0.1%	1.1	1.0%	1.5	1.3%
Norfolk	161	0.4	0.2%	23.9	14.9%	30.7	19.1%
Poquoson	7	-	0.0%	4.3	61.8%	6.1	86.9%
Portsmouth	81	0.0	0.0%	16.5	20.3%	20.2	24.8%
Suffolk	201	0.1	0.0%	1.0	0.5%	1.2	0.6%
Virginia Beach	298	1.2	0.4%	13.8	4.6%	16.1	5.4%
Williamsburg	26	-	0.0%	-	0.0%	-	0.0%
York County	81	-	0.0%	0.6	0.7%	0.7	0.9%
Total	**1,578**	**2.4**	**0.1%**	**93.7**	**5.9%**	**119.8**	**7.6%**

*Centerline miles are cumulative for Scenarios 2 and 3. For example, Scenario 2 includes roadway segments from Scenarios 1 and 2. Scenario 3 includes roadway segments from Scenarios 1, 2, and 3.

Potential Submergence of Roadways by 2045 by Jurisdiction (2 Ft Sea Level Rise and 50-Yr Storm Surge) – 2045 Analysis Network



- Norfolk – 19.1% (30.7 centerline miles)
- Hampton – 17.8% (17.5 centerline miles)
- Chesapeake – 9.4% (21.9 centerline miles)
- Virginia Beach – 5.4% (16.1 centerline miles)

Existing Local Roadways

Only 0.4% (35.1 centerline miles) of the Existing Local Roadways is expected to be submerged by 2045 for the 2-foot SLR scenario. However, 11.6% (919.3 centerline miles) and 14.5% (1,147.2 centerline miles) of the Existing Local Roadways are expected to be submerged for Scenarios 2 and 3 respectively.

The jurisdictions that have the highest risks roadway flooding by 2045 for the 2-foot relative sea level rise and 50-year storm (Existing Local Roadways) are:

- Poquoson – 97.8% (49.1 centerline miles)
- Hampton – 38.4% (230.0 centerline miles)
- Portsmouth – 32.3% (130.9 centerline miles)
- Norfolk – 30.7% (242.2 centerline miles)
- Gloucester – 18.0% (104.5 centerline miles)
- Chesapeake – 15.9% (155.4 centerline miles)
- York – 10.0% (57.0 centerline miles)
- Virginia Beach – 9.3% (144.6 centerline miles)

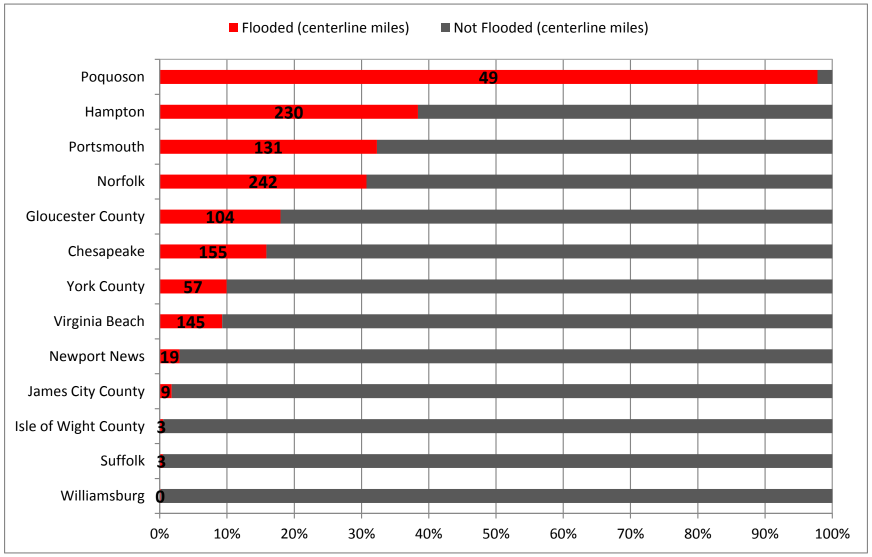
Potential Submergence of Roadways by 2045 by Jurisdiction – Existing Local Roadways**

		Scenario 1: 2 Ft Sea Level Rise		Scenario 2: 2 Ft Sea Level Rise + 25-Yr Storm Surge*		Scenario 3: 2 Ft Sea Level Rise + 50-Yr Storm Surge*	
Hampton Roads Jurisdiction	Total Centerline Miles	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded
Chesapeake	980	2.8	0.3%	125.4	12.8%	155.4	15.9%
Gloucester County	582	15.7	2.7%	95.7	16.4%	104.5	18.0%
Hampton	599	3.3	0.6%	186.5	31.1%	230.0	38.4%
Isle of Wight County	574	0.4	0.1%	2.4	0.4%	2.9	0.5%
James City County	490	0.3	0.1%	8.0	1.6%	8.7	1.8%
Newport News	635	0.5	0.1%	14.7	2.3%	18.6	2.9%
Norfolk	788	4.8	0.6%	182.0	23.1%	242.2	30.7%
Poquoson	50	1.8	3.5%	44.1	87.7%	49.1	97.8%
Portsmouth	405	0.2	0.0%	97.8	24.1%	130.9	32.3%
Suffolk	653	0.1	0.0%	2.4	0.4%	3.2	0.5%
Virginia Beach	1,560	3.9	0.2%	115.8	7.4%	144.6	9.3%
Williamsburg	49	-	0.0%	0.1	0.2%	0.1	0.2%
York County	573	1.3	0.2%	44.4	7.8%	57.0	10.0%
	7,938	**35.1**	**0.4%**	**919.3**	**11.6%**	**1,147.2**	**14.5%**

*Centerline miles are cumulative for Scenarios 2 and 3. For example, Scenario 2 includes roadway segments from Scenarios 1 and 2. Scenario 3 includes roadway segments from Scenarios 1, 2, and 3.

**Existing Local Roadways include all other roadways not included in the 2045 Analysis Network, such as local and collector streets, ramps, and roads on military installations.

Potential Submergence of Roadways by 2045 by Jurisdiction (2Ft Sea Level Rise and 50-Yr Storm Surge) – Existing Local Roadways



All Roadways (2045 Analysis Network and Existing Local Roadways)

The overall results (2045 Analysis Network and Existing Local Roadways) show that a 2-foot relative sea level rise will have a minor impact on roadways for many jurisdictions (0.4% of all roadways will be flooded). The combination of a 2-foot relative sea level rise and a 25-year storm surge (10.6% of all roadways will be flooded) or 50-year storm surge (13.3% of all roadways will be flooded) will have tremendous impacts to many roadways.

The jurisdictions that have the highest risks roadway flooding by 2045 for the 2-foot relative sea level rise and 50-year storm (All Roadways) are:

- Poquoson – 96.5% (55.2 centerline miles)
- Hampton – 35.5% (247.5 centerline miles)
- Portsmouth – 31.0% (151.1 centerline miles)
- Norfolk – 28.8% (272.9 centerline miles)
- Gloucester – 16.2% (106.1 centerline miles)
- Chesapeake – 14.6% (177.3 centerline miles)
- York – 8.8% (57.7 centerline miles)
- Virginia Beach – 8.6% (160.7 centerline miles)

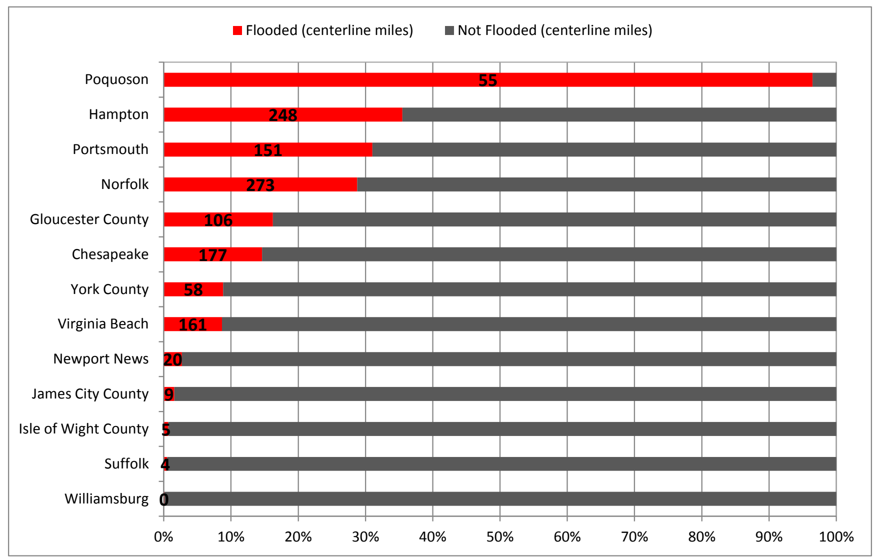
Potential Submergence of Roadways by 2045 by Jurisdiction – All Roadways (2045 Analysis Network and Existing Local Roadways)**

		Scenario 1: 2 Ft Sea Level Rise		Scenario 2: 2 Ft Sea Level Rise + 25-Yr Storm Surge*		Scenario 3: 2 Ft Sea Level Rise + 50-Yr Storm Surge*	
Hampton Roads Jurisdiction	Total Centerline Miles	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded
Chesapeake	1,213	3.1	0.3%	143.4	11.8%	177.3	14.6%
Gloucester County	653	15.7	2.4%	96.9	14.8%	106.1	16.2%
Hampton	698	3.6	0.5%	197.7	28.3%	247.5	35.5%
Isle of Wight County	680	0.4	0.1%	4.0	0.6%	4.5	0.7%
James City County	592	0.3	0.1%	8.6	1.5%	9.4	1.6%
Newport News	746	0.5	0.1%	15.8	2.1%	20.1	2.7%
Norfolk	948	5.2	0.5%	205.9	21.7%	272.9	28.8%
Poquoson	57	1.8	3.1%	48.4	84.5%	55.2	96.5%
Portsmouth	487	0.2	0.0%	114.3	23.5%	151.1	31.0%
Suffolk	854	0.2	0.0%	3.3	0.4%	4.3	0.5%
Virginia Beach	1,858	5.1	0.3%	129.6	7.0%	160.7	8.6%
Williamsburg	75	-	0.0%	0.1	0.1%	0.1	0.1%
York County	654	1.3	0.2%	45.0	6.9%	57.7	8.8%
	9,516	**37.5**	**0.4%**	**1,013.0**	**10.6%**	**1,267.0**	**13.3%**

*Centerline miles are cumulative for Scenarios 2 and 3. For example, Scenario 2 includes roadway segments from Scenarios 1 and 2. Scenario 3 includes roadway segments from Scenarios 1, 2, and 3.

**Existing Local Roadways include all other roadways not included in the 2045 Analysis Network, such as local and collector streets, ramps, and roads on military installations.

Potential Submergence of Roadways by 2045 by Jurisdiction (2Ft Sea Level Rise and 50-Yr Storm Surge) – All Roadways



ADAPTATION STRATEGIES

This section contains general adaptation strategies, design considerations, best practices, and lessons learned from other coastal regions, such as the Gulf Coast[22]. Hampton Roads' planners and engineers can use this information when planning, designing, constructing, or retrofitting transportation infrastructure (e.g., roadways, tunnels, bridges) due to climate impacts. This section does not contain cost estimates for specific adaptation projects. Jurisdictional staffs are encouraged to work with stakeholders to develop specific projects and costs for vulnerable roadway segments—identified within this study—and to incorporate these adaptation strategies into future planning efforts.

REDUCING POTENTIAL IMPACTS AND CONSEQUENCES THROUGH ADAPTIVE STRATEGIES

According to FHWA, adaptation strategies are actions taken to respond to vulnerabilities and risks associated with current and future hazards (including those associated with climate change) to ensure transportation system reliability and resiliency. Examples of strategies include, but are not limited to:

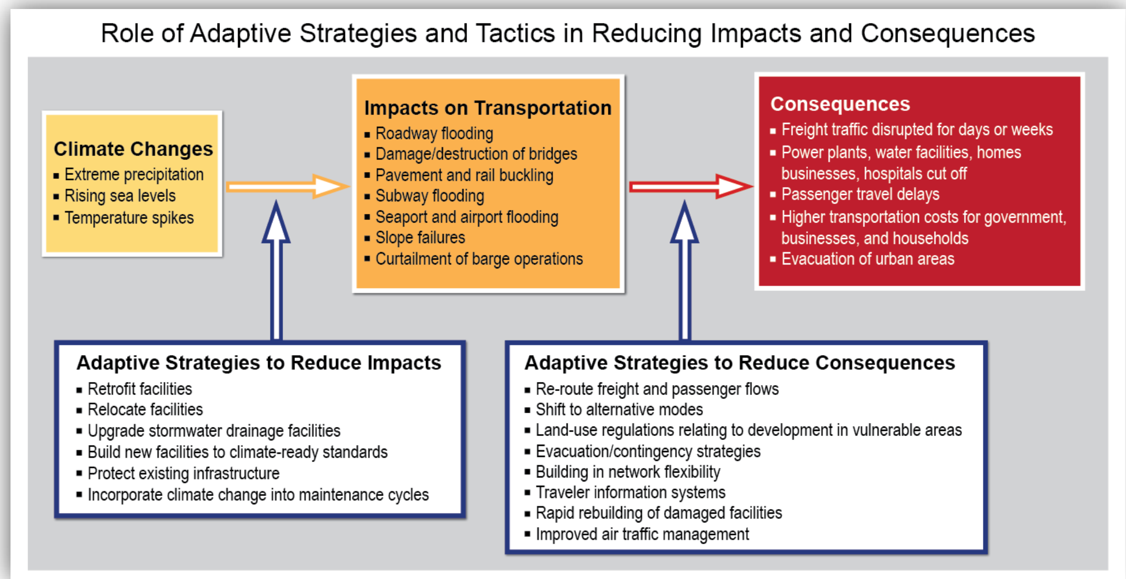
- Installing new flood barriers
- Elevating specific elements of critical infrastructure so that they would be above the projected flood elevations
- Moving entire facilities to higher ground
- Designing new assets for quick restoration after an extreme weather event (e.g. hurricane)
- Modifying statewide and/or local roadway design stands and guidelines
- Evacuation route planning

The flow chart on this page provides additional examples of adaptive strategies to reduce the potential impacts and consequences of changing climatic conditions on the transportation system.

General Design Considerations for Transportation Infrastructure

With the combination of accelerated projections in relative sea level rise and more intense hurricanes and tropical storms, it is important for planners and engineers to consider the following design-related questions when building new transportation facilities or retrofitting existing structures in the Hampton Roads region:

1. How might environmental conditions change during an asset's design life?
2. Will the changes be significant enough to adversely affect the asset?
3. What type of adaptation options are available and are they effective?
4. At what rate will changes in climate occur and how may the changes influence the timing of a response?
5. How can alternatives be evaluated and/or pursued given the large uncertainties involved in projections of sea level rise coupled with potential storm surge?



Source: Climate Change Impacts in the U.S.: The Third National Climate Assessment, Chapter 5 Transportation, 2014

[22] *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2*, Task 3.2: Engineering Assessments of Climate Change Impacts and Adaptation Measures, August 2014.

Bridges Over Navigable Channels Exposed to Sea Level Rise
As sea levels continue to rise, vertical clearances below bridge decks will be reduced over time such that navigation is impeded. Bridge structural corrosion might also be accelerated, and in some cases, the bridge itself (or its approaches) may become permanently inundated. Planners and engineers will need to monitor and analyze clearance reductions due to sea level rise over the design life and determine if any remedial action is necessary. It is important that all bridges along a navigable channel be monitored and/or adapted because if only one bridge is adapted, water access may be impeded by other bridges along the same waterway. Some adaptation strategies include:

- Raising the bridge deck
- Redesigning for a thinner deck and shorter spans
- Retrofitting the bridge with moveable spans
- Using the latest sea level rise trends before designing and constructing new bridges

Bridge Approach Embankments Exposed to Sea Level Rise and Storm Surge
Sea level rise can contribute to increased wave heights and potentially impact the stability of the bridge approach embankment over time. An embankment is defined as a raised bank or wall that is built to carry a roadway or hold back water. One strategy is to raise the roadway and abutment to a height that would significantly reduce the risk of overtopping from wave run-up in order to maintain the functionality of the roadway embankment.

It is important to note that the flooding vulnerability GIS-based analysis showed that, under the three sea level rise/storm surge scenarios in this study, many bridges were not expected to be inundated but the roadway approaches were susceptible to flooding. This finding supports other studies that have found that bridge approaches can be far more vulnerable to sea level rise than the main spans. Even though the bridge itself may not flood, if the bridge approaches are overtopped with water, the bridge will be unusable. For this reason, bridge approaches may need to be built or modified to higher elevations.

Bridge Abutments Exposed to Sea Level Rise and Storm Surge
A bridge abutment refers to the substructure at the ends of a bridge span where the structure's superstructure rests or contacts. The combination of

I-264 West flooding in Portsmouth.

sea level rise and more intense storm surges may create the need to incorporate protective features to protect the bridge abutment (e.g. riprap, willow mattress pad, timber bulkhead).

Bridge Structural Components Exposed to Storm Surge
During intense storm surges, bridges are susceptible to three different types of failure:

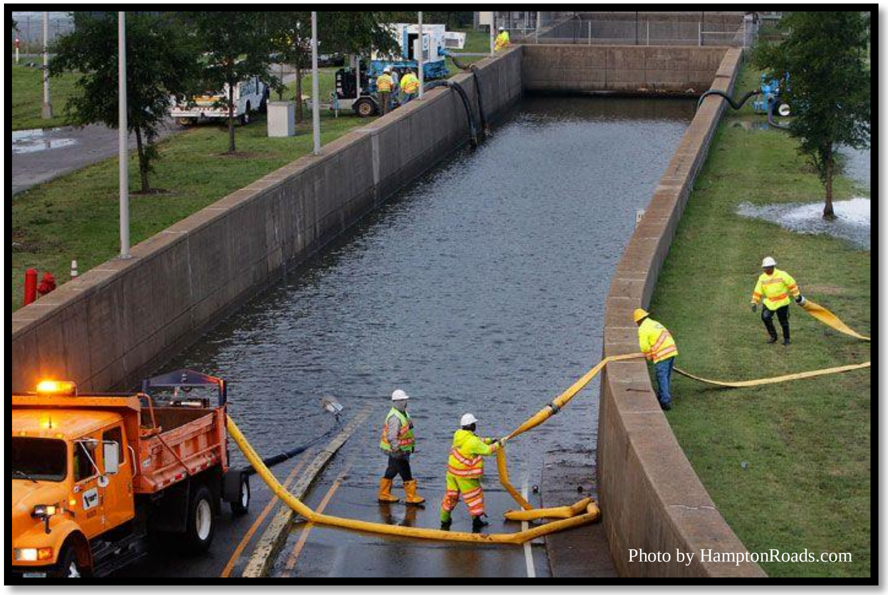
1) the superstructure (e.g., deck) is uplifted by waves and washes away,
2) the substructure (e.g., bents, pier caps) fails due to lateral forces from waves, and
3) the substructure fails due to excessive scouring.

To make bridges more resilient to storm conditions, consideration should be given to designs that allow the superstructure to break away during a significant storm surge so that the substructure remains intact. Under this scenario, the bridge structure could be rebuilt much faster and for less cost than if the substructure was damaged. An additional adaptation measure would be to safely store superstructure design documentation files so they are easily accessible after an event in order to process a replacement quickly. It is also important to consider the community needs served by the bridge, and whether the community can continue to function well if use of the bridge is temporarily lost due to a storm event. If it is deemed critical, then more aggressive protection measures may be warranted.

Tunnels Exposed to Storm Surge
Consideration must also be given to anticipated wave heights resulting from potential storm surge at tunnels. Large waves during a storm could overtop

some of the portal walls and create a flooding situation, such as the Midtown Tunnel during Hurricane Isabel.

Other Roadway Impacts from Sea Level Rise and Storm Surge
Certain materials (such as concrete) are less vulnerable to erosive flow than others (such as soil and grass), and the selection of building materials could influence the vulnerability of roadway crossings or elevated roadway surfaces. A roadway drainage system could also be impacted by both increased precipitation intensity and by higher water levels at the system outlet (tail water) due to storm surge. Given the slope of various roadways, this will likely decrease the ability of a drainage system to handle water flows.



Hurricane Isabel caused flooding inside the Midtown Tunnel between Norfolk and Portsmouth in 2003.

FUTURE INTEGRATION INTO THE PLANNING PROCESS

This section discusses the integration of adaptation strategies into metropolitan planning. It also describes the current criteria and scoring used in the Hampton Roads Long-Range Transportation Plan (LRTP) Project Prioritization Tool[23] and proposes reallocating points within the tool to account for potential flooding impacts to roadways from sea level rise and storm surge.

INTEGRATING ADAPTATION STRATEGIES INTO METROPOLITAN PLANNING

The analyses within this study are intended to be a "high level" planning tool to screen regional roadway assets for vulnerability to flooding under three sea level rise and storm surge scenarios for the next long-range transportation planning (LRTP) horizon. The HRTPO Board can use these results by choosing projects for currently vulnerable roads in the HRTPO's Transportation Improvement Program (TIP) and LRTP (2040).

Because of the disconnect between the timeframe of most metropolitan long-range transportation plans (20-25 years) and the 50-80 year timeframe associated with most climate change adaptation planning[24], the results in this study may also be used as a baseline for developing future adaptation strategies beyond 2045. Some adaptation projects can be identified and implemented today. Other adaptation strategies that can be incorporated prior to the design and construction of new transportation infrastructure will reduce the impacts and consequences of climate change and help strengthen the overall resiliency of the transportation system.

Individual adaptation projects should be considered in the context of larger investment programs. One important question is where will funding come from to pay for adaptation-related projects? One potential solution is for decision makers within coastal regions, like Hampton Roads, to identify co-benefits of adaptation strategies in conjunction with capacity, safety, security, and economic development. With limited resources and funding, coastal resilience grants (e.g. NOAA 2015 Regional Coastal Resilience Grant Program) should be pursued to incorporate adaptation-related strategies and designs in order to ensure a transportation asset is resilient over the design life.

PROJECT PRIORITIZATION TOOL CRITERIA AND SCORING

In 2010, the HRTPO created a Project Prioritization Tool to score candidate transportation projects to assist decision makers in selecting projects to be included in the LRTP. The prioritization methodology evaluates projects based on three components: Project Utility, Project Viability, and Economic Vitality. The maximum score that a candidate project can receive is 300 points (100 points per component).

HRTPO staff makes refinements to the tool as new studies are conducted and new data becomes available. This section describes the existing criteria and scoring for specific categories within the Project Utility component and provides suggestions to reallocate points within categories to incorporate a new category—flooding vulnerability.

HRTPO staff plans to discuss these potential modifications with the LRTP Subcommittee and other regional stakeholders to obtain input. If support is received, staff will incorporate changes into future iterations of the LRTP Project Prioritization Tool to assist decision makers in considering potential flooding impacts to roadways as they select future transportation projects.

Recommendations for two project types are presented below:

- Highway and Interchange Projects
- Bridge and Tunnel Projects

[23] Hampton Roads Prioritization of Transportation Projects, HRTPO, December 2010.

[24] *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2*, Task 3.2: Engineering Assessments of Climate Change Impacts and Adaptation Measures, August 2014.

Highway and Interchange Projects

Currently, within the Project Utility component for highways and highway interchanges, projects are awarded a maximum score of 25 points for the "System Continuity and Connectivity" category. Within the "Safety and Security" category, projects are awarded a maximum score of 15 points. The "Safety and Security" category's 15 points are broken into two subcategories: (1) the project provides improvement to incident management or evacuation routes (0 or 7 points) and (2) based on crash ratio (0 to 8 points).

Recommendation for Point Reallocation:

- Reduce "System Continuity and Connectivity" from 25 points to 20 points
- Reduce "Safety and Security" from 15 points to 13 points by reducing subcategory for improvement to incident management or evacuation routes from 7 points to 5 points.
- Reallocate and award a maximum of 7 points to projects based on the "Flooding Vulnerability" analysis conducted within this study as follows:

  Flooding Vulnerability (7 points maximum)
  - **7 points.** Roadway contains segment(s) with inundation – Sea Level Rise (2 feet or applicable future year projection).
  - **5 points.** Roadway contains segment(s) with inundation – Sea Level Rise (2 feet or applicable future year projection) + 25-year storm surge.
  - **3 points.** Roadway contains segment(s) with inundation – Sea Level Rise (2 feet or applicable future year projection) + 50-year storm surge.

  For a candidate project on an **existing roadway**, points would be awarded based on a flooding vulnerability analysis along the existing roadway.

  For a candidate project along a **new roadway alignment** (yet to be constructed), points would be awarded based on a flooding vulnerability analysis along an existing parallel roadway facility as defined within the LRTP Project Prioritization Tool.

Bridge and Tunnel Projects

Currently, within the Project Utility component for bridges and tunnels, projects are awarded a maximum score of 20 points for the "Infrastructure Condition" category.

Recommendation for Point Reallocation:

- Reduce "Infrastructure Condition" from 20 points to 16 points.
- Reallocate and award a maximum of 4 points to projects based on the "Flooding Vulnerability" analysis conducted within this study as follows:

  Flooding Vulnerability (4 points maximum)
  - **4 points.** Roadway contains segment(s) with inundation – Sea Level Rise (2 feet or applicable future year projection).
  - **3 points.** Roadway contains segment(s) with inundation – Sea Level Rise (2 feet or applicable future year projection) + 25-year storm surge.
  - **2 points.** Roadway contains segment(s) with inundation – Sea Level Rise (2 feet or applicable future year projection) + 50-year storm surge.

  For a candidate project on an **existing roadway**, points would be awarded based on a flooding vulnerability analysis along the existing roadway.

  For a candidate project along a **new roadway alignment** (yet to be constructed), points would be awarded based on a flooding vulnerability analysis along an existing parallel roadway facility as defined within the LRTP Project Prioritization Tool.

Conclusions and Recommendations

Summary

The Hampton Roads region contains one of the largest natural harbors in the world, making the region an attractive location for ports, military, tourism, and other businesses. This coastal location also makes many of these regional assets susceptible to projected relative sea level rise (the combined effects of land subsidence and absolute sea level rise) and potential storm surge threats.

Repetitive flooding on roadways and at critical transportation facilities can severely impact travel and hurt regional and local economies. When streets are impassable during and after flooding events, it often results in damages to personal property and missed work time, which has a crippling effect on communities. For this reason, it is imperative for Hampton Roads to plan for climate change impacts to transportation infrastructure and to develop adaptation strategies for those facilities. It is also important to consider the latest projections in sea level rise and storm surge when the region builds new roadway infrastructure or rebuilds existing roadway infrastructure.

In this study, HRTPO staff has partnered with HRPDC staff to conduct a comprehensive GIS-based flooding vulnerability analysis for potential sea level rise and storm surge impacts to regional roadways by 2045 (next Long-Range Transportation Plan horizon year).

Given the uncertainty in how much relative sea level rise (SLR) will occur over time, current research suggests that 2.0 feet of rise could occur in Hampton Roads sometime between 2043 and 2083. With the forecast year of the next HRTPO Long-Range Transportation Plan being 2045, a 2.0 foot relative sea level rise scenario was conservatively used in this analysis.

The three scenarios used in the flooding vulnerability analysis were as follows:

1) 2.0 foot relative sea level rise
2) 2.0 foot relative sea level rise + 25-year storm surge
3) 2.0 foot relative sea level rise + 50-year storm surge

For Scenario 2 (2.0 feet of sea level rise plus a 25-year storm surge) the water surface elevation ranged from 2.7 feet NAVD (North American Vertical Datum, 1988) to 10 feet NAVD across Hampton Roads. At Sewell's Point in Norfolk, the water surface elevation in this scenario was approximately 8.1 feet NAVD.

For Scenario 3 (2.0 feet of sea level rise plus a 50-year storm surge) the water surface elevation ranged from 3.1 feet NAVD to 11.1 feet NAVD across the region, with a water surface elevation of approximately 8.8 feet NAVD at Sewell's Point.

For comparison purposes, during Hurricanes Isabel (September 18, 2003) and Irene (August 27-28, 2011), the water surface elevation was 6.28 feet NAVD and 5.94 feet NAVD at Sewell's Point, respectively.

This study used elevation data from the HRPDC in conjunction with Geographic Information System (GIS) software to identify potential flooding for the "2045 Analysis Network" and "Existing Local Roadways", specific segments that would be submerged by each of the three sea level rise and storm surge scenarios. **Maps of these locations are provided on pages 23-41.** The results show that the roadways in the Cities of Poquoson, Hampton, Portsmouth, Norfolk, Gloucester County, Chesapeake, York County and Virginia Beach are most vulnerable to potential future relative water rise.

Based on the flooding vulnerability GIS-based analysis for the 2045 Analysis Network in Hampton Roads, the most significant threat to our primary roadway infrastructure was deemed to be the storm surges (25-year and 50-year) caused by such extreme events as hurricanes or nor'easters coupled with the projected 2-foot sea level rise. Only 0.1% (2.4 centerline miles) of the 2045 Analysis Network is expected to be submerged by 2045 for the 2-foot SLR scenario. However, 5.9% (93.7 centerline miles) and 7.6% (119.8 centerline miles) of the 2045 Analysis Network are expected to be submerged for Scenarios 2 and 3 respectively.

The results showed that in many cases, very small sections of the road are expected to flood. Even though a majority of the road itself may not flood, if a small section is inundated with water, a large portion of that roadway may be unusable.

Furthermore, the analysis showed that, under the three sea level rise/storm surge scenarios, many bridges were not expected to be inundated but the roadway approaches were susceptible to flooding. This finding supports other studies that have found that bridge approaches can be far more vulnerable to sea level rise than the main spans. Even though the bridge itself may not flood, if the bridge approaches are overtopped with water, the bridge will be unusable. For this reason, bridge approaches may need to be built or modified to higher elevations.

The analyses within this study are intended to be a "high level" planning tool to screen regional roadway assets for vulnerability to flooding under three sea level rise and storm surge scenarios for the next long-range transportation planning (LRTP) horizon. The HRTPO Board can use these results by choosing projects for currently vulnerable roads in the HRTPO's Transportation Improvement Program (TIP) and LRTP (2040).

Because of the disconnect between the timeframe of most metropolitan long-range transportation plans (20-25 years) and the 50-80 year timeframe associated with most climate change adaptation planning[25], the results in this study may also be used as a baseline for developing future adaptation strategies beyond 2045. Some adaptation projects can be identified and implemented today. Other adaptation strategies that can be incorporated prior to the design and construction of new transportation infrastructure will reduce the impacts and consequences of climate change and help strengthen the overall resiliency of the transportation system.

Individual adaptation projects should be considered in the context of larger investment programs. One important question is where will funding come from to pay for adaptation-related projects? One potential solution is for decision makers within coastal regions, like Hampton Roads, to identify co-benefits of adaptation strategies in conjunction with capacity, safety, security, and economic development. With limited resources and funding, coastal resilience grants (e.g. NOAA 2015 Regional Coastal Resilience Grant Program) should be pursued to incorporate adaptation-related strategies and designs in order to ensure a transportation asset is resilient over the design life.

[25] *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2*, Task 3.2: Engineering Assessments of Climate Change Impacts and Adaptation Measures, August 2014.

Recommendations

Based on the analysis presented in this report, the following recommendations are provided below:

- It is recommended that the HRTPO Board consider relative sea level rise and potential storm surge impacts when selecting future transportation projects. New/improved roadways can be built higher, removing the potential for flooding due to submergence. Therefore, the HRTPO staff plans to review components of the HRTPO Project Prioritization Tool[26] with the LRTP subcommittee and other regional stakeholders and incorporate "flooding vulnerability" as discussed in this study (pages 48-49) if supported.
- It is recommended that engineers and planners within cities and counties work with the Virginia Department of Transportation (VDOT) to develop detour plans for all roadways that are projected to be submerged for the three scenarios analyzed in this study (See pages 23-41).
- It is recommended that VDOT/cities/counties incorporate the latest projections for relative sea level rise/storm surge when a roadway project is designed. Design standards need to be reviewed and modified on an ongoing basis as sea levels continue to rise.
- It is recommended that cities/counties include climate change mitigation measures and adaptation projects into ongoing capital improvement plans, which can extend over long periods and help distribute the mitigation costs.
- It is recommended that VDOT/cities/counties consider and implement adaptation strategies as discussed in this study (pages 45-47) when planning, designing, constructing, or retrofitting transportation infrastructure (e.g., roadways, tunnels, bridges). Some examples include:
    - Build bridge approaches to higher elevations to reduce flooding risks.
    - Install protective features to protect roadway assets (e.g., flood barrier, riprap, willow mattress pad, timber bulkhead).

[26] *Hampton Roads Prioritization of Transportation Projects*, HRTPO, December 2010.

- Design bridges that allow the superstructure to break away during a significant storm surge so that the substructure remains intact.
- Raise existing bridge decks.
- Use higher vertical clearance standards for bridges to account for rising sea levels over the design life so that navigation is not impeded.
- Relocate roadway infrastructure that is susceptible to flooding.
- Consider anticipated wave heights resulting from potential storm surge when designing new tunnels.
- Consider building materials when constructing new roadways. Certain materials (such as concrete) are less vulnerable to erosive flow than others (such as soil and grass).