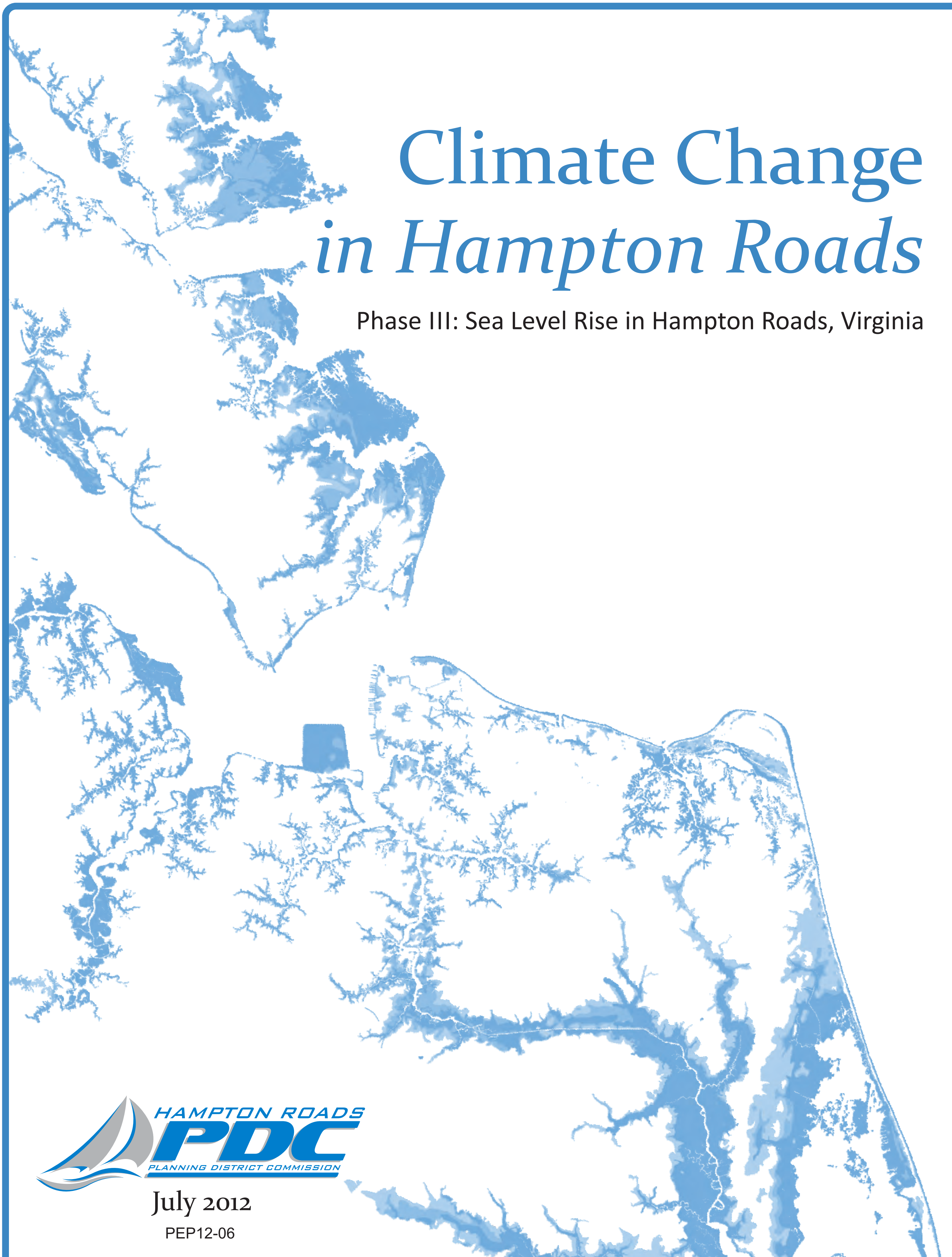
Climate Change *in Hampton Roads*

Phase III: Sea Level Rise in Hampton Roads, Virginia



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CLIMATE CHANGE IN HAMPTON ROADS
PHASE III: SEA LEVEL RISE IN HAMPTON ROADS, VIRGINIA

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The views expressed herein are those of the authors and do not necessarily reflect the views of the U.S Department of Commerce, NOAA or any of its subagencies.

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Prepared by the staff of the Hampton Roads Planning District Commission

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ABSTRACT
This report provides a summary of the third and final year of the Hampton Roads Planning District Commission's Climate Change Adaptation project. The report contains six major sections. The first section discusses historic and projected sea level rise in Hampton Roads. The second section describes the various datasets used in this analysis. The third section describes the methodology used for the analysis. The fourth section provides a brief summary of the results. The fifth section summarizes the project, provides some recommendations, and offers some next steps. The report also includes documentation of the project's public outreach and coordination efforts and a map book as appendices.

ACKNOWLEDGEMENTS
This report was funded, in part, by the Virginia Coastal Zone Management Program at the Virginia Department of Environmental Quality through Grant #NA09NOS4190163 from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, under the Coastal Zone Management Act of 1972, as amended. The views expressed herein are those of the authors and do not necessarily reflect the views of the U.S. Department of Commerce, NOAA, or any of its sub-agencies.

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Virginia Coastal Zone
MANAGEMENT PROGRAM

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

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Executive Summary

Since 2008, the Hampton Roads Planning District Commission (HRPDC) has been engaged in a three-year focal area grant project, partially funded by the Virginia Coastal Zone Management Program (VCZMP), on Climate Change Adaptation. This report summarizes the work for the third and final year of that project. The first year focused on researching the types of impacts that the Hampton Roads region could potentially experience from climate change and on engaging and educating local government staffs about those impacts. The focus during the second year was on analyzing the impacts of storm surge flooding on various sectors, such as the built environment and economy, and on engaging the public. This final year has focused on analyzing the potential future impacts of sea level rise on the region's population, built environment, infrastructure, economy, and natural environment. This was done through the use of geographic information systems (GIS) analysis, which had two primary goals: first, to develop a GIS tool to model the impacts of sea level rise, and second, to demonstrate the use of this tool for Hampton Roads.

The geographic analysis presented in this report attempts to identify which areas in Hampton Roads are potentially vulnerable to sea level rise and to estimate the region's exposure and vulnerability to sea level rise, using datasets that represent the region's elevation and topography, population, housing, private property, businesses, and natural resources. The analysis is based on a one-meter local sea level rise scenario. This scenario was chosen based on the quality of the available elevation data; one meter of global sea level rise is also considered to be possible by the end of the 21st century according to current research. Since Hampton Roads is experiencing sea level rise at a rate greater than the current global average, a one-meter scenario of local sea level rise by 2100 is both plausible and defensible for this analysis. Although planning for that far into the future is not common for many localities, the planning decisions made today may have consequences significantly longer than the typical twenty, thirty, or forty-year planning horizon. Since a regionally consistent LIDAR dataset was not available, the analysis uses an elevation dataset developed by the U.S. Environmental Protection Agency that measure elevation of dry land relative to spring high tide. This makes the dataset useful for measuring potential impacts to the built environment. However, the quality of the elevation data is not as high as LIDAR; for this reason the analysis is based on a scenario of one meter of sea level rise. It includes low, medium, and high estimates that explicitly take into account the uncertainty in the elevation data. This may in some cases overestimate the actual exposure of individual localities and the region. However, since the elevation data is referenced to spring high tide, it is almost certain that the exposure estimates will be higher than an analysis using data referenced to mean sea level. As such, any comparisons between analyses should be done with care. It is also important to note that the maps produced in the analysis do not show areas that would only be permanently inundated, but also areas that would be occasionally or regularly subjected to tidal flooding.

The results indicate that Hampton Roads has many assets that are vulnerable to future sea level rise. Several localities, including Chesapeake, Gloucester County, Hampton, Norfolk, Poquoson, Portsmouth, Virginia Beach, and York County, appear to be particularly vulnerable. However, for several reasons, the results should be treated as general estimates resulting from potential sea level rise. The maps and calculations result from projections based on the analysis assumptions and should not be viewed as predictions of future conditions. Principally among these is that the analysis was based solely on elevation and did not attempt to incorporate either flood protection or shoreline stabilization infrastructure. As such, the results should be interpreted as baseline estimates of potential impacts should no adaptation occur. Given that Hampton Roads has experienced a significant long-term sea level rise trend in the recent past, it is likely that some sea level rise will occur locally in the future. Since some development has already occurred and continues to occur in vulnerable areas, localities should begin planning now for sea level rise. Possible measures that localities can take include modifying comprehensive and other long-range plans and incorporating future sea level conditions into the planning, design, and construction of projects in vulnerable areas. Which adaptation strategies are most appropriate will depend on both the resources available to localities and the amount and character of existing developments. Sea level rise also poses challenges for the implementation of regulatory programs and laws, such as the Chesapeake Bay Preservation Act and its associated regulations, wetlands protection, floodplain management, and hazard mitigation efforts. These programs provide potential opportunities for localities to adapt to sea level rise within the existing regulatory framework.

Based on the work conducted during this three-year grant project, including analysis, research, and discussions with locality staffs and other stakeholders, HRPDC staff has developed the following findings and recommendations.

Table 1: Findings and Recommendations

FINDINGS	RECOMMENDATIONS
Hampton Roads does not yet have the necessary regionally consistent elevation data to accurately assess sea level rise impacts.	HRPDC should continue to work to acquire the necessary data.
Sea level rise will be a major issue for several Hampton Roads localities.	Localities should begin planning for sea level rise through their comprehensive plans and other plans and policies, including working with other stakeholders in the region, such as educational institutions and major government landowners and agencies.
There is not yet official state or federal regulatory guidance for addressing sea level rise.	Hampton Roads should work with state and federal elected officials and staff to develop and fund guidance and assistance to affected communities.
The U.S. Army Corps of Engineers has developed guidance for incorporating sea level rise into infrastructure projects.	Localities and other should consider using this guidance for project planning and design.
Subsidence and its impacts on local sea level rise rates are not well-documented.	The region should continue to study the causes and rates of subsidence in Hampton Roads and their impacts on relative sea level rise.
Effective adaptation strategies will vary based on context, feasibility, and popular support.	The region should continue studying potential strategies for adapting to sea level rise and other climate change impacts.

Acknowledgements:

As part of the review process for this report, comments were solicited from Hampton Roads local governments through the regional Stormwater Management and Chesapeake Bay Committees, as well as several academic and non-government organizations. Comments were received from the Cities of Hampton, Poquoson, and Virginia Beach, as well as representatives from Old Dominion University and the Virginia Institute of Marine Science. These comments were incorporated into the report and analysis to the best extent possible. The Hampton Roads Planning District Commission thanks all those who took the time to review and comment on the report.

INTRODUCTION

Since 2008, the staff of the Hampton Roads Planning District Commission has been working on a three-year Sustainable Coastal Communities Focal Area Grant, partially funded by the Virginia Coastal Zone Management Program (VCZMP), focused on Climate Change Adaptation. The first year of the HRPDC's Climate Change Adaptation project focused on identifying the broad impacts of climate change on the Hampton Roads region and engaging local governments in identifying vulnerabilities and adaptation options. Through that process as well as cooperative efforts with other researchers and stakeholders, sea level rise and storm surge flooding were identified as two of the region's most pressing concerns related to climate change. The second year of the grant followed up on the first year's findings, focusing on quantitatively analyzing the region's current vulnerability to storm surge flooding. During the second phase of the project HRPDC staff used geographic information systems (GIS) to analyze the impacts of storm surge flooding on the region's population, businesses, roadways, and critical infrastructure. This analysis provided quantitative support for anecdotal evidence that the Hampton Roads region is already significantly vulnerable to flooding during storm events. More specifically, the analysis found that Chesapeake, Hampton, Norfolk, Poquoson, Portsmouth, and Virginia Beach were particularly vulnerable to storm flooding. This third phase focuses explicitly on vulnerability to sea level rise, in terms of potential impacts to the region's population, property, infrastructure, economy, and natural resources.

While understanding and analyzing current vulnerabilities to storm surge flooding is important for a variety of reasons, such as protecting lives and property, understanding how sea level rise could affect the region in the future is particularly important. Localities need to make informed decisions about the location and character of private development and infrastructure construction. Sea level rise will affect existing development, but it may also affect development that has not yet taken place if potential future conditions are not taken into account. Without planning for sea level rise, localities may encourage development in areas that will be increasingly vulnerable to flooding or inundation, which will inflict costs on both residents and local governments. Currently, many local governments have planned for the continued development of areas that are vulnerable to sea level rise (Titus, et al. 2009). Developing these lands will not only increase the vulnerability of the built environment to sea level rise; it will also negatively affect the natural environment as it attempts to adapt to rising waters.

This report documents efforts to improve upon the GIS tool developed for the storm surge analysis to analyze the potential impacts of sea level rise on the Hampton Roads region. Assessing the vulnerability of existing development to future conditions is an intermediate step to future work, which will analyze the exposure and vulnerability of future development to sea level rise. Quantifying this vulnerability will help decision makers to adapt their localities to the challenges of climate change. Each step in the development of this tool serves a specific purpose:

- Quantifying storm surge vulnerability and potential impacts can help with the development of appropriate hazard mitigation plans and policies.
- Analyzing the potential impacts of sea level rise on existing development can help decision-makers select cost-effective adaptation responses
- Analyzing projected development patterns for their susceptibility to climate change impacts can help decision-makers decide whether or not to modify long-range development plans.
- Knowing how fast sea levels will rise can help decision-makers with the prioritization of adaptation plans or projects.

This report consists of six substantive sections. The first part describes historic sea level rise in Hampton Roads. It also describes a methodology that can be used to project future sea level rise.. The second part describes the datasets used in the sea level rise analysis. The third part describes the methodology used for the analysis. The fourth part describes the results of the analysis and includes summaries of those results in tables and maps. The fifth and final section summarizes the work of the focal area grant project, includes some recommendations for local governments and others that might be affected by sea level rise, and identifies some additional steps that will be taken to further the region's planning for climate change. The report includes three appendices. The first two document the project's public outreach and coordination measures. The third appendix provides links to related efforts funded by the Virginia Coastal Zone Management Program. The fourth appendix is a map book of the areas in the region identified as potentially vulnerable to sea level rise.

Section I: Sea Level Rise – Past, Present, and Future

While long-term sea level trends are a useful starting point in addressing the future consequences of sea level rise, climate change science indicates that sea level will rise at faster rates than were seen in the 20th century. Understanding how much sea level rise can be expected over a given length of time and how fast that rise will occur is a critical part of making sound planning and infrastructure decisions in coastal areas. Projecting future sea level rise requires an understanding of its drivers, how they might change, and what conditions could cause those drivers to change.

As described in the previous Phase I and Phase II HRPDC reports, sea level rise at the global level occurs as ice melts from glaciers and ice sheets and as oceans warm up. Climate change science indicates that both atmospheric and ocean temperatures are warming, which will cause the oceans to experience thermal expansion (U.S. Global Change Research Program 2009). Higher atmospheric temperatures will cause more ice to melt, which will add additional water to the world's oceans. At the local level, global average sea level rise is affected by ocean current and temperature variations as well as the vertical movement of land, which can be either uplift (land rising) or subsidence (land sinking). Subsidence is of greater concern when addressing sea level rise. Subsidence can be caused by several factors; in Hampton Roads, the main contributors to subsidence are glacial isostasy (the rebound of land once covered by glaciers), faulting and consolidation of sediments in the Chesapeake Bay Impact Crater, and sediment compaction caused by groundwater withdrawals (Boon, Brubaker and Forrest 2010). While the precise influences of these separate factors is unknown, scientists from the Virginia Institute of Marine Science have estimated that subsidence accounts for approximately one-half to two-thirds of the sea level rise experienced in the Hampton Roads region (Boon, Brubaker and Forrest 2010). While climate science projects global sea level rise rates to increase as temperatures increase, at this time it is more difficult to project how and if regional subsidence rates will change. Part of this difficulty stems from the various causes of subsidence and their relative contributions to how much total subsidence affects Hampton Road. For example, subsidence due to long-term geologic phenomena such as glacial isostasy would not be expected to stop in the near future, while subsidence caused by groundwater withdrawals may actually be halted, slowed, or reversed. Different causes of subsidence will thus require different policy responses.

The long-term sea level trends observed in Hampton Roads provide sufficient information to begin planning for sea level rise. As described in the Phase II HRPDC report, long-term sea level trend data for this region is available for five different sites, though only four have long enough records to establish a confident rate of sea level rise, and only two of those sites remain active (McFarlane, Climate Change in Hampton Roads Phase II: Storm Surge Vulnerability and Public Outreach 2011). The five long-term data trends are available for the Chesapeake-Bay Bridge-Tunnel (CBBT), Gloucester Point, Kiptopeke, Portsmouth, and Sewell's Point (see Map 1). The CBBT water level station has only been active since 1975 (approx. 37 years); about 40 years (or two tidal epochs) of data are needed to establish confidence in its sea level trend (U.S. Army Corps of Engineers 2011). Both the Gloucester Point and Portsmouth water level stations have been deactivated, though both have been replaced by new stations nearby at USCG Training Center Yorktown and Money Point, respectively. The Sewell's Point station provides the longest record (approx. 85 years); the rate observed at this station is approximately 4.44 mm/year (0.175 in/year). The available long-term trends are shown in figures in this section; more information is available from NOAA's Tides & Currents Website (National Oceanic and Atmospheric Administration 2011).[1]

These long-term sea level trends can be combined with global sea level rise projections based on climate science to establish possible sea level rise scenarios for the Hampton Roads region. Global average sea level rise projections currently range from less than half a meter to about two meters by the end of the 21st century (approximately 1.5 to 6 feet). Fletcher summarized the state of the science in 2009, identifying papers estimating various amounts of sea level rise: 0.18 to 0.59m of sea level rise by 2099 (Intergovernmental Panel on Climate Change (IPCC) 2007); 0.5 to 1.4m between 1990 and 2100 (Rahmstorf 2007); and 0.8 to 2.0m by 2100 (Pfeffer, Harper and O'Neel 2008). Based on this assessment, he states that one meter of global average sea level rise "constitutes an appropriate planning target at this time" (Fletcher 2009). This change will not occur linearly; estimating the amount of sea level rise to be expected within a certain timeframe requires modeling how the rate will change in order to meet an estimated end point. To address this need, in October 2011, the U.S. Army Corps of Engineers (USACE) issued Engineer Circular 1165-2-212, which provides guidance "for incorporating the direct and indirect physical effects of projected future sea-level change" on USACE civil works activities and projects (U.S. Army Corps of Engineers 2011). This circular accomplishes two goals: it mandates that USACE projects incorporate sea level rise into the planning, design, and maintenance of USACE projects, and it provides a methodology

[1] www.tidesandcurrents.noaa.gov

and identifies appropriate reference material to support this methodology. The circular uses a scenario approach to planning for sea level rise, establishing low, medium, and high scenarios; the historic rate is used as the low scenario. The other two scenarios descended from two scenarios developed by the National Research Council (NRC), which have been modified to account for more recent findings regarding the rates of sea level rise and projections of future sea level rise. The circular states that a "credible upper-bound" of global average sea level rise by 2100 is two meters, based on an assessment of the minimum and maximum estimates from eight separate papers or reports published between 1987 and 2010 (U.S. Army Corps of Engineers 2011). The USACE tool incorporates estimates of local subsidence, which allows for projections of future sea level rise at most NOAA tide stations in the United States.

Map 1: NOAA Water Level Stations in Hampton Roads

(Data source: NOAA)

The 1987 NRC report included an equation to calculate future sea level rise based on three sea level rise scenarios (0.5, 1.0, and 1.5 meters by 2100) (National Research Council 1987):

$$E(t) = 0.0012t + bt^2$$

$E(t)$ is the amount of eustatic (global) sea level rise as a function of t

0.0012 is the historic rate of global average sea level rise

t is time measured in years

b is a constant (derived for each scenario)

The equation combines the historic sea level rise rate with a rising rate of future sea level rise to calculate the sea level rise at any point after 1986. The USACE guidance updates the formula developed by NRC based on the current estimate of global average sea level rise (1.7mm/year) to calculate new sea level rise curves; it also changes the base date from 1986 to 1992. The new equation is:

$$E(t) = 0.0017t + bt^2$$

A second equation is provided that allows for comparing sea level rise between any two years instead of the base year of 1992:

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2)$$

t_2 is the planning horizon

t_1 is the beginning of the plan or project in years after 1992

The circular also includes a flowchart and step-by-step directions on whether and how to account for sea level rise in projects. The USACE has provided a website and Excel spreadsheet which can be used to model future sea level rise at any NOAA water level station with the necessary length of sea level trend data (U.S. Army Corps of Engineers 2012). These tools combine global sea level rise with local and regional sea level trends to project sea level rise at specific locations for three scenarios: a low scenario based on the current rate of sea level rise, and intermediate and high scenarios developed by modifying two of the original NRC scenarios. The NRC scenarios were modified to account for more recent research and observations. The charts produced using these tools for each of the five water level stations in Hampton Roads are included below (see Figures 1 – 10), along with the historic sea level trend charts from NOAA's Tides & Currents service. The low scenario projects sea level rise between 0.32 and 0.45 meters between 2010 and 2100 in Hampton Roads (see Table 1). The medium scenario projects sea level rise between 0.63 and 0.76 meters, and the high scenario projects between 1.61 and 1.74 meters. These projections are summarized in the following chart. Please note that the NOAA charts below show historic data (for example, the chart for the Sewell's Point station shows sea level trends from 1927 to 2006), while the USACE charts show projections of future sea level rise from 1992 to 2100.

Table 2: Projected Sea Level Rise at Hampton Roads Water Level Stations, 2010 – 2100 (meters)

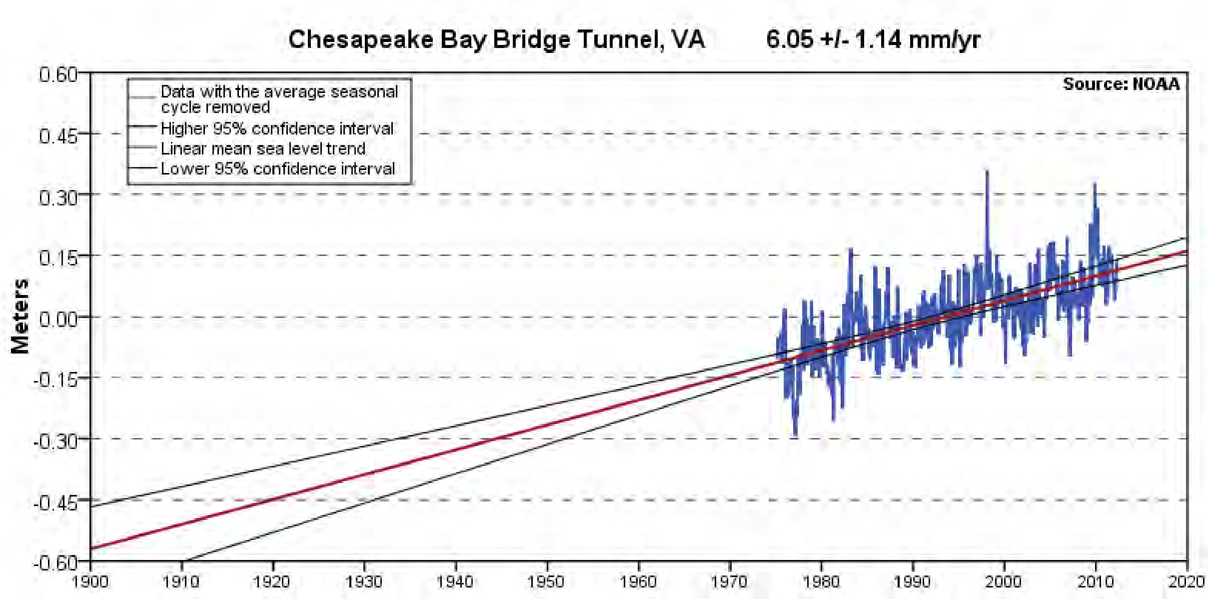
STATION	LOW SCENARIO	MEDIUM SCENARIO	HIGH SCENARIO
Chesapeake Bay Bridge-Tunnel	0.45	0.76	1.74
Gloucester Point	0.37	0.68	1.65
Kiptopeke	0.32	0.63	1.61
Portsmouth	0.34	0.65	1.62
Sewell's Point	0.39	0.70	1.67

Table 3: Projected Sea Level Rise at Hampton Roads Water Level Stations, 2010 – 2100 (feet)

STATION	LOW SCENARIO	MEDIUM SCENARIO	HIGH SCENARIO
Chesapeake Bay Bridge-Tunnel	1.49	2.50	5.69
Gloucester Point	1.22	2.22	5.42
Kiptopeke	1.06	2.07	5.27
Portsmouth	1.11	2.12	5.31
Sewell's Point	1.27	2.28	5.48

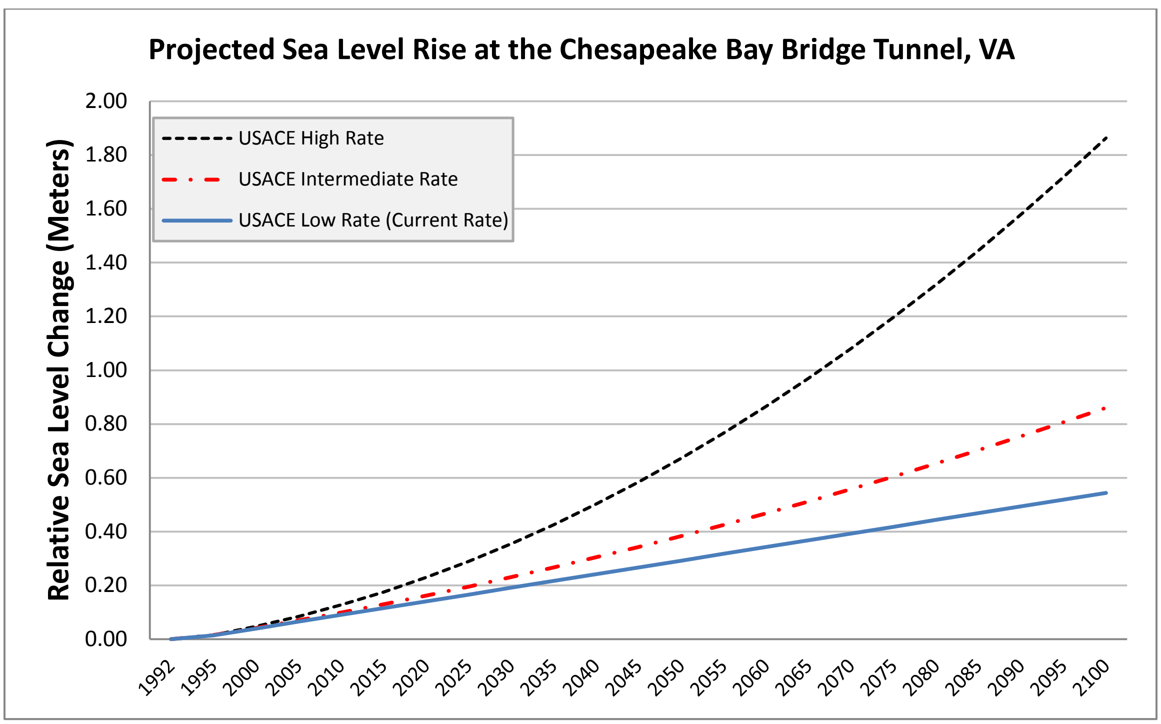
This tool provides two primary benefits to Hampton Roads localities. First, it provides a practical method for incorporating sea level rise into project planning by calculating the potential sea level conditions a project may experience over its design life. Second, the tool is easily adaptable to use in multiple scenarios. The tool can be easily updated to account for newer information as climate science progresses and newer assessments are made concerning future sea level rise. Hampton Roads localities and property owners can use this tool to begin planning for sea level rise in terms of project design as well as identifying locations that may be more vulnerable to flooding in the future.

Figure 1: Mean Sea Level Trend, Chesapeake Bay Bridge-Tunnel Station (1975 – 2006)



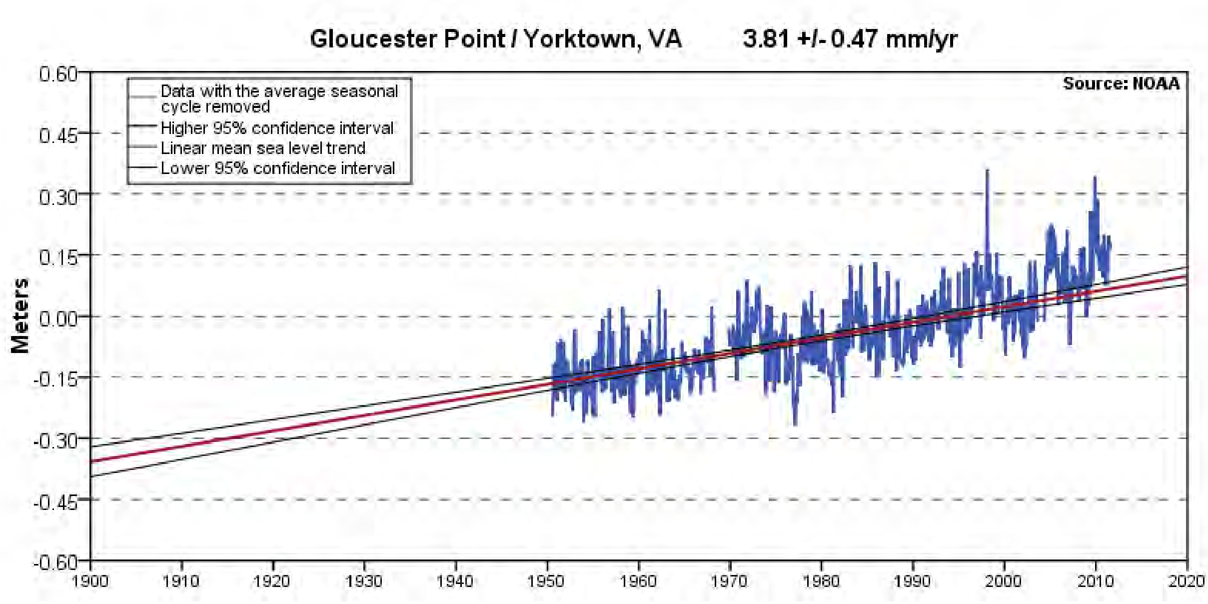
The long-term mean sea level trend at the Chesapeake Bay Bridge-Tunnel tide gauge from 1975 to 2006 was 6.05 ± 1.14 mm/yr. The observed rate equals a rate of 1.98 feet over 100 years (National Oceanic and Atmospheric Administration 2011).

Figure 2: Projected Sea Level Rise, Chesapeake Bay Bridge-Tunnel Station Station (1992 – 2100)



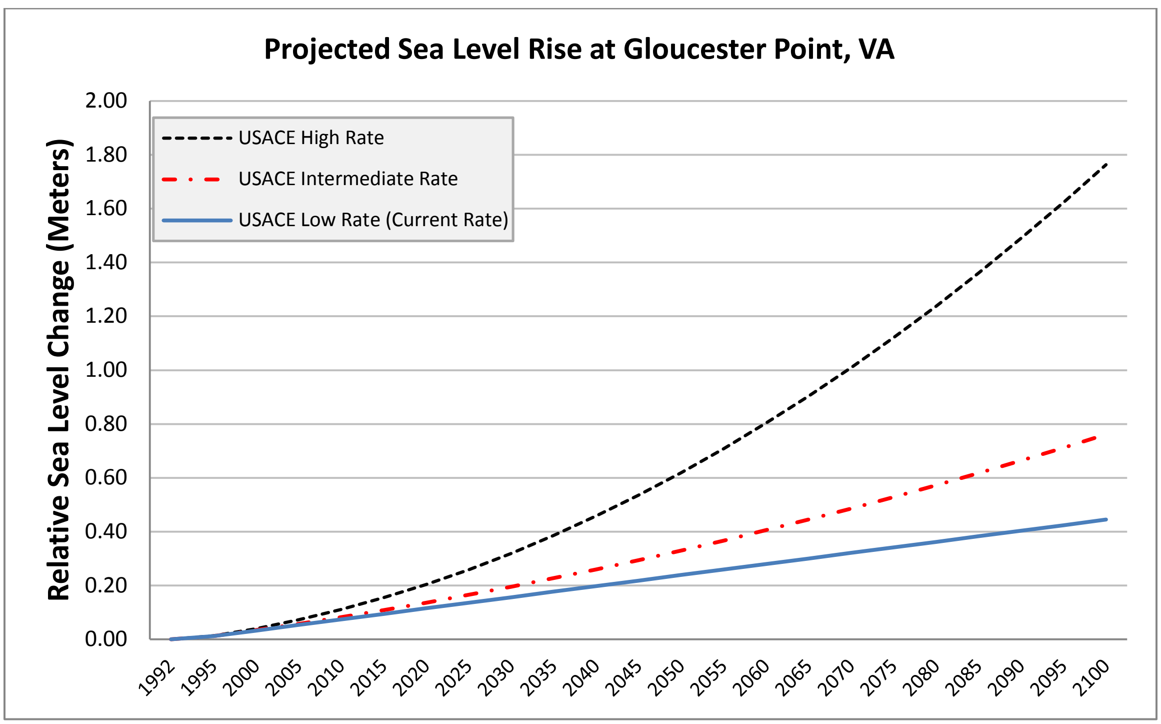
The USACE Sea Level Change Calculator projects long-term sea level rise at the Chesapeake Bay Bridge-Tunnel to be between 0.54 and 1.86 meters (1.79 – 6.11 feet) between 1992 and 2100. The solid line represents a continuation of the trend in the upper figure (U.S. Army Corps of Engineers 2012).

Figure 3: Mean Sea Level Trend, Gloucester Point/Yorktown Station (1950– 2003)



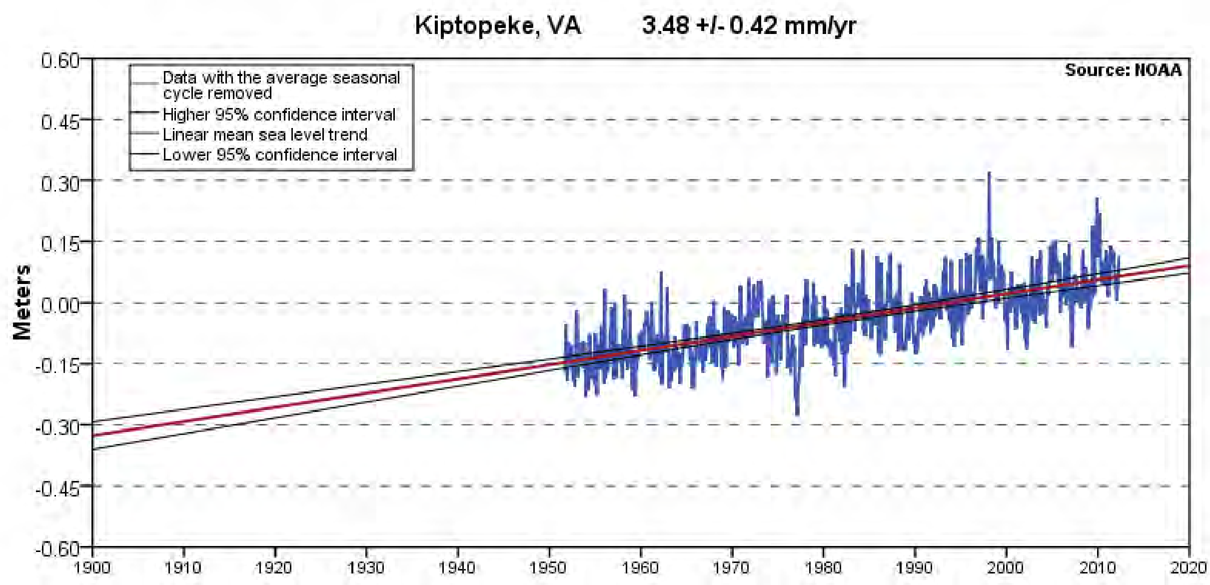
The long-term mean sea level trend at the Gloucester Point/Yorktown tide gauge from 1950 to 2003 was 3.81 ± 0.47 mm/yr. The observed rate equals a rate of 1.25 feet over 100 years (National Oceanic and Atmospheric Administration 2011).

Figure 4: Projected Sea Level Rise, Gloucester Point Station (1992 – 2100)



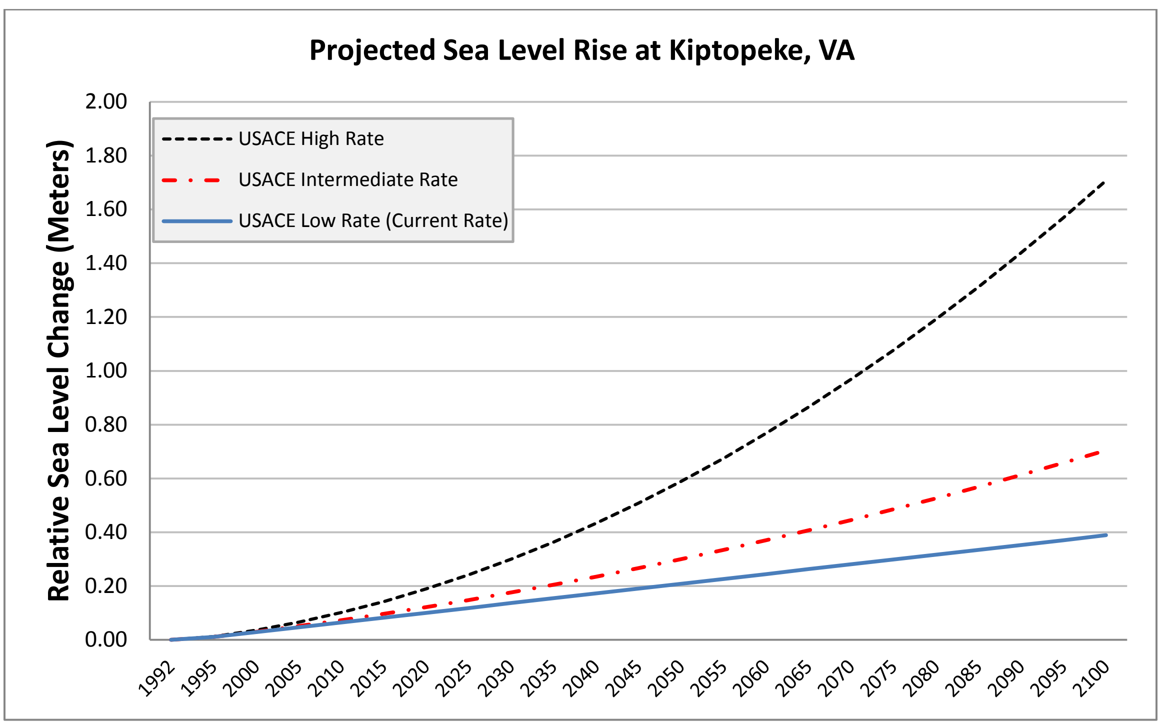
The USACE Sea Level Change Calculator projects long-term sea level rise at Gloucester Point to be between 0.44 and 1.76 meters (1.46 – 5.78 feet) between 1992 and 2100. The solid line represents a continuation of the trend in the upper figure (U.S. Army Corps of Engineers 2012).

Figure 5: Mean Sea Level Trend, Kiptopeke Station (1951 – 2006)



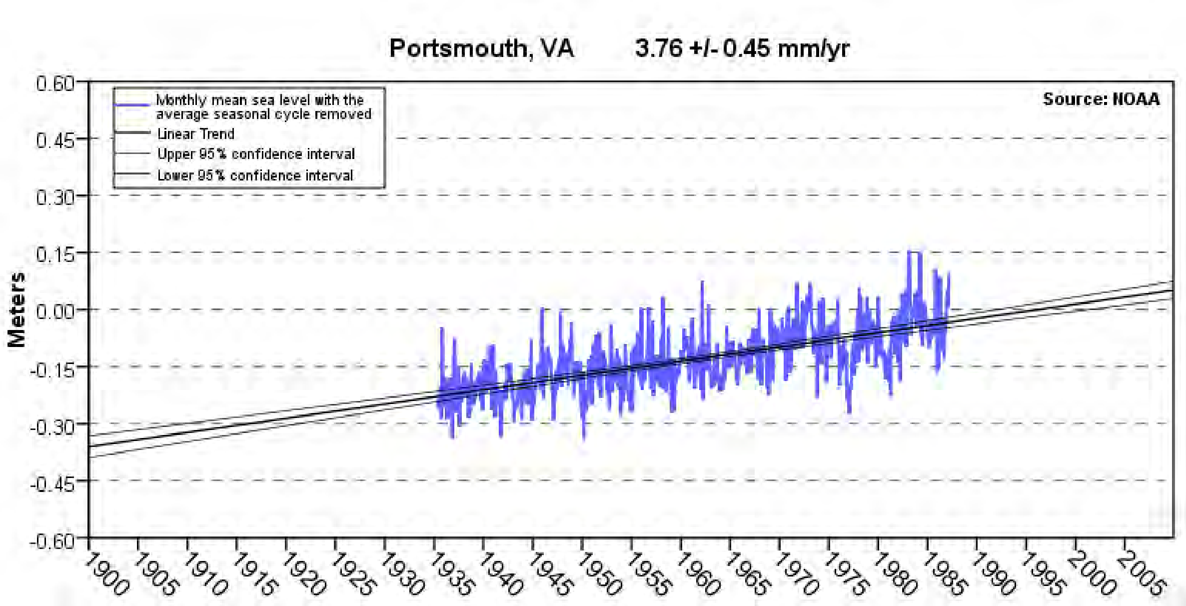
The long-term mean sea level trend at the Kiptopeke tide gauge from 1951 to 2006 was 3.48 ± 0.42 mm/yr. The observed rate equals a rate of 1.14 feet over 100 years (National Oceanic and Atmospheric Administration 2011).

Figure 6: Projected Sea Level Rise, Kiptopeke Station (1992 – 2100)



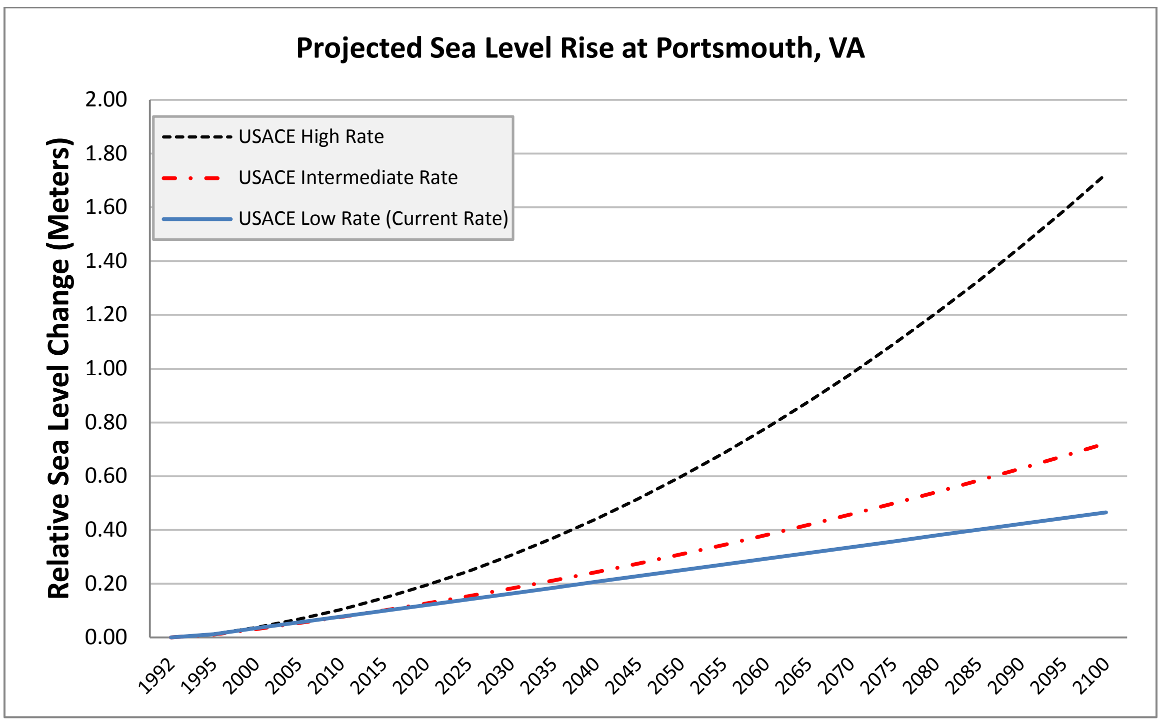
The USACE Sea Level Change Calculator projects long-term sea level rise at Kiptopeke to be between 0.39 and 1.71 meters (1.28 – 5.60 feet) between 1992 and 2100. The solid line represents a continuation of the trend in the upper figure (U.S. Army Corps of Engineers 2012).

Figure 7: Mean Sea Level Trend, Portsmouth Station (1935 – 1987)



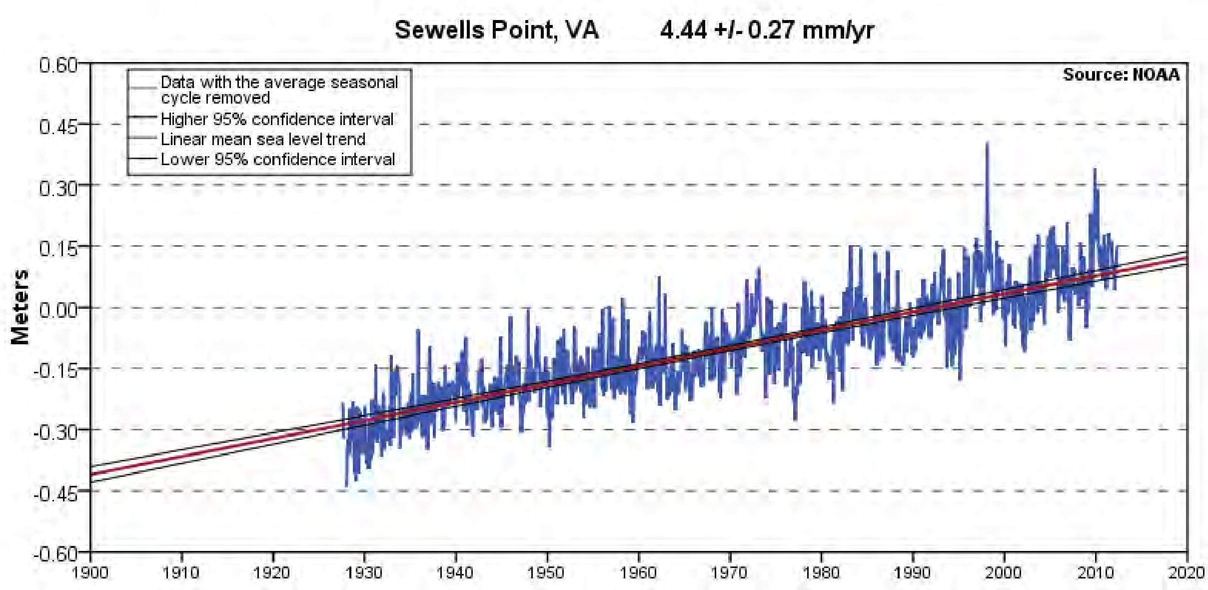
The long-term mean sea level trend at the Portsmouth tide gauge from 1935 to 1987 was 3.76 ± 0.45 mm/yr. The observed rate equals a rate of 1.23 feet over 100 years (National Oceanic and Atmospheric Administration 2011).

Figure 8: Projected Sea Level Rise, Portsmouth Station (1992 – 2100)



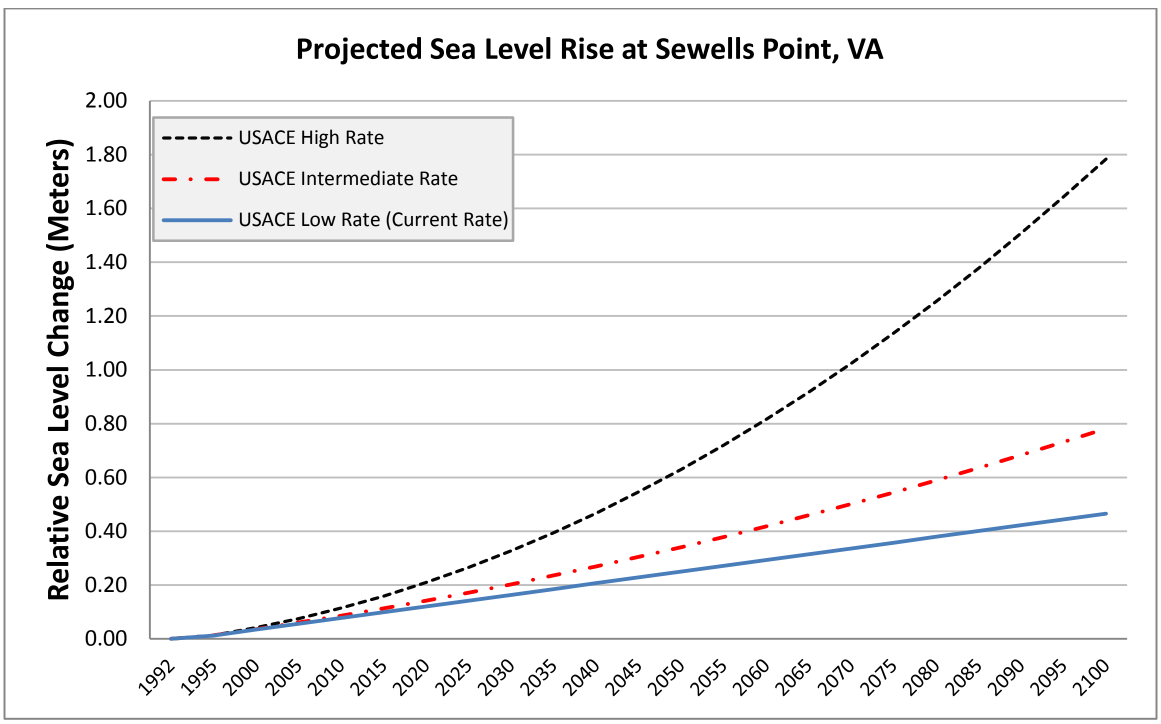
The USACE Sea Level Change Calculator projects long-term sea level rise at Portsmouth to be between 0.41 and 1.72 meters (1.33 – 5.66 feet) between 1992 and 2100. The solid line represents a continuation of the trend in the upper figure (U.S. Army Corps of Engineers 2012).

Figure 9: Mean Sea Level Trend, Sewell's Point Station (1927 – 2006)



The long-term mean sea level trend at the Sewell's Point tide gauge from 1927 to 2006 was 4.44 ± 0.27 mm/yr. The observed rate equals a rate of 1.46 feet over 100 years (National Oceanic and Atmospheric Administration 2011).

Figure 10: Projected Sea Level Rise, Sewell's Point Station (1992 – 2100)



The USACE Sea Level Change Calculator projects long-term sea level rise at Sewell's Point to be between 0.44 and 1.76 meters (1.46 – 5.78 feet) between 1992 and 2100. The solid line represents a continuation of the trend in the upper figure (U.S. Army Corps of Engineers 2012).

SECTION II: ANALYSIS DATA

The data used in this vulnerability analysis came from multiple sources and was modified and analyzed using geographic information systems (GIS). The goal of this analysis, to estimate the vulnerability of the Hampton Roads region to sea level rise, required identifying areas throughout the region that are low lying, and then assessing what assets, resources, and population existed within those zones. The goal of this vulnerability analysis was to estimate the amount of residents, employees, businesses, roads, property, and natural resources in areas that are vulnerable to sea level rise.

ORIGINAL DATA SOURCES

Six data categories were identified for this study: general information, built environment, infrastructure, economy, natural environment, and elevation. For each category, HRPDC staff identified relevant datasets and sources, obtained data, and processed that data into a form that would be useful for both current and future projects. The elevation data provided the base for analyzing the other datasets for exposure to sea level rise. Many of the datasets used in this sea level rise exposure analysis are the same as or similar to those used for the Phase II storm surge exposure analysis (McFarlane and Walberg, Climate Change in Hampton Roads: Impacts and Stakeholder Involvement 2010). Descriptions of the various data used in this analysis are given below.

General Information

The general information needed for this analysis provides a rough summary of the exposure of any given area in the region to sea level rise in terms of current population and housing stock as well as the area affected. Areas affected were determined using locality boundary files developed by HRPDC that reflect coastlines; using these boundaries provides for consistent comparisons with other regional studies since they are used for many different HRPDC and local projects. Estimates for population and housing units in vulnerable areas were developed using block-level data from the 2010 U.S. Census, using the data for total population and housing units.[2] Census data is assigned

[2] The 2010 U.S. Census population figures for the City of Norfolk were adjusted to correct an error. This adjustment was discussed in detail in the Phase II report, which also included documentation of the change from the U.S. Census Bureau.

to geographic areas, so populations are represented as groups living within a given area and not as individuals living at specific points (see Map 2).

Built Environment

To represent the built environment, HRPDC staff acquired property data from each Hampton Roads locality, including parcel boundaries and assessments for improvement values, and total values. Parcel boundaries allow for the analysis to estimate the number of properties and property owners potentially affected by sea level rise, while improvement values represent the amount of investments in buildings and other non-land improvements in those properties, which allows the analysis to estimate how much immovable property is exposed (see Map 3).

Infrastructure

Whereas property data provides an indication of private investment, infrastructure data represents public investments. Data showing the location and type of roadways in Virginia is readily available from the Virginia Geographic Information Network (VGIN). The Road Centerline database includes information such as location (both geographic and as segment descriptions), road names, route numbers, and classification. The dataset is a "seamless digital road centerline file", jointly maintained by VGIN and localities (Virginia Geographic Information Network 2007). This analysis required some of the same data as the previously conducted storm surge vulnerability analysis: location, length, and classification. Classifications (interstate, primary, secondary, and local or private) were based off the shield classification values included in the original dataset.[3] This change was made from the previous year because not all road segments were assigned a display classification, while all segments were assigned a shield classification (see Map 4).

Economy

Two datasets were used to assess economic impacts. The first was the business dataset developed for the previous storm surge analysis. This dataset included locations, types, and numbers of employees, and was obtained using Esri's Business Analyst extension for the ArcGIS software suite (Esri 2011). Each business is included in the dataset as a specific geographic location using longitude and latitude coordinates. Along with its location, the data includes such characteristics as the business name, address, and classification, using both the Standard Industrial Classification

[3] Classifications were based on shield classification: interstate (100), primary (200 – 299), secondary (300), and local or private (0 or <Null>).

(SIC) and North American Industry Classification System (NAICS). For this analysis, the important information for each business was its location and number of employees (see Map 5).

The second dataset used to assess economic impacts came from the local property datasets. To represent economic impacts, the total value of each parcel was used to represent the total financial assets exposed (in many vulnerable areas, land values are higher than improvement values, since waterfront property is highly desirable). While improvement values indicate how much has been built at a given location, total value indicate how much that whole property is truly worth to the owner, banks and insurance companies, and the market (see Map 3).

Natural Environment

Two datasets were acquired to represent natural resources in the Hampton Roads region. The first was a dataset of lands protected from development, such as parks and conservation easements. This dataset is intended to represent areas that have already been identified as important enough to protect that they have been either already acquired for preservation or recreation or have had development restrictions placed upon them. This dataset was initially developed as part of the Hampton Roads Green Infrastructure Plan and included, in addition to easements and parks, properties owned by the U.S. Department of Defense (Walberg, Kidd and McFarlane 2010). While those lands are currently protected from private development, there was no way to differentiate between operational and undeveloped areas. For this reason, properties owned by the Department of Defense or any branches of the military were excluded from this analysis (see Map 6).

In addition to the protected lands dataset, HRPDC staff took advantage of other work funded by the Virginia Coastal Zone Management Program in the form of the Coastal Virginia Ecological Value Assessment (VEVA), which combines datasets from several state agencies, including the Departments of Conservation and Recreation (DCR), Game and Inland Fisheries (DGIF), and Environmental Quality (DEQ) as well as the Virginia Commonwealth University Center for Environmental Studies (CES) and the Virginia Institute of Marine Science Center for Coastal Resources Management (CCRM).[4] Combining these datasets into a single dataset allows for a systematic ranking of all terrestrial and aquatic areas in Virginia's Coastal Zone for their ecological value. One aim of this dataset was to help planners and decision makers identify areas that would

[4] The individual datasets incorporated into VEVA included: Priority Wildlife Conservation Areas (DGIF), Natural Heritage Conservation Sites (DCR), Natural Lands Network (DCR), Aquatic Resource Integrity (CES), Aquatic Priority Conservation Areas (CCRM), and Virginia's Healthy Waters (DEQ).

be ideal for preserving from development; to this end, areas are ranked on a scale from General (1) to Outstanding (5). For this particular analysis, the VEVA data represents areas of high ecological value in the region, regardless of whether or not they are protected; areas ranked as having high, very high, and outstanding ecological value were included (see Map 7).

Elevation

Elevation data is a key part of any study of vulnerability to flooding and sea level rise. For a regional analysis such as Hampton Roads, an ideal elevation dataset would be regionally consistent and available for the entire extent of the study, accurate, and spatially precise. In addition, the data must be processed in such a way as to make comparisons between current and future (potential) conditions possible. For example, the National Elevation Dataset[5] (NED) is referenced to the North American Vertical Datum of 1988 (NAVD 88). It does not correspond to local tidal conditions, which are measured using unique tidal datums for each tide station. For this reason, it is more useful to measure sea level rise relative to tidal conditions, such as mean sea level or mean high water, instead of an arbitrary zero elevation point. Most local elevation datasets in Hampton Roads are benchmarked to mean sea level, while regional datasets are benchmarked to NAVD 88, as with the NED. While many Hampton Roads localities possess high resolution LIDAR data, these datasets were collected at different times, have different resolutions, and are set to different vertical datums.[6] At this time HRPDC has been unable to locate or create a seamless regional LIDAR dataset, though staff is working with local, state, and federal government partners to do so. HRPDC expects all localities in Hampton Roads to have LIDAR data of some sort by 2015, and will continue to work to acquire and integrate data for all sixteen localities.

Given that consistent LIDAR data for the entire region does not exist, HRPDC staff elected to use a dataset developed by the U.S. Environmental Protection Agency that modified the National Elevation Dataset to reflect tidal conditions (Titus and Wang, Maps of Lands Close to Sea Level along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR 2008). This dataset, appropriately titled "An Elevation Dataset to Use While Waiting for LIDAR" (see Map 8), is benchmarked to spring high tide (high tides occurring during full and new

[5] http://ned.usgs.gov/

[6] HRPDC staff was able to acquire LIDAR data or LIDAR-derived data from several sources for all localities except for Southampton County and Franklin. However, the datasets obtained for Newport News, Norfolk, Portsmouth, and York County had significant missing areas, and not all datasets had the same horizontal and vertical resolutions and reference systems. LIDAR data for Franklin and Southampton County is expected to be available through FEMA or another agency in the near future.

moons) to establish the elevation of dry land (land that is never inundated by tides). A dataset containing tidal wetlands was also completed as part of this study and was incorporated into this analysis. This dataset was specifically developed to analyze lands vulnerable to sea level rise. This dataset has both advantages and disadvantages. Its advantages include consistency and availability for the entire region, prior assessment of its accuracy, and a readily understandable vertical reference point – if elevation is greater than zero, that land is not inundated by tides (it should be dry all year except during storms or anomalous events). This dataset does not include tidal wetlands as dry lands because wetlands are both subject to greater regulation than dry lands and are not suitable for many forms of development. The disadvantages of this dataset include its relative imprecision (30-meter pixels) and uncertainty (the root mean square error is either 76.2 or 152.4 cm, depending on the source USGS topographic data – see Map 9), which decreases its utility when addressing increments of sea level rise less than approximately one meter. While this dataset should not be used for delineating areas for legal purposes, it can be useful for identifying areas for further, more detailed study as well as for general impacts over large geographic areas (though not for projecting future shorelines).

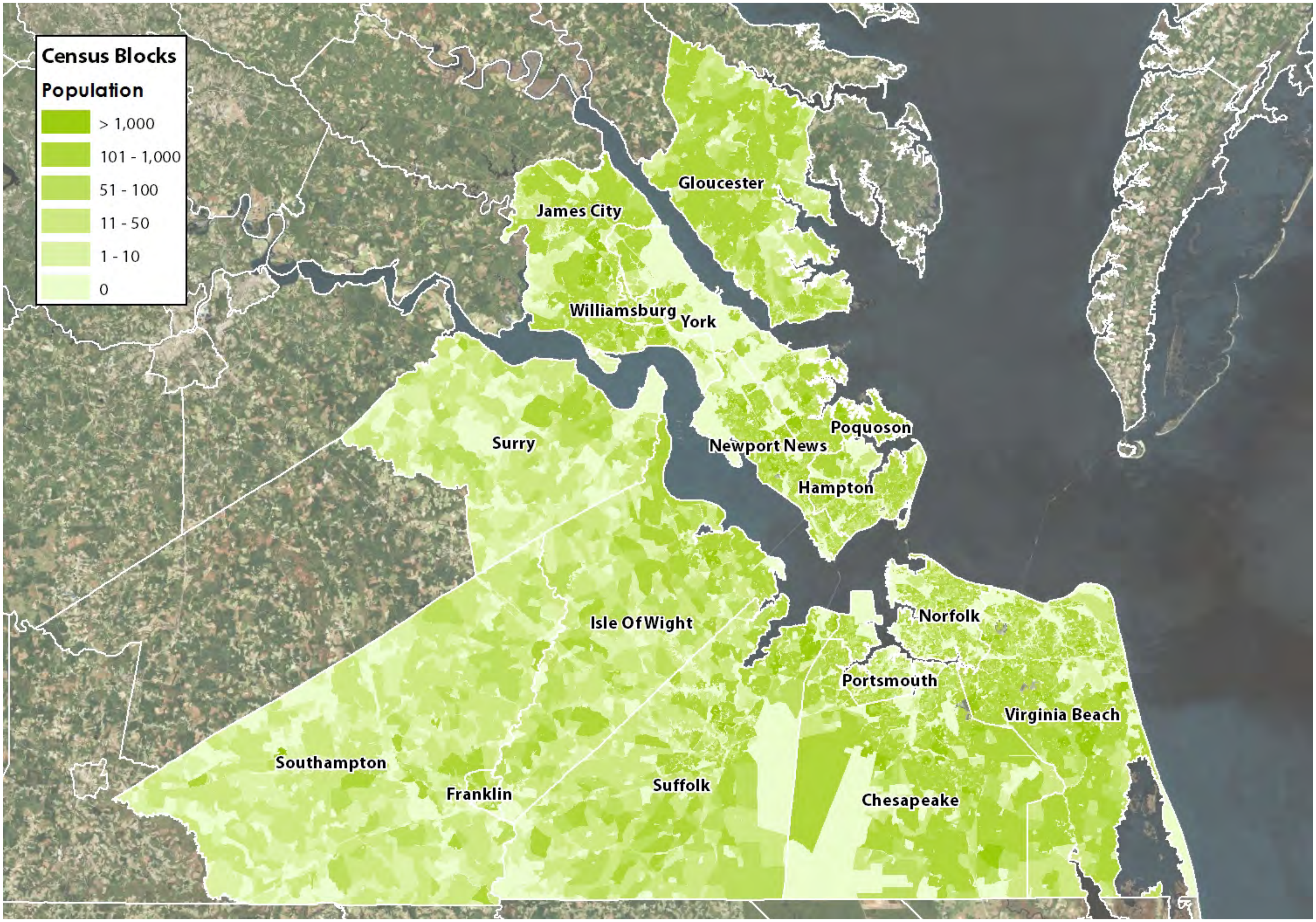
DATA NOTES

As with any data-driven analysis, this assessment is limited by the quality and availability of the data and processing capacity available. Datasets are often accurate only to a certain level, and can be incomplete and imprecise (especially in terms of geographic precision). Some of the known concerns with each of the above datasets are noted in the table below. Because of these limitations, the results of this analysis should be taken as estimates for general planning purposes and not as predictions of actual population, property, and resources vulnerable to sea level rise. The goal in this analysis is to provide a general idea of which areas in Hampton Roads are vulnerable to sea level rise, not a specific value for property or population that would be useful for a project cost-benefit analysis or specific planning decision (such as a rezoning of a particular property).

Table 4: Potential Concerns with Datasets Used for Sea Level Rise Vulnerability Analysis

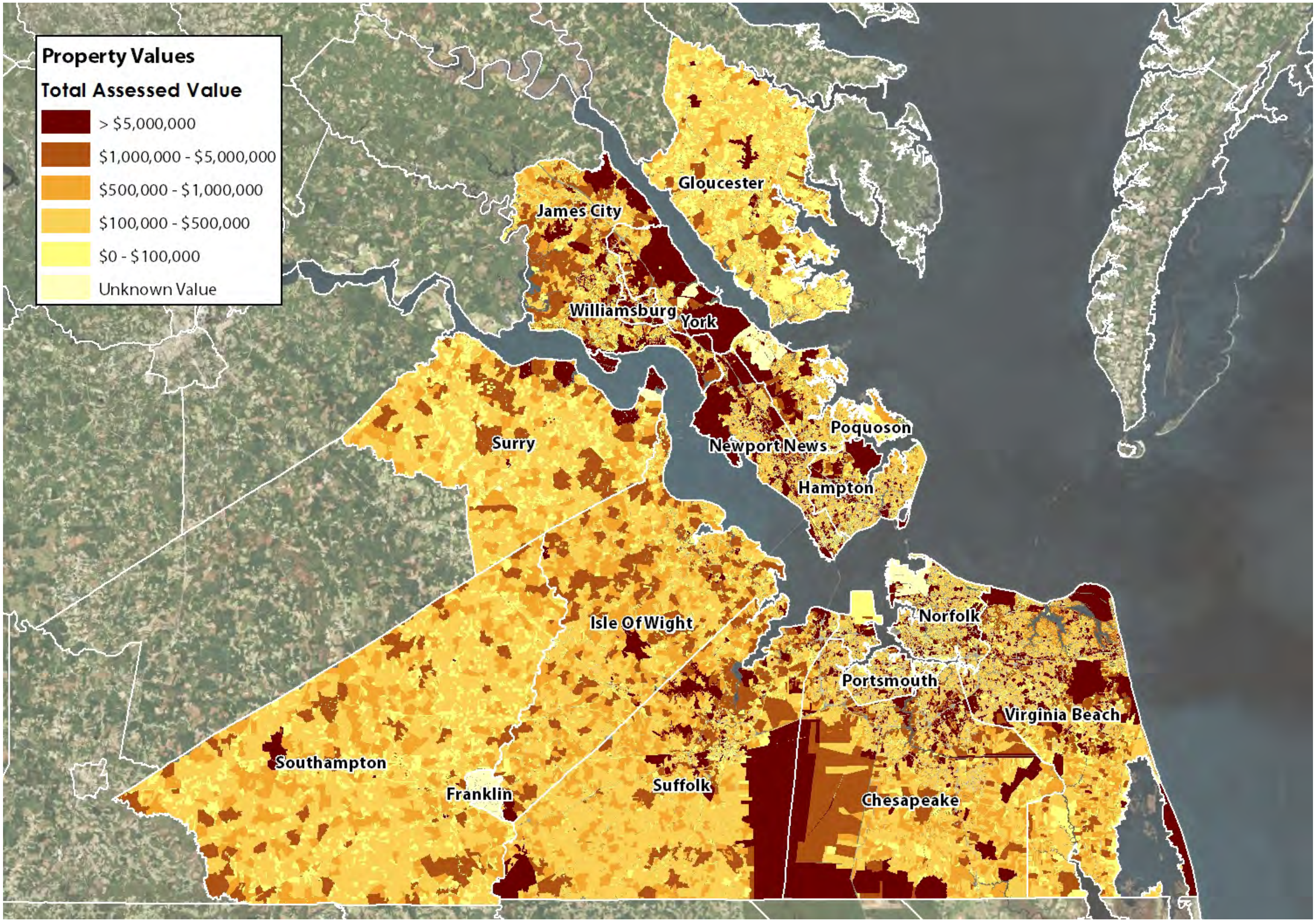
DATASET	POTENTIAL CONCERNS
Locality Boundaries	Coastlines may not account for erosion or other shoreline changes.
Population and Housing Units (Census)	Data is only collected decennially. Population and housing unit numbers are provided for geographic areas, not specific locations (points). Distribution of population and housing units within blocks is not provided.
Property Boundaries	Property boundaries from adjacent localities may overlap in some cases.
Property Assessments	Assessments vary from year to year and may not represent "true" values. Current assessment values will almost certainly change before these properties are affected by sea level rise. The most recent available data was obtained from each locality in late 2011.
Roads	Roads are assumed to be at grade. Analysis does not account for widths of roadways. Dataset does not include roads added to network beginning in 2011.
Businesses	Locations of businesses appear to be determined from or near streets as opposed to actual building locations within sites, which may affect results for businesses located near coasts or low-lying areas. Employment numbers may not be provided or may be inaccurate. Not all businesses are included.
Protected Lands	Dataset may not include all protected lands. Preserved areas within Department of Defense properties not included.
VEVA	Dataset is not very precise (30-meter pixels). Dataset does not include all of Southampton County or the City of Franklin (these two localities are not included in the Coastal Zone).
Elevation	Elevation data is relatively imprecise (30-meter pixels) and uncertain (standard deviation of at least 76.2 cm), which limits usefulness for identifying vulnerable areas at a small scale. In addition, the large pixel size makes it hard to identify levees or similar flood protection infrastructure.

Map 2: Population of Census Blocks in Hampton Roads



(Data sources: U.S. Census, Bing Maps)

Map 3: Total Assessed Value of Property Parcels in Hampton Roads

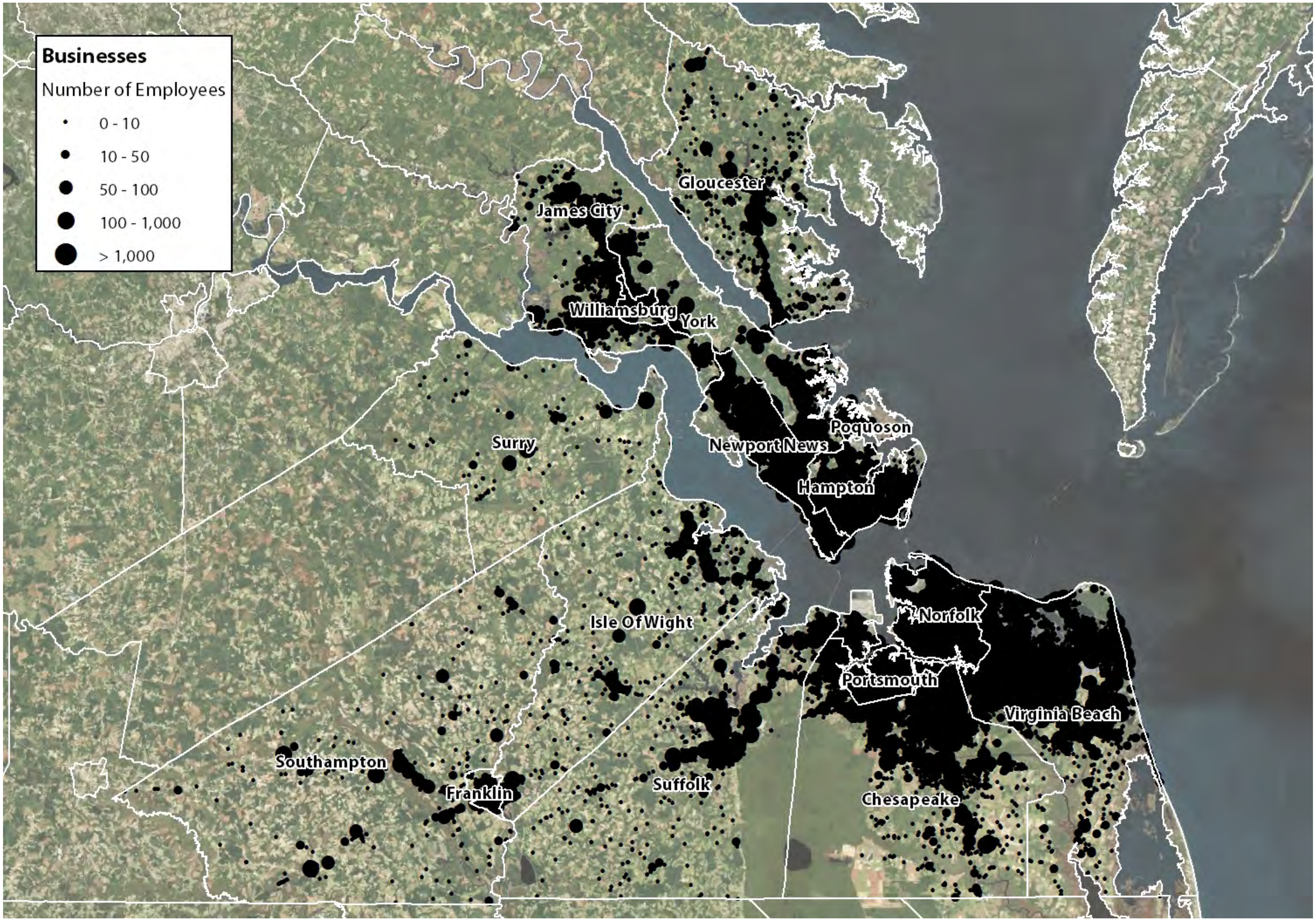


(Data sources: various localities, Bing Maps)

Map 4: Classification of Roads in Hampton Roads

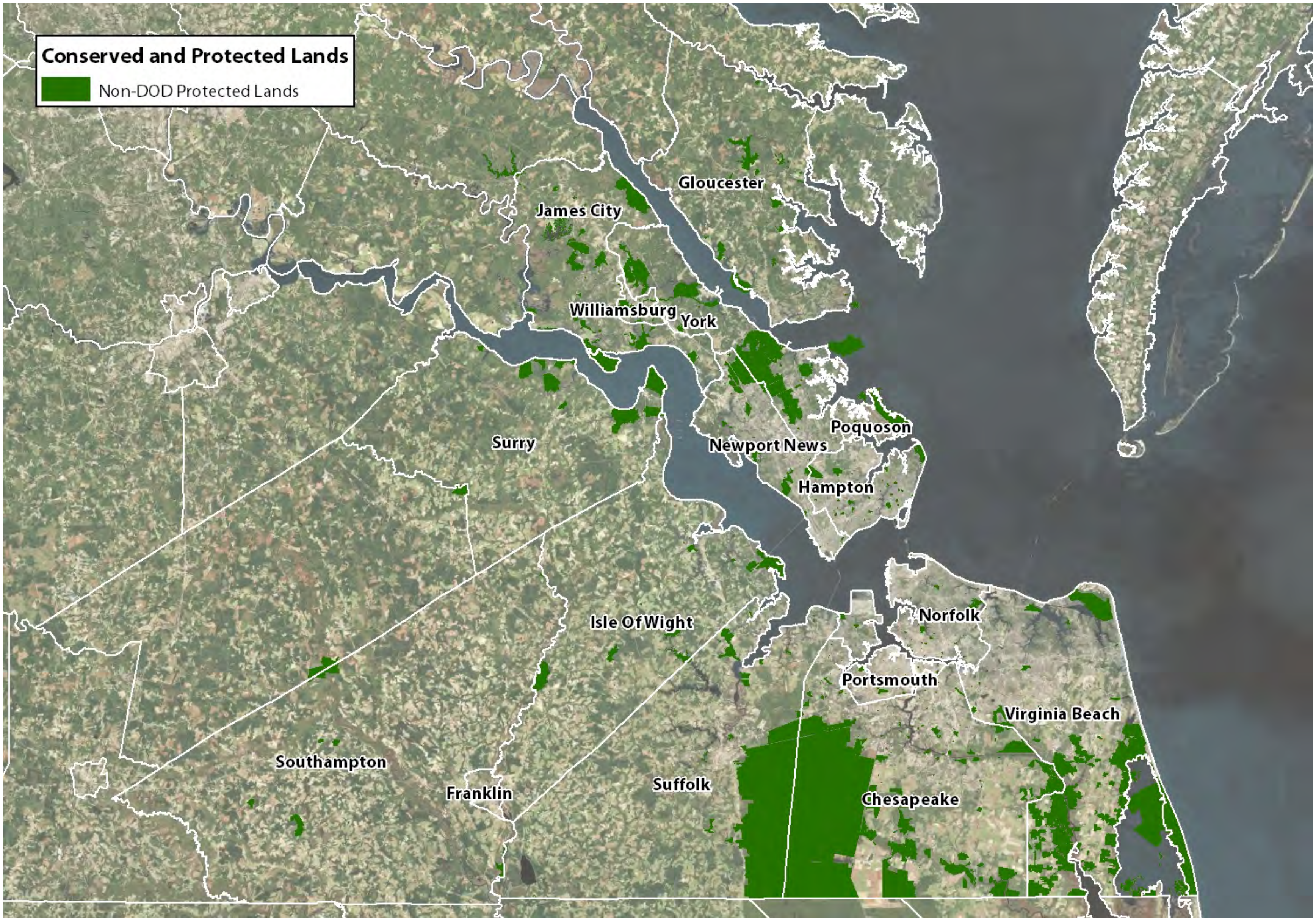
(Data sources: Esri, Bing Maps)

Map 5: Location and Employment of Hampton Roads Businesses



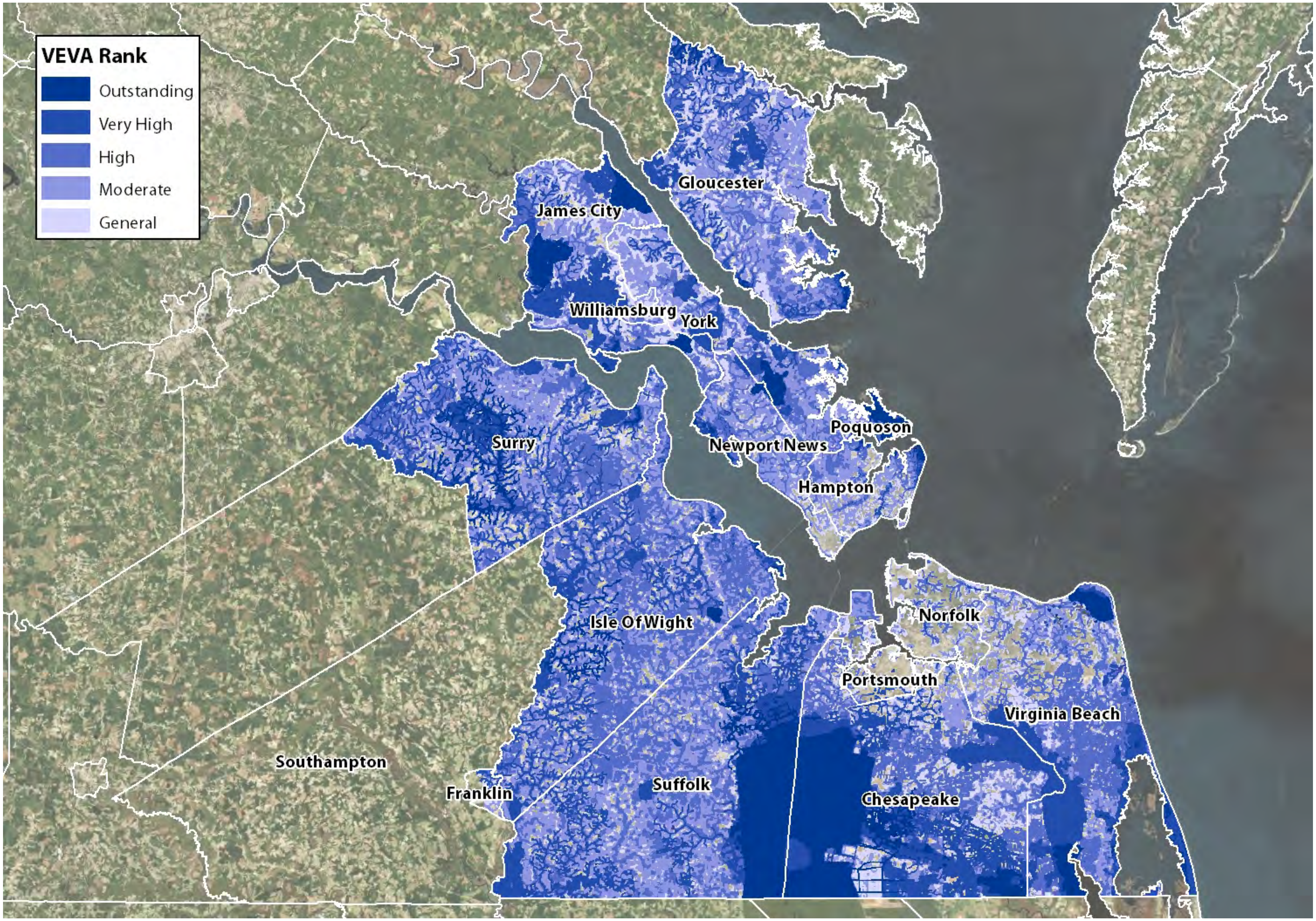
(Data sources: Esri, Bing Maps)

Map 6: Non-Department of Defense Protected Lands in Hampton Roads



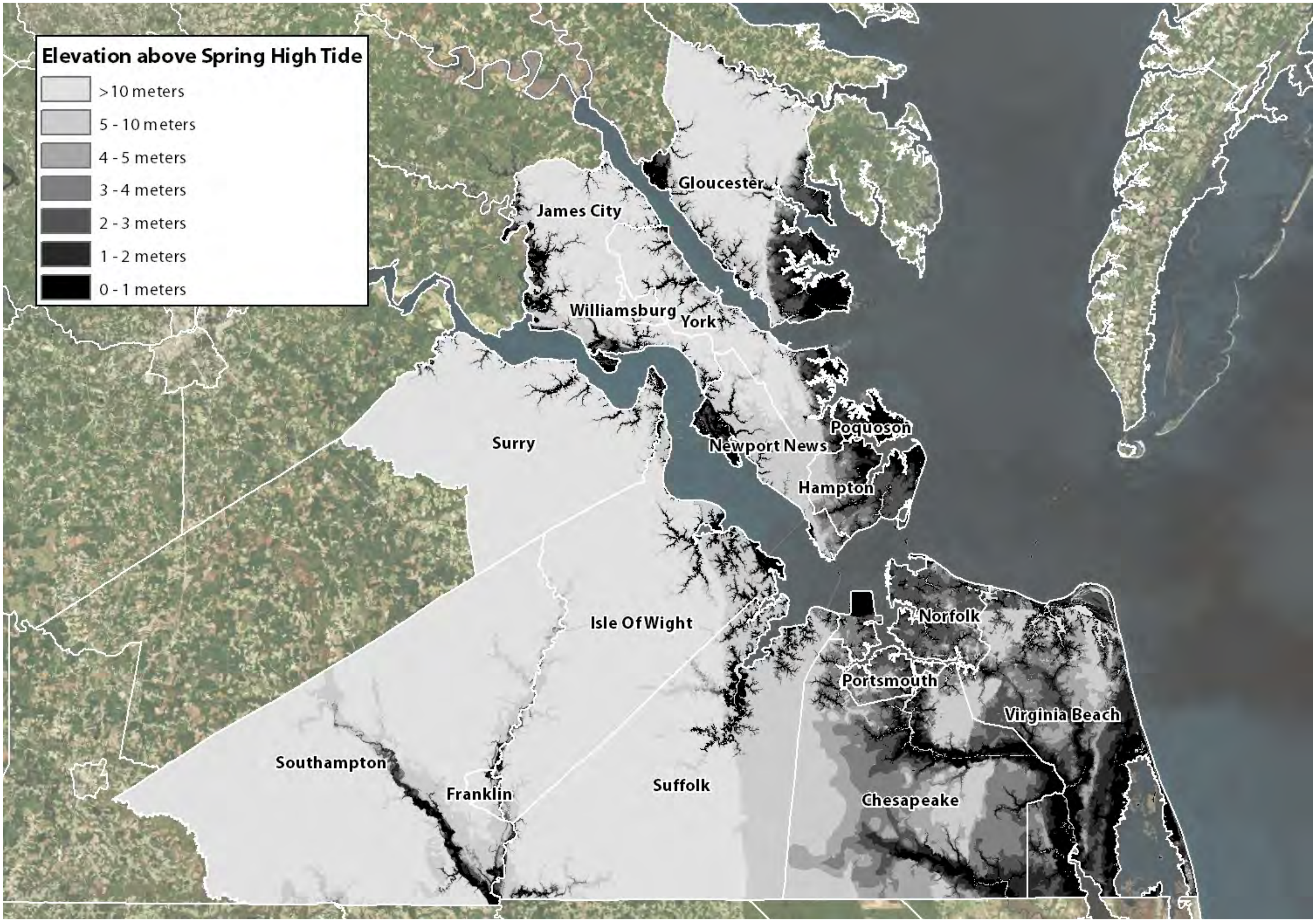
(Data sources: HRPDC, various state agencies, Bing Maps)

Map 7: Coastal Virginia Ecological Value Assessment Resources in Hampton Roads



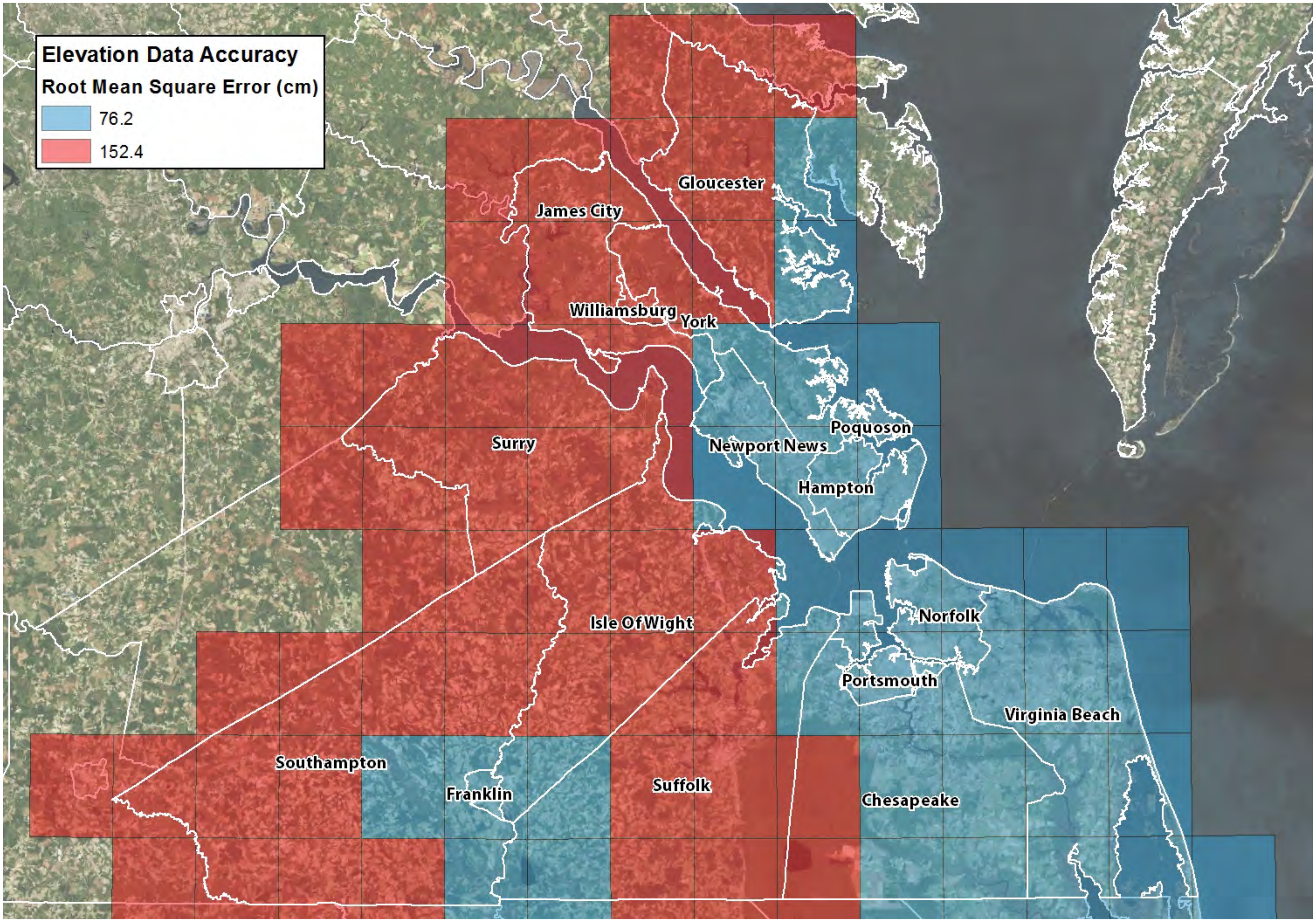
(Data sources: Virginia Coastal Zone Management Program, Bing Maps)

Map 8: Elevation of Land in Hampton Roads above Spring High Tide



(Data sources: Titus and Wang, 2008, Bing Maps)

Map 9: Accuracy of USGS Elevation Data in Hampton Roads



(Data sources: Titus and Cacela, 2008, U.S. Geological Survey, Bing Maps)

SECTION III: ANALYSIS METHODOLOGY

The risk a locality or area faces from a hazard is a function of the probability and the consequences of that hazard occurring. The probability of sea level rise affecting an area is directly related to elevation and nearness to the coast; consequences of sea level rise impacts such as inundation or temporary flooding can be estimated by calculating how many people and assets are located in vulnerable areas and how they would be affected by sea level rise (e.g. injury or loss of life, damage to or destruction of property, etc.). This analysis identifies areas that could be inundated by sea level rise and calculates the amount of population, property, and other assets in those areas to estimate the Hampton Roads region's exposure from sea level rise using a spatial overlay analysis.

Performing map-based analysis of sea level rise vulnerability is a useful way of communicating the scale of the issue as well as more practical information on which areas and assets could be at risk. Maps can be combined with summaries of various assets at risk to create compelling narratives of the need to respond to sea level rise, as well as to support specific adaptation responses (Gesch, Gutierrez and Gill 2009). HRPDC adapted NOAA's Coastal Inundation Mapping process using a step-by-step approach to identifying areas that are vulnerable to various levels of sea level rise (NOAA Coastal Services Center 2009).

- Step 1: Obtain and prepare elevation data. Various types of elevation data are available, such as LIDAR[7], IfSAR (or InSAR)[8], and photogrammetry[9].
- Step 2: Use the elevation data to create a water surface reflecting a change in sea level.
- Step 3: Map inundation based on the water surface using geographic information systems (GIS)
- Step 4: Visualize the inundation using either static maps or dynamic mapping tools (NOAA Coastal Services Center 2009).

HRPDC's analysis took advantage of previous work by the U.S. EPA that developed an elevation dataset that was referenced to spring high tide (Titus and Wang, Maps of Lands Close to Sea Level

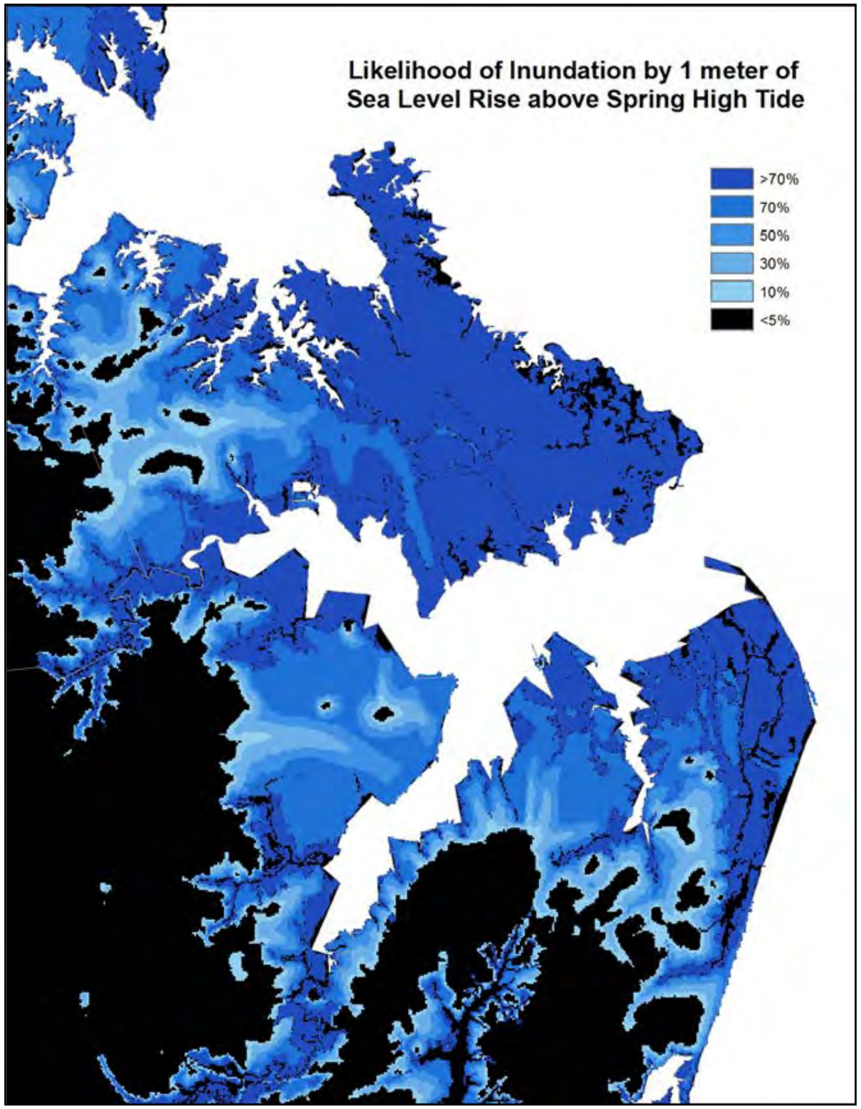
[7] Light Detection and Ranging – integrated with GPS; uses the time to return for laser pulses to measure precise elevations
[8] Inteferometric Synthetic Aperture Radar – calculates elevation using two radar images
[9] Photogrammetry involves the use of stereo aerial imagery to derive elevation.

along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR 2008). Spring high tide is used as the benchmark since lands above that line are currently dry; additional sea level rise would convert these lands to wetlands and eventually open water if they are not protected. Because the underlying elevation data had varying accuracy (due to the origin and type of the original data), Titus and Wang modeled the uncertainty range for each region, resulting in the creation of lower and upper bounds in addition to the stated elevation (Titus and Cacela, Uncertainty Ranges Associated with EPA's Estimates of the Area of Land Close to Sea Level 2008). The accuracy of this elevation data is shown on Map 9; areas shaded in blue have a root mean square error of approximately 2.5 feet, while areas shaded in red have a root mean square error of approximately 5 feet. Since there is some error involved in determining the elevation of spring high water, the actual error varies based on location and elevation. HRPDC staff obtained the original EPA data and replicated the uncertainty range analysis to create low, middle, and high estimates of the areas potentially inundated by one meter of sea level rise above spring high tide. These estimates are not analogous to the scenarios developed using the USACE tool described in Section I.) This uncertainty analysis incorporates both the uncertainty in the elevation data as well as the uncertainty in identifying the elevation of spring high tide. For the areas shaded in blue on Map 9, the low and high estimates extend approximately 2.5 feet below and above the given elevation; for the areas shaded in red, the low and high estimates extend roughly five feet below and above the given elevation. Since the disparity between the estimates is quite large it is important to note that this analysis and the resulting maps should not be used to determine vulnerable areas for site-specific planning purposes. Instead, the maps serve two main purposes: identifying areas that are potentially vulnerable and are thus suitable for further study with better data, and serving as an example of implanting a GIS tool to study the impacts of sea level rise on localities. Once the three elevation scenarios were developed, HRPDC staff used GIS to develop individual water level layers that could be combined with other datasets to estimate the region's vulnerability to sea level rise. Each estimate also included existing tidal wetlands (as identified in the same EPA dataset) as vulnerable to inundation. No shoreline protection structures were included in the analysis, for several reasons. First, factoring in different forms of shoreline protection would be extremely complicated and would be arbitrary. Incorporating no shoreline protection structures provides a regionally consistent approach and a baseline estimate for a "status quo" or a "do nothing" approach to planning for sea level rise. Second, most shoreline protection structures are designed to mitigate erosion, not flooding. Third, the implementation of most shoreline protection structures depends on many factors, including individual property owners' willingness, cost, and regulations.

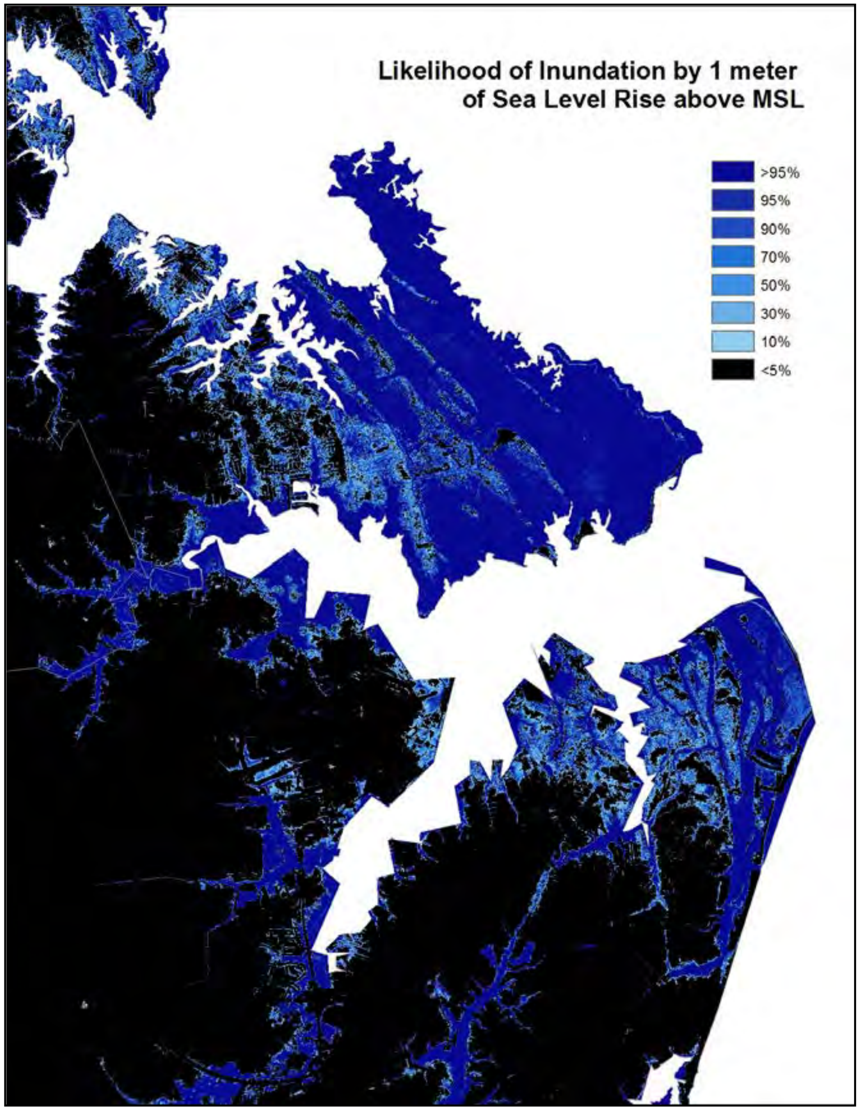
One of the major goals of HRPDC's climate change work has been to acquire or develop the case for acquiring higher resolution elevation data for the entire region. While many localities have LIDAR data, some do not, and in most cases the various locality datasets are not perfectly compatible. Comparing existing LIDAR data with the USGS and U.S. EPA data used in this analysis illustrates the benefits gained by acquiring and using better elevation data instead of more coarse data. HRPDC staff utilized a method documented in NOAA's "Mapping Inundation Uncertainty" pamphlet to analyze an area's likelihood of being inundated by one meter of sea level rise (NOAA Coastal Services Center 2010). This method relies on statistical analysis to calculate the likelihood of inundation based on the increment of sea level rise being modeled and the accuracy of the underlying elevation data. HRPDC staff analyzed a LIDAR-derived digital elevation model (DEM) and the EPA elevation dataset using this method, using a section of the Peninsula as a test area (see Figure 11). Acquiring and using LIDAR data will substantially improve the quality and utility of future sea level rise research and impact analysis in Hampton Roads.

The increment of sea level rise used for planning purposes should be constrained by two factors. First, it should be reasonable that the given amount of sea level rise could occur over the planning or project horizon. For example, mapping ten meters of sea level rise for Hampton Roads would not be appropriate or useful, since that amount of sea level rise is not expected to occur for centuries, if ever. Second, the increment selected should be appropriate to the accuracy of the elevation data; mapping one foot of sea level rise using elevation data with a standard deviation of more than two feet (as in this case) would not be appropriate, since one would not be able to state with certainty the difference between any two points only a foot apart in elevation. For this analysis, one meter of sea level rise was viewed as appropriate and useful, since it can be modeled relatively accurately using the available elevation data, and one meter of sea level rise is well within the range of sea level rise projected for Hampton Roads by the end of the 21st century. Additional analyses can be performed for smaller increments of sea level rise once more accurate and higher resolution elevation data becomes available for the entire region. Localities that already possess the necessary data can perform individual analyses now.

Figure 11: Comparing Elevation Data Accuracy



Mapping the likelihood of inundation using the EPA digital elevation model (DEM). Note that no areas are considered to have very high likelihood of being inundated, and the extent of areas that have any chance of inundation at all is quite large.



Mapping the likelihood of inundation using LIDAR data. Note that some areas are over 95% likely to be inundated by 1 meter of sea level rise (compared to only greater than 70% for the DEM), and that fewer areas overall are marked as at risk. This illustrates the greater certainty that is present when using LIDAR.

Table 5: Exposure Analysis Steps

Step 1: Identify Analysis Scenarios	The first step in this analysis is to define the scenarios by which to measure an area's vulnerability, such as an increment of sea level rise. Please see the discussion on pages 29-30 for more information.
Step 2: Develop Vulnerability Areas	Once the scenarios are identified, the areas affected must be identified, either using a storm model like SLOSH or using elevation data and water levels.
Step 3: Identify Assets to Analyze	The next step is to select which assets or other indicators, such as infrastructure or land use, need to be analyzed. For this analysis, five asset groups were selected: general, built environment, infrastructure, economy, and natural resources.
Step 4: Overlay Assets on Vulnerability Areas	Once assets are identified, they are overlaid on the vulnerable areas for each scenario using GIS.
Step 5: Extract Vulnerable Assets	Using GIS, those assets lying within vulnerable areas are extracted from their original datasets, creating a new dataset containing only those assets within each vulnerable area.
Step 6: Aggregate Vulnerable Asset totals by scenario and locality	The new datasets from Step 5 are analyzed as tables and aggregated, either within the GIS program or using a program such as Microsoft Excel.

Once the individual data layers were processed using geographic information systems (GIS) software, they were exported as tables. Spreadsheets were used to sort and aggregate the data in order to categorize each dataset by locality. Totals for each dataset were made for each locality for each sea level rise scenario. The totals were then aggregated regionally to create overall totals for the entire Hampton Roads Planning District. In addition to the data summaries, maps were created showing areas vulnerable to sea level rise.

General

Land area data for each locality was based on existing HRPDC boundary GIS files. Population data was acquired from the U.S. Census in two parts, a boundary file and a separate database of demographic data (including a unique identifier, the total population, and the total number of housing units for each block). Once a single GIS dataset was created it was clipped using the three elevation scenarios described above. The clipped datasets were then joined to the original dataset to compare the total area to the vulnerable area of each block to calculate a ratio for each scenario. These ratios were then applied to both the total population and total housing units of each census blocks to estimate the number of people and housing units potentially affected by sea level rise under each scenario. The vulnerable areas of each block were summed to calculate the total area of each locality that could be potentially inundated (either permanently or tidally). Since block-level population and housing unit counts were the best data available, the analysis of vulnerable population relied on an assumption of uniform distribution throughout each block. Since population distribution varies considerably among blocks, the results should be taken as a rough estimate only and not as a precise count.

Built Environment

Data representing the built environment consisted of parcel boundaries and assessment data acquired from individual Hampton Roads localities.[10] Two indicators were used to represent built environment impacts: the number of parcels affected and the total improvement value of those parcels. Two sub-scenarios for each main scenario were developed to account for instances where parcels were only partially included in vulnerable areas. For the first sub-scenario, any parcel that had any portion included in a vulnerability zone was included (this approach identified all parcels that were intersected by the vulnerable areas). For the second sub-scenario, only parcels that had their centroid (weighted middle of the polygon) within a vulnerability zone were included. These two sub-scenarios approximate the properties that could be affected by one meter of sea level rise above high tide (the intersection sub-scenario) and the properties that could be significantly affected by one meter of sea level rise above spring high tide (the centroid sub-scenario). For each sub-scenario the total number of parcels and the total improvement value was summed for each locality and the region.

Infrastructure

VDOT's road centerline database was used as the base data for this layer. Roads were categorized as interstate, primary, secondary, and local or private using VDOT's classification system. The database was split using county and city boundaries, with the resulting layers merged back together. This merged layer was then spatially joined with the locality boundary layer to give each road segment a county/city identifier. The data layer was overlaid on top of each vulnerability zone and clipped to create a separate layer representing the vulnerable roads in each of the three scenarios. The length of each segment in each of the road/storm surge layers was calculated in miles. Total length was summed by category for each locality and the region. Multiple lanes are not accounted for in these calculations. All roads are assumed to be at grade since the elevation data is not precise enough to separate roads from the surrounding land.

[10] Assessment data was not available for Franklin.

Economy

Two datasets were used to represent economic impacts. As with the Phase II report, business data was obtained as a set of points representing individual business locations from Esri's Business Analyst suite. The required information from the dataset included business locations and number of employees. The business layer was spatially joined to a locality boundary layer to give each business a county/city identifier. The data layer was overlaid on top of each sea level vulnerability zone. The total number of businesses and employees was calculated for each scenario for all sixteen Hampton Roads localities and the region as a whole.

Parcel information was also used to represent economic impacts; in this case, the total value of each parcel was used to represent investments in real property. As described in the Built Environment section above, sub-scenarios were used to identify areas at all or significantly potentially affected by sea level rise. For each sub-scenario, the total value of parcels was summed by locality and for the region.

Natural Environment

Two datasets were used to represent the natural environment. The first was a dataset developed by HRPDC staff that includes lands in Hampton Roads that are legally protected from being developed, such as government properties (federal, state, and local) and lands under conservation easement. Since the dataset did not differentiate between preserved and developed areas of military installations, all Department of Defense properties were excluded. The remaining areas were clipped using the vulnerability zone datasets to calculate the total amount of protected lands vulnerable in each scenario for each locality and the region.

The second dataset was the Coastal Virginia Ecological Value Assessment (VEVA). The data was clipped using the vulnerability zone datasets to calculate the total amount ecologically valuable lands vulnerable in each scenario for each locality and the region. The VEVA dataset classifies all lands based on a 1 (general) to 5 (outstanding) ranking; lands of outstanding, very high, or high value were included in this analysis.

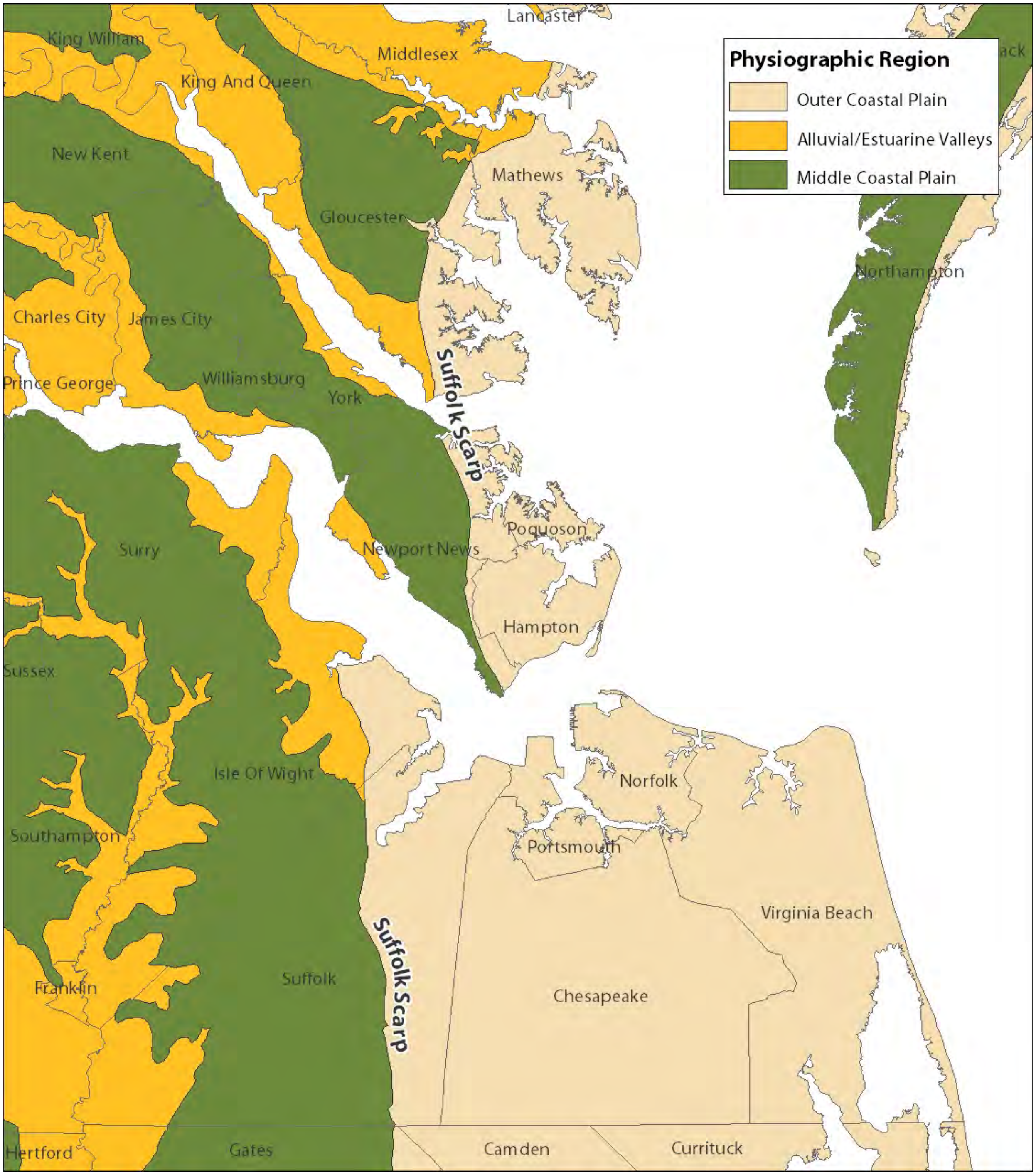
SECTION IV: ANALYSIS RESULTS

The results of this sea level rise vulnerability analysis of the Hampton Roads region are presented below using data summary tables and maps of potential inundation. Summary tables are provided for the region as well as for each locality in the Hampton Roads Planning District: Chesapeake, Franklin, Gloucester County, Hampton, Isle of Wight County, James City County, Newport News, Norfolk, Poquoson, Portsmouth, Southampton County, Suffolk, Surry County, Virginia Beach, Williamsburg, and York County (see Tables 4 – 20).

The results of this analysis should be interpreted as estimates of the region's vulnerability to sea level rise and not as predictions of which areas will be permanently inundated. The use of elevation data referenced to spring high tide suggests that some of these areas are likely to be permanently inundated, while others will become subject to tidal flooding. The utility of this elevation data lies not only in showing which areas could be permanently flooded, but in identify all areas that would be affected by sea level rise, which will result in tides reaching areas they currently do not. While the maps (see Maps 11 – 27) depict areas that are potentially vulnerable to being inundated by sea level rise, they should not be interpreted as identifying future shorelines, which will be shaped by several forces in addition to sea level rise (e.g. storms, waves, etc.). The results provide a general idea of which localities in the region are most vulnerable to sea level rise. Since shoreline and flood protection infrastructure is not included in the analysis, the results may be best interpreted as general baseline estimates of sea level rise impacts in the absence of adaptation measures.

The results support the observation that sea level rise is and will be a serious concern for all Hampton Roads localities. Localities that are particularly vulnerable include Chesapeake, Gloucester County, Hampton, Norfolk, Poquoson, Portsmouth, Virginia Beach, and York County. Those localities and parts of localities to the east of what is called the Suffolk Scarp (the geological feature that marks where the Mid-Atlantic's Outer Coastal Plain ends and the Middle Coastal Plain begins) are low-lying, poorly drained, and dominated by tidal streams and rivers. These features make them more susceptible to increased flooding and inundation from sea level rise (Ator, et al. 2005). The Suffolk Scarp runs from north to south through several Mid-Atlantic states; in Hampton Roads, the feature passes through Gloucester County, York County, Newport News, and Suffolk (see Map 10).

Map 10: Physiography of Hampton Roads, Virginia - The Suffolk Scarp



(Data source: U.S. Geological Survey)

Population

This analysis shows that a significant number of residents currently live in or near areas that could be inundated, permanently or regularly, by sea level rise by the end of the 21st century. The estimates range from nearly sixty-thousand (59,059) under the low scenario to over one hundred seventy-five thousand (176,124) under the high scenario. The most exposed individual localities in terms of absolute numbers of people living in areas vulnerable to one meter of sea level rise above spring high tide (middle scenario) are Chesapeake (15,983), Hampton (14,066), Norfolk (25,715), and Virginia Beach (21,160). These localities also, not surprisingly, have the greatest number of exposed housing units as well. In terms of the share of the population affected, the most exposed localities are Gloucester County (12%), Hampton (10%), Norfolk (11%), and Poquoson (56%). Since vulnerability is in part defined by adaptive capacity, further study of vulnerable populations, including low-income residents and the elderly, could help localities identify neighborhoods that are both at risk and currently have fewer resources to adapt. In terms of land area, Chesapeake, Gloucester County, and Virginia Beach have the greatest amount of land vulnerable to inundation, in part due to the large amount of tidal wetlands in those localities. By percentage of land area affected, Hampton, Poquoson, Portsmouth, and Virginia Beach are most exposed to potential inundation.

Built Environment

The region's built environment, as represented by property improvements, could be significantly affected by sea level rise. Across the region, over sixty thousand (61,254) parcels would be located entirely or partially in the middle scenario's vulnerable area, while over thirty-five thousand (35,654) parcels had a significant portion located in the vulnerable area. In the first group, the total improvement value of the affected parcels is over $26 billion; in the second, narrower case, the total improvement value of the affected parcels across the region is nearly $9 billion. Localities with the most exposure in this category include Chesapeake, Hampton, Newport News, Norfolk, and Virginia Beach.

Infrastructure

A significant amount of transportation infrastructure in the region is potentially at risk of inundation due to sea level rise. Across the region, approximately five hundred miles of roadways are exposed, including nearly fourteen miles of interstate highways, nearly fifty miles of state primary roads, over seventy miles of secondary roads, and nearly four hundred miles of local and private roads. Localities with the most exposed road infrastructure include Chesapeake, Gloucester County, Hampton, Norfolk, and Virginia Beach. A more detailed analysis using high resolution elevation data would help identify which roadways are at or above grade and provide a better assessment of which are at risk from flooding. In addition, while this analysis aims to identify which roads could be inundated, as sea level rises more roads would be vulnerable to temporary flooding during storm events.

Economy

Potential economic impacts from sea level rise are indicated by the number of businesses within areas vulnerable to inundation from sea level rise and the total number of employees working at those businesses. Also, the total value of affected parcels in vulnerable areas has been summed to provide some indication of the investments in real property that could be lost due to sea level rise. The results indicate that sea level rise could have significant economic impacts on the Hampton Roads region, potentially forcing businesses and their employees to relocate and investments in property to be lost. Localities with the most businesses and employees located and working in vulnerable areas include Chesapeake, Hampton, Norfolk, Portsmouth, and Virginia Beach. Localities with the most exposure in terms of total property values include Chesapeake, Hampton, Newport News, Norfolk, Poquoson, and Virginia Beach.

Natural Environment

Sea level rise will also significantly impact the natural environment. Many of the region's most valuable ecological resources are located in areas vulnerable to sea level rise. The results indicate that approximately 120,000 acres of the most valuable areas (those designated as high, very high, or outstanding in terms of ecological value by the Coastal Virginia Ecological Value Assessment) are vulnerable to sea level rise of one meter above spring high tide. Localities with the most highly rated VEVA resources exposed to sea level rise include Chesapeake, Gloucester County, James City County, Suffolk, and Virginia Beach. Protected lands – areas that localities and other owners have invested in to protect them from development – may also be inundated, resulting in the loss of both the resources and the funds used to acquire or protect those resources. Nearly forty thousand acres of protected lands are also exposed under the middle scenario. Localities with the most protected lands exposed include Chesapeake, Poquoson, Surry County, and Virginia Beach.

Many of the natural resources identified as vulnerable in this analysis are already below spring high tide. Sea level rise could potentially result in the permanent inundation of some or all of these areas. However, sea level rise will presumably result in the migration of existing wetlands or creation of new wetlands. While the analysis shows areas that could be potentially inundated, it is not intended to identify areas where wetlands could migrate inland, though such an investigation would be a logical extension of this work.

Maps and Data

Maps and data tables for the Hampton Roads region are included below. A summary data table is provided for the region as well as for each of sixteen localities in the Hampton Roads Planning District. A map is also included for each locality showing the three elevation scenarios: low estimate, middle estimate, and high estimate. A map book showing all vulnerable areas of Hampton Roads at the same scale is included in Appendix D. Please note that the areas in the low estimate scenarios are the most exposed; they are projected to be affected even if the elevation data is significantly underestimating actual elevations. Also note that since the analysis uses elevation relative to spring high tide, any comparisons between the maps produced in this analysis and those using other elevation datasets should be done with caution, as many elevation datasets, including LIDAR, are referenced to mean sea level or another vertical datum, and not spring high tide.

In general, these results should be interpreted as general estimates. An analysis conducted with LIDAR elevation data would allow for much greater precision in identifying areas vulnerable to different scenarios of sea level rise. HRPDC staff intends to conduct a similar regional analysis once LIDAR data is available for the entire planning district.

Data sources:

Inundation areas: (Titus and Wang, Maps of Lands Close to Sea Level along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR 2008)

Background aerial imagery: Bing Maps (2012)

Map Disclaimer: *These maps are designed to promote discussion and for use as general long-range planning tools, with the caveats mentioned in this report. They are not designed to be used for specific planning decisions or site planning. The depictions of areas vulnerable to sea level rise do not account for existing shoreline protection. These maps should not be used to assess actual coastal hazards,* *determine insurance requirements, or for property assessments. These maps do not in any way replace or relate to Flood Insurance Rates Maps issued by the Federal Emergency Management Agency (FEMA). For Flood Insurance information, residents or interested parties should contact their local governments or FEMA. More information on the National Flood Insurance Program or Flood Insurance Rate Maps is available on FEMA's website, www.fema.gov.*[11]

Table Disclaimer: *The following tables are for informational purposes only. Figures in the following tables are estimates and are derived using the methodology described in this report. They should not be used as predictions of damages or future conditions. The tables contain estimates for low, medium, and high scenarios (as determined by the accuracy of the underlying elevation data) for one meter of sea level rise above spring high tide. As discussed elsewhere in this report, one meter of sea level rise is within current estimates of sea level rise to be expected by the end of the 21st century; it is also a reasonable increment to measure given the quality of the elevation data. Based on the precision of the underlying elevation data, the data have been rounded in some cases. A 30-meter pixel is equal to approximately 9,688 square feet, which is about 0.22 acres. 30 meters equals 98.425 feet, which is approximately 0.02 miles. To account for this, all data represented as miles or square miles has been rounded to the nearest tenth, and all data represented as acres has been rounded to the nearest whole acre. All other datasets were calculated as described in the methodology section of this report.*

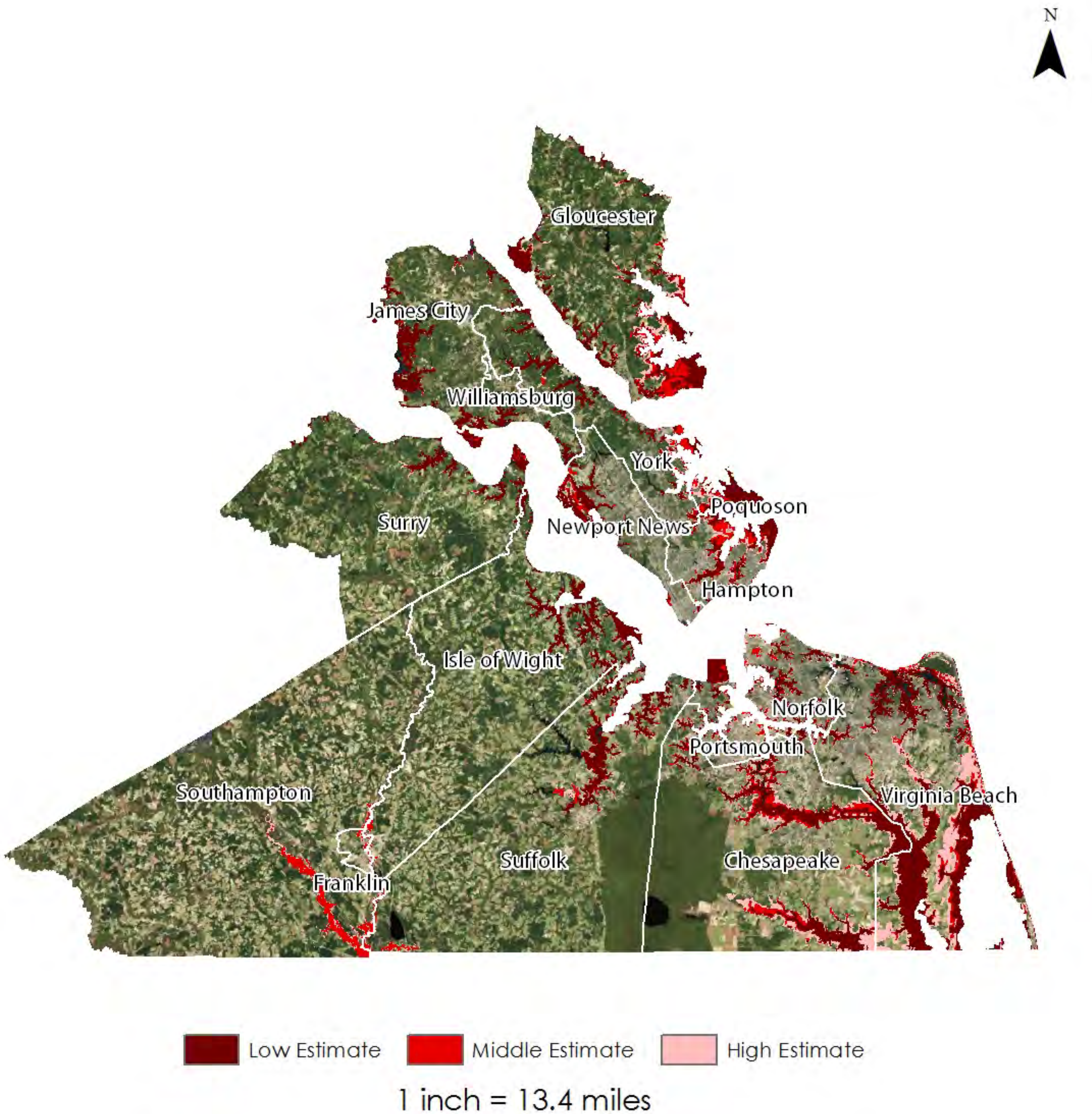
[11] http://www.fema.gov/plan/prevent/floodins/infocon.shtm

Table 6: Exposure to One Meter of Sea Level Rise above Spring High Tide in Hampton Roads, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	2,948.2	173.1	238.5	311.4
Population	1,666,310	59,059	112,794	176,124
Housing Units	677,549	24,436	45,791	71,548
BUILT ENVIRONMENT				
Number of Parcels (intersection)	605,284	39,564	61,254	84,780
Number of Parcels (centroid)	605,284	16,000	35,654	58,651
Improvement Value of Parcels (intersection)	$128,305,696,321	$20,328,915,919	$26,161,421,399	$30,833,003,959
Improvement Value of Parcels (centroid)	$128,305,696,321	$4,142,308,080	$8,766,633,550	$13,410,140,979
INFRASTRUCTURE				
Roads (total miles)	11,767.2	161.5	506.8	877.2
Roads (Interstate)	249.9	5.7	14.0	17.8
Roads (Primary)	1,460.4	17.1	49.6	77.3
Roads (Secondary)	2,216.3	24.0	72.2	98.2
Roads (Local or Private)	7,840.7	114.7	371.1	683.9
ECONOMY				
Businesses	57,579	575	2,026	3,659
Employees	719,835	5,237	25,088	50,869
Total Value of Parcels (intersection)	$215,436,678,988	$38,892,731,860	$48,067,888,230	$56,306,819,672
Total Value of Parcels (centroid)	$215,436,678,988	$8,513,744,141	$16,466,833,462	$25,104,125,807
NATURAL ENVIRONMENT				
Protected Lands (acres)	224,497	34,122	38,800	46,251
VEVA – Outstanding (acres)	166,276	19,257	20,454	23,566
VEVA – Very High (acres)	319,728	48,947	58,707	70,994
VEVA – High (acres)	374,797	31,007	42,798	57,285

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 11: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Hampton Roads, Virginia



Disclaimer: This map is for informational purposes only. Areas depicted as vulnerables are based on estimates only and should not be construed as being in imminent danger of inundation. The analysis depicted does not account for flood protection or control infrastructure. This map should not be used in place of official FEMA flood insurance rate maps. Users agree to hold harmless and blameless the Hampton Roads Planning District Commission and its representatives and its agents for any liability associated with the use of this map.

Table 7: Exposure to One Meter of Sea Level Rise above Spring High Tide in Chesapeake, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	350.1	21.5	32.4	48.8
Population	222,209	7,893	15,983	23,917
Housing Units	83,196	2,806	5,731	8,510
BUILT ENVIRONMENT				
Number of Parcels (intersection)	82,602	4,330	8,260	11,631
Number of Parcels (centroid)	82,602	1,796	5,258	8,583
Improvement Value of Parcels (intersection)	$17,564,561,900	$1,479,752,100	$2,299,717,300	$2,924,589,300
Improvement Value of Parcels (centroid)	$17,564,561,900	$442,439,500	$1,083,591,800	$1,674,952,000
INFRASTRUCTURE				
Roads (total miles)	1,326.6	17.0	65.2	122.1
Roads (Interstate)	47.9	2.3	4.7	6.1
Roads (Primary)	186.7	5.9	15.7	22.9
Roads (Secondary)	0.0	0.0	0.0	0.0
Roads (Local or Private)	1,092.0	8.9	44.8	93.1
ECONOMY				
Businesses	7,485	71	380	599
Employees	90,966	581	5,713	7,680
Total Value of Parcels (intersection)	$30,568,320,900	$2,827,287,400	$4,241,643,400	$5,411,895,800
Total Value of Parcels (centroid)	$30,568,320,900	$956,092,900	$2,156,277,100	$3,277,653,600
NATURAL ENVIRONMENT				
Protected Lands (acres)	112,089	8,441	10,177	11,997
VEVA – Outstanding (acres)	61,400	2,074	2,375	4,473
VEVA – Very High (acres)	63,202	8,662	12,346	17,532
VEVA – High (acres)	41,142	2,309	3,865	5,567

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 12: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Chesapeake, Virginia

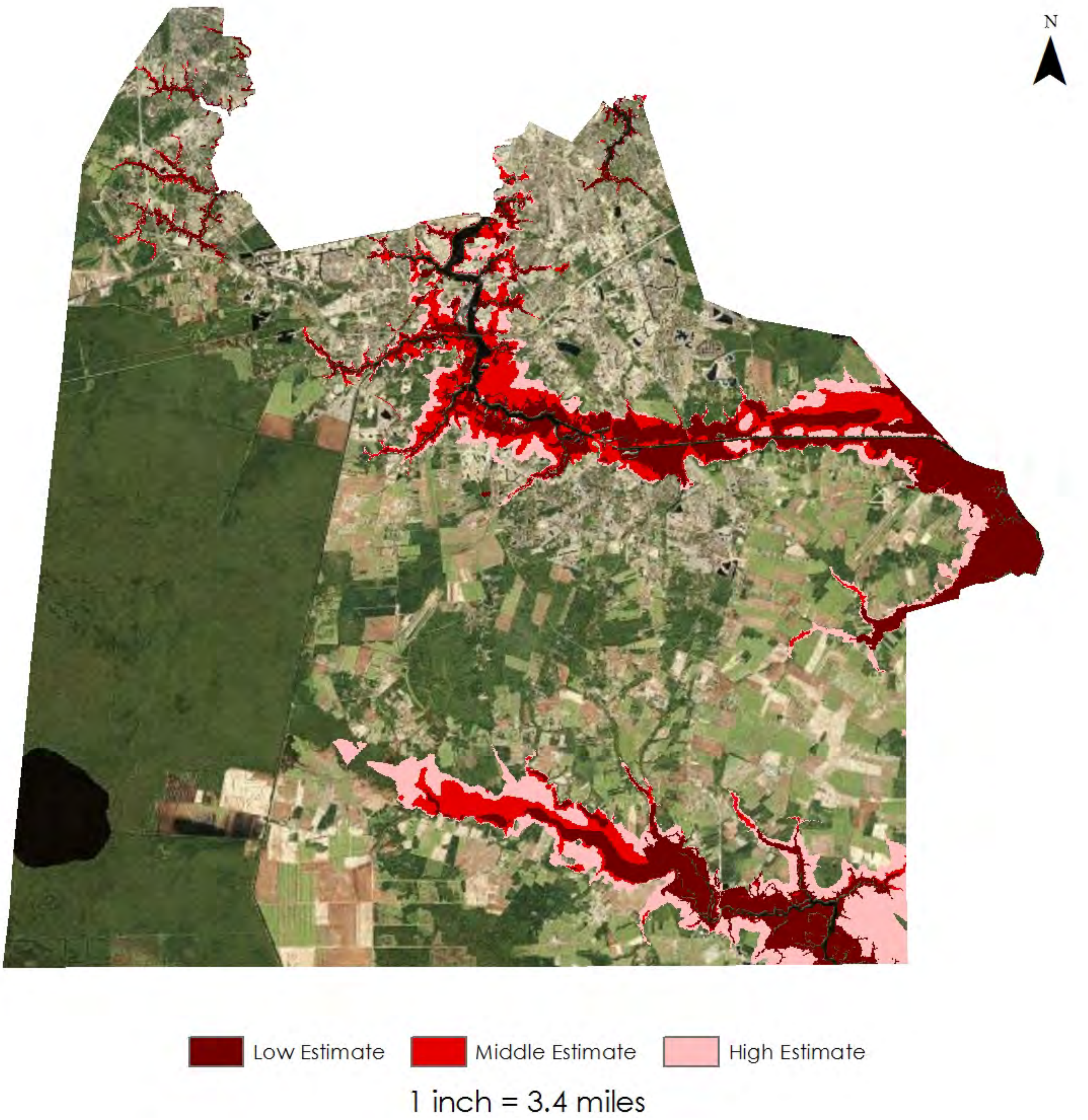


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Table 8: Exposure to One Meter of Sea Level Rise above Spring High Tide in Franklin, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	8.4	0.0	0.6	1.0
Population	8,582	0	74	145
Housing Units	3,901	0	33	66
BUILT ENVIRONMENT				
Number of Parcels (intersection)	5,023	0	43	73
Number of Parcels (centroid)	5,023	0	13	36
Improvement Value of Parcels (intersection)	*	*	*	*
Improvement Value of Parcels (centroid)	*	*	*	*
INFRASTRUCTURE				
Roads (total miles)	62.2	0.0	0.1	0.1
Roads (Interstate)	0.0	0.0	0.0	0.0
Roads (Primary)	9.9	0.0	0.0	0.1
Roads (Secondary)	1.7	0.0	0.0	0.0
Roads (Local or Private)	50.7	0.0	0.0	0.1
ECONOMY				
Businesses	543	0	0	0
Employees	4,402	0	0	0
Total Value of Parcels (intersection)	*	*	*	*
Total Value of Parcels (centroid)	*	*	*	*
NATURAL ENVIRONMENT				
Protected Lands (acres)	18	0	3	12
VEVA – Outstanding (acres)	30	0	25	29
VEVA – Very High (acres)	991	0	272	361
VEVA – High (acres)	340	0	106	171

Note: More information on the centroid and intersection methodologies can be found on page 34.

* Assessment data in the appropriate format was not available for the City of Franklin at the time of this analysis. HRPDC staff is working with Franklin city staff to develop or acquire the necessary data.

Map 13: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Franklin, Virginia

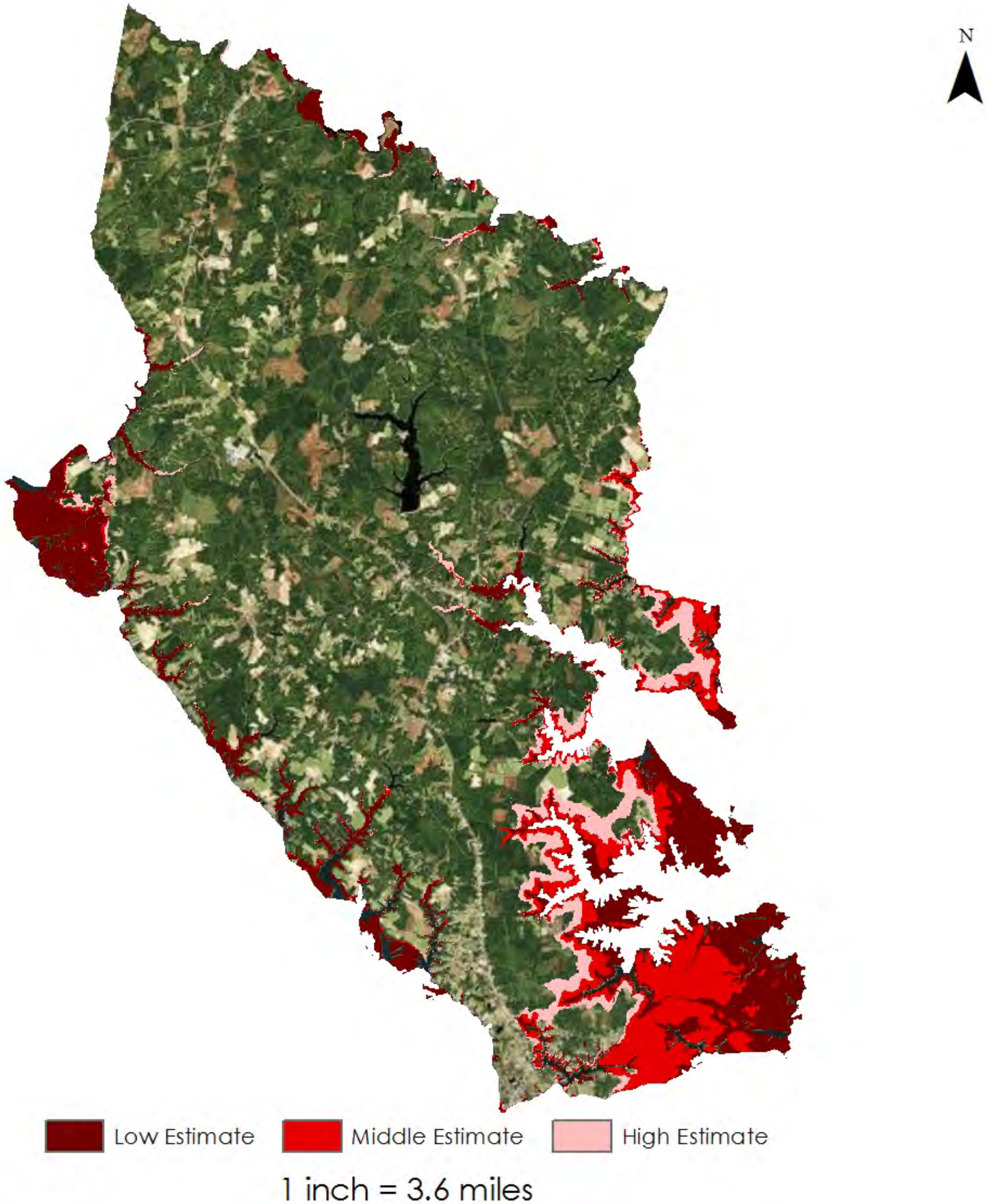
Disclaimer: This map is for informational purposes only. Areas depicted as vulnerables are based on estimates only and should not be construed as being in imminent danger of inundation. The analysis depicted does not account for flood protection or control infrastructure. This map should not be used in place of official FEMA flood insurance rate maps. Users agree to hold harmless and blameless the Hampton Roads Planning District Commission and its representatives and its agents for any liability associated with the use of this map.

Table 9: Exposure to One Meter of Sea Level Rise above Spring High Tide in Gloucester County, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	222.2	21.7	33.0	39.6
Population	36,858	2,207	4,503	5,369
Housing Units	15,852	1,063	2,160	2,597
BUILT ENVIRONMENT				
Number of Parcels (intersection)	24,719	4,488	6,064	6,699
Number of Parcels (centroid)	24,719	1,697	3,834	4,457
Improvement Value of Parcels (intersection)	$2,967,678,200	$586,010,500	$742,348,300	$798,825,000
Improvement Value of Parcels (centroid)	$2,967,678,200	$167,532,000	$419,621,900	$488,676,600
INFRASTRUCTURE				
Roads (total miles)	702.4	32.4	85.0	112.7
Roads (Interstate)	0.0	0.0	0.0	0.0
Roads (Primary)	93.0	0.1	1.6	2.5
Roads (Secondary)	300.3	16.1	41.4	54.8
Roads (Local or Private)	309.2	16.2	41.9	55.4
ECONOMY				
Businesses	1,451	41	78	87
Employees	10,981	240	448	533
Total Value of Parcels (intersection)	$4,738,497,438	$1,148,483,800	$1,388,025,900	$1,484,785,300
Total Value of Parcels (centroid)	$4,738,497,438	$310,408,800	$742,922,500	$873,523,300
NATURAL ENVIRONMENT				
Protected Lands (acres)	4,531	501	570	629
VEVA – Outstanding (acres)	3,579	1,457	1,475	1,520
VEVA – Very High (acres)	29,280	5,624	6,458	6,866
VEVA – High (acres)	31,699	4,677	6,781	7,820

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 14: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Gloucester County, Virginia



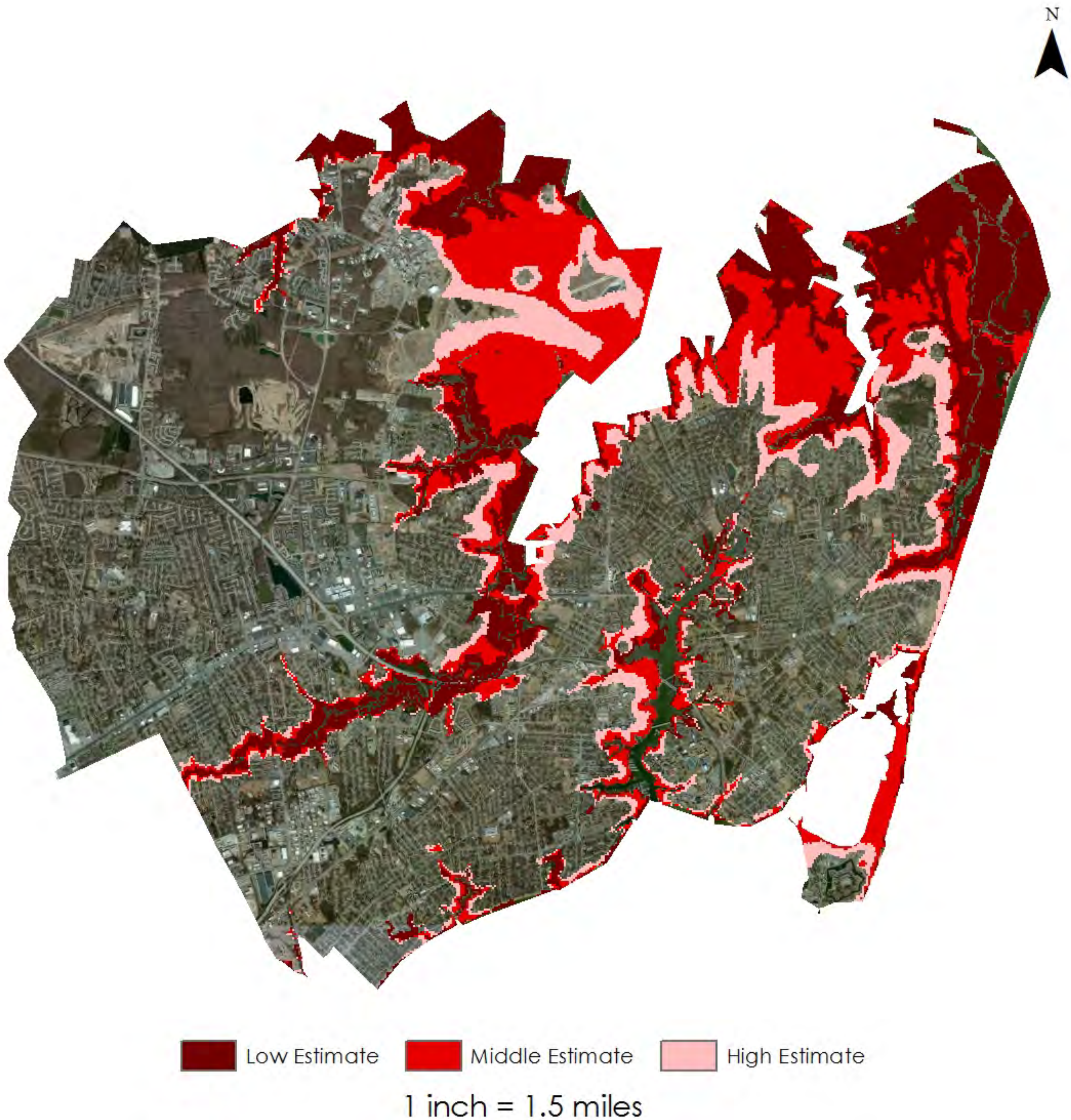
Disclaimer: This map is for informational purposes only. Areas depicted as vulnerables are based on estimates only and should not be construed as being in imminent danger of inundation. The analysis depicted does not account for flood protection or control infrastructure. This map should not be used in place of official FEMA flood insurance rate maps. Users agree to hold harmless and blameless the Hampton Roads Planning District Commission and its representatives and its agents for any liability associated with the use of this map.

Table 10: Exposure to One Meter of Sea Level Rise above Spring High Tide in Hampton, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	52.9	6.8	12.6	16.2
Population	137,436	6,300	14,066	22,888
Housing Units	59,566	2,911	6,011	9,796
BUILT ENVIRONMENT				
Number of Parcels (intersection)	50,872	3,666	6,652	10,168
Number of Parcels (centroid)	50,872	1,869	4,829	8,436
Improvement Value of Parcels (intersection)	$10,977,296,700	$2,787,879,600	$3,383,609,700	$3,955,014,500
Improvement Value of Parcels (centroid)	$10,977,296,700	$552,166,900	$1,046,154,700	$1,689,250,000
INFRASTRUCTURE				
Roads (total miles)	781.3	22.0	97.0	155.1
Roads (Interstate)	24.6	1.1	2.5	2.9
Roads (Primary)	73.5	1.4	5.2	8.8
Roads (Secondary)	0.1	0.0	0.0	0.0
Roads (Local or Private)	683.2	19.5	89.3	143.5
ECONOMY				
Businesses	4,148	44	263	467
Employees	53,135	224	1,815	4,605
Total Value of Parcels (intersection)	$15,190,766,200	$3,668,339,600	$4,551,238,900	$5,354,577,300
Total Value of Parcels (centroid)	$15,190,766,200	$805,364,500	$1,605,416,200	$2,513,996,800
NATURAL ENVIRONMENT				
Protected Lands (acres)	2,349	575	642	690
VEVA – Outstanding (acres)	848	751	760	760
VEVA – Very High (acres)	2,489	1,278	1,565	1,653
VEVA – High (acres)	7,466	1,679	3,091	3,594

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 15: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Hampton, Virginia



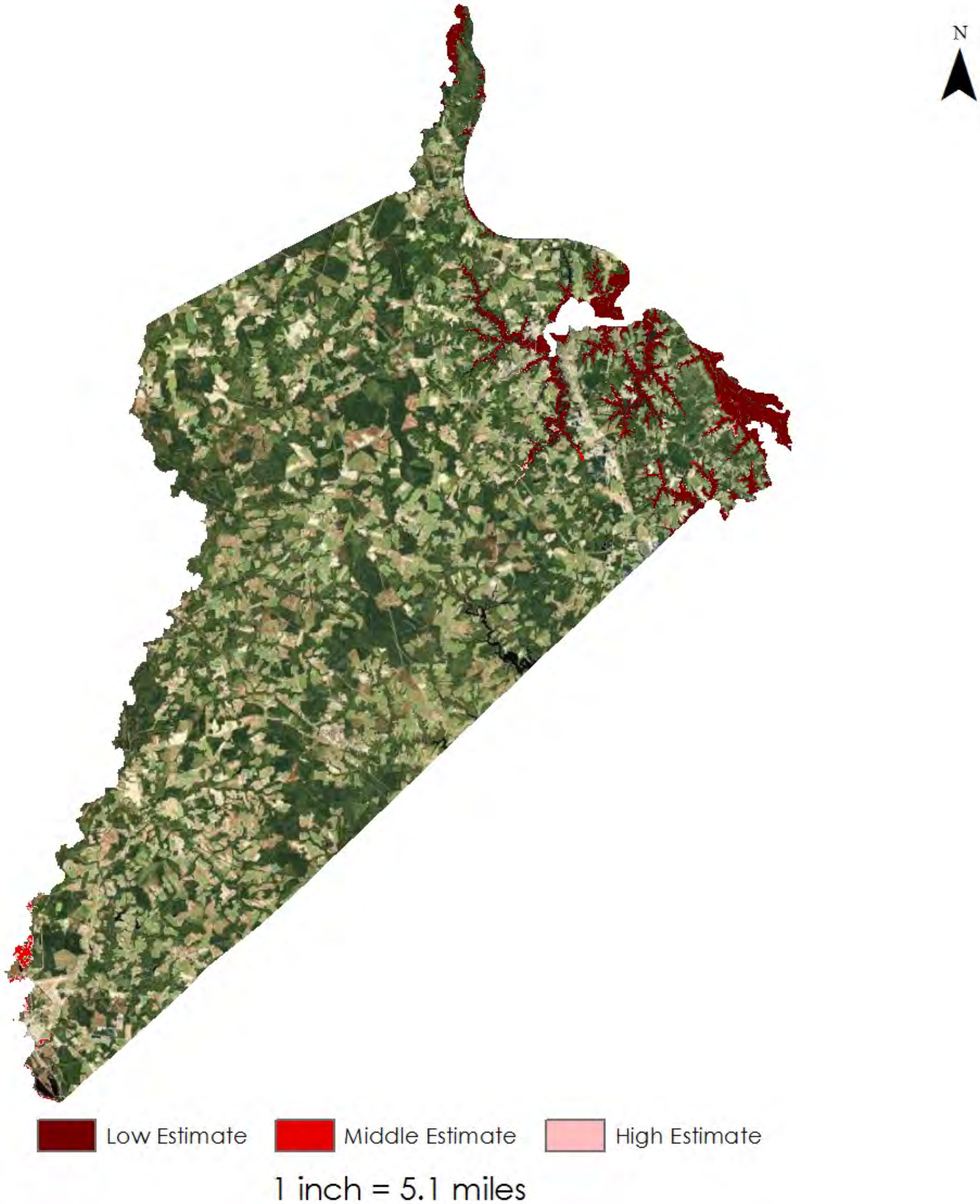
Disclaimer: This map is for informational purposes only. Areas depicted as vulnerables are based on estimates only and should not be construed as being in imminent danger of inundation. The analysis depicted does not account for flood protection or control infrastructure. This map should not be used in place of official FEMA flood insurance rate maps. Users agree to hold harmless and blameless the Hampton Roads Planning District Commission and its representatives and its agents for any liability associated with the use of this map.

Table 11: Exposure to One Meter of Sea Level Rise above Spring High Tide in Isle of Wight County, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	320.6	12.3	13.4	14.4
Population	35,270	2,872	3,046	3,223
Housing Units	14,633	1,192	1,263	1,339
BUILT ENVIRONMENT				
Number of Parcels (intersection)	21,055	2,316	2,503	2,704
Number of Parcels (centroid)	21,055	811	930	1,008
Improvement Value of Parcels (intersection)	$3,498,990,300	$414,734,800	$1,144,544,300	$1,175,711,400
Improvement Value of Parcels (centroid)	$3,498,990,300	$140,085,300	$256,090,800	$361,498,200
INFRASTRUCTURE				
Roads (total miles)	708.1	4.6	5.6	6.8
Roads (Interstate)	0.0	0.0	0.0	0.0
Roads (Primary)	92.7	1.7	2.0	2.1
Roads (Secondary)	428.5	1.4	1.8	2.3
Roads (Local or Private)	186.9	1.5	1.9	2.4
ECONOMY				
Businesses	1,158	13	16	17
Employees	12,279	69	80	180
Total Value of Parcels (intersection)	$6,184,254,100	$874,068,800	$1,689,819,500	$1,764,825,100
Total Value of Parcels (centroid)	$6,184,254,100	$267,508,300	$403,803,300	$526,074,300
NATURAL ENVIRONMENT				
Protected Lands (acres)	4,996	1,538	1,562	1,577
VEVA – Outstanding (acres)	8,947	516	521	529
VEVA – Very High (acres)	38,860	2,942	3,309	3,609
VEVA – High (acres)	77,986	4,165	4,460	4,690

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 16: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Isle of Wight County, Virginia



Disclaimer: This map is for informational purposes only. Areas depicted as vulnerables are based on estimates only and should not be construed as being in imminent danger of inundation. The analysis depicted does not account for flood protection or control infrastructure. This map should not be used in place of official FEMA flood insurance rate maps. Users agree to hold harmless and blameless the Hampton Roads Planning District Commission and its representatives and its agents for any liability associated with the use of this map.

Table 12: Exposure to One Meter of Sea Level Rise above Spring High Tide in James City County, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	150.3	13.3	14.9	15.7
Population	67,009	1,449	1,796	2,048
Housing Units	29,797	680	835	952
BUILT ENVIRONMENT				
Number of Parcels (intersection)	32,816	1,483	1,671	1,835
Number of Parcels (centroid)	32,816	540	721	836
Improvement Value of Parcels (intersection)	$9,165,772,400	$695,290,500	$743,224,500	$817,299,600
Improvement Value of Parcels (centroid)	$9,165,772,400	$168,951,900	$215,443,200	$237,300,500
INFRASTRUCTURE				
Roads (total miles)	651.6	2.6	4.5	5.7
Roads (Interstate)	22.0	0.0	0.0	0.0
Roads (Primary)	91.0	0.4	0.5	0.6
Roads (Secondary)	291.7	1.5	2.7	3.7
Roads (Local or Private)	246.9	0.7	1.3	1.5
ECONOMY				
Businesses	2,346	8	12	16
Employees	25,139	12	52	57
Total Value of Parcels (intersection)	$13,809,208,600	$2,046,237,000	$2,130,105,500	$2,243,406,000
Total Value of Parcels (centroid)	$13,809,208,600	$862,867,000	$987,671,600	$1,025,480,400
NATURAL ENVIRONMENT				
Protected Lands (acres)	8339	1,099	1,427	1,446
VEVA – Outstanding (acres)	12,599	2,688	2,918	2,998
VEVA – Very High (acres)	30,890	4,057	4,649	4,906
VEVA – High (acres)	14,886	1,450	1,586	1,751

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 17: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, James City County, Virginia

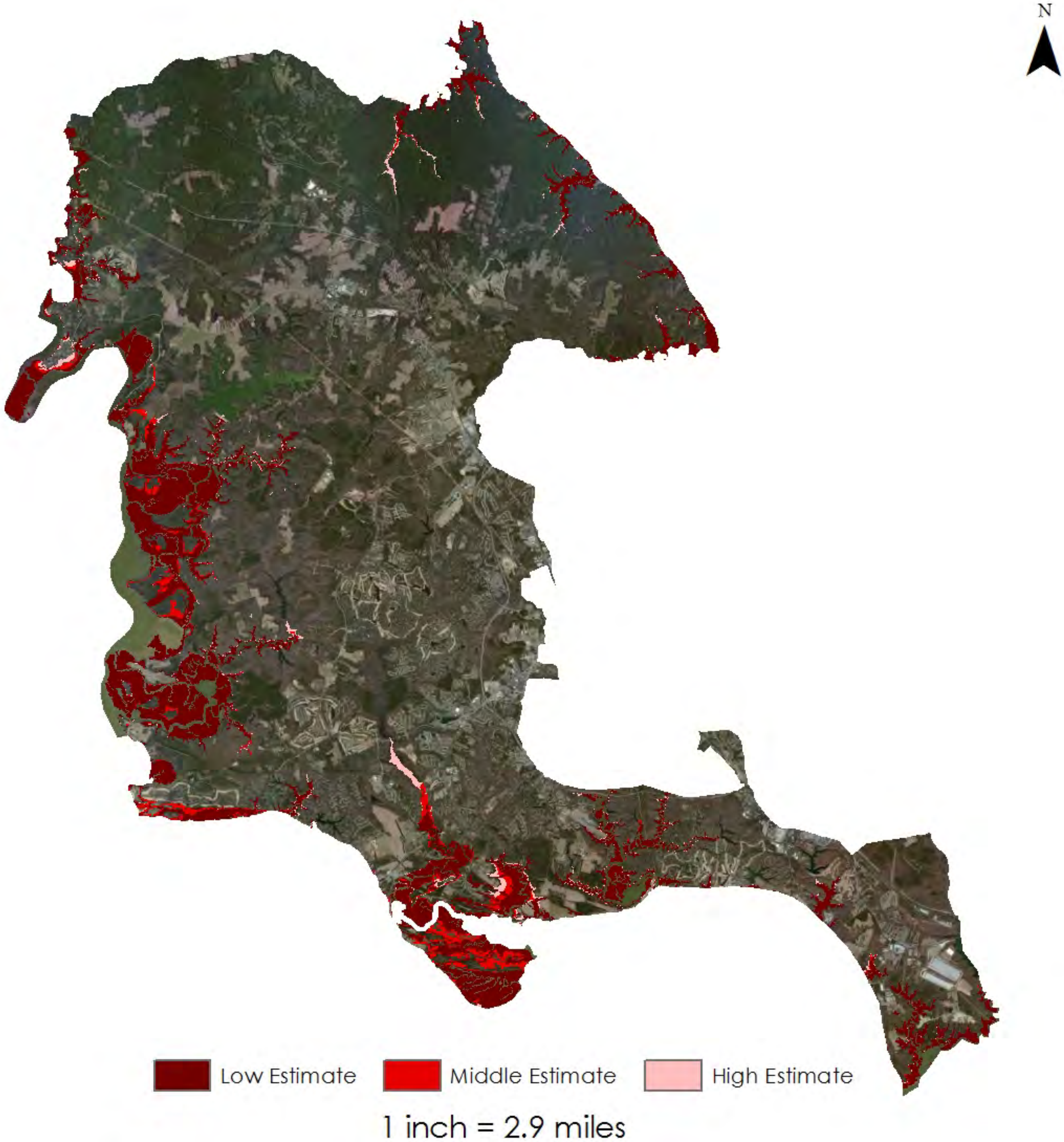


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Table 13: Exposure to One Meter of Sea Level Rise above Spring High Tide in Newport News, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	70.2	6.8	9.5	10.5
Population	180,719	3,196	4,321	5,000
Housing Units	76,198	1,342	1,896	2,213
BUILT ENVIRONMENT				
Number of Parcels (intersection)	54,382	1,320	1,780	2,053
Number of Parcels (centroid)	54,382	404	664	928
Improvement Value of Parcels (intersection)	$13,632,235,146	$1,919,115,700	$1,993,948,300	$2,027,680,500
Improvement Value of Parcels (centroid)	$13,632,235,146	$826,086,600	$1,355,314,200	$1,384,853,400
INFRASTRUCTURE				
Roads (total miles)	806.9	2.6	8.3	12.1
Roads (Interstate)	31.5	0.2	0.3	0.3
Roads (Primary)	101.9	0.4	0.9	1.2
Roads (Secondary)	0.1	0.0	0.0	0.0
Roads (Local or Private)	673.5	2.0	7.1	10.5
ECONOMY				
Businesses	6,516	2	28	38
Employees	90,221	14	510	644
Total Value of Parcels (intersection)	$22,413,311,190	$2,637,584,900	$2,751,954,500	$2,800,769,200
Total Value of Parcels (centroid)	$22,413,311,190	$1,098,182,700	$1,714,920,000	$1,758,915,700
NATURAL ENVIRONMENT				
Protected Lands (acres)	5,979	141	155	167
VEVA – Outstanding (acres)	1,539	584	671	706
VEVA – Very High (acres)	3,425	1,466	1,820	1,928
VEVA – High (acres)	12,875	1,905	2,685	2,944

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 18: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Newport News, Virginia

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Table 14: Exposure to One Meter of Sea Level Rise above Spring High Tide in Norfolk, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	55.9	3.1	6.5	9.2
Population	242,803	9,841	25,715	36,134
Housing Units	95,018	3,502	8,955	12,896
BUILT ENVIRONMENT				
Number of Parcels (intersection)	65,979	4,555	8,251	11,567
Number of Parcels (centroid)	65,979	1,757	4,968	8,204
Improvement Value of Parcels (intersection)	$13,494,681,500	$1,703,705,500	$3,207,444,200	$3,917,995,600
Improvement Value of Parcels (centroid)	$13,494,681,500	$350,808,300	$1,325,957,300	$2,234,621,300
INFRASTRUCTURE				
Roads (total miles)	1,150.2	14.7	75.5	129.2
Roads (Interstate)	54.9	1.7	5.3	6.8
Roads (Primary)	152.5	1.0	9.1	13.2
Roads (Secondary)	0.0	0.0	0.0	0.0
Roads (Local or Private)	942.9	12.0	61.1	109.1
ECONOMY				
Businesses	9,118	111	532	946
Employees	136,292	1,924	9,818	15,014
Total Value of Parcels (intersection)	$20,670,093,500	$3,189,941,400	$5,357,247,300	$6,485,310,600
Total Value of Parcels (centroid)	$20,670,093,500	$627,145,700	$2,225,096,200	$3,860,392,700
NATURAL ENVIRONMENT				
Protected Lands (acres)	868	122	195	245
VEVA – Outstanding (acres)	34	7	21	25
VEVA – Very High (acres)	1,510	378	541	618
VEVA – High (acres)	4,480	761	1,267	1,515

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 19: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Norfolk, Virginia

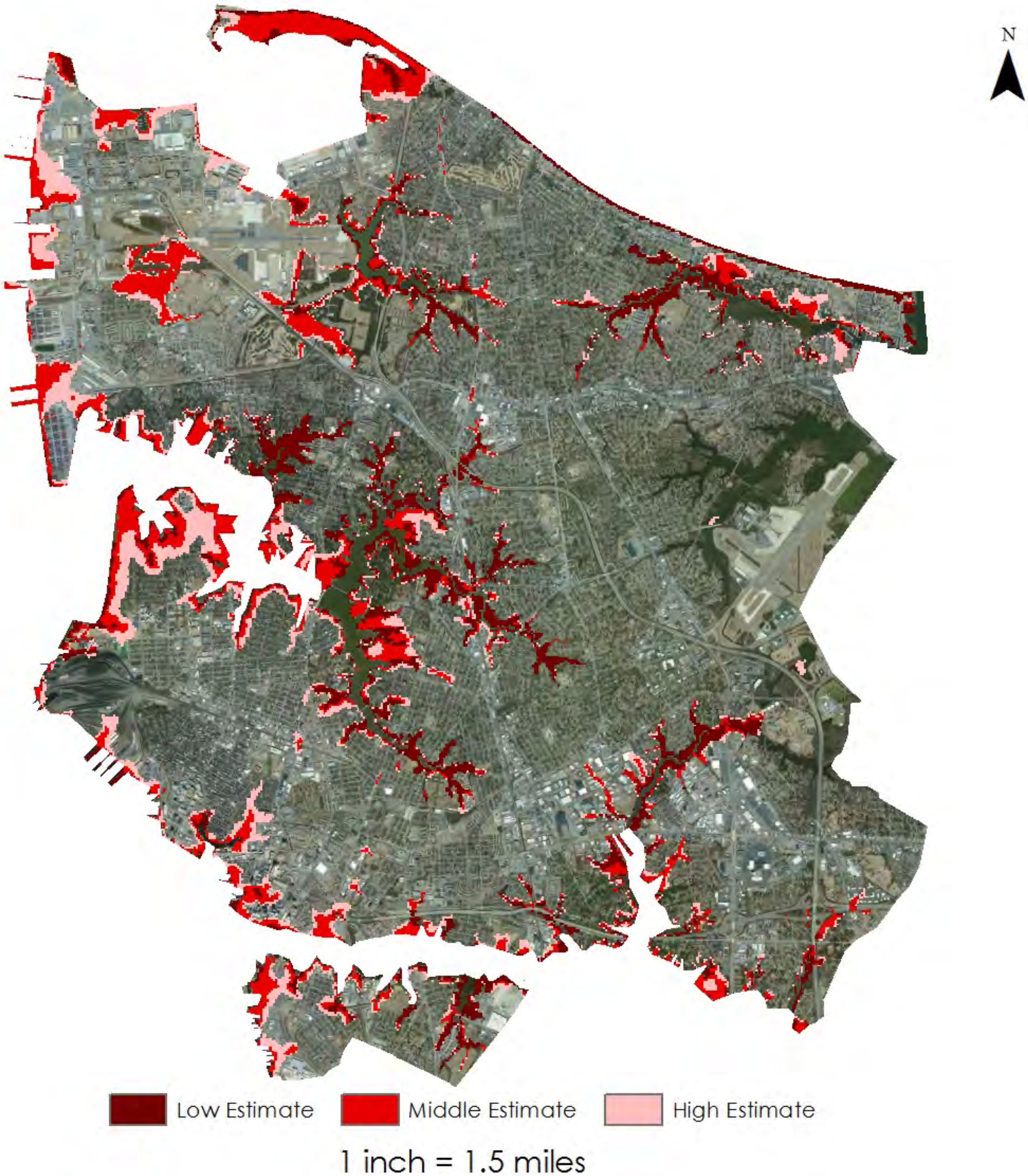

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Table 15: Exposure to One Meter of Sea Level Rise above Spring High Tide in Poquoson, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	13.4	9.4	11.8	13.0
Population	12,150	3,242	6,770	8,957
Housing Units	4,726	1,257	2,597	3,461
BUILT ENVIRONMENT				
Number of Parcels (intersection)	5,517	2,087	3,691	4,707
Number of Parcels (centroid)	5,517	1,454	3,330	4,444
Improvement Value of Parcels (intersection)	$934,088,500	$310,317,500	$599,508,700	$778,387,700
Improvement Value of Parcels (centroid)	$934,088,500	$177,112,000	$516,907,100	$716,057,400
INFRASTRUCTURE				
Roads (total miles)	66.0	13.3	38.7	51.4
Roads (Interstate)	0.0	0.0	0.0	0.0
Roads (Primary)	7.9	2.4	5.1	5.9
Roads (Secondary)	0.0	0.0	0.0	0.0
Roads (Local or Private)	58.1	10.9	33.6	45.5
ECONOMY				
Businesses	312	57	115	180
Employees	2,339	125	508	1,552
Total Value of Parcels (intersection)	$1,723,031,200	$677,862,300	$1,168,759,200	$1,454,712,100
Total Value of Parcels (centroid)	$1,723,031,200	$400,143,900	$1,025,090,400	$1,346,305,000
NATURAL ENVIRONMENT				
Protected Lands (acres)	3,099	2,202	2,213	2,215
VEVA – Outstanding (acres)	4,246	3,951	3,957	3,958
VEVA – Very High (acres)	974	708	773	776
VEVA – High (acres)	2,089	882	1,386	1,603

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 20: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Poquoson, Virginia

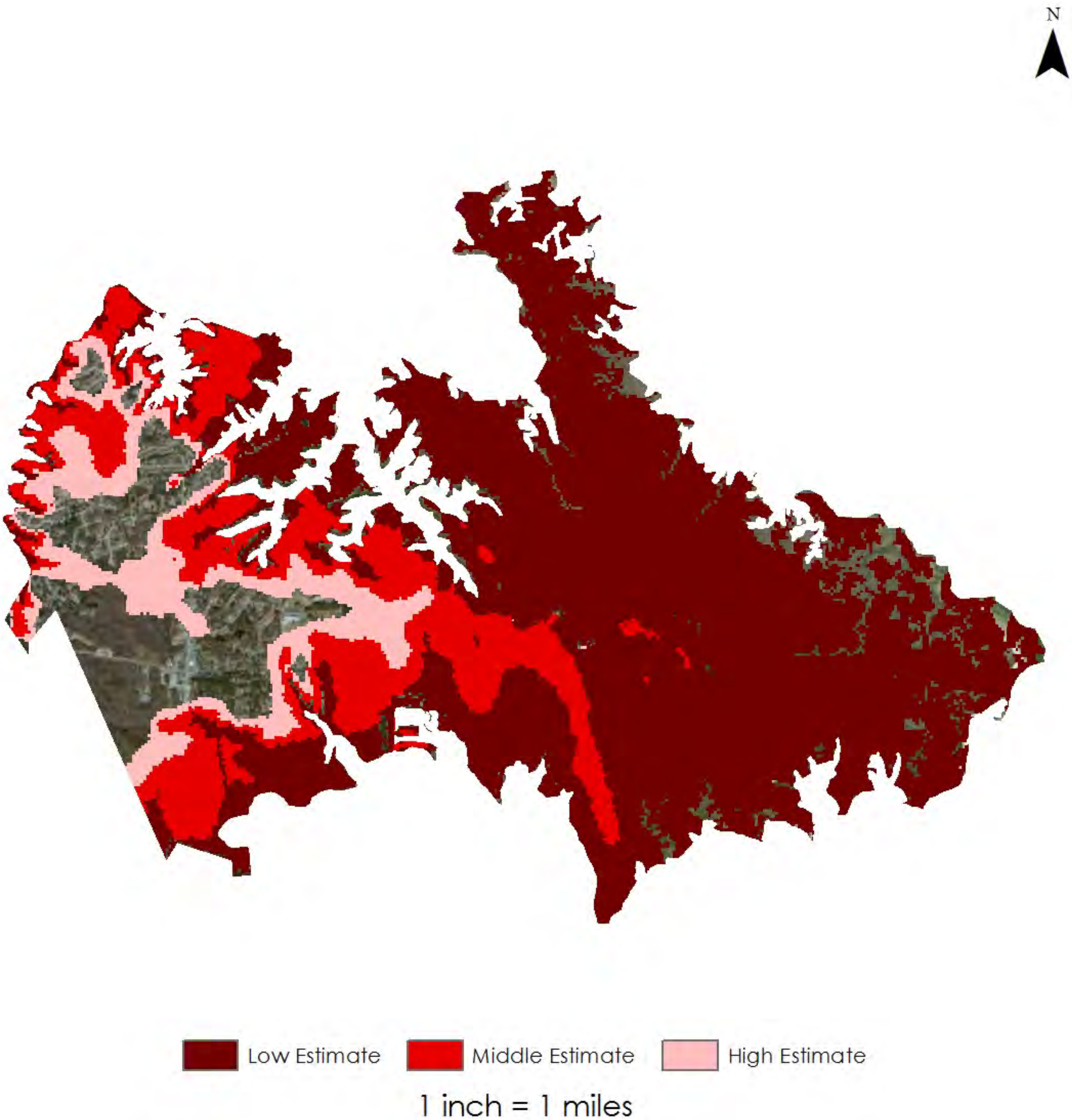

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Table 16: Exposure to One Meter of Sea Level Rise above Spring High Tide in Portsmouth, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	33.6	5.2	7.0	8.2
Population	95,535	2,246	4,655	7,655
Housing Units	40,806	941	2,089	3,567
BUILT ENVIRONMENT				
Number of Parcels (intersection)	36,051	1,714	3,074	4,295
Number of Parcels (centroid)	36,051	641	1,596	2,730
Improvement Value of Parcels (intersection)	$11,644,279,608	$4,765,599,210	$5,145,115,990	$5,458,380,750
Improvement Value of Parcels (centroid)	$11,644,279,608	$244,582,030	$515,879,550	$916,582,670
INFRASTRUCTURE				
Roads (total miles)	520.5	4.0	17.5	34.3
Roads (Interstate)	11.4	0.0	0.5	0.7
Roads (Primary)	54.9	0.6	1.4	2.6
Roads (Secondary)	0.0	0.0	0.0	0.0
Roads (Local or Private)	454.2	3.4	15.5	30.9
ECONOMY				
Businesses	3,008	19	127	276
Employees	45,384	61	2125	8,709
Total Value of Parcels (intersection)	$16,260,870,838	$6,424,363,950	$6,946,685,170	$7,360,474,380
Total Value of Parcels (centroid)	$16,260,870,838	$489,868,690	$881,165,030	$1,559,118,040
NATURAL ENVIRONMENT				
Protected Lands (acres)	694	60	84	103
VEVA – Outstanding (acres)	35	17	25	25
VEVA – Very High (acres)	1,535	343	437	508
VEVA – High (acres)	3,845	1,333	1,593	1,725

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 21: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Portsmouth, Virginia

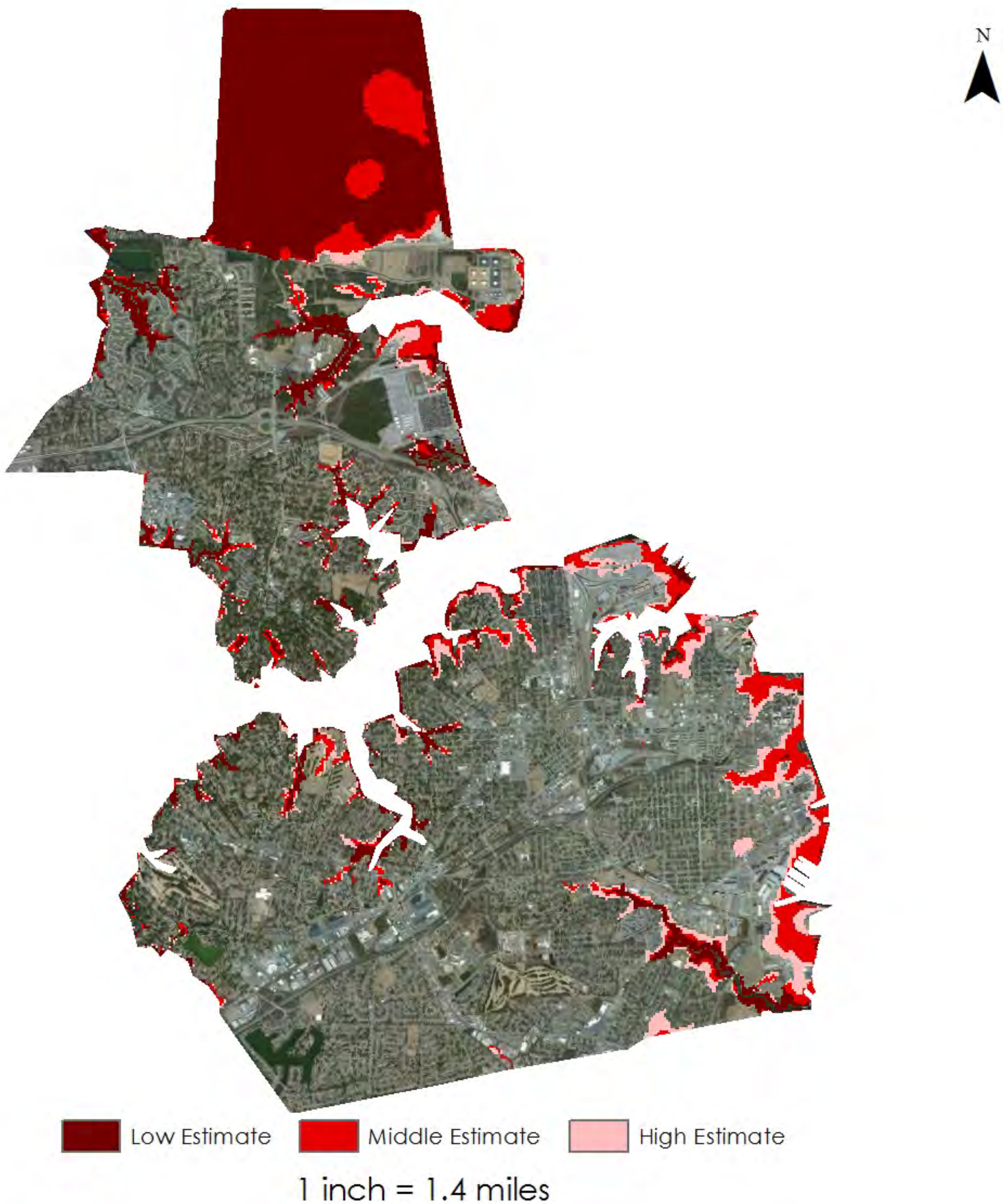

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Table 17: Exposure to One Meter of Sea Level Rise above Spring High Tide in Southampton County, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	602.4	0.0	7.8	10.9
Population	18,570	0	149	224
Housing Units	7,473	0	64	93
BUILT ENVIRONMENT				
Number of Parcels (intersection)	15,849	0	241	331
Number of Parcels (centroid)	15,849	0	117	161
Improvement Value of Parcels (intersection)	$1,134,717,700	$0	$9,879,300	$13,782,900
Improvement Value of Parcels (centroid)	$1,134,717,700	$0	$6,037,400	$7,379,400
INFRASTRUCTURE				
Roads (total miles)	843.5	0.0	2.0	3.1
Roads (Interstate)	0.0	0.0	0.0	0.0
Roads (Primary)	128.6	0.0	0.5	1.1
Roads (Secondary)	647.6	0.0	1.0	1.4
Roads (Local or Private)	67.3	0.0	0.5	0.6
ECONOMY				
Businesses	474	0	1	2
Employees	3,577	0	1	13
Total Value of Parcels (intersection)	$2,438,989,700	$0	$55,470,700	$68,210,300
Total Value of Parcels (centroid)	$2,438,989,700	$0	$14,703,000	$21,744,400
NATURAL ENVIRONMENT				
Protected Lands (acres)	3,419	0	209	292
VEVA – Outstanding (acres)	78	0	0	1
VEVA – Very High (acres)	189	0	79	99
VEVA – High (acres)	45	0	11	12

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 22: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Southampton County, Virginia

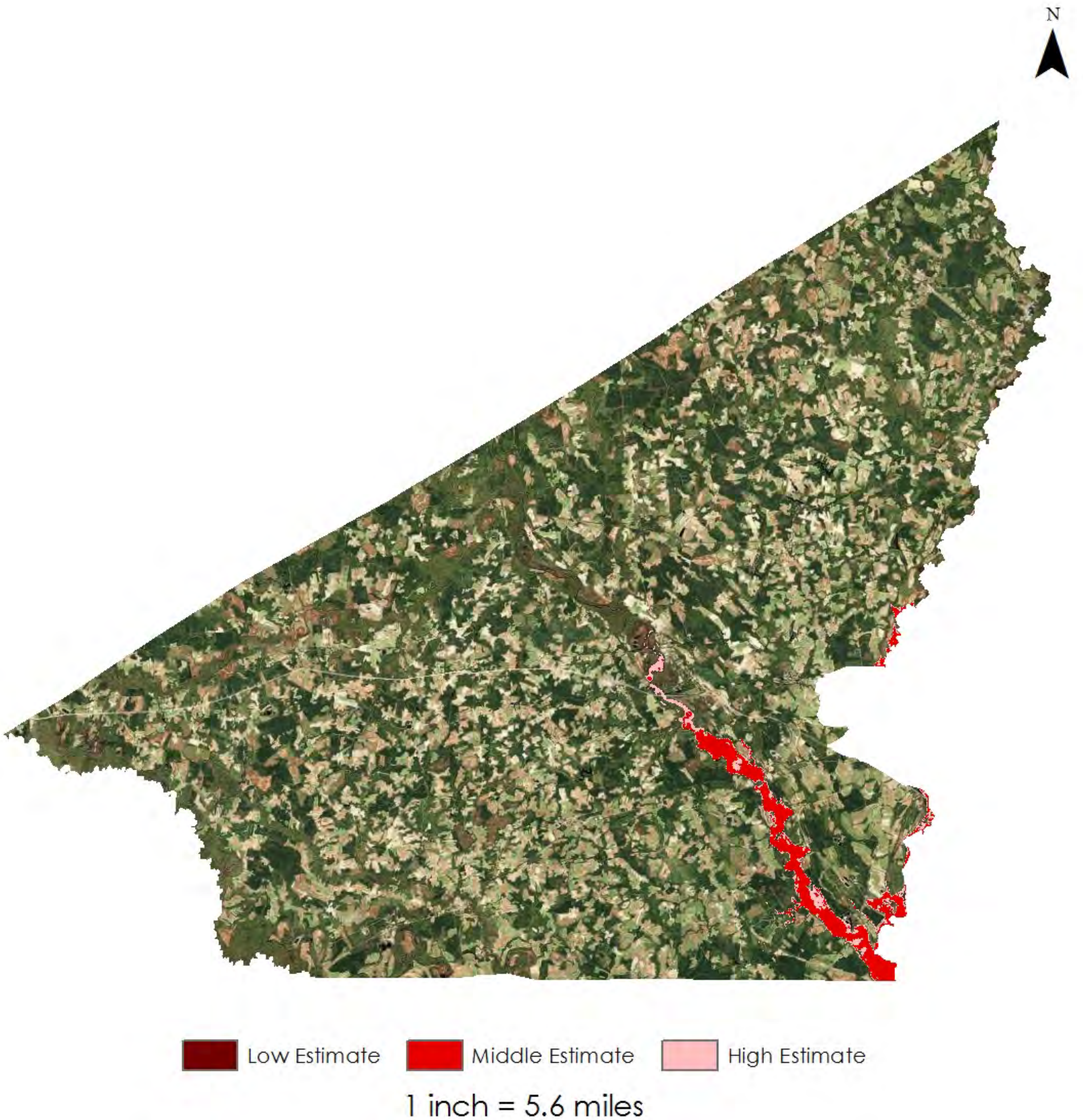

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Table 18: Exposure to One Meter of Sea Level Rise above Spring High Tide in Suffolk, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	411.4	11.0	14.4	15.9
Population	84,585	3,871	4,691	4,997
Housing Units	33,035	1,408	1,715	1,821
BUILT ENVIRONMENT				
Number of Parcels (intersection)	39,290	2,308	2,876	3,068
Number of Parcels (centroid)	39,290	686	894	1,000
Improvement Value of Parcels (intersection)	$6,467,878,700	$772,838,400	$910,374,800	$957,980,600
Improvement Value of Parcels (centroid)	$6,467,878,700	$165,731,200	$201,957,200	$231,584,000
INFRASTRUCTURE				
Roads (total miles)	1,030.8	2.0	4.7	6.2
Roads (Interstate)	6.8	0.0	0.1	0.1
Roads (Primary)	176.7	0.4	1.5	2.4
Roads (Secondary)	0.4	0.0	0.0	0.0
Roads (Local or Private)	846.9	1.6	3.1	3.8
ECONOMY				
Businesses	2,265	12	21	22
Employees	25,126	92	111	141
Total Value of Parcels (intersection)	$10,372,632,100	$1,426,058,400	$1,685,691,700	$1,768,778,800
Total Value of Parcels (centroid)	$10,372,632,100	$287,530,300	$360,603,700	$406,340,200
NATURAL ENVIRONMENT				
Protected Lands (acres)	2,458	220	281	323
VEVA – Outstanding (acres)	43,039	1,123	1,300	1,334
VEVA – Very High (acres)	51,511	4,030	5,345	5,868
VEVA – High (acres)	65,899	1,649	2,165	2,436

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 23: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Suffolk, Virginia

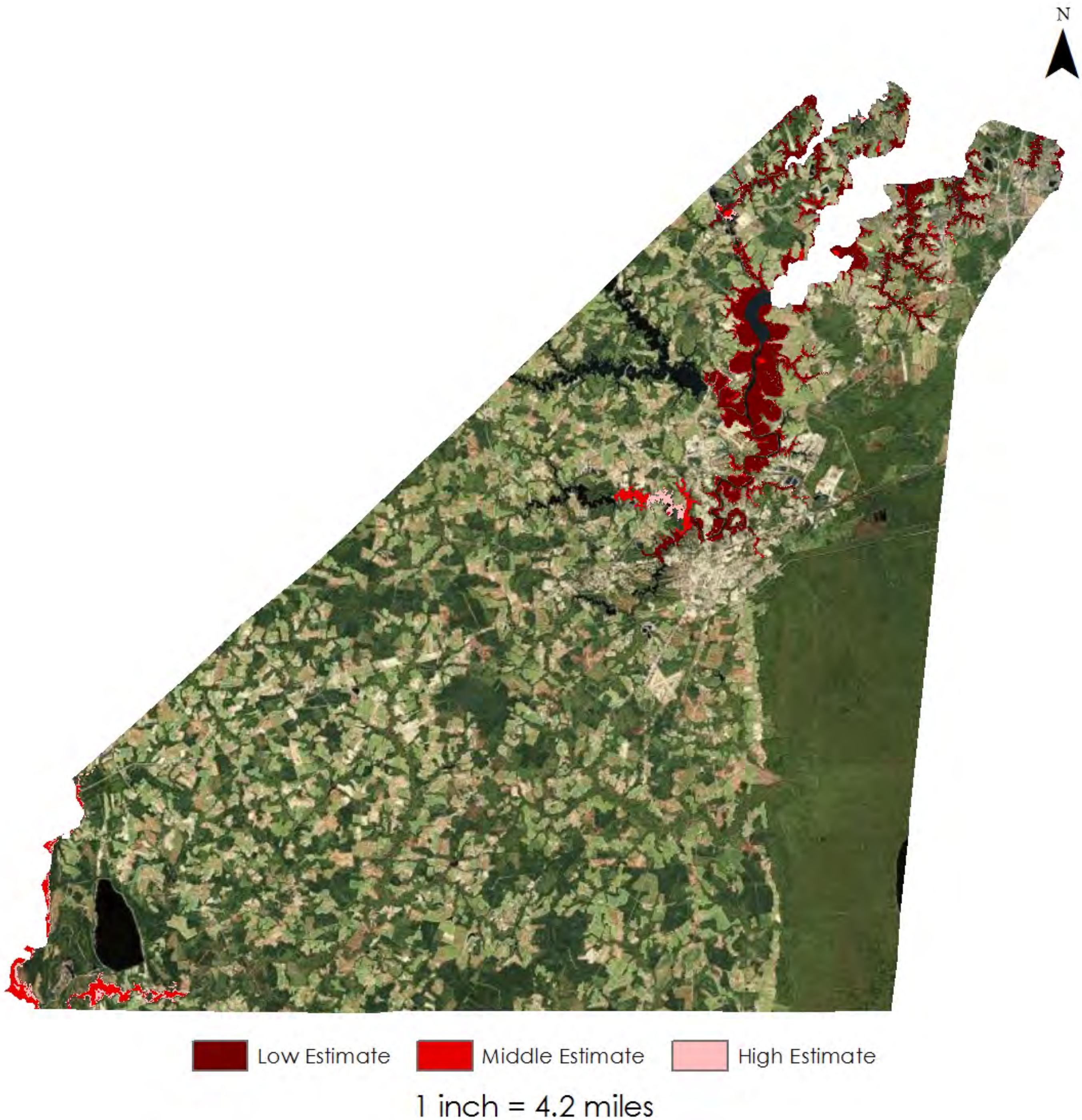

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Table 19: Exposure to One Meter of Sea Level Rise above Spring High Tide in Surry County, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	281.7	4.7	5.4	6.0
Population	7,058	98	107	124
Housing Units	3,444	52	59	70
BUILT ENVIRONMENT				
Number of Parcels (intersection)	6,508	382	445	526
Number of Parcels (centroid)	6,508	65	94	135
Improvement Value of Parcels (intersection)	$510,007,400	$52,204,100	$57,283,300	$64,129,800
Improvement Value of Parcels (centroid)	$510,007,400	$4,379,900	$6,757,200	$9,380,000
INFRASTRUCTURE				
Roads (total miles)	341.8	0.5	1.3	2.0
Roads (Interstate)	0.0	0.0	0.0	0.0
Roads (Primary)	48.5	0.0	0.0	0.0
Roads (Secondary)	252.6	0.3	1.0	1.5
Roads (Local or Private)	40.7	0.2	0.3	0.5
ECONOMY				
Businesses	209	0	0	0
Employees	1,931	0	0	0
Total Value of Parcels (intersection)	$1,051,099,800	$172,966,600	$187,203,600	$201,702,700
Total Value of Parcels (centroid)	$1,051,099,800	$12,221,300	$22,571,300	$27,867,700
NATURAL ENVIRONMENT				
Protected Lands (acres)	8,409	1,570	1,872	1,966
VEVA – Outstanding (acres)	16,371	157	166	180
VEVA – Very High (acres)	45,391	1,164	1,287	1,460
VEVA – High (acres)	40,962	1,434	1,609	1,743

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 24: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Surry County, Virginia

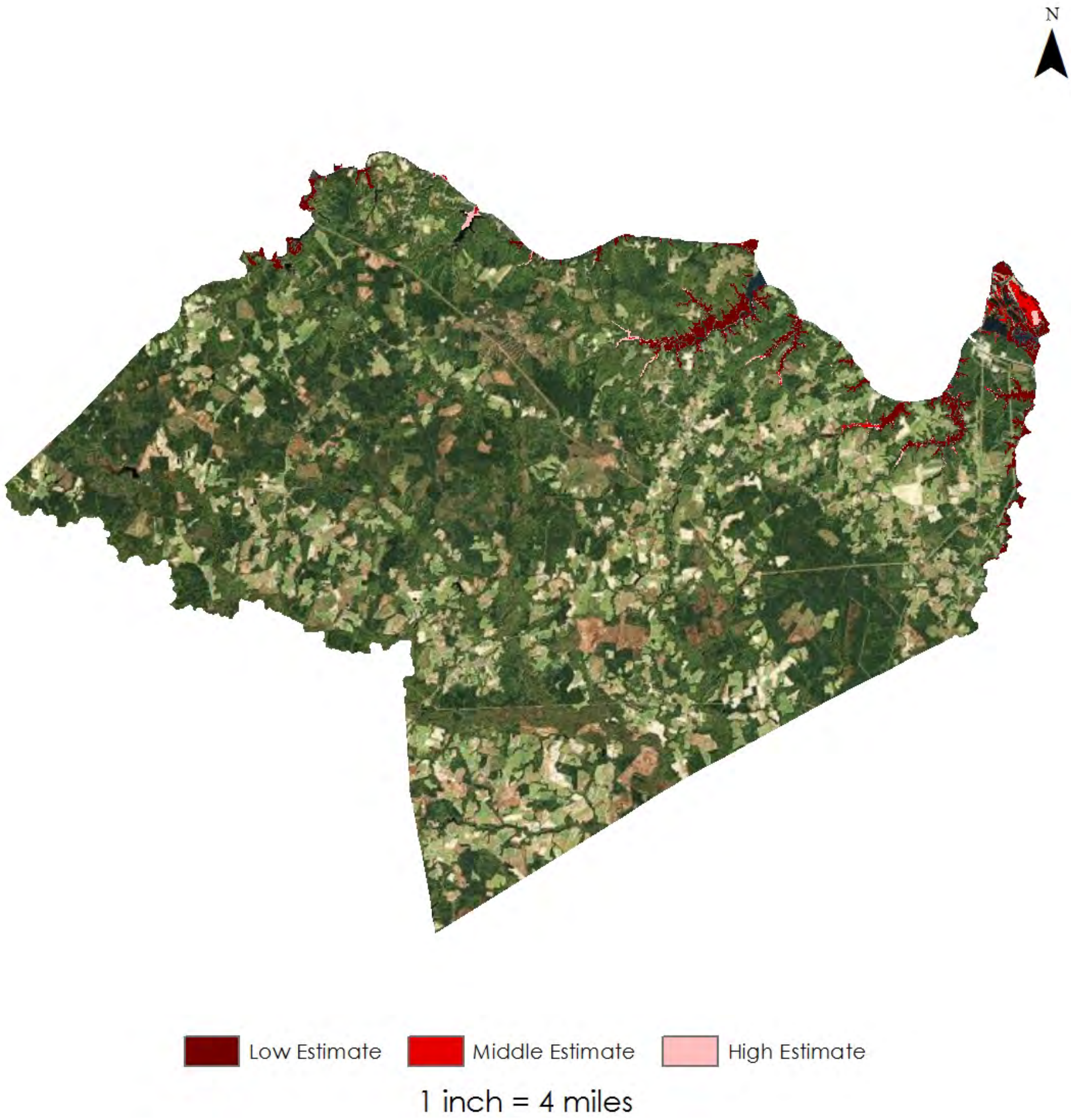

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Table 20: Exposure to One Meter of Sea Level Rise above Spring High Tide in Virginia Beach, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	258.3	49.9	58.0	89.1
Population	437,994	13,412	21,160	47,962
Housing Units	177,879	6,288	10,051	21,185
BUILT ENVIRONMENT				
Number of Parcels (intersection)	134,078	9,641	14,185	25,251
Number of Parcels (centroid)	134,078	3,599	5,843	14,337
Improvement Value of Parcels (intersection)	$27,395,409,467	$3,185,803,959	$4,096,732,259	$6,331,824,759
Improvement Value of Parcels (centroid)	$27,395,409,467	$793,935,950	$1,343,490,100	$2,823,490,109
INFRASTRUCTURE				
Roads (total miles)	1,982.0	36.0	66.9	188.6
Roads (Interstate)	28.3	0.2	0.2	0.5
Roads (Primary)	138.0	1.7	4.4	11.7
Roads (Secondary)	0.0	0.0	0.0	0.0
Roads (Local or Private)	1,815.6	34.2	62.3	176.4
ECONOMY				
Businesses	15,456	182	389	900
Employees	179,114	1,821	3,586	10,854
Total Value of Parcels (intersection)	$52,643,104,122	$7,804,380,210	$9,671,535,260	$13,992,056,092
Total Value of Parcels (centroid)	$52,643,104,122	$2,144,912,551	$3,358,135,232	$6,654,848,867
NATURAL ENVIRONMENT				
Protected Lands (acres)	46,077	16,367	18,015	23,031
VEVA – Outstanding (acres)	10,155	5,691	5,999	6,788
VEVA – Very High (acres)	34,690	16,386	17,638	22,494
VEVA – High (acres)	54,129	6,735	8,910	17,798

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 25: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Virginia Beach, Virginia

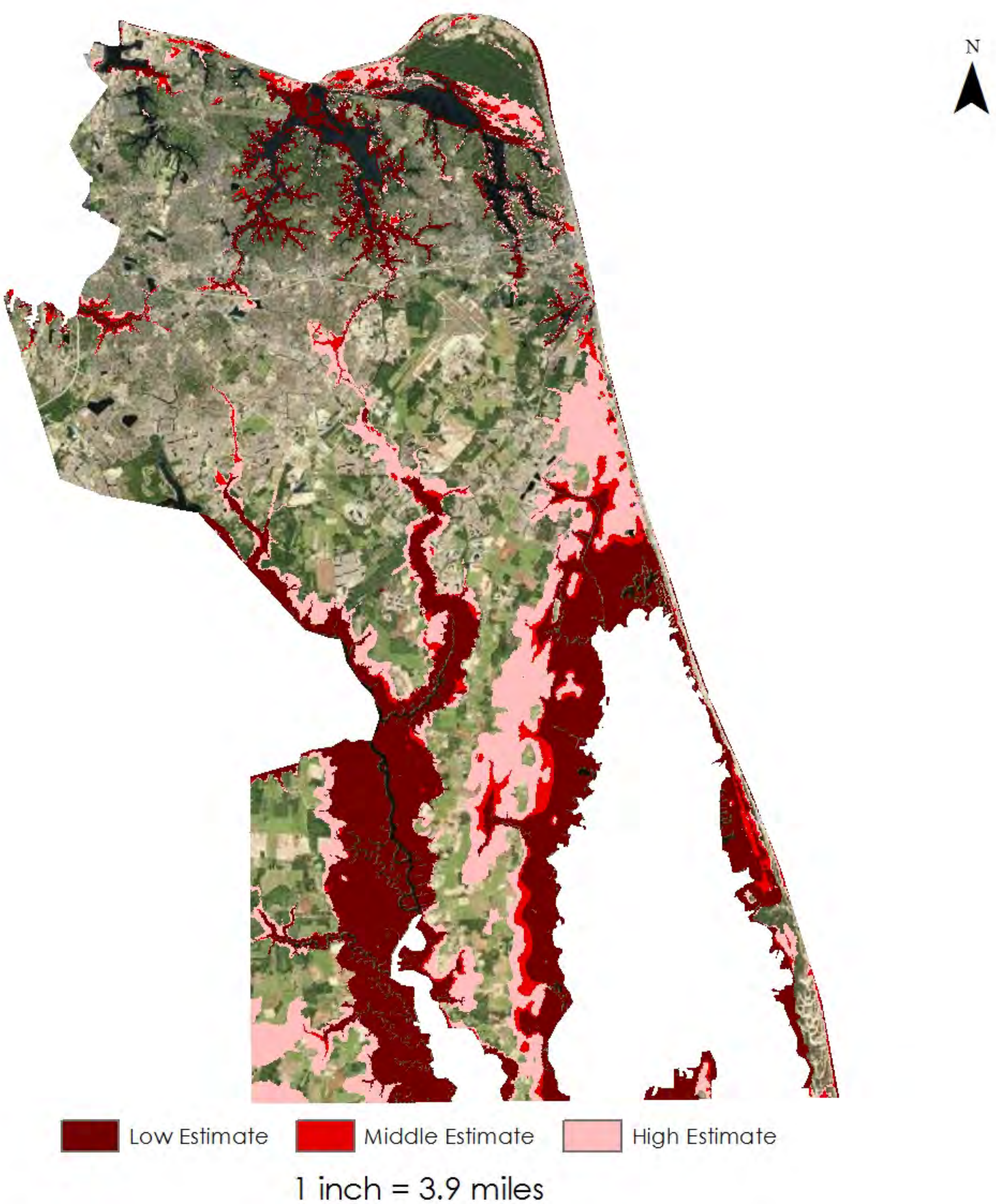

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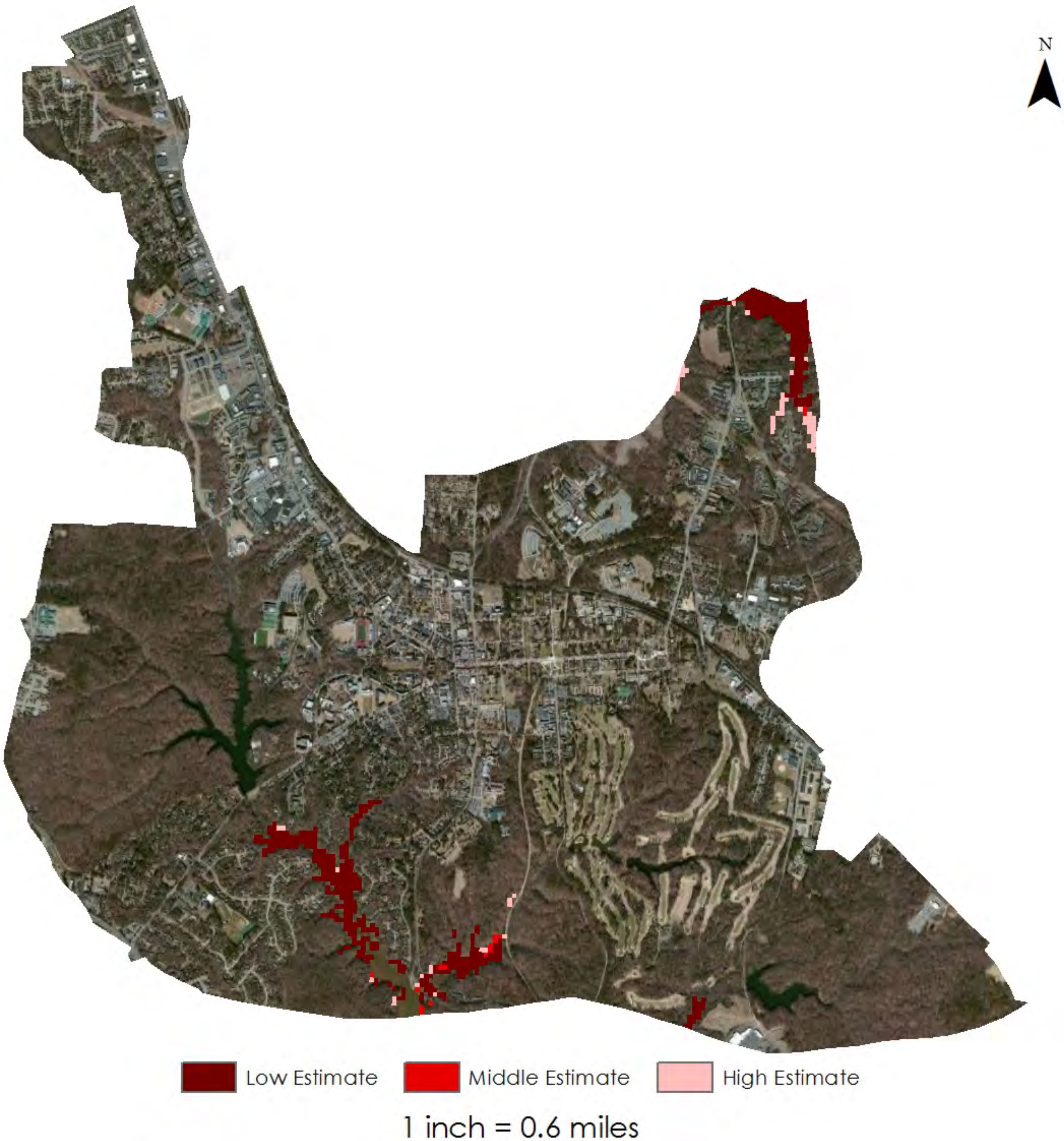
Table 21: Exposure to One Meter of Sea Level Rise above Spring High Tide in Williamsburg, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	8.7	0.2	0.2	0.2
Population	14,068	271	275	317
Housing Units	5,176	135	137	158
BUILT ENVIRONMENT				
Number of Parcels (intersection)	4,461	86	86	88
Number of Parcels (centroid)	4,461	14	15	16
Improvement Value of Parcels (intersection)	$1,604,982,000	$21,193,400	$21,193,400	$28,845,900
Improvement Value of Parcels (centroid)	$1,604,982,000	$695,100	$695,100	$695,100
INFRASTRUCTURE				
Roads (total miles)	95.8	0.1	0.1	0.2
Roads (Interstate)	0.0	0.0	0.0	0.0
Roads (Primary)	21.6	0.1	0.1	0.2
Roads (Secondary)	1.2	0.0	0.0	0.0
Roads (Local or Private)	73.0	0.0	0.0	0.0
ECONOMY				
Businesses	980	0	0	0
Employees	17,492	0	0	0
Total Value of Parcels (intersection)	$2,490,017,500	$59,209,200	$59,209,200	$69,289,800
Total Value of Parcels (centroid)	$2,490,017,500	$1,330,600	$1,332,200	$1,332,200
NATURAL ENVIRONMENT				
Protected Lands (acres)	854	0	0	1
VEVA – Outstanding (acres)	0	0	0	0
VEVA – Very High (acres)	890	12	12	13
VEVA – High (acres)	1,252	76	79	83

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 26: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, Williamsburg, Virginia



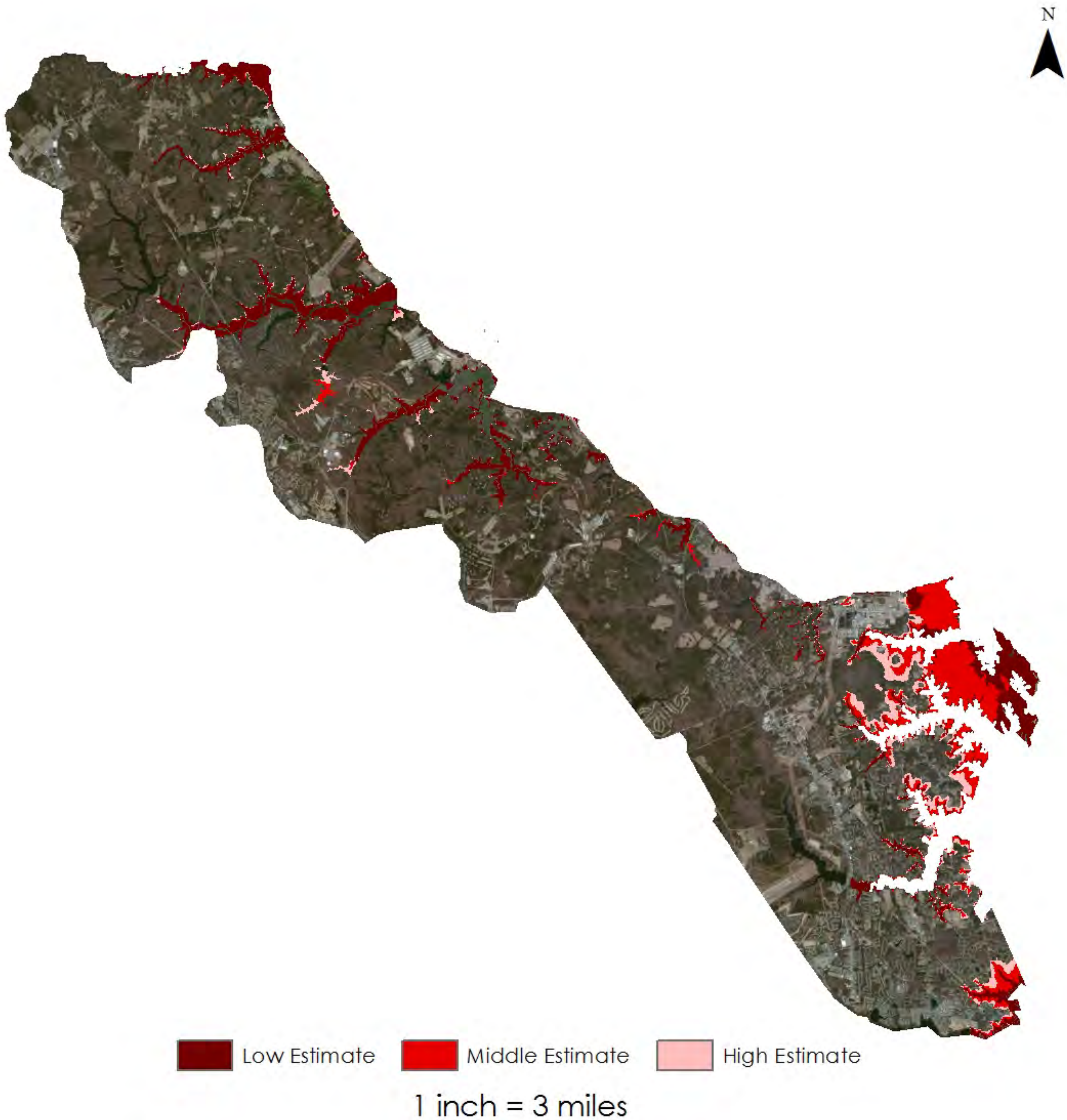
Disclaimer: This map is for informational purposes only. Areas depicted as vulnerables are based on estimates only and should not be construed as being in imminent danger of inundation. The analysis depicted does not account for flood protection or control infrastructure. This map should not be used in place of official FEMA flood insurance rate maps. Users agree to hold harmless and blameless the Hampton Roads Planning District Commission and its representatives and its agents for any liability associated with the use of this map.

Table 22: Exposure to One Meter of Sea Level Rise above Spring High Tide in York County, Virginia

	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
GENERAL				
Land Area (square miles)	108.1	7.1	11.0	12.9
Population	65,464	2,161	5,483	7,164
Housing Units	26,849	859	2,195	2,824
BUILT ENVIRONMENT				
Number of Parcels (intersection)	26,082	2,233	3,752	4,449
Number of Parcels (centroid)	26,082	667	2,548	3,340
Improvement Value of Parcels (intersection)	$7,313,116,800	$1,761,206,200	$2,122,659,500	$2,278,661,600
Improvement Value of Parcels (centroid)	$7,313,116,800	$107,801,400	$472,736,000	$633,820,300
INFRASTRUCTURE				
Roads (total miles)	697.5	9.9	34.6	47.6
Roads (Interstate)	22.5	0.3	0.3	0.3
Roads (Primary)	83.1	1.1	1.7	2.1
Roads (Secondary)	292.3	4.7	24.3	34.6
Roads (Local or Private)	299.6	3.8	8.4	10.6
ECONOMY				
Businesses	2,110	15	64	109
Employees	21,457	74	321	887
Total Value of Parcels (intersection)	$14,882,481,800	$6,222,276,400	$6,773,958,000	$7,019,887,200
Total Value of Parcels (centroid)	$14,882,481,800	$250,166,900	$967,125,700	$1,250,532,600
NATURAL ENVIRONMENT				
Protected Lands (acres)	20,317	1,285	1,394	1,558
VEVA – Outstanding (acres)	3,376	241	241	241
VEVA – Very High (acres)	13,902	1,896	2,177	2,303
VEVA – High (acres)	15,702	1,951	3,204	3,833

Note: More information on the centroid and intersection methodologies can be found on page 34.

Map 27: Areas Exposed to One Meter of Sea Level Rise above Spring High Tide, York County, Virginia



Disclaimer: This map is for informational purposes only. Areas depicted as vulnerables are based on estimates only and should not be construed as being in imminent danger of inundation. The analysis depicted does not account for flood protection or control infrastructure. This map should not be used in place of official FEMA flood insurance rate maps. Users agree to hold harmless and blameless the Hampton Roads Planning District Commission and its representatives and its agents for any liability associated with the use of this map.

SECTION V: RECOMMENDATIONS AND NEXT STEPS

This report has summarized the work of the third and final grant period of the Hampton Roads Planning District Commission's Climate Change Adaptation Focal Area Grant, funded in part by the Virginia Coastal Zone Management Program. The goals of this grant period were to refine and enhance the tools and analysis conducted in the first two years of the grant: to analyze the potential impacts of sea level rise on the region, its localities, and its residents; to involve the public and institutions in discussing and planning for climate change through education and engagement; and to develop ways in which local governments can begin planning for climate change. This report includes the results of an analysis of the vulnerability of the Hampton Roads region to sea level rise. The analysis shows that the region is significantly vulnerable to sea level rise and provides justification to localities to begin incorporating climate change and sea level rise into the planning and decision-making processes. Based on the research, analysis, and outreach conducted over the course of the entire focal area grant, HRPDC staff makes the following findings and recommendations:

Table 23: Findings and Recommendations

Findings	Recommendations
Hampton Roads does not yet have the necessary regionally consistent elevation data to accurately assess sea level rise impacts. While several localities have high-resolution elevation data (LIDAR), the quality and characteristics of the data is not necessarily sufficient for analyzing sea level rise.	HRPDC should continue to work to acquire the necessary data.
Sea level rise will be a major issue for several Hampton Roads localities. Potential impacts include the permanent loss of significant areas as well as the greater or new exposure of some areas to regular or storm flooding.	Localities should begin planning for sea level rise through their comprehensive plans and other plans and policies, including working with other stakeholders in the region, such as educational institutions and major government landowners and agencies.

Findings	Recommendations
There is not yet official state or federal regulatory guidance for addressing sea level rise at the community level. While considerable research has been done and recommendations have been made by both government agencies and non-governmental organizations, it has not been turned into official policies from the federal government or the Commonwealth that address how localities should address sea level rise. Effective adaptation will likely require some sort of partnership between local, state, and federal governments.	Hampton Roads should work with state and federal elected officials and staff to develop and fund guidance and assistance to affected communities.
The U.S. Army Corps of Engineers has developed guidance for incorporating sea level rise into infrastructure projects. This guidance incorporates both historical rates of relative sea level rise and projections of global sea level rise due to climate change.	Localities and other should consider using this guidance for project planning and design.
Subsidence and its impacts on local sea level rise rates are not well-documented.	The region should continue to study the causes and rates of subsidence in Hampton Roads and their impacts on relative sea level rise.
Effective adaptation strategies will vary based on context, feasibility, and popular support.	The region should continue studying potential strategies for adapting to sea level rise and other climate change impacts. This should include studying how existing regulatory authorities can be used to help localities adapt to sea level rise. The region should also work with other stakeholders, such as government agencies (especially those with significant landholdings in the region and/or technical expertise), academic institutions, non-governmental organizations, and private interests to develop the necessary support for these strategies.

Over the course of this focal area grant project, HRPDC staff has collaborated with many partners, including public agencies, local governments, and non-governmental organizations, to further discussion of sea level rise and climate change impacts in the region. Continued collaboration with these partners will be vital to developing effective and regionally appropriate sea level rise adaptation strategies and policies for Hampton Roads localities. HRPDC will continue to work with these organizations, including Old Dominion University, the University of Virginia, and the Virginia Institute of Marine Science, on future grants and projects. HRPDC is currently working with groups from Old Dominion University and the University of Virginia on related climate change projects. HRPDC staff will also explore opportunities to work with other partners.

Although the focal area grant project has ended, HRPDC staff will continue to plan for the region's responses to climate change through related Virginia Coastal Zone Management Program grants and other opportunities as they become available.

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APPENDIX A: OUTREACH AND COORDINATION

During the third year of HRPDC's climate change work, HRPDC staff continued efforts to reach out to the general public as well as local governments and other organizations. Most of these efforts consisted of presentations given to various groups and organizations, as well as some coordination meetings with other government actors. During this grant period, from October 2010 to December 2011, HRPDC staff participated in twenty-two (22) events and meetings. In addition to these efforts, HRPDC staff continued to work with several partners on related projects that promoted climate change education and adaptation. These related projects included:

- Collaborating with faculty from Old Dominion University to analyze the economic impacts of flooding on Hampton Roads localities and businesses
- Partnering with the Institute for Environmental Negotiation, Old Dominion University, Wetlands Watch, and the City of Virginia Beach to plan and implement a series of four public listening sessions in Virginia Beach that allowed the public to hear about and discuss the issues of sea level rise and flooding (described in the FY2009-2010 report[12]);
- Partnering with the Institute for Environmental Negotiation, Old Dominion University, Wetlands Watch, and the City of Virginia Beach to develop climate change and sea level rise material to be discussed by a focus group comprised of selected stakeholders in Virginia Beach;
- Collaborating with the Virginia Department of Transportation and faculty from the University of Virginia's School of Engineering and Applied Science on a pilot study funded by the Federal Highway Administration to assess the vulnerability of transportation infrastructure to climate change.

Two sample presentations are included in Appendix B. Attendance numbers are approximate. Presentations and meetings marked with an asterisk (*) overlapped with the previous year's grant; full descriptions are available in the FY2009-2010 report. HRPDC staff that participated in these outreach and coordination efforts included:

[12] *Climate Change in Hampton Roads Phase II: Storm Surge Vulnerability and Public Outreach*, available online at http://www.hrpdcva.gov/Documents/Phys%20Planning/2011/HRPDC_ClimateChange2010_FINAL.PDF.

- John Carlock, AICP, Deputy Executive Director
- Lisa Hardy, Physical and Environmental Planner
- Julia Hillegass, Public Information and Community Affairs Administrator
- Whitney Katchmark, P.E., Principal Water Resources Engineer
- J. Rax-McBride, Principal Regional Planner
- Benjamin McFarlane, AICP, Regional Planner

PRESENTATIONS & OUTREACH

Many of the events that HRPDC staff participated in during this grant year involved presentations to government staff or the public. Nine (9) of the events during this grant period are included in this category.

Table 24: Presentations and Outreach Events

DATE	DESCRIPTION
November 15, 2010*	Mr. McFarlane gave a presentation at a workshop organized by the Cabell Brand Center for Global Poverty and Resource Sustainability Studies. *Attendance: 15*
February 2, 2011*	Mr. McFarlane gave a presentation on climate change planning and HRPDC's climate change work to an online class taught by a professor at Old Dominion University. *Attendance: 5*
March 1, 2011*	Mr. Carlock and Mr. McFarlane gave a presentation to the Hampton Waterway Management Plan Steering Committee. *Attendance: 50*
April, 20, 2011	Mr. McFarlane gave a presentation to the York River Group Sierra Club on sea level rise planning in Hampton Roads. The presentation included an overview of HRPDC's climate change efforts, including an assessment of the region's vulnerability to storm surge. The presentation also included some discussion of the challenges involved in planning for climate change. *Attendance: 25*
April 25, 2011	Mr. McFarlane gave a presentation to a graduate class at Old Dominion University.[13] The presentation covered HRPDC's climate change efforts and included an assessment of the region's vulnerability to storm surge. *Attendance: 15*

[13] PADM 632 Environmental Planning, taught by Mr. Al Riutort

DATE	DESCRIPTION
June 16, 2011	Mr. McFarlane briefed the Hampton Roads Planning District Commission on the findings from the 2009-2010 grant year of climate change work. The report was approved for publication and distribution. *Attendance: 50*
September 28, 2011	Mr. McFarlane gave a presentation on planning for sea level rise and climate change from a regional perspective at a NASA Langley workshop, "Adapting to a Changing Climate". The workshop was attended by a wide range of NASA Langley researchers and facility staff. *Attendance: 40*
October 26, 2011	Mr. McFarlane gave a presentation as part of a stakeholder panel to the NOAA Hydrographic Services Review Panel at a meeting held in Norfolk, Virginia. The presentation described how HRDPC utilizes NOAA's Hydrographic Services, with an emphasis on tide gauge data used to plan for sea level rise. *Attendance: 40*
November 11, 2011	Mr. McFarlane gave a presentation, titled "Using GIS to Plan for Sea Level Rise in Hampton Roads", at Old Dominion University's GIS Day. The presentation included an overview of climate change science and its projected impacts on Hampton Roads and described how HRPDC staff was using GIS to identify and study those impacts. *Attendance: 30*

Coordination & Workshops

HRPDC staff also participated in several coordination meetings and workshops with other representatives from local, state, and federal agencies and governments. 13 (13) of the events during this grant period are included in this category. On occasion, these events also included HRPDC staff presentations.

Table 25: Coordination and Workshops

DATE	DESCRIPTION
February 1, 2011	HRPDC staff met with Drs. James Koch and Vinod Agarwal from Old Dominion University to discuss the need for a study of the economic impacts of sea level rise and flooding on Hampton Roads localities.
February 14, 2011	HRPDC staff met with Drs. Koch and Agarwal to discuss the particulars of a proposed joint project studying the economic impacts of flooding on Hampton Roads localities.

DATE	DESCRIPTION
March 22, 2011*	HRPDC staff met with staff from the U.S. Geological Survey and VIMS to discuss subsidence and sea level rise in Hampton Roads. *Attendance: 8*
April 9, 2011	Mr. McFarlane attended and participated in the American Planning Association's (APA) Delegate Assembly at the APA's National Conference in Boston, Massachusetts. The main focus of the assembly was a list of proposed changes to APA's Climate Change Policy Guide.
May 3, 2011	HRPDC staff met with Drs. Koch and Agarwal to discuss the particulars of a proposed joint project studying the economic impacts of flooding on Hampton Roads localities.
May 10, 2011	Mr. McFarlane participated in a storm surge prediction workshop at the Virginia Institute of Marine Science (VIMS). VIMS faculty described a Real-Time Storm Tide Observation and Forecast System they developed to deliver regularly updated predictions of tides for the Lower Chesapeake Bay.
August 10, 2011	Mr. McFarlane attended a sea level rise technical forum organized by Old Dominion University. The focus of the forum was to identify research and academic needs related to the impacts of sea level rise on regional infrastructure.
September 19, 2011	Mr. McFarlane met with faculty from the University of Virginia's School of Engineering and Applied Science to work on a decision support tool to help with transportation planning in the context of climate change.
September 22, 2011	Mr. McFarlane met with staff from Old Dominion University and Virginia Sea Grant to discuss a joint proposal for a Hampton Roads Climate Change Adaptation Forum that would be funded by the national Sea Grant program. *Attendance: 4*
September 26-27, 2011	Mr. McFarlane attended and participated in the FHWA Partner Exchange in Seattle, Washington. The exchange included presentations and status updates from each of the pilot studies, including a section by Mr. McFarlane on how the Virginia pilot study complemented HRPDC's climate change work.
October 25, 2011	Ms. Hillegass and Mr. McFarlane attended a Coastal Zone Program-sponsored workshop in Richmond on Civil Public Participation, designed to offer tips and techniques to planners and others working on climate change and other contentious issues to promote effective public participation.
December 6, 2011	HRPDC staff attended a meeting with representatives from the Federal Emergency Management Agency (FEMA), the U.S. Army Corps of Engineers, and their consultants to hear an update on the status and initial results of FEMA's Region III Storm Surge Study.

DATE	DESCRIPTION
December 12, 2011	HRPDC staff met with the Planning Directors, Public Works Directors, and their representatives from most Hampton Roads localities to discuss regional and local efforts and possible coordination between localities to address flooding and sea level rise. *Attendance: 22*

Old Dominion University/HRPDC Collaboration

At the July 21, 2010 Quarterly Commission Meeting, Dr. James Koch from Old Dominion University (ODU) gave a presentation to the Commission on the issue of sea level rise and proposed an analysis of the financial and economic implications on the region and the need for LIDAR elevation data. Following this presentation, Dr. Koch worked with HRPDC staff to develop the proposed study into a detailed proposal, which was then presented and approved at the Commission's September 15, 2010 Executive Committee Meeting. HRPDC staff worked with Dr. Koch and Dr. Vinod Agarwal, a Professor of Economics at ODU, to identify needed data for the study and to divide tasks between ODU and HRPDC. Data collected for this study included population and housing unit numbers from the U.S. Census, employment and business data, and property assessments from the region's localities. This study is ongoing.

FHWA Pilot Study

In July 2010 staff from the Virginia Department of Transportation contacted the Hampton Roads Transportation Planning Organization (HRTPO) and HRPDC to discuss the possibility of a joint application for a pilot study funded by the Federal Highway Administration (FHWA) studying the vulnerability of transportation infrastructure to climate change. FHWA established this program to fund metropolitan planning organizations (MPOs) and state departments of transportation (DOTs) to pilot a conceptual model FHWA developed to conduct vulnerability and risk assessments of transportation infrastructure to climate change impacts.[14] This conceptual model consists of three main steps: inventorying (transportation) assets, gathering relevant climate information, and assessing the risk to the identified assets from climate change impacts.[15] Five agencies and agency partnerships were funded: the Metropolitan Transportation Commission (San Francisco, California); New Jersey DOT/North Jersey Transportation Planning Authority (Coastal and Central New Jersey); VDOT (Hampton Roads, Virginia); Washington Department of Transportation

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[14] http://www.fhwa.dot.gov/hep/climate/pilots.htm
[15] http://www.fhwa.dot.gov/hep/climate/conceptual_model62410.htm

(Washington State); and Oahu MPO (Island of Oahu, Hawaii). The pilot studies were completed in November 2011. HRPDC and HRTPO staff worked with representatives from VDOT and researchers from the University of Virginia to develop and implement the proposal, which was to develop an analysis framework for incorporating climate change impacts into the region's transportation planning processes. HRPDC staff contributed information on the general impacts of climate change on the Hampton Roads region and on transportation infrastructure. In addition, HRPDC staff helped the research team devise scenarios for reassessing the region's transportation priorities, based on climate change and other factors. The project included briefings by the UVA research team to both the HRPDC's Joint Environmental Committee (comprised mainly of planners, public works staff, and stormwater management) and the HRTPO's Transportation Technical Advisory Committee. These briefings included opportunities for the region's local governments to provide direct feedback to the research team. HRPDC staff also worked directly with the research team in Charlottesville, Virginia, and attended a Partner Exchange Workshop in September 2011 in Olympia, Washington along with the project teams from each of the other pilot studies. During this meeting, the Virginia research team, including HRPDC staff, presented a project status report and described how the project complemented the region's other climate change planning efforts. After this workshop HRPDC and HRTPO staff continued to work with the research team to refine the tool and discuss how it could be utilized in the HRTPO's upcoming 2040 long-range transportation plan. These discussions are ongoing. More information about the Hampton Road FHWA pilot study is available on the project's website: http://www.virginia.edu/crmes/fhwa_climate/.

UVA Institute for Environmental Negotiation

HRPDC staff continued to work with the Institute for Environmental Negotiation (IEN) in 2011 and 2012 to build upon the four listening sessions conducted in Virginia Beach in March 2011. The focus of the second year of work was on developing material for a workshop with a small group of participants. HRPDC staff worked with IEN, Wetlands Watch, and the City of Virginia Beach to develop an agenda and informational material for participants. IEN and graduate planning students at the University of Virginia produced two reports that documented the results of the listening sessions and case study research; the findings were presented to the Virginia Beach City Council on May 17, 2011.

Appendix B: Sample Presentations

The following appendix contains slides from two presentations given by HRPDC staff on work for this project. The first presentation was given to a graduate student class at Old Dominion University on April 25, 2011. The second presentation was given to the Hampton Roads Planning District Commission on June 16, 2011. The event is described in greater detail in Appendix A.

CLIMATE CHANGE AND SEA LEVEL RISE IN HAMPTON ROADS

Benjamin McFarlane
Regional Planner
Hampton Roads Planning District Commission

April 25, 2011

What is the HRPDC?

- 1 of 21 Regional Planning Agencies
- State enabled; locally created
- 16 Cities & Counties; several Towns; 1.7 million people; 3,000 square miles; 5,000 miles shoreline
- Commission – 45 local elected officials & CAO
- Staff – Executive Director & 45 staff
- Funding – Local contributions, grants, and contracts
- Functions – Economics, Housing, Transportation, Environmental, Emergency Management
- Budget $12,000,000 +
- Role – Policy & Technical Analysis, Planning & Engineering Studies, Cooperative Problem Solving, Coordination

What does HRPDC do?

- The Commission:
  - "**serves as a forum** for local and elected officials and chief administrators to **deliberate** and **decide** issues of **regional importance**"
- The Staff:
  - "provides the local governments and citizens of Hampton Roads credible and timely **planning, research, and analysis** on matters of mutual concern, and"
  - "**provides leadership and offers strategies and support services** to other public and private, local, and regional agencies, in their efforts to improve the region's quality of life."

What is Climate Change?

- Climate change refers to changes in long-term weather patterns
- "Greenhouse gas effect" main driver of climate change
  - Additional GHG emissions from human activity causing an increase in global average temperature
- 3 main effects:
  1. Temperature rise
  2. Changing precipitation patterns
  3. Sea level rise

Rising Temperatures

- Global average temperature has increased by 1.5°F since 1900
- Projected to increase a further 2-11.5°F by 2100
- Governor's Commission: +5.6°F(3.1°C) in Virginia by 2100

Changing Precipitation Patterns

- 11% overall increase in precipitation in Virginia (Governor's Commission)
- More concentrated rainfall punctuated by longer periods of dry weather
- More intense storm events
- Effect on quantity of storm events is uncertain

Sea Level Rise

- Global sea level rise caused by combination of thermal expansion and melting ice (considerable uncertainty with latter)
- Local sea level rise affected by ocean currents, winds, and subsidence
- Observed SLR of 4.42 mm/yr at Sewell's Point since 1927
- IPCC: 0.21-0.48m (8-19 inches) global sea level rise
- Chesapeake Bay Program: 0.7-1.6m (2.3 – 5.2 feet) along the Chesapeake Bay

Sector Impacts: Built Environment

- More frequent and persistent flooding from storm surge
- Permanent inundation of some areas if not protected
- Risk to industry and private property
- Infrastructure at risk: transportation, military, etc.

Sector Impacts: Natural Environment

- Flooding
- Inundation
- Species shifts
- Reduced water quality
- Ecosystem loss or transition
- Erosion
- Wetlands drowning

Sector Impacts: Water Supply

- Changes to available water supply from surface sources due to altered rainfall
- Changes to frequency and volume of precipitation will impact water supply infrastructure
- Potential reduced supplies during longer periods of dry weather
- Overwhelmed storage capacity during larger storm events
- Water quality impacts

Sector Impacts: Economy

- Damage to private and public property from storms and sea level rise
- Infrastructure at risk
- Vulnerable industries: tourism, shipping and shipbuilding, military
- Opportunities: wind energy development and logistical support, modeling and simulation

Sector Impacts: Socioeconomic

- Potential for injury and death during storm events and associated flooding
- Potential increases in diseases from air pollution as well as warm climate diseases
- Social justice concerns: some groups more vulnerable to climate change impacts

Hampton Roads Climate Change and Sea Level Rise Adaptation Initiative

- 3-year grant project with the Virginia Coastal Zone Management Program
- Year 1: Begin stakeholder process and identify broad impacts of climate change on Hampton Roads
- Year 2: Assessment of impacts and development of policy recommendations
- Year 3: Analysis of infrastructure and economic impacts and completion of the regional framework for mitigation and adaptation to climate change

Hampton Roads Climate Change and Sea Level Rise Adaptation Initiative

- Three parts:
  1. Coordination
  2. Outreach
  3. Research and Analysis

Coordination

- Working with other organizations and institutions to promote awareness of sea level rise and flooding issues in Hampton Roads
- ODU Initiative
- UVA-CRMES: Vulnerability of transportation infrastructure
- ODU: Economic impacts of flooding and sea level rise
- Storm Surge modeling with VIMS

Outreach

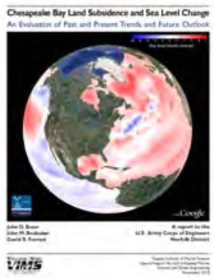
- Engaging local governments, citizens, and stakeholders through public meetings
- UVA-IEN/Wetlands Watch: Listening sessions in Virginia Beach
- Other public meetings to city councils and citizen groups

Research and Analysis

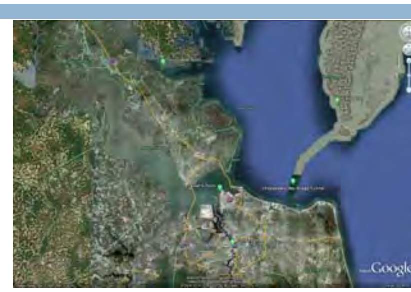
- HRPDC Climate Change/Sea Level Rise Impact Analysis and Policy Development
  - 3-year grant project with the Virginia Coastal Zone Management Program
  - Year 1: Begin stakeholder process and identify broad impacts of climate change on Hampton Roads
  - Year 2: Assessment of impacts and development of policy recommendations
  - Year 3: Analysis of infrastructure and economic impacts and completion of the regional framework for mitigation and adaptation to climate change

Identifying the Problem

- Sea level rise is both global and local
- Global rates combines steric and eustatic SLR
- Local rates include the movement of land relative to water



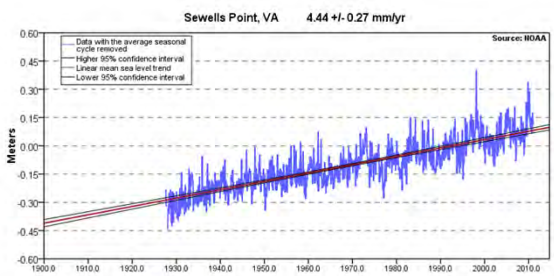
NOAA Tide Stations



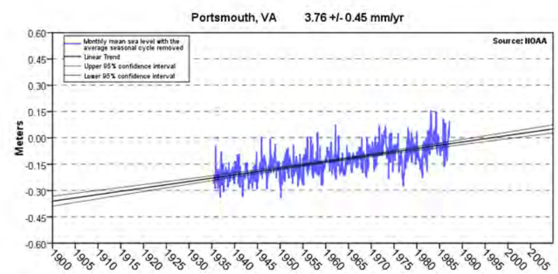
NOAA Tide Stations in Hampton Roads that measure sea level trends

www.tidesandcurrents.noaa.gov

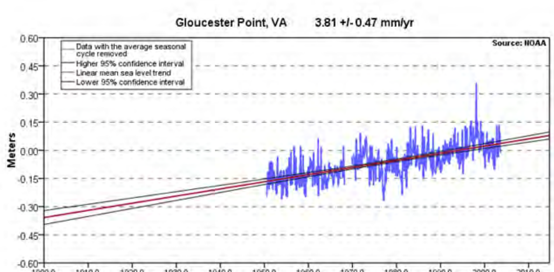
Norfolk, VA



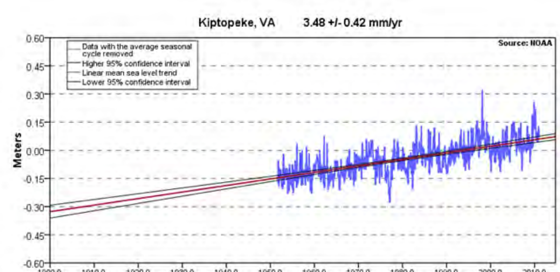
Portsmouth, VA



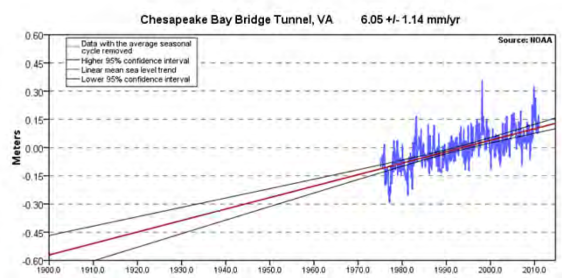
Gloucester County, VA



Northampton County, VA

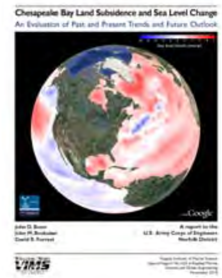


Chesapeake Bay



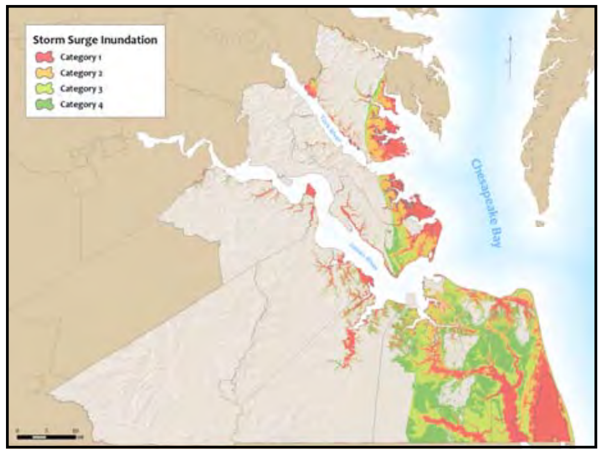
Identifying the Problem

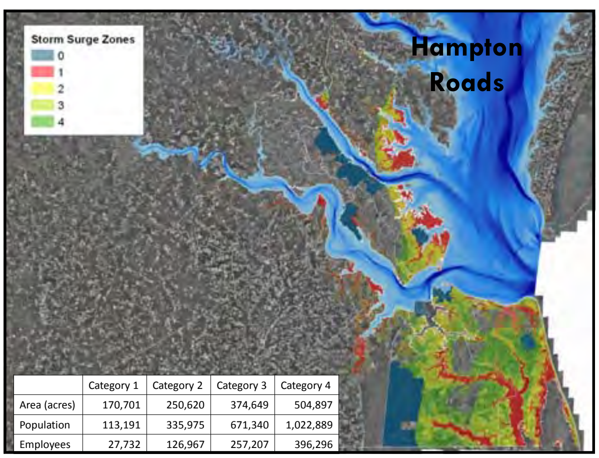
- The causes and the rate of local sea level rise are both important.
- In Hampton Roads, absolute sea level rise rates seem to be lower than average, but "local subsidence more than makes up for it."



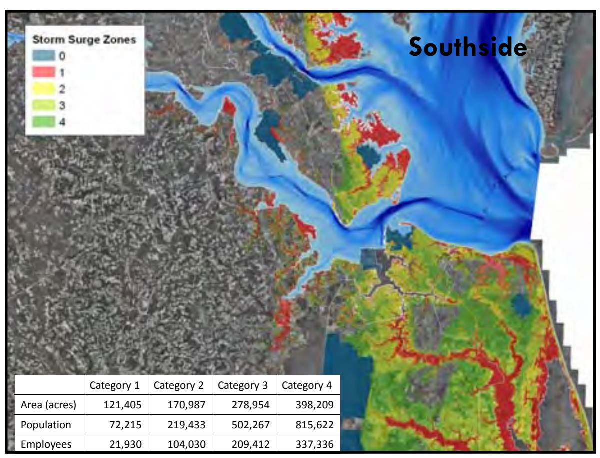
Analyzing Impacts and Vulnerability

- Estimates of population, economic activity, natural resources, and infrastructure at risk of temporary or permanent inundation from storm surge or sea level rise
- Data
  - Aerial imagery: Virginia Base Mapping Project (2009)
  - Population: U.S. Census Bureau (2010 Census)
  - Employment: Esri Business Analyst (2009)
  - Storm Surge: Virginia Department of Emergency Management (2007)

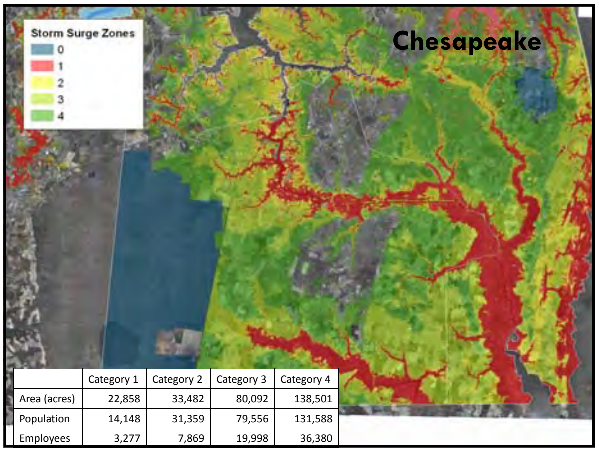




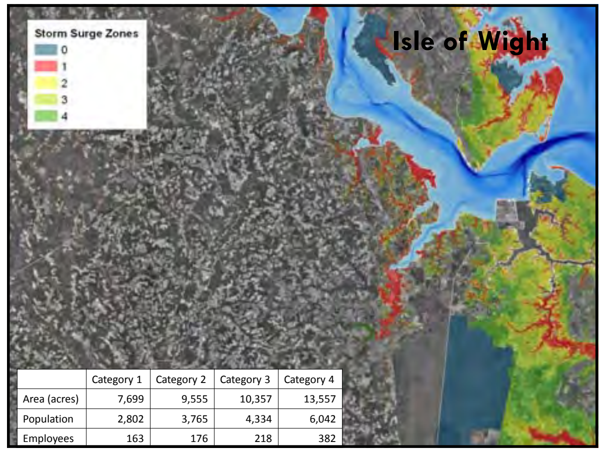
	Category 1	Category 2	Category 3	Category 4
Area (acres)	170,701	250,620	374,649	504,897
Population	113,191	335,975	671,340	1,022,889
Employees	27,732	126,967	257,207	396,296



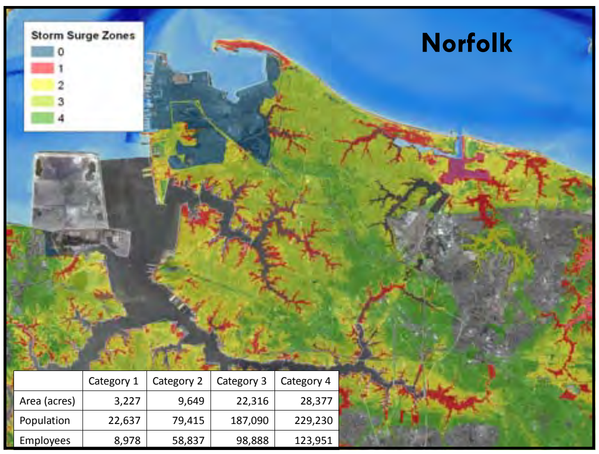
	Category 1	Category 2	Category 3	Category 4
Area (acres)	121,405	170,987	278,954	398,209
Population	72,215	219,433	502,267	815,622
Employees	21,930	104,030	209,412	337,336



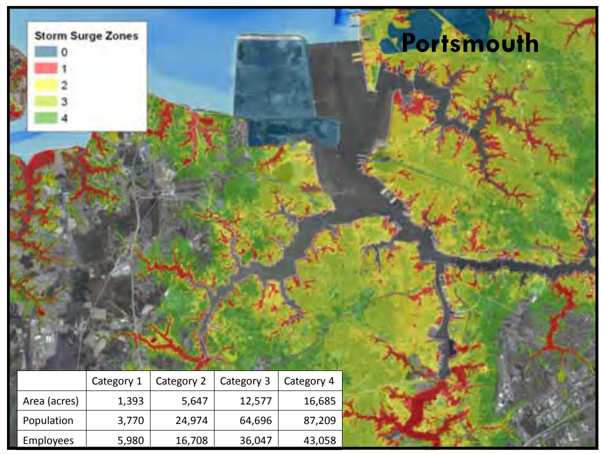
	Category 1	Category 2	Category 3	Category 4
Area (acres)	22,858	33,482	80,092	138,501
Population	14,148	31,359	79,556	131,588
Employees	3,277	7,869	19,998	36,380



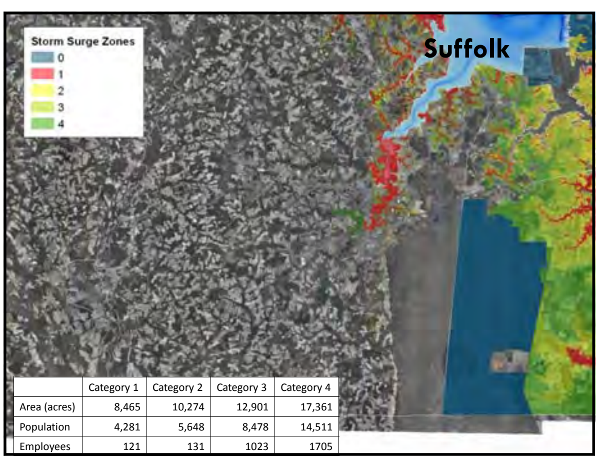
	Category 1	Category 2	Category 3	Category 4
Area (acres)	7,699	9,555	10,357	13,557
Population	2,802	3,765	4,334	6,042
Employees	163	176	218	382



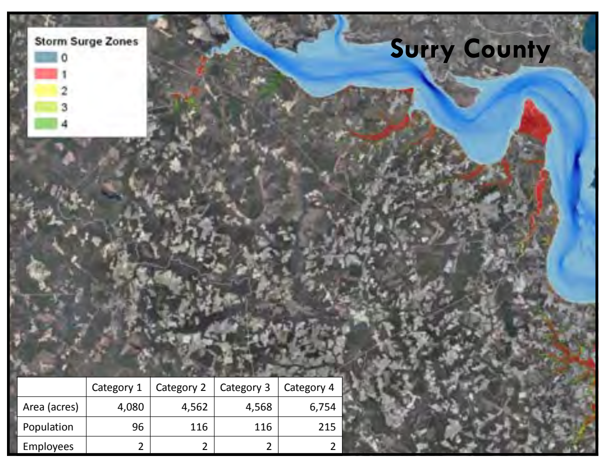
	Category 1	Category 2	Category 3	Category 4
Area (acres)	3,227	9,649	22,316	28,377
Population	22,637	79,415	187,090	229,230
Employees	8,978	58,837	98,888	123,951



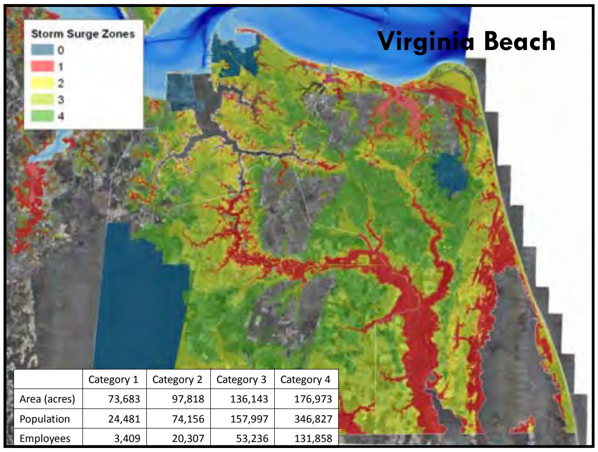
	Category 1	Category 2	Category 3	Category 4
Area (acres)	1,393	5,647	12,577	16,685
Population	3,770	24,974	64,696	87,209
Employees	5,980	16,708	36,047	43,058



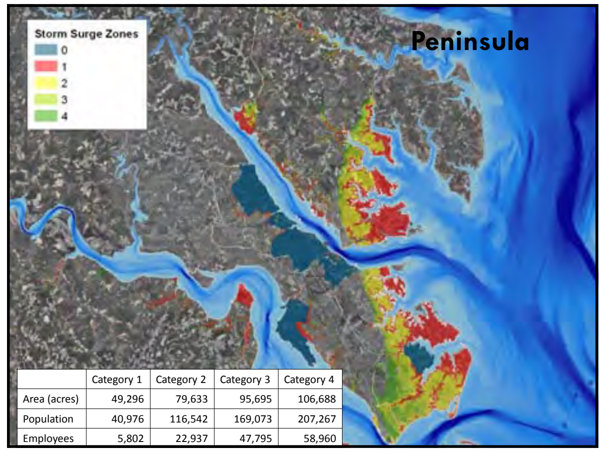
	Category 1	Category 2	Category 3	Category 4
Area (acres)	8,465	10,274	12,901	17,361
Population	4,281	5,648	8,478	14,511
Employees	121	131	1023	1705



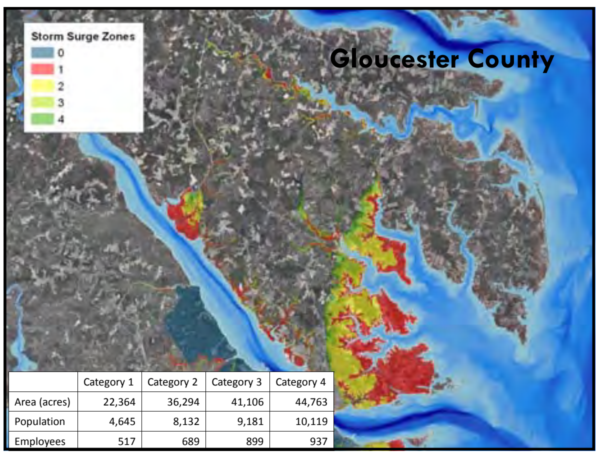
	Category 1	Category 2	Category 3	Category 4
Area (acres)	4,080	4,562	4,568	6,754
Population	96	116	116	215
Employees	2	2	2	2



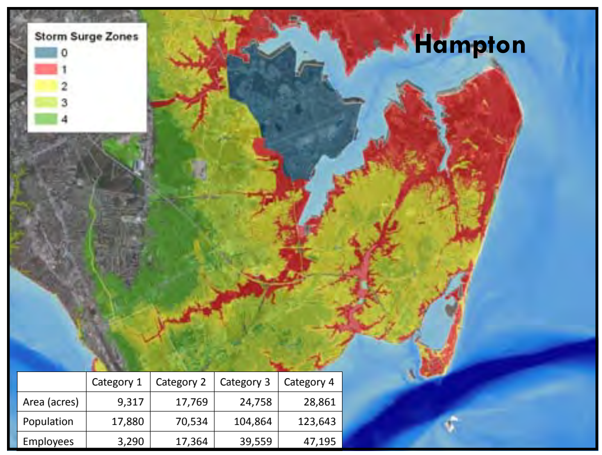
	Category 1	Category 2	Category 3	Category 4
Area (acres)	73,683	97,818	136,143	176,973
Population	24,481	74,156	157,997	346,827
Employees	3,409	20,307	53,236	131,858



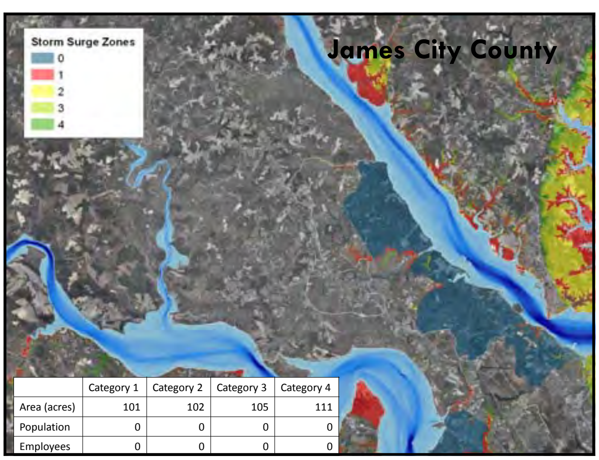
	Category 1	Category 2	Category 3	Category 4
Area (acres)	49,296	79,633	95,695	106,688
Population	40,976	116,542	169,073	207,267
Employees	5,802	22,937	47,795	58,960



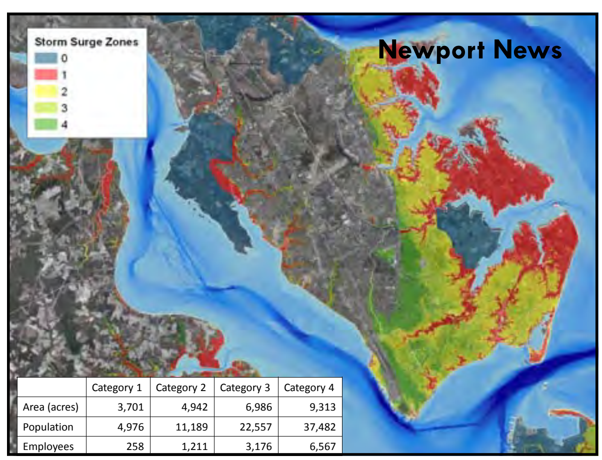
	Category 1	Category 2	Category 3	Category 4
Area (acres)	22,364	36,294	41,106	44,763
Population	4,645	8,132	9,181	10,119
Employees	517	689	899	937



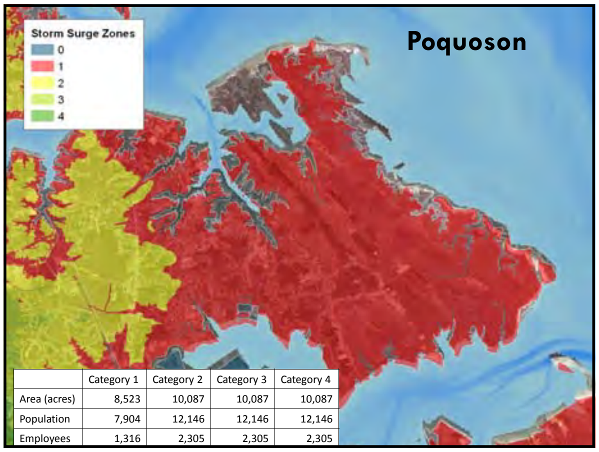
	Category 1	Category 2	Category 3	Category 4
Area (acres)	9,317	17,769	24,758	28,861
Population	17,880	70,534	104,864	123,643
Employees	3,290	17,364	39,559	47,195



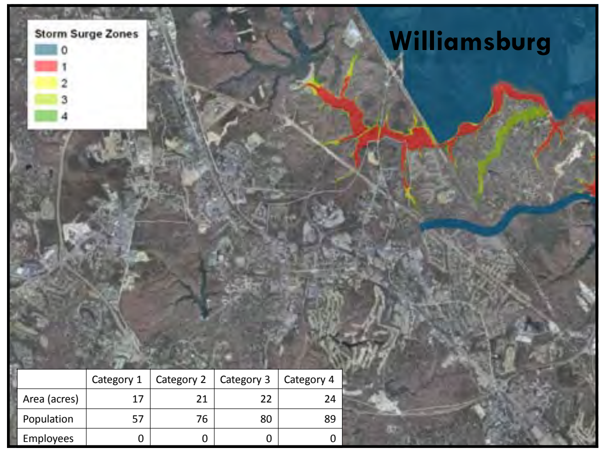
	Category 1	Category 2	Category 3	Category 4
Area (acres)	101	102	105	111
Population	0	0	0	0
Employees	0	0	0	0



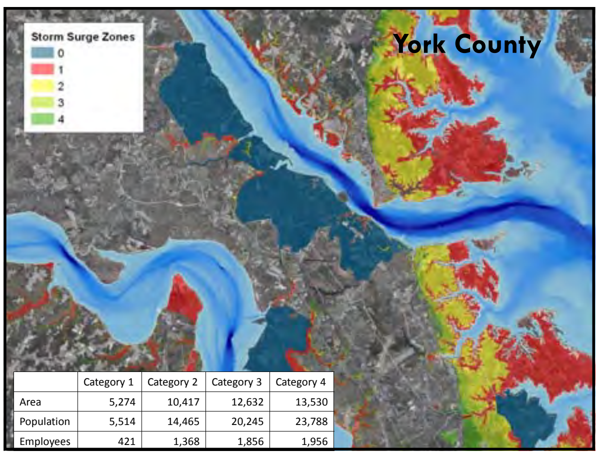
	Category 1	Category 2	Category 3	Category 4
Area (acres)	3,701	4,942	6,986	9,313
Population	4,976	11,189	22,557	37,482
Employees	258	1,211	3,176	6,567



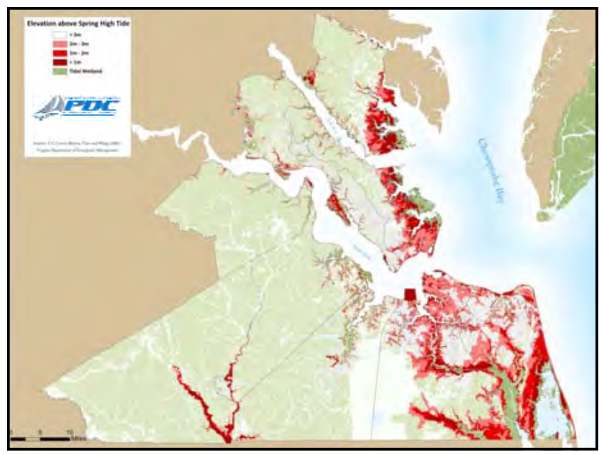
	Category 1	Category 2	Category 3	Category 4
Area (acres)	8,523	10,087	10,087	10,087
Population	7,904	12,146	12,146	12,146
Employees	1,316	2,305	2,305	2,305



	Category 1	Category 2	Category 3	Category 4
Area (acres)	17	21	22	24
Population	57	76	80	89
Employees	0	0	0	0



	Category 1	Category 2	Category 3	Category 4
Area	5,274	10,417	12,632	13,530
Population	5,514	14,465	20,245	23,788
Employees	421	1,368	1,856	1,956



Exploring Options for Adaptation

- Mitigation: reducing the amount of sea level rise that occurs
- Adaptation
  - Protection (seawalls, storm surge barriers)
  - Accommodation (elevating structures, beach nourishment)
  - Retreat (setbacks, easements)
- Near-term vs. Long-term solutions
  - Storm and Tidal Flooding ≠ Sea Level Rise

Adapting to Climate Change

- Adaptation will have some negative impacts
  - Dikes prevent flooding, but also prevent wetlands from migrating inland
  - Seawalls reduce erosion and protect against flooding, but result in the elimination of the beach and increased erosion at edges
- It will also be expensive
  - Seawall: >$6,500 in 2009 dollars (Herberger et al.)

Planning for Climate Change

- Challenges
  - Legal: What authorities to local and regional governments/agencies have?
  - Economic: How much adaptation can localities afford?
  - Political: How do localities and regions decide which areas to protect and which to retreat from?
  - Scientific: How do localities and regions know which areas are vulnerable and how much they will be affected?

Planning for Climate Change

- Incorporate sea level rise and precipitation projections into building and infrastructure location and construction
- Alter zoning codes to reduce construction in vulnerable areas, through density restrictions, setbacks, and easements

Next Steps

- Engagement and discussions with stakeholders: local governments, businesses, citizens, other stakeholders
- More data and better models are needed to understand impacts
  - Consistent High-resolution elevation data (LiDAR)
  - Sea level rise and storm surge models
  - Natural system responses

Climate Change Resources

- Intergovernmental Panel on Climate Change (www.ipcc.ch)
- Pew Center on Global Climate Change (www.pewclimate.org)
- U.S. Global Change Research Program (formerly Climate change Science Program) (www.globalchange.gov)

Climate Change Initiatives

- Local
- Regional
- State

Questions?

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CLIMATE CHANGE IN HAMPTON ROADS

PHASE II: STORM SURGE VULNERABILITY AND PUBLIC OUTREACH

Agenda Item #23

Presented to the
Hampton Roads Planning District Commission

June 16, 2011

Benjamin J. McFarlane
Regional Planner

Report Organization

2

- **Sea Level Rise in Hampton Roads**
- Case Studies
- **Data**
- **Methodology**
- **Results**
- Public Outreach
- Policy Options
- **Conclusions and Next Steps**

Sea Level Rise in Hampton Roads

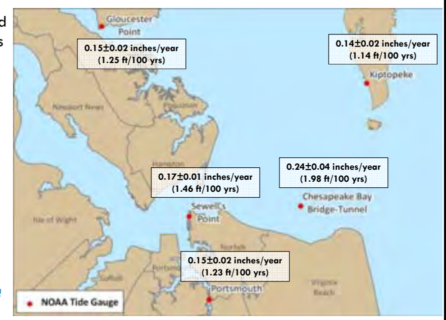
3

- Absolute sea level rise refers to the increase in mass or volume of the oceans
  - Typically reported as a global average
- Relative sea level rise is measured at the local level and includes the vertical movement of land
  - Typically reported for specific points such as tide gauges

Sea Level Rise in Hampton Roads

4

- Trends are based on measurements from last 30 to 80 years
- Regional average is 1-2 feet of sea level rise over 100 years



Data and Methodology

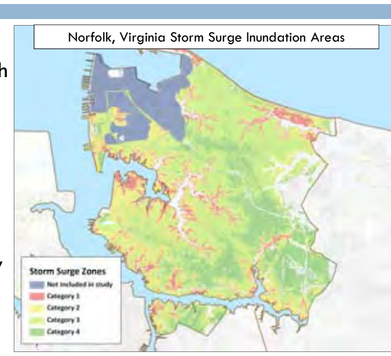
5

- Developed based on case study research and available data
- Use asset datasets from several sources with storm surge areas to estimate regional and local vulnerability to hurricane storm surge flooding and sea level rise
- Use geographic information systems (GIS) analysis to show which assets are in vulnerable areas and sum the results by locality and storm surge category

Results – Norfolk (example)

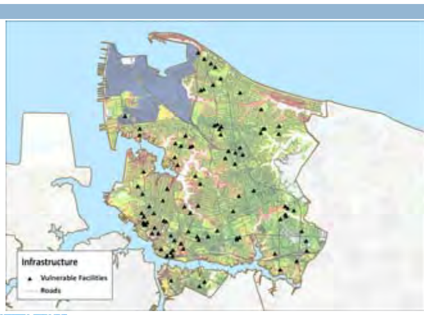
6

- Local results are included for each of the twelve Hampton Roads localities included in the 2008 Virginia Hurricane Evacuation Study



Results – Norfolk (example)

7



Roads and Critical Infrastructure Vulnerable to Storm Surge in Norfolk, Virginia

Results – Norfolk (example)

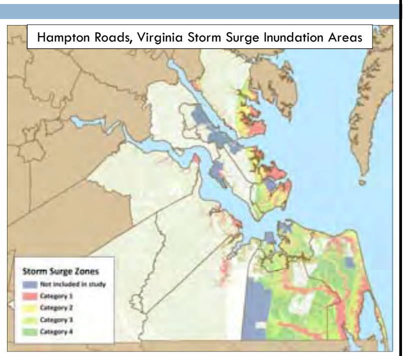
8

Businesses Vulnerable to Storm Surge in Norfolk, Virginia

Results – Region

9

- Overall, high level of exposure to storm surge across the region
- Southside is more vulnerable to larger events than the Peninsula
- Significant population, infrastructure, critical facilities, and businesses at risk



Conclusions

10

- Hampton Roads is significantly vulnerable to storm surge and sea level rise
- Baseline assumption of sea level rise equal to historical trend is appropriate
- Acceleration of sea level rise will depend on many factors, so it should be monitored and planning assumptions updated as needed
- New data should be incorporated as available

Next Steps

11

- HRPDC staff will continue:
  - To analyze regional vulnerability to sea level rise using elevation data
  - To research and develop policy options
  - To work with other regional partners, such as ODU and VIMS, on related projects

Recommended Action

12

- Approve report for distribution

Appendix C: Climate Change Adaptation Work By Other Coastal-Zone PDCs

Several other Planning District Commissions in Virginia's Coastal Zone have also been working on climate change-related projects along with the Hampton Roads Planning District Commission. Two of these, the Middle Peninsula Planning District Commission (MPPDC) and the Northern Virginia Regional Commission (NVRC), were funded under the same Virginia Coastal Zone Management Program (VCZMP) Focal Area Grant program as HRPDC. In addition, the Northern Neck Planning District Commission (NNPDC) has been working to incorporate climate change impacts into its blue and green infrastructure planning efforts. Links to these efforts are listed below.

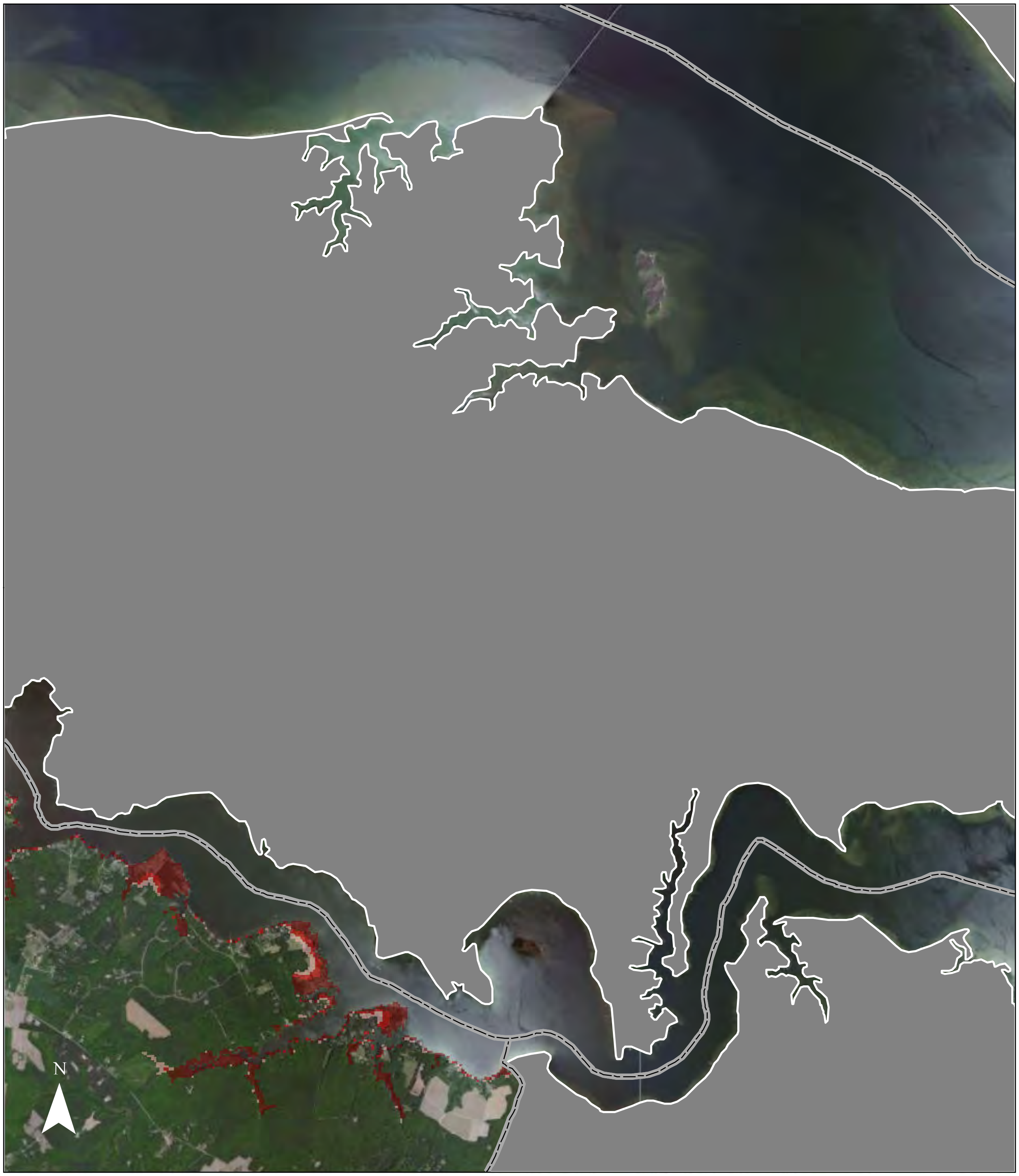
Table 26: PDC Climate Change Projects in the Virginia Coastal Zone

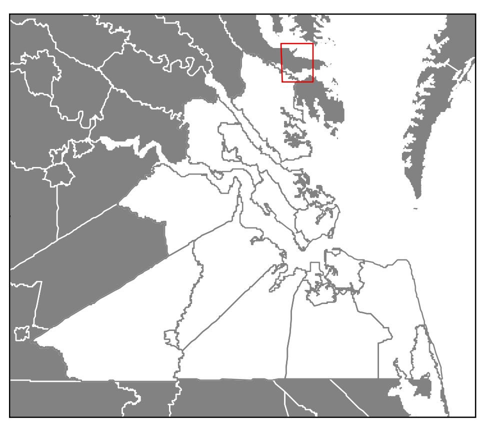
Organization	Project Name	Website
MPPDC	Climate Change Phase 1, 2, 3	http://www.mppdc.com/index.php/climate-change-phase-123
MPPDC	Middle Peninsula Sea Level Rise Assessment	http://www.mppdc.com/index.php/reports/2009
NVRC	Sustainable Shorelines Community Management	http://novaregion.org/index.aspx?nid=968
VCZMP	Virginia CZM Program Climate Adaptation Efforts	http://www.deq.virginia.gov/Programs/CoastalZoneManagement/CZMIssuesInitiatives/ClimateChange.aspx

APPENDIX D: HAMPTON ROADS SEA LEVEL RISE MAP BOOK

The following appendix contains a map book showing all the areas identified in this analysis as potentially vulnerable to one meter of sea level rise above spring high tide. The map book is one tool that local governments or agencies can use to illustrate vulnerable areas at a consistent scale across a large geographical area while producing maps useful for visualizing vulnerable areas. This specific map book uses the boundaries of USGS Quadrangles as the extent for each individual map, though any grid could be used, depending on the specific need of the local government or agency. In addition, these areas correlate directly with the relatively accuracy of the elevation data shown on Map 9 of the main report. The underlying GIS data showing vulnerable areas is available to local governments upon request.

Hampton Roads Sea Level Rise
Map 1: Wilton, VA Quadrangle





Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles

N
W E
S

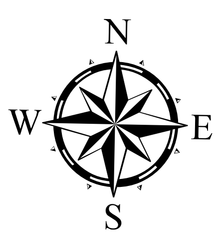
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

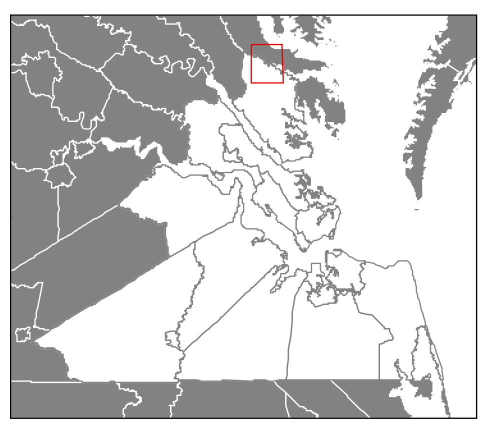
Hampton Roads Sea Level Rise
Map 2: Saluda, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles



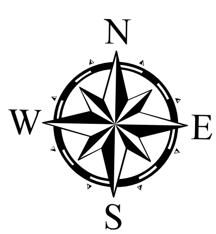


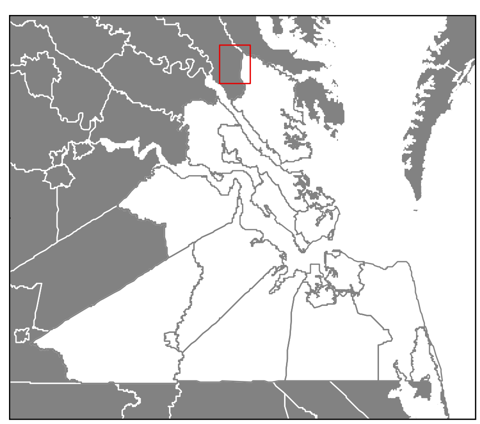
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 3: Shacklefords, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

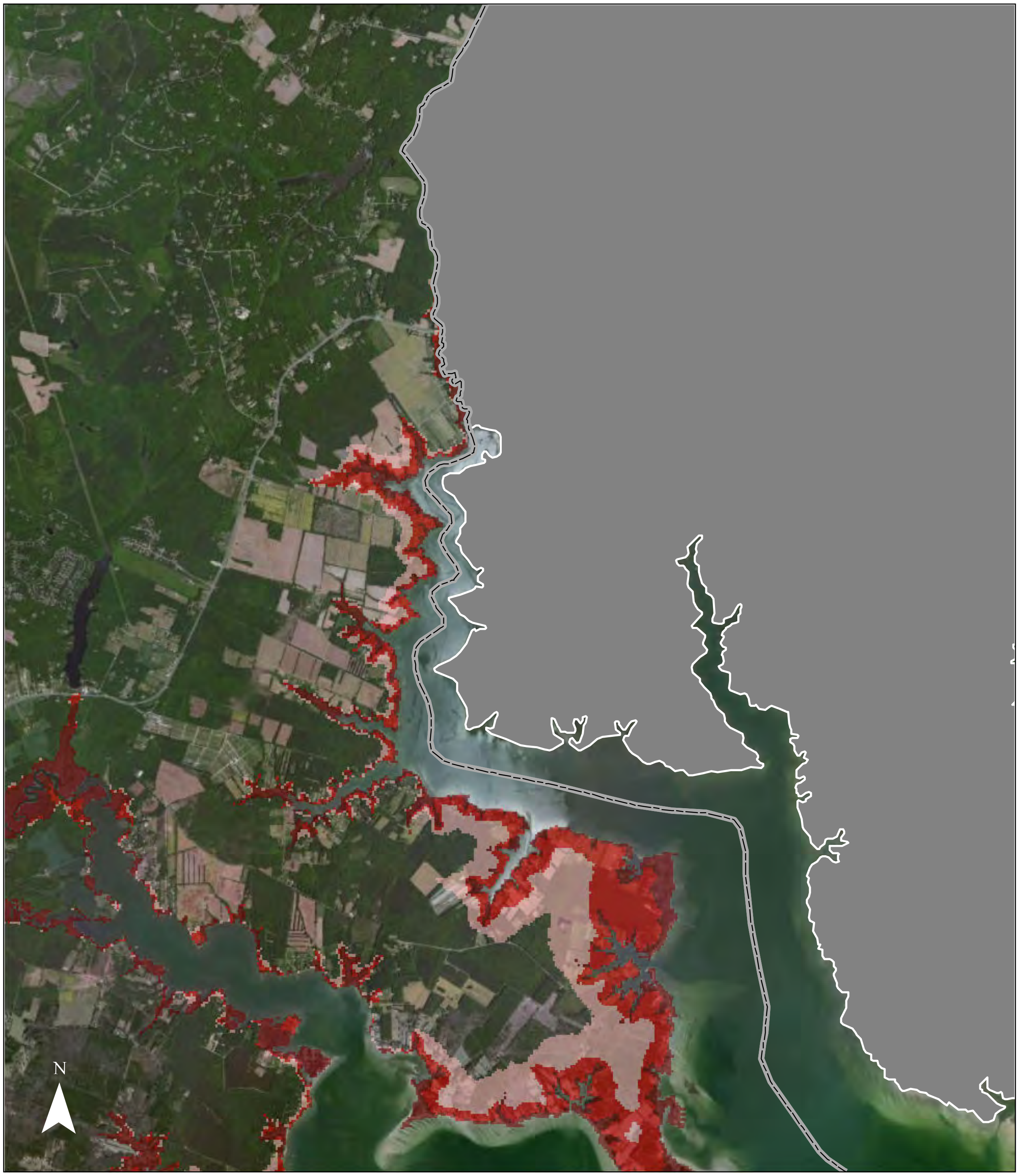




0 0.75 1.5 Miles

Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

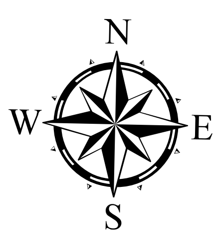
Hampton Roads Sea Level Rise
Map 4: Ware Neck, VA Quadrangle

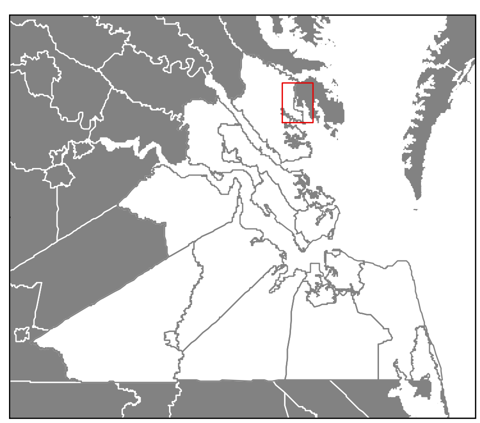


Legend

- Low Estimate
- Middle Estimate
- High Estimate

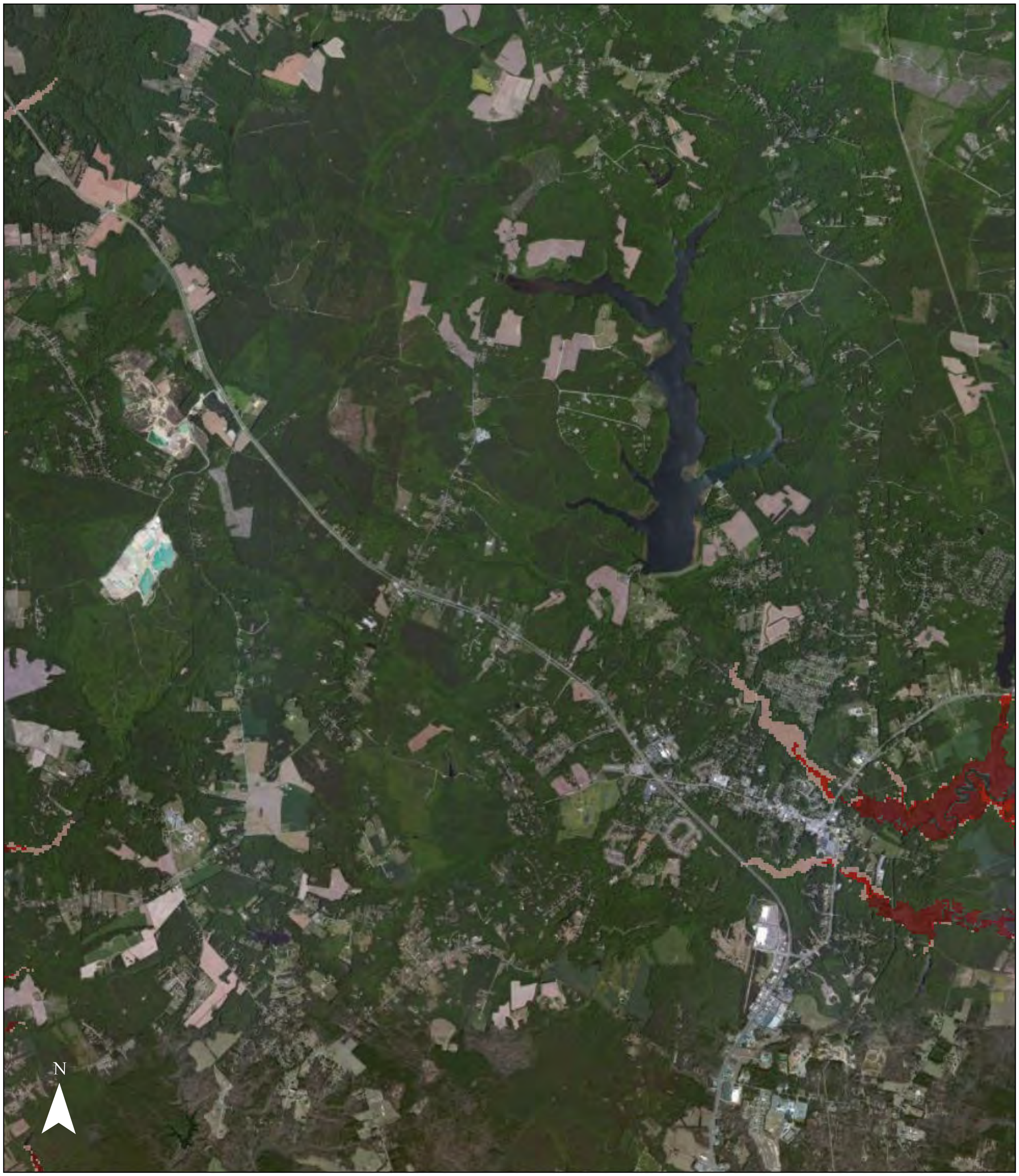
0 0.75 1.5 Miles





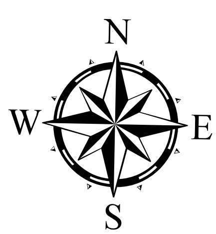
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 5: Gloucester, VA Quadrangle



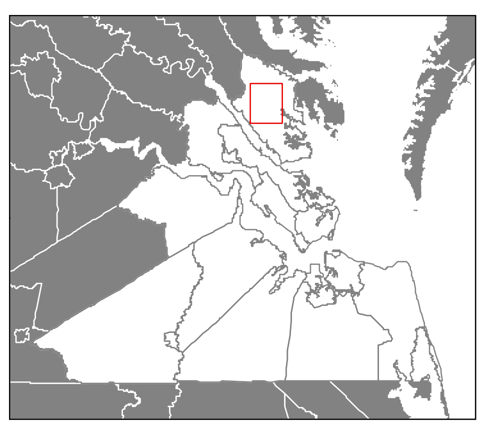
Legend

- Low Estimate
- Middle Estimate
- High Estimate

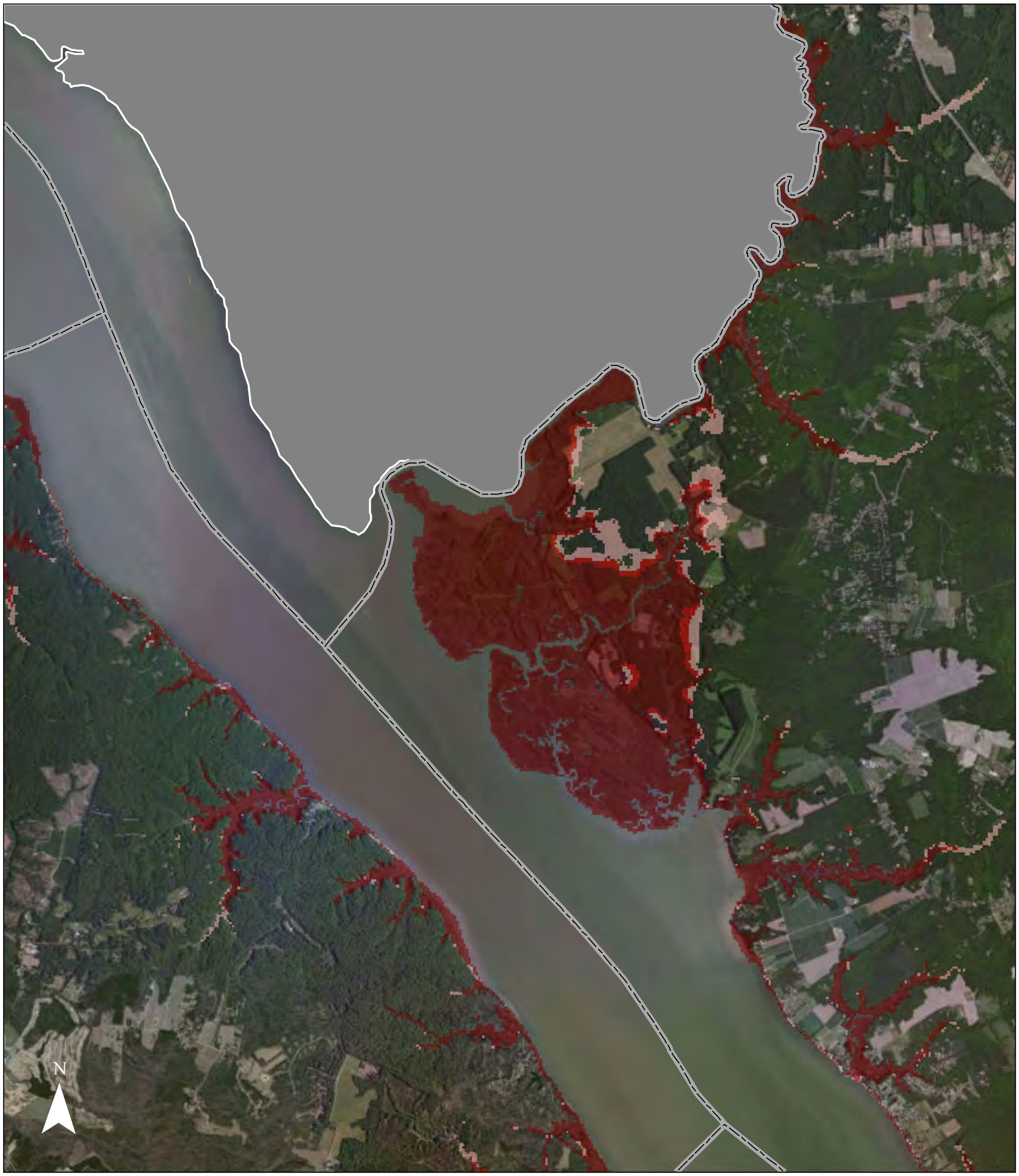


0 0.75 1.5 Miles

Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

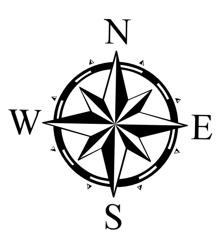


Hampton Roads Sea Level Rise
Map 6: Gressitt, VA Quadrangle

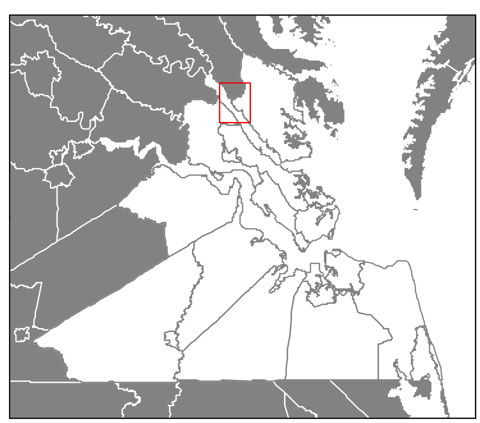


Legend

- Low Estimate
- Middle Estimate
- High Estimate



0 0.75 1.5 Miles

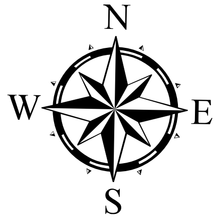


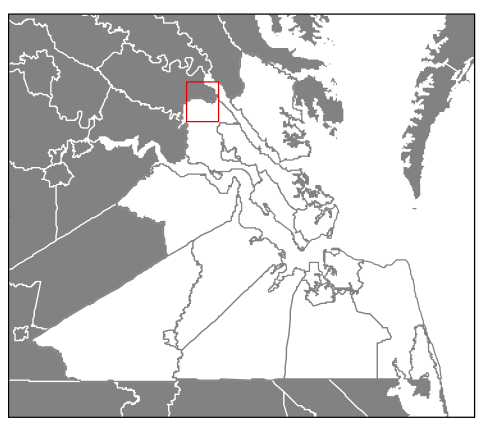
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 7: Toano, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate





0 0.75 1.5 Miles

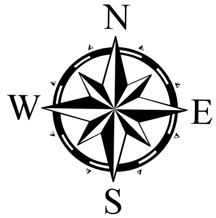
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

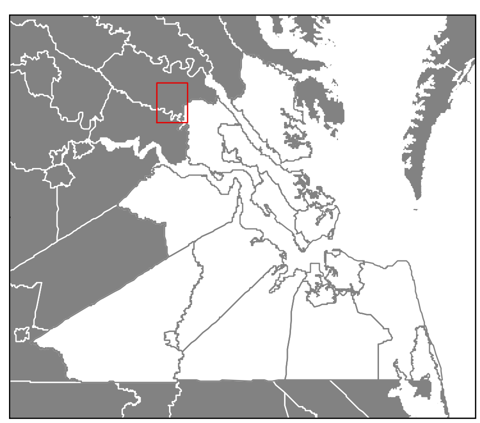
Hampton Roads Sea Level Rise
Map 8: Walkers, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

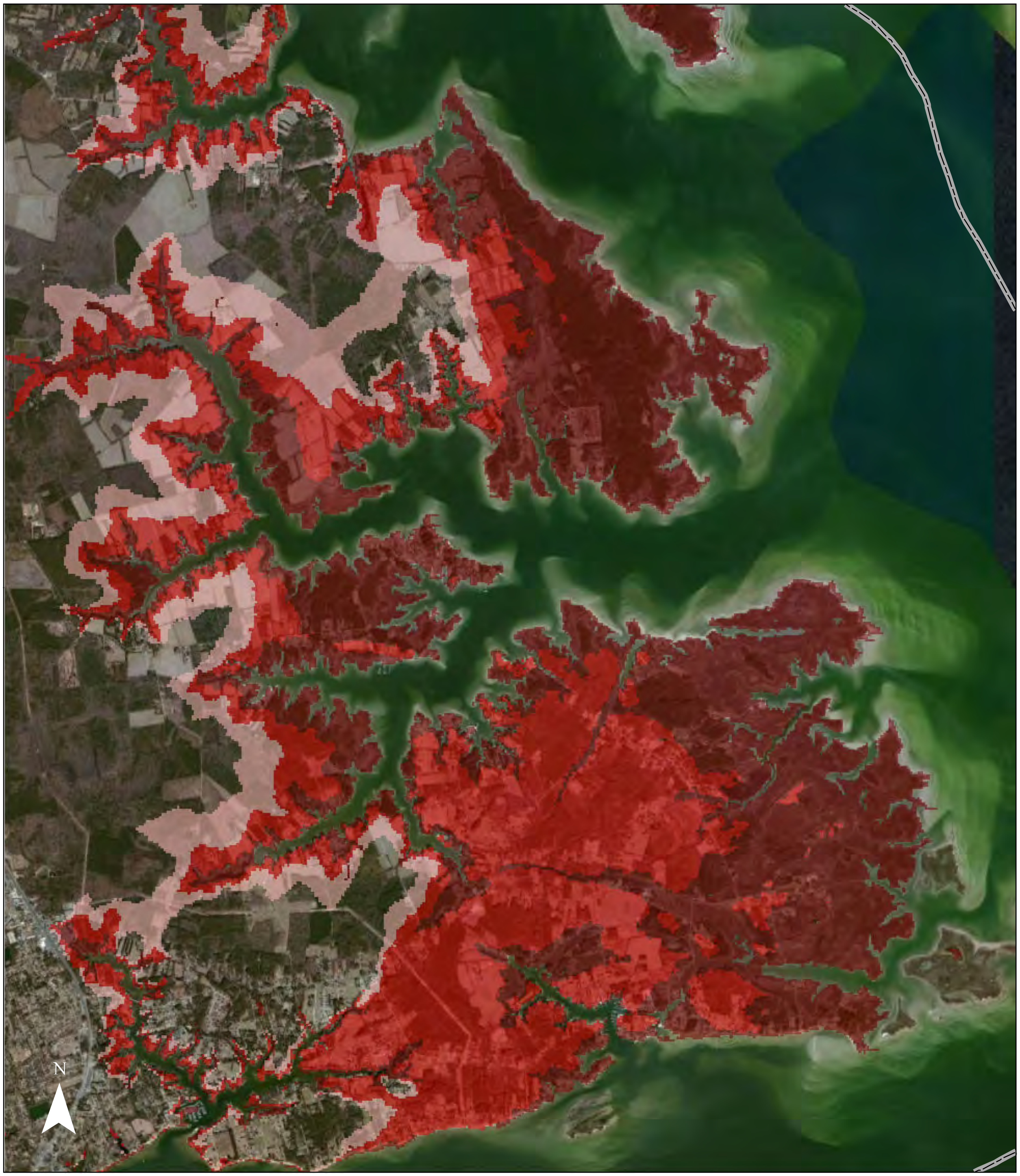
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

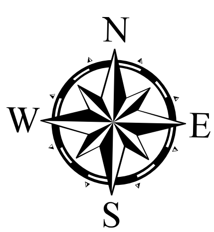
Hampton Roads Sea Level Rise
Map 9: Achilles, VA Quadrangle

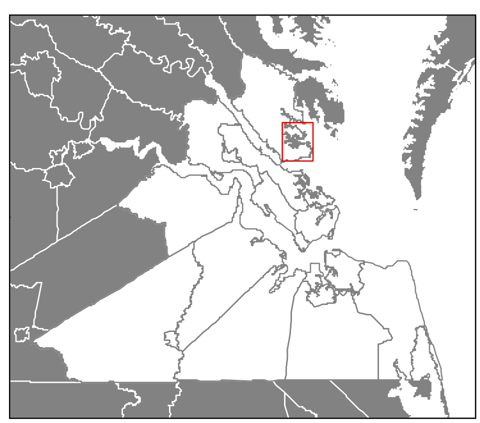


Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 10: Clay Bank, VA Quadrangle

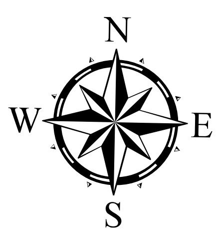
Legend

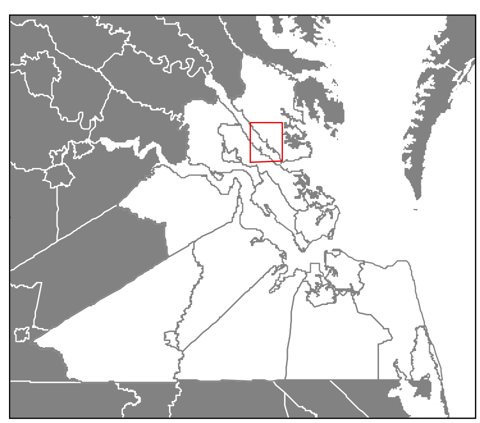
Low Estimate

Middle Estimate

High Estimate

0 0.75 1.5 Miles



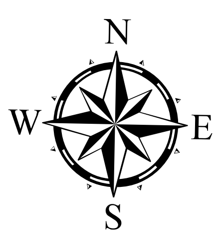


Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

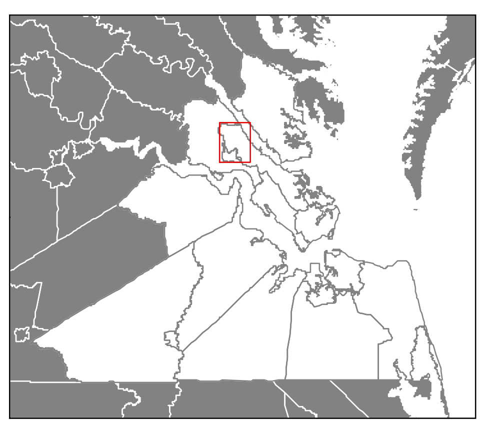
Hampton Roads Sea Level Rise
Map 11: Williamsburg, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

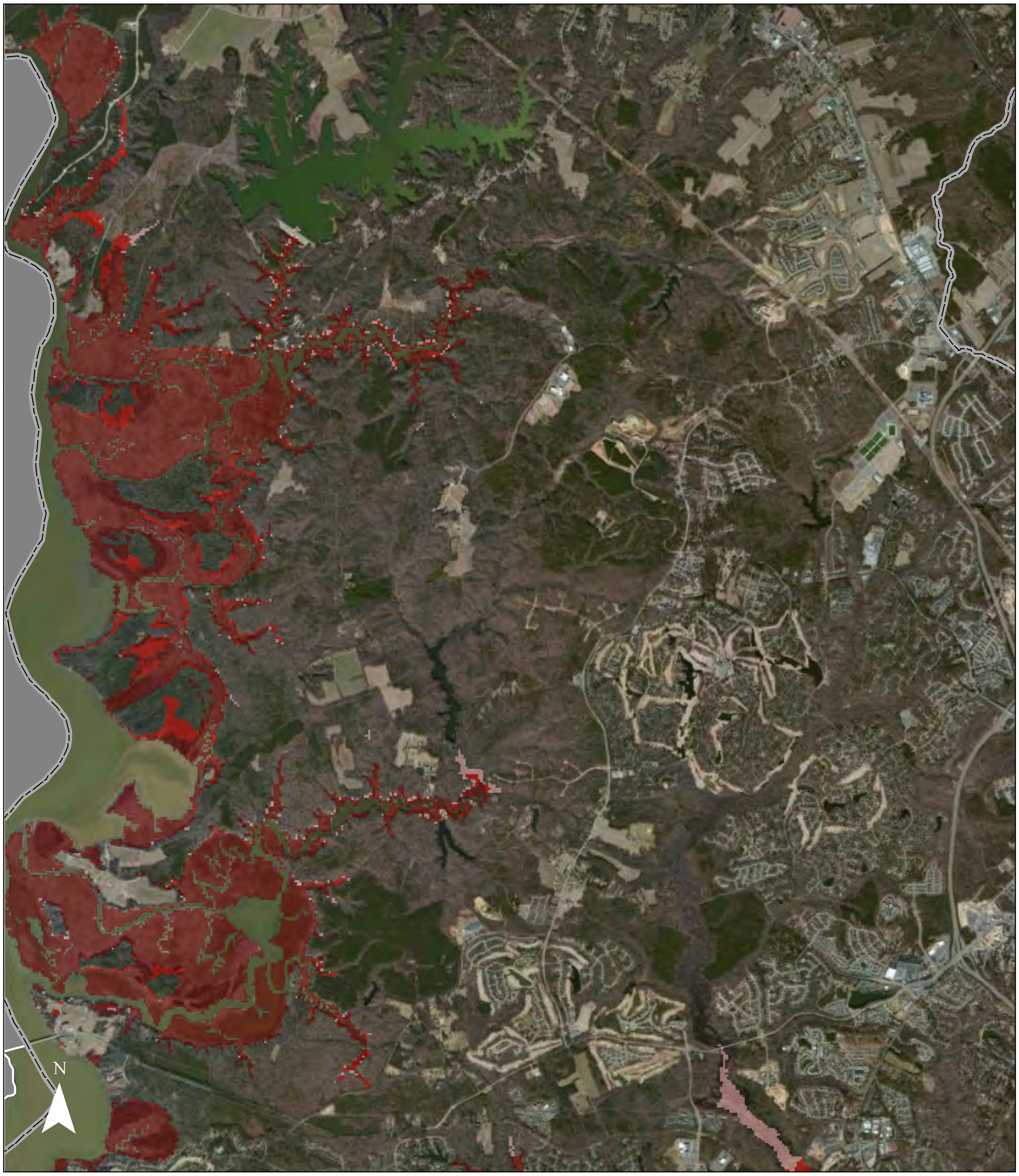


0 0.75 1.5 Miles



Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

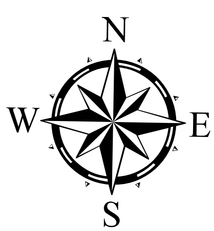
Hampton Roads Sea Level Rise
Map 12: Norge, VA Quadrangle

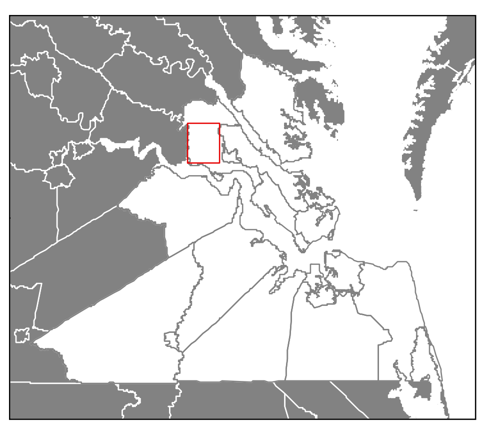


Legend

- Low Estimate
- Middle Estimate
- High Estimate

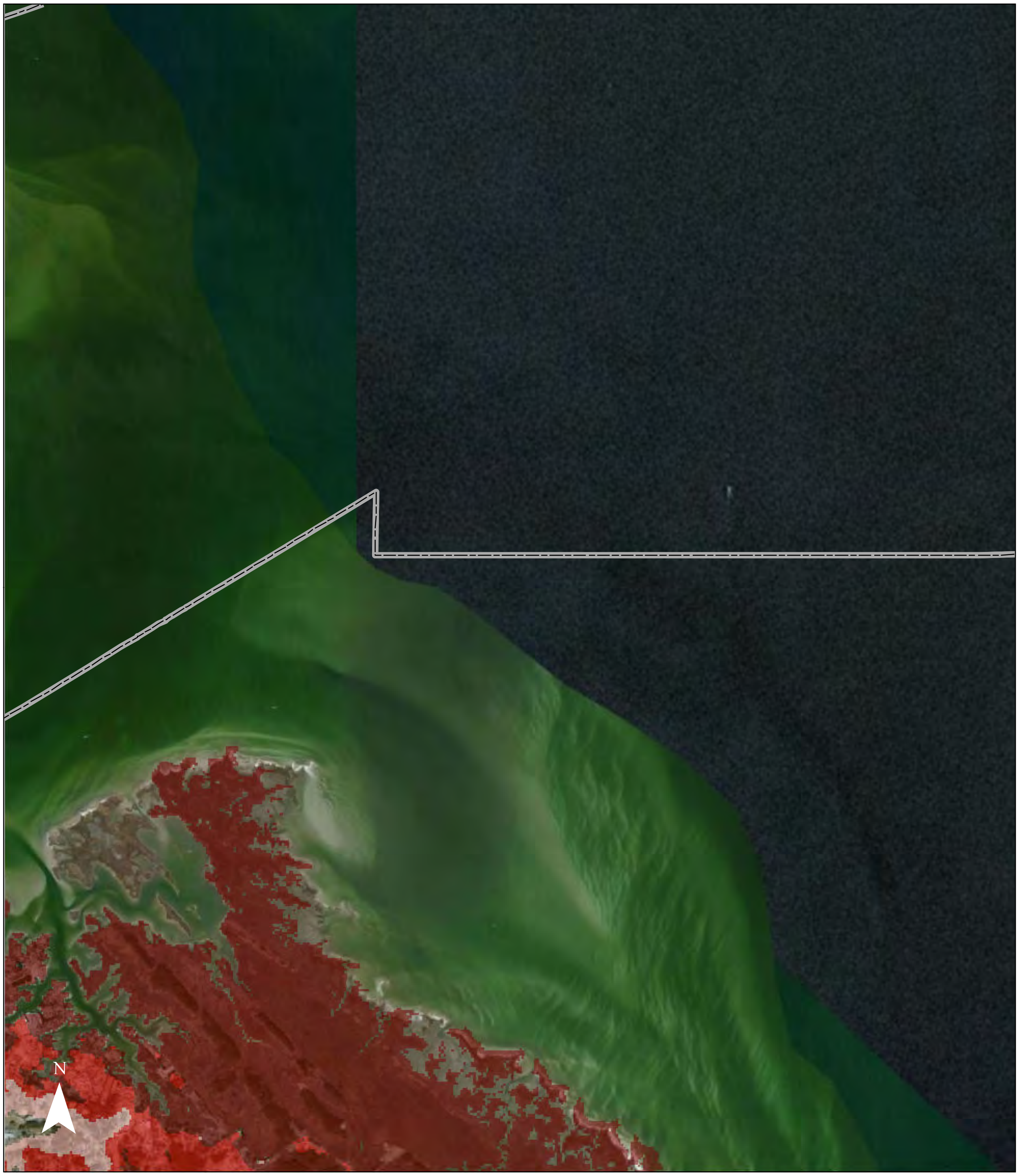
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

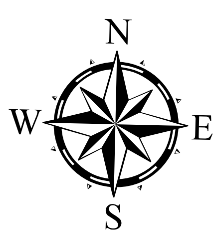
Hampton Roads Sea Level Rise
Map 13: Poquoson East, VA Quadrangle

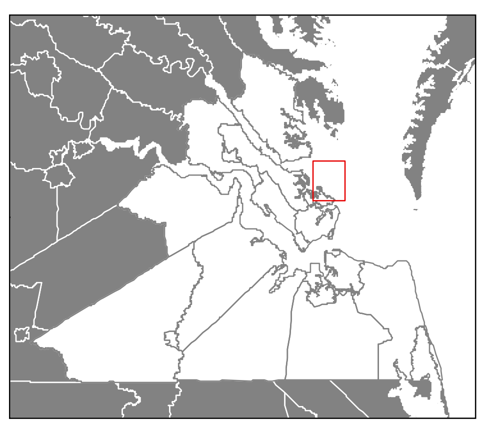


Legend

- Low Estimate
- Middle Estimate
- High Estimate

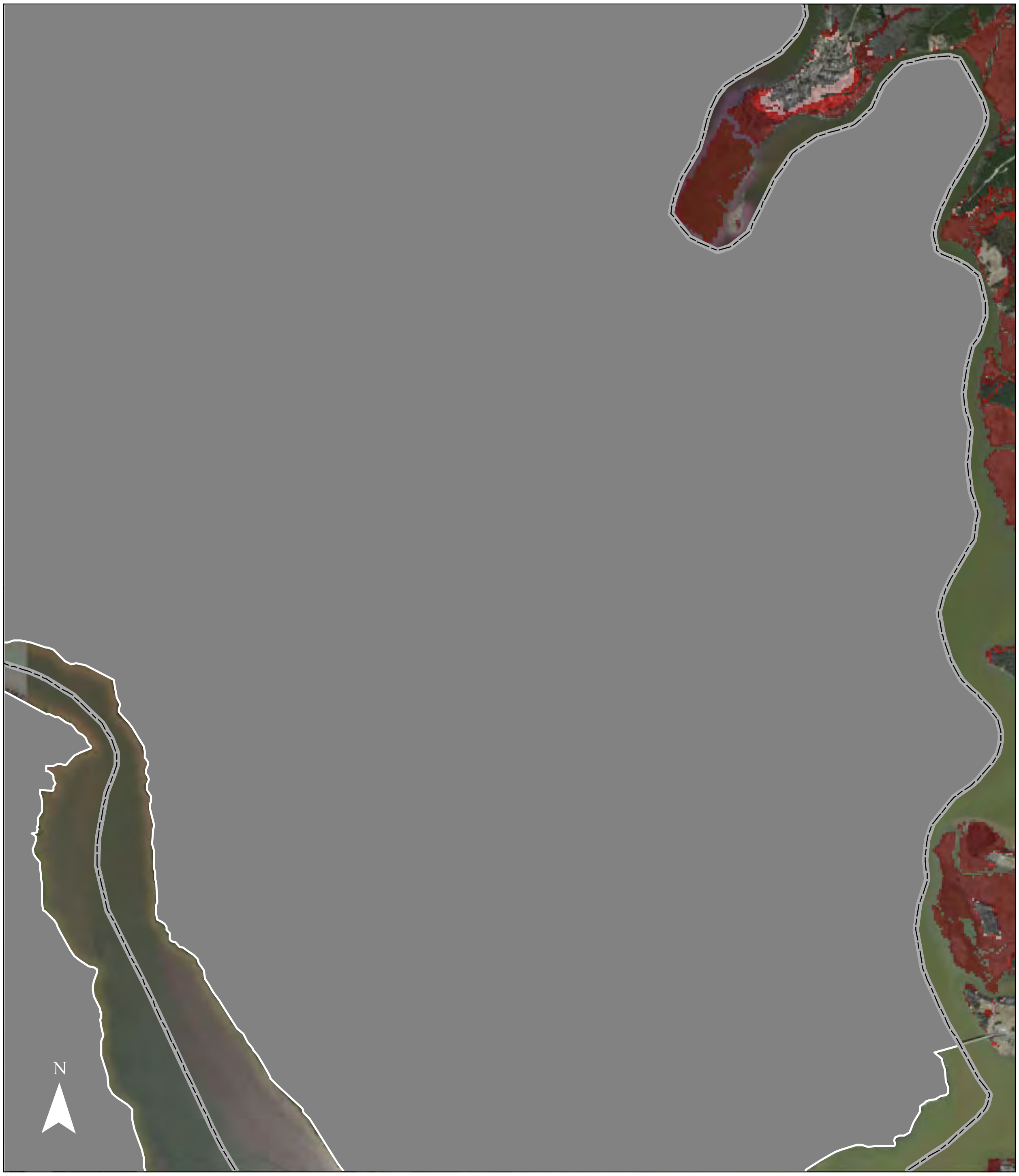
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

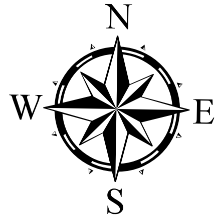
Hampton Roads Sea Level Rise
Map 14: Brandon, VA Quadrangle

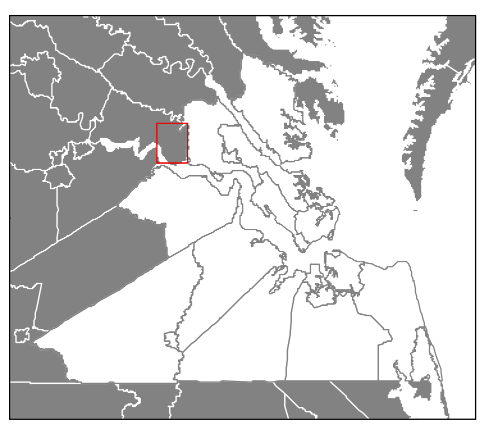


Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





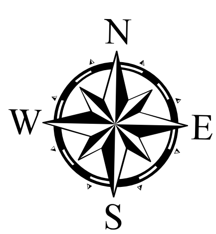
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 15: Poquoson West, VA Quadrangle

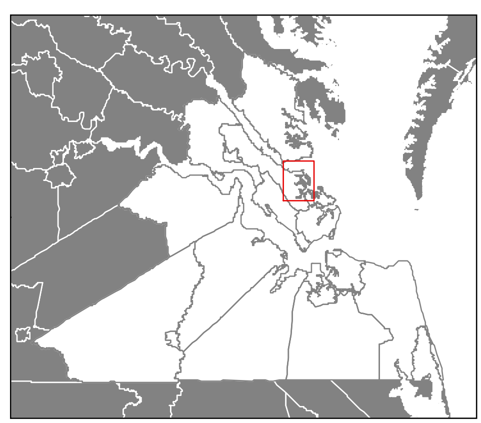
Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles



Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

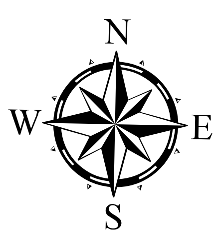


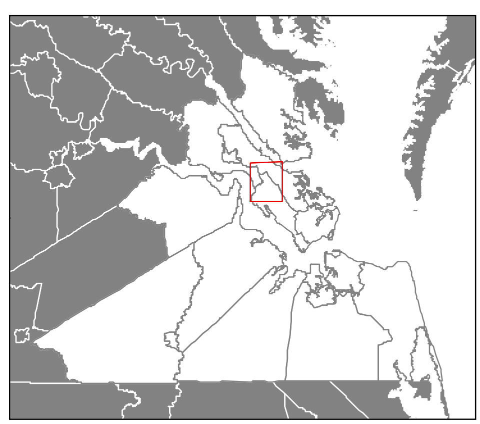
Hampton Roads Sea Level Rise
Map 16: Yorktown, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





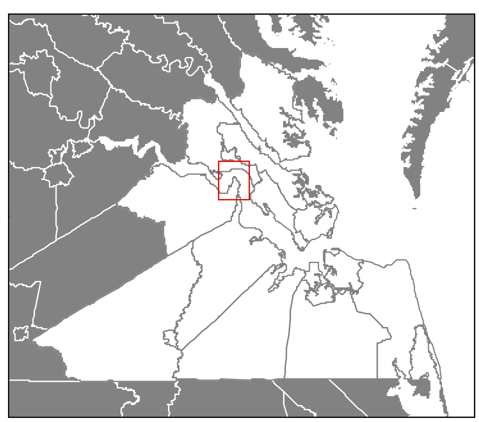
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 17: Hog Island, VA Quadrangle

Legend

Low Estimate
Middle Estimate
High Estimate

0 0.75 1.5 Miles



Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 18: Surry, VA Quadrangle

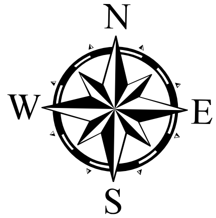
Legend

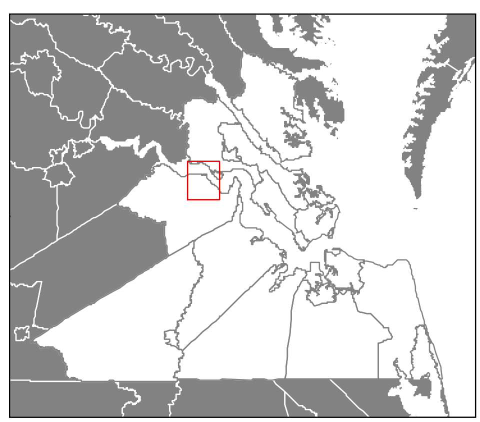
Low Estimate

Middle Estimate

High Estimate

0 0.75 1.5 Miles





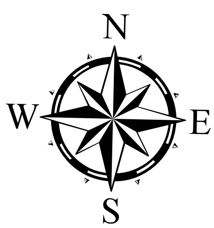
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

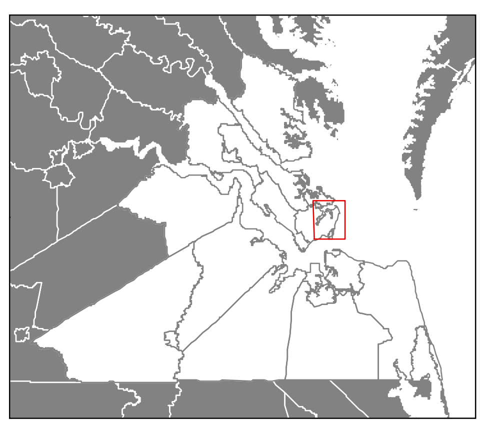
Hampton Roads Sea Level Rise
Map 19: Hampton, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





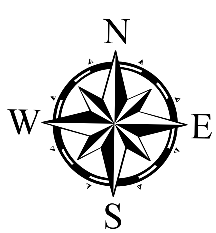
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

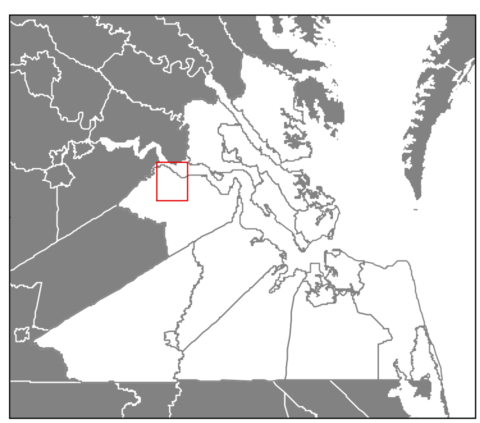
Hampton Roads Sea Level Rise
Map 20: Claremont, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





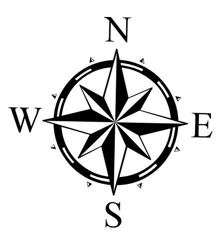
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

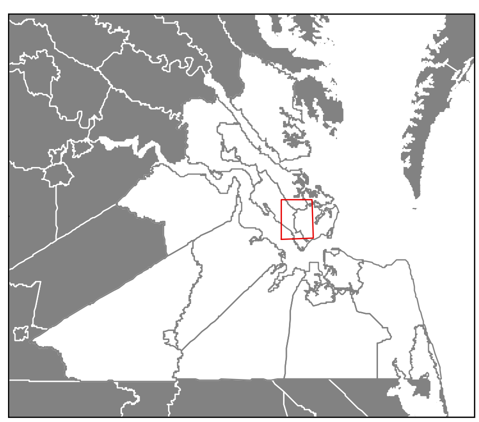
Hampton Roads Sea Level Rise
Map 21: Newport News North, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles



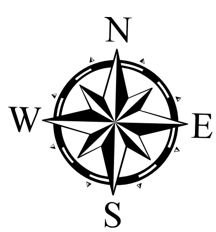


Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

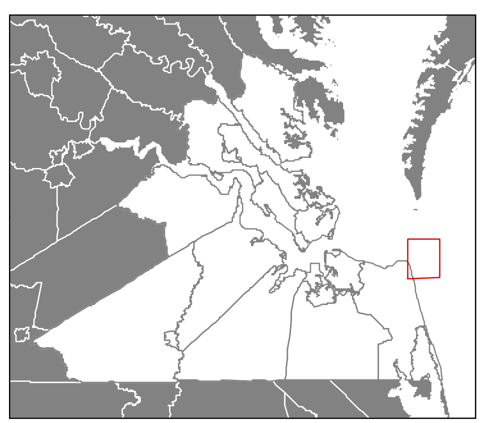
Hampton Roads Sea Level Rise
Map 22: North Virginia Beach, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate



0 0.75 1.5 Miles



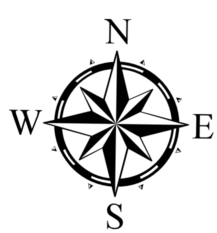
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

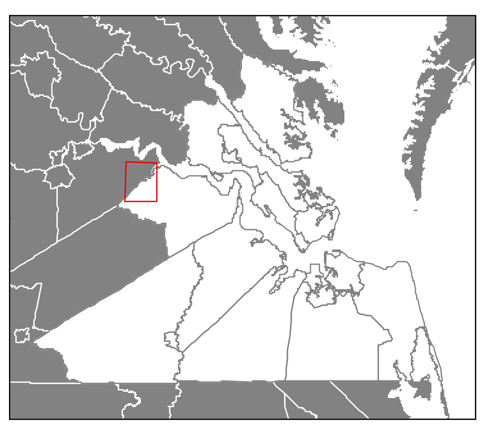
Hampton Roads Sea Level Rise
Map 23: Savedge, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





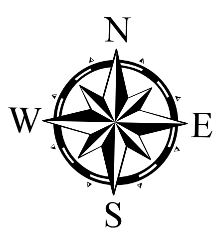
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

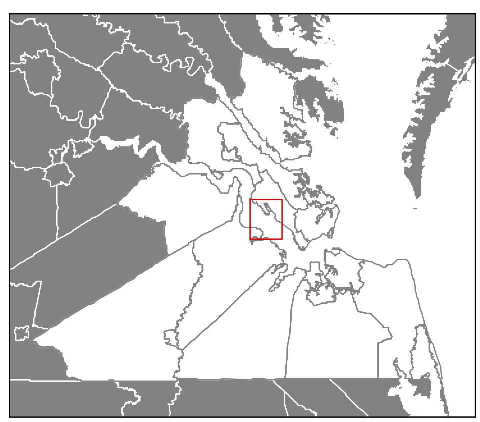
Hampton Roads Sea Level Rise
Map 24: Mulberry Island, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





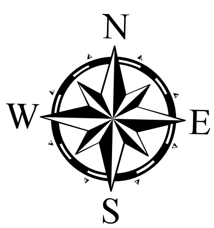
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

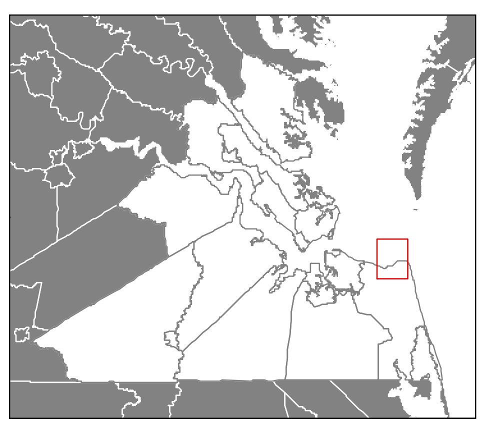
Hampton Roads Sea Level Rise
Map 25: Cape Henry, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





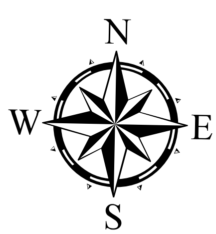
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

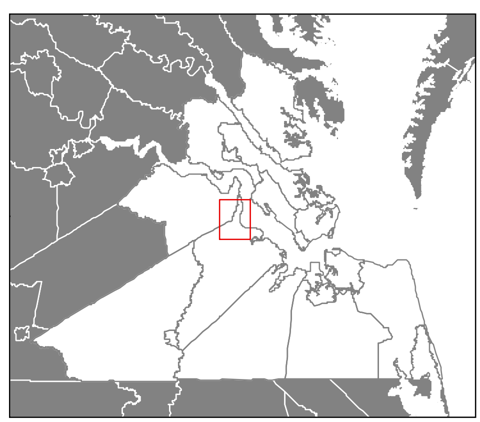
Hampton Roads Sea Level Rise
Map 26: Bacons Castle, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





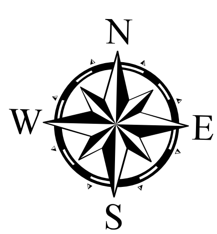
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

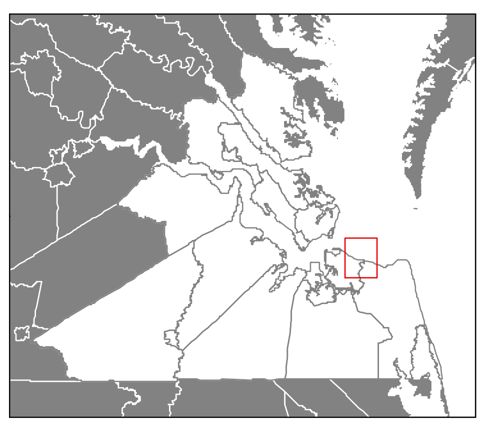
Hampton Roads Sea Level Rise
Map 27: Little Creek, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





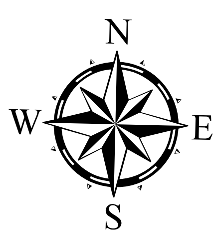
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

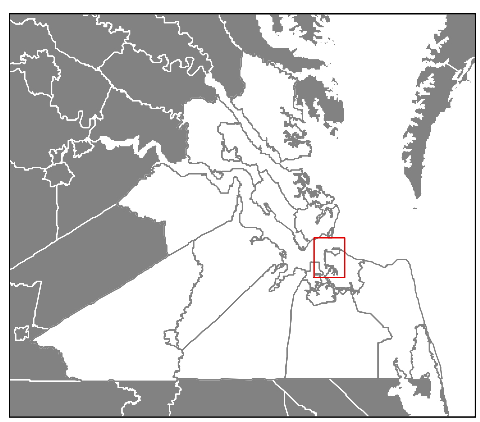
Hampton Roads Sea Level Rise
Map 28: Norfolk North, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





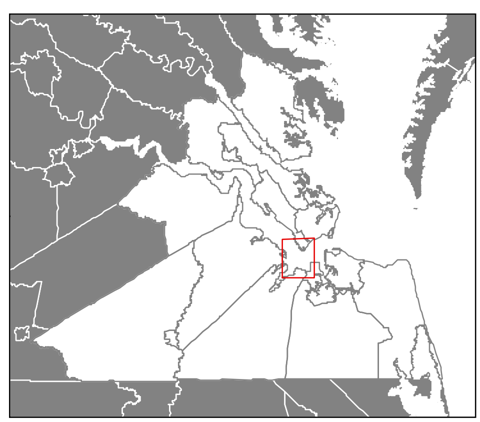
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 29: Newport News South, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles



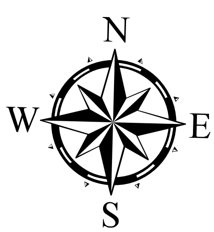
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

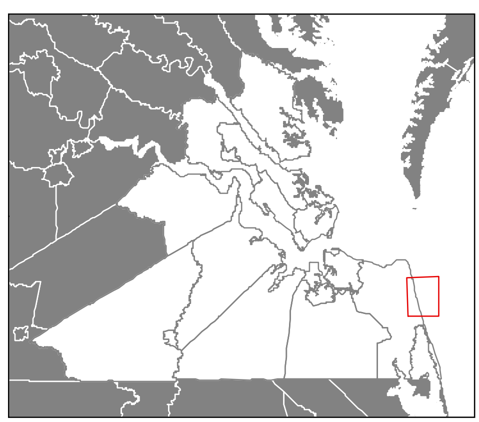
Hampton Roads Sea Level Rise
Map 30: Virginia Beach, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





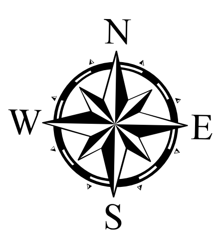
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

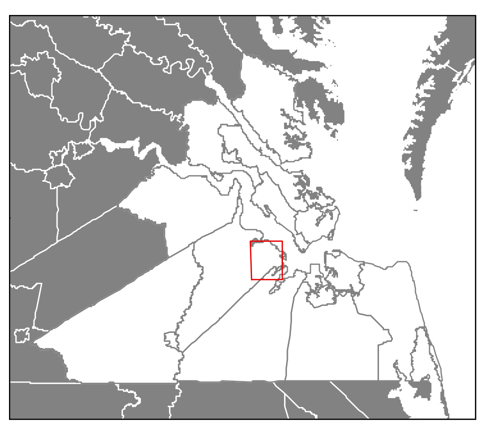
Hampton Roads Sea Level Rise
Map 31: Benns Church, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

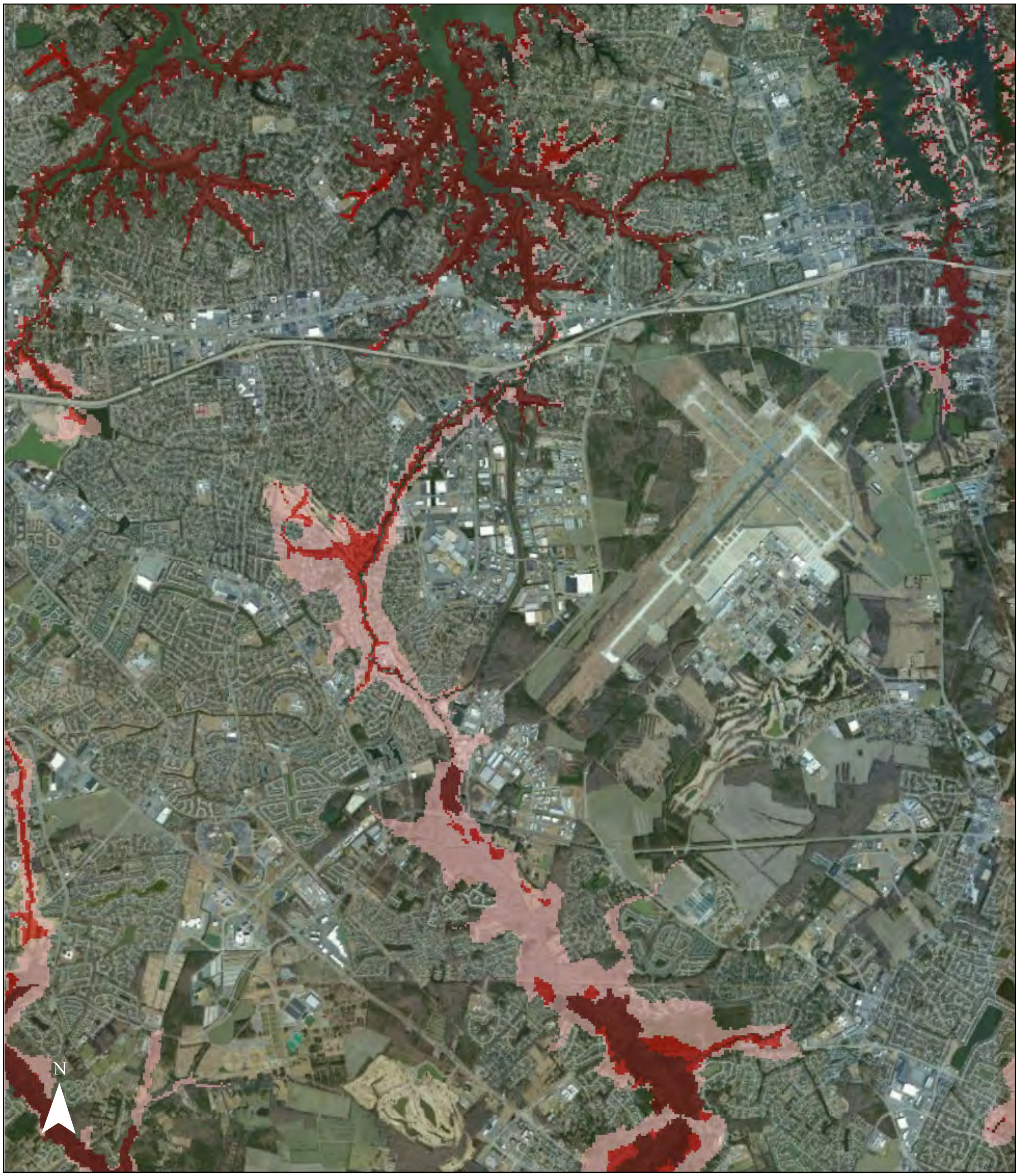
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

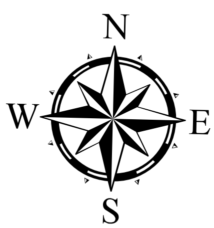
Hampton Roads Sea Level Rise
Map 32: Princess Anne, VA Quadrangle

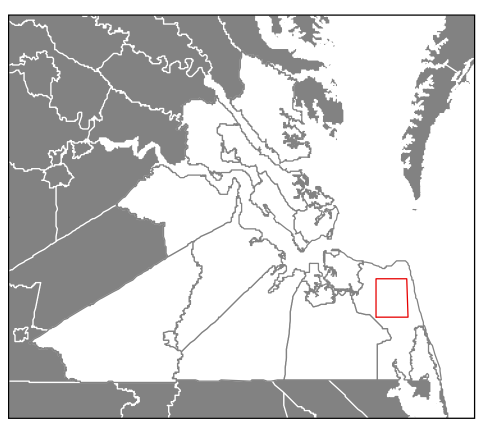


Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles



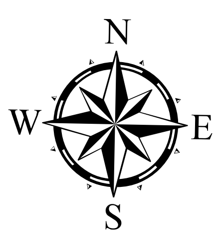


Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

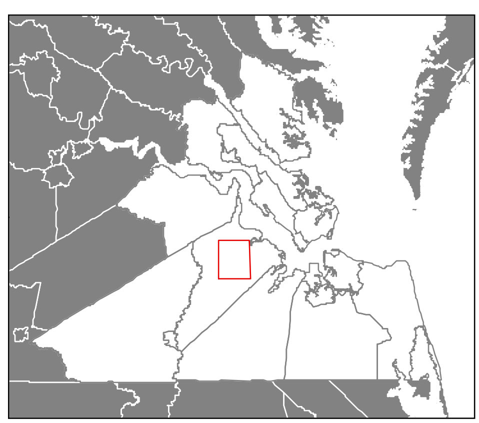
Hampton Roads Sea Level Rise
Map 33: Smithfield, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

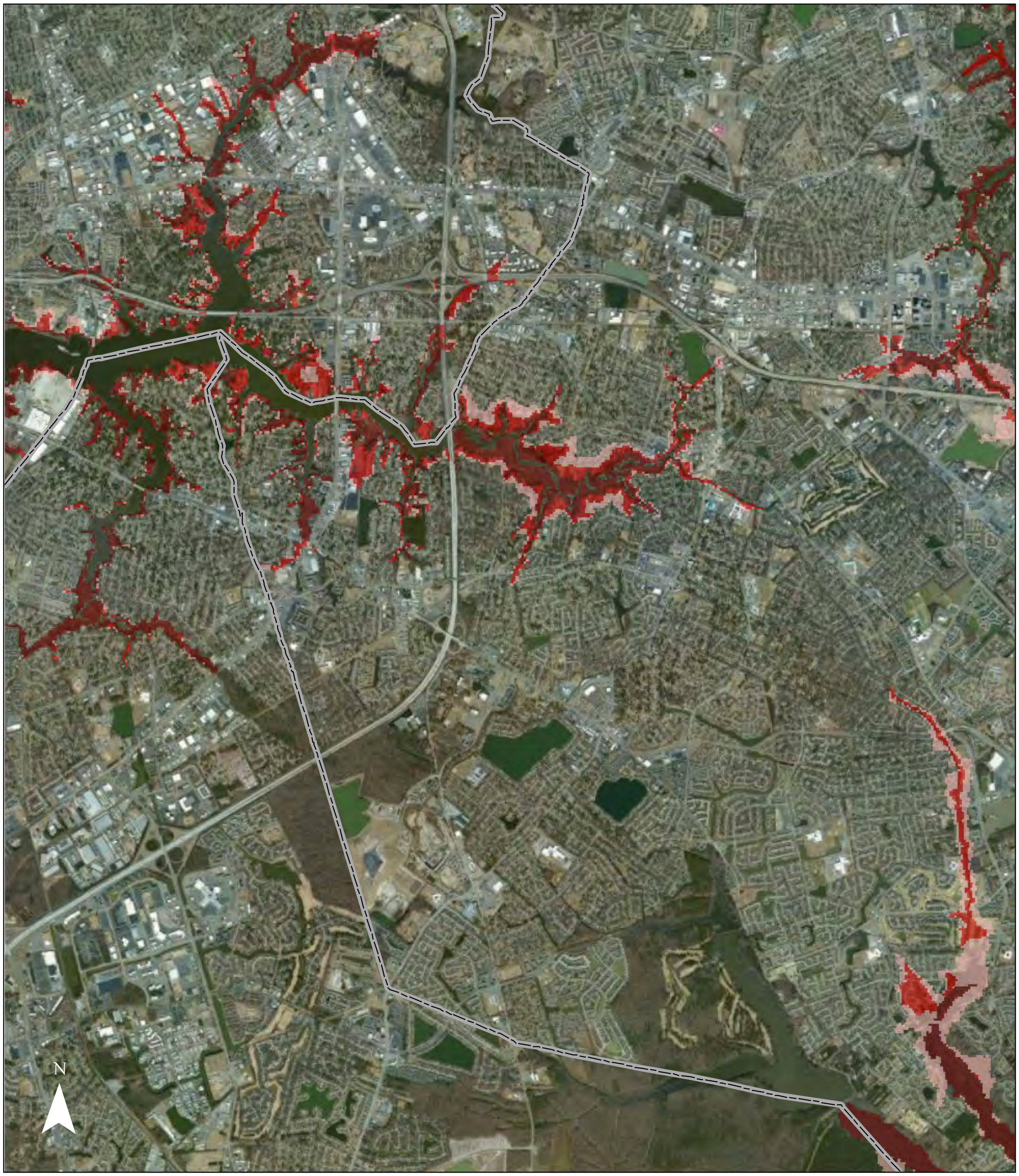


0 0.75 1.5 Miles



Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

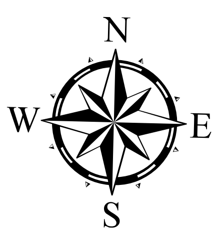
Hampton Roads Sea Level Rise
Map 34: Kempsville, VA Quadrangle

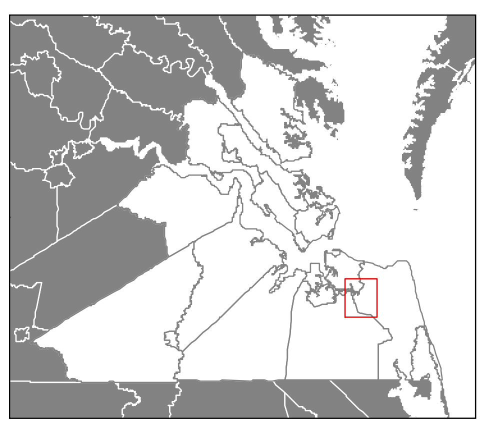


Legend

- Low Estimate
- Middle Estimate
- High Estimate

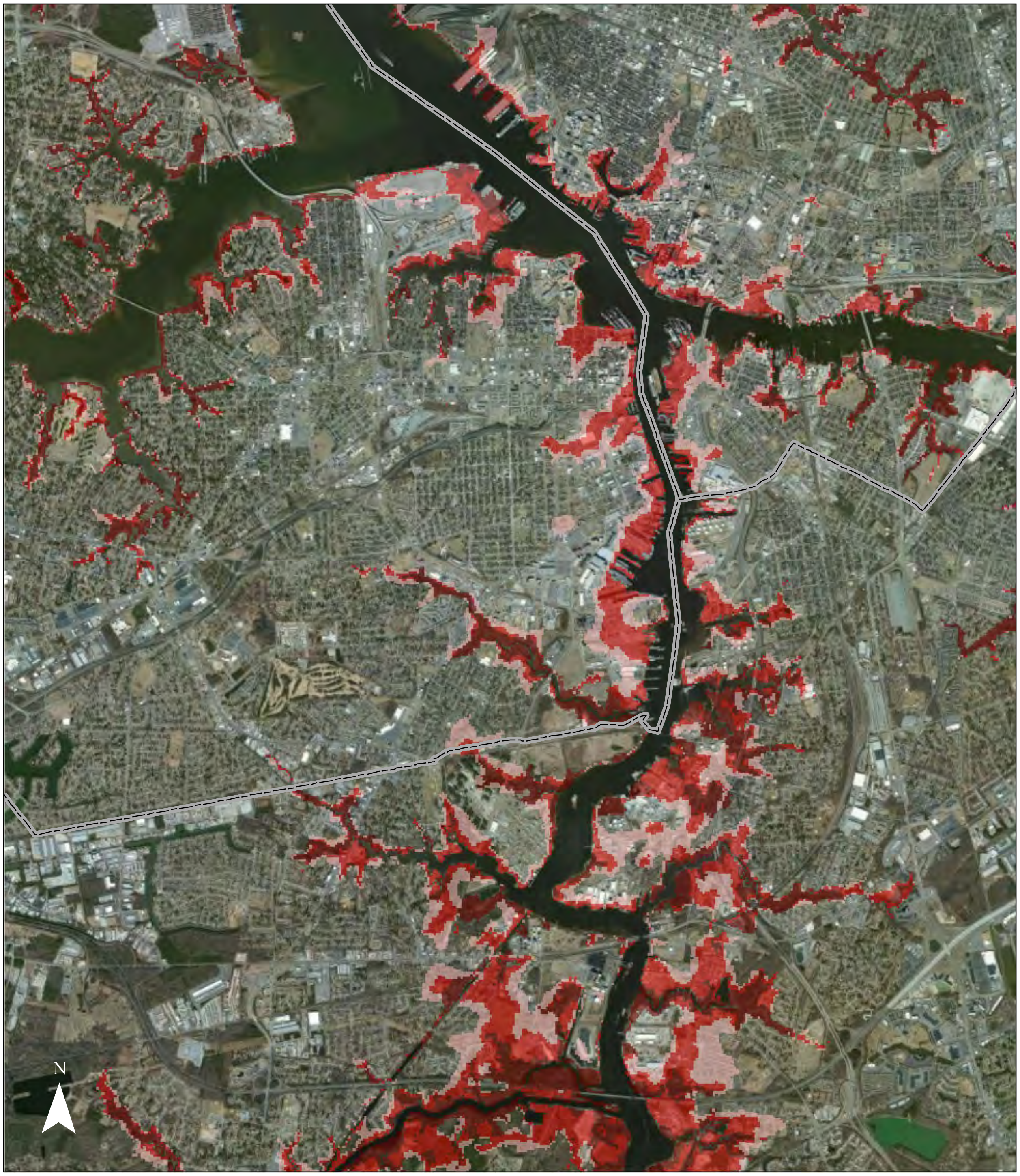
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 35: Norfolk South, VA Quadrangle



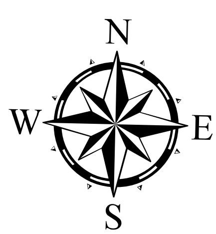
Legend

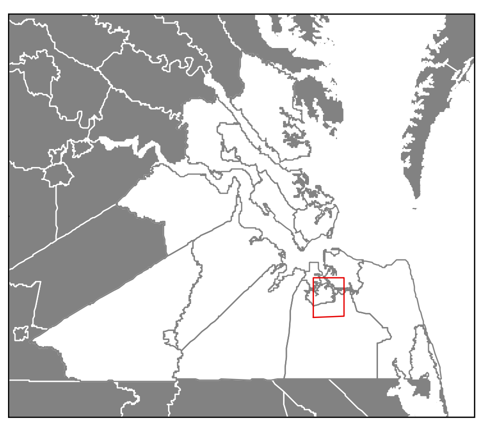
Low Estimate

Middle Estimate

High Estimate

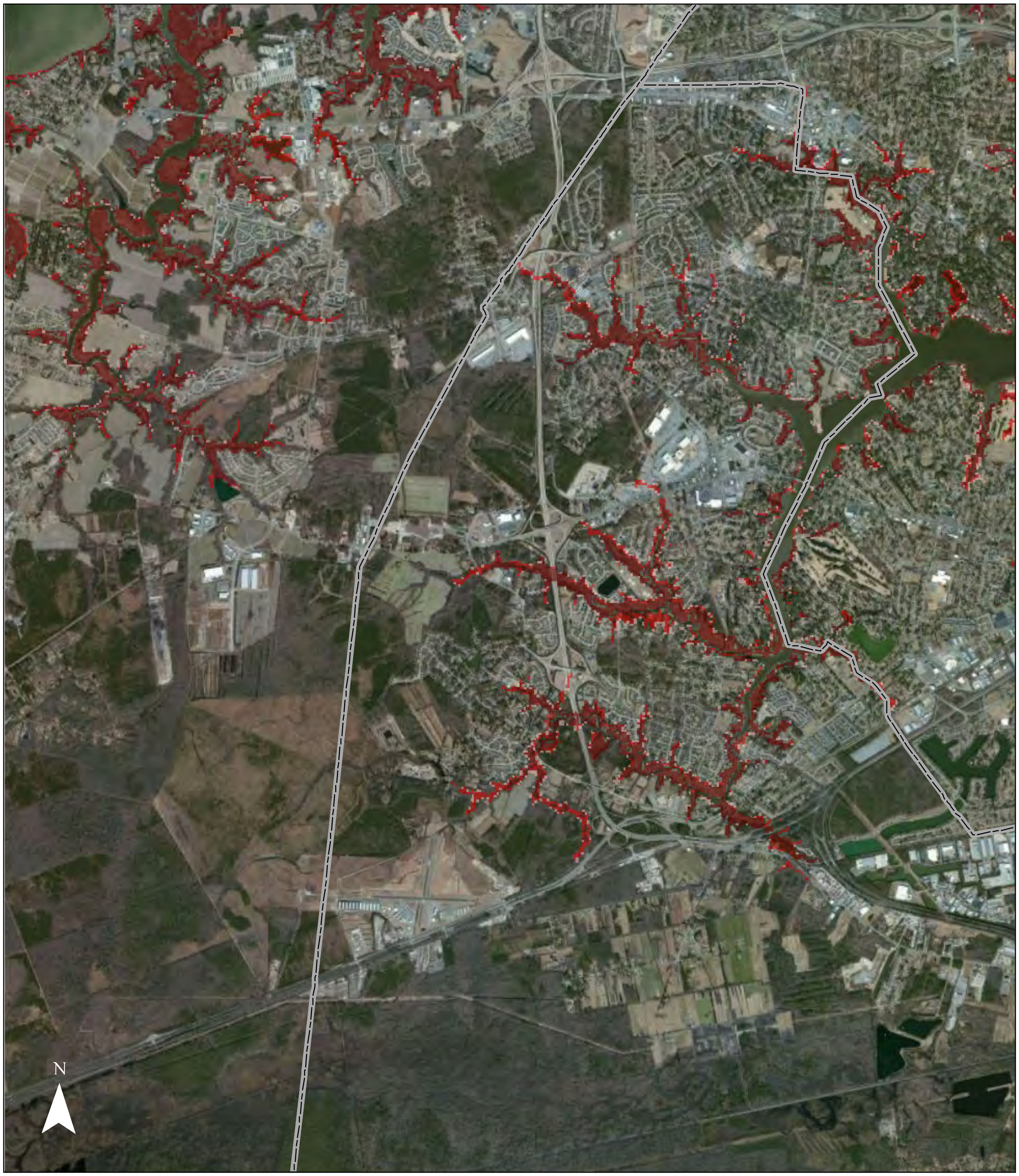
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

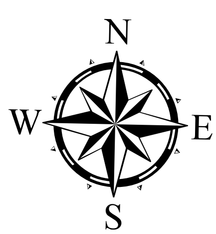
Hampton Roads Sea Level Rise
Map 36: Bowers Hill, VA Quadrangle

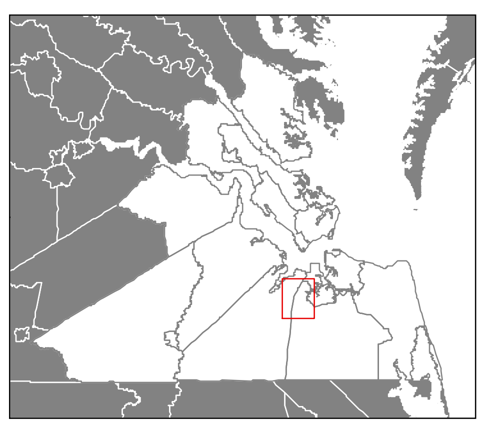


Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





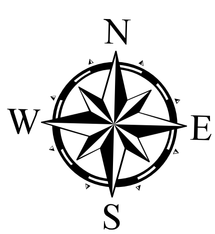
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

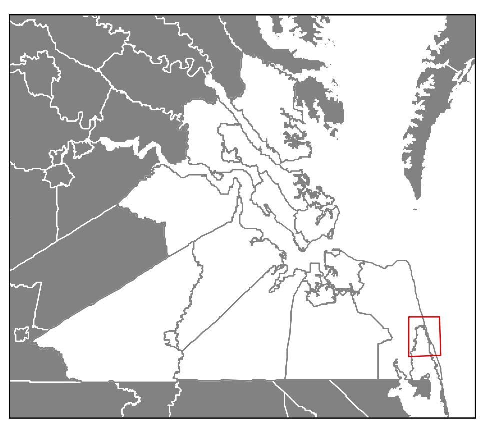
Hampton Roads Sea Level Rise
Map 37: North Bay, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

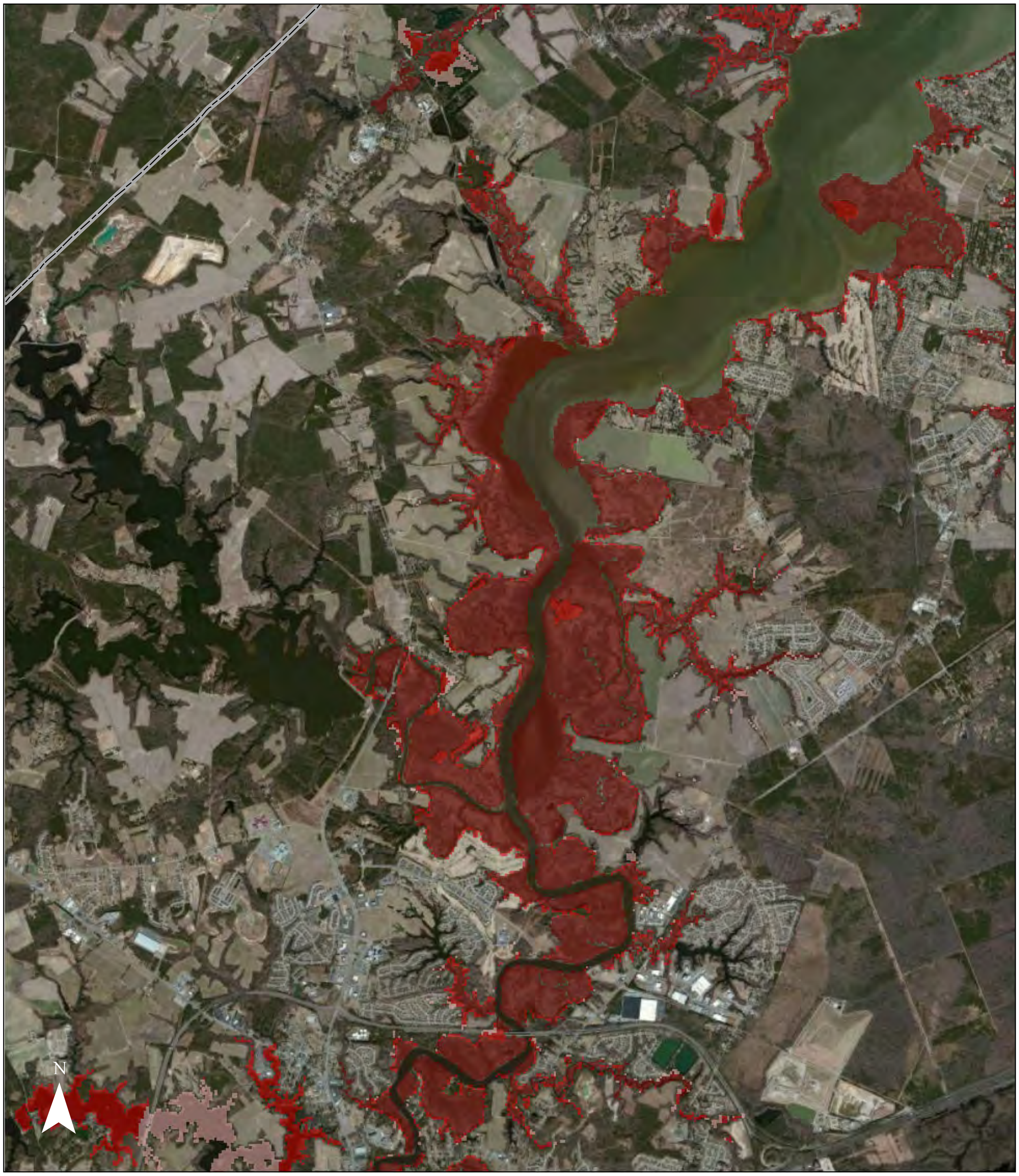
0 0.75 1.5 Miles





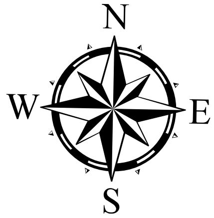
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 38: Chuckatuck, VA Quadrangle

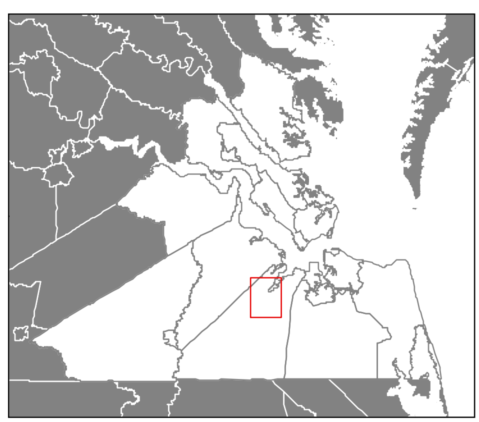


Legend

- Low Estimate
- Middle Estimate
- High Estimate

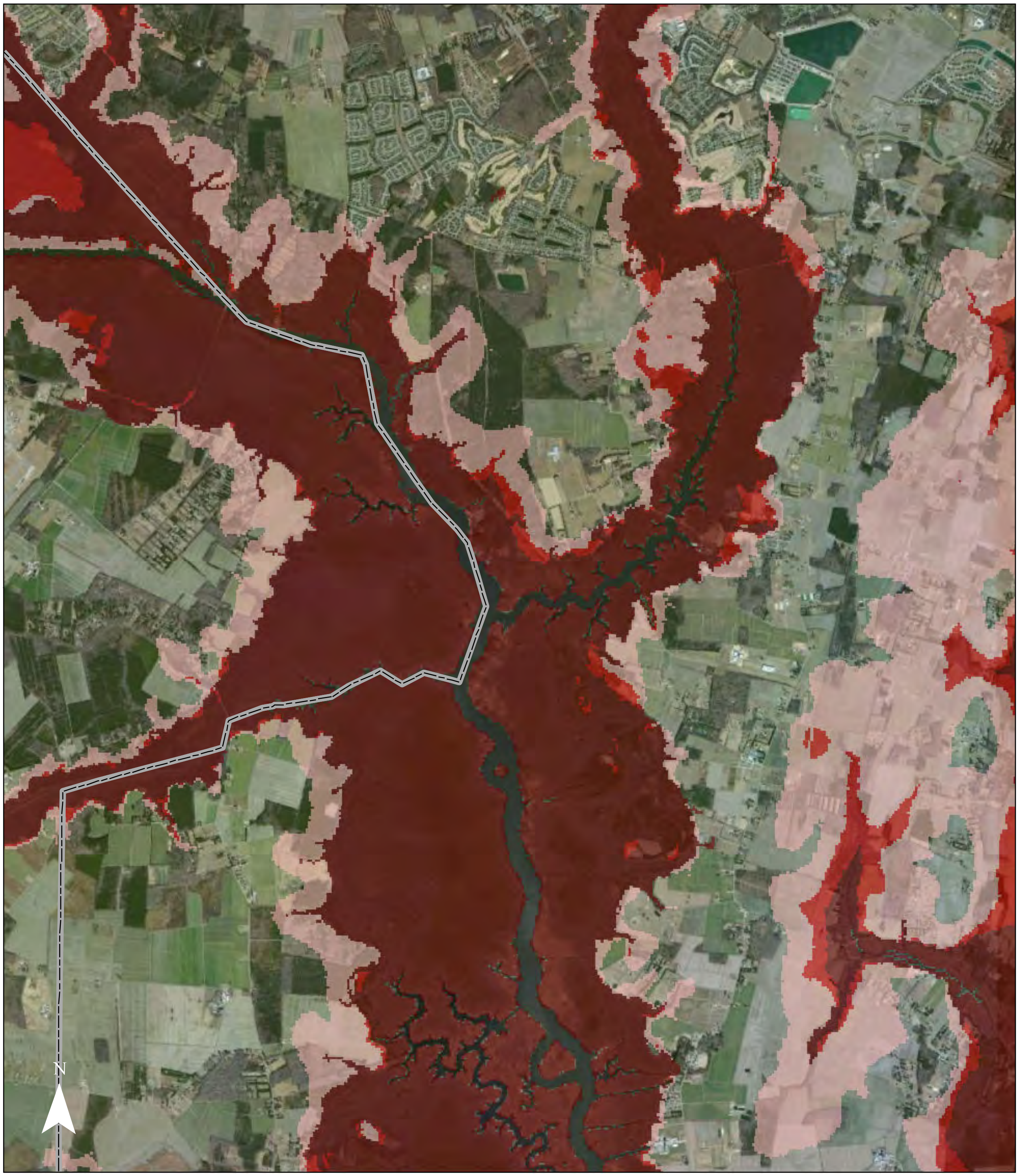


0 0.75 1.5 Miles



Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

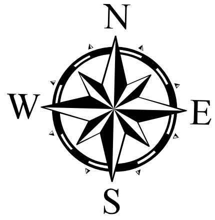
Hampton Roads Sea Level Rise
Map 39: Pleasant Ridge, VA Quadrangle

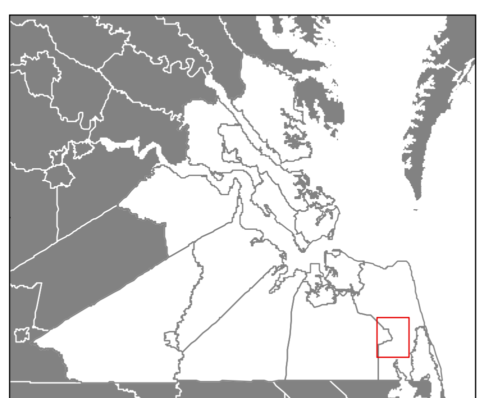


Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





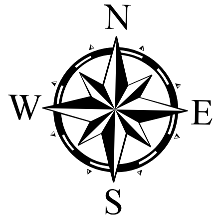
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

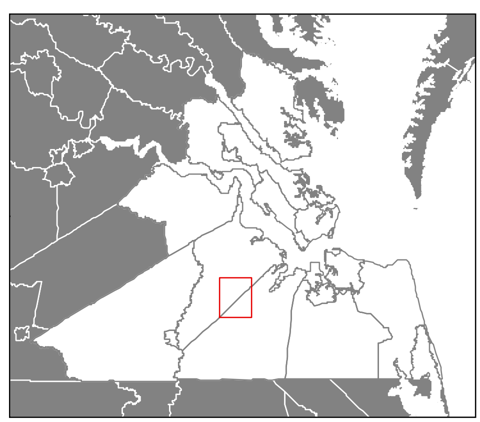
Hampton Roads Sea Level Rise
Map 40: Windsor, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

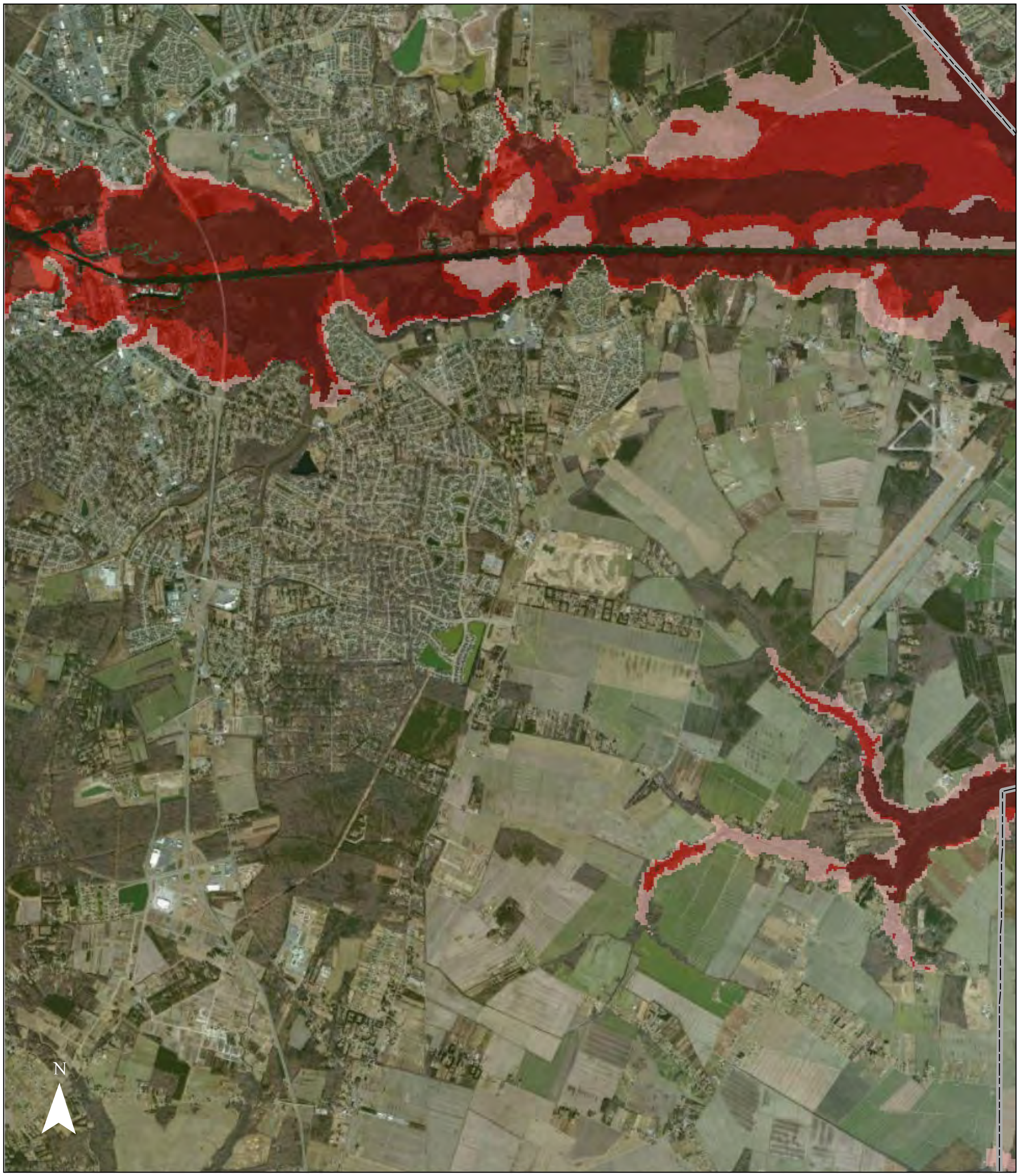
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

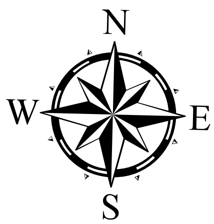
Hampton Roads Sea Level Rise
Map 41: Fentress, VA Quadrangle

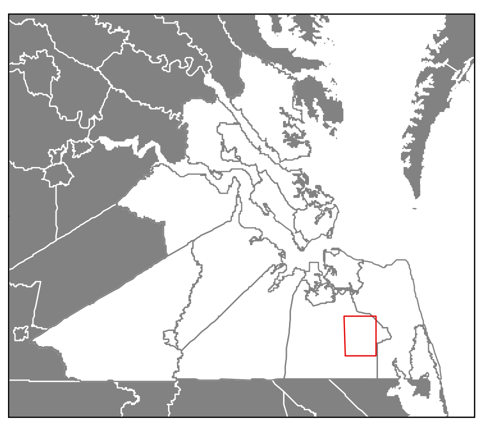


Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





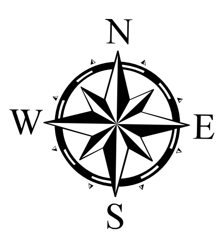
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

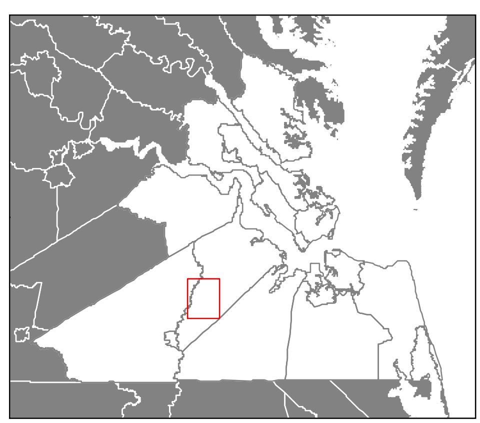
Hampton Roads Sea Level Rise
Map 42: Zuni, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

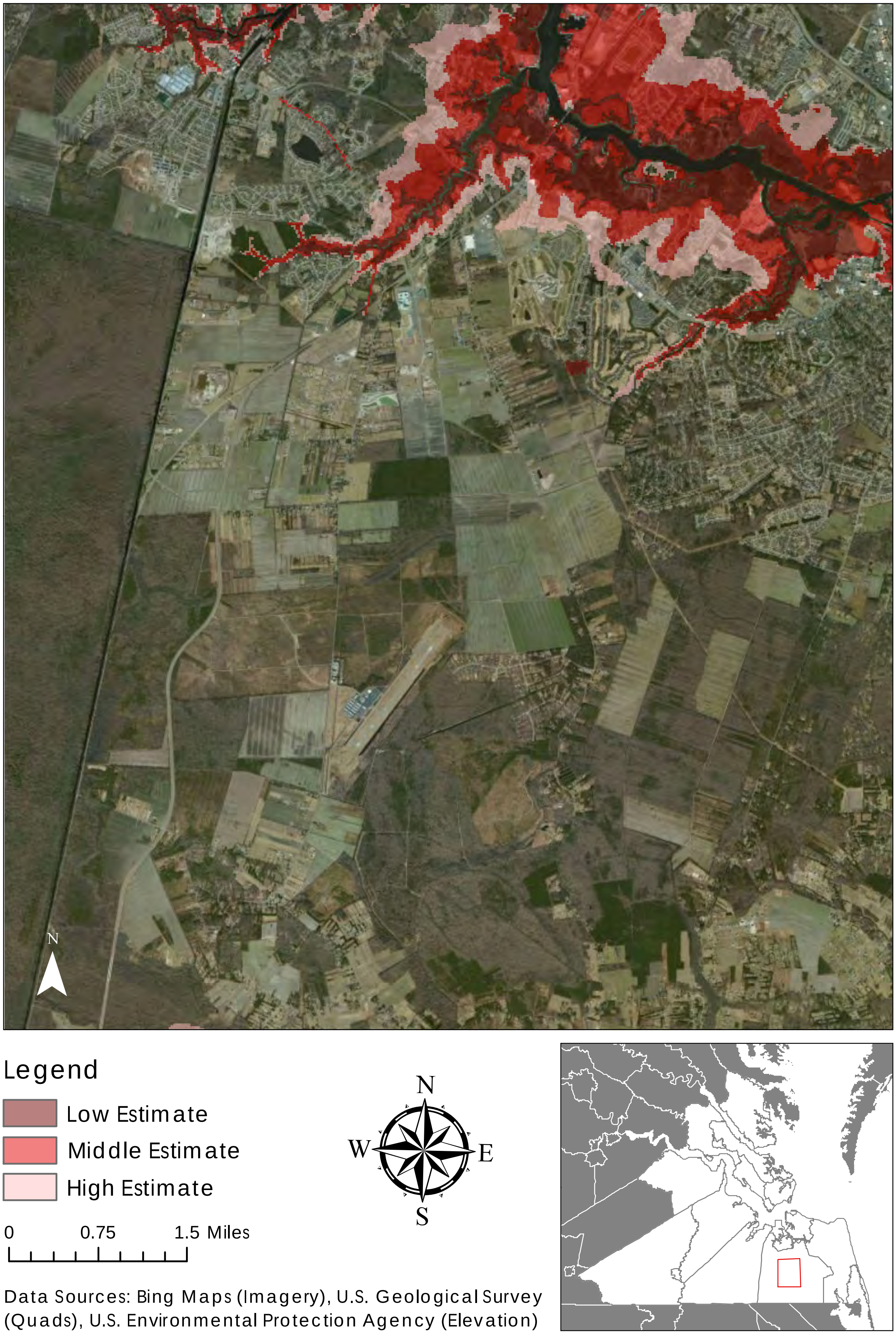
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

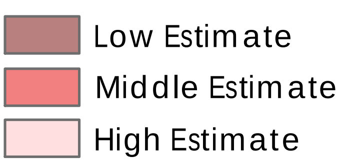
Hampton Roads Sea Level Rise
Map 43: Deep Creek, VA Quadrangle

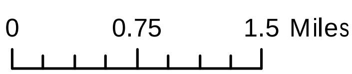


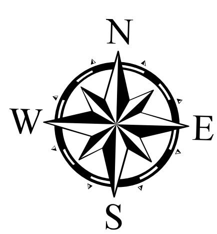
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

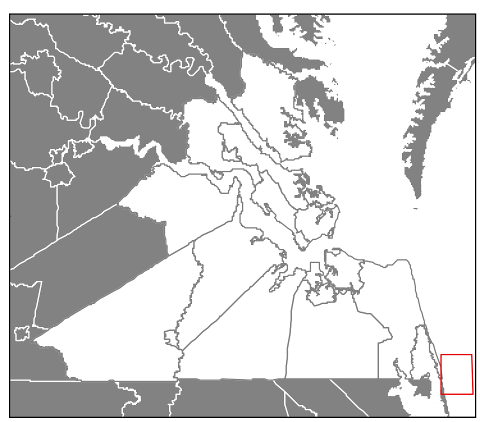
Hampton Roads Sea Level Rise
Map 44: Knotts Island OE E, NC-VA Quadrangle

Legend









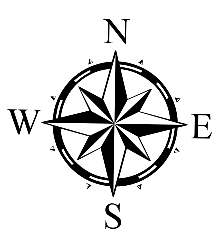
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

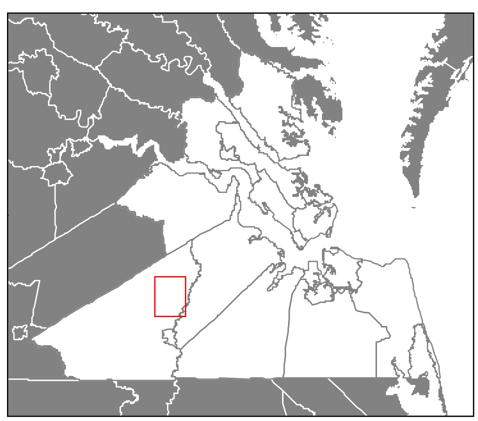
Hampton Roads Sea Level Rise
Map 45: Sedley, VA Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

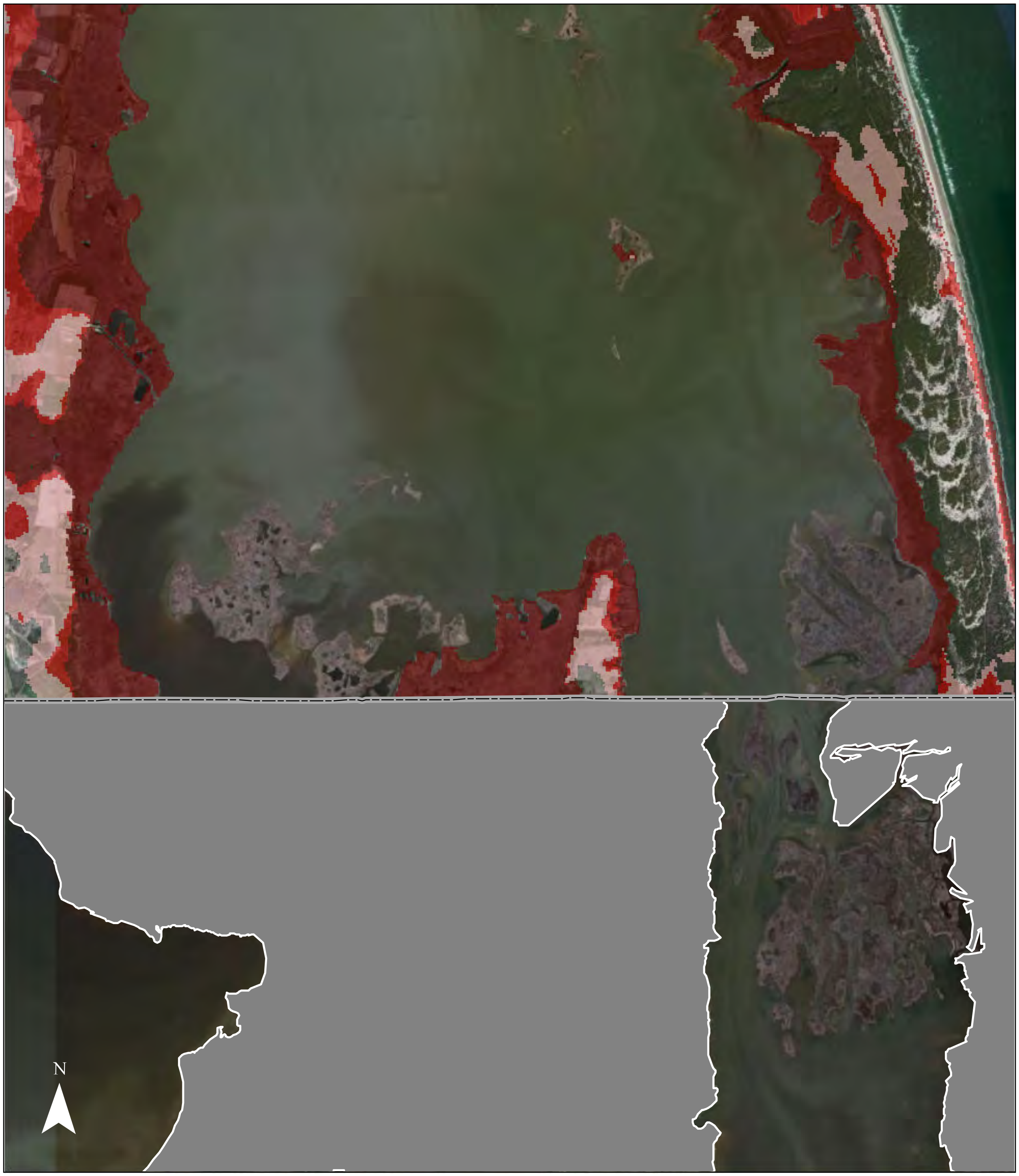
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

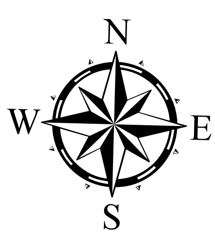
Hampton Roads Sea Level Rise
Map 46: Knotts Island, VA-NC Quadrangle

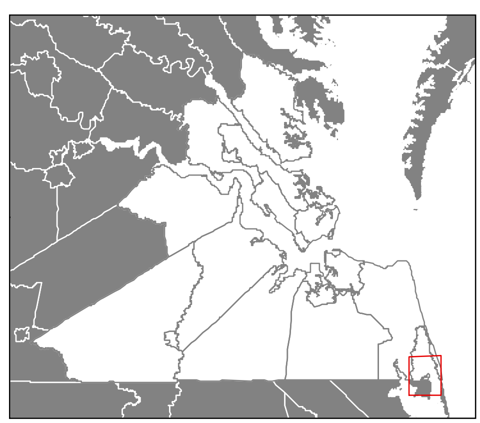


Legend

- Low Estimate
- Middle Estimate
- High Estimate

0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 47: Suffolk, VA Quadrangle

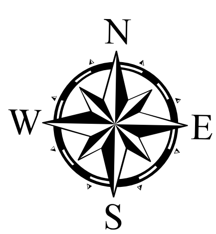
Legend

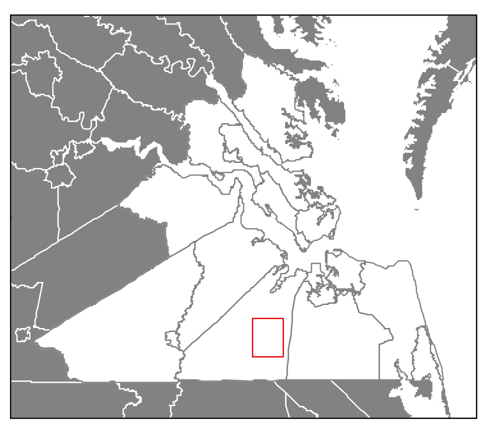
Low Estimate

Middle Estimate

High Estimate

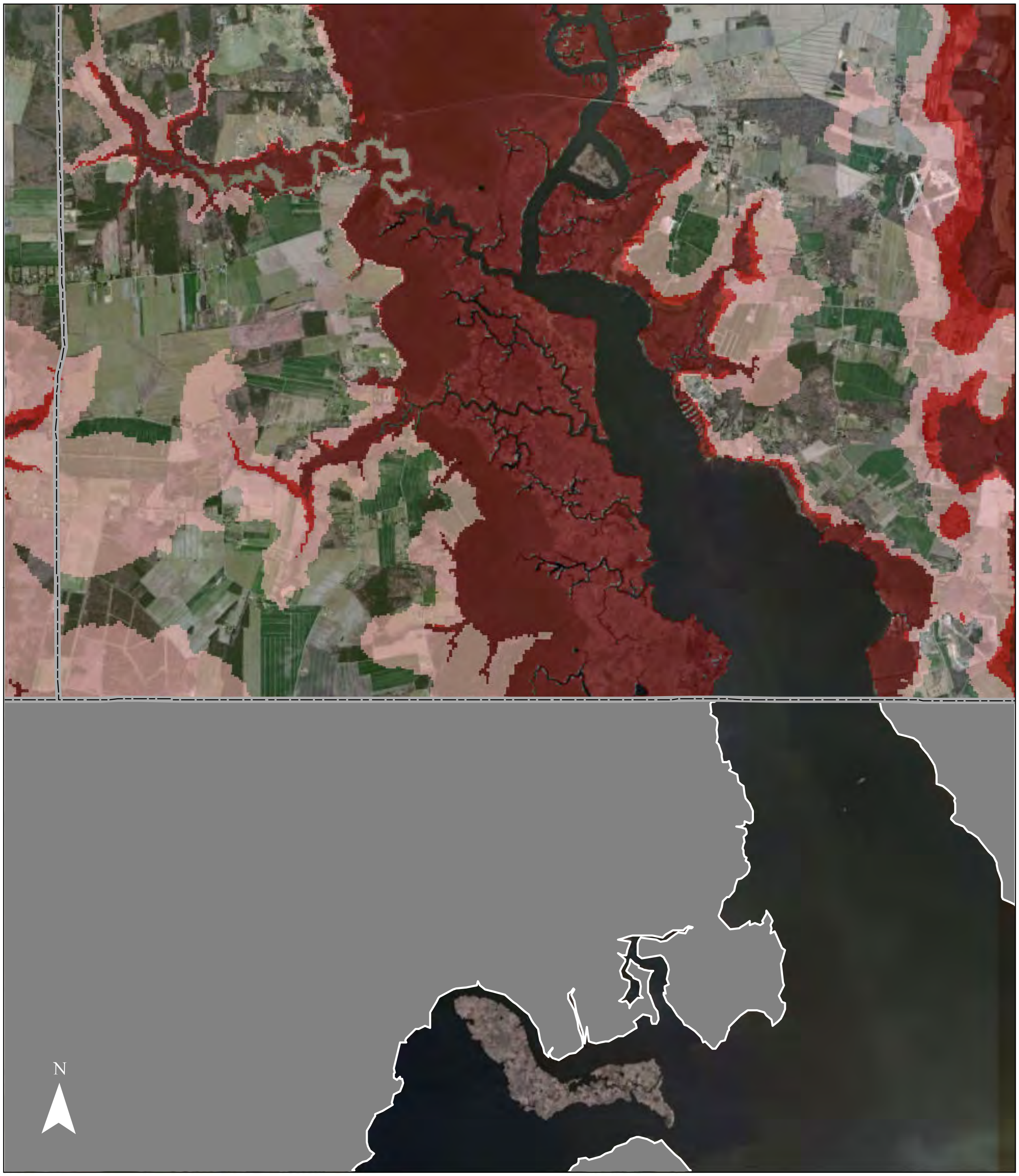
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

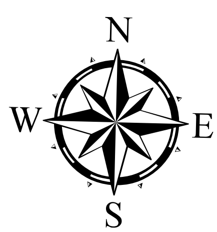
Hampton Roads Sea Level Rise
Map 48: Creeds, VA-NC Quadrangle

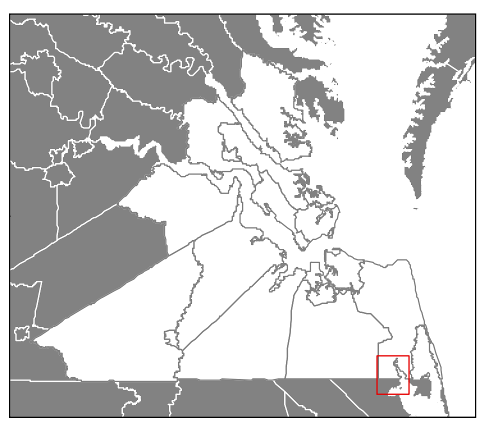


Legend

- Low Estimate
- Middle Estimate
- High Estimate

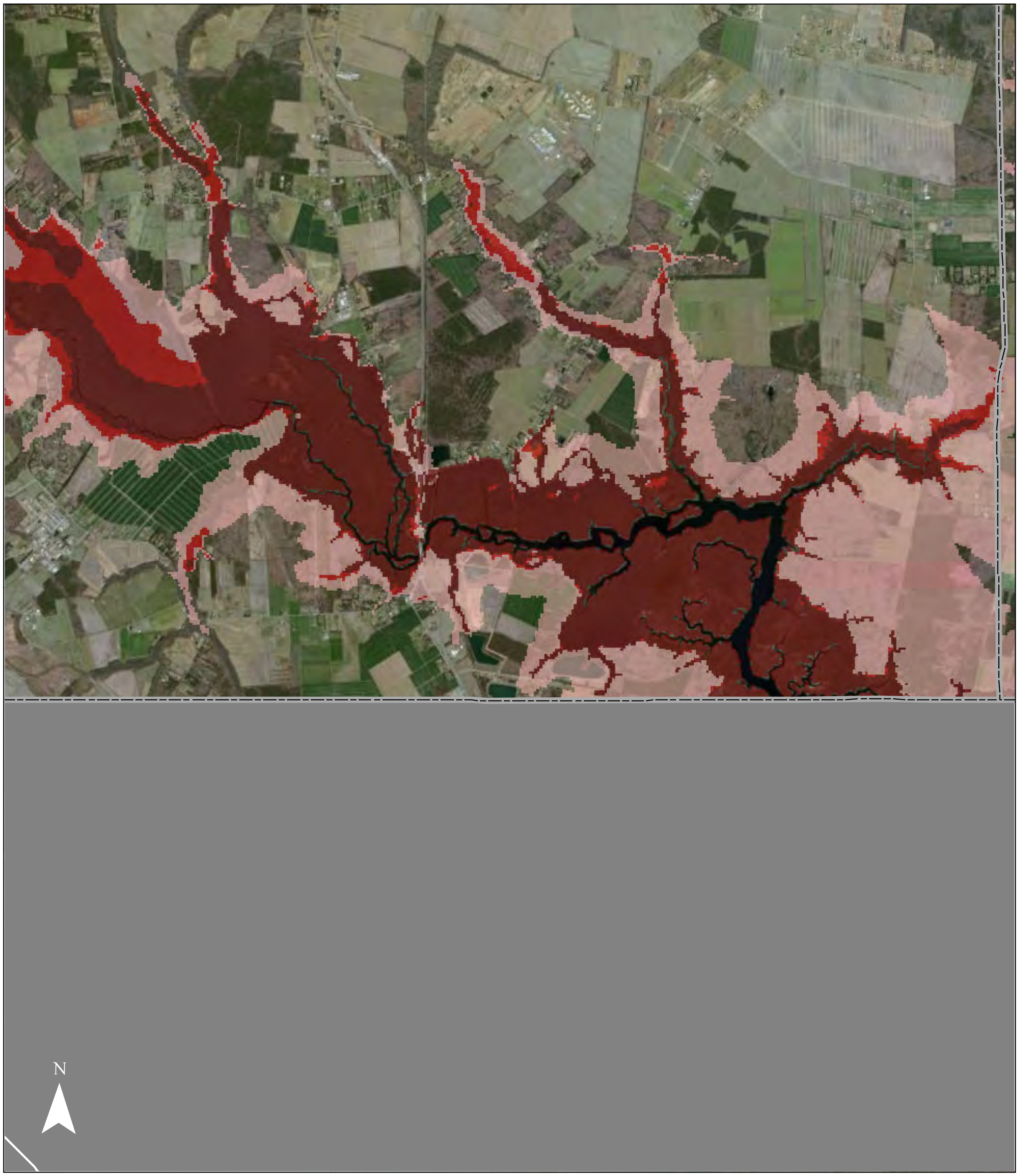
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

Hampton Roads Sea Level Rise
Map 49: Moyock, VA-NC Quadrangle



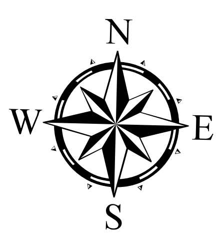
Legend

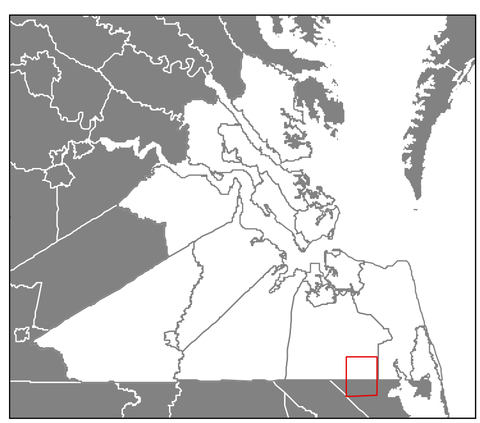
Low Estimate

Middle Estimate

High Estimate

0 0.75 1.5 Miles





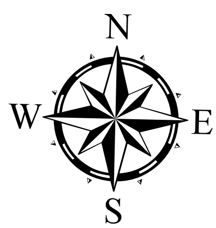
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

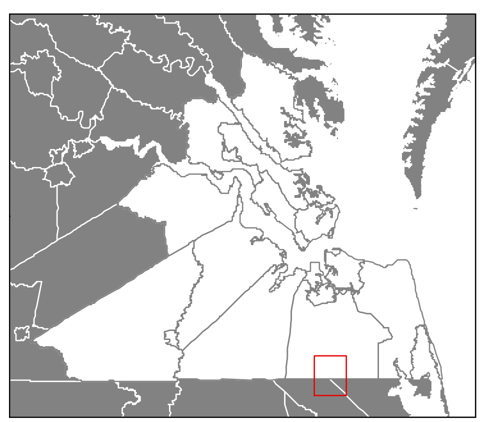
Hampton Roads Sea Level Rise
Map 50: Lake Drummond SE, VA-NC Quadrangle

Legend

- Low Estimate
- Middle Estimate
- High Estimate

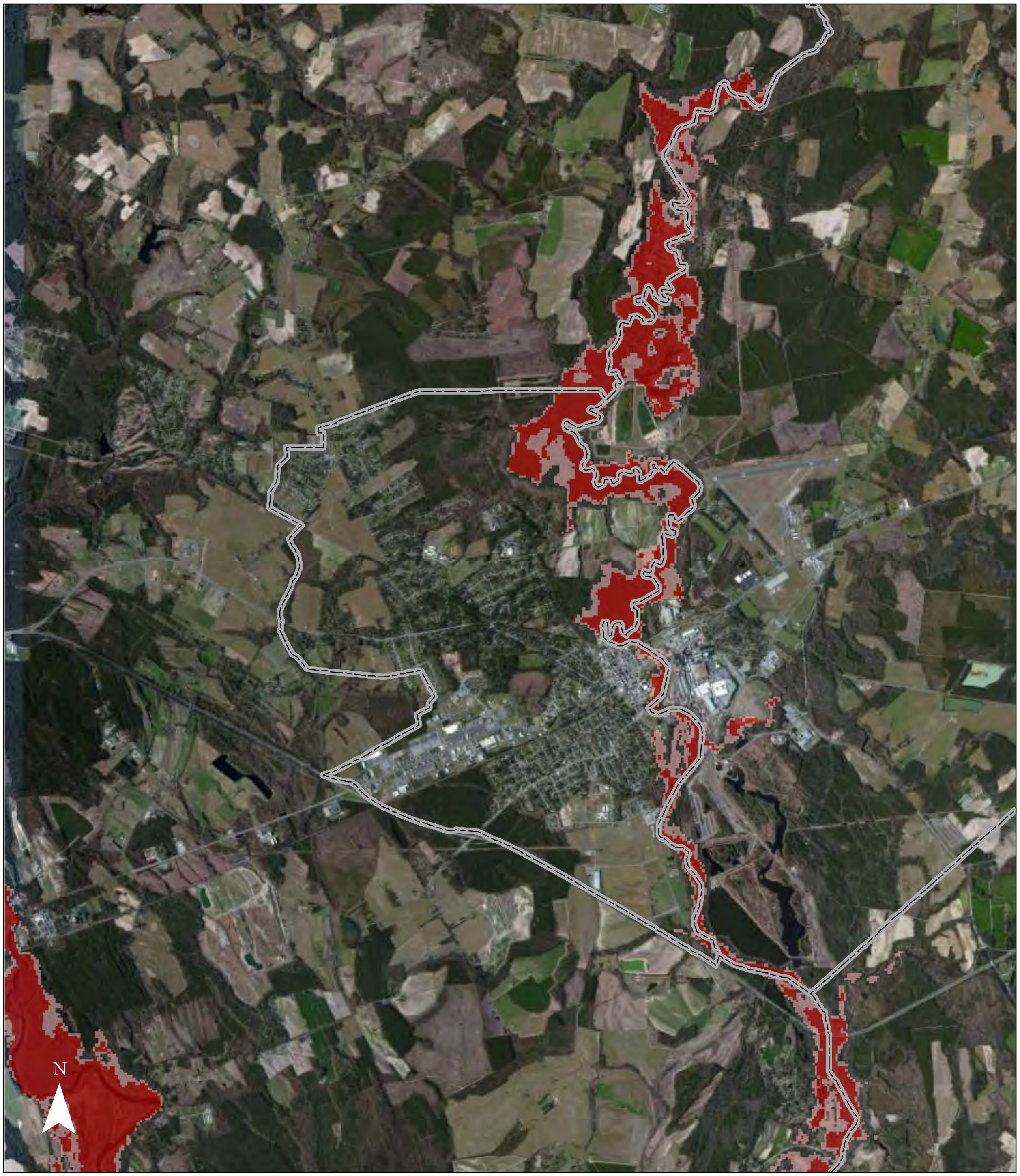
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

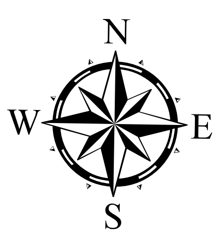
Hampton Roads Sea Level Rise
Map 51: Franklin, VA Quadrangle

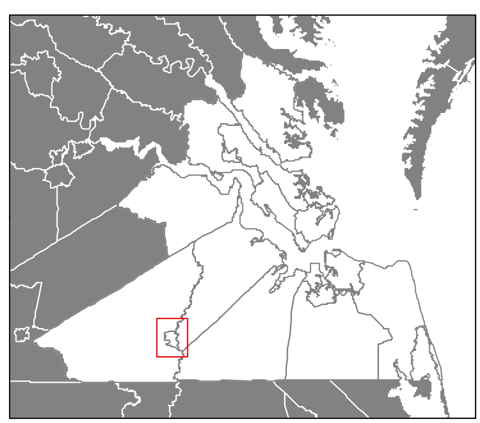


Legend

- Low Estimate
- Middle Estimate
- High Estimate

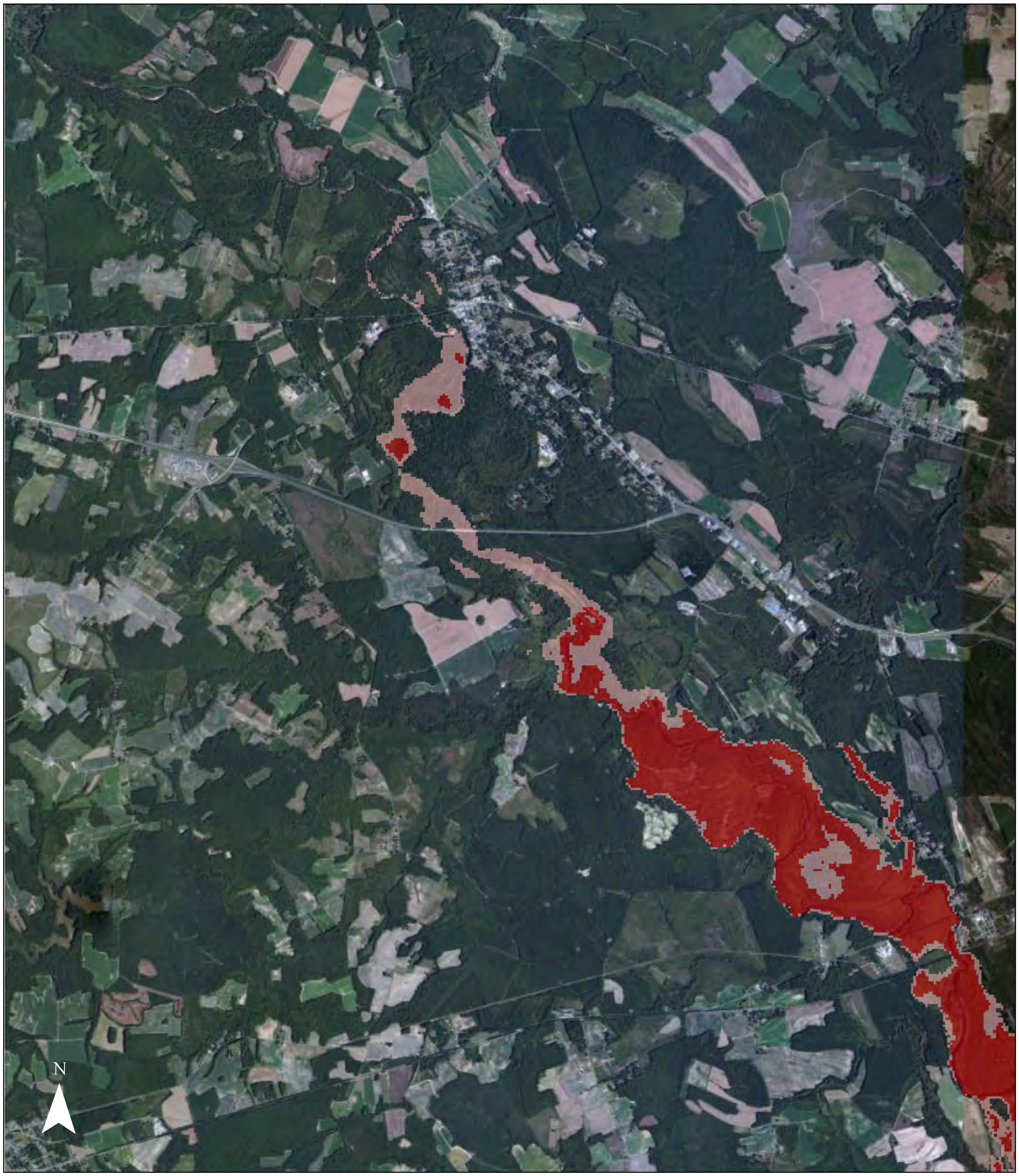
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

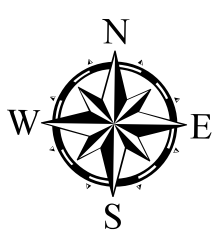
Hampton Roads Sea Level Rise
Map 52: Courtland, VA Quadrangle

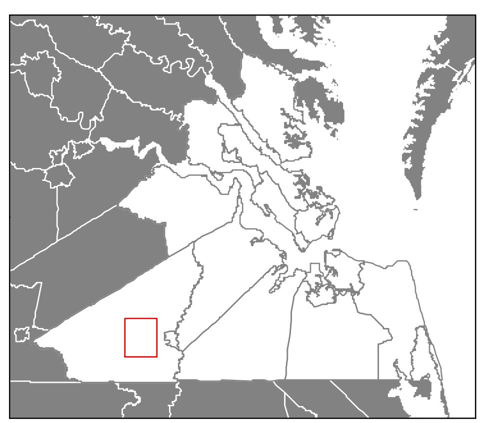


Legend

- Low Estimate
- Middle Estimate
- High Estimate

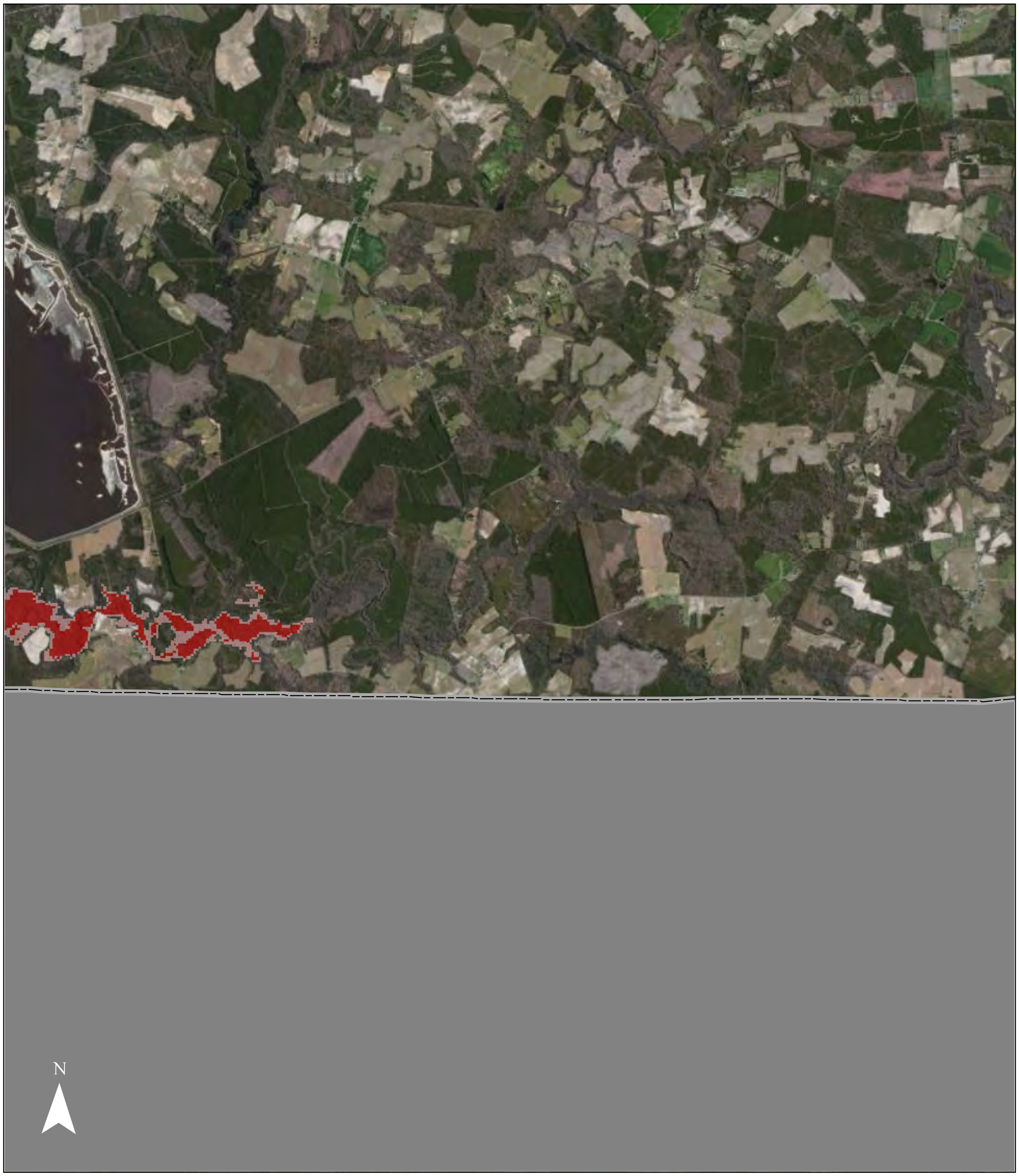
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

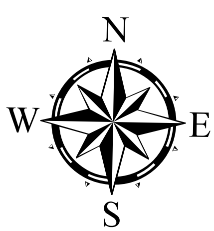
Hampton Roads Sea Level Rise
Map 53: Gates, VA-NC Quadrangle

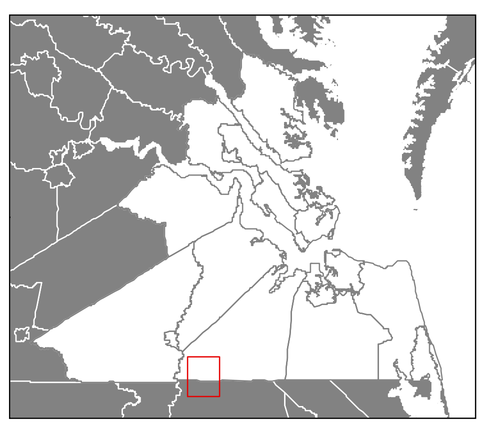


Legend

- Low Estimate
- Middle Estimate
- High Estimate

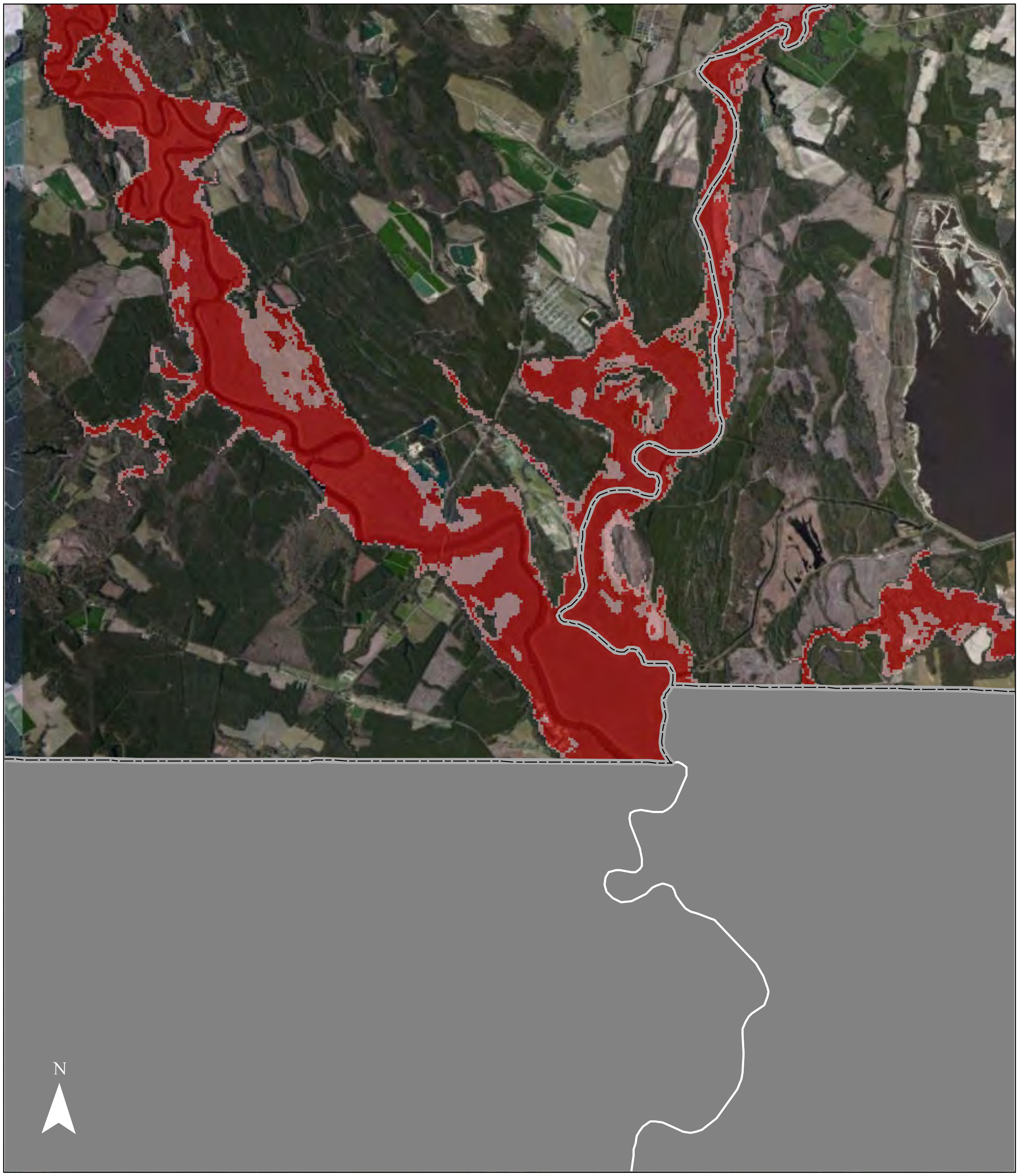
0 0.75 1.5 Miles





Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

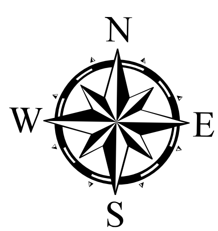
Hampton Roads Sea Level Rise
Map 54: Riverdale, VA-NC Quadrangle

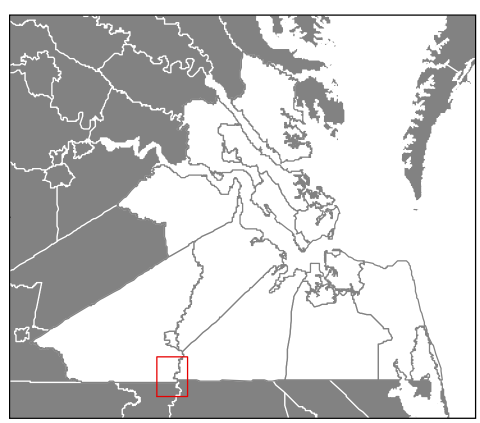


Legend

- Low Estimate
- Middle Estimate
- High Estimate

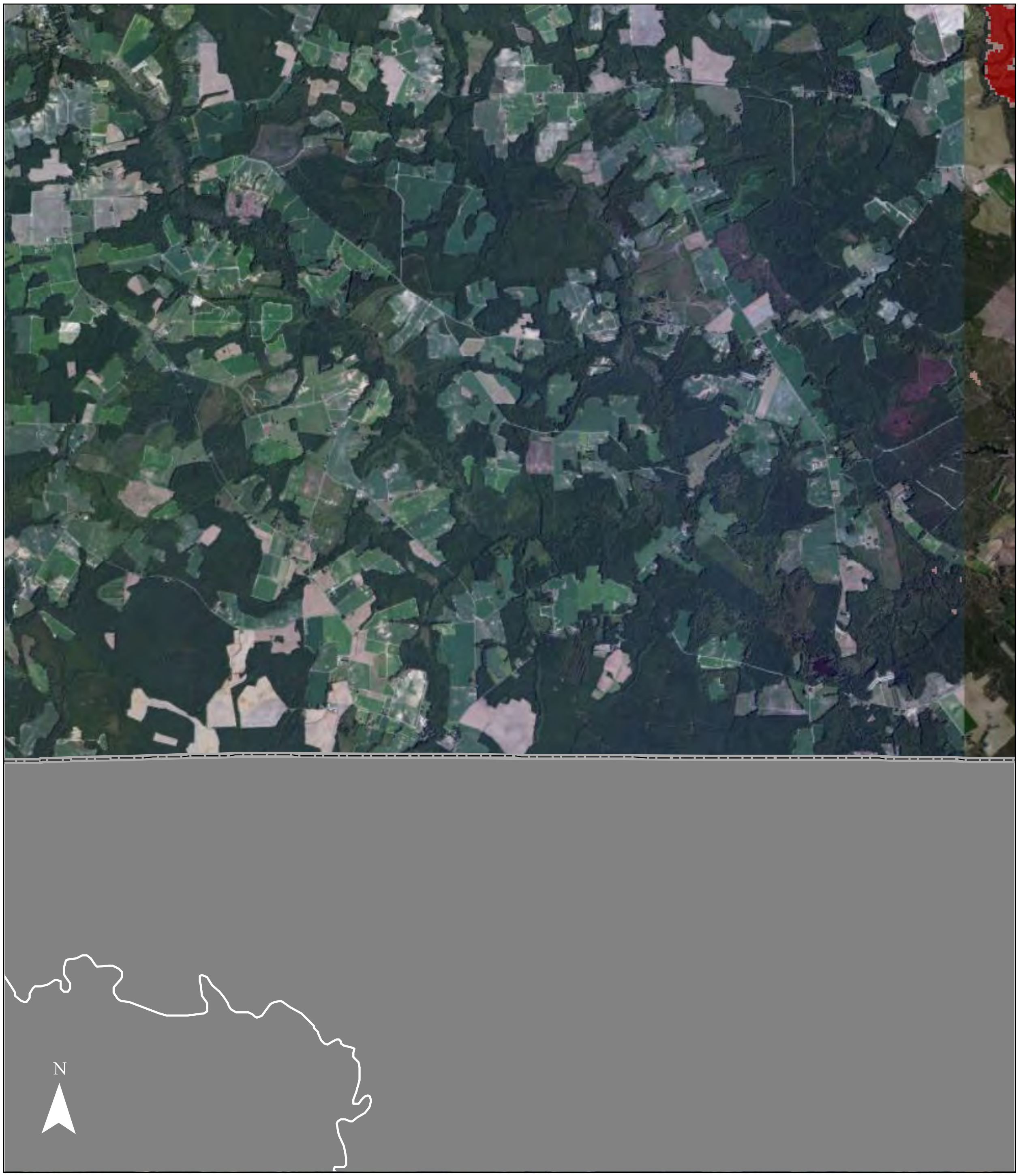
0 0.75 1.5 Miles





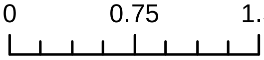
Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)

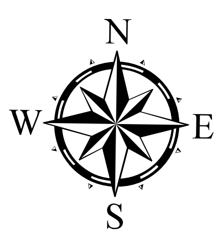
Hampton Roads Sea Level Rise
Map 55: Sunbeam, VA-NC Quadrangle

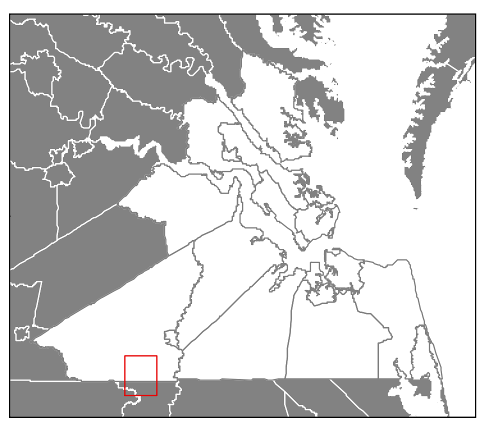


Legend

- Low Estimate
- Middle Estimate
- High Estimate







Data Sources: Bing Maps (Imagery), U.S. Geological Survey (Quads), U.S. Environmental Protection Agency (Elevation)