Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment

May, 2015

Accomack-Northampton Planning District Commission

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Prepared For:

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PREFACE

The purpose of this study was to assess vulnerability of the Eastern Shore of Virginia's transportation infrastructure to inundation occurring on a daily basis during normal tidal and meteorological conditions from sea-level rise. The study was conducted for long-range planning purposes and was made possible through a grant from the National Ocean and Atmospheric Administration (NOAA) and the Virginia Coastal Zone Management Program (VCZMP). It is expected that additional work will be needed to develop specific engineering solutions for each segment of infrastructure identified as vulnerable to long-term inundation from sea-level rise.

The study was conducted in cooperation with the Virginia Department of Transportation (VDOT), but does not necessarily reflect the official views or policies of VDOT. The maps or content do not constitute a standard, specification, or regulation and is intended for long-term planning purposes only. Do not attempt to use this report or the maps contained herein for the purpose of storm evacuation or other emergencies.

ACKNOWLEDGEMENTS

This research project was funded by NOAA and the VCZMP. The project would not have been possible without the assistance of VDOT staff in the Hampton Roads District Office, especially Keisha Wilkins who conducted the GIS analysis and developed the maps in this report. In addition, this research project would not have been possible without the work, advice, and guidance provided by the members of the Eastern Shore of Virginia Transportation Technical Advisory Committee and the Eastern Shore of Virginia Climate Adaptation Working Group. It is important to note that any errors or omissions in this report are the responsibility of A-NPDC staff and not those who provided assistance along the way.

DEFINITIONS

Bathtub mapping of sea level rise
Sea level rise mapping using a single value of water level rise in all locations. This method does not take into account storm tide, waves, or wind (NOAA).

Causeway
A raised road or track across low or wet ground (Merriam-Webster).

Datum
Any position or element in relation to which others are determined, as datum point, datum line, datum plane (NOAA).

Datum (vertical)
For marine applications, a base elevation used as a reference from which to reckon heights or depths. It is called a tidal datum when defined in terms of a certain phase of the tide. Tidal datums are local datums and should not be extended into areas that have differing hydrographic characteristics without substantiating measurements. So that they may be recovered when needed, such datums are referenced to fixed points known as benchmarks (NOAA).

Geographic Information System (GIS)
A geographic information system (GIS) integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information (NOAA).

Global Sea Level Rise
The worldwide increase in the volume of the world's oceans due to expansion as the oceans warm and to the melting of land-based ice (i.e. ice sheets and glaciers (NOAA).

Inundation
Water covering normally dry land (NOAA). For the purpose of this study, inundation is referred to as water covering land on a daily basis during normal tidal and meteorological conditions (i.e. as result of long-term sea level rise). These conditions are commonly referred to as "stillwater" conditions in the report. Inundation is expected to occur gradually. The first impacts on roadways are expected to occur daily during high tide cycles under normal tidal and stillwater conditions. Over time, as sea level gradually rises, roadways will become inundated during both high and low tide. It is also important to consider that the inundation scenarios described in this study could potentially be worsened and hastened by conditions not considered in the study including stormwater and groundwater flooding, coastal erosion, seasonal astronomical conditions, and changes in precipitation and wind patterns.

LiDAR
An instrument capable of measuring distance and direction to an object by emitting timed pulses of light in a measured direction and converting to the equivalent distance the measured interval of time between when a pulse was emitted and when its echo was received Also called laser radar. When combined with a Global Positioning System (GPS), lidar technology can be used to map coastal topography faster and more thoroughly than traditional surveying methods (NOAA).

Mean Higher High Water (MHHW)
A tidal datum. The average of the water height during the higher of two daily high tides 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 (NOAA).

DEFINITIONS

Relative Sea Level Rise
A local increase in the level of the ocean relative to the land due to ocean rise or land subsidence (e.g. from groundwater withdrawal, glacioisostatic rebound, tectonic activity) (NOAA).

Risk
The probability of harmful consequences or expected losses (death and injury, losses of property and livelihood, economic disruption, or environmental damage) resulting from interactions between natural or human-induced hazards and vulnerable conditions.

Sea Level
The average level of tidal waters, generally measured over a 19-year period. The 19-year cycle is necessary to smooth out variations in water levels caused by seasonal weather fluctuations and the 18.6-year cycle in the moon's orbit. The sea level measured at a particular tide gauge is often referred to as local mean sea level (LMSL) (Titus et al. 2010).

Six-Year Improvement Program
Overseen by VDOT, it is the method for allocating funds for rail, public transit, and highway projects. Localities are responsible for working directly with VDOT to identify projects proposed for construction, development, or funding over the next six fiscal years. The program is reviewed annually.

Subsidence
Land subsidence is a gradual settling or sudden sinking of the Earth's surface owing to subsurface movement of earth materials. Subsidence is a global problem, and in the United States, more than 17,000 square miles in 45 states, an area roughly the size of New Hampshire and Vermont combined, have been directly affected by subsidence (NOAA).

Stormwater runoff
Stormwater runoff is water generated from precipitation events that flows over land or impervious surfaces and does not percolate into the ground (U.S. Environmental Protection Agency).

Storm Surge
An abnormal rise of water generated by a storm, over and above the predicted astronomical tide. It is caused primarily by the winds from a storm and is linked to both tropical and extratropical storms (NOAA).

Storm Tide
The water level rise during a storm due to the combination of storm surge and the astronomical tide (NOAA).

Vulnerability
The potential for damage to people, property, and resources, from hazard events.

EXECUTIVE SUMMARY

A number of studies have recently documented that relative sea-level rise is occurring and appears to be accelerating on the Eastern Shore of Virginia. A number of areas are currently vulnerable to road closures during storm events and it is expected that future elevated water levels will have increasingly significant impacts on transportation infrastructure and the communities, facilities, and economies that depend upon them. To begin to address these long-range issues, this study set out to conduct a screening-level assessment to determine 1) which transportation infrastructure is vulnerable to inundation from relative sea level rise, 2) which communities are at risk to having limited access or becoming inaccessible altogether, and 3) when these changes are projected to occur.

To accomplish these objectives, the Accomack-Northampton Planning District Commission (A-NPDC) worked in cooperation with the Virginia Department of Transportation (VDOT) to evaluate existing inundation models, digital transportation infrastructure data, local knowledge, and relative sea-level rise projections for the Eastern Shore. Two separate assessments were conducted: a regional transportation infrastructure inundation vulnerability assessment and a community and critical facility accessibility assessment.

The method of this assessment assumes the inundation scenarios are to occur under “stillwater” conditions and does not consider other mechanisms for increase in water levels including groundwater and stormwater flooding, storm surge and astronomical tides or other natural processes such as shoreline erosion that are expected to exacerbate the impacts and hasten the timing of inundation of transportation infrastructure.

The inundation vulnerability assessment determined that 33 miles of roads in the region are vulnerable to inundation sometime between 2025 and 2050 with 1 foot of relative sea-level rise above mean higher high water. This number peaks to 371 miles, or 24.5% of all roads, are potentially vulnerable in the region as early as 2090 with 6 feet of relative sea-level rise. Over 80% of all vulnerable roads identified were located in Accomack County with some of this being attributed to the communities and facilities located in tidal marshes and on barrier islands.

The accessibility assessment evaluated over 50 communities and facilities in the region that are potentially vulnerable to inundation of routes providing entrance and egress by sometime over the next 100 years or by the beginning of the next century. It is projected that seven communities including the Incorporated Town of Saxis, may be disconnected or inaccessible during high tide and stillwater conditions beginning sometime between 2025 and 2050 with 1 foot of relative sea-level rise. Additionally, the Chincoteague Causeway (SR-175) which serves as the sole access route to the Town of Chincoteague, the Chincoteague National Wildlife Refuge, and the Assateague Island National Seashore was found to be vulnerable to inundation beginning sometime between 2045 and 2090.

These assessments are intended to support long-term planning efforts that can ultimately result in a more resilient and cost-effective management approach of transportation infrastructure that ensures the viability of coastal communities to the greatest extent possible.

Recommendations for accomplishing this include considering relative sea-level rise and other potential coastal flooding impacts when selecting and prioritizing future transportation projects, updating this study regularly utilizing new and updated data, and conducting further and additional studies to determine potential impacts on specific transportation infrastructure, roadway drainage systems, buried utilities, signalization, and right-of-ways.

I. Introduction

The Eastern Shore of Virginia consists of more land susceptible to inundation from sea-level rise than any other coastal region in Virginia[1] and is extremely vulnerable to flooding generated from both the Atlantic Ocean to the east and the Chesapeake Bay to the west. The overall rural character of the region is connected by a vast network of roads, bridges, causeways, and railways that have historically provided access throughout the region including access to low-lying waterfront areas. This network of transportation infrastructure is vital to the region's social, economic, cultural, and historical wealth. A significant amount of this infrastructure is located in floodplains and not engineered to accommodate future elevated sea level making the roads and the communities and economies that depend on them for access extremely vulnerable in the short term from coastal flooding events and in the long term from inundation from relative sea-level rise.

This report summarizes an effort conducted by the Accomack-Northampton Planning District Commission (A-NPDC) during 2014 and 2015 utilizing best-available data and information to determine which transportation infrastructure on the Eastern Shore of Virginia is at risk to inundation from rising sea-levels and to determine when inundation is projected to occur. The assessment was conducted in cooperation with the Virginia Department of Transportation (VDOT) and is intended to support long-term planning efforts that will ultimately result in a more resilient and cost-effective management approach that ensures the viability of coastal communities to the greatest extent possible.

Geographical and Jurisdictional Setting

The Eastern Shore of Virginia is a narrow, approximately 70-mile peninsula separating the Chesapeake Bay from the Atlantic Ocean (**Figures 1 and 2**). The peninsula is buffered from coastal impacts along its Atlantic coast by a barrier island chain and vast tidal marshes and along some areas of its Chesapeake Bay coast by various islands and tidal marshes. The two Counties and 19 Incorporated Towns in the region have historically experienced a broad variety of impacts to the built and natural environment as result of their unique location and topography. The region's proximity to such large water bodies and its vast expanses of topographically-low lands make it extremely vulnerable to both damaging winds and coastal flooding from storm surge events and sea-level rise. Additionally, the region is characterized by poorly-drained soils, high groundwater elevations, and shallow surface gradients resulting in high vulnerability to stormwater flooding.

[1] Titus, et al., 2010. "Virginia" in *The Likelihood of Shoreline Protection along the Atlantic Coast of the United States: Vol. 1: Mid-Atlantic*. Report to U.S. Environmental Protection Agency.

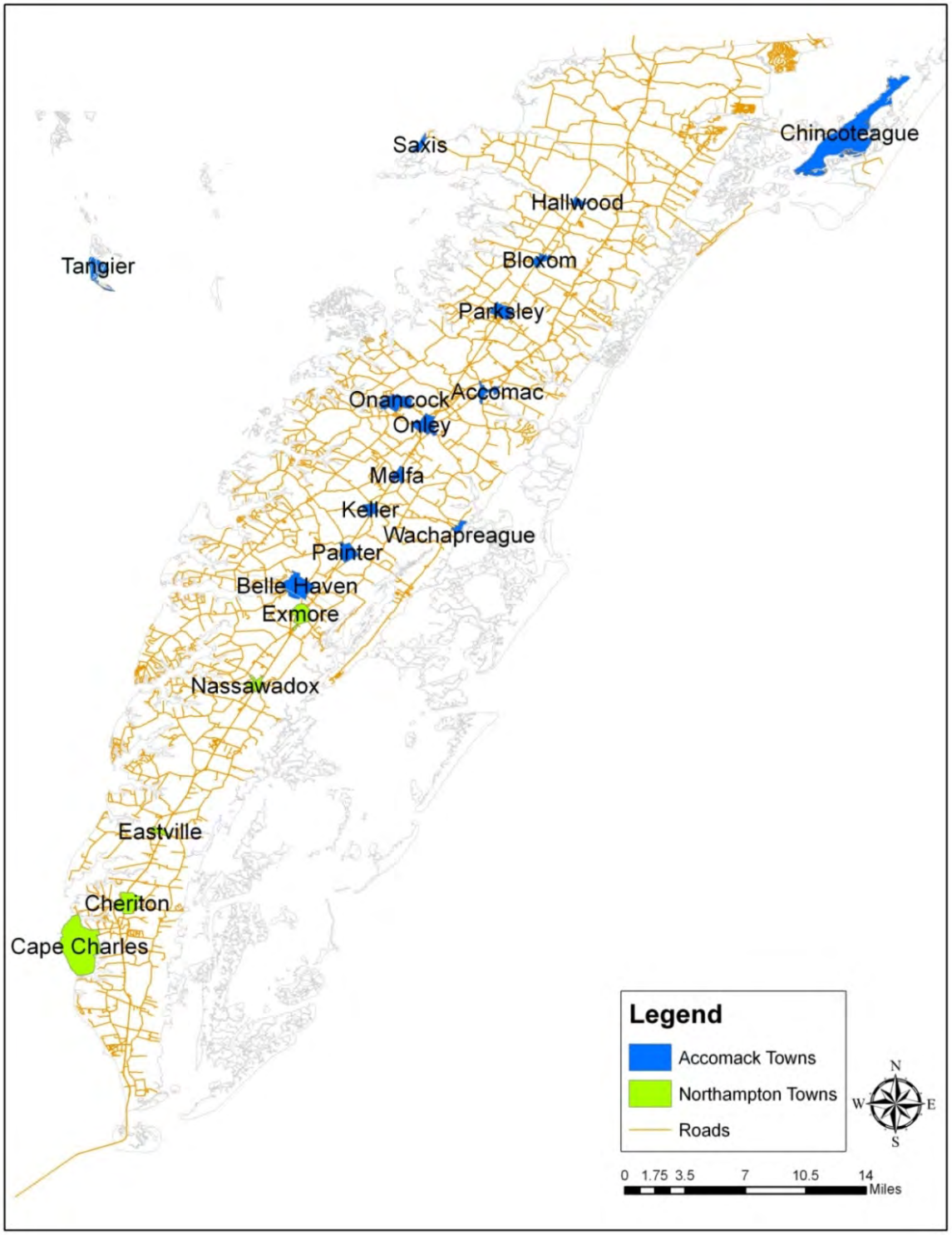

***Figure 1* - Vicinity Map of the Eastern Shore of Virginia**

The locations of the 19 Incorporated Towns and the regional road infrastructure netwerk are illustrated.

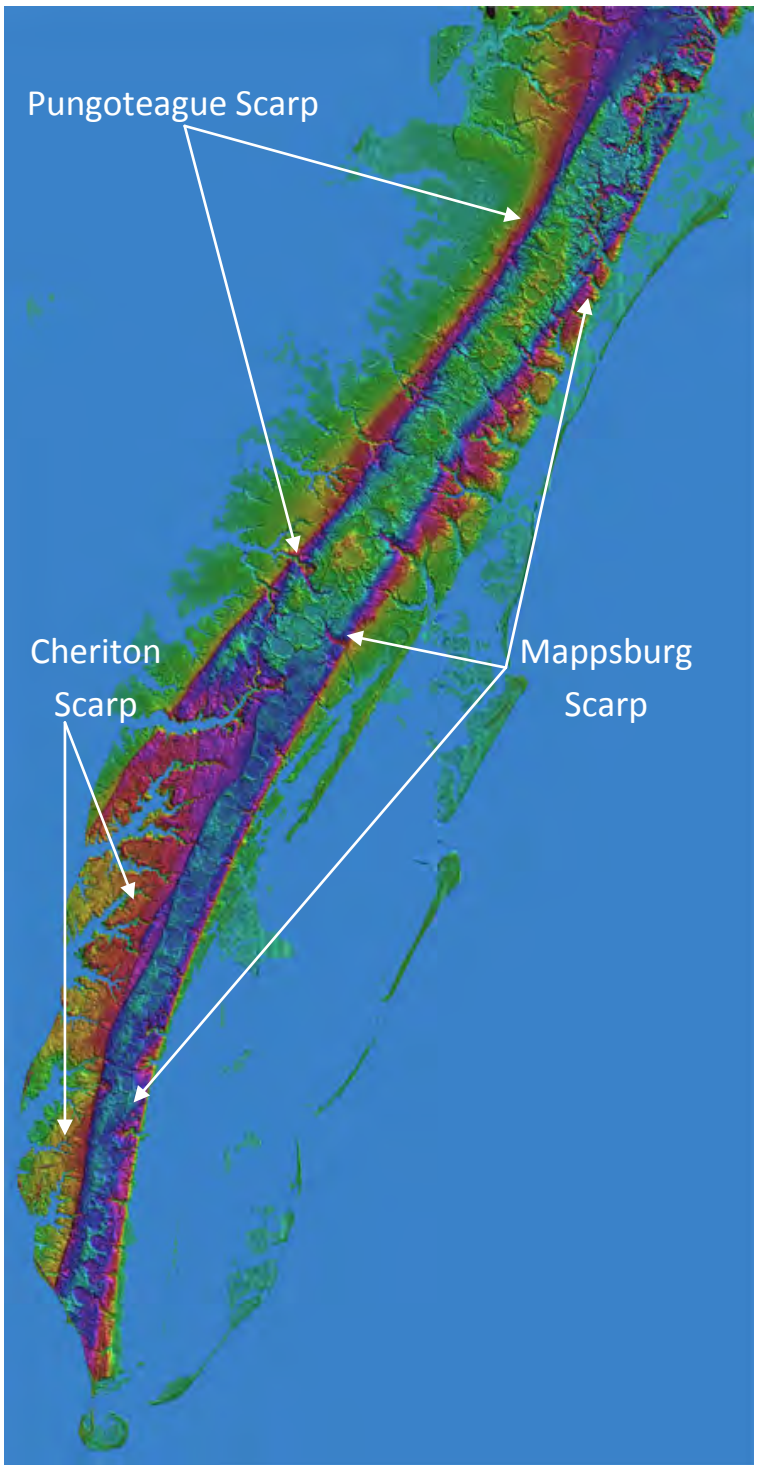

***Figure 2* – Topography of the Eastern Shore of Virginia**

High-resolution light detection and ranging (LiDAR) elevation data shows the terraced topographic profile and topographic features of the mainland peninsula. The higher elevations are located along the central spine of the peninsula. The lower elevations are located to the east and west of the central spine and are bound by scarps. Image by Cintos (2012).

Mainland Peninsula

The peninsula was both deposited by and shaped by fluctuations in sea level during the past 200,000 years.[2] [3] The highest land elevations vary from approximately 25-50 feet along a "spine" trending northeast-southwest along the center of the peninsula with greater elevations occurring in Accomack County to the north. The central spine is bound by topographic features called scarps to the east and west, creating a terraced topographic profile (**Figure 2**). The scarps were created during sea-level highstands and include the Mappsburg Scarp to the east of the central spine and the Pungoteague and Cheriton Scarps to the west.[4] The lowest land elevations in the region occur "below", or to the east and west of, the scarps on the Seaside and Bayside.

Islands and Tidal Marshes

The Eastern Shore of Virginia is buffered from coastal impacts along its Atlantic Coast due largely to the presence of a discontinuous barrier island chain, of which the majority has not been developed as result of conservation efforts. Furthermore, the region faces unique challenges with regards to coastal flooding and inundation from sea-level rise, in that it has three incorporated towns on islands (Chincoteague, Saxis, Tangier) and facilities vital to local economies on barrier islands (Assateague Island National Seashore, Chincoteague National Wildlife Refuge, NASA-Wallops Flight Facility, Mid-Atlantic Regional Spaceport, Fisherman Island National Wildlife Refuge/Chesapeake Bay Bridge-Tunnel). Access to these islands is summarized in the table below (**Figure 3**).

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[2] Colman, et al., 1988. The record of major Quaternary sea-level changes in a large Coastal Plain estuary, Chesapeake Bay, eastern United States: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 68, no. 2-4, p. 99–116.
[3] Colman, et al., 1990. Ancient channels of the Susquehanna River beneath Chesapeake Bay and the Delmarva Peninsula: Geological Society of America Bulletin, v. 102, no. 9, p. 1,268–1,279.
4 Ibid

Incorporated Towns	*Description*
Town of Chincoteague	Solely reliant on State Route (SR) 175 which includes approximately 5 miles of causeway over tidal marshland and bridges over waterways.
Town of Saxis	Solely reliant on SR-695 which includes approximately 3 miles of causeway over tidal marshland and bridges over waterways.
Town of Tangier	Only accessible via vessel or aircraft.
Critical Facilities	*Description*
Assateague Island National Seashore	Accessed via SR-175 (Chincoteague Causeway) and SR-2113. These routes provide contiguous access and include the Assateague Channel Bridge and causeway over Tom's Cove.
Chincoteague National Wildlife Refuge	Accessed via SR-175 (Chincoteague Causeway) and SR-2113. These routes provide contiguous access and include the Assateague Channel Bridge.
NASA-Wallops Flight Facility/Mid-Atlantic Regional Spaceport	Accessed via SR-803 which includes approximately 2.5 miles of causeway over tidal marshland and a bridge over Cat Creek.
Fisherman Island National Wildlife Refuge	From mainland Eastern Shore: Accessed via U.S. Route 13 including bridge over Fishermans Inlet and causeway on Fishermans Island.
Chesapeake Bay Bridge-Tunnel	From mainland Eastern Shore: Accessed via U.S. Route 13 including bridge over Fishermans Inlet and causeway on Fishermans Island. Includes four man-made islands each accessed via bridge and tunnels.
Note: Access routes considered only include roadways and railways. Access via vessel or aircraft not considered.	

***Figure 3* – Summary of Transportation Infrastructure Providing Access to Eastern Shore of Virginia Islands**

The table describes how Incorporated Towns and critical facilities in the region are currently accessed.

Transportation Infrastructure

The following sections describe the conditions and setting of various types of transportation infrastructure in the region considered in the vulnerability assessment.

Primary and Secondary Roads

There are 1,516 miles of primary and secondary roads in Accomack and Northampton Counties.[5] The network of roadways is centered on US-13 and access to and from it. US-13 is located along the central spine of the Eastern Shore, is the primary north-south corridor, and the only hurricane evacuation route in the region. Other north-south corridors include SR-178, SR-316, and SR-600. East-west primary corridors include SR-175, SR-180, SR-182, and SR-184. The east-west corridors are limited in distance due to the narrow geography of the region and not as critical as the north-south corridors, particulary US-13. One exception is SR-175, which provides access to Chincoteague and Assateague Islands and includes a 5-mile causeway.[6]

[5] Virginia Base Mapping Program Road Centerline Data, 2014
[6] A-NPDC, 2035 Regional Long-Range Transportation Plan, 2011.

With the exception of SR-175 and SR-600, which provide access to the island communities of Chincoteague and Saxis, respectively, the vast majority of primary roads in the region are located at higher elevations atop the various scarps in the region and therefore, have lesser vulnerabilities to coastal flooding and inundation from sea-level rise. However, roads less vulnerable to inundation are commonly highly susceptible to stormwater flooding as the result of drainage issues. It is expected that as sea-levels rise and begin to inundate ditches, the ditches will not be able to accommodate the volume of stormwater they were designed for, thereby worsening stormwater flooding resulting in more frequent road closures during precipitation events. This scenario can currently be observed along many roadways in low-lying areas.

VDOT policies require secondary roads to have an 11-year design horizon over which the road must be minimally adequate. For other systems and selected urban secondary roads, a 22-year design horizon is required. [7]

Bridges

While most of the bridges on the Eastern Shore are not expected to become inundated by sea-level rise over their functional lifespans, it is reasonable to expect that bridges will become increasingly vulnerable to temporary inundation and damage during future storm surge events as sea-level increases. Furthermore, bridges may not be accessible in the future should the adjoining roadways become inundated by sea-level rise.

The A-NPDC's *2035 Regional Long-Range Transportation Plan* (2011) identified five bridges on the Eastern Shore classified by the VDOT to be structurally deficient and in need of replacement. Another 15 bridges were classified as being functionally obsolete and needing upgrades and repairs.

The VDOT's current policy is to design bridges to be functional for 50 years.[7] Currently there are many bridges in the region that have surpassed 50 years in age.

Considering the current need for work on bridges in the region and the expected functional lifespans of bridges, it is important that information regarding sea-level rise be considered in the design process.

Causeways

The Chincoteague and Saxis causeways along with other causeways providing access to coastal communities on the mainland peninsula (i.e. Quinby/Upshurs Neck, Bells Neck, etc.) were constructed predominantly during the early 20th Century and typically constructed with dredged materials from adjacent wetlands and other available materials sometimes including oyster shells and timber.[8] These

[7] VDOT, Functional Classification Comprehensive Guide, June 2014.

[8] Turman, Nora Miller. "XVI". The Eastern Shore of Virginia 1603-1964 (1964, 2007 facsimile reprint , Heritage Books, Inc., ed.)

unsolid foundations have presented challenges for continued maintenance and are expected to present additional challenges when significant reengineering or retrofitting is necessary.

Additionally, these roads were constructed when sea level was approximately 1'-1.5' lower than current levels. The longest running tide gauge on the Eastern Shore of Virginia is located at Kiptopeke State Park and has measured nearly 10" of relative sea-level rise since its installation in 1951.[9] The longest running tide gauge in Virginia, the Sewells Point gauge in Hampton, has taken measurements continuously since 1927 nearly dating to the timing of construction of the oldest causeways on the Eastern Shore. Measurements at the Sewells Point gauge in Hampton indicate that 14" of relative sea-level rise have occurred at that location.[10] The regular flooding events that now impact these roads likely did not have the same impact as when the roads were first constructed. The causeways to the federal facilities (Fisherman Island NWR/Chesapeake Bay Bridge-Tunnel, NASA-Wallops Flight Facility were constructed during the mid to late 20th Century and engineered to a much higher standard than their regional predecessors. These causeways are built to greater elevations and are much less vulnerable to coastal flooding and inundation from sea-level rise.

Railroad

The Eastern Shore of Virginia has one railroad spanning from Cape Charles to the Maryland border. The Bay Coast Railroad, formerly known as the Eastern Shore Railroad, was constructed in 1884 and is the most direct route between the urban markets of the northeastern United States and Norfolk, Virginia. The railroad includes 70-miles of mainline and a 26-mile car float operation across the mouth of the Chesapeake Bay between Cape Charles and Little Creek, Virginia.[11] One barge (car float) of 25 railcar capacity is used on the 26-mile water route, which is one of only two remaining in the Eastern United States and is the longest water route in the country.[12] While the mainline is constructed along the elevated central spine of the region, the car float landing and rail yard in Cape Charles are located in relatively lower areas and are subject to flooding.

Culverts and Ditches

The VDOT manages design of culverts in the same manner as bridges. Culverts located in topographically-low areas are designed to remain functional for a minimum of 50 years and it is expected that they may not be able to accommodate a sufficient capacity of stormwater should sea-level inundate part or all of a culvert. Additionally, corrosion of the culvert as a result of prolongued exposure to salt water could compromise the structural integrity of the structure. There are many culverts currently exposed to these conditions and it is expected that this number will increase with future sea-level rise.

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[9] Permanent Service for Mean Sea Level Data and Station Information for Kiptopeke Beach. Summary of NOAA data. Available at http://www.psmsl.org/data/obtaining/stations/636.php

[10] Permanent Service for Mean Sea Level Data and Station Information for Sewells Point, Hampton Roads. Summary of NOAA data. Available at Permanent Service for Mean Sea Level Data and Station Information for Kiptopeke Beach. Summary of NOAA data. Available at http://www.psmsl.org/data/obtaining/stations/636.php

[11] Bay Coast Railroad, Inc. website, www.varail.com/baycoast.htm

[12] A-NPDC, 2011. 2035 Regional Long Range Transportation Plan. Available at http://www.a-npdc.org/2035RLRPFINAL.pdf

Many ditches on the Eastern Shore currently are regularly inundated with salt water from tidal and wind forcing. These ditches are easily identified by the presence of tidal marsh grasses that have populated the ditch. The issues stemming from these conditions are two-fold. Firstly, inundated ditches lack the desired capacity to accommodate stormwater, thereby increasing stormwater flooding vulnerability of the road. Secondly, these conditions increase the vulnerability of surrounding areas by serving as a conduit for storm surge.

An assessment of vulnerabilities for culverts and ditches was not completed in this study and additional research will be required to properly address these issues.

Signalization Infrastructure

Signalization infrastructure, or electronics utilized primarily for traffic control and emergency management, are highly vulnerable to corrosion from salt water. Signalization infrastructure is not common in the lowest elevations on the Eastern Shore; however, the Town of Chincoteague does have a significant amount in areas currently vulnerable to coastal flooding and locations vulnerable to sea-level-induced inundation.

Additional considerations will be required to address long-term vulnerabilities regarding design and placement of signalization infrastructure as this study did not address this issue.

Utilities and Right-of-Way

Buried utilities are highly vulnerable to corrosion from salt water. Placement of these underground utilities is restricted by the area available within an existing right-of-way (ROW). Additional consideration needs to be made of the vulnerability of the entire ROW to long-term sea-level rise. While this study did not investigate the presence of buried utilities, it is expected that a significant number of roads vulnerable to inundation include buried utilities within the ROW that are equally vulnerable. Additional research will be needed to adequately assess this issue.

Relative Sea-Level Rise and Inundation

It is well documented that water levels are rising and land subsidence is occurring on the Eastern Shore of Virginia.[13] [11] [12] [13] [14] The combination of these and other phenomena is referred to as relative sea-level rise and is the subject of this study. The causes of relative sea-level rise are well understood and recent analyses suggest the rate is accelerating.[14] [15] [16] [17]

Three factors influence relative sea-level rise: ocean water volume, the elevation of the shoreline, and the movement of water in the ocean. All three factors have recently experienced changes resulting in long-term and recent acceleration of water levels in the region.[10] [11] [12] [13] [14]

The volume of water in the ocean is increasing due to additional melt water from the Greenland and Antarctic glaciers, ice caps, and ice sheets entering the ocean. The ice in these locations is melting due to increases in global atmospheric temperature, which also is resulting in warming of the Earth's oceans. As the oceans warm, they expand, causing sea levels to increase as result. Both of these processes are believed to have added over six inches to global sea level during the past century and have increased recently to the point where they now are adding water to the oceans' volume at about twice the former rate. [10] [11] [12] [13] [14]

There are a number of factors influencing regional land subsidence. The primary cause is the continuing adjustment of the Earth's crust following the melting and northward retreat of a massive ice sheet over one-mile thick about 20,000 years ago, referred to as isostatic rebound. The pressure on the Earth's crust created by the ice sheet caused the region around Virginia to bulge up. This bulge has continuously been sinking and slowly readjusting ever since. Other local processes that contribute to the region's subsidence are the continued compaction of a buried impact crater underlying a 60-mile-wide area near the mouth of the Chesapeake Bay and the removal of groundwater at unsustainable rates. While it is projected that the impact crater does contribute slightly to Northampton County's subsidence rate, its influence on subsidence in Accomack County is not as well understood. Groundwater withdrawals have been measured to have a significant impact on subsidence in specific areas west of the Chesapeake Bay, but are believed to have lesser impact on the Eastern Shore. Cumulatively, isostatic rebound, crater sediment

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[13] VIMS, 2013. Recurrent Flooding Study for Tidewater Virginia, p.93 available at http://ccrm.vims.edu/recurrent_flooding/Recurrent_Flooding_Study_web.pdf.

[14] Hershner, C. and M. Mitchell, 2012. Rising Tides, Sinking Coast: How Virginia's coastal communities can adapt to surging sea levels. Virginia Issues and Answers 17(2):22-27

[15] Boon, J.D., 2012. Evidence of sea level acceleration at U.S. and Canadian tide stations, Atlantic Coast, North America, 28 J. COASTAL RESEARCH 1437, 1437 (2012), available at http://www.jcronline.org/doi/pdf/10.2112/JCOASTRES-D-12-00102.1

[16] Ezer and Corlett, 2012. Analysis of relative sea level variations and trends in the Chesapeake Bay: Is there evidence for acceleration in sea level rise?, IEEE Xplore Paper # 2478367, MTS/IEEE Oceans '12 (2012), available at www.ccpo.odu.edu/~tezer/PAPERS/2012_MTS-IEEE_SLR.pdf.

[17] Sallenger et al., 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America.

compaction, and groundwater withdrawals have caused subsidence in eastern Virginia that nearly doubles the effect of increasing and warming ocean volume. [10 11 12 13 14]

Research of subsidence rates in eastern Virginia have shown that subsidence does not occur uniformly across the region. Subsidence on the Eastern Shore was found to be relatively slower than the 3.1 mm/year experienced in the Hampton Roads area. Furthermore, subsidence rates on the Eastern Shore were also found to not be uniform with rates varying from 1.2 mm/year at Kiptopeke to 1.6 mm/year at Wachapreague upwards to 2.0 mm/year at Assateague Island.[18] It is important to note that subsidence rates along roadways, especially older roads constructed from sediments from adjacent wetlands, could be even greater due to compaction of the unconsolidated materials making up the road bed.

The third factor influencing regional sea-level rise is the movement of water in the ocean. Vast volumes of water move as currents in the oceans. These can be driven by winds and differences in water densities. The predominant current along the Mid-Atlantic Coast is the Gulf Stream, which flows northward and tends to move water away from the coast. Recent changes to the speed and volume of the Gulf Stream have been observed resulting in recent rapid rise in local sea levels. [10 11 12 13 14]

Sea-Level Modeling: Where will inundation occur?

Modeling where inundation can occur can be accomplished through a variety of available models which vary in the types of natural processes considered in the simulation process.

One common criteria necessary for any modeling effort is high-resolution elevation data. High-resolution light detection and ranging (LiDAR) elevation data was acquired and developed for the Eastern Shore of Virginia in 2010 making the region the first in the Commonwealth to have comprehensive coverage. Soon after the data was made available, the National Oceanic and Atmospheric Administration (NOAA) utilized the data to supplement their Sea-Level Rise and Coastal Flooding Impacts Viewer (available at http://coast.noaa.gov/slr/). One element of the Flooding Impacts Viewer is an inundation model, which was selected to be used in this study.

The NOAA inundation model utilized the LiDAR data for the Eastern Shore. The LiDAR data has a vertical accuracy of 0.53', which represented a drastic improvement from prior elevation data. NOAA transformed the LiDAR data so that it would accurately combine topographic and bathymetric elevation data. This transformed data was then coupled to a tidal datum, mean higher high water (MHHW). MHHW represents an average of the water level during the higher of two daily high tides occurring in the region over a period of 19 years.

The NOAA inundation model depicts water levels at sea-level rise scenarios from 0-6 feet above MHHW at 1-foot increments. The model does not take into account levees and/or hydraulic features such as culverts, pipes, levees, and bridges. Additionally, the model scenarios represent "stillwater" conditions

[18] Holdahl and Morrison, 1974. Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data. Technophysics 23: 373-90.

meaning that it does not consider water level fluctuations due to wind, precipitation/stormwater flooding, or astronomical tides. Furthermore, the model does not consider natural process such as erosion, subsidence, or future construction. It is expected that the vulnerability of any section of road would decrease or increase should any of these conditions change. The NOAA inundation model does not project a time for which these changes are expected to occur.[19]

In the context that this study is using the NOAA model, it should be inferred that a road illustrated as being inundated at a specific sea-level scenario means that that section of road will be inundated at least during one high tide cycle daily at first. When additional feet are added to the sea level it becomes increasing likely that the section of road will be inundated at all time making it entirely non-functional under normal "stillwater" conditions. The NOAA inundation model was selected for this study because it provided the capacity to be utilized as a screening tool for determining long-term vulnerability to sea-level rise that can greatly benefit long-range transportation planning in the region.

Sea-Level Projections: When will inundation occur?

Accurate forecasting of when various inundation scenarios are likely to occur is critical to many facets of management and planning in the coastal zone. This especially rings true for transportatiion planning considering the extensive expected life horizon for transportation infrastructure engineering projects, the indadequacy of current levels of funding to support all needed maintenance and engineering work, and the critical nature of public safety during emergencies.

The VIMS Recurrent Flooding Study for Tidewater Virginia (2013) included the first projections for sea-level in the Commonwealth. VIMS utilized what it deemed to be the best-available projections of sea-level rise, the National Climate Assessment[20], and modified them using the best available subsidence data for eastern Virginia. The projections included four different scenarios representing plausible trajectories based on a combination of factors (**Figure 4 and Tabular Data included in Appendix A**). The lowest scenario projects the historically-observed rates of sea-level rise going back at least a century and includes no acceleration. VIMS discounts this scenario and does not recommend its use for planning purposes as current rates of sea-level rise based on satellite altimetry already exceed this trajectory. The other three scenarios assume sea-level rise rates are accelerating. The "low" scenario is based on the Intergovernmental Panel on Climate Change's 4th Assessment model which used conservative assumptions about future greenhouse gas emissions (the B1 scenario) and represents risk primarily from ocean warming. The "high" scenario is based on the upper end of projections from semi-empirical models using statistical relationships in global observations of sea level and atmospheric temperature. The "highest" scenario is based on estimated consequences from global warming combined with the

[19] NOAA, March 2014. Frequent Questions: Digital Coast Sea Level Rise and Coastal Flooding Impacts Viewer. Available at http://coast.noaa.gov/digitalcoast/_/pdf/SLRViewerFAQ.pdf

[20] Parris et al., 2012. Global Sea Level Rise Scenarios for the United States National Climate Assessment. Available at http://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf

maximum possible contribution from ice-sheet loss and glacial melting, which represents a practical worst-case scenario based on current understanding.[21]

The VIMS projections were modified using subsidence rates for the Hampton Roads area (3.13 mm/year), which is understood to be significantly greater than subsidence experienced on the Eastern Shore. During 2014, the VIMS projections were recalculated using the same methodology as VIMS utilized during their 2013 study to develop a customized set of projections for sea-level rise on the Eastern Shore (**Figure 4 and Appendix A**). The projections for the Eastern Shore are based on the annual local subsidence rate in Wachapreague (1.6 mm/year) based on Holdahl and Morrison (1974). The Wachapreague rate was selected because of its central location in the middle and because it fell in the middle of other rates on the Eastern Shore (Kiptopeke: 1.2 mm/year and Assateague: 2.0 mm/year).

VIMS recommended to the Virginia General Assembly that the high scenario was the most likely and most appropriate trajectory for which planning and management considerations should be based upon in the Commonwealth. For the Eastern Shore of Virginia the high scenario forecasts 0.6‘ by 2025, 1.6’ by 2050, 2.8’ by 2075, and 4.5’ by 2100 (**Figure 4 and Appendix A**). It is important to note that confidence in the model projections declines moving further into the future. For example, the range of projections between the highest and historic rates for 2025 is 0.5’; whereas, the range for 2100 is 6.0’.[22]

[21] VIMS, 2013. Recurrent Flooding Study for Tidewater Virginia, p.93 available at http://ccrm.vims.edu/recurrent_flooding/Recurrent_Flooding_Study_web.pdf.
[22] Ibid

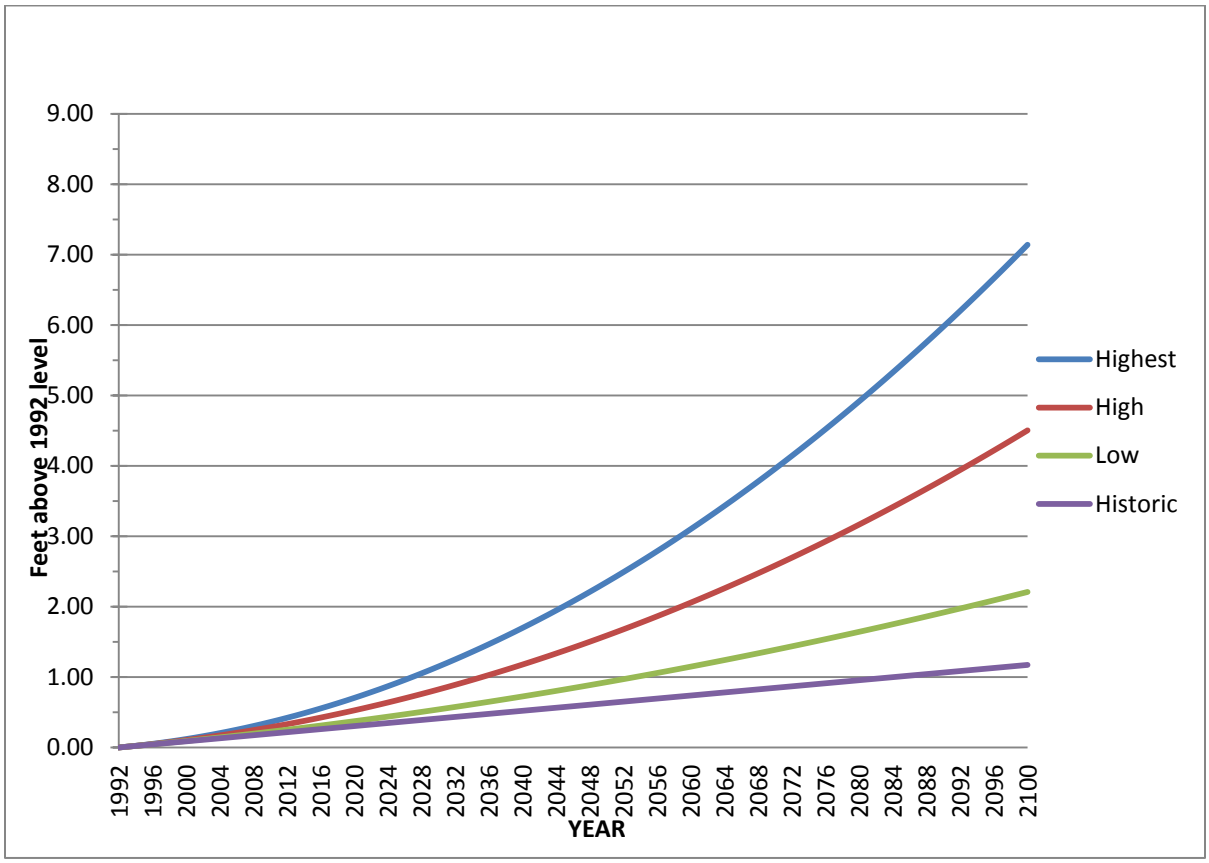


Figure 4 – Relative Sea-Level Rise Scenarios above 1992 Sea Level for Virginia's Eastern Shore

This is the most recent version of the relative sea-level rise curves for the Eastern Shore of Virginia. Curves were calculated using the same methodology and data sources as the VIMS 2013 "Recurrent Flooding Study for Tidewater Virginia" report prepared for the Virginia General Assembly. The curves are based on the 2014 National Climate Assessment sea-level rise curves adjusted for the annual local subsidence rate in Wachapreague, Virginia (1.6 mm/year) based on Holdahl and Morrison (1974). This information is included in tabular format in Appendix A.

Inundation Impacts on Transportation Infrastructure

The 2013 VIMS Recurrent Flooding Study for Tidewater, Virginia identified three primary threats to transportation infrastructure from the combination of sea-level rise and storm surge: flooding of evacuation routes, increased hydraulic pressure on tunnels, and alteration to drainage capacity.[23] It is expected that as sea level continues to rise that flooding from winds, tides, and groundwater will become increasingly problematic. As the frequency of inundation increases, it can be expected that the roadway will become increasingly vulnerable to damage from tidal water, stormwater, and wave action and that

[23] VIMS, 2013. Recurrent Flooding Study for Tidewater Virginia, p.93 available at http://ccrm.vims.edu/recurrent_flooding/Recurrent_Flooding_Study_web.pdf.

accessibility of the roadway will become increasingly limited and challenging. These issues are described in greater detail in the following sections.

Impacts to Physical Infrastructure

Relative sea-level rise is requiring several long-standing engineering assumptions be changed to better mitigate future impacts from salt water inundation. The U.S. Department of Transportation Federal Highway Administration (FHWA) is integrating considerations for future impacts from relative sea-level rise into the agency's programs, guidance, and policies in a manner that is consistent with transportation law and Executive Order 13653 on climate preparedness. Specifically, the FHWA is conducting engineering analyses of adaptation options such as raising bridges and conducting necessary research. VDOT currently has not employed actions similar to those of the FHWA.

The FHWA identifies the following mechanisms as being highly damaging to transportation infrastructure: wave attack, coastal "weir-flow", bluff erosion and shoreline recession, damage to bridges by waves on surge, wave runup, overtopping, and damage by tsunamis.[24]

Wave attack refers to erosion of embankments or natural bluffs upon which coastal roads can be constructed. This mechanism often occurs during extreme coastal events and results in damage that the roadway pavement is undermined and damaged (**Figure 5**). Embankments used as approaches to coastal bridges are highly susceptible to these damages primarily because they are at higher elevations than most of the roadway due to bridge clearance issues. Being at higher elevations, the embankments are subjected to higher wave action; whereas, nearby lower-elevation roadway sections are submerged beneath much of the wave action. The extent of damage is primarily dependent on the characteristics of the given storm (storm surge level and duration, wave heights, etc.) as well as the embankment condition/design (grass, exposed sand, slope protection, etc.).[25]

Figure 5 – Photograph of wave attack damage to embankment (from FHWA, 2014)

[24] FHWA, 2014. Hydraulic Engineering Circular 25, Vol. 2: Highways in the Coastal Environment: Assessing Extreme Events. Available at http://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi14006/nhi14006.pdf
[25] Ibid

Coastal "weir-flow" refers to storm surge waters flowing across a road and down an embankment often resulting in erosion and scour (**Figure 6**). Much of this type of damage occurs on the landward side of the road and often as the storm surge recedes. The sensitivity of roadways depends on both the hydraulics moving water and the embankment conditions (slopes, elevations, cover type).[26]

Figure 6 – Photograph of weir-flow damage mechanism as it occurs (from FHWA, 2014)

Bluff erosion and shoreline recession are mechanisms that work in tandem often resulting in severe damages to roadways. It is often observed that this type of damage occurs during an extreme event but the vulnerability had previously been increased by the ongoing shoreline recession (**Figure 7**). Roadways vulnerable to this damage type are often located along higher-energy receding shorelines. Shoreline recession damages are expected to continue to occur as sea level rises. The damage and sensitivity of the rate of shoreline recession is a function of the site-specific geology of the area.[27]

Figure 7 – Photograph of shoreline recession resulting in roadway damage (from FHWA, 2014)

Storm surge waters reaching the bridge deck, can result in wave-induced damages or destruction to the infrastructure. Sensitivity to this damage mechanism depends on the level of storm surge and wave heights which can strike the structure during a storm. It has been observed that most bridge decks can survive wave-induced impacts if only the crests of the largest wave heights are striking the bridge deck. The sensitivity of bridge decks to extreme events are directly related to the combination of effects from storm surge, wave heights, and sea-level rise. It is expected that sea-level rise will increase the vulnerability of many existing coastal bridges.[28]

Wave runup refers to quickly-moving water in individual waves flowing above the storm surge that rushes up a slope or structure. This damage mechanism often results in structural damage and scour. This extent of wave runup is a factor of storm surge, wave effect of storm surge, wave heights, and sea-

[26] Ibid
[27] Ibid
[28] Ibid

level rise. It is expected that damages caused by wave runup will increase as sea level rises and storm surge impacts worsen.[29]

Tunnel and road damage by overtopping occurs when storm surge exceeds the elevation of a tunnel entrance. The Chesapeake Bay Bridge-Tunnel currently has two tunnels whose vulnerability to this damage type is expected to increase as sea level rises. Additionally, plans to construct additional tunnels should consider future sea level in the design and engineering processes. A related issue for some tunnels and coastal roadways is flooding due to wave overtopping. Wave overtopping is water splashing over an embankment or seawall when runup exceeds the elevation of the top of the structure. This phenomena is fairly common in the region and is expected to become increasingly damaging to infrastructure in the region as sea level rises.[30]

Tsunamis damage transportation infrastructure through extreme water loading, scour, and impacts from floating debris. Both bridges and embankments are highly vulnerable to these forces. During the 2011 Japan tsunami, some lower elevation bridges survived while higher elevation bridges did not. Much of the damages observed to embankments resembled weir-flow damages common in storm surge events.[31]

Other potential impacts that could be expected to impact or exacerbate damages to local roads on the Eastern Shore are corrosion (inundation and salt spray), groundwater inundation, and stormwater drainage.

Corrosion from salt water can have damaging impacts on railroads, roads and bridges. Concrete bridge decks, steel rebar, and railroad infrastructure are susceptible to corrosion from salt and can lead to infrastructure deterioration over time. Salt is commonly introduced during coastal flooding events both by inundation and by salt spray. Salt spray occurs as winds carry salt water during storm events. This phenomena can have damaging impacts on railroads, bridges, roadways and vegetation. Salt spray landing on concrete roadways impacts the concrete directly and can reach rebar via cracks in the roadway surface. Salt spray can also kill vegetation along a roadway leading to dangers from falling or downed trees or from increased erosion vulnerability or decreased stabilization of embankments as vegetation perishes from over-exposure to salt. As sea level rises, it can be expected that the impacts of these phenomena will worsen along current tidal shorelines and also begin to impact areas currently not impacted by this phenomena.

The Eastern Shore of Virginia has many areas which experience very high groundwater elevations.[32] Fresh groundwater is less dense than salt or brackish water and this water "floats" atop salt water as result. As sea level rises, it may be likely that inundation under stillwater conditions will first be observed in the

[29] Ibid
[30] Ibid
[31] Ibid
[32] A-NPDC and Eastern Shore of Virginia Ground Water Committee, 2013. Eastern Shore of Virginia Groundwater Resource Protection and Preservation Plan. 88p.

form of inundation from groundwater in many low-lying areas on the Eastern Shore. In these areas, fresh groundwater will be forced to the surface making areas increasingly wetter throughout the year. Ultimately, it should be expected that this freshwater will become increasingly brackish and impacts to vegetation in the area will occur as well. For roads, this phenomena could mean that the sub-surface of the roadway will remain wetter or saturated, thereby potentially decreasing the stability of the road and potentially resulting in a faster rate of road deterioration. Additionally, groundwater will begin to fill existing ditches and culverts as sea-level rises, thereby decreasing a road system's stormwater drainage capacity. In this case, precipitation would remain standing on roadways for longer periods of time, thereby putting the structural integrity of the road at greater risk to the hazard.

Impacts to Accessibility

Road closures due to coastal flooding are a common occurrence on many Eastern Shore roads. Road closures in these areas can be a hindrance to evacuation and emergency services and can be problematic to productivity of local economic activities. Many roads leading to waterfront areas in the region only provide one route of entrance and egress to that area meaning that alternative or detour routes are lacking and that a closure on a main road can result in long and complicated detours or no access at all for extended periods of time. Local residents attempting to drive through salt or brackish flood water are putting their own well-being at risk as well as emergency responders. Additionally, local residents can incur excessive damages to vehicles if driving through salt or brackish water. While these conditions are familiar to many current residents, they are expected to become increasingly frequent in the future.

Many communities on the Eastern Shore exist on land that is at higher elevations than the surrounding land resulting in the access routes being more vulnerable to inundation than the properties within the jurisdiction. Depending on topography and how roadways were designed, communities can have a single or multiple routes by which to access the area. It is important that transportation planning activities consider which roads are most vulnerable to coastal flooding and inundation to ensure that access is provided to the fullest extent possible. Access limited by coastal flooding and inundation of vulnerable roadways threatens both the safety of residents and the viability of the entire community.

If roads at risk are not reengineered or retrofitted to accommodate future increases in sea level, it should be expected that the frequency of temporary (hours to days) inundation will increase. For this study, inundation can be defined as salt water covering an area. As an area or road first becomes inundated, it is expected that the water will be relatively shallow under stillwater conditions and this water will only remain on the roadway throughout a single high-tide cycle. Since this study assesses inundation vulnerability above the tidal datum, MHHW, it can be expected that only the higher of the two daily high tides will inundate the roadway at first. Over time as sea level rises, it is expected that the roadway will begin becoming inundated over both daily high tide cycles and remain dry during low tide cycles. Assuming that the road is not elevated, eventually inundation of the roadway will occur at all times of the day under stillwater conditions making the roadway practically unpassable. Some residents and communities may determine that accomodating these conditions from day to day is viable under stillwater conditions. However, emergency managers' roles in alerting residents of astronomical and meteorological elevated tidal levels will become increasingly important.

II. Methodology

The purpose of this section is to explain the methodology utilized to determine areas where transportation infrastructure is vulnerable to inundation by relative sea-level rise and to determine when inundation is likely to occur. The analysis estimates inundation occurring only by submergence during "stillwater" and normal tidal conditions and is intended to serve as a screening tool to support long-term decision making and planning efforts. The analysis included two separate assessments – a Regional Inundation Assessment and a Community and Critical Facility Accessibility Assessment – which are described in detail in the following sections.

Regional Inundation Vunerability Assessment

The regional inundation vulnerability assessment involved incorporating geographic information system (GIS) mapping techniques utilizing best-available data with recently developed local sea-level rise projections to produce a series of maps showing which transportation infrastructure is vulnerable to inundation and when inundation is projected to occur.

GIS Mapping Methodology

GIS methodology used to determine inundation vulnerability involved utilizing model outputs from the NOAA Sea Level Rise Inundation model developed for the Eastern Shore of Virginia and incorporated into NOAA's Sea Level Rise and Coastal Flooding Impacts Viewer (available at http://coast.noaa.gov/slr/) to determine which areas of land would be submerged. These data were then overlain with the most recent roadway network shapefile from the Virginia Base Mapping Program to determine individual vulnerabilities of road segments throughout the region.

The NOAA Sea Level Rise Inundation model utilizes best available digital elevation data to determine which areas of land are likely to be submerged under various sea-level rise scenarios. For the Eastern Shore of Virginia, NOAA incorporated a digital elevation model (DEM) using LiDAR elevation data acquired and developed in 2010. The DEM was referenced to a tidal datum utilizing VDatum, a software program created by NOAA. The tidal surface created represents MHHW. MHHW represents an average of local water levels during the higher of two daily high tides occurring in the region over a period of 19 years (1983-2001). The tidal surface and the DEM were then projected to NAVD88 to create a consistent surface. NOAA then added 1-foot increments from 0-6 feet above MHHW and compared the results to existing land elevations **(Figure 8)**.

Each pixel within the elevation layer represented an area of 10' by 10'. The consolidated vertical accuracy of the elevation data is 0.53'. The land surface utilized in the NOAA inundation model is assumed to represent the surface of roadways; however, it is recommended that additional surveying be performed on any roadway being considered for reengineering.

It is important to note that the NOAA inundation model projects submergence from relative sea-level rise only. These scenarios represent stillwater conditions meaning that it does not consider water level fluctuations due to wind, precipitation/stormwater flooding, or astronomical tides. Furthermore, the model does not consider natural process such as erosion, subsidence, or future construction.

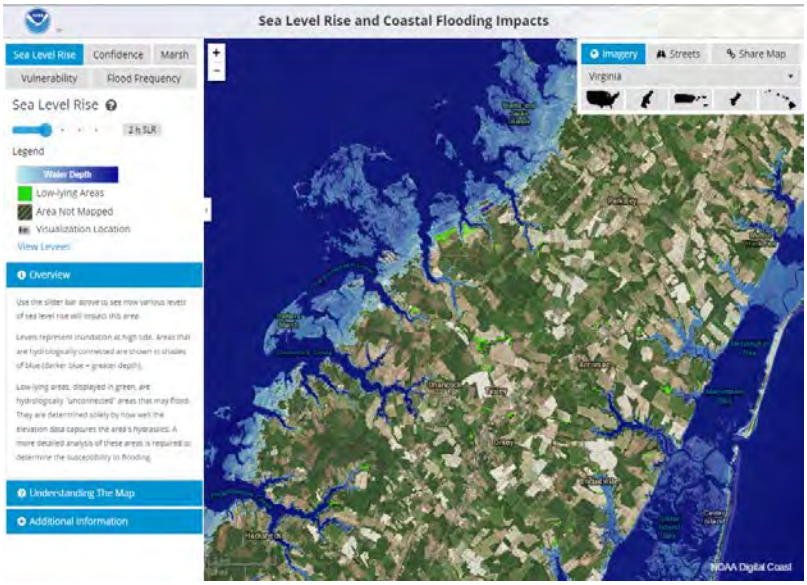


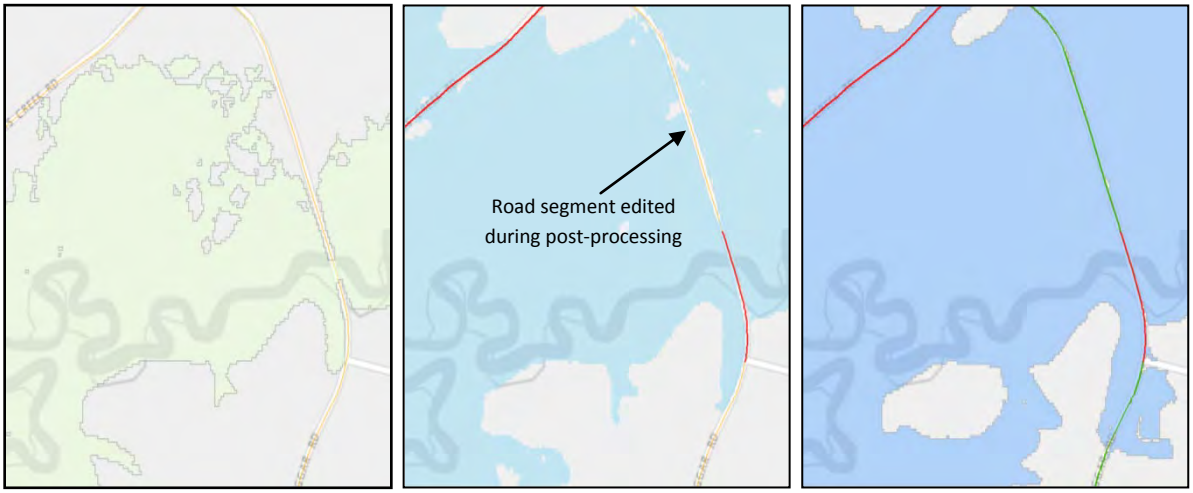
Figure 8 – Example of NOAA Sea Level Inundation Model

The projected inundated areas (light and dark blue) as seen on the NOAA Sea Level Rise and Coastal Flooding Impacts Viewer are the result of combining high-resolution elevation data with tidal corrections.

Road centerline data for 2014 from the Virginia Base Mapping Program were then overlain on the inundation scenarios to test potentially inundated areas. The road centerline data represent the center of a road segment spanning from one intersection to another. The breadth of the dataset includes all public and private roads, driveways over 200' in length, and vehicular navigable trails greater than 200' in length. The dataset includes attribution consisting of street names, address ranges, and VDOT route numbers.

The selection geoprocessing tool was used to extract centerlines that overlapped road segments that would be inundated under the various inundation scenarios. Road segments identified as being inundated were then individually analyzed by A-NPDC staff to address the following issues:

- Only one inundation grid cell intersecting a road centerline feature was required to trigger an entire road segment as being defined as inundated. Analysis of inundated road segments discovered that several segments were identified as being inundated due to inadequate resolution in the inundation data layer. These situations often produced discernible patterns such as the one illustrated in **Figure 9** where embankments, causeways, ditches, etc. could be interpreted. A-NPDC staff also utilized Google maps to verify these interpretations.
- To identify road segments containing bridges or culverts that incorrectly illustrated the road segment as being inundated. Additional VDOT datasets and Google maps were used to identify existing bridges and culverts and attributes were edited for each corresponding road segment accordingly. This scenario is depicted in **Figure 9** and occurs because above-ground features are filtered out of the elevation data during the development of the DEM. As result, the inundation model wrongfully assumes that a bridge is of the same elevation as the contiguous lower road segment and wrongfully identifies the road segment as being inundated.



0 feet	1 feet above MHHW	2 feet above MHHW
•Current MHHW conditions (light green) •Dry land at MHHW (gray) •No road segments inundated (yellow) •Bridge segment post-processed by ANPDC staff	•Inundated areas (light blue) •Two road segments inundated (red) •Road segment north of bridge (yellow) initially shown as inundated but changed by A-NPDC staff during post-processing. Closer examination determined that the embankment approaching the bridge was wrongfully identified due to inadequate resolution in the inundation data layer	•Inundated areas (blue) •Dry land at MHHW (gray) •Same two road segments from 1 ft. scenario inundated (red) •Two new road segments inundated (green)

***Figure 9* – Inundation Assessment Example Outcomes and Explanation of Post-Processing**

Sea-Level Rise Projections

A-NPDC staff consulted members of the Eastern Shore of Virginia Climate Adaptation Working Group (CAWG) to determine which sea-level rise projections were to be included in the assessment. The CAWG considered the four projections included in VIMS' 2013 Recurrent Flooding Study and adjusted for subsidence rates on the Eastern Shore (**Figure 4**). The group requested that a range of dates be incorporated into the study for the highest, higher, and low projections. A range of dates was included for only the 1' and 2' scenarios since these were the only scenarios where the highest, high, and low projections occurred each were projected to occur by 2100 (**Figure 10**). For the 3' through 6' scenarios, complete ranges were not included. Instead the projected date of occurrence was presented as occurring as soon as the projection for the highest scenario.

Sea-Level Scenario above MHHW	*Projected Date of Occurrence*
1 Foot	≈2025-2050
2 Feet	≈2045-2090
3 Feet	>2060
4 Feet	>2070
5 Feet	>2080
6 Feet	>2090
Note: Projections from the VIMS Recurrent Flooding Study for Tidewater Virginia (2013) and adjusted for local subsidence rate for Wachapreague, VA (1.6 mm/year) based on Holmdahl and Morrison (1974).	

***Figure 10* – Projected Dates of Inundation from Relative Sea-Level Rise above MHHW**

The table summarizes projected dates of occurrence to be included in the regional inundation assessment and community and critical facility accessibility assessment.

Community and Critical Facility Accessibility Assessment

The community and critical facility accessibility assessment involved interpreting GIS data and incorporating recently developed local sea-level rise projections to produce a series of maps showing which communities and facilities are vulnerable to accessibility issues and when these conditions are projected to occur.

Method Illustration

The GIS results from the Regional Inundation Assessment described above were utilized by A-NPDC staff to identify accessibility under the inundation scenarios for 1' through 6' above MHHW. A-NPDC first contacted staff from Accomack and Northampton Counties to solicit input on which communities and critical facilities were to be included in the assessment. Once finalized, all communities and critical facilities included in the assessment were plotted on maps utilizing GIS.

A-NPDC assessed each community and critical facility to determine the number of routes that provide direct access into a community or critical facility. For incorporated towns, the jurisdictional boundaries were used to define the extent of a community. For unincorporated communities and critical facilities, the extent of a community or critical facility was defined as an area with the greatest concentration of development as best inferred by the A-NPDC staff member.

A-NPDC staff then assessed each access route to characterize accessibility to the community or critical facility under each inundation scenario. **Figure 11** summarizes the definitions for each category utilized in the asessment.

Community/Facility Access Category	*Description*
Access Not Impacted	No access routes inundated. Temporary road closures may occur during storm events.
Access Limited	At least one access route is inundated. The community/ facility will still be accessible via other roadways. Less than half of the roadways within the community/facility are not inundated.
Disconnected/Inaccessible	All access routes are inundated and less than half of the roadways within the community/facility are not inundated. The community/facility would be inaccessible during high tide conditions at first and during all times at some point thereafter.
Majority of Roads Inundated	At least half of the roadways within the community/facility are inundated during high tide conditions at first and during all times at some point thereafter.

***Figure 11* – Summary of Accessibility Categories Utilized in the Community and Critical Facility Accessibility Assessment**

Sea-Level Rise Projections

The Community and Critical Facility Accessibility Assessment incorporated the same range of dates utilized in the Regional Inundation Assessment and described in **Figure 10** to project when the anticipated accessibility issues are likely to occur for each community and critical facility.

III. Results

The following sections summarize the findings of the Regional Transportation Infrastructure Inundation Vulnerability and Community and Critical Facility Accessibility Assessments and discuss several relevant management options for managing and mitigating future impacts from relative sea-level rise.

Regional Transportaton Infrastructure Inundation Vulnerability Assessment

A significant amount of transportation infrastructure in the region is highly vulnerable to inundation from relative sea-level rise beginning over the next 10-25 years and worsening over the remainder of the century. The findings of the assesment are summarized in **Figure 12**, illustrated in **Figures 13 through18** (Regional Maps) and **Figures 19 through 24** (Town Maps).

Jurisdiction	Total Miles of Roads	Sea Level Scenarios Above Current MHHW											
		1 Foot		2 Feet		3 Feet		4 Feet		5 Feet		6 Feet	
		Total Miles Inundated	% of Total in Jurisdiction	Total Miles Inundated	% of Total in Jurisdiction	Total Miles Inundated	% of Total in Jurisdiction	Total Miles Inundated	% of Total in Jurisdiction	Total Miles Inundated	% of Total in Jurisdiction	Total Miles Inundated	% of Total in Jurisdiction
Eastern Shore of Virginia	1516	33	2.2%	131	8.6%	209	13.8%	270	17.8%	319	21.0%	371	24.5%
Accomack County	1014	31	3.1%	115	11.3%	183	18.0%	236	23.3%	275	27.1%	316	31.2%
Town of Belle Haven	7	0	0.0%	0	0.0%	0	0.0%	0.11	1.6%	0.11	1.6%	0.32	4.6%
Town of Chincoteague	60	4	6.7%	38	63.3%	56	93.3%	60	100.0%	60	100.0%	60	100.0%
Town of Onancock	13	0	0.0%	0.43	3.3%	0.79	6.1%	1	7.7%	1	7.7%	1	7.7%
Town of Saxis	4	0.25	6.3%	1	25.0%	2	50.0%	4	100.0%	4	100.0%	4	100.0%
Town of Tangier	4	4	100.0%	4	100.0%	4	100.0%	4	100.0%	4	100.0%	4	100.0%
Town of Wachapreague	5	0.12	2.4%	0.12	2.4%	0.88	17.6%	2	40.0%	2	40.0%	5	100.0%
Northampton County	502	2	0.4%	16	3.2%	26	5.2%	34	6.8%	44	8.8%	55	11.0%
Town of Cape Charles	28	0	0.0%	0	0.0%	0	0.0%	0.2	0.7%	6	21.4%	8	28.6%

Figure 12 – Regional Transportation Infrastructure Inundation Vulnerability Assessment Summary

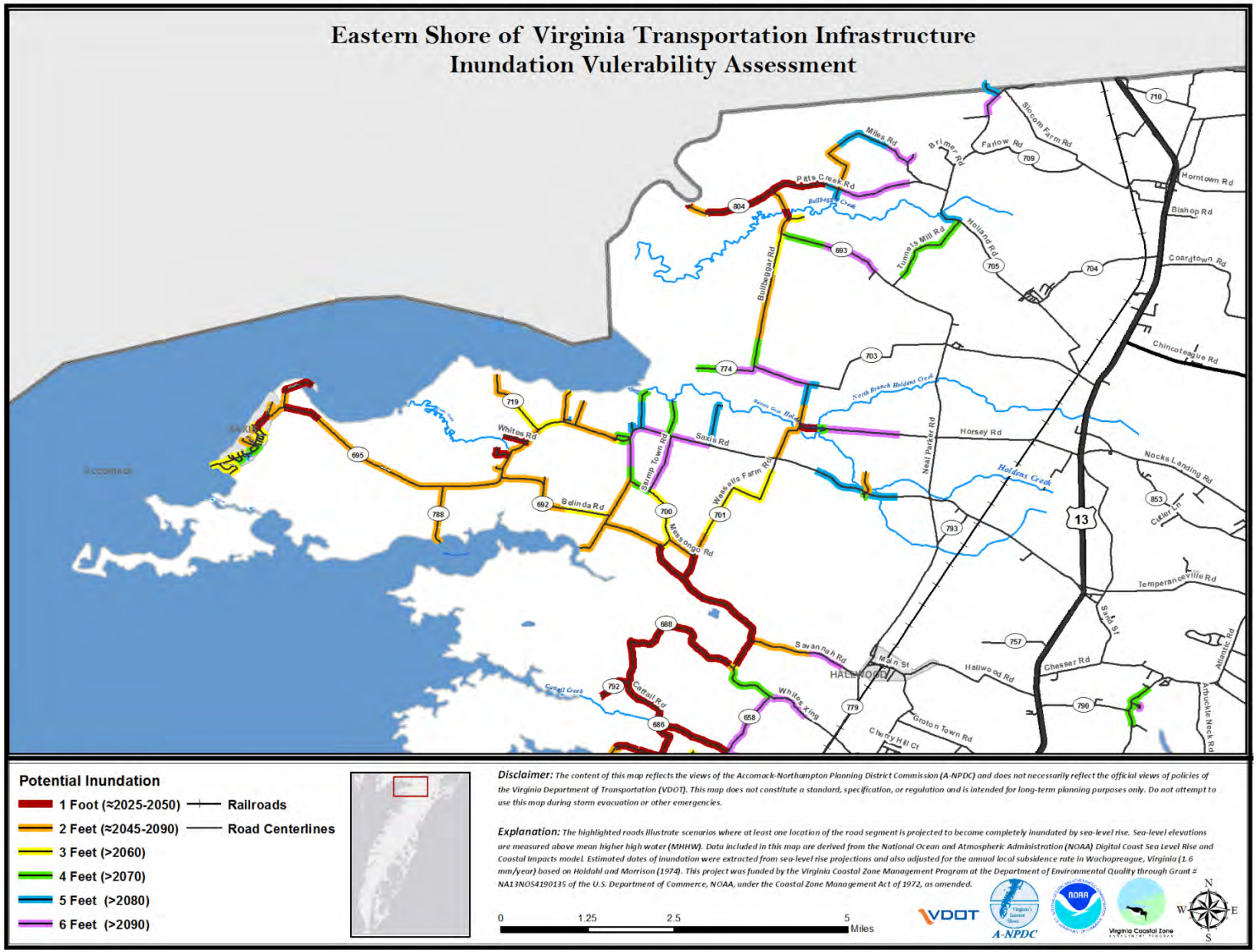


Figure 13 – Northwestern Accomack County Transportation Infrastructure Inundation Vulnerability

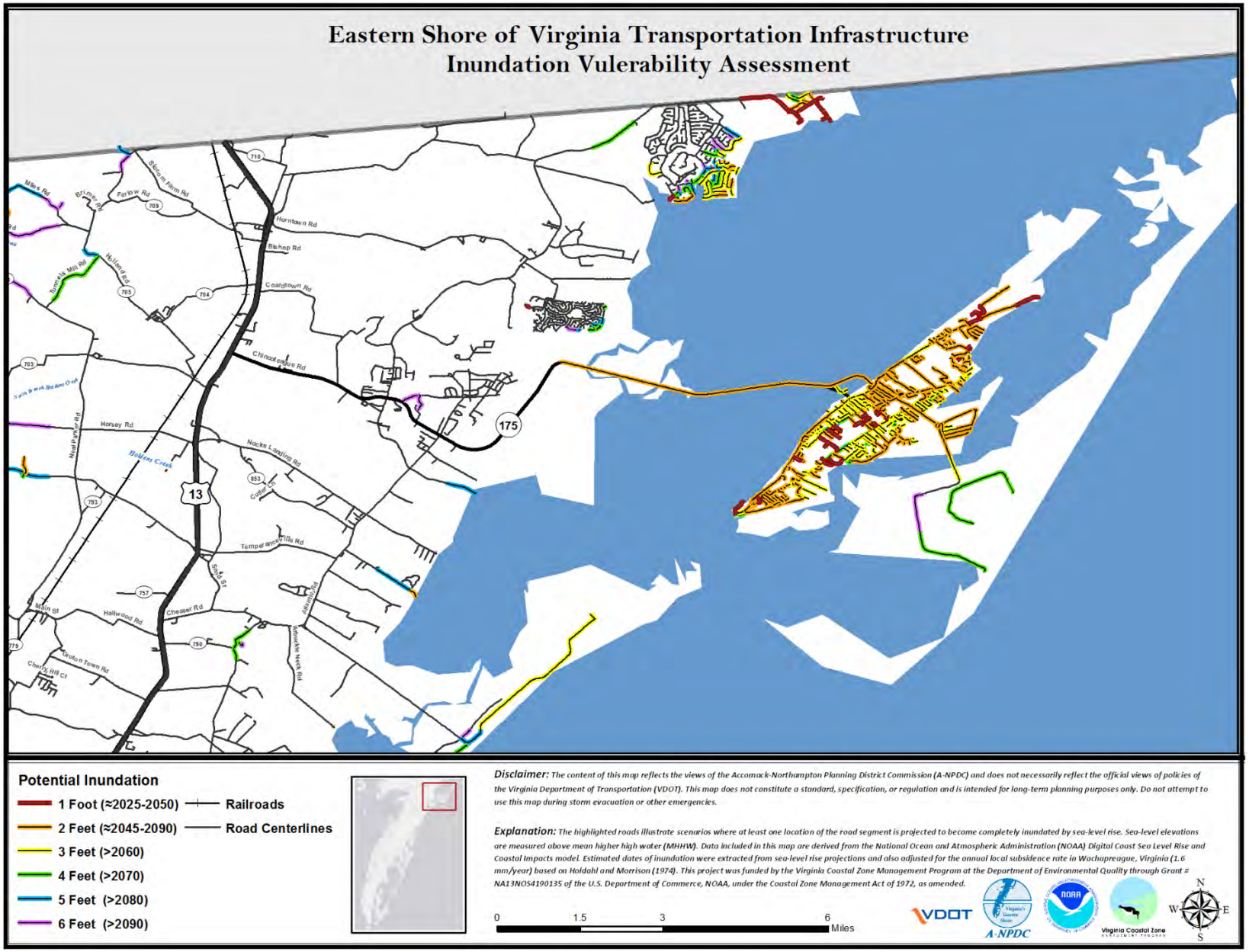


Figure 14 – Northeastern Accomack County Transportation Infrastructure Inundation Vulnerability

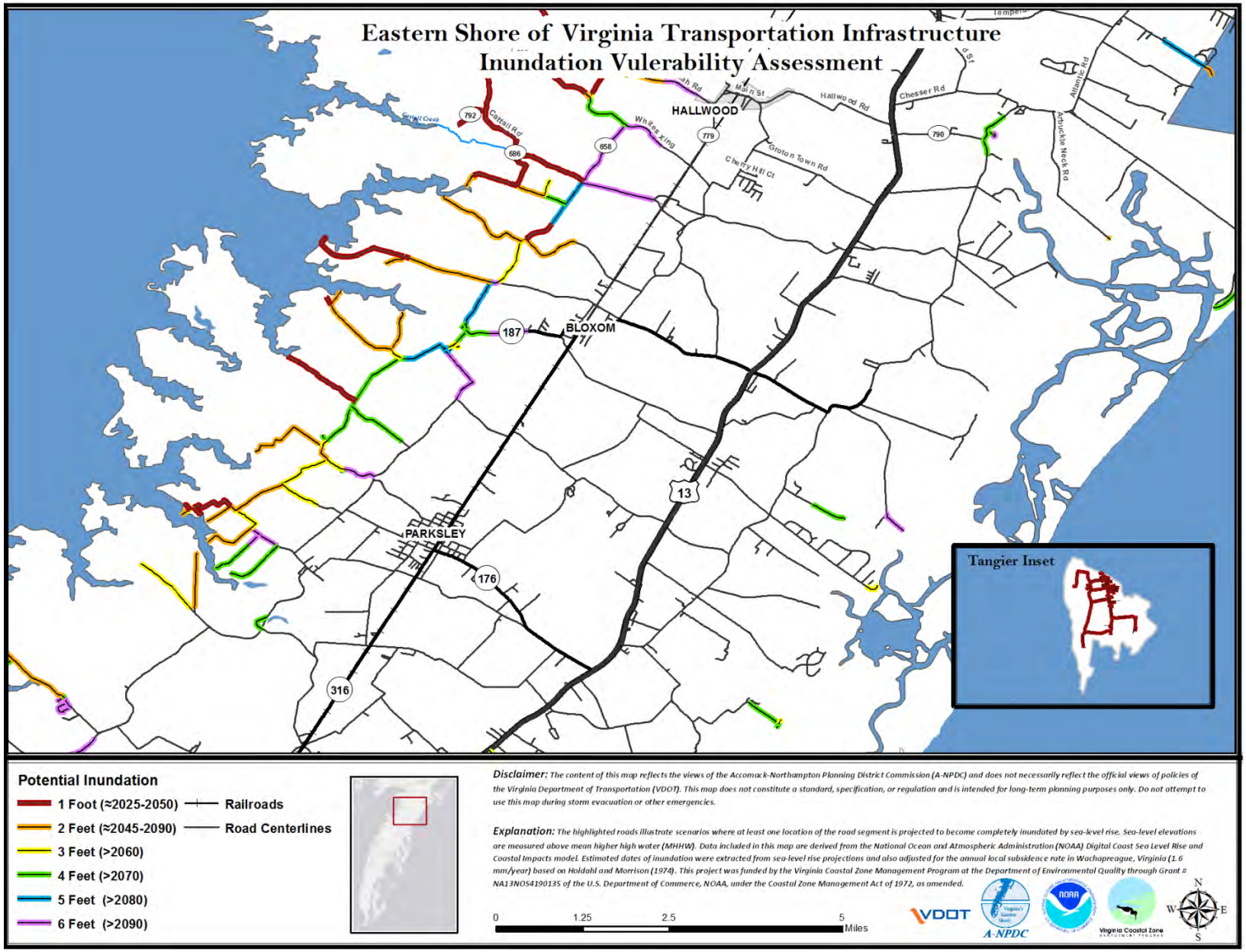


Figure 15 – Central Accomack County Transportation Infrastructure Inundation Vulnerability

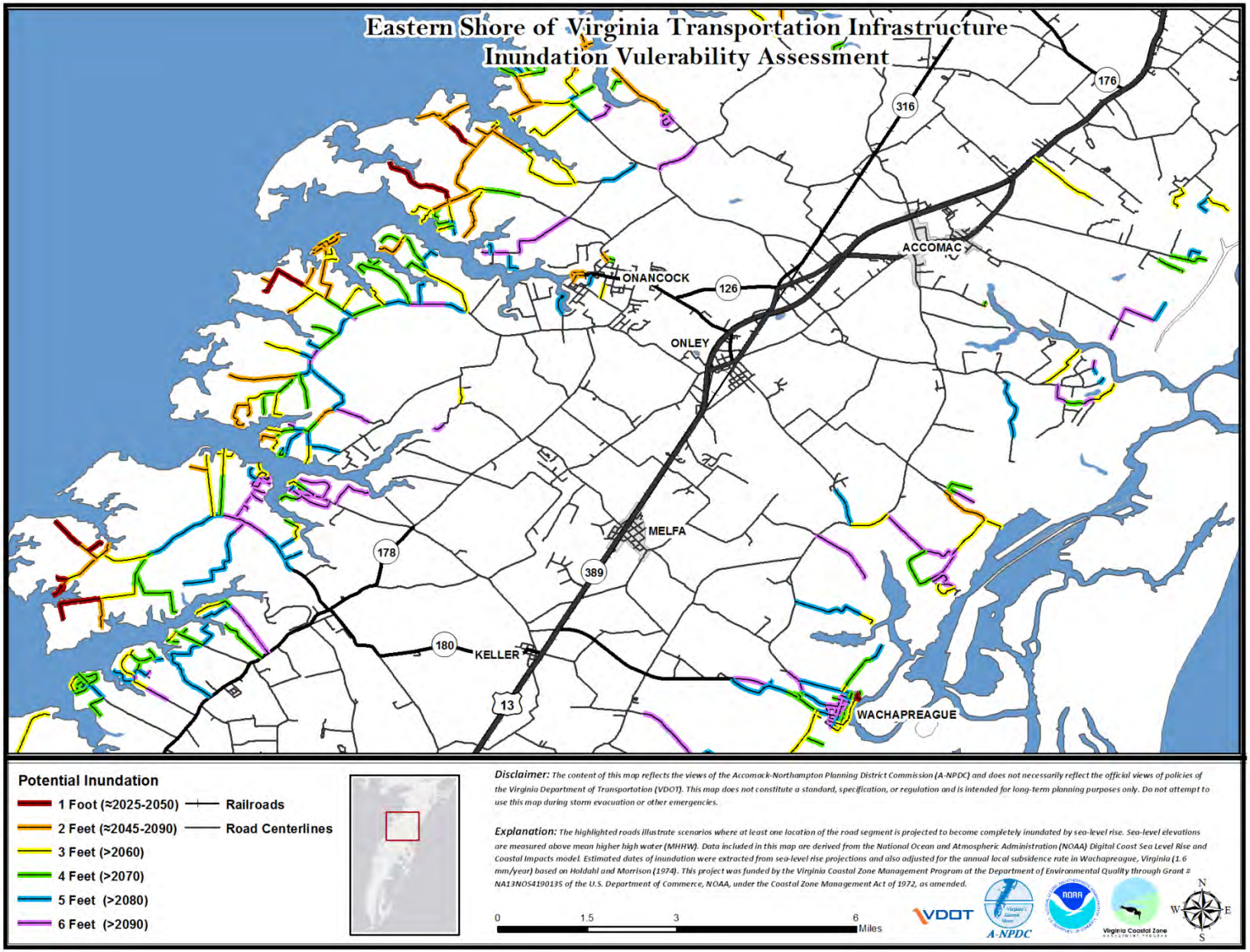


Figure 16 – Southern Accomack County Transportation Infrastructure Inundation Vulnerability

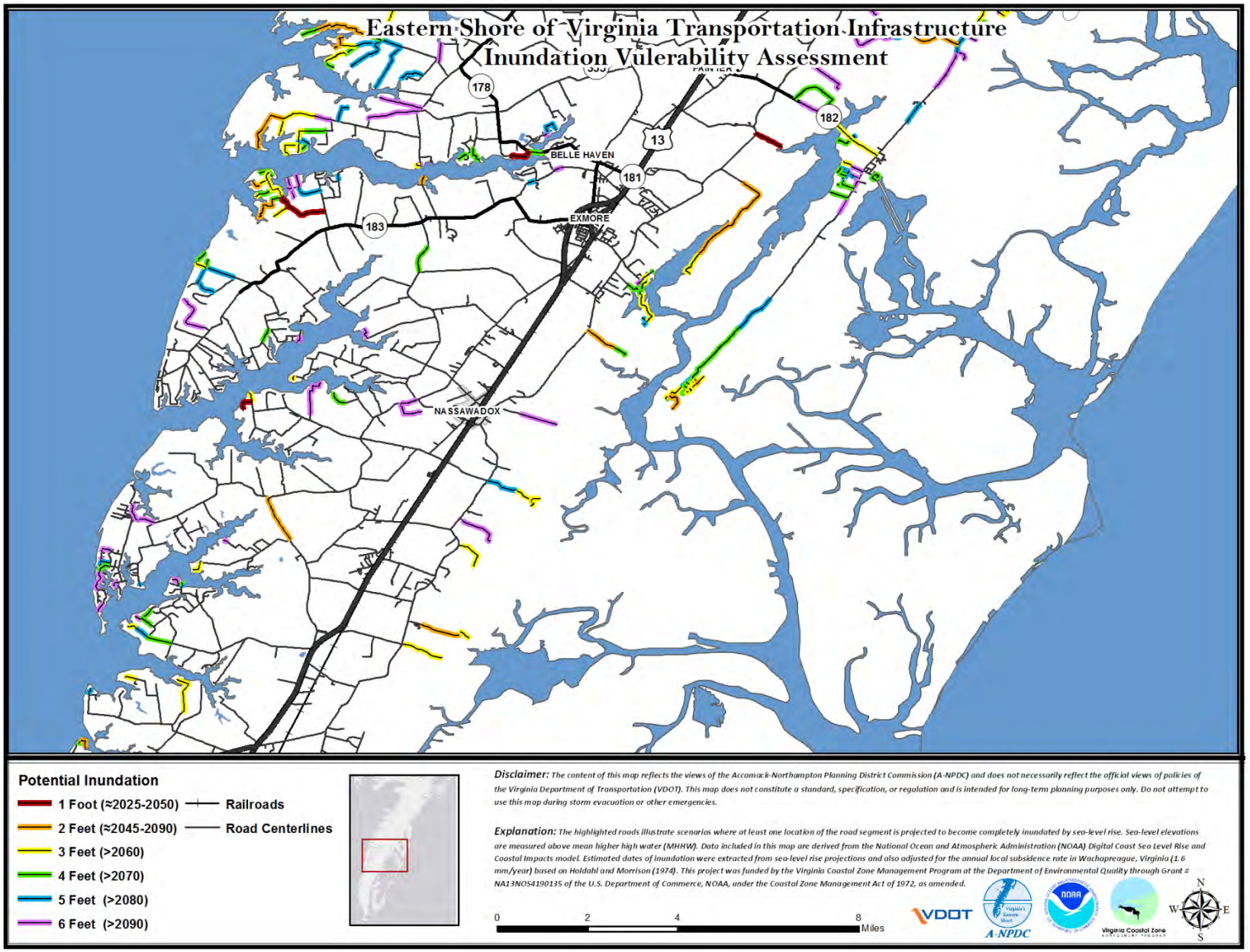


Figure 17 – Northern Northampton County Transportation Infrastructure Inundation Vulnerability

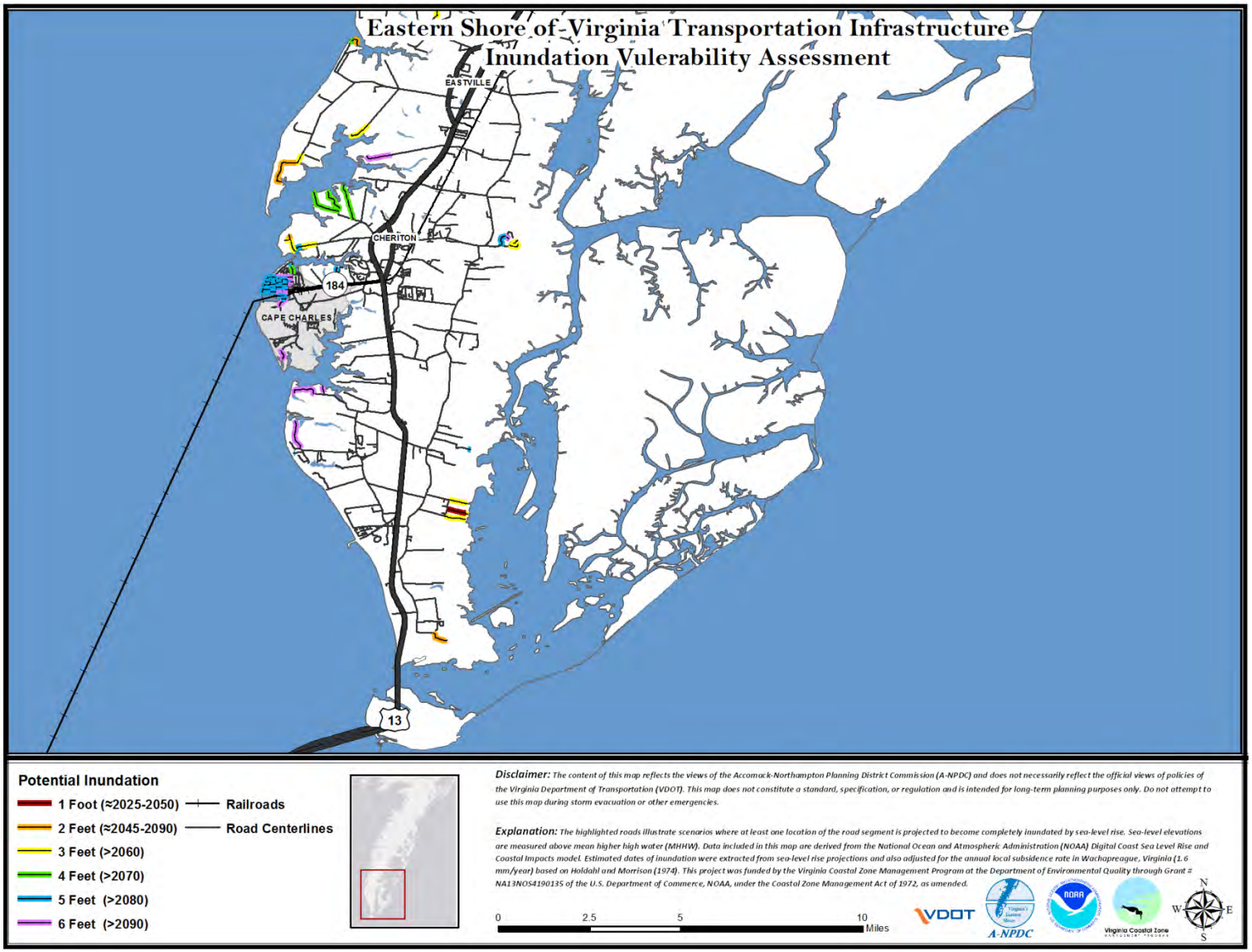


Figure 18 – Southern Northampton County Transportation Infrastructure Inundation Vulnerability

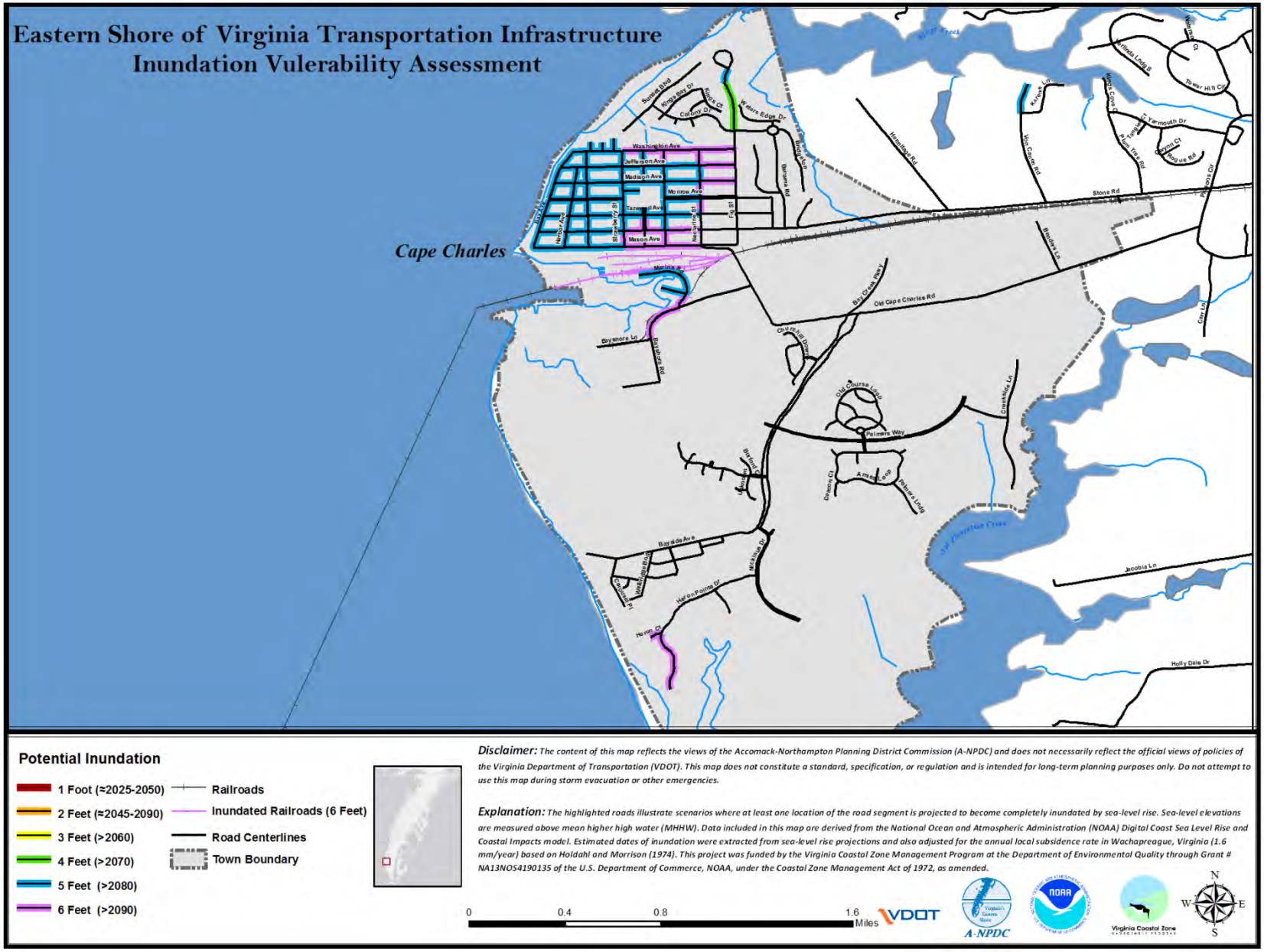


Figure 19 – Town of Cape Charles Transportation Infrastructure Inundation Vulnerability

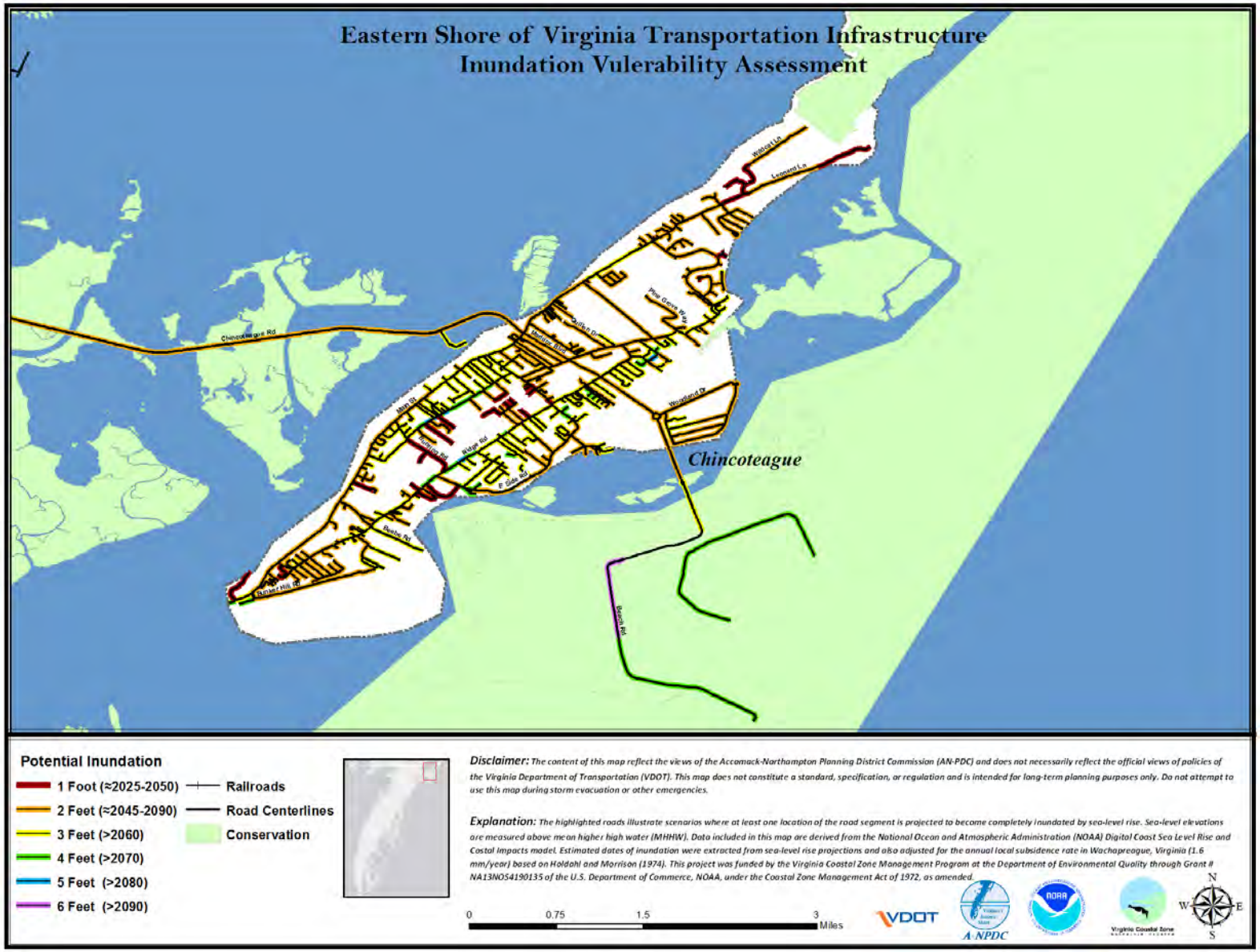


Figure 20 – Town of Chincoteague Transportation Infrastructure Inundation Vulnerability

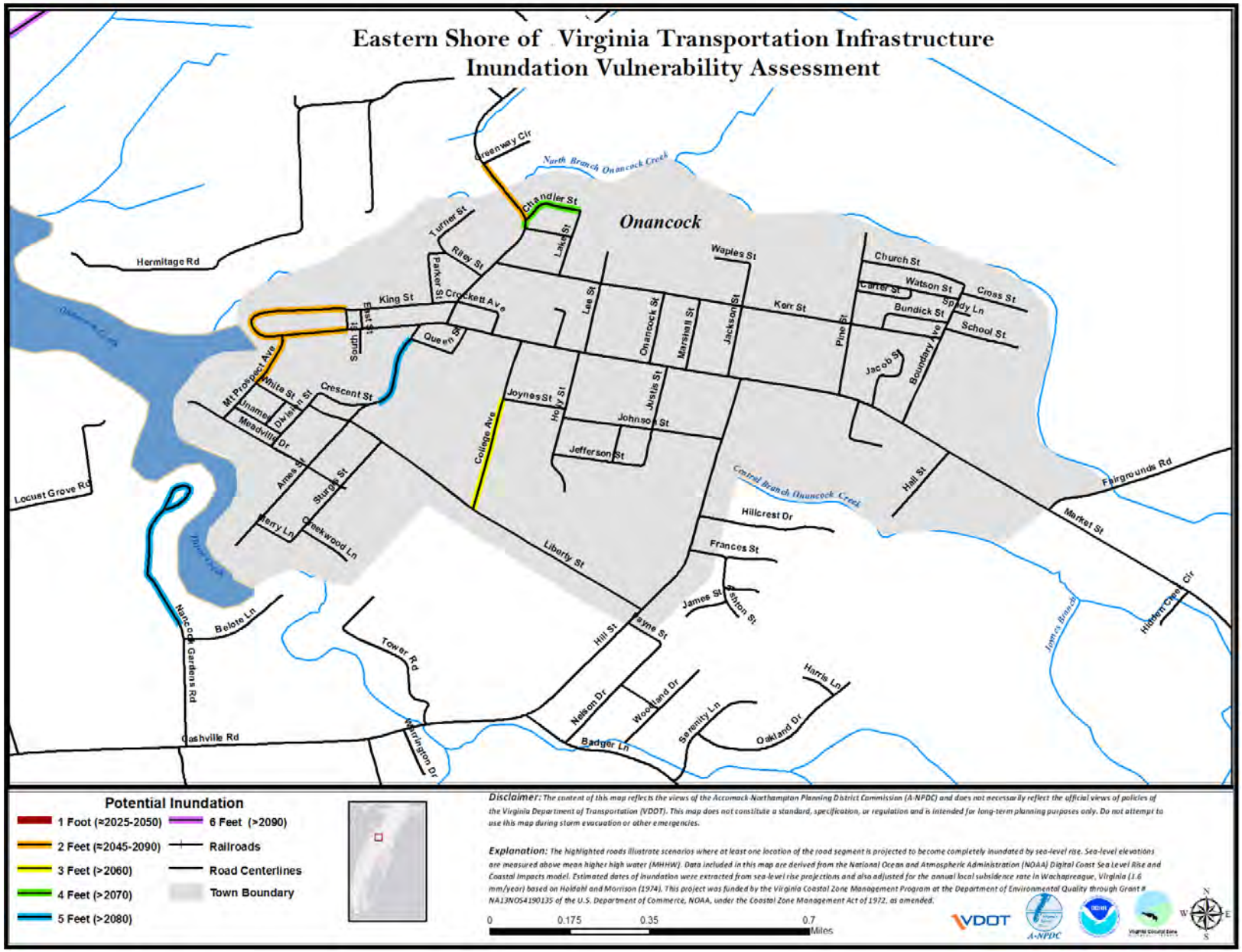


Figure 21 – Town of Onancock Transportation Infrastructure Inundation Vulnerability

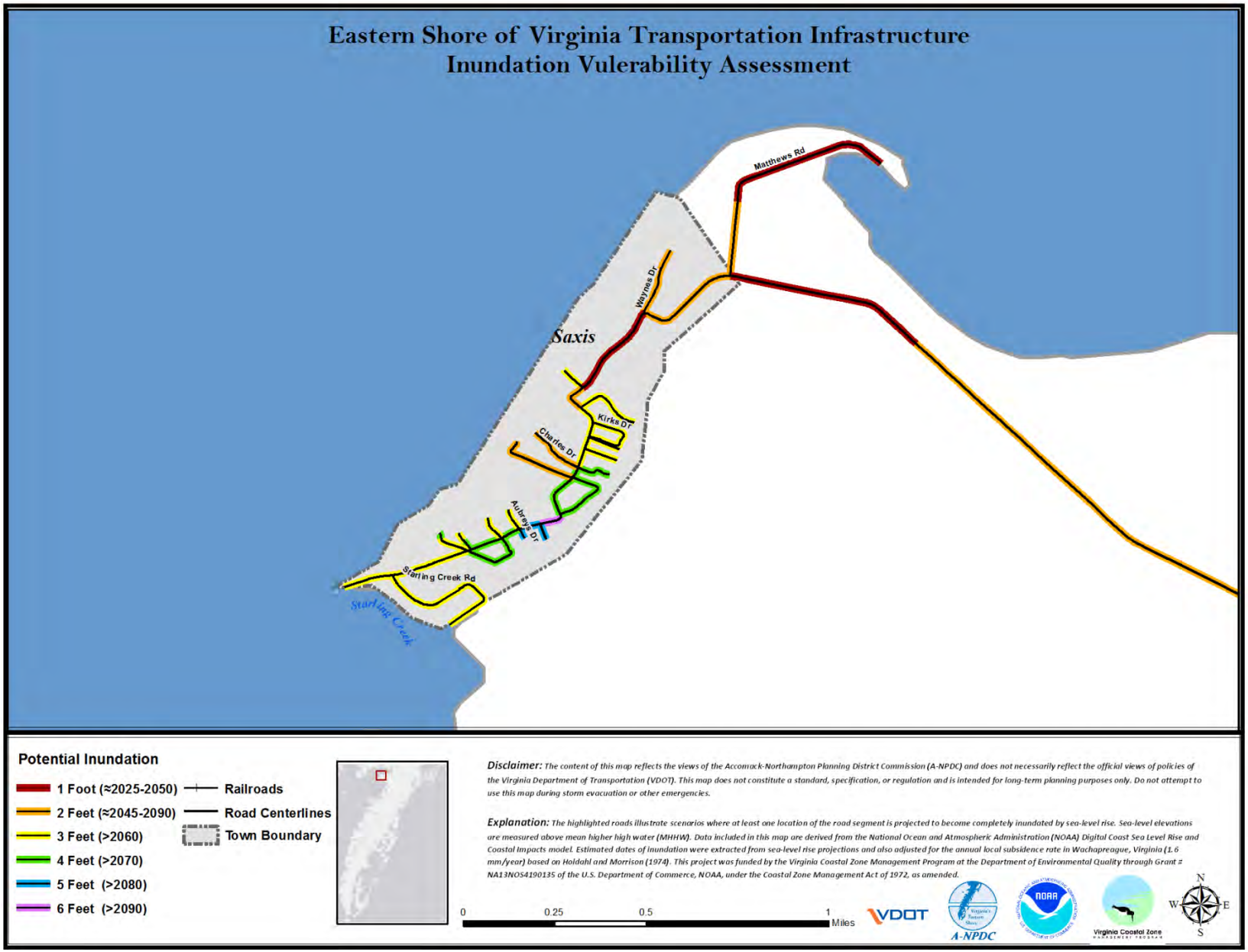


Figure 22 – Town of Saxis Transportation Infrastructure Inundation Vulnerability

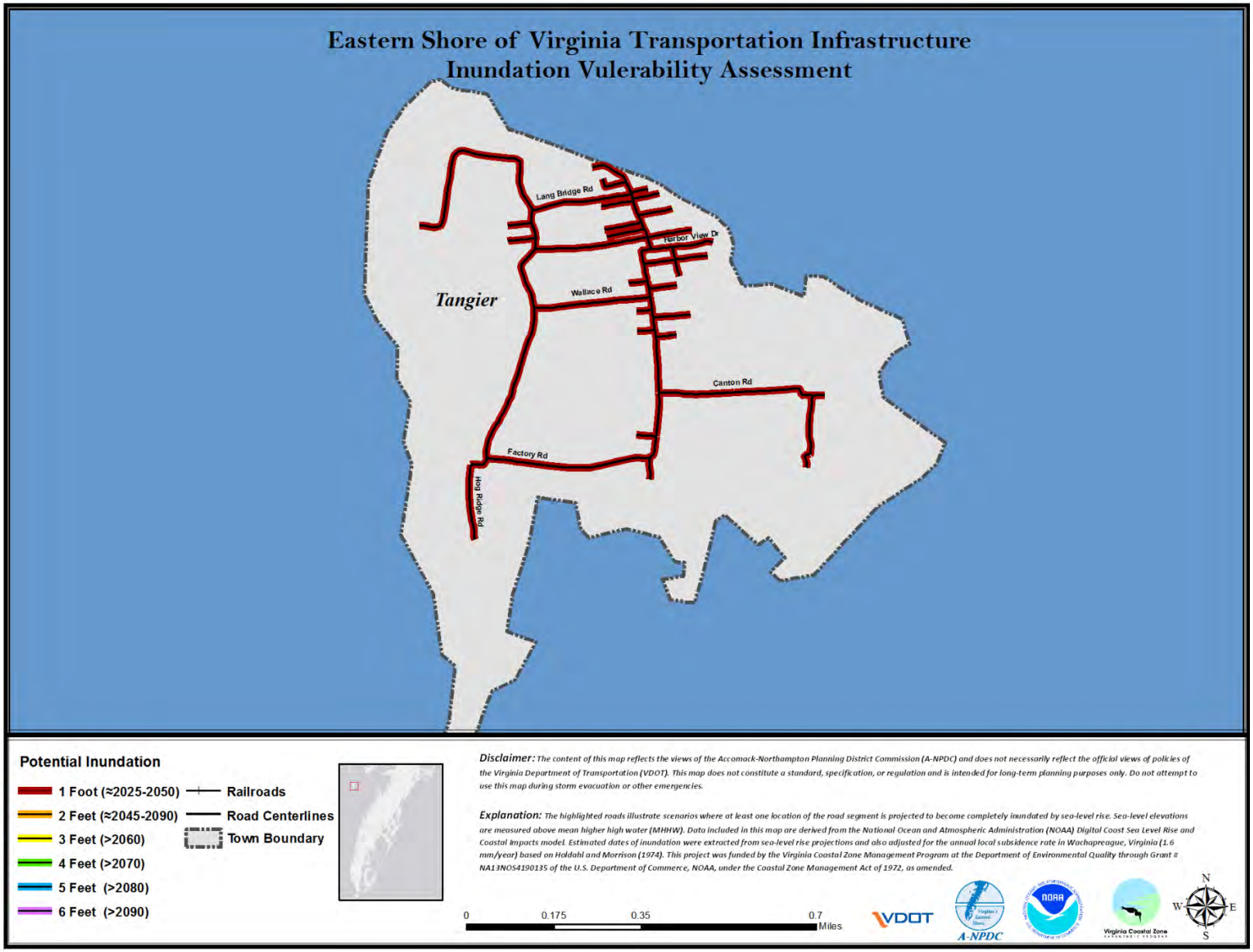


Figure 23 – Town of Tangier Transportation Infrastructure Inundation Vulnerability

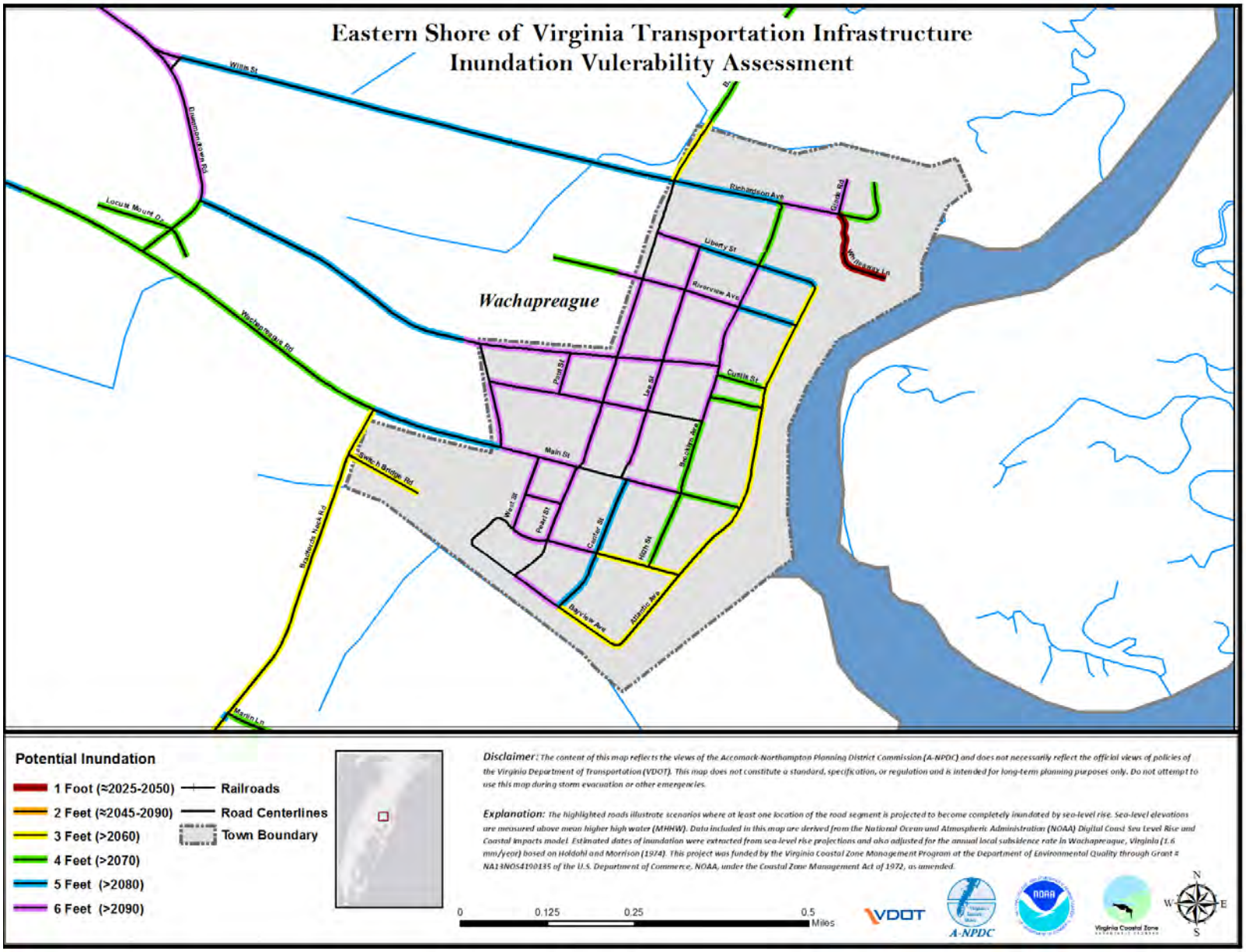


Figure 24 – Town of Wachapreague Transportation Infrastructure Inundation Vulnerability

Primary and Secondary Roads

Figures 12 through 24 summarize the outcomes of the inundation vulnerability assessment. Significant impacts on transportation infrastructure are projected for the two inundation scenarios with the highest certainty (1' occurring ≈2025-2050 and 2' occurring ≈2045-2090) for when they could occur. These time horizons fall within the design horizon of local roads in the region. If no engineering solutions are utilized to address these roadways' vulnerabilities to inundation, it should be expected that the livelihood and safety of communities and the integrity of the roadway will be negatively affected as a consequence.

Accomack County was found to have a much greater vulnerability to relative sea-level rise than Northampton County (**Figure 12**). As discussed in prior sections, this finding is not surprising considering the varying topographic conditions in each county and the fact that Accomack County has multiple communities and facilities located on topographically-low islands.

A number of road segments leading to working waterfronts (i.e. wharfs, harbors, marinas, etc.) were identified as being vulnerable to inundation. Further inspection of these areas revealed that the vast majority of the road segment will likely not be impacted by inundation and only the road ending or working waterfront facility is vulnerable. Some examples of this scenario included Davis Wharf, Morleys Wharf, Bayford Landing, and many others. Working waterfront facilities are critical to local and regional economies and as such, additional research and planning will be required to reconfigure access to these facilities based on local topography as relative sea-level rise occurs.

The 2013 VIMS Recurrent Flooding Study for Tidewater Virginia included a GIS vulnerability assessment of roads utilizing a similar methodology and reported 370 miles (326 miles in Accomack County and 44 miles in Northampton County) of roads in the region were vulnerable to 1.5' of relative sea-level rise combined with a 3' storm surge (4.5' total water elevation). These findings are comparable to findings from this study but not exact. This study found that with 4' of relative sea-level rise, there are potentially 270 miles of roads vulnerable to inundation (236 miles in Accomack County and 34 miles in Northampton County) and with 5' of relative sea-level rise there are 319 miles of roads vulnerable to inundation (275 miles in Accomack County and 44 miles in Northampton County) in the region (**Figure 12**).

Railroad

The rail yard in Cape Charles is the only section of the railroad that is potentially vulnerable to inundation from relative sea-level rise. Inundation of the rail yard could begin as early as the end of the century (2090, see **Figure 19**). It is projected that the areas of the rail yard located west of Old Cape Charles Road will be inundated with 6' of relative sea-level rise. It is expected that flooding will occur with greater frequency over the decades leading up to 2090. Inundation of this infrastructure would be a major economic loss to the local and regional economy.

Community and Critical Facility Accessibility Assessment

Figures 25 through 32 summarize the outcomes of the accessibility assessment. Should sea level rise 1' sometime between 2025 and 2050 as projected by current research; eight communities and facilities are at risk of becoming disconnected or inaccessible, two are projected to lose at least one access route, and

Community/ Critical Facility	# of Access Routes	*Inundation from Sea-Level Rise Above MHHW*						Explanation
		1 feet (≈2025-2050)	2 feet (≈2045-2090)	3 feet (>2060)	4 feet (>2070)	5 feet (>2080)	6 feet (>2090)	
Accomack County								
Assawoman	3	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Westerly approach of Atlantic Rd. inundated at 4' limiting access to community.
Baileys Neck	1	Access Not Impacted	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	One road within community inundated at 2' and primary road accessing community inundated at 3'.
Battle Point/ Baylys Neck	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Belle Haven	4	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Westerly approach inundated at Shields Bridge at 4' limiting westerly access to community.
Bell Neck	1	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Bell Neck Rd. inundated at 2' at "causeway" disconnecting community. Additional sections of roads within community inundated at 3'.
Bloxom	4	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Guilford Rd. inundated at 4' limiting access from westerly approach to community.
Captains Cove	3	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Horntown Rd. inundated at 4' limiting access to community. Roads within community become increasingly inundated but never reach majority.
Cashville	2	Access Not Impacted	Access Not Impacted	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Both access roads inundated at 4' with majority of roads within community inundated at 5'.
Cedar View	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Chincoteague	1	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Chincoteague causeway inundated at lowest spots at 2' and completely inundated at 3'. Roads within town increasingly inundated beyond 3'.

Figure 25 – Accomack County Community and Critical Facility Accessibility Assessment Summary

Community/ Critical Facility	# of Access Routes	*Inundation from Sea-Level Rise Above MHHW*						Explanation
		1 feet (≈2025-2050)	2 feet (≈2045-2090)	3 feet (>2060)	4 feet (>2070)	5 feet (>2080)	6 feet (>2090)	
Accomack County								
Chincoteague NWR & Assateague Island Nat. Seashore	1	Access Not Impacted	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Majority of Roads Inundated	Chincoteague causeway and Assateague causeway inundated at lowest spots at 2' and completely inundated at 3'.
Crystal Beach	1	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Low spot in Crystal Beach Rd. inundated at 1' disconnecting access to community.
East Point	1	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Three low spots in East Point Rd. inundated at 2' disconnecting access to community.
Davis Wharf	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	One road within community inundated at 2' and primary road within community mostly inundated at 6'.
Deep Creek	1	Access Not Impacted	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Gladding Landing	1	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Greenbackville	2	Access Limited	Access Limited	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	State Line Rd. access inundated at 1' and Stockton Ave. access inundated at 3' disconnecting access to community
Guard Shore	1	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Guilford	3	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Majority of Roads Inundated	Majority of Roads Inundated	Northerly access from Winterville Rd. inundated at 3'. Majority of access roads and roads within community inundated at 5'.
Hacksneck	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Harborton Rd. access inundated at 5' disconnecting community. An increasing number of roads within community inundated beginning at 2'.

***Figure 25 (continued)* – Accomack County Community and Critical Facility Accessibility Assessment Summary**

Community/ Critical Facility	# of Access Routes	Inundation from Sea-Level Rise Above MHHW						Explanation
		1 feet (≈2025-2050)	2 feet (≈2045-2090)	3 feet (>2060)	4 feet (>2070)	5 feet (>2080)	6 feet (>2090)	
Accomack County								
Harborton	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Harborton Rd. access inundated at 5' disconnecting community. An increasing number of roads within community inundated beginning at 2'.
Hopkins	1	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Hopkins Rd. access inundated at 1' disconnecting community.
Henry's Point	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Disconnected/ Inaccessible	
Locustville	2	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Access Limited	Drummondtown Rd. westerly approach inundated at 3'. Additional roads within community inundated at 6'.
Mount Nebo	3	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Access Limited	Dingleys Mill Rd. inundated at 3' eastern access to community. Cashville Rd. inundated at 4' at Cashville limiting second access to community. Evans Wharf Rd. inundated at 5' further limiting westerly access to community. Community still accessible via northerly access from Mt. Nebo Rd. through at least 6' inundation.
Nandua Bay	1	Access Not Impacted	Access Not Impacted	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Fairview Rd. inundated at 3' disconnecting access to community.
NASA Wallops Flight Facility - Main Base	2	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Mill Dam Rd. inundated at 6' limiting access to Main Base from westerly approach.
NASA Wallops Flight Facility - Mid-Atlantic Regional Spaceport	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Wallops causeway and bridge not inundated at <6'. Majority of roads on island inundated at 4' with several locations inundated at 3'.

***Figure 25 (continued)* – Accomack County Community and Critical Facility Accessibility Assessment Summary**

Community/ Critical Facility	# of Access Routes	Inundation from Sea-Level Rise Above MHHW						Explanation
		1 feet (≈2025-2050)	2 feet (≈2045-2090)	3 feet (>2060)	4 feet (>2070)	5 feet (>2080)	6 feet (>2090)	
Accomack County								
North Chesconessex	1	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Northside Rd. inundated at 2' disconnecting access to community.
Pitts Creek Landing	1	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Poplar Cove	1	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Sanford	2	Access Not Impacted	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Saxis	1	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Saxis causeway inundated at specific locations at 1' with causeway mostly inundated at 2'.
Schooner Bay	1	Access Not Impacted	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Schooner Bay Rd. inundated at 2' disconnecting access to community.
Tangier	0	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	
Trails End	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Five road segments inundated between 4-6' limiting access within community.
Quinby/ Upshurs Neck	3	Access Not Impacted	Access Limited	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Disconnected/ Inaccessible	One of 3 access roads (Piggin Rd.) inundated at 2' limiting access to community. Other 2 access roads inundated at 3' disconnecting community. Inundation of roads worsens to the south from Quinby. Majority of roads within Quinby not inundated at 6' unlike areas to south.

Figure 25 (continued) – Accomack County Community and Critical Facility Accessibility Assessment Summary

Community/ Critical Facility	# of Access Routes	*Inundation from Sea-Level Rise Above MHHW*						Explanation
		1 feet (≈2025-2050)	2 feet (≈2045-2090)	3 feet (>2060)	4 feet (>2070)	5 feet (>2080)	6 feet (>2090)	
Accomack County								
Wachapreague	4	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Southerly access via Bradfords Neck Rd. inundated at 3' limiting access to community. Westerly access via Wachapreague Rd. inundated at 4' further limiting access to community. Remaining access roads (Custis St. and Willis St.) inundated at 5' disconnecting community. Majority of roads within community inundated at 6'.

Figure 25 (continued) – Accomack County Community and Critical Facility Accessibility Assessment Summary

Community/ Critical Facility	# of Access Routes	*Inundation from Sea-Level Rise Above MHHW*						Explanation
		1 feet (≈2025-2050)	2 feet (≈2045-2090)	3 feet (>2060)	4 feet (>2070)	5 feet (>2080)	6 feet (>2090)	
Northampton County								
Arlington Plantation	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Majority of Roads Inundated	
Bayford	1	Access Limited	Access Limited	Access Limited	Access Limited	Access Limited	Access Limited	Access south of Bayford Landing likely to become limited due to inundation of segment of road at Bayford Landing at 1'.
Cape Charles	2	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Majority of Roads Inundated	Majority of Roads Inundated	Inundation likely to occur mainly at roads in historic Cape Charles with very minor inundation occurring in Bay Creek neighborhood.
Cherrystone	1	Access Not Impacted	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Cherrystone Campground likely to have limited access at 1' and have majority of roads inundated by 3'. The remaining areas to become disconnected at 3'.
Church Neck	1	Access Not Impacted	Access Limited	Access Limited	Access Limited	Access Limited	Access Limited	Access via Bayside Rd. from the south becomes inundated at headwaters of Hungars Creek at 2'.
Clearview	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Inundation of select roads within community at 5' and 6'.
Franktown	4	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Southerly approach of Bayside Rd. inundated by Waterhouse Creek at 6'.
Johnsons Cove/Old Neck	1	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Old Neck Rd. inundated at two specific locations at 1'.
Oyster	2	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Disconnected/ Inaccessible	Majority of Roads Inundated	Roads on southside of harbor inundated at 3'. Northside of harbor disconnected when access roads become inundated at 5'. North and southsides primarily inaccessible at 6'.
The Peacefuls	2	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Access Limited	Roads serving areas within Peaceful Lakes inundated at 3', 4', and 5'. Peaceful Way inundated at 6'.
Red Bank	1	Access Not Impacted	Access Not Impacted	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Red Bank Rd. primarily inundated at 3'.

Figure 26 – Northampton County Community and Critical Facility Accessibility Assessment Summary

Community/ Critical Facility	# of Access Routes	*Inundation from Sea-Level Rise Above MHHW*						Explanation
		1 feet (≈2025-2050)	2 feet (≈2045-2090)	3 feet (>2060)	4 feet (>2070)	5 feet (>2080)	6 feet (>2090)	
Northampton County								
Vaucluse Shores	1	Access Not Impacted	Access Not Impacted	Access Not Impacted	Access Limited	Disconnected/ Inaccessible	Disconnected/ Inaccessible	Heron Dr. inundated at 4' limiting access to western portion of community. Roads serving several other areas within the community inundated at 5' and 6'.
Webbs Island	1	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Access road to community inundated at 2' with majority of roads within community inundated at 3'
Willis Wharf	2	Access Not Impacted	Access Not Impacted	Access Limited	Access Limited	Access Limited	Access Limited	Access to areas within community increasingly limited beginning at 3'
Wise Point Landing - ESVA NWR	1	Access Not Impacted	Disconnected/ Inaccessible	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Majority of Roads Inundated	Ramp Ln. inundated at 2' disconnecting access to landing

Figure 26 (continued) – Northampton County Community and Critical Facility Accessibility Assessment Summary

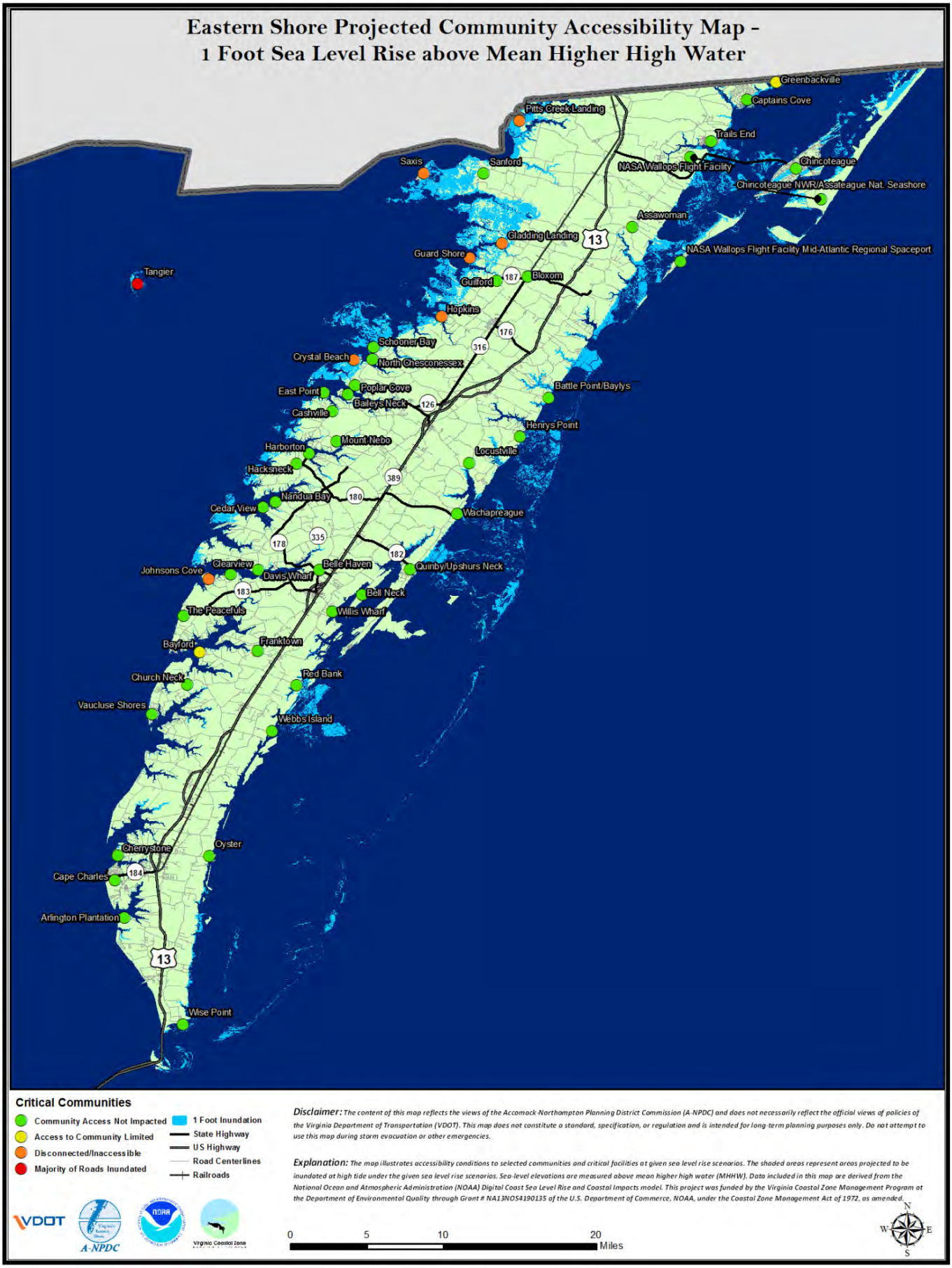


Figure 27 – Regional Community and Critical Facility Accessibility Vulnerability Assessment: 1 Foot Relative Sea-Level Rise Above MHHW

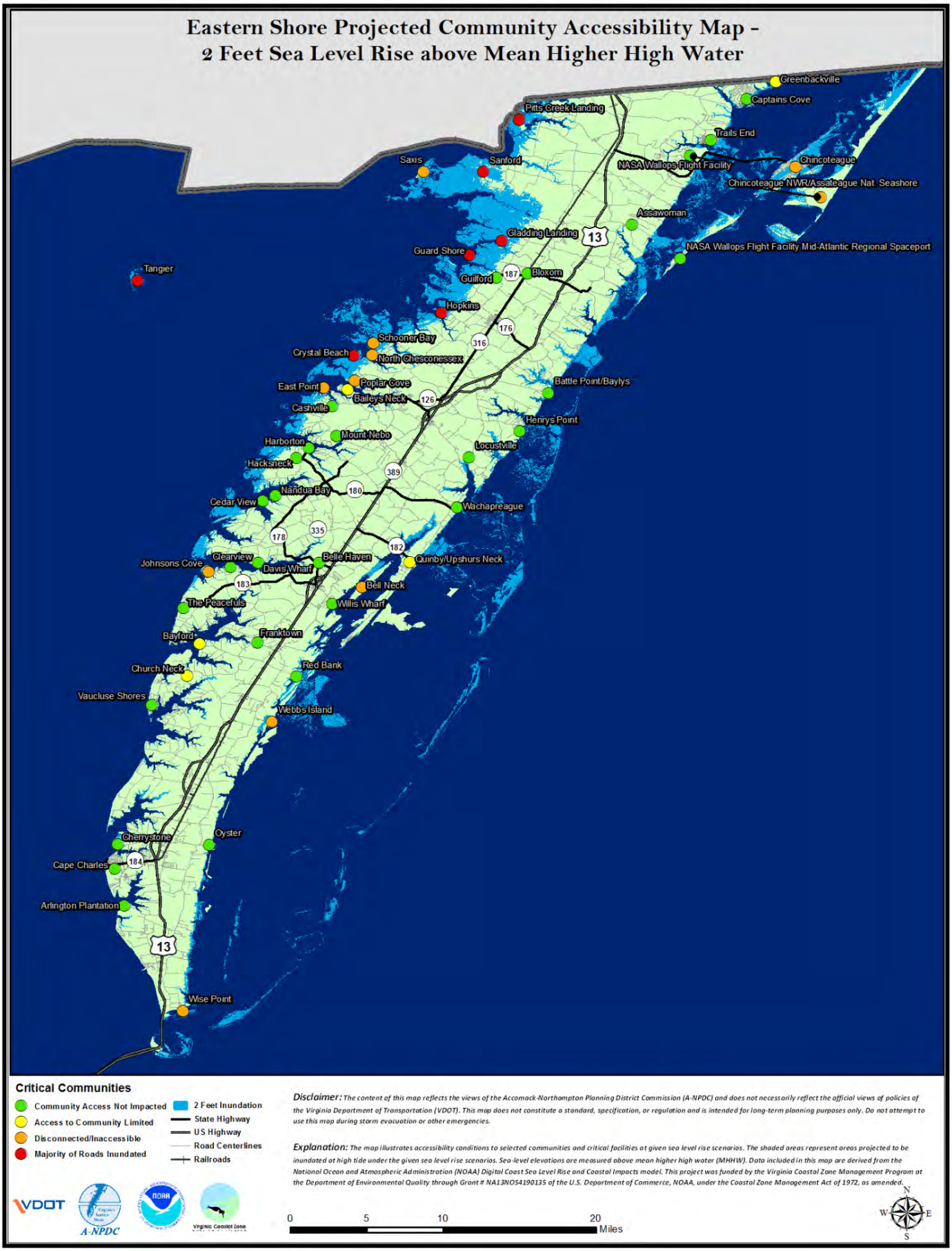


Figure 28 – Regional Community and Critical Facility Accessibility Vulnerability Assessment: 2 Feet Relative Sea-Level Rise Above Mean Higher High Water

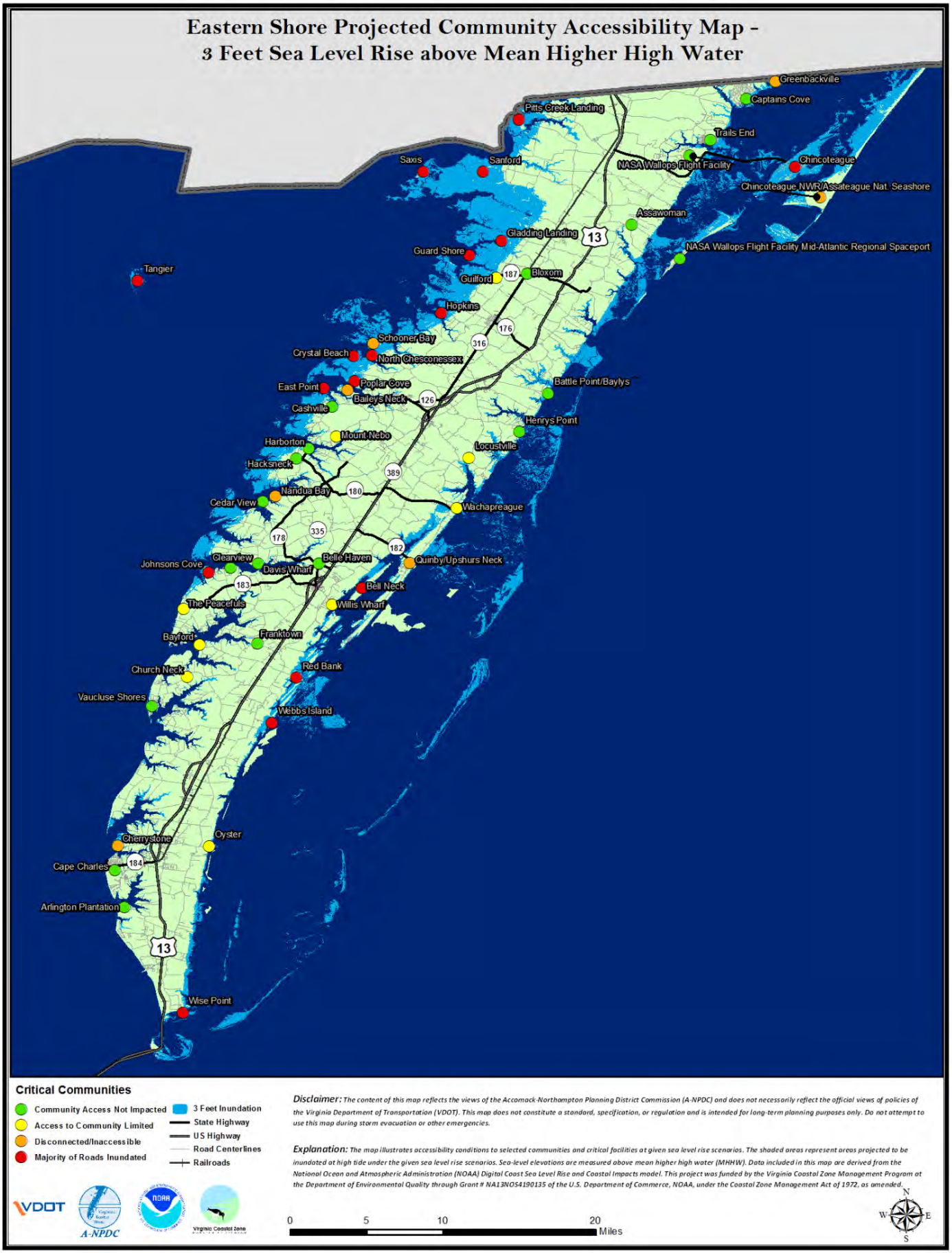


Figure 29 – Regional Community and Critical Facility Accessibility Vulnerability Assessment: 3 Feet Relative Sea-Level Rise Above Mean Higher High Water

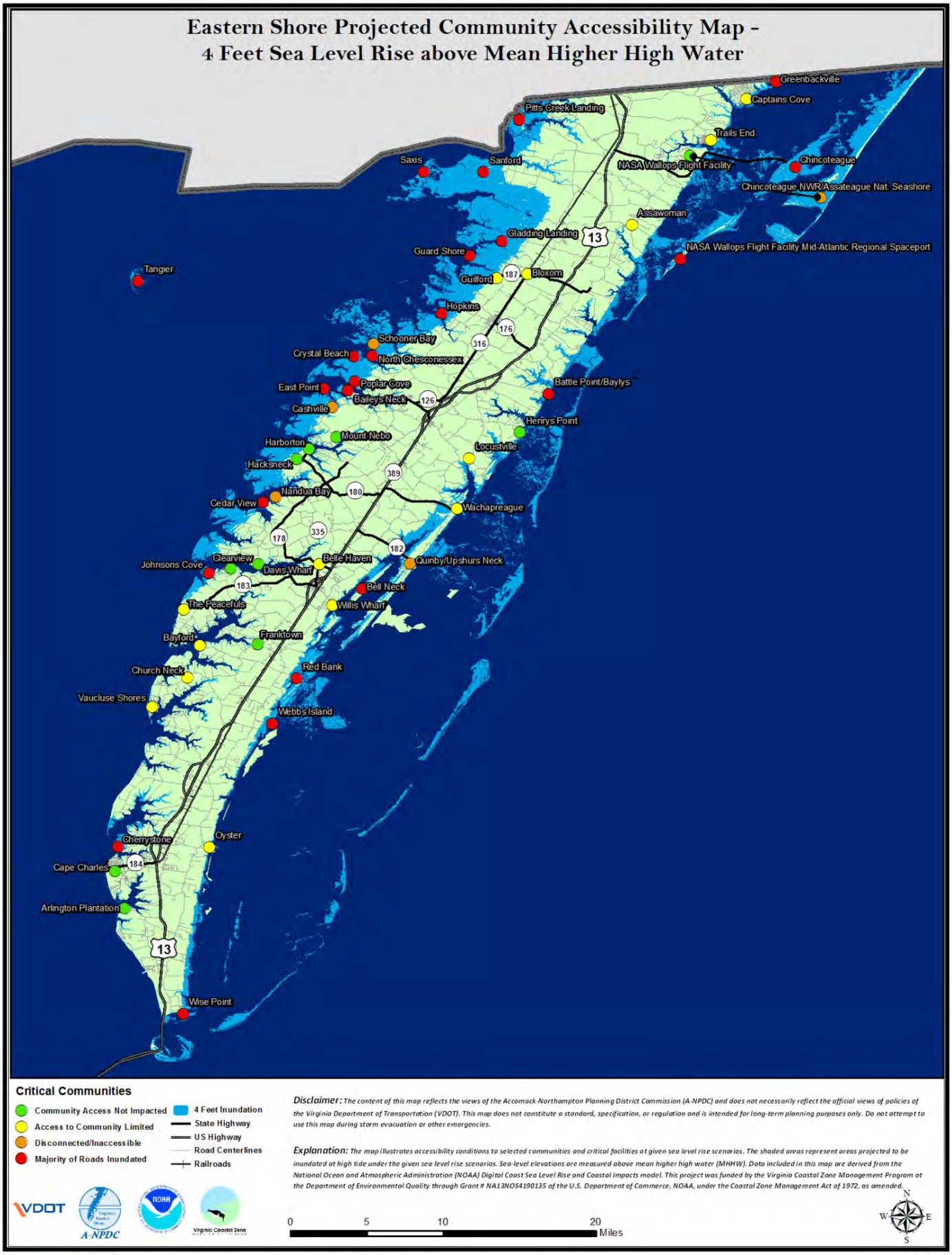


Figure 30 – Regional Community and Critical Facility Accessibility Vulnerability Assessment: 4 Feet Relative Sea-Level Rise Above Mean Higher High Water

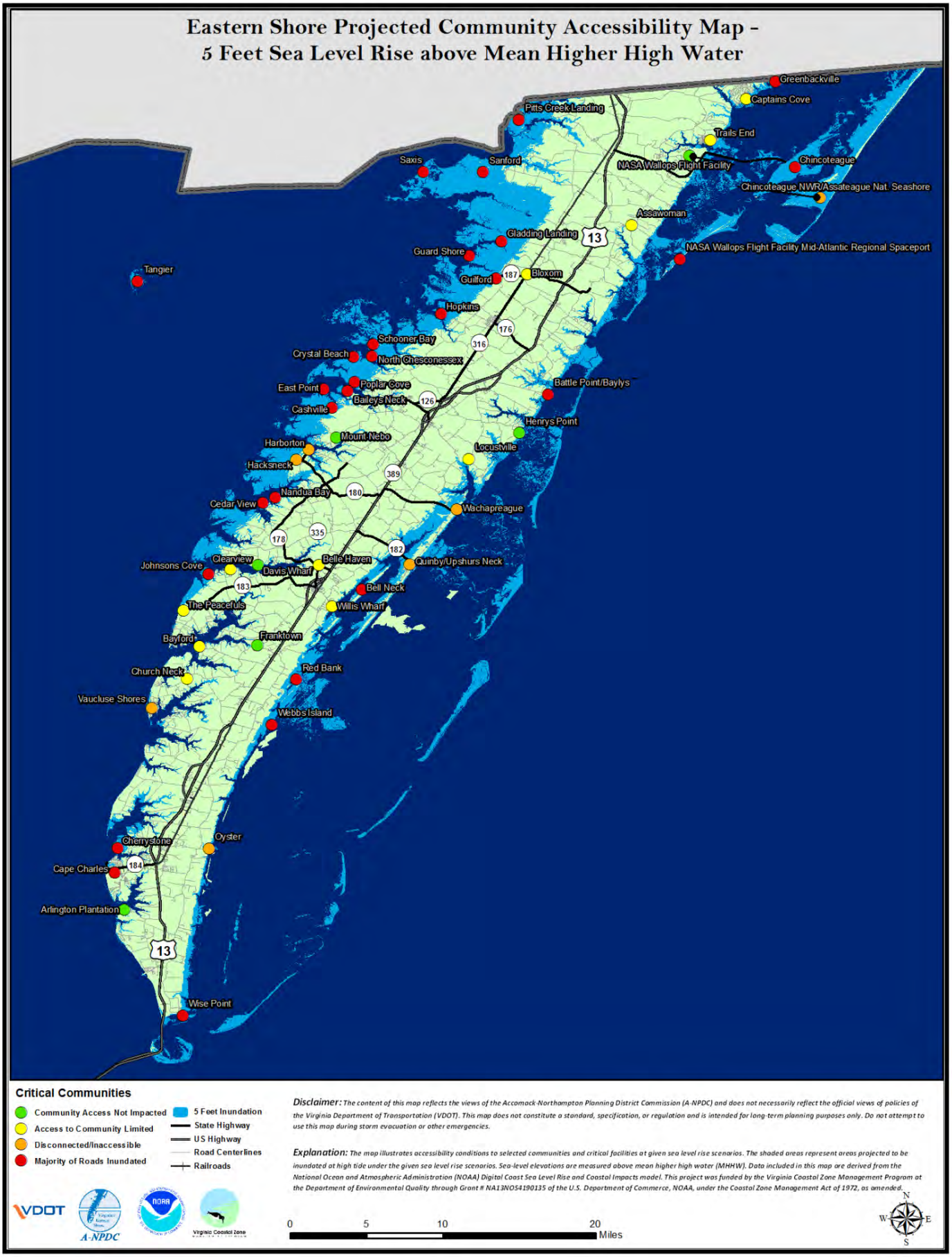


Figure 31 – Regional Community and Critical Facility Accessibility Vulnerability Assessment: 5 Feet Relative Sea-Level Rise Above Mean Higher High Water

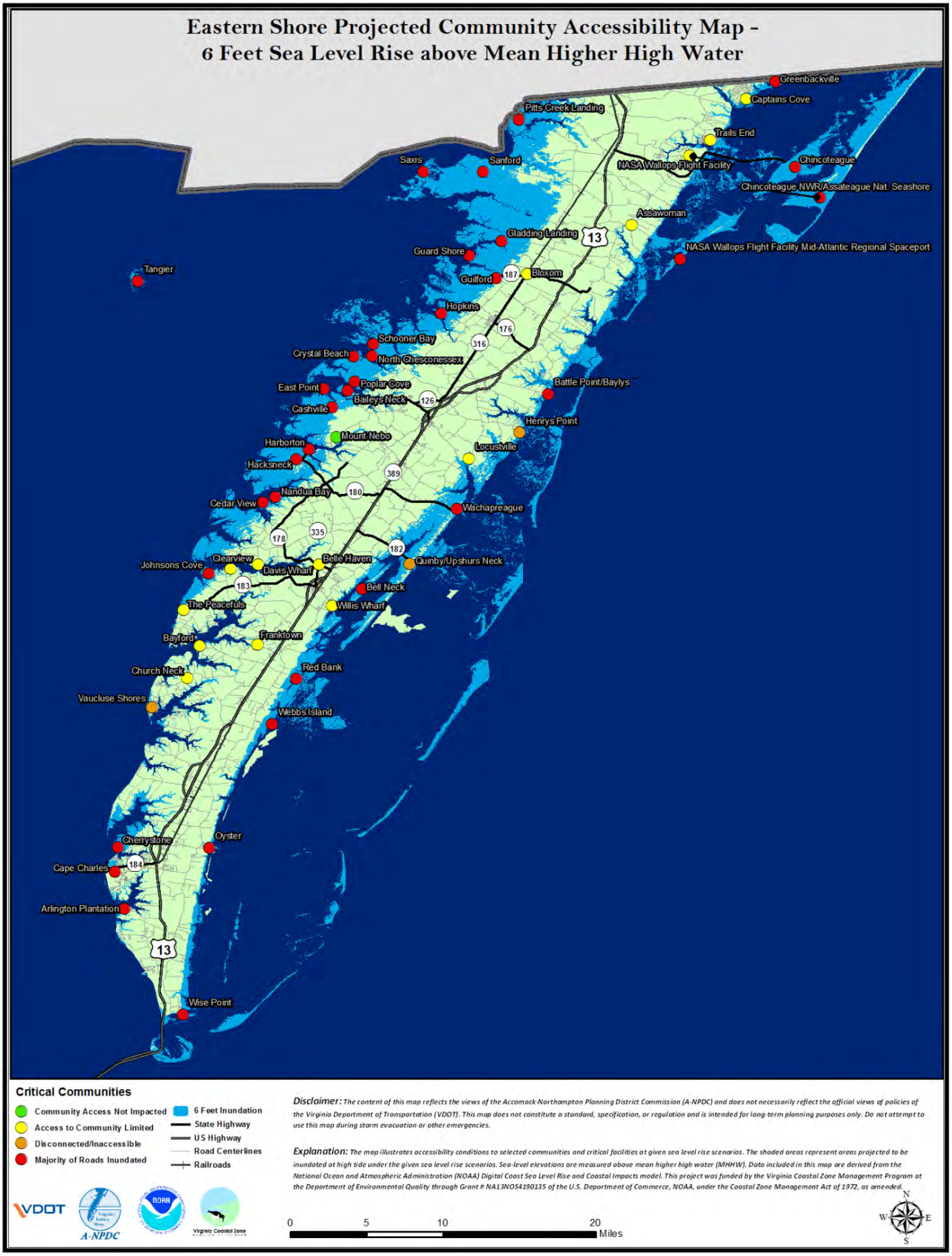


Figure 32 – Regional Community and Critical Facility Accessibility Vulnerability Assessment: 6 Feet Relative Sea-Level Rise Above Mean Higher High Water

one is vulnerable to having the majority of its roads inundated during high tides during that time span. It is important to note that groundwater flooding, especially in low-lying areas, could exacerbate these conditions resulting in inundation prior to the projected times of occurrence. Furthermore, it is expected that accessibility will become further compromised as sea-level continues to rise and accelerate.

Discussion

Based on the results of the inundation vulnerability assessment and the accessibility assessment, nearly one-quarter of all roads (**Figure 12**) and over 50 communities and facilities (**Figures 25 and 26**) on the Eastern Shore of Virginia are potentially vulnerable to relative sea-level rise. However, much larger areas may be inundated in low-lying areas where the groundwater table may concurrently rise or where other flooding-related issues may exacerbate the problem. As a result, a larger number of roads may be subject to flooding than what is indicated by this study.

In either case, there is a need to prioritize major investments in transportation infrastructure. The design of more resistant and adaptive transportation infrastructure and network systems will be required to adequately manage impacts from relative sea-level rise. New design requirements may involve the development of new performance measures for assessing the ability and resiliency of roads, bridges, causeways, culverts, etc. and enhanced design standards and design and construction guidelines for resilient transportation facilities. Options that will need to be considered for vulnerable transportation infrastructure may include retrofitting, material protective measures, rehabilitation, and in some cases, relocation.

As described in Bloetscher, et al. (2012) adaptation efforts should first focus on protecting the roadway base of a road vulnerable to inundation. They recommend protecting the roadway's base by ensuring that adequate drainage systems are maintained in a manner that meets both current and future conditions. This could involve installing wellpoint systems to provide more permanent drainage once water levels rise; although this option could be cost prohibitive and may require additional treatment to address water quality concerns. Other options could involve elevating roads for low-lying areas; however, this option may exceed the cost of new roads and may have significant negative impacts on adjacent properties and environments. A final option is abandonment of roadways, which should require an entire host of planning activites to ensure that local residents can adequately prepare for the potential domino-effect of changes that could occur in local communities.[33] In Virginia, if the Commonwealth abandons a roadway, the responsibility of maintaining the road transfers to local governments.

Estimating costs for replacing, upgrading, and repositioning roads, bridges, culverts, and other infrastructure due to inundation and any resulting lack of accessibility has been found by multiple studies to be problematic since construction costs vary widely depending on specific site conditions. Two construction cost estimates have been developed for roads vulnerable to inundation in regions nearby to

[33] Bloetscher, et al., 2012. Identification of Physical Transportation Infrastructure Vulnerable to Sea Level Rise. Journal of Sustainable Development; vol. 5, no. 12.

the Eastern Shore. In 2004, the Maryland Department of Natural Resources published a summary and analysis of a study conducted in 2003 on sea-level rise vulnerabilities and potential costs for actions needed to properly prepare for sea-level rise in three communities on the Chesapeake Bay in Maryland.[34] Cost estimates used in this study ranged from $385,000 to $750,000 to $1.5 million per lane mile and were approximated from estimates made from a variety of existing studies from the U.S Department of Transportation, Maryland and County Highway Administrations, and private asphalt and concrete-paving firms.[35] Another similar study was conducted in 2009 for the Middle Peninsula of Virginia by the Middle Peninsula Planning District Commission. This study utilized estimates provided by VDOT engineers for short-term and long-term roadway engineering alternatives of $149 per square foot and $745 per square foot, respectively.[36] For one community on the Middle Peninsula with an estimated 6.75 miles of roads vulnerable to inundation, it was estimated that approximately $5.3 million would be needed for short-term engineering alternatives and approximately $26.5 million for long-term engineering alternatives.[37] The estimates provided by each study would need to be increased for inflation to more accurately project current costs for the Eastern Shore. It is expected that many of the road segments on the Eastern Shore identified within this study will likely require elevation or relocation and considering previous cost estimates, the needed work would come at a cost that could prove to be prohibitive in some cases considering current levels of available funding to support the needed engineering.

Locally, it will be critical that the Eastern Shore of Virginia Transportation Technical Advisory Committee (TTAC) and the Eastern Shore of Virginia Climate Adaptation Working Group continue working closely with VDOT to integrate future relative sea-level projections into transportation planning and management efforts. Specifically, the Eastern Shore of Virginia 2035 Long Range Transportation Plan does not currently consider relative sea-level rise impacts; however, significant inundation of roadways could occur with 1' of relative sea-level rise, which is projected to occur sometime between 2025 and 2050 – within the forecast year of the plan. Incorporating the findings of this analysis into the plan during the next scheduled update is important. Additionally, considering the findings of this analysis within the criteria used by the TTAC when prioritizing local VDOT projects for the Six-Year Improvement Program will be a critical mechanism for implementing necessary adaptation actions for local transportation infrastructure.

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[34] Maryland Department of Natural Resources, 2004. Summary and Analysis of the Report "The Economic Cost of Sea Level Rise to Three Chesapeake Bay Communities". Available at http://www.dnr.state.md.us/CoastSmart/pdfs/2003ec_SeaLevelRise.pdf
[35] Ibid
[36] Middle Peninsula Planning District Commission, 2009. Asssessing the economic and ecological impacts of sea level rise for select vulnerable locations within the Middle Peninsula. Available at http://www.mppdc.com/articles/reports/FINAL_MPPDC_Sea%20Level%20Rise%20Assessment.pdf
[37] Ibid

IV. Summary and Conclusions

The Eastern Shore of Virginia's history, culture, and economies are closely connected to the region's proximity to tidal waters. The oldest communities in the region were located adjacent to navigable waterways which provided critical access to other urban markets along the Atlantic seaboard. Some of these communities were ideally located atop topographically-high scarps; however, others developed in lower areas and have become increasingly vulnerable to coastal flooding induced by relative sea-level rise. Additionally, residential development has occurred in many low-lying areas in more recent times making these properties susceptible to projected relative sea-level rise. The threat of inundation and coastal flooding is a concern for communities and economies in the region since they require a functional transportation network to provide regular access and ensure public safety.

To address these concerns, the A-NPDC worked with VDOT to assess which transportation infrastructure was vulnerable, how it may affect accessibility to communities, and determine when these impacts could occur. This study builds on previous work and methodologies employed by national, state, regional, and local organizations and utilizes the best-available information for the Eastern Shore of Virginia.

Current research suggests that relative sea-level rise is accelerating and projections with the highest certainty suggest that 1' of rise could occur sometime between 2025 and 2050. To determine where the 1' inundation scenario and other inundation scenarios up to 6', model outcomes from an inundation model produced by NOAA using high-resolution LiDAR elevation data acquired for the region were overlain with VBMP Road Centerline data using GIS software. The end result were the identification of specific road segments vulnerable to inundation under the various scenarios (**Figure 12 (Summary Table), Figures 13 through 18 (Regional Inundation Maps), Figures 19 through 24 (Town Inundation Maps).** These segments were then utilized by A-NPDC staff to assess how accessibility to selected communities and facilities may be impacted under the same inundation scenarios (**Figures 25 and 26 (Accessibility Summary Tables) and Figures 27 through 32 (Regional Accessibility Maps)**).

The results of these assessments indicate that the Eastern Shore of Virginia, including many communities and facilities and the transportation infrastructure that they depend upon, are vulnerable to potential inundation induced by relative sea-level rise and potentially increased severity of storm damage resulting from elevated sea level.

V. Recommendations

The following recommendations provided below are based on the assessments and findings presented in this report:

- It is recommended that the Eastern Shore Transportation Technical Advisory Committee (TTAC) consider relative sea-level rise and other potential coastal flooding impacts when selecting and prioritizing future transportation projects. These considerations should be incorporated into the Long Range Transportation Plan, the project prioritization process for the VDOT's Six-Year Improvement Program, and other TTAC activities as appropriate. Additionally, local governments and local operators of state and federal facilities should incorporate these considerations into emergency response, comprehensive planning activities, and economic development activities.
- It is recommended that the Eastern Shore TTAC and Climate Adaptation Working Group (CAWG) conduct education and outreach activities to inform those potentially impacted by near-term coastal flooding and long-term inundation of potential hazards and present options to properly mitigate potential damages.
- It is recommended that the assessment be updated regularly (every 5 or 10 years) to incorporate new data and information as it becomes available. Potential data and information could include, but is not limited to:
    - Updated relative sea-level rise projections as they become available;
    - Most recent LiDAR elevation data
        - This is currently being acquired for the Eastern Shore and would need to be incorporated into the NOAA inundation model and other inundation/storm surge models.
        - It would also be beneficial to conduct additional inundation analyses using scenarios at less than one foot incremental resolution;
    - Measurements of local relative sea-level rise from local permanent tide gauges;
    - Measurements of local land subsidence;
    - Information regarding how dynamic environments critical to buffering flooding impacts upon transportation infrastructure (i.e. barrier islands and tidal marshes)may evolve in response to relative sea-level rise;
    - Projections for how future storm surge, groundwater levels, precipitation patterns, and storm frequency and intensity may change over similar time scales as relative sea-level rise;
    - Updated Road Centerline data as it becomes available;
    - New digital transportation datasets to address current data gaps including VDOT right-of-way; and
    - New state and federal legislation regarding transportation policy.
- It is recommended that the VDOT, counties, towns, and state and federal facility operators conduct further studies to determine potential impacts on specific transportation infrastrure facilities, roadway drainage systems, buried utilities, signalization, and right-of-way considering projected relative sea-level rise and coastal flooding.

Appendix A

Table of Relative Sea-Level Rise Projections for the Eastern Shore of Virginia

Relative Sea-Level Rise Scenarios for VA Eastern Shore

Table of Relative SLR in feet above 1992 Level

Year	Highest	High	Low	Historic
1992	0	0	0	0
1994	0.02	0.02	0.02	0.02
1996	0.05	0.05	0.04	0.04
1998	0.08	0.08	0.07	0.06
2000	0.12	0.10	0.09	0.09
2002	0.16	0.14	0.12	0.11
2004	0.20	0.17	0.14	0.13
2006	0.25	0.21	0.17	0.15
2008	0.30	0.25	0.20	0.17
2010	0.36	0.29	0.22	0.19
2012	0.42	0.33	0.25	0.22
2014	0.49	0.38	0.28	0.24
2016	0.55	0.42	0.31	0.26
2018	0.63	0.47	0.34	0.28
2020	0.70	0.53	0.37	0.30
2022	0.79	0.58	0.40	0.32
2024	0.87	0.64	0.44	0.35
2026	0.96	0.70	0.47	0.37
2028	1.05	0.76	0.50	0.39
2030	1.15	0.82	0.54	0.41
2032	1.25	0.89	0.58	0.43
2034	1.36	0.96	0.61	0.45
2036	1.47	1.03	0.65	0.48
2038	1.58	1.10	0.69	0.50
2040	1.70	1.18	0.72	0.52
2042	1.82	1.26	0.76	0.54
2044	1.95	1.34	0.80	0.56
2046	2.08	1.42	0.84	0.58

Year	Highest	High	Low	Historic
2048	2.21	1.50	0.89	0.61
2050	2.35	1.59	0.93	0.63
2052	2.49	1.68	0.97	0.65
2054	2.64	1.77	1.01	0.67
2056	2.79	1.86	1.06	0.69
2058	2.94	1.96	1.10	0.71
2060	3.10	2.06	1.15	0.74
2062	3.27	2.16	1.19	0.76
2064	3.43	2.26	1.24	0.78
2066	3.60	2.37	1.29	0.80
2068	3.78	2.47	1.34	0.82
2070	3.96	2.58	1.39	0.84
2072	4.14	2.70	1.44	0.87
2074	4.33	2.81	1.49	0.89
2076	4.52	2.93	1.54	0.91
2078	4.72	3.04	1.59	0.93
2080	4.92	3.17	1.64	0.95
2082	5.12	3.29	1.69	0.97
2084	5.33	3.41	1.75	1.00
2086	5.54	3.54	1.80	1.02
2088	5.76	3.67	1.86	1.04
2090	5.98	3.81	1.91	1.06
2092	6.20	3.94	1.97	1.08
2094	6.43	4.08	2.03	1.10
2096	6.66	4.22	2.09	1.13
2098	6.90	4.36	2.15	1.15
2100	7.14	4.50	2.21	1.17

This table represents the underlying data used to create the sea-level rise scenario curves. These numbers are based on the 2014 National Climate Assessment sea-level rise curves adjusted for the annual local subsidence rate in Wachapreague, Virginia (1.6 mm/year). Please see citations above for more information.