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Modeling the Impacts of Sea Level Rise in Coastal Virginia at Multiple Scales

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MODELING THE IMPACTS OF SEA LEVEL RISE IN COASTAL VIRGINIA AT MULTIPLE SCALES

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ABSTRACT

MODELING THE IMPACTS OF SEA LEVEL RISE IN COASTAL VIRGINIA AT MULTIPLE SCALES

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Old Dominion University, 2023
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Relative sea level is increasing along the Mid-Atlantic coast of the United States and the rate of relative sea level rise (ΔRSL) for Coastal Virginia is approximately double the rate of global sea level rise (ΔSLRG)(*1*). The potential impacts posed to communities by ΔRSL are best understood by examining the spatial relationship between the upper limits of ocean-connected waters and the geographic positioning of critical natural and societal assets. This research examines this problem at three spatial scales to quantify the impacts of ΔRSL and storm flooding events on (i) structural and transportation infrastructure for the tide-influenced coastal zone of Virginia, (ii) physical and socioeconomic assets in Hampton Roads, and (iii) critical infrastructure at Port of Virginia's Norfolk International Terminal South (NITS).

Spatial modeling of future sea level rise produced data and maps of potential inundation and provided an assessment of impacts to land areas, roadways, and buildings throughout coastal Virginia. The total land area predicted to be inundated by sea level rise was 424 square miles (682 km^2) in 2040, 534 square miles (859 km^2) in 2060, and 649 square miles (1044 km^2) in 2080.

Modeling of a Category 1 hurricane (like Florence in 2018) making landfall near Virginia Beach and travelling westward through Hampton Roads with future ΔRSL of +1.5 feet (.46 m) and +3 feet (.91 m) predicted significant flooding and physical damages, including impairment to critical emergency services such as police, fire, and emergency medical transport.

Modeling of hurricane storm surge with future ΔRSL to predict potential flooding at Port

of Virginia's NITS facility proved to be an effective screening tool for estimating current and future risk to critical facilities. Modeling revealed a near-linear pattern of vulnerability wherein the surface area predicted to be inundated by storms of identical category progressively increased as sea level increased.

The multi-scale, -source, and -temporal techniques developed in this inundation modeling research provide data and replicable methodologies that others may use as a proven platform to calculate potential losses of natural resource, property, economy, and life resulting from inundation resulting from ΔRSL.

To my mother who instilled a love for learning and, most importantly, taught me that the best gift is kindness, both given and received.

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The motivation, support, and love provided by my family have always been the *reason* to continue moving forward, to strive to learn more, and to be a better human being. There are no words to express my gratitude for my partner, Shannon, for spending nearly three decades "growing up" and learning with me. Our three children, Koa, Niamh, and Aven have enriched my life beyond measure and have given me the lifelong opportunity to try to set a good example.

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NOMENCLATURE

ANPDC	Accomack-Northampton Planning District Commission
CAT	Hurricane category
CCRFR	Commonwealth Center for Recurrent Flooding Resiliency
CPDC	Crater Planning District Commission
DDM	Digital depth model
DEM	Digital elevation model
ΔRSL	Change in relative sea level (feet or meters)
ΔSLRG	Change in global sea level (feet or meters)
FEMA	Federal Emergency Management Agency
GIS	Geographic information systems
GWRC	George Washington Regional Council
HRPDC	Hampton Roads Planning District Commission
HRSLR	Hampton Roads sea level rise
IPCC	Intergovernmental Panel on Climate Change
LE	Linear error
LIDAR	Light detection and ranging
MC	Monte Carlo
MEOW	Maximum envelope of water
MHHW	Mean higher high water (feet or meters)
MLLW	Mean lower low water (feet or meters)
MOMs	Maximum of maximums
MPPDC	Middle Peninsula Planning District Commission

NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NCOSBM	North Carolina Office of State Budget and Management
NDA	Non-disclosure agreement
NFIP	National Flood Insurance Program
NGC	National Geospatial Program
NHC	National Hurricane Center
NIBS	National Institute of Building Sciences
NITS	Norfolk International Terminal South
NNPDC	Northern Neck Planning District Commission
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NVA	Non-vegetated vertical accuracy
NVRC	Northern Virginia Regional Council
NWS	National Weather Service
PAT	Polygon attribute table
PD	Planning district
PlanRVA	Richmond Regional Planning District Commission
QL	Quality level
RAMMB	Regional and Mesoscale Meteorology Branch
RMSEz	Vertical root mean square error (cm)
RMW	Radius to max winds
SERDP	Strategic Environmental Research and Development Program
SLR	Sea level rise

SLOSH	Sea Lake and Overland Surge from Hurricanes
TRB	Transportation Research Board
UAV	Uncrewed aerial vehicles
USACE	United States Army Corps of Engineers
USD	United States dollars
USDOT	United States Department of Transportation
USGS	Unites States Geological Survey
UTM	Universal Transverse Mercator
VGIN	Virginia Geographic Information Network

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CHAPTER I

INTRODUCTION

BACKGROUND

Sea Level Rise in Coastal Virginia and the Hampton Roads Region

The National Oceanic and Atmospheric Administration (NOAA) projects that relative sea level will continue to increase at an accelerating rate in the coming decades in the Mid-Atlantic region of the United States, which includes the states of New Jersey, Delaware, Maryland, Virginia, and North Carolina (*2*). According to NOAA, the average sea level along the Mid-Atlantic coast has risen by over 1 foot (.305 m) since 1900 and is projected to rise an additional 1 to 4 feet (1.22 m) by 2100, depending on future emissions of greenhouse gases (*2*). The rate of sea level rise in the Mid-Atlantic region is among the highest on the U.S. East Coast, due to the combination of global sea level rise and regional factors such as subsidence (*1*). NOAA also warns that the impacts of sea level rise in the Mid-Atlantic region are already being felt, with increased frequency and severity of coastal flooding, erosion of beaches and marshes, and saltwater intrusion into groundwater aquifers, among other impacts. These impacts have significant implications for the environment, economy, and communities in the region.

A multitude of studies have been performed to both identify and quantify the underlying causes of global and regional sea level rise. In 2012, Boon's (*3*) analysis of monthly mean sea level measurements at tide stations along the Atlantic seaboard revealed statistically significant acceleration in sea level rise. Further analysis by Ezer and Corlett (*4*) confirmed positive sea level acceleration in the Chesapeake Bay with rates nearly double those of 60 years prior. Sallenger et al. (*5*) provided additional confirmation by identifying a 1000 km long hotspot of sea level acceleration on the mid-Atlantic coast north of Cape Hatteras which they found to be consistent with a slowing of the Atlantic Meridional Overturning Current (AMOC).

Atkinson et al. (*6*) explained that change in relative sea level (ΔRSL) in the Mid-Atlantic is higher than global sea level rise (ΔSLRG) for several reasons including: local subsidence from groundwater withdrawal and settling of sub-structural fill, regional subsidence resulting from glacial isostatic rebound, and changes in ocean surface elevation related to ocean circulation dynamics and weakening of the Gulf Stream. Examination and understanding of the natural and societal impacts caused by the location specific combination of these ΔRSL-influencing factors necessitates highly localized analyses.

The Hampton Roads region is effectively surrounded by water. It is positioned in a coastal plain at the convergence of the Atlantic Ocean, Chesapeake Bay, and several rivers and is bordered on the south by Back Bay/Currituck/Albemarle Sounds. Review of digital elevation data for areas east of the Suffolk scarp reveals that much of Hampton Roads is positioned only 1-2 meters above mean high water (MHW). There is very little natural slope and large contiguous areas are uniformly elevated. These characteristics allow for potential wide-spread flooding when sea level and storm surges reach certain heights. We could think of these areas on the hypsometric curves as "tipping points." Sea level rise may seem inconsequential as it approaches one of these points, but once the threshold elevation is eclipsed, flooding and damages emerge in bursts.

A recent NOAA report (*7*) found that significant direct impacts of long-term will occur when key elevation thresholds in the coastal environment are exceeded. In one study of the Upper Florida Keys, Zhang (*8*) discovered that inundation dynamics exhibit non-linear behavior and demonstrate tipping points beyond which the inundation of land, population, and property accelerates. Increasing ΔRSL will amplify non-linear inundation and cause tipping points to be reached sooner.

Critical elevation thresholds for localities will vary widely due to regional differences in topography and hydrology. Delineation of critical elevations may be discovered through the categorization and examination of elevation increments within a relatively homogenous study region. Strauss et al. (*9*) provided a national example using similar "elevation slicing" to illustrate topographic vulnerability within elevation bands for the contiguous United States. They estimated that 3.7 million people, over 10% of the population, live on land within 1 m of high tide.

There have been numerous studies detailing the impacts of sea level rise on Virginia. Kirwan et al. (*10*) found that sea level rise is causing increased flooding and erosion in Virginia, leading to the loss of marshes and other coastal habitats, as well as damage to infrastructure and property. The study also highlights the need for effective adaptation strategies to address these impacts. Buzzanga (*11*) found that sea level rise is causing saltwater intrusion into groundwater aquifers in Virginia, affecting the quality of drinking water for coastal communities such that managed aquifer recharge and other adaptation measures may be necessary to protect freshwater resources in the face of sea level rise. In 2015, Ezer and Atkinson (*12*) explored the impacts of sea level rise on coastal communities in Virginia, including increased flood risk, reduced property values, and increased costs for infrastructure maintenance and repair. They further argued for the implementation of effective adaptation measures, such as the use of green infrastructure and coastal wetlands, to reduce the impacts of sea level rise on communities in the state.

The rate of relative sea level rise (ΔRSLR) for Hampton Roads is approximately double that of the rate of estimated global sea level rise (ΔSLRG) and is increasing (*1*). In 2018, McAlpine and Porter (*13*) explored the vulnerability of coastal communities to sea level rise and storm surge, including the potential impacts on property values, housing prices, and economic activity. The study argued for the need for effective adaptation measures, such as the use of green infrastructure and zoning policies, to reduce the vulnerability of coastal communities to sea level rise and storm surge. Another study found that sea level rise is leading to increased coastal flooding in Norfolk, causing damage to infrastructure, homes, and businesses, as well as economic losses (*14*). The study highlights the need for effective adaptation measures, such as the use of green infrastructure and shoreline armoring, to reduce the impacts of sea level rise in the city.

Another recent study of the Lafayette River basin by Fugro (*15*) reported that Norfolk's relatively low elevation and drainage gradients result in a significant percentage of the city being prone to tidal flooding and storm surges. The level of risk caused by this inherent condition is exacerbated by increasing local ΔRSL. As Atkinson et al. (*6*) pointed out, our best gauge of local ΔRSL is the Sewells Point tide gauge at the Norfolk Naval Base which has been making measurements since 1927 (Figure 1) and is one of the longer records in the United States.

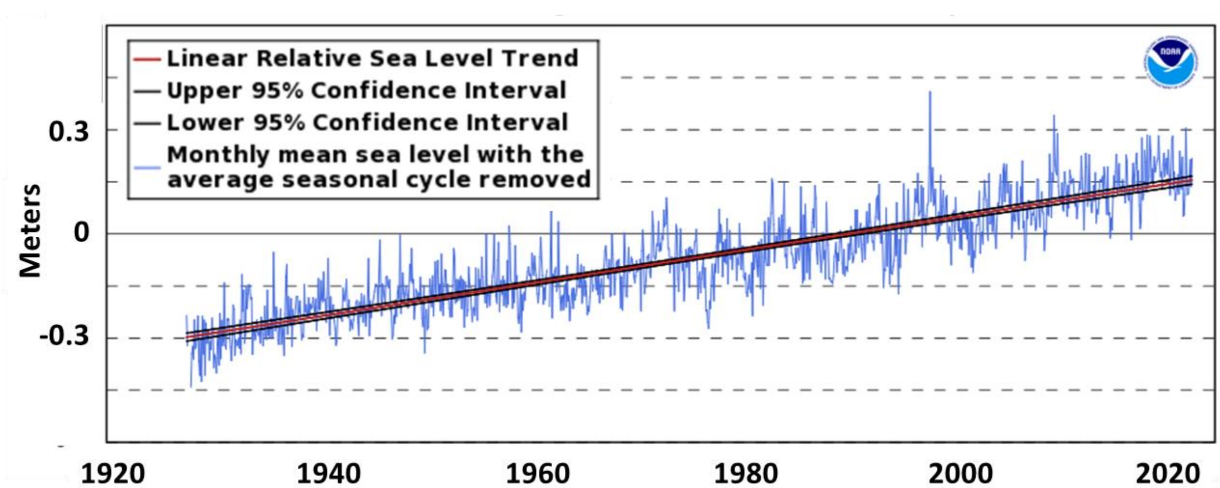


Figure 1. Water level height at the Sewells Point NOAA tide station in Norfolk

Total sea level rise since 1928 has been about 1.45 feet and the current rate is 4.74 mm/yr. *(16)*

Anecdotal reports of recurrent tidal flooding, often called "nuisance" flooding, have been increasing throughout coastal Virginia. Nuisance flooding is defined as a water level measured by NOAA tide gauges above the local NOAA National Weather Service (NWS) threshold for minor impacts established for emergency preparedness (*16*). Fugro's study (*15*) provided support for these claims by indicating that tidal flooding in Norfolk is frequent and is expected to worsen over time as mean sea level rises. Atkinson et al. (*6*) provided an extrapolation of higher tides into the future which shows that by the year 2050 a major transportation corridor, Hampton Boulevard, in central Norfolk will be flooded at every high tide.

Well before 2050, it is expected that the number of days of tidal flooding will increase apace with rising RSL. In 2017, Sweet and Marra calculated the nuisance flooding level for Norfolk, VA, to be 0.53m above MHHW and predicted an accelerating trend of tidal flooding days per year (*16*).

Regional & Local Impacts, Morphological Response, and Impacts modeling

The Governor's Climate Change committee (*17*) found that sea level rise poses a "serious and growing threat" to Virginia's roads, railways, ports, utility systems, and other critical infrastructure. Physical impacts of sea level rise will be the most direct, some being more obvious than others. For nature-based systems, sea level fluctuations are natural events to which these systems are adapted. However, they have become tightly coupled with human infrastructure and systems. Frequently, this coupling both diminishes the capability of natural systems to respond to SLR and increases the vulnerability of conjoined human systems. Vulnerable natural systems in the Hampton Roads region include beaches, shorelines mudflats, wetlands, and submerged vegetation. The loss of these habitats engenders the loss of ecological services that reduce coastal erosion, sequester carbon, and support a diverse assemblage of flora and fauna, including economically important fin- and shellfish populations.

Mitchell et al. found that "natural resources" throughout Tidewater respond differently to increasing SLR, depending on the topographic character, land cover, and land use of the area (*18*). For example, their report suggested that ocean-exposed beaches are at risk of large losses, while most estuarine beaches increase in size. However, they also recommended that shoreline hardening projects and other municipal infrastructure can limit the upward migration of natural habitats, resulting in losses greater than those predicted by most models.

While the impacts of flooding of natural systems are potentially devastating, the physical impacts on the human-built environment will likely garner more attention. Hampton Roads provides an excellent example of the development of the system of links (transportation, utilities, communications) and nodes (housing, commercial) necessary to support the energy flows of a dense population (*19*). Vulnerability of each of these assets is either by direct flood damage or by breakage of a critical link. The Recurrent Flooding Study for Tidewater, Virginia, recommended high resolution mapping of storm surge and flood frequency as essential to identifying vulnerabilities in populations, infrastructure, and natural resources (*18*). Atkinson et al. also underscored the critical need for mapping and add that geographic information systems (GIS)-based mapping can also be used to identify where resources and expenditures could have the biggest impact on mitigating the risk of ΔRSL (*6*).

OBJECTIVES

The inherent flood hazard posed by sea level rise can be illuminated and better understood by examining the spatial relationship between the upper limits of ocean-connected waters and the geographic/topographic positioning of population centers and critical infrastructure. This research attempted to provide that understanding through GIS-based modeling of sea level rise and hurricane storm surge impacts at several spatial and temporal scales that addresses the following questions:

Research Question 1: What will be the extent of permanent flooding due to relative sea level rise for all coastal zone planning districts within the Commonwealth of Virginia in the years 2040, 2060, and 2080?

Hypothesis: A non-linear pattern of expanding areas of permanent and recurrent flooding above the current "high tide line" (MHHW, mean higher high water datum) and concomitant increases in at-risk infrastructure will be revealed throughout coastal Virginia.

Research Question 2: Under near-future increased sea level scenarios, what physical damages and related first-order socioeconomic costs would result from a Hurricane Florence-like Category 1 storm making landfall near Virginia Beach and travelling westward through Hampton Roads?

Hypothesis: Modeling of a Category 1 hurricane striking Hampton Roads with elevated sea level will forecast large increases in damages and associated economic costs over damages and costs predicted for the same storm at present day sea level.

Research Question 3: How will sea level rise, coupled with hurricane storm surge, impact critical marine infrastructure of a single Port of Virginia container terminal facility?

Hypothesis: Due to the terminal's inherent low elevation and proximity to open water, with increased sea level even moderate storm surges could impact critical structures and impair future operations.

SIGNIFICANCE

In 2008, the National Research Council (NRC) suggested that the greatest impact of sea level rise and related storm surges will be flooding of coastal roads, railways, transit systems, and runways (*20*). They stressed that the magnitude of costs to redesign and retrofit infrastructure creates the need for incorporation of climate change and ΔRSL into long-term plans and requires thorough analysis, strategic risk-based investment, and data-driven emergency response planning.

Surging Seas found that significant land areas, populations, structures, and critical defense and municipal infrastructure in Virginia are situated less than 5 feet above the present-day high tide line (*21*). Assets below this elevation are enumerated below:

- 54,000 homes valued collectively at more than $17.4 billion, over a third of which is in Virginia Beach alone
- Residential (nighttime) population of over 107,000
- More than 25,000 people in the high Social Vulnerability Index (SoVI) class
- 1,469 miles of public roadway
- 7 schools
- 67 houses of worship
- 1 power plant
- 148 EPA listed sites, mostly facilities with significant hazardous materials
- 13% of Naval Station Norfolk, the world's largest naval complex
- 32% of Norfolk Naval Shipyard
- 40% of the Air Force-Army Joint Base Langley-Eustis

The Governor's Panel on Climate Change reinforced the serious nature of the threat to coastal Virginia from inundation by highlighting far reaching impacts such as wetland and habitat loss, salt-water intrusion in the aquifer, and possible incapacitation of critical military installations and impairment of national defense readiness (*17*). In 2020, the Department of Defense and its contractors in Hampton Roads collectively employed roughly 140,000 people who accounted for $14.7 billion in wage compensation (*22*). Even a partial impairment of this critical economic engine represents a potentially devastating loss to the region and the Commonwealth.

The most recent report to Congress by the United States Department of Transportation Bureau of Transportation Statistics highlighted that the Port of Virginia is ranked third by cargo volume on the East Coast and tenth nationally by tonnage in the United States (*23*). The Port of Virginia's critically important status is underscored by a 2022 report indicating that the port and related activities supported 436,667 jobs and generated $2.7 billion in state and local taxes (*24*).

In Norfolk and throughout Hampton Roads, increases in precipitation, storm frequency, and sea level rise will almost certainly lead to increased severity of flooding events. Understanding the potential impacts of rising sea level at fine spatial scales is critical for private property owners, public officials, and stewards of the environment. A concise three-point summary of the challenges in understanding the problem of rising sea level in Virginia was offered in the report of Mitchell et al. (*18*):

1. Recurrent flooding is a significant issue in Virginia coastal localities and one that is predicted to become worse over reasonable planning horizons (20-50 years).
2. The risks associated with recurrent flooding aren't the same throughout all areas of Tidewater.
3. Data are lacking for comprehensive, fine resolution analysis of flood risks in the region.

The chain of vulnerabilities to ΔRSL in Hampton Roads begins with the impacts on the natural environment, branches multiplicatively into impacts on man-made infrastructure, and cascades exponentially into impacts on our complex interconnected webs of commerce and society. Loss of natural resources, property, economy, and even life are very real possibilities and demand that multi-scale studies such as this research be developed, implemented, and replicated throughout the Commonwealth.

CHAPTER II

FUTURE SEA LEVEL AND RECURRENT FLOODING RISK FOR COASTAL VIRGINIA

PREFACE

A modified version of this chapter was published by the Commonwealth Center for Recurrent Flooding Resiliency (CCRFR) as Report #11 in the CCRFR special reports series. The right to reproduce this article in theses or dissertation is retained by the author under the author rights agreement with CCRFR.

BACKGROUND

This research was developed partially in response to a request from the Secretary of Natural Resources and Special Assistant to the Governor for Coastal Adaptation and Protection to assist with meeting the Executive Order No. 24 (2018), Increasing Virginia's Resilience to Sea Level Rise and Natural Hazards directive set forth in Section 2 Part A requiring the development of a Coastal Resilience Master Plan (*25*). This request called for the analysis of the best available existing data on coastal land elevation, sea level rise projections, vertical land motion, and building and transportation assets for future years 2040, 2060, and 2080. These benchmark timelines were selected to closely coincide with common planning time horizons, similar to the Hampton Roads Coastal Resilience Working Group's adopted Sea Level Rise Planning Policy (*26*). Following the recommendation of the Commonwealth Center for Recurrent Flooding Resiliency (CCRFR), the NOAA 2017 Intermediate-High sea level curve was used to model flood surfaces (*27*). Sea level rise projections were to be analyzed as Relative SLR (RSLR), combining the effects of vertical water rise (or "eustatic" change) with regional trends in vertical land motion, or subsidence. The study was designed to make use of publicly available digital elevation data, buildings, and roads as well as several sources of federal data, including sea level trends, tidal flooding and datums, and peer-reviewed and government reports. Maps of potential future inundation would be developed to represent a baseline assessment of impacts to land areas, including wetlands, parcels and development, roadways, and buildings within the Commonwealth. Specific parameters requested by the Governor's office at the inception of this study included the following:

- Use of NOAA intermediate-high sea level rise scenario as recommended as the preferred planning scenario by Considine et al. (*27*)
- Model and map areas of inundation from sea level rise for future years 2040, 2060, 2080
- Perform enhanced inundation modeling to delineate expected areas of minor and moderate flooding for each period of increased sea level
- Aggregate inundation model results to each of eight planning districts comprising coastal Virginia using imperial measurement units to promote adoption by municipal planners

The examined geographic regions include the member cities and counties that comprise the eight coastal Virginia planning districts: Northern Virginia Regional Council (NVRC), George Washington Regional Council (GWRC), Northern Neck Planning District Commission (NNPDC), Middle Peninsula Planning District Commission (MPPDC), Richmond Regional Planning District Commission (PlanRVA), Crater Planning District Commission (CPDC), Hampton Roads Planning District Commission (HRPDC), and Accomack-Northampton Planning District Commission (A-NPDC). Figure 2 provides an overview map of the coastal planning districts, showing their locations relative to one another, the Chesapeake Bay, and Atlantic Ocean.

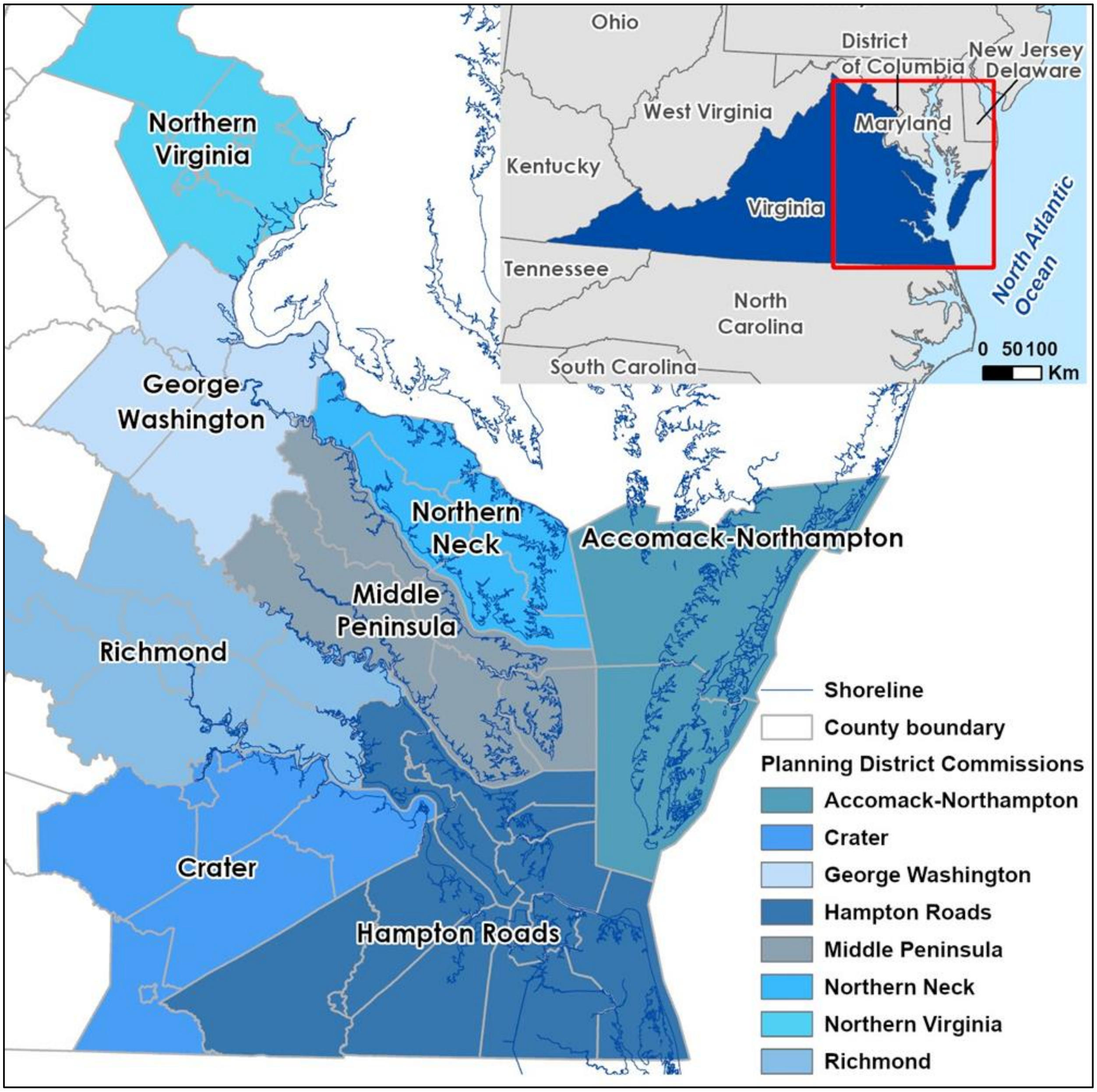


Figure 2. Coastal Virginia planning districts

The research presented here sought to answer the question: What will be the extent of inundation due to relative sea level rise and minor and moderate flood events for all coastal zone planning districts within the Commonwealth of Virginia in the years 2040, 2060, and 2080? It was hypothesized that nonlinear increases in flooding above present day MHHW and concomitant increases in at-risk infrastructure will be revealed throughout coastal Virginia.

APPROACH AND METHODS

Modeling SLR impacts on the natural and built environment

NOAA has outlined a four-step process, listed below for the mapping of coastal flooding, which this study employed specifically for sea level rise (*28*).

1. Obtain and Prepare Elevation Data
2. Prepare Water Levels
3. Map Inundation
4. Visualize Inundation

Preparation of data and creation of new inundation layers and maps serve as the foundation for impacts modeling. For each sea level rise study year and scenario, spatial analytics tools and customized GIS modeling were used to examine and quantify the vulnerability of coastal areas and infrastructure. Quantitative measurements of potentially impacted land areas, property, and transportation networks were modeled and summarized in tabular and graphical form.

For any given scenario, sea level rise estimates vary slightly throughout coastal Virginia and the Chesapeake Bay. Accordingly, inundation modeling was conducted independently for the following four geographically contiguous coastal study areas: (1) southern Bay and Atlantic (Hampton Roads), (2) Middle Peninsula, (3) Northern Neck and Northern Virginia, and (4) the Eastern Shore. Nine unique model scenarios were developed for each of the four study areas:

1. 2040 sea level rise only
2. 2040 sea level rise plus minor flooding
3. 2040 sea level rise plus moderate flooding
4. 2060 sea level rise only
5. 2060 sea level rise plus minor flooding

6. 2060 sea level rise plus moderate flooding
7. 2080 sea level rise only
8. 2080 sea level rise plus minor flooding
9. 2080 sea level rise plus moderate flooding

Compliance with Commonwealth-requested parameters resulted in the reaggregation of 36 model-run results to the boundaries of the 8 coastal planning districts. Thus, 72 unique planning district-specific scenarios were developed by a customized modeling approach that generally adhered to NOAA's four-step process. Specific methods used in each step are discussed in the following sections.

Spatial Reference

Given that the study comprised areas spanning the longitudinal extent of Virginia, the Universal Transverse Mercator (UTM) system was employed to provide a standard frame of reference that could be applied to all the analytical subdivisions used in this study. The eight coastal Virginia planning districts fall entirely with Zone 18 north of the UTM system. UTM standard units of measure are meters/kilometers for length and square meters/kilometers for area calculations. The Commonwealth's requirements for this study necessitated the conversion of standard calculations into imperial units of measure. Accordingly, values shown in the text body, tables, and figures of this document will report primarily imperial units, with standard conversion values noted parenthetically or in captions. All spatial data were referenced vertically to the North American Vertical Datum of 1988 (NAVD88) and horizontally to the North American Datum of 1983 (NAD83), both with units of meters. Local tidal datums were also used for inundation modeling as described later in this document.

Elevation Data

Digital elevation data are required for spatial modeling of the impacts of sea level rise. As these data serve as the foundation for mapping coastal inundation, NOAA underscores the importance of evaluating elevation data accuracy and goodness of fit for the specific requirements of any modeling or analysis effort. Uncertainty in the model analyses results, in large part, from the accuracy of elevation data. For this reason, acknowledging and understanding the accuracy of elevation data when modeling inundation is important. Positional error in inundation modeling relates to this uncertainty in vertical measurements and to issues of datum conversion, projection, and interpolation methods. Potential error may cause the inundation zone to move either landward or seaward. Multiple studies have affirmed the critical importance of elevation data for the modeling of sea level rise and flooding (*29-32*).

Gesch (*29*) noted that coastal elevation is such an important parameter in sea level rise impact studies, it must be known precisely, and the data used to model elevations in the analyses must support the accurate delineation of elevation zones that correspond to specific sea-level rise scenarios. In 2012, Gesch reiterated that input elevation information is a primary contributor to the uncertainty associated with inundation hazard assessments and that, because these data are such a critical component in coastal hazard assessments, the vertical accuracy strong influences the reliability of the results (*30*). Mitchell et al. (*18*) provides the following concise affirmation, "The key factor for all of these (flooding) analyses is the accuracy of the underlying elevation data." Figure 3, adapted from Gesch, illustrates how the uncertainty of elevation data affects the delineation of coastal elevation zones (*29*).

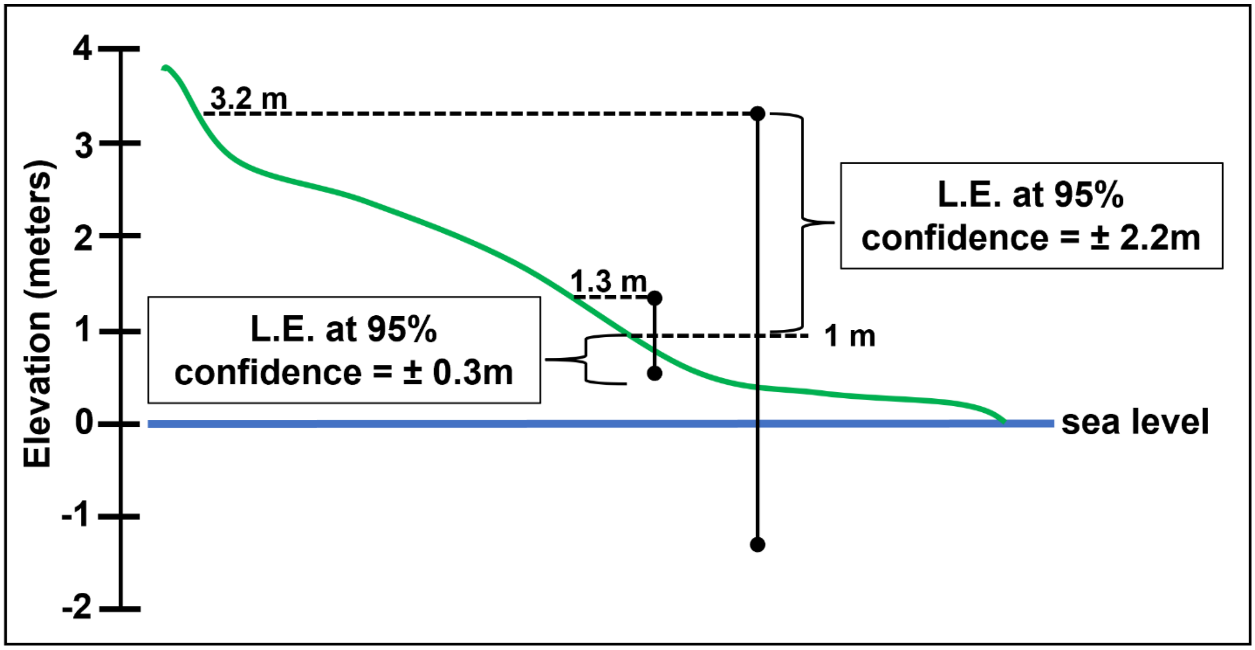


Figure 3. Sea-level rise of 1 meter is mapped onto the land surface against two elevation datasets with differing linear error (LE) and vertical accuracies

The more accurate elevation model results in a delineation of inundation zones with much less uncertainty. Adapted from Gesch. (*29*)

Digital elevation data are produced using a variety of methods including photogrammetry, radar, digitization from analog topographic maps, point surveys, and light detection and ranging (lidar). For the purpose of sea level rise assessments, Gesch found that lidar-derived elevation data are substantially better than non-lidar elevation datasets (*29*).

Utilization of "best available" lidar having both high spatial resolution and accuracy is preferable. Accordingly, quality level 2 (QL2) lidar-derived elevation data used in this study met both these criteria and were acquired directly from NOAA's Sea Level Rise Data Download website (*33*).

Digital Elevation Models

NOAA has developed publicly available digital elevation models (DEMs) intended specifically for use in coastal inundation modeling. These DEMs are generally constructed by NOAA using the best available lidar elevation data collected for each region. This research required the utilization of the following four Coastal Inundation DEMs all published original in August 2016:

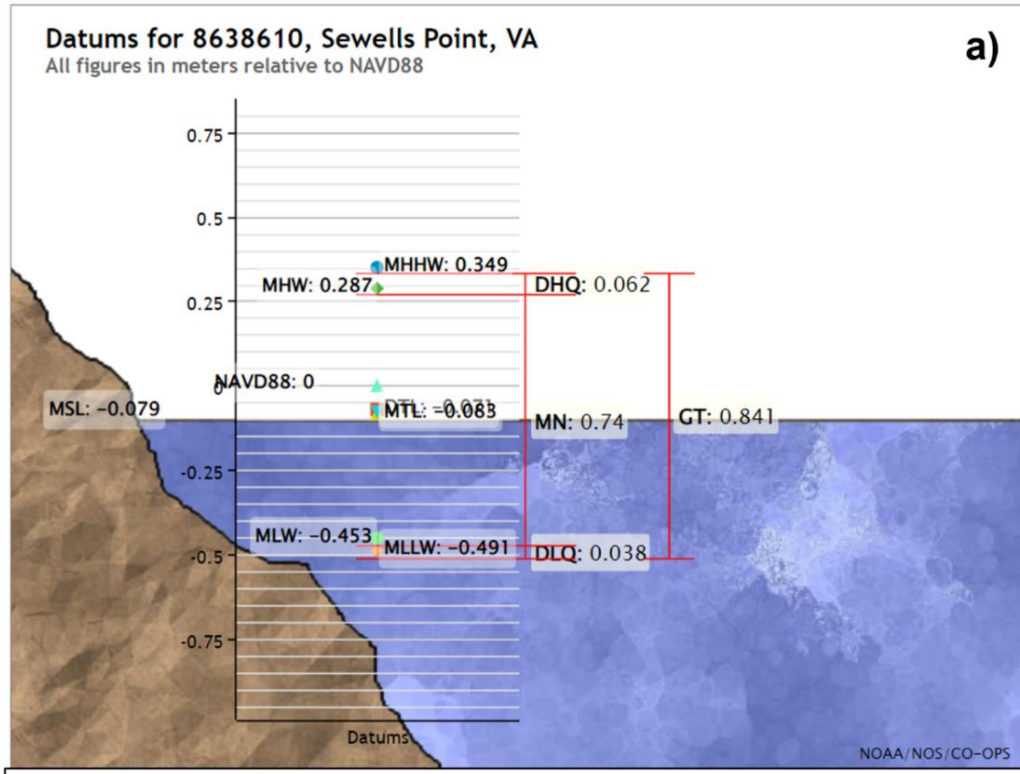
1. NOAA Office for Coastal Management Coastal Inundation Digital Elevation Model: Virginia, Southern. Produced from a composite of 5 unique lidar data sets. (*34*)
2. NOAA Office for Coastal Management Coastal Inundation Digital Elevation Model: Virginia, Middle. Produced from a composite of 4 unique lidar data sets. (*35*)
3. NOAA Office for Coastal Management Coastal Inundation Digital Elevation Model: Virginia, Northern. Produced from a composite of 3 unique lidar data sets. (*36*)
4. NOAA Office for Coastal Management Coastal Inundation Digital Elevation Model: Virginia, Middle. Produced from a composite of 1 unique lidar data set. (*37*)\

NOAA reported that neither horizontal nor vertical accuracy were tested for these DEMs, due to the requirement that all source lidar data used in constructing the DEMs was to meet FEMA Specifications for Flood Hazard Mapping. According to the NOAA Office for Coastal Management, the Coastal Inundation DEMs require that all source lidar data used in constructing the DEM to meet FEMA Specifications for Flood Hazard Mapping (*34-37*). FEMA's *Guidance for Flood Risk Analysis and Mapping – Elevation Guidance* publication details that all elevation data comply with the Unites States Geological Survey (USGS) LiDAR Base Specification v1.2 at a minimum (*38*). Base Specification v1.2 states that the minimum acceptable quality level (QL) for all National Geospatial Program (NGP) and 3-dimensional Elevation Program (3DEP) collections is QL2, which stipulates an absolute vertical accuracy for lidar digital elevation models meet a Non-vegetated Vertical Accuracy (NVA) of 19.6 centimeters or better at the 95-percent confidence level (≤10cm RMSEz) (*39*).

Water Level Preparation

Water inundation raster surfaces, referenced to the standard project spatial reference, were generated for each sea level rise scenario being analyzed. These inundation surfaces represented future Mean Higher High Water (MHHW) levels under each sea level rise scenario. MHHW represents the average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch, a 19-year period established by the National Ocean Service for collecting observations on water levels and calculating tidal datum values. Water levels above MHHW represent a threshold at which flooding above "normal" tidal conditions is easily identified by the presence of wetlands, high water marks, or wrack lines. In 2013, Boon concisely noted that, "nautical charts use MLLW to reference charted depths conservatively so that a mariner will know that the water depths shown on the chart can be counted on for safe passage," and conversely that, "Reversing direction and looking upward instead of downward, MHHW can be used to conservatively reference storm tides so that coastal residents will know how much additional rise to expect above the highest levels of the astronomical tide."(*40*) Figure 4 provides graphical illustration and tabular example of the differences between local water level datums and NAVD88 at the Sewells Point tide station (*41*). These illustrations of the difference between MHHW and NAVD88 underscore the need for the application of water level surface correction if inundation is to be accurately mapped.

For each of the analysis areas covered by the four Coastal Inundation DEMs, corresponding raster surfaces representing the MHHW tidal datum were developed using NOAA's VDatum tool. According to NOAA, VDatum was designed to vertically transform geospatial data among a variety of vertical datums to allow for data conversion from different horizontal/vertical references into a common system (*42*). While developing MHHW surfaces for the study area, the author discovered that NOAA was developing their own MHHW-correction surfaces, as well as raster surfaces representing minor and moderate flooding thresholds. Personal communication with NOAA staff confirmed this and allowed for the direct acquisition and usage of NOAA's tidal datum correction and flooding threshold surfaces (*43*). NOAA MHHW datum water level surfaces were used as the basis for development of inundation raster surfaces to be employed for each modeling scenario for the years 2040, 2060, 2080. The modeling process that subtracts the surface values of the DEM from those of the scenario-based water level surfaces can be generally described as a modified bathtub approach that accounts for tidal variability and, to some degree, hydrological connectivity.



Station ID: 8638610 **PUBLICATION DATE:** 08/07/2013 **b)**
Name: SEWELLS POINT, HAMPTON ROADS VA
NOAA Chart: 12245 **Latitude:** 36° 56.8' N (36.94667)
USGS Quad: NORFOLK NORTH **Longitude:** 76° 19.8' W (-76.33000)

T I D A L   D A T U M S

Tidal datums at SEWELLS POINT, HAMPTON ROADS based on:

LENGTH OF SERIES:	19 YEARS
TIME PERIOD:	January 1983 - December 2001
TIDAL EPOCH:	1983-2001
CONTROL TIDE STATION:	

Elevations of tidal datums referred to Mean Lower Low Water (MLLW), in METERS:

HIGHEST OBSERVED WATER LEVEL (08/23/1933)		= 2.444
MEAN HIGHER HIGH WATER	MHHW	= 0.840
MEAN HIGH WATER	MHW	= 0.778
North American Vertical Datum	NAVD88	= 0.491
MEAN SEA LEVEL	MSL	= 0.412
MEAN TIDE LEVEL	MTL	= 0.408
MEAN LOW WATER	MLW	= 0.038
MEAN LOWER LOW WATER	MLLW	= 0.000
LOWEST OBSERVED WATER LEVEL (01/31/1966)		= -1.092

Figure 4. Tidal Datums at Sewells Point Tide Gauge

a) Graphical representation of tidal datums in meters relative to NAVD88,

b) Tidal datum comparisons measured in meters relative to MLLW datum

Sea Level Rise (only)

SLR-related water level raster surfaces representing future flooding were created by adding the NOAA Intermediate High SLR value for the modeled year to the MHHW-adjusted raster surface. Values for these flood surfaces were obtained by examining the NOAA Intermediate-high curve at tide stations throughout coastal Virginia. The US Army Corps of Engineers (USACE) Sea Level Rise Calculator was used to derive the relative SLR heights of tidal flooding, combining a NOAA SLR projection (Intermediate-High) for eustatic water level rise with local subsidence (varies throughout coastal Virginia) taken from regional measurements (*44*). Figure 5 details sea level rise predictions for the Sewells Point tide gauge in Norfolk, Virginia, and pinpoints the values along the intermediate-high curve that were employed in this study.

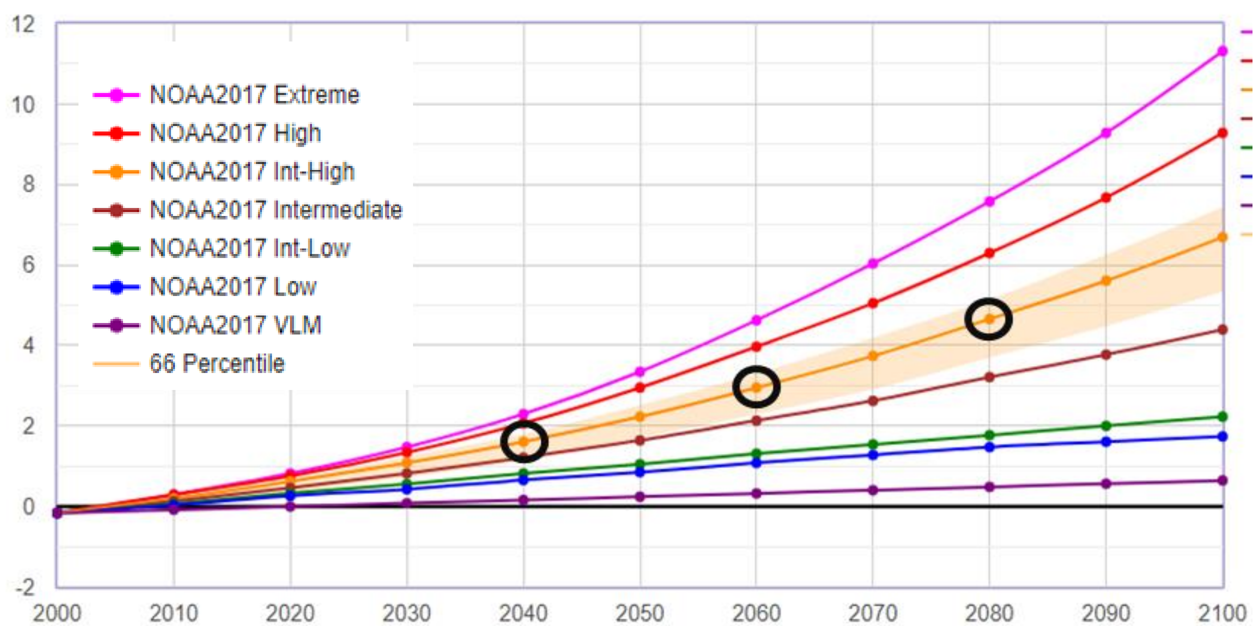


Figure 5. Relative Sea Level Rise Scenarios, years 2000 to 2100, Sewells Point, Norfolk, VA Circles show the points representing the sea level increase values in feet used by this study (1 ft = .301 m). Adapted from USACE Sea Level Rise Calculator. *(44)*

Future sea level estimates were acquired using representative tide stations for each of the four modeling regions within the study area. Table 1 details the values in meters used to represent the increased water level owing to sea level rise for each study year and the corresponding NOAA DEM used for each region's inundation model.

Table 1. Increases in sea level in meters for each analysis region (1 meter = 3.28 feet)

Year	NOAA DEM	Int-High SLR VALUE (m)
2040	Eastern Shore	0.41
2060	Eastern Shore	0.81
2080	Eastern Shore	1.3
2040	Southern	0.49
2060	Southern	0.9
2080	Southern	1.42
2040	Middle	0.52
2060	Middle	0.92
2080	Middle	1.43
2040	Northern	0.57
2060	Northern	0.95
2080	Northern	1.44

Sea Level Rise with Minor or Moderate Flooding

NOAA has established three thresholds for coastal flood severity: (1) minor, (2) moderate, and (3) major. These thresholds are "based upon water level heights empirically calibrated to NOAA tide gauge measurements from years of impact monitoring" (*45*). Minor refers to flooding which is more disruptive than damaging (includes tidal nuisance flooding), moderate refers to damaging flooding, and major is used to describe destructive flooding.

To model the additional impacts of minor or moderate flooding events in addition to future sea level rise, raster surfaces representing increased water levels for each category were added to the SLR-adjusted MHHW flood surfaces developed during the SLR modeling phase of this research. Minor and Moderate flood surfaces were both minor and moderate flooding for Virginia and were supplied by NOAA. These water surfaces were added to create new future sea level plus flooding raster surfaces representing future MHHW plus minor and MHHW plus moderate flooding levels.

Inundation Impacts Mapping

Depth Grid Development. Areas of anticipated flooding were modeled and mapped by subtracting the ground surface elevation values of the DEM from those of the scenario-based water level surfaces. Resultant raster surfaces developed by raster math subtraction contain pixel values that are equal to the expected depth of flooding at the pixel location. These flood surfaces are also known as digital depth models (DDMs), or more commonly "depth grids," and delineate the areal extent and depth of flooding predicted by the model for each scenario. All calculations for the impacts of ΔRSL for each modeled year (2040, 2060, 2080) are naturally inclusive of all prior years and not additive. However, calculations of the additional impacts of minor and moderate flooding are in addition to the impacts of ΔRSL.

Preparation of water level surfaces, inundation modeling, and all related impacts analysis and mapping were performed using a combination of GIS software tools, specifically ArcMap and ArcGIS Pro, developed by Esri (formerly Environmental Systems Research Institute). Techniques detailed in this research are specific to those software applications, however, are easily modified to be performed using other commercial and open-source GIS tools.

Subtractions of DEM elevations from water level surfaces were achieved using conditional

(Con) statements. For each scenario, Con statements compared the water surface elevation value to the DEM surface value. Where the water surface value was found to equal or exceed the land surface, a subtraction of the DEM value from the water value was performed. The output of this function was a depth raster grid with positive water depth values for only those areas that were predicted to be inundated. Areas where the DEM surface value exceeded the water surface value were "dry" and were removed from the newly modeled depth grid. An example Con statement for the Eastern Shore study area is as follows:

Con("VA_EasternShore_GCS_3m_NAVDm.img"<="Acc_2040_int_hi_mhhw",
"Acc_2040_int_hi_mhhw"-"VA_EasternShore_GCS_3m_NAVDm.img")

Polygon Flooding Zone Development. Depth grids created by this process served as the primary input for additional analysis designed to produce polygon area of flooding data that allow for ease of measurement, attribution, and overlay operations with other geospatial data, and were also useful for future studies that relate depth, frequency, and duration of flooding to damage estimation. Development of polygon flood areas began with the conversion of floating-point values encoded in depth grids to a uniform integer. The following example shows how another Con statement is used to examine the depth grid, determine all areas with positive depth, and output a new raster surface of only flooded areas with a grid cell value of 10:

Con("VA_EasternShore_2040_Int_high_mhhw_flood">= 0, 10)

Once cells of the flood raster surface were encoded with a standard integer, they were grouped into a flooded "regions" by pixel value, with many pixel groupings being spatially disconnected. This process was critically important to the development of polygonal zones because, without it, an excessive and unwieldy number of polygons would have been produced from the myriad of values encoded in unique raster cells. Region grouping develops zones comprised of all raster cells with the same value. When these zones are disconnected, they are identified as a separate entity and assigned a new region identifying number (*46*).

Resulting region-grouped rasters were converted to polygon vector data to allow for the encoding of attributes and additional vector-based analysis. Owing to the natural elevation variability of topographic surfaces and their digital analogues, DEMs, region-grouped data included many relatively small (<100 m^2) regions that appeared throughout the study region. The disconnected state, abundance, and small area of these regions dramatically increased the uncertainty of their future flooding state and, therefore they were removed to reduce the potential for error of commission. The 2-dimensional area (m^2) of each new polygon flood region was calculated and encoded in the polygon attribute table (PAT). Flooded regions measuring greater than 100 m^2 were output to a new polygon flood layer. Each of these new flood region polygons was comprised of one large “primary” contiguous polygon, representing tidally connected waters, and many other “secondary” polygons with uncertain tidal connectivity. A field was added to the PAT to encode primary polygons with a value of “1” and secondary with a value of “2” to allow for future fine-scale investigation of potential hydrological connectivity.

For all SLR-only scenarios, the resultant polygon extents ranged from the boundary of open tidal waters to the furthest upland water extent, representing the future MHHW line. Concurrent with the analysis of ΔRSL impacts, the additional potential impacts of both minor (tidal) and moderate (storm) flood events were modeled for the entire study region for the years 2040, 2060, 2080. Tidal flooding water surface elevation data provided directly by NOAA were employed in these modeling efforts. Per NOAA staff, these experimental data are “based on interpolation from the NOAA report thresholds” (*43*). Rather than relying only on a single tidal flooding threshold value (e.g., 0.53m), these surfaces establish a range of tidal water levels which would generate minor or moderate flooding throughout coastal Virginia. Predictive modeling using these data revealed areas at highest risk of being inundated during minor and moderate flooding events.

When considering the impacts of minor and moderate flooding with sea level rise, it was desirable to enumerate the additional impact of flooding specifically attributable to the effects specifically attributable to those events. Accordingly, the extent of minor and moderate flooding was identified as the flooded area occurring between the future MHHW line and the upland boundary of the flood, thus avoiding duplicate counting of SLR-only impacts. For each study year, overall areas of flooding for sea level rise, sea level rise plus minor flooding, and sea level rise plus moderate flooding were modeled. The latter two modeled surfaces and resulting polygon data area naturally inclusive of the sea level rise surface. Therefore, modeled flood areas resulting from the SLR-only scenario were used as a mask for the minor and moderate scenarios to erase the SLR-only areas from each, allowing for tabulation of the impacts uniquely attributable to enhanced flooding.

As these analyses were performed according to four separate geographic study regions, it was necessary to merge the output data into data layers spanning the entirety of coastal Virginia for each of the nine required scenarios. Scenario-based statewide polygon layers are enumerated below:

1. 2040 sea level rise zones
2. 2040 minor flooding zones
3. 2040 moderate flooding zones
4. 2060 sea level rise zones
5. 2060 minor flooding zones
6. 2060 moderate flooding zones
7. 2080 sea level rise zones
8. 2080 minor flooding zones
9. 2080 moderate flooding zones

Infrastructure and Area Analysis. Analysis was conducted to approximate the impact of future sea-level inundation on real property parcels, buildings, and major roads throughout coastal Virginia and within each planning district. Statewide polygon flood region data layers developed by this research were those used as the foundation for calculation of total areas of flooding for each scenario and for analysis of potential impacts to with landcover, parcel, building footprint, and transportation features.

Virginia statewide land cover, parcel, building, and roadway data were retrieved from the Virginia GIS Clearinghouse (*47*) and analyzed in conjunction with modeled scenarios to assess the number of parcels and buildings impacted, miles of roadway flooded, and predicted land cover area flooded by class (Open Water, Developed, Barren, Forested, Shrub/ Scrub, Harvested/Disturbed, Turf Grass, Planted/ Cultivated, Wetlands). Comparative overlay analyses were performed for parcels, buildings, and roadways, wherein future flooding scenario polygons were examined for intersection with these features. Parcels and buildings that intersected with the predicted flood extent were tallied as being "impacted." Impacts to existing buildings and other building-like structures were also modeled. The data supplied by VGIN for this analysis are described as follows, "Building footprints are polygon outlines of built structures digitized by Virginia Base Mapping Program's digital ortho-photogrammetry imagery or digitizing of local government subdivision plats" (48). Similarly, the length of all portions of roadway (miles) located entirely within a flood area was tabulated as impacted and vulnerable.

Calculation of vulnerable land areas required the recognition that government officials and citizens would view the inundation of different types of landcover with levels of concern that would vary according to their personal interests and perspectives, proximity, and profession. Discussion with Commonwealth officials requesting this research led to the separate calculation of flooding areas in wetland and non-wetland land cover classes. For this reason, land area inundation was calculated both with and without present-day wetland areas predicted to be flooded in the future. For each scenario, the flood extent polygon was used to clip statewide landcover data and allow for calculation of the future flooded area of each landcover type.

Planning District Aggregation. The requirement to deliver the findings of this research at the planning district scale necessitated subdivision of statewide impacts data and metrics into metrics and maps specific to each of Virginia's eight coastal planning districts. Accordingly, planning district boundaries were used to clip infrastructure and area impacts layers. Figures, tables, and maps are organized primarily according to planning district impacts. The following data layers were created for each of Virginia's coastal planning districts for each of the benchmark years of 2040, 2060, and 2080.

1. Areas (polygon) at risk of permanent flooding by sea level rise
2. Areas (polygon) at risk of flooding by minor flooding events
3. Areas (polygon) at risk of flooding by moderate flooding (excludes tropical events)
4. Buildings (polygon) at risk of permanent flooding by sea level rise
5. Buildings (polygon) at risk of flooding by minor flooding events
6. Buildings (polygon) at risk of flooding by moderate flooding (excludes tropical events)
7. Parcels (polygon) at risk of permanent flooding by sea level rise
8. Parcels (polygon) at risk of flooding by minor flooding events
9. Parcels (polygon) at risk of flooding by moderate flooding (excludes tropical events)
10. Streets (polyline) at risk of permanent flooding by sea level rise
11. Streets (polyline) at risk of flooding by minor flooding events
12. Streets (polyline) at risk of flooding by moderate flooding (excludes tropical events)

RESULTS AND DISCUSSION

Impacts from Sea Level Rise

Land Area Vulnerable to ΔRSL. This work uses the 2020 MHHW tidal datum as the baseline reference point for measuring inundation resulting from ΔRSL. Therefore, land area flooded by solely ΔRSL is considered to be zero. Cumulative future inundation for all land cover (open water excluded) for coastal Virginia, shown in Figure 6 broken down by planning district (PD), was predicted to be 424 square miles (682 km^2) in 2040, 534 square miles (859 km^2) in 2060, and 649 square miles (1044 km^2) in 2080. Inundated wetland accounts for the majority of future flooding, representing 91%, 84%, and 74% in 2040, 2060, and 2080, respectively. This trend of decreasing percentage signifies that upland areas will be increasingly subjected to flooding as wetlands become permanently flooded. This research assumed continuity of present day natural and built infrastructure and did not speculate on future changes. Neither artificial structural modifications nor geomorphological processes, such as wetland migration or sediment erosion-accretion, were considered. As the impacts of ΔRSL on wetlands include both loss and migration, these environmental resources are at great risk and require additional, careful study and monitoring. Future analysis should consider the geomorphological impacts of ΔRSL on tidal and non-tidal wetlands.

Modeling of dry upland inundation (wetlands excluded) predicted a total combined flood extent for coastal Virginia planning districts of 40 square miles (104 km^2) in 2040, 86 square miles (223 km^2) in 2060, and 170 square miles (440 km^2) in 2080. For comparison, the total areas of Alexandria, Norfolk, and Richmond are 15 square miles (39 km^2), 54 square miles (140 km^2), and 60 square miles (155 km^2), respectively.

Aggregation of inundation values to the scale of individual coastal planning districts allowed for examination of potential disparity of impact between coastal regions. Figure 6 illustrates that, when both upland and wetland are considered, Accomack-Northampton PD were predicted to have the most flooded area for each study year, followed closely by Hampton Roads PD. However, Accomack-Northampton is mostly rural, comprised of large areas of farmland and tidal wetlands, whereas Hampton Roads is highly urbanized with large areas of dense infrastructure and population. When inundation areas were tabulated to exclude flooded wetlands (Figure 7), modeling predicted that Hampton Roads would experience more area of inundation at each study year than any other planning district. For example, flooded upland estimates for Hampton Roads total approximately 14 square miles (36 km^2) in 2040, 29 square miles (75 km^2) in 2060, and 64 square miles (166 km^2) in 2080, representing 175%, 133%, and 156%, respectively, of the predicted upland flooding for Accomack-Northampton. Further analyses described below demonstrate that disproportionate upland flooding of dense population centers and infrastructure in Hampton Roads was predicted to amplify the potential socioeconomic impacts of ΔRSL.

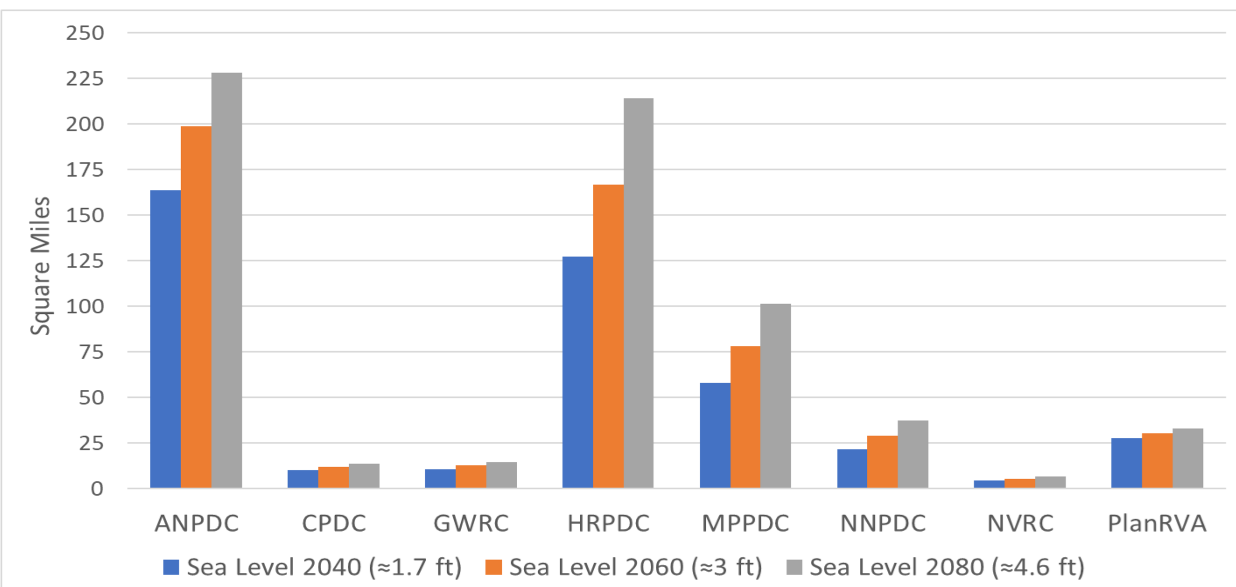


Figure 6. Present day land area (including wetlands) in each planning district that will be flooded by sea level rise (1 mi2 = 2.59 km2)

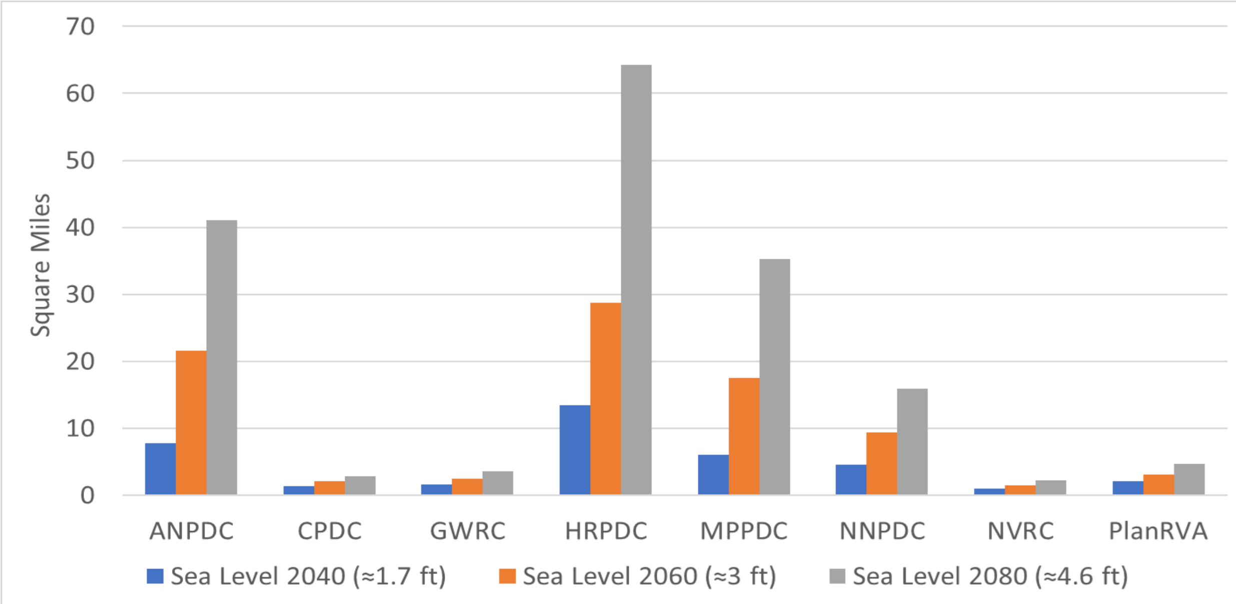


Figure 7. Present day land area (excluding wetlands) in each planning district that will be flooded by sea level rise (1 mi2 = 2.59 km2)

Real Property Parcels Impacted by ΔRSL. Real property comprises land ownership boundaries (parcels) and the buildings on them. For the purpose of this assessment, analyses were subdivided into potential parcel impacts and buildings.

For parcels, the study considered any inundation that either wholly or partially overlaid with the predicted relative sea level rise extent as a potential impact. Such parcels were tallied as "impacted" by future sea level rise.

Hence, this research provided a first approximation of exposure of a parcel, whereas a more detailed vulnerability study would incorporate susceptibility of a parcel flooding by functional use, assessed value, or damage, including acreage of land loss to permanent flooding. This overlay by intersection captured the extent that future high tide encroaches within the boundary of a parcel, thereby reducing or eliminating (in many cases) the land area available for use or development.

The predicted number of parcels impacted by ΔRSL (Figure 8) was by far the greatest in the Hampton Roads region, owing to both the large area of predicted flooding and density of population and development. Despite areas of high population density and infrastructure in the Northern Virginia planning region, model predictions of relatively small areas of upland flooding result in comparatively minimal predicted impacts to parcels and buildings. Conversely, expansive predicted upland flooding in Accomack-Northampton resulted in a much higher count of impacted properties despite its much lower population density than Northern Virginia.

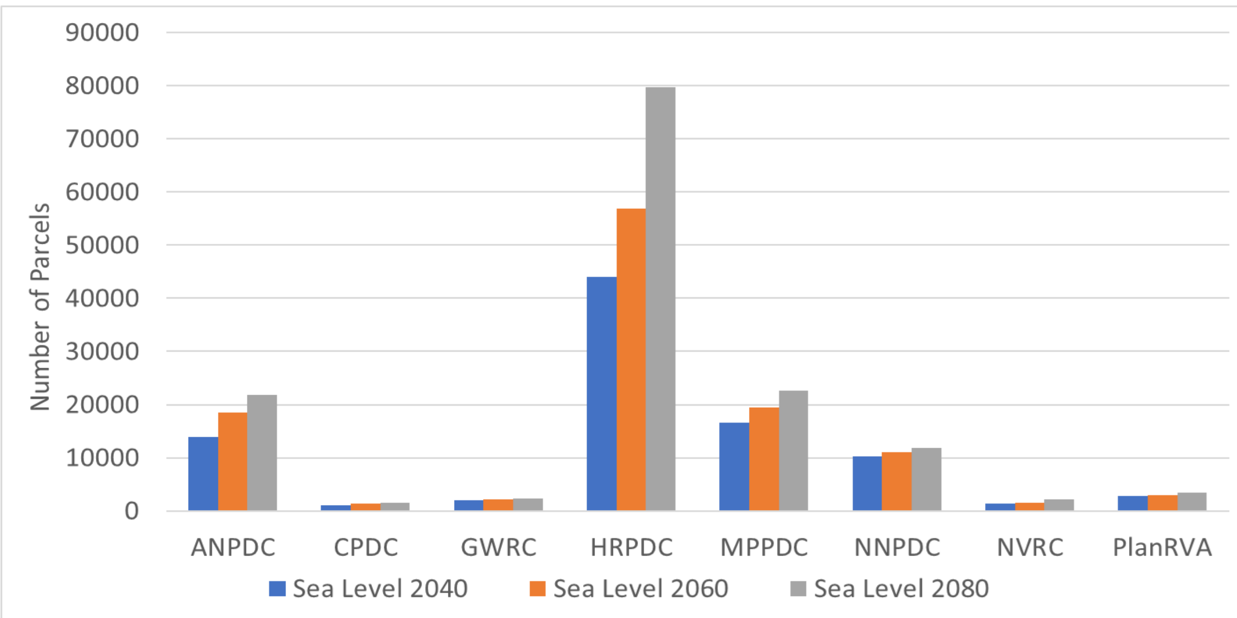


Figure 8. Existing Parcels in each planning district that will be impacted by ΔRSL

Buildings Impacted by ΔRSL. It is probable that buildings at or below the future high tide line will be rendered entirely unusable, necessitating relocation or demolition. Therefore, buildings with a footprint either entirely within or intersecting the predicted future sea level boundary were considered to be impacted by sea level rise. While it is unlikely that the building footprint data set captured 100% of buildings in the study area, the data were sufficiently complete to provide an indication of relative risk to buildings in the coastal planning districts (Figure 9). The predicted number of impacted structures in Hampton Roads was 2,614 in 2040, 12,022 in 2060, and 36,612 in 2080. Predicted impacted structures in all the other seven planning regions combined were 3,590 in 2040, 11,409 in 2060, and 19,566 in 2080. Despite having similar values for future ΔRSL, this disparity in predicted vulnerability resulted from a combination of factors that enhances the vulnerability of Hampton Roads, including low land elevation, low topographic slope, proximity to the Atlantic Ocean, high tidal range (relative to most other VA planning regions), and high population and corresponding infrastructure density.

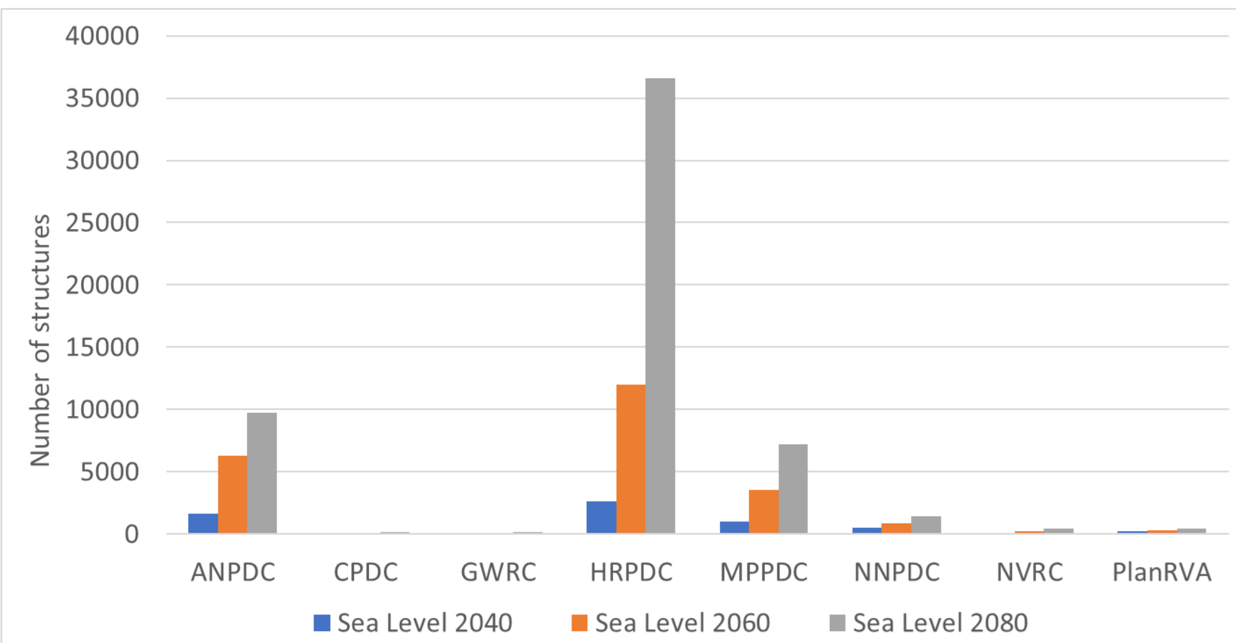


Figure 9. Existing buildings in each planning district potentially impacted by ΔRSL

Roadways Flooded by ΔRSL. Streets were deemed to be impacted when portions of the street centerlines fell below the high tide line boundaries of future predicted sea level. Modeling across the coastal planning regions predicted a pattern of future roadway flooding similar to that of parcels and buildings (Figure 10), with totals for Hampton Roads near or greater than the combined total of all other regions. The predicted number of miles of impacted roadway in Hampton Roads was 76 (122 km) in 2040, 180 (290 km) in 2060, and 483 (777 km) in 2080. Predicted impacted miles of roadway in all the other seven planning regions combined was 86 (138 km) in 2040, 259 (417 km) in 2060, and 479 (771 km) in 2080. The greatest impacts to roadway networks were predicted for the three planning districts (Hampton Roads, Accomack-Northampton, Middle Peninsula) with the most direct exposure to the open waters of the Atlantic Ocean and Chesapeake Bay. From 2040 to 2080, across all eight districts of coastal Virginia, modeling predicted a 578% increase in roadway inundated by future sea level rise. This preliminary, screening-level assessment did not differentiate among road type or function, USDOT classification, or vehicle miles traveled per day. Nonetheless, the spatial overlay of future flooding and existing roadways provided a baseline for further detailed transportation studies, including capturing vulnerability and susceptibility and structural adaptation or mitigation.

Many states, for instance, are conducting detailed transportation planning studies to inform future capital improvements, state and federal budget priorities, and identifying engineering alternatives for mitigation or roadway adaptation. Roadway impacts are also notable for potential underestimation, such as not considering the right of way and stormwater drainage conveyance, vegetated swales, or culverts and catch-basins bridges, etc. In addition, indirect impacts are not addressed here, including ecological flows, stormwater, fish passages, and other cascading impacts beyond this study.

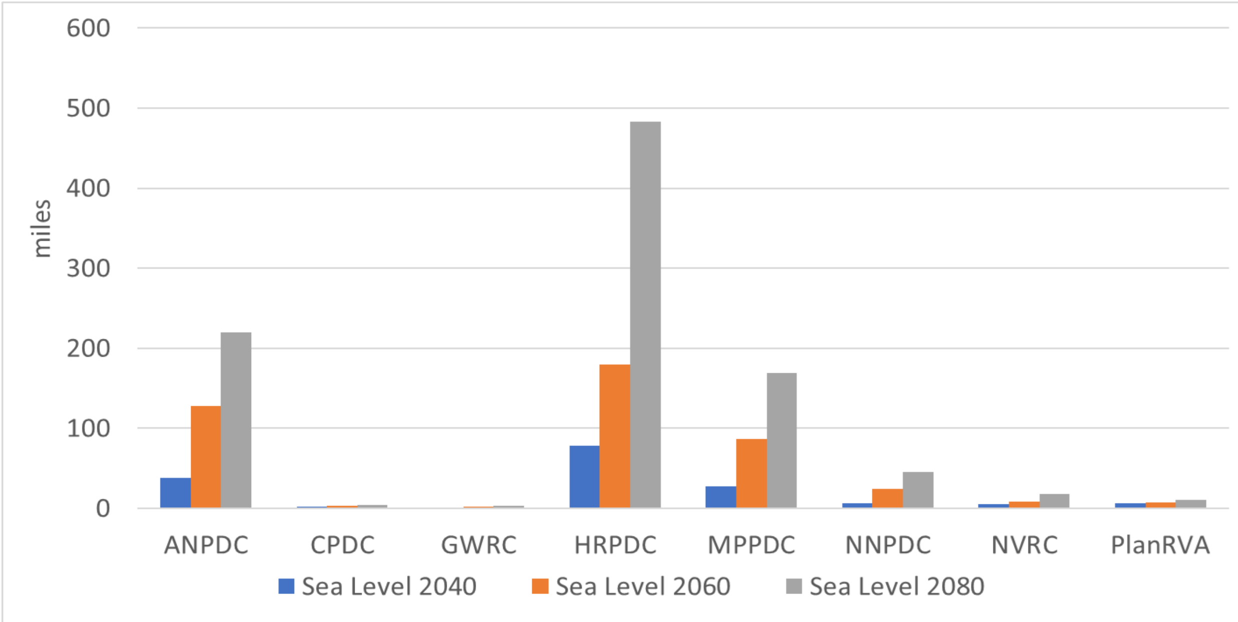


Figure 10. Miles of roadway predicted to be flooded by ΔRSL (1 mi = 1.61 km)

Comparison of Cumulative Impacts of ΔRSL. As Virginia's coastal planning districts vary widely in size, topography, infrastructure, population density, and rurality, simple totals of predicted impacts of ΔRSL require additional context to better understand and compare regional severity. For each planning district, normalization of inundation area by total area was used to describe the percentage of total land, non-wetland (upland), and wetland predicted to be vulnerable to flooding with ΔRSL (Table 2a-c). These data illustrate more clearly that the scope of the predicted threat to the Eastern Shore of Virginia (Accomack-Northampton), inundation of 11% of non-wetland and nearly 30% of wetland, far exceeds that of the other regions. By 2080, total land area from all 8 planning regions predicted to be permanently inundated by ΔRSL comprised only 2% of all non-wetland, 5% of wetland area, and 3% of total land area.

Table 2. Area and percent of predicted inundation for each planning region**. a)** all land area, **b)** non-wetland area, and **c)** wetland area. Highest % values highlighted in pink. (1 mi^2 = 2.59 km^2)

a)		**Inundated Area (sq. miles)**			**Inundation %**		
Coastal PDC	**Area (sq. miles)**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	1043	164	199	228	16	19	22
CPDC	3549	10	12	14	0.3	0.3	0.4
GWRC	2685	11	13	15	0.4	0.5	0.6
HRPDC	4248	127	167	214	3.0	3.9	5.0
MPPDC	2394	58	78	101	2.4	3.3	4.2
NNPDC	1429	22	29	101	1.5	2.0	7.1
NVRC	2576	5	6	7	0.2	0.2	0.3
PlanRVA	4068	28	30	33	0.7	0.7	0.8
Totals	21992	425	534	713	1.9	2.4	3.2

b)		**Inundated Area (sq. miles)**			**Inundation %**		
Coastal PDC	**Upland (sq. miles)**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	384	8	24	41	2	6	11
CPDC	1673	1	2	3	0.1	0.1	0.2
GWRC	1296	2	3	4	0.2	0.2	0.3
HRPDC	1864	14	29	64	0.8	1.6	3.4
MPPDC	1115	6	18	35	0.5	1.6	3.1
NNPDC	686	5	9	16	0.7	1.3	2.3
NVRC	1266	1	2	2	0.1	0.2	0.2
PlanRVA	1945	2	3	5	0.1	0.2	0.3
Totals	10229	39	90	170	0.4	0.9	1.7

c)		**Inundated Area (sq. miles)**			**Inundation %**		
Coastal PDC	**Wetland (sq. miles)**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	659	156	175	187	24	27	28
CPDC	1876	9	10	11	0.5	0.5	0.6
GWRC	1389	9	10	11	0.6	0.7	0.8
HRPDC	2384	113	138	150	4.7	5.8	6.3
MPPDC	1278	52	60	66	4.1	4.7	5.2
NNPDC	743	17	20	85	2.3	2.7	11.4
NVRC	1310	4	4	5	0.3	0.3	0.4
PlanRVA	2123	26	27	28	1.2	1.3	1.3
Totals	11763	386	444	543	3.3	3.8	4.6

Examination of the total-normalized impacts to property, buildings and roadways provided additional insight into the breadth of impacts and severity for each planning region (Table 3a-c). The percentages of the total inventory of buildings and roads within Accomack-Northampton predicted to be flooded were much higher that the percentages of all other planning regions, including Hampton Roads that was predicted to have 2-3 times the actual number of flooded buildings, parcels, and roadway miles. The consistent prediction of a higher number of property and roadway impacts in Hampton Roads, despite having lower percentages of impacted area and infrastructure inventory, results from high urbanization, population density, and abundant supporting infrastructure.

Comparative ranking of infrastructure impacts for each planning regions by both total count and by percentage of total inventory consistently revealed that Accomack-Northampton was predicted to be the most impacted by percentage inventory, while Hampton Roads was predicted to have the highest number of impacts (Table 4a-c). The Middle Peninsula repeatedly ranked 3rd by count and 2nd by percentage of inventory for predicted impacts for all study years.

Table 3. Predicted inundated a) roads, b) buildings, and c) parcels. Values normalized by total inventory for each planning region. Highest % values are highlighted in pink. (1 mi = 1.61 km)

a)		**Inundated Buildings**			**Inundation %**		
Coastal PDC	**Road miles**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	1522	38	128	220	2.5	8.4	14.5
CPDC	3463	2	3	4	0.1	0.1	0.1
GWRC	4108	1	2	3	0.0	0.0	0.1
HRPDC	11002	78	180	483	0.7	1.6	4.4
MPPDC	2666	27	87	169	1.0	3.3	6.3
NNPDC	1781	6	24	45	0.3	1.3	2.5
NVRC	11747	6	8	18	0.1	0.1	0.2
PlanRVA	9502	6	7	10	0.1	0.1	0.1
Totals	45789	164	439	952	0.4	1.0	2.1

b)		**Inundated Buildings**			**Inundation %**		
Coastal PDC	**Buildings**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	47316	1656	6294	9755	3.5	13.3	20.6
CPDC	126562	34	94	165	0.0	0.1	0.1
GWRC	204256	76	101	151	0.0	0.0	0.1
HRPDC	871182	2614	12022	36612	0.3	1.4	4.2
MPPDC	63717	874	3537	7231	1.4	5.6	11.3
NNPDC	34501	492	846	1425	1.4	2.5	4.1
NVRC	661025	117	233	409	0.0	0.0	0.1
PlanRVA	674463	241	306	430	0.0	0.0	0.1
Totals	2683022	6104	23433	56178	0.2	0.9	2.1

c)		**Inundated Buildings**			**Inundation %**		
Coastal PDC	**Parcels**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	64406	13833	18509	21766	21.5	28.7	33.8
CPDC	98801	1128	1335	1477	1.1	1.4	1.5
GWRC	173195	1931	2104	2255	1.1	1.2	1.3
HRPDC	594985	43951	56840	79692	7.4	9.6	13.4
MPPDC	83046	16567	19387	22576	19.9	23.3	27.2
NNPDC	73366	10322	11057	11887	14.1	15.1	16.2
NVRC	766085	1321	1570	2175	0.2	0.2	0.3
PlanRVA	439873	2758	2950	3504	0.6	0.7	0.8
Totals	2293757	91811	113752	145332	4.0	5.0	6.3

Table 4. Planning region ranking by total count and percent inundation to roads and buildings by year **a)** 2040, **b)** 2060, and **c)** 2080. Highest % values are highlighted in pink. Noted are average elevation (NAVD88) and slope of the planning region. (1 mi = 1.61 km, 1 m = 3.28 ft)

a)	Ranking		Count 2040		Pct 2040		Region Means	
Coastal PDC	count	%	Buildings	Roads (mi)	Buildings %	Roads %	elevation (m)	slope (%)
ANPDC	**2**	**1**	1656	38	3.50	2.50	4.6	1.3
CPDC	7	5	34	2	0.03	0.06	42.3	3.6
GWRC	8	8	76	1	0.04	0.02	60.5	7.2
HRPDC	**1**	4	2614	78	0.30	0.71	12.2	2.4
MPPDC	**3**	**2**	874	27	1.37	1.01	23.0	5.3
NNPDC	4	**3**	492	6	1.43	0.34	19.8	6.3
NVRC	6	6	117	6	0.02	0.05	104.5	7.3
PlanRVA	5	7	241	6	0.04	0.06	57.4	5.6

b)	Ranking		Count 2060		Pct 2060		Region Means	
Coastal PDC	count	%	Buildings	Roads (mi)	Buildings %	Roads %	elevation (m)	slope (%)
ANPDC	**2**	**1**	6294	128	13.30	8.41	4.6	1.3
CPDC	7	5	94	3	0.07	0.09	42.3	3.6
GWRC	8	8	101	2	0.05	0.05	60.5	7.2
HRPDC	**1**	4	12022	180	1.38	1.64	12.2	2.4
MPPDC	**3**	**2**	3537	87	5.55	3.26	23.0	5.3
NNPDC	4	**3**	846	24	2.45	1.35	19.8	6.3
NVRC	6	6	233	8	0.04	0.07	104.5	7.3
PlanRVA	5	7	306	7	0.05	0.07	57.4	5.6

c)	Ranking		Count 2080		Pct 2080		Region Means	
Coastal PDC	count	%	Buildings	Roads (mi)	Buildings %	Roads %	elevation (m)	slope (%)
ANPDC	**2**	**1**	9755	220	20.62	14.45	4.6	1.3
CPDC	7	5	165	4	0.13	0.12	42.3	3.6
GWRC	8	8	151	3	0.07	0.07	60.5	7.2
HRPDC	**1**	3	36612	483	4.20	4.39	12.2	2.4
MPPDC	**3**	**2**	7231	169	11.35	6.34	23.0	5.3
NNPDC	4	**4**	1425	45	4.13	2.53	19.8	6.3
NVRC	6	6	409	18	0.06	0.15	104.5	7.3
PlanRVA	5	7	430	10	0.06	0.11	57.4	5.6

To better understand why Accomack-Northampton, Hampton Roads, and Middle Peninsula were consistently predicted to suffer greater impacts from ΔRSL, mean elevation (NAVD88) and ground slope parameters were calculated from the DEM for each planning region (Table 4a-c). With a mean elevation of 4.6 m and average slope of 1.3%, Accomack-Northampton is easily the lowest and flattest of all regions. Hampton Roads is similarly low and flat with a mean elevation of 12.2 m and average slope of 2.4%. The implication that low land elevation and low topographic slope promote greater vulnerability to coastal flooding is evident. Examination of these metrics for the remaining planning regions suggests that elevation and slope are certainly not the only factors driving susceptibility to inundation. The Middle Peninsula region has higher mean elevation (23 m) than the Northern Neck (19.8 m) and a greater average slope (5.3 %) than the Crater region (3.6 %) but was predicted to have much higher impacts in both count and percent of total inventory. Additional factors such as length of coastline exposed to tidal waters and distance from open ocean waters are likely to be major contributing factors to level of inundation from ΔRSL.

Minor and Moderate Flooding with Sea Level Rise

Land Area Vulnerable to Minor (Tidal) Flooding with ΔRSL. Modeling predicted that over 140 square miles (363 km^2) of land will be vulnerable to frequent recurrent minor flooding by the year 2040. Owing to their relatively low elevation and slope and proximity to the open tidal waters of the Atlantic Ocean and Chesapeake Bay, Hampton Roads, the Eastern Shore, and Middle Peninsula display high vulnerability to minor recurrent flooding (Figure 11). Minimal minor recurrent future flooding is predicted for planning regions (Northern Virginia, Richmond, Crater, George Washingtons) with the least exposure to tidally influenced water bodies and higher mean elevation. However, it is important to note that even comparatively "minimal" flooding of 1 or 2 square miles, while not catastrophic, may pose serious inconvenience or hazard to infrastructure.

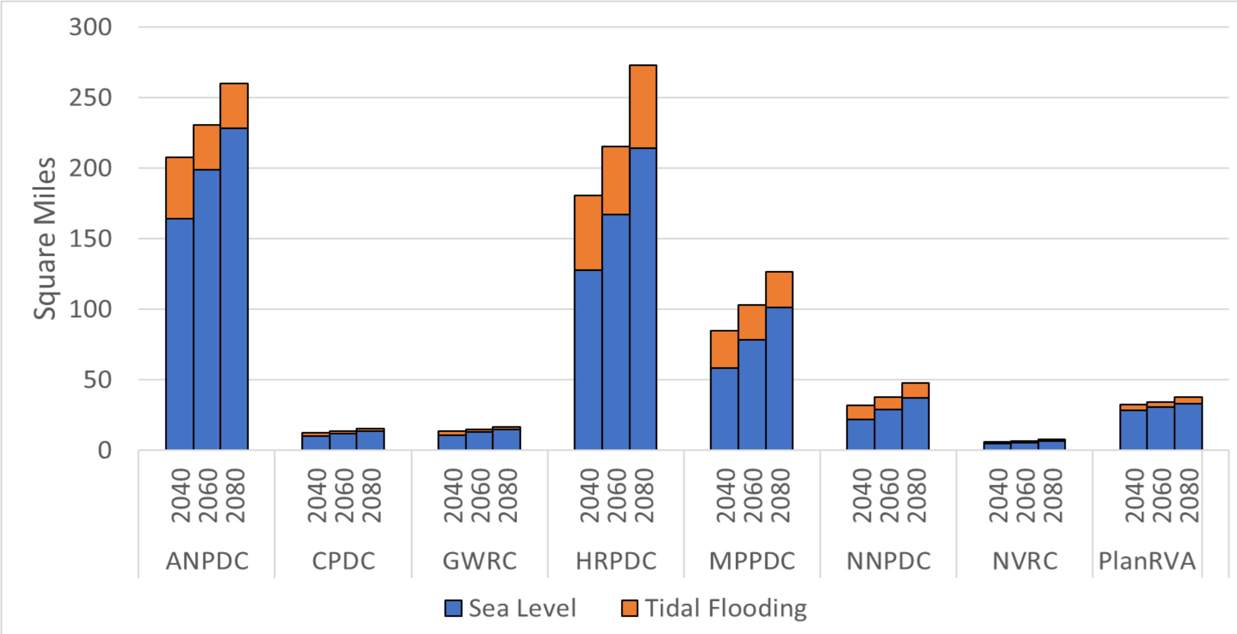


Figure 11. Present-day land area (including wetlands) in each planning district that will be flooded by ΔRSL (blue) and at-risk during minor flooding events (orange)

The stacked bars indicate that sea level rise progressively increases the extent of flooded areas. (1 mi^2 = 2.59 km^2)

Buildings and Roadways impacted by Minor (Tidal) Flooding with ΔRSL. By the year 2060, the impacted number of buildings (25,858) and miles of roadway (313 mi, 504 km) in Hampton Roads from minor flooding were predicted to far exceed these impacts of all other planning regions combined (8,449 buildings and 230 mi/370 km of roadway). The disparity between Hampton Roads and other planning regions was predicted to grow even larger in 2080 with 47,734 structures and 580 miles (933 km) at risk in Hampton Roads versus only 7,633 structures and 230 miles (370 km) of roadway total for all other regions (Figures 12 and 13). Hampton Roads high population density, coastal proximity, and low relief result in disproportionately high risk to infrastructure.

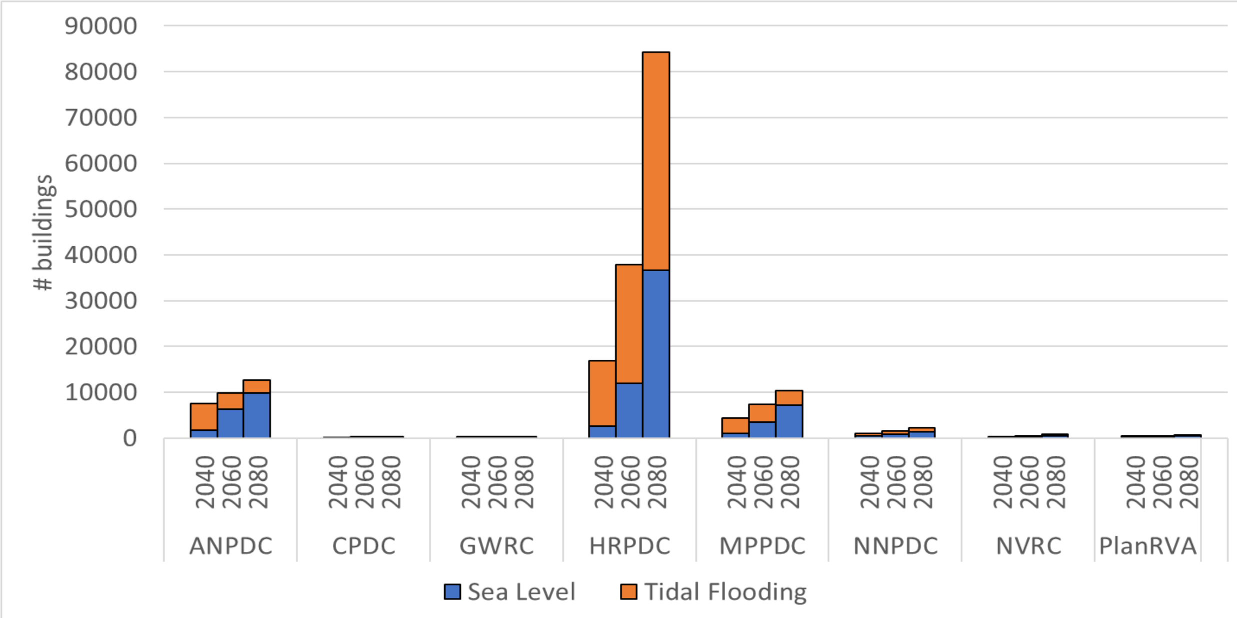


Figure 12. Buildings potentially affected by relative sea level rise (blue) and at-risk during minor flooding events (orange)

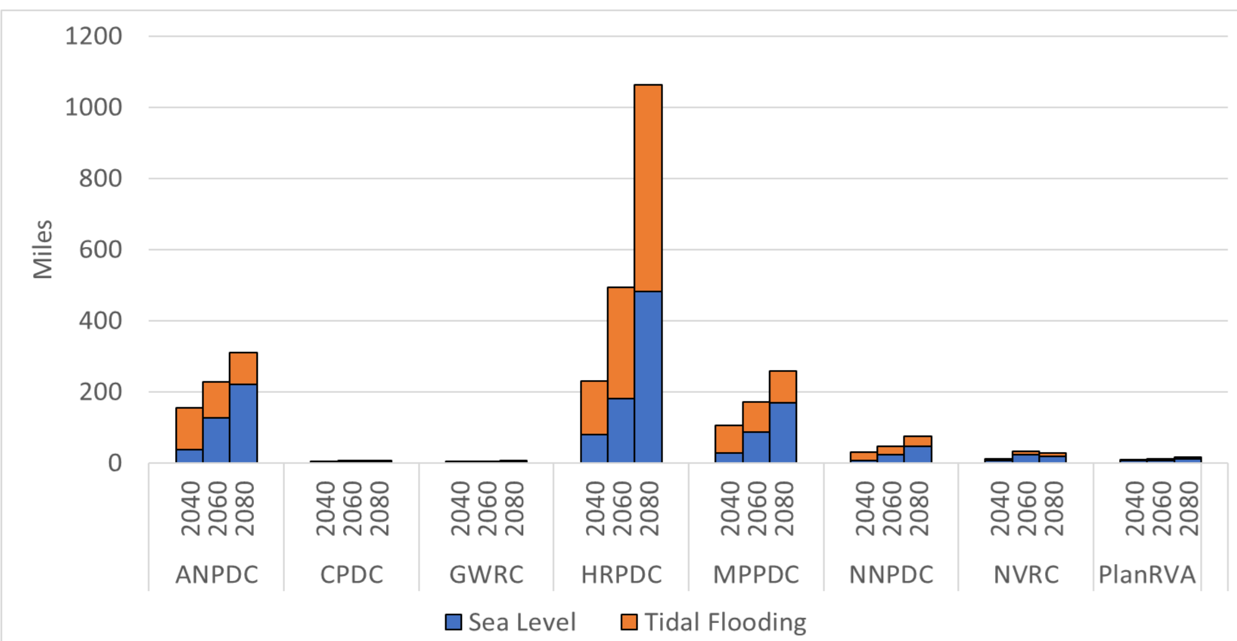


Figure 13. Streets potentially affected by relative sea level rise (blue) and at-risk during minor flooding events (orange)

Cumulative Exposure of Minor (Tidal) Flooding with ΔRSL. Impacts predicted to result from minor flooding events were examined by total count and percentage of total inventory. Minor flooding events were predicted to have very minimal impact (< 0.1% of infrastructure inventory) in the Northern Virginia, George Washington, PlanRVA, and Crater planning districts. Among the other four regions, the most acutely impacted were again Hampton Roads, with the highest total impact counts, and Accomack-Northampton, with the highest percent of impacted inventory (Table 5). As minor flooding events include king tides and other recurrent phenomena, it is noteworthy that the counts shown in Table 5 represent impacted infrastructure that may flood several times per year *in addition to* land, buildings, and roadway already permanently inundated by ΔRSL.

Table 5. Planning region impacts from minor flood events. Total count and percentage impacts for **a)** total area, **b)** miles of roadway, and **c)** buildings. Highest values are highlighted in pink.

a)		Inundated Area (sq. miles)			Inundation %		
Coastal PDC	Area (sq. miles)	2040	2060	2080	2040	2060	2080
ANPDC	1043	44	32	32	4	3	3
HRPDC	4248	53	48	58	1.2	1.1	1.4
MPPDC	2394	27	24	25	1.1	1.0	1.0
NNPDC	1429	10	9	10	0.7	0.6	0.7

b)		Inundated Area (sq. miles)			Inundation %		
Coastal PDC	Roads (miles)	2040	2060	2080	2040	2060	2080
ANPDC	1522	116	99	90	8	7	6
HRPDC	11002	152	313	580	1.4	2.8	5.3
MPPDC	2666	79	85	90	3.0	3.2	3.4
NNPDC	1781	24	22	30	1.3	1.2	1.7

c)		Inundated Area (sq. miles)			Inundation %		
Coastal PDC	Buildings	2040	2060	2080	2040	2060	2080
ANPDC	47316	5970	3563	2961	13	8	6
HRPDC	871182	14200	25858	47734	1.6	3.0	5.5
MPPDC	63717	3439	3828	3045	5.4	6.0	4.8
NNPDC	34501	525	613	822	1.5	1.8	2.4

Land Area Vulnerable to Moderate Flooding with ΔRSL. Areas at risk from moderate flood events are naturally inclusive of those that would also be impacted by minor tidal flooding. The threshold for moderate flooding, as defined by NOAA, is met when there is damaging flooding not associated with tropical storms and hurricanes. Once again, planning regions with significant coastline exposed to the Atlantic Ocean and Chesapeake Bay (Hampton Roads, Accomack-Northampton, Middle Peninsula) were predicted to be the most acutely impacted by moderate storm flooding (Figure 14). Examination of the potential impact to buildings and roadways once again underscores regional disparities arising from differences in topography, proximity to open water, and population density and highlights the critical nature of the problem for Hampton Roads. Hampton Roads was predicted to be the most severely impacted for all study years, with 77-85 square miles (199-220 km^2) of flooded land, 328-987 miles (528-1588 km) of impacted roadway, and 30,756-83,941 buildings impacted between 2040 and 2080 (Figures 14-16).

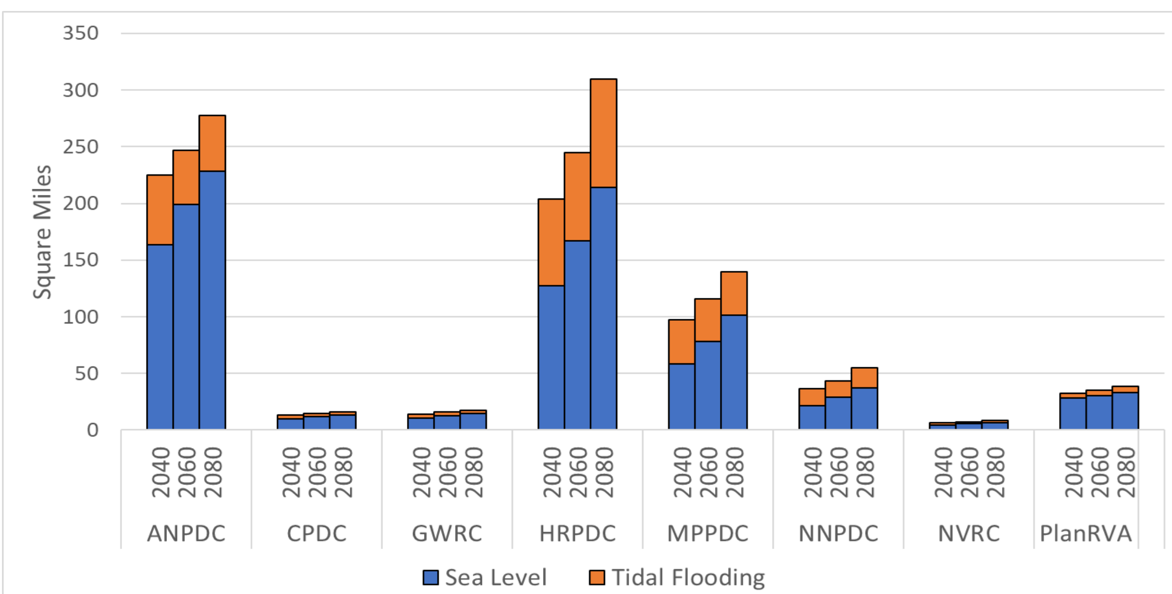


Figure 14. Present-day land area (with wetlands) in each planning district that will be flooded by sea level rise (blue) and at-risk during moderate flooding events (orange) (1 mi^2 = 2.59 km^2)

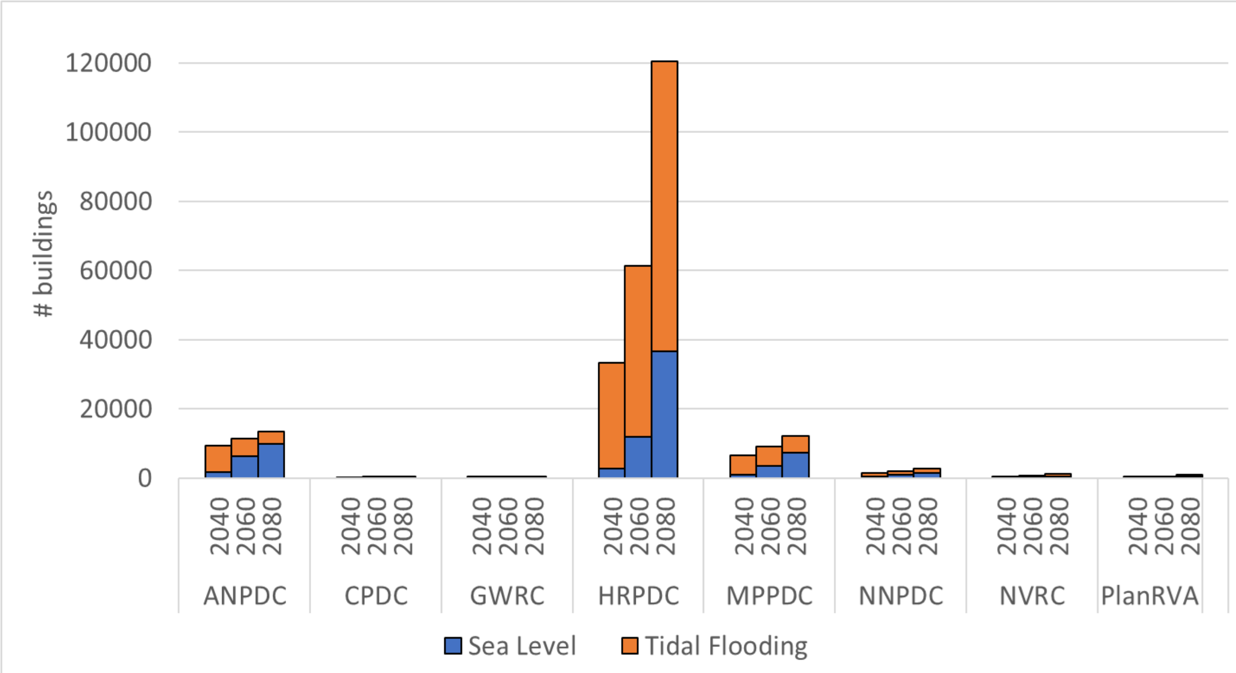


Figure 15. Buildings flooded by sea level rise (blue) and moderate flooding events (orange)

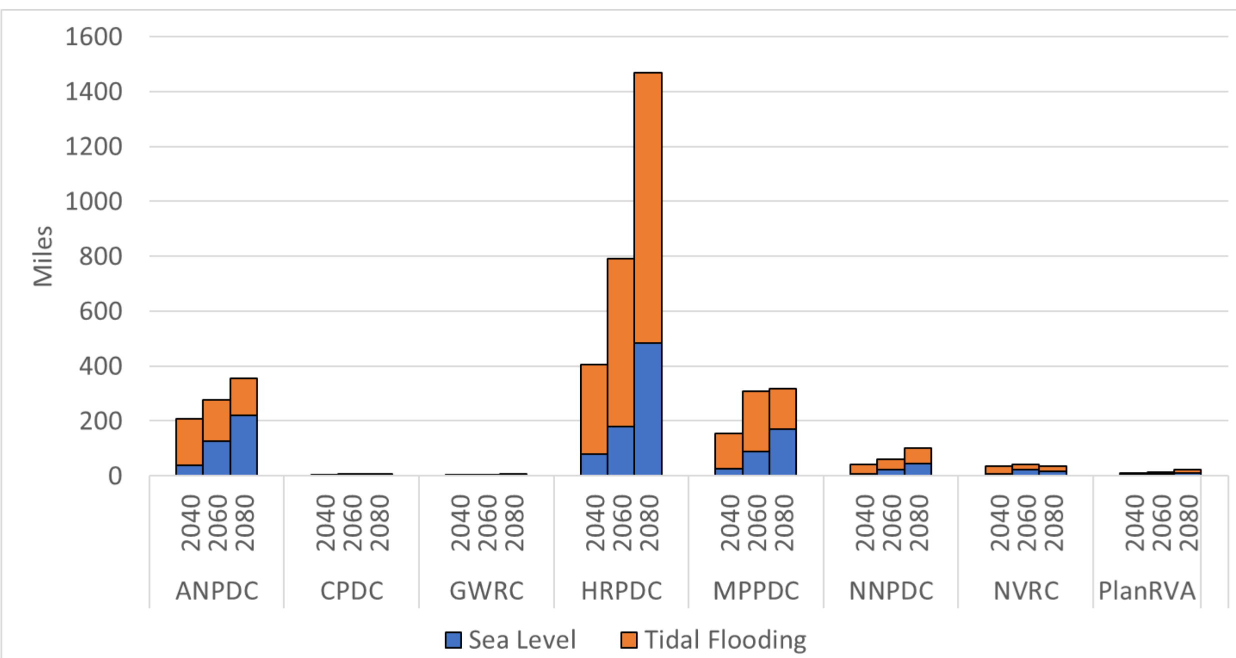


Figure 16. Roads flooded by sea level rise (blue) and at-risk during moderate flooding events (orange) (1 mi = 1.61 km)

Cumulative Exposure of Moderate Flooding with ΔRSL. Impacts predicted to result from additional inundation from moderate flooding events were also examined by total count and percentage of total inventory. Moderate flooding events were predicted to have very minimal impact (< 0.5% of infrastructure inventory) in the Northern Virginia, George Washington, PlanRVA, and Crater planning districts. Among the other four regions, the most acutely impacted were again Hampton Roads, with the highest total impact counts, and Accomack-Northampton, with the highest percent of impacted inventory (Table 6). Moderate flooding events occur less frequently than recurrent minor events, yet their impacts are potentially more devastating. In Hampton Roads alone, tens of thousands of additional buildings and hundreds of miles of roadway were predicted to be inundated by moderate storms with future increase sea level.

Table 6. Planning region impacts from moderate storm events by total count and percent

Impacts for a) total area, b) roadway miles, and c) buildings. Highest values highlighted in pink

a)		Inundated Area (sq. miles)			Inundation %		
Coastal PDC	**Area (sq. miles)**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	1043	61	48	49	6	5	5
HRPDC	4248	77	78	95	1.8	1.8	2.2
MPPDC	2394	40	38	39	1.7	1.6	1.6
NNPDC	1429	15	14	18	1.0	1.0	1.3

b)		Inundated Area (sq. miles)			Inundation %		
Coastal PDC	**Roads (miles)**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	1522	170	149	135	11	10	9
HRPDC	11002	328	610	987	3.0	5.5	9.0
MPPDC	2666	127	222	147	4.8	8.3	5.5
NNPDC	1781	37	38	57	2.1	2.1	3.2

c)		Inundated Area (sq. miles)			Inundation %		
Coastal PDC	**Buildings**	**2040**	**2060**	**2080**	**2040**	**2060**	**2080**
ANPDC	47316	7808	5068	3638	17	11	8
HRPDC	871182	30756	49300	83941	3.5	5.7	9.6
MPPDC	63717	5575	5569	4836	8.7	8.7	7.6
NNPDC	34501	870	1075	1404	2.5	3.1	4.1

Data Visualization

Static Maps. Newly created inundation data layers were mapped to provide visual context to existing natural and man-made systems and structures within the study area. Map data and graphics were requested by the Commonwealth to be "print-ready" for inclusion in the Coastal Resilience Master Planning Framework report (*48*). An overview map graphic of the entire study area, inclusive of all eight coastal Virginia PDCs was developed to provide a high-level single page assessment of cumulative ΔRSL flooding impacts for the Commonwealth (Figure 17).

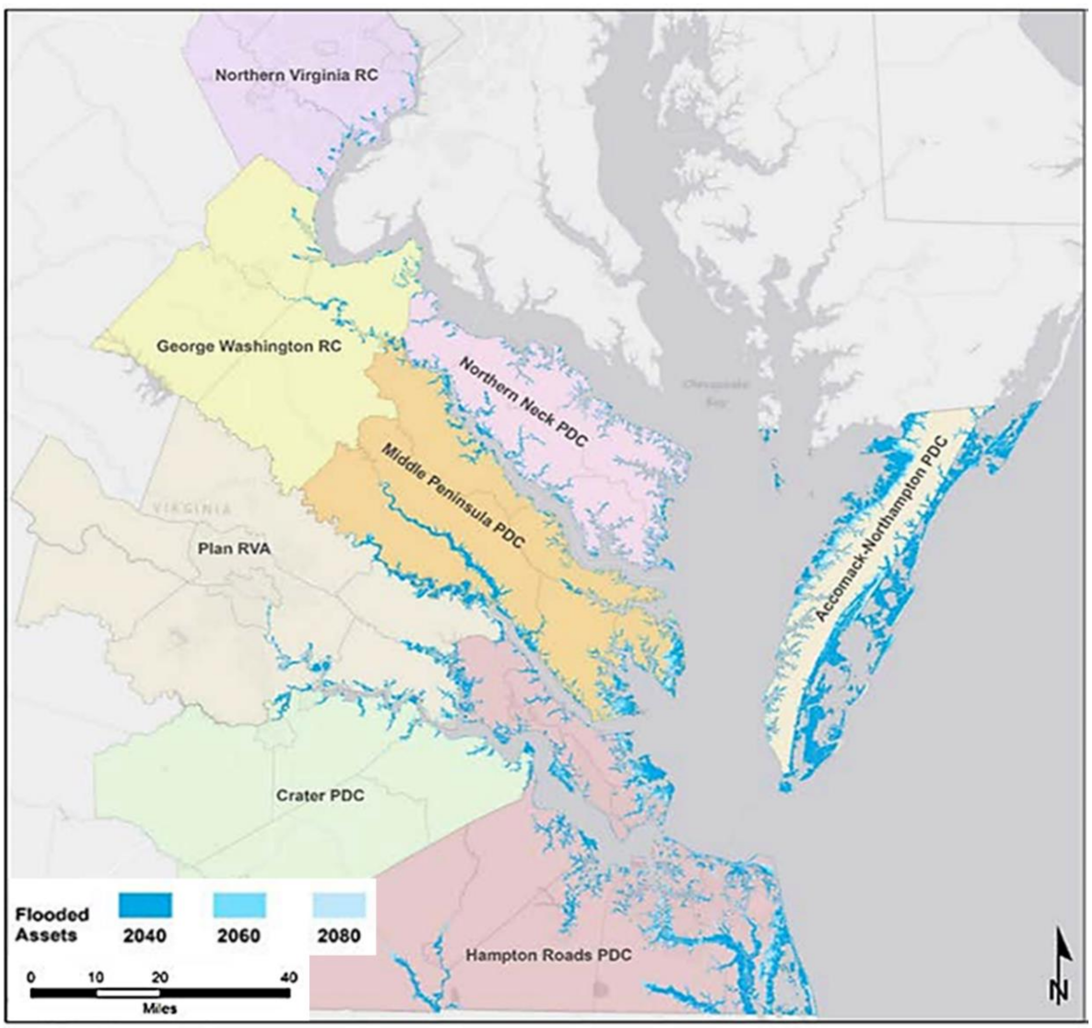


Figure 17. Future sea level: Coastal Virginia (1 mi^2 = 2.59 km^2, 1 mi = 1.61 km)

Maps representing the unique impacts to each of the eight planning districts were also created. These maps provide a graphical depiction of future flooding extent, while also providing an accounting of the impacts to parcels, buildings, land areas, and roadways at the planning district level. Figure 18 details potential impacts to the Accomack-Northampton Planning District and provides an example of a print-ready single-page summary map that can be easily incorporated by regional officials into planning documents and other governmental reports.

Detailed map illustrations of the localized impacts of ΔRSL, minor, and moderate flooding in both urban and rural environments were also developed for specific areas at the request of Commonwealth officials to underscore the increasing threat of sea level over time. The example shown in Figure 19 provides an overview of the Ghent, Downtown, and nearby areas of Norfolk, Virginia, illustrating that the potential infrastructure impacts of flooding in highly-urbanized areas such as this is extremely high despite a relatively constrained area of flooding. In this map visualization, areas of predicted inundation were shaded from dark blue (2040) to light blue (2080) according to the modeled year. Color gradient symbology was also used to indicate the year of arrival of predicted flood impacts to buildings and roadways with red denoting year 2040, orange denoting year 2060, and yellow denoting year 2080.

Figure 20 used the same colors and symbols to provide a contrasting example that focuses on an area known as Guinea, a rural fishing community in southeastern Gloucester County on Virginia's Middle Peninsula. Noting that the scales of each of these figures are the same, this map demonstrates the potential for the areal extent of flooding to be far greater in rural environments with unprotected shorelines.

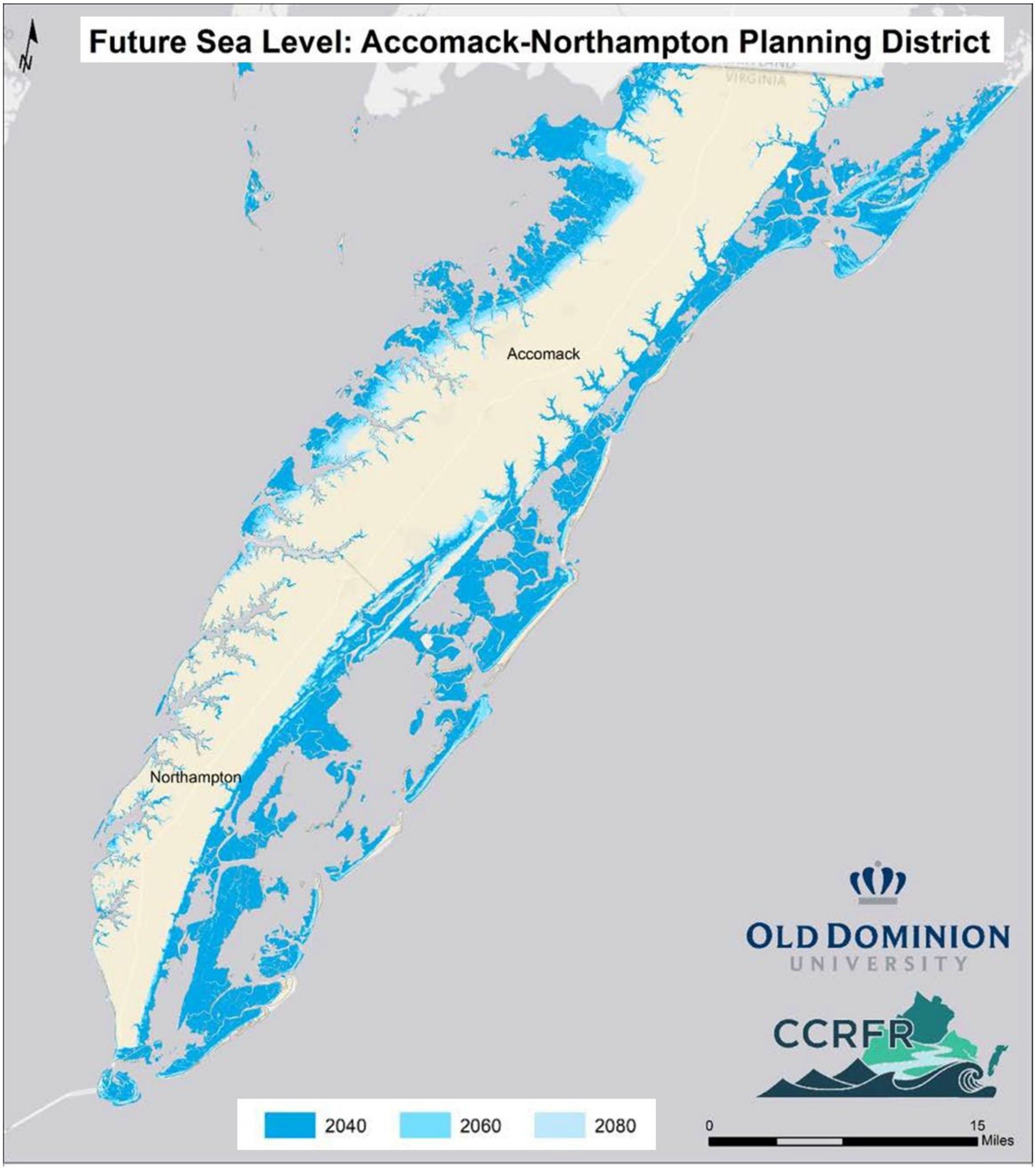


Figure 18. Accomack-Northampton PDC (1 mi^2 = 2.59 km^2, 1 mi = 1.61 km)

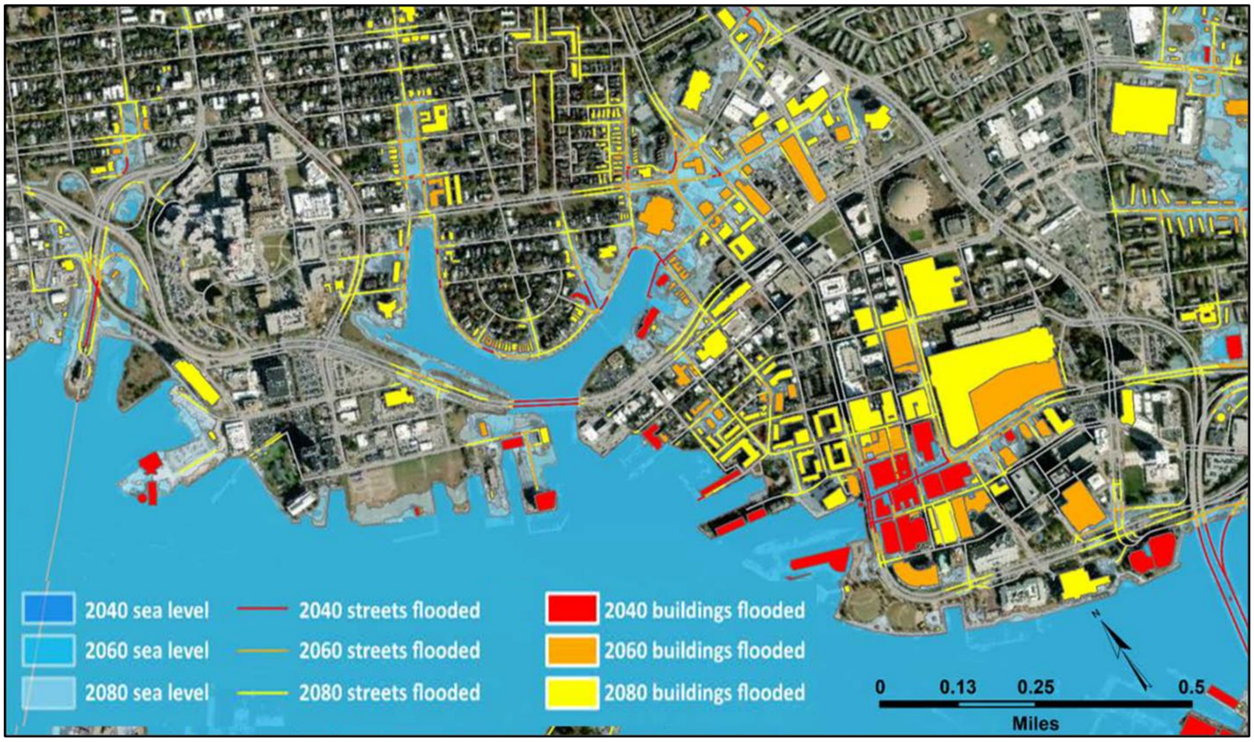


Figure 19. Norfolk (Downtown and Ghent neighborhoods) (1 mi = 1.61 km)

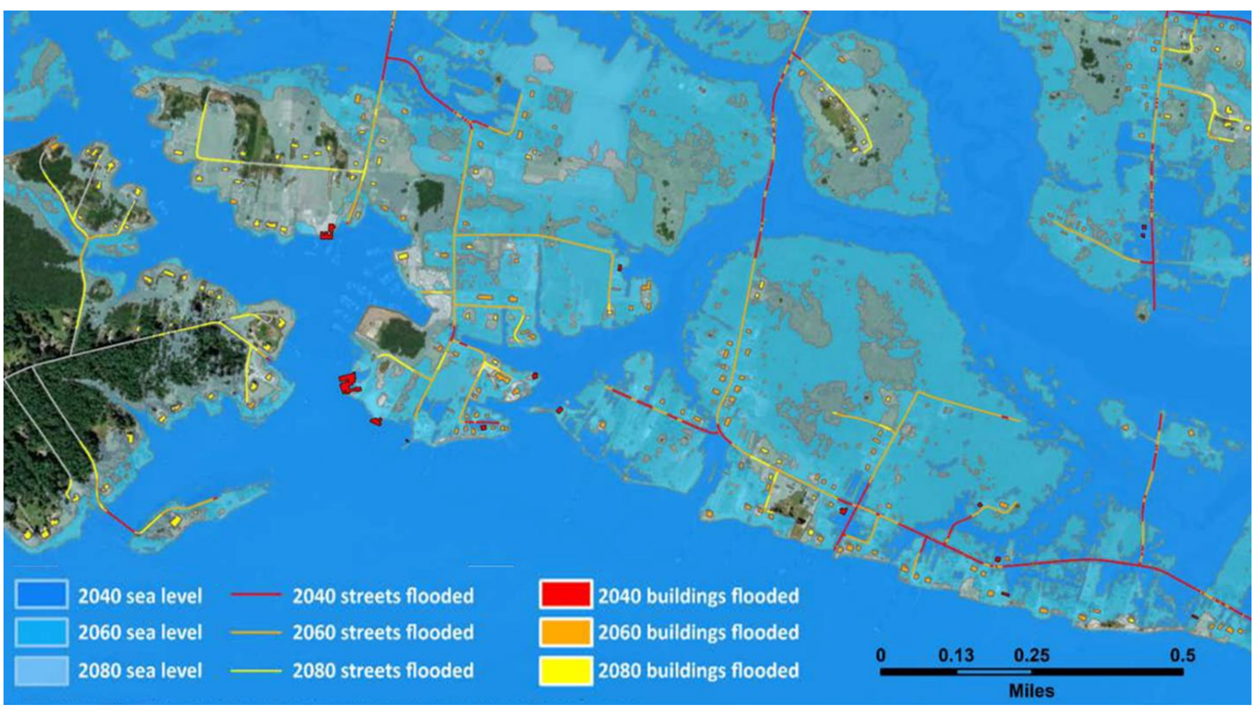


Figure 20. Guinea community, Gloucester County (1 mi = 1.61 km)

These maps and many more for each planning district found in the appendices of the Coastal Resilience Master Planning Framework report (*48*) provide static representations of future sea level risk that are naturally limited by their printed format.

Dynamic Maps. To vastly enhance the utility of these data to government officials, community planners, and the public, an online web mapping application was developed. This application allows the user to view the impacts to land areas, buildings, and streets vulnerable to inundation by sea level rise and both minor (tidal) and moderate flooding throughout Virginia for each of the study years at multiple scales, and for specific locations according to the user's needs. The application is found on the web using the map title or the website URL as detailed below:

Web Map Name: Coastal Virginia Sea Level with Minor and Moderate Flooding (NOAA Int-High Scenario 2017)

URL: https://tinyurl.com/CoVA-SLR-Inundation-NOAA2017

The presentation of data in the web mapping application was designed to be informative and easy to understand for the viewer (Figure 21). Blue shading hues were used to represent inundation types (SLR, minor flooding, moderate flooding). Red features represent those at risk of permanent inundation by sea level rise, orange represent those at risk of inundation by minor flooding (aka "nuisance), yellow features represent those at risk of inundation by moderate (non-tropical) flooding events.

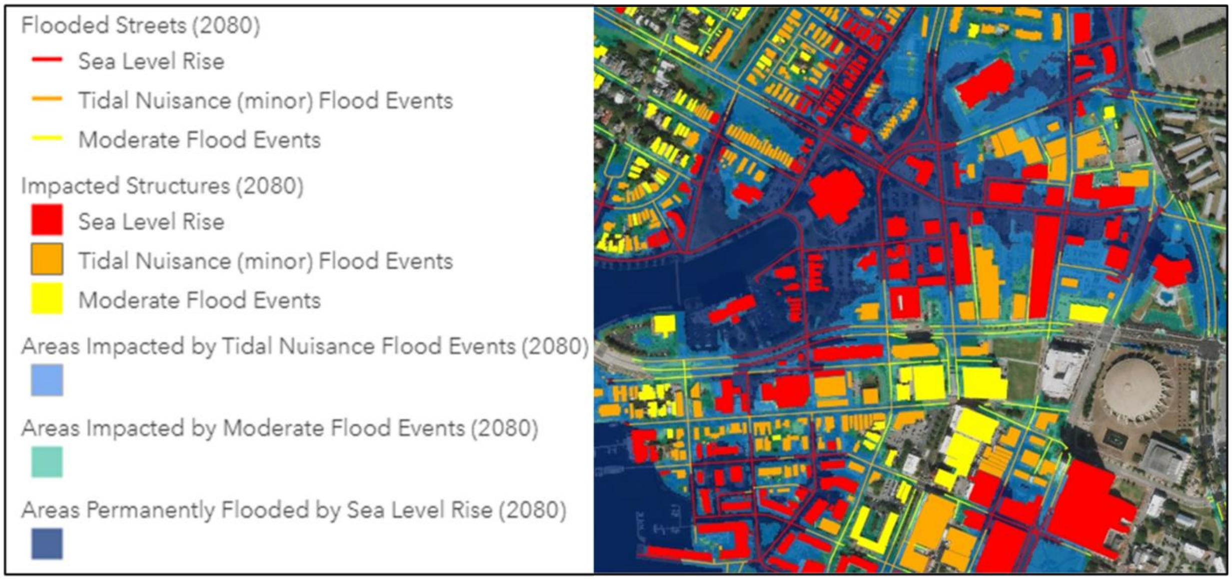


Figure 21. Web Mapping Application example

Planners or other users can access the publicly shared map as streaming Web Map Services (WMS) layers.

Limitations

The accuracy of inundation modeling is largely dependent upon the quality of digital elevation data used in the analysis. Errors in elevation surfaces will naturally propagate to final model results. Elevation discrepancies may result in shifts in the predicted flood boundary. These shifts may have the effect of either over- or under-predicting flooding extent depending on the direction (positive or negative) of elevation error.

The use of high-quality lidar-derived elevation surfaces for this study helps to minimize positional errors. Further improvements could be developed to refine the areas of impact by applying fine scale hydrocorrection, which would also improve roadway and drainage analyses and property susceptibility by reducing areas of omission of flooding impacts (*49*).

In addition to the accuracy of underlying elevation data, some variables were not modeled and require further research, such as dynamic geomorphology, vertical land motion and subsidence, infrastructure improvements, storm water system connectivity, groundwater hydrology; these and other local factors may all impact future flooding severity and connectivity.

Local land subsidence data are very limited and presented a constraint to this study, which relied on long-term, high-precision tide gauge data. The development of accurate and comprehensive geospatial subsidence data for the study area would allow for much more precise identification of localized flooding in smaller geographic regions. The study also did not address storm surges and changes in storminess associated with climate change that will co-occur with sea-level rise. Integrating climate change more widely into sea level rise risk assessment requires highly computational modeling and consideration of multiple interacting probabilistic changes (increasing tidal flooding, increasing storm energy, potential increase frequency of storms) well beyond the scope of tidal flooding in this research.

CHAPTER III

MODELING THE POTENTIAL IMPACTS OF A HURRICANE STRIKING HAMPTON ROADS WITH INCREASED SEA LEVEL

PREFACE

A modified version of this chapter was published by the Commonwealth Center for Recurrent Flooding Resiliency (CCRFR) as Report #10 in the CCRFR special reports series.

BACKGROUND

On the morning of Friday, September 14, 2018, Hurricane Florence made landfall as a Category 1 storm near Wilmington, North Carolina. Despite a reduction in wind speed, this wide and slow-moving storm dropped over 30 inches (76.2 cm) of rain in some parts of the state. Extreme precipitation and riverine discharge in combination with storm surge resulted in widespread flooding that damaged or destroyed tens of thousands of structures (*50*).

In the aftermath of the storm, a detailed impacts assessment was provided by the North Carolina Office of State Budget and Management (OSBM) (*51*). The NC OSBM concluded that Florence caused nearly $17 billion in total damage and loss, with a significant portion coming in the form of direct economic loss and property damage (*51*). Of these losses, research firm CoreLogic concluded that insured flood losses for Florence totaled between $5 and $9 billion (*52*).

Only days before landfall, on September 11th, Florence was a Major Category 4 hurricane with maximum sustained winds of 140 mph and was expected to strengthen (*53*). The future path of the storm was still highly uncertain with several forecast model runs predicting landfall near

Virginia Beach and the mouth of the Chesapeake Bay, directly impacting the Hampton Roads region on September 15-16 (Figure 22) (*54*).

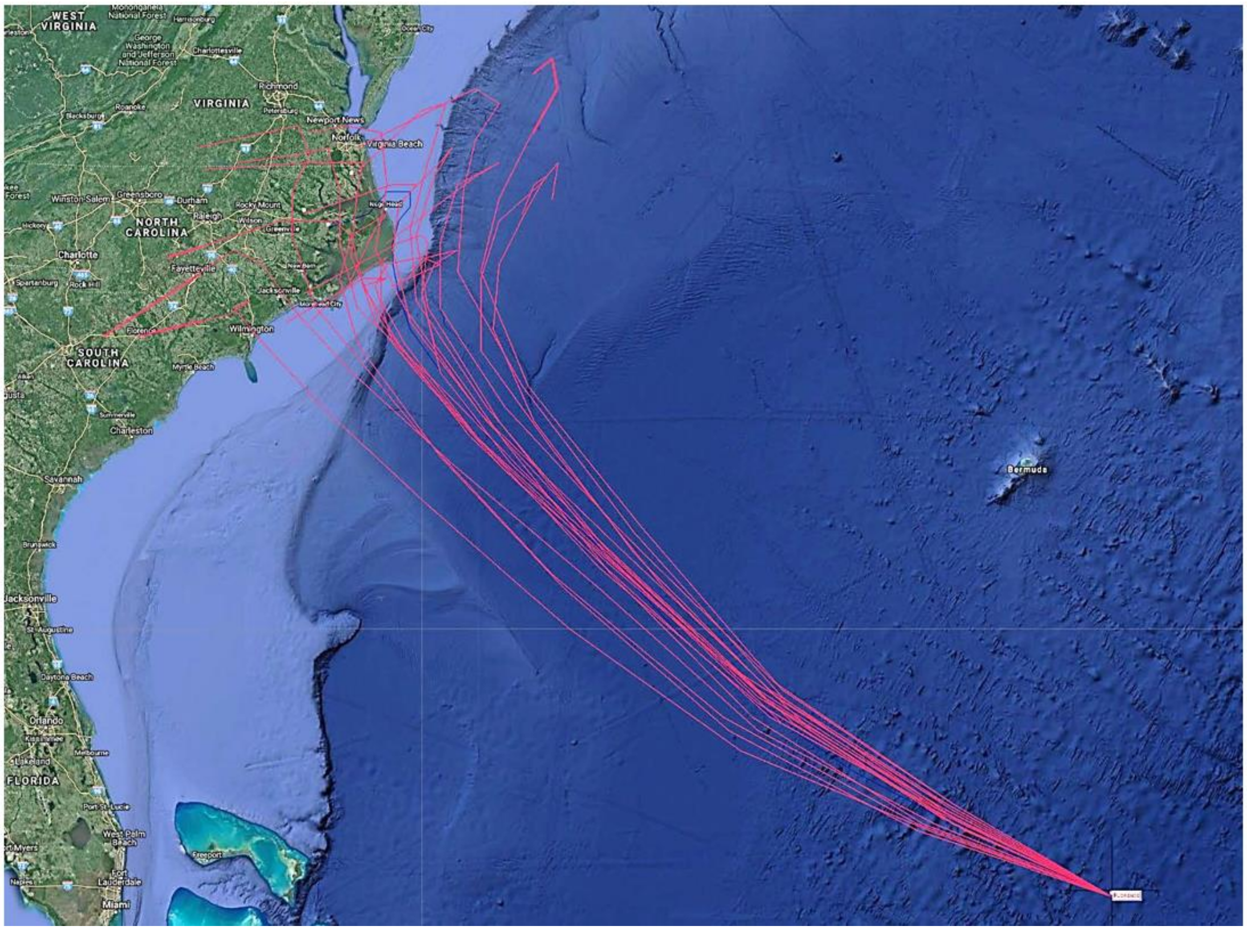


Figure 22. Plot of Global Ensemble Forecast System (GEFS) Data for potential Hurricane Florence Track valid on September 11, 2018, at 00 UTC NOAA, https://ruc.noaa.gov/tracks/

In preparation for this potentially catastrophic possibility, many schools and businesses in Hampton Roads announced closures and municipal leaders began implementing pre-storm action plans. The decision by Virginia Governor Ralph Northam to order mandatory evacuation for approximately 250,000 residents living in Evacuation Zone A, the area most vulnerable to storm surge, underscored the seriousness of the risk posed by the storm. Mobilization, action, and preparation were driven by the fundamental question, “What if Florence strikes our region?”

In the days following the storm, a collective sigh of relief was breathed in coastal Virginia as the aftermath of Florence’s devastating winds, rainfall, and storm surge on the Carolinas became fully realized. This near-miss event prompted many in State and local governments to rephrase that fundamental question. What would have happened if Florence had made landfall directly at and through the major population centers and heavily developed areas of Hampton Roads?

In a recently published report entitled, “An Analysis of the Potential Costs and Consequences of a Hurricane Impacting the Virginia Beach-Norfolk- Newport News Metropolitan Area”, researchers posed that very question and estimated that physical damages resulting from a Florence type hurricane striking Hampton Roads would approach $18 billion (*55*). Model calculations revealed that approximately 38,000 structures in Hampton Roads would be damaged, 2.4 million tons (2.44 million metric tons) of debris would be generated, and over 200,000 people would be immediately displaced following the storm.

Calculations of physical damages only represented a portion of the total impact on the economy. Impacts such as inability to work, reduction or closure of businesses, and impairment of major transportation infrastructure (i.e., highways, ports, railways) would ripple through the economy, resulting in an estimated total impact in excess of $25 billion (*55*). Damage of this magnitude would make Florence by far the costliest hurricane to impact the Commonwealth, exceeding by ten-fold the $2.5 billion total of Isabel (2003) (*56*).

However, it is important to realize that these damage estimates represent a single snapshot in time for a hurricane occurring with present-day sea level. As sea levels continue to rise, it becomes even more important for us understand the potential future impacts of such a storm on Hampton Roads infrastructure and human populations.

Storm Surge Enhanced by Sea Level Rise in Hampton Roads

The rate of sea level rise along the mid-Atlantic coast of North America, which includes Virginia and the Hampton Roads region, is among the highest in the world for several reasons including: local subsidence from groundwater withdrawal and settling of sub-structural fill, regional subsidence resulting from glacial isostatic rebound, and changes in ocean surface elevation related to ocean circulation dynamics and weakening of the Gulf Stream current (*6*). Boon et al. (*57*) used quadratic trend forecasting to estimate +0.49 m (1.6 ft) of ΔRSL for the Sewells Point tide station in Norfolk, VA, by the year 2050.

As early as 2008, state officials were taking notice of this trend. The Governor's Panel on Climate Change recognized the serious threats posed to coastal Virginia from sea level rise and storm surges, inundation including wetland and habitat loss, incapacitation of critical military installations, and impairment of national defense readiness (*17*). In Norfolk and throughout Hampton Roads, Mitchell et al. (*18*) reported that increases in sea level, precipitation, and storm frequency would likely result in increased severity of flooding events.

A recent report by CoreLogic identified the Virginia Beach metropolitan area (Hampton Roads) as 5th in the nation for storm surge risk posed to single-family homes and 10th in the nation for storm-surge exposure for multi-family dwellings (*52*). Recognizing that vulnerability to storm surge increases as the "platform" of sea level is elevated leads us to explore the impacts of a hurricane such as Florence under future sea level conditions. Accordingly, modeling of the direct physical impacts of Hurricane Florence on Hampton Roads with an additional 1.5 feet (0.46 m) and 3 feet (0.91 m) of future sea level rise was performed.

This research examined the physical damage and related socioeconomic costs that would result from a Category 1 hurricane striking Hampton Roads directly with near-future elevated sea level. It was hypothesized that storm surge would be exacerbated by elevated sea level and would produce large increases in damages and associated economic costs over those predicted for the same storm at present day sea level.

APPROACH AND METHODS

Geospatial data manipulation and analytical techniques were employed in concert with FEMA's Hazus model for this study to generate the damage estimates for a simulated storm making landfall over Hampton Roads with the addition of sea level rise. The Hazus model is a GIS-based regional multi-hazard model, developed by the Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS) to "assist in risk-informed decision-making efforts by estimating potential losses from earthquakes, floods, hurricanes, and tsunamis and visualizing the effects of such hazards"(*58*).

Using Hazus modeling in this manner allows for the representation of possible future storm scenarios which are based on state-of-the-art scientific and engineering knowledge and software architecture. The methods within the Hazus Model are commonly used by federal, state, and local agencies for planning studies. Uncertainties are inherent in any loss estimation methodology and may arise from incomplete scientific knowledge concerning floods and their effects upon buildings and facilities, or from approximations that are necessary for comprehensive analyses (*59*). These estimates are most valuable when used in concert with expert knowledge and related information as the basis for developing mitigation plans and policies, emergency preparedness and response, recovery planning, and to inform other synergistic research efforts.

Hurricane Track Creation and Modification

Actual historical data for Hurricane Florence were retrieved from Regional and Mesoscale

Meteorology Branch (RAMMB) at Colorado State University (*60*) and were used as input parameters for Hazus hurricane impacts modeling. These parameters included exact wind speed, pressure, track geometry, time of storm location, and radius of maximum winds (distance between the center of a cyclone and its band of strongest winds) recorded at 6-hour time intervals along the track of Hurricane Florence. Figure 23 displays a GOES-16 infrared satellite image of the position of the Category 4 storm on September 12, 2018, as it approached the coast of North Carolina *(61).* To simulate a direct impact on southeastern Virginia, it was necessary to modify the historical storm track prior to using the storm track as a model input. Accordingly, GIS data modification techniques were employed to shift the historical track such that Hurricane Florence made simulated landfall in southern Virginia and continued on a northwesterly path through Hampton Roads. The vector data line feature representing the historical track was spatially adjusted northward by 3° latitude, approximately 207 miles (333 km), with no longitudinal (east-west) repositioning nor geometric rotation (Figure 24). Nodes (vertices) along the vector track were temporally spaced to represent storm observations recorded every six hours at specific locations, each encoded with storm metrics (wind speed, pressure, radius to maximum winds) that were used to drive the Hazus hurricane model.

The historical track line for Hurricane Florence was created by vectorizing descriptive tabular data, retrieved from RAMMB (*60*), using ArcGIS Pro desktop GIS software. Maximum windspeed, pressure, and radius to max winds (RMW) values were obtained from tables denoting aircraft observations then matched to the synoptic time corresponding to each 6-hour node of the hurricane track and entered into the track polyline attribute table. No assumptions were made regarding changes that may have occurred to the storm's path, translation speed, or intensity as it travelled northward over the relatively cooler waters of marginally higher latitudes.

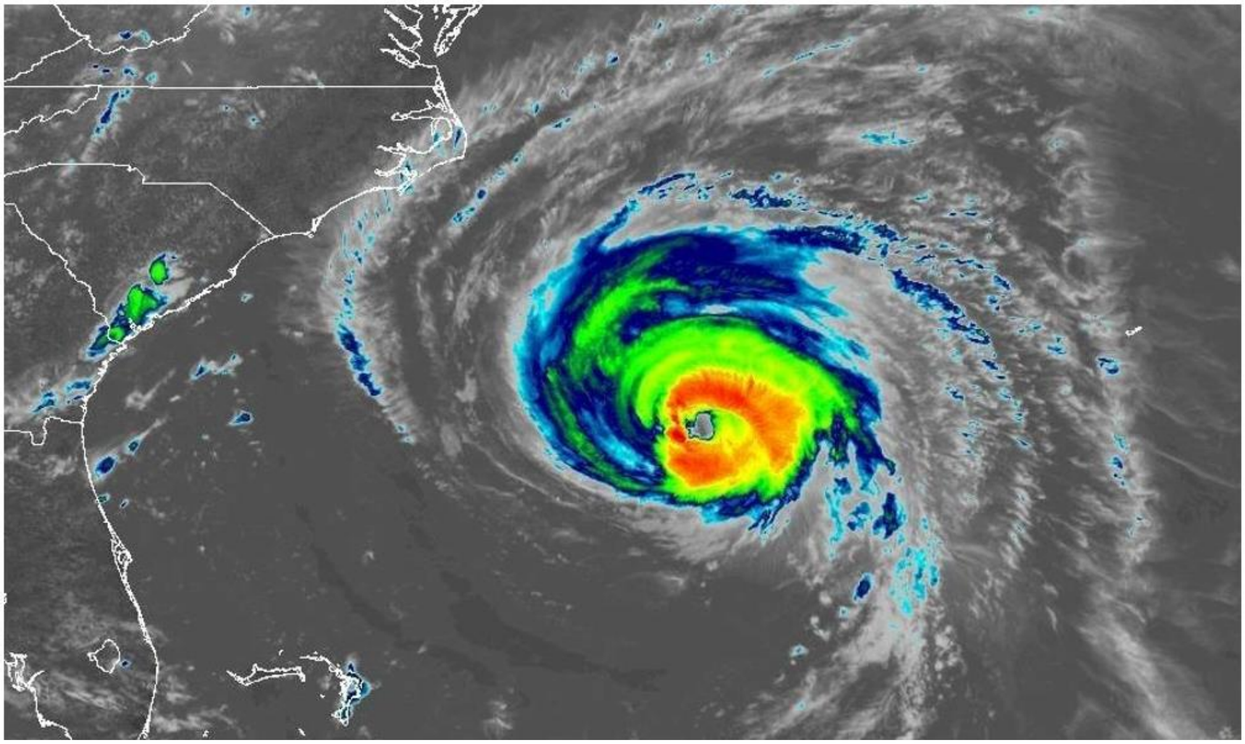


Figure 23. Infrared Image of Florence Captured by GOES-16 on September 12, 2018

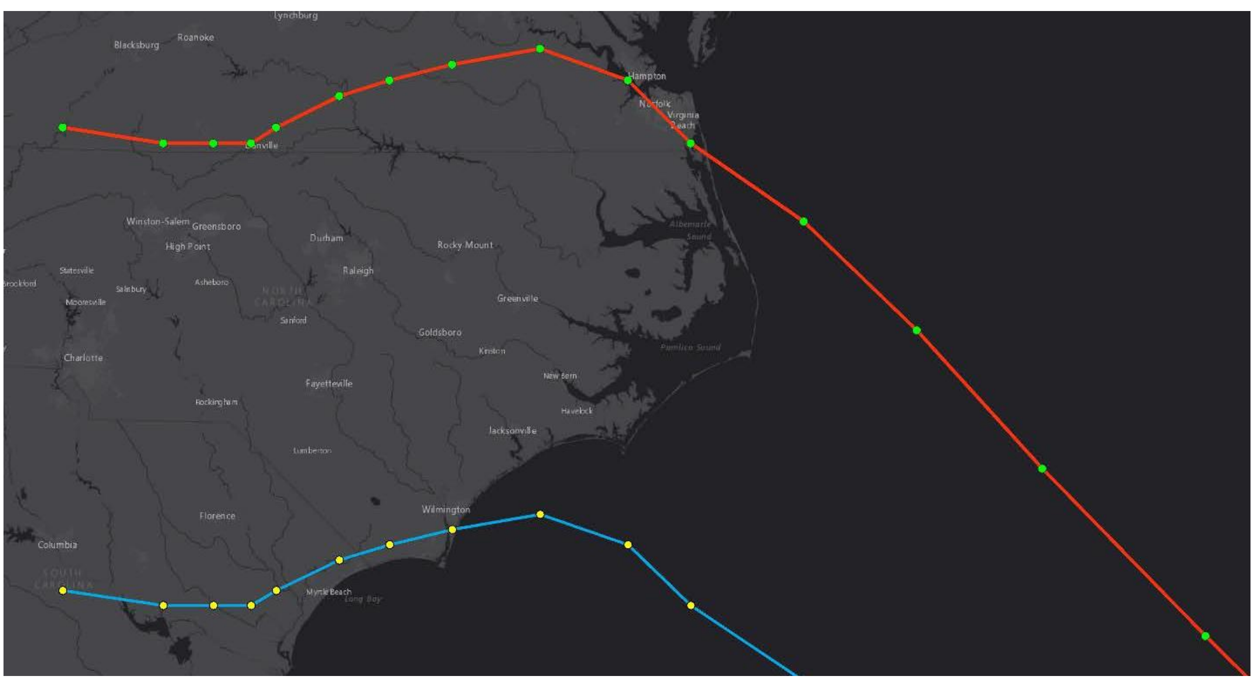


Figure 24. Actual path (blue) of Hurricane Florence that came ashore at Wilmington, NC. Simulated path (red) of Florence making simulated landfall at the Virginia coast.

Hurricane Impacts Modeling with Hazus

The modified Virginia-intersecting track with storm intensity metrics unique to Hurricane Florence and future forecasted sea level were used as inputs to the Hazus model to generate the following types of wind- and flood-related loss estimates:

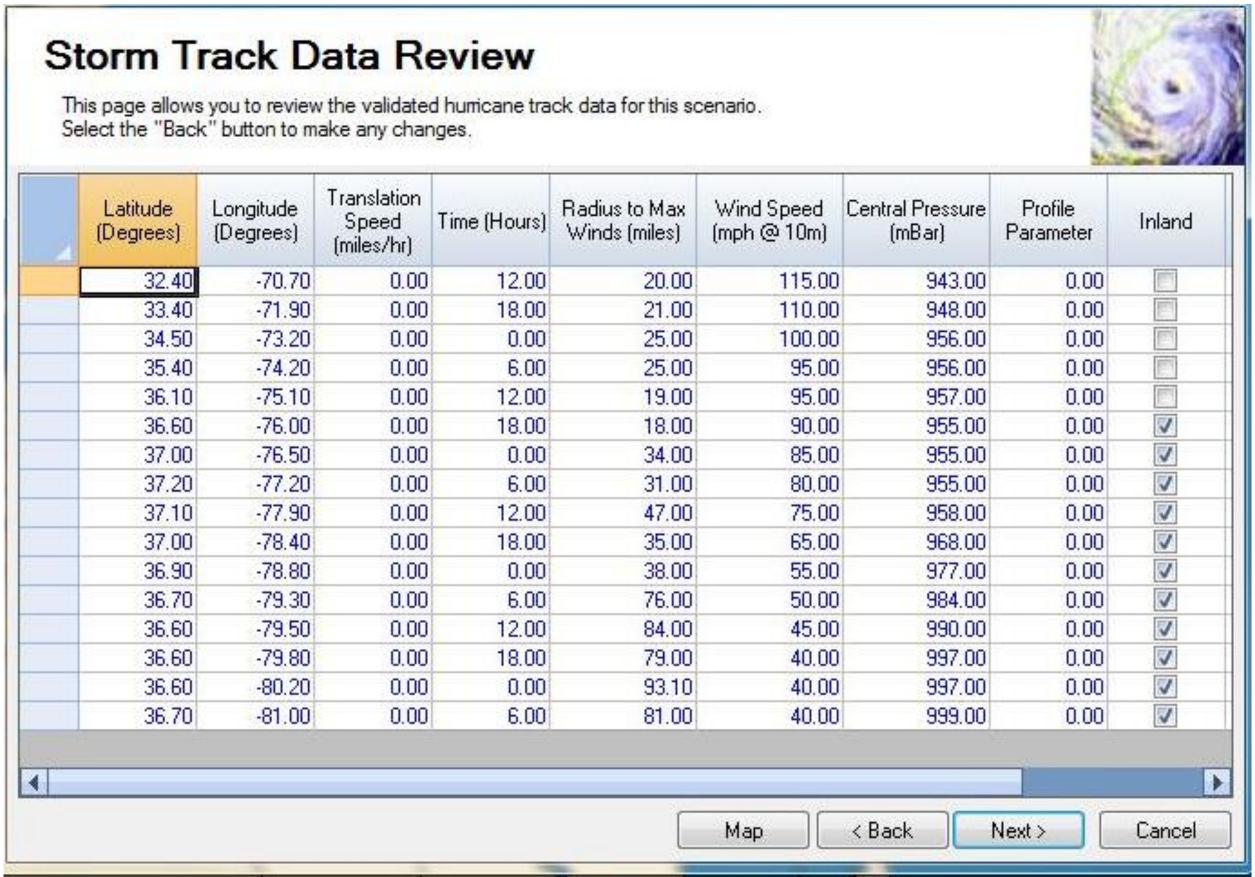
- Physical damage – damage to various building stock
- Economic loss – incorporates loss associated with damages to businesses, estimated workforce losses due to damages to buildings that prevent employees from returning to work, etc.
- Social impacts – societal impacts due to individuals being displaced based on the amount of damage caused by a storm

Study Region Creation. Development of the simulated storm model for this research began with the creation of a geographical study region. Hazus modeling software contains an expansive database of polygon data representing the geographic boundaries of cities, counties, and census tracts that are encoded with infrastructure inventory and partial census data. The cities and counties comprising Hampton Roads used to develop the single study region in this modeling were: Virginia Beach, Norfolk, Portsmouth, Chesapeake, Suffolk, Southampton County, Hampton, Newport News, Poquoson, Gloucester County, Isle of Wight County, Franklin, Smithfield, York County, Williamsburg, and James City County (Figure 25). Infrastructure inventory data for each of these cities and counties served as the foundation for predicted hurricane wind and flood impacts analysis. It is plausible, and even likely, that some of the present infrastructure in the current Hazus inventory will no longer exist at the time when 3 feet (0.91 m) of sea level rise is reached. However, this study made no assumption regarding either the loss of existing or construction of new infrastructure in the future.

Figure 25. Hampton Roads region location in southeastern coastal Virginia

Hazard Selection. As Hazus is a multi-hazard modeling platform, it was necessary to specify which modules would be employed for this research. To fully examine hurricane impacts, both the Hurricane model that accounts primarily for wind damage and the Flood model that accounts for storm surge were selected and implemented in this research.

Scenario Development and Execution. Hazus allows for both the modeling of historical storm data and the development of customized hurricane scenarios. As data for Hurricane Florence were not yet included in the Hazus inventory of historical storms, a custom storm was created using the simulated storm track data that were previously developed by this research. Hazus gives the option of defining a storm track by choosing between three pairs of parameters for each node along the track: (1) synoptic time or translation speed, (2) RMW or Radius to Hurricane Force Winds, and (3) max wind speed or a profile parameter. The timing of a storm's position between each node was predicted in Hazus either by the encoding of exact times of the storm position (if available) or by providing a translation speed, lateral velocity of the storm, if exact times were not available. Since synoptic times, RMW, and maximum wind speed observations were available for Hurricane Florence, these parameters were employed for this research (Figure 26).



Latitude (Degrees)	Longitude (Degrees)	Translation Speed (miles/hr)	Time (Hours)	Radius to Max Winds (miles)	Wind Speed (mph @ 10m)	Central Pressure (mBar)	Profile Parameter	Inland
32.40	-70.70	0.00	12.00	20.00	115.00	943.00	0.00	☐
33.40	-71.90	0.00	18.00	21.00	110.00	948.00	0.00	☐
34.50	-73.20	0.00	0.00	25.00	100.00	956.00	0.00	☐
35.40	-74.20	0.00	6.00	25.00	95.00	956.00	0.00	☐
36.10	-75.10	0.00	12.00	19.00	95.00	957.00	0.00	☐
36.60	-76.00	0.00	18.00	18.00	90.00	955.00	0.00	☑
37.00	-76.50	0.00	0.00	34.00	85.00	955.00	0.00	☑
37.20	-77.20	0.00	6.00	31.00	80.00	955.00	0.00	☑
37.10	-77.90	0.00	12.00	47.00	75.00	958.00	0.00	☑
37.00	-78.40	0.00	18.00	35.00	65.00	968.00	0.00	☑
36.90	-78.80	0.00	0.00	38.00	55.00	977.00	0.00	☑
36.70	-79.30	0.00	6.00	76.00	50.00	984.00	0.00	☑
36.60	-79.50	0.00	12.00	84.00	45.00	990.00	0.00	☑
36.60	-79.80	0.00	18.00	79.00	40.00	997.00	0.00	☑
36.60	-80.20	0.00	0.00	93.10	40.00	997.00	0.00	☑
36.70	-81.00	0.00	6.00	81.00	40.00	999.00	0.00	☑

Figure 26. Storm track data in Hazus for simulated hurricane

Using identical storm track and intensity parameters, two scenarios were developed to model the potential impacts of this storm with future sea levels consistent with those forecast for Hampton Roads for the years 2040 and 2060. Scenario 1 modeled the storm's potential impacts with +1.5 feet (.46 m) ΔRSL and scenario 2 modeled impacts with +3 feet (.91 m) ΔRSL. These values for ΔRSL were input during the model setup process and an "initial water level" parameter in feet above present day mean sea level.

For each of the two scenarios, the Hazus Hurricane model was employed to generate single hurricane wind event loss estimates. After these single storm event scenarios were modeled, coastal storm surge and wave estimates were modeled using the Hazus Flood model. In addition to storm track and intensity data developed during execution of the Hurricane model, the Flood Model also requires analysis of digital elevation and shoreline data. United States Geological Survey (USGS) 1 arc second DEMs, with approximately 30 m grid cell resolution, were acquired via direct download from the USGS through the Hazus software. Coarse shoreline data representing major interfaces between land and water in Hampton Roads were also acquired from the Hazus inventory database. To optimize the flood model, it was necessary to classify major shoreline segment into one of four classes (open coast, moderate exposure, minimal exposure, sheltered) according to their relative exposure to open water. Open coast refers to a shoreline where the storm surge and waves come directly from open waters without protection by any land mass. Shorelines with moderate exposure have small islands or sandbars that help break the direct force of the waves. Shorelines with minimal exposure are running parallel to direction of storm surge and waves and not bearing the brunt of the wave fronts. Sheltered shorelines are those within bays or protected by larger barrier islands (*59*). For the Hampton Roads study region, most shorelines were either classified as open coast or moderately exposed.

Elevation and classified shoreline data were used in concert with storm track and intensity information to develop depth-limited wave runup and delineate the surge floodplain predicted for the modeled storm. The resulting floodplains for both scenario 1 (Figure 27) and scenario 2 were expansive and were used to generate surge loss estimates which, when combined wind loss estimates, comprised the combined losses for each scenario. Reporting of analytic outputs and calculation of losses from both wind and surge was performed according to user-defined specifications, including aggregation of losses to city/county level, direct physical damages to general buildings and critical facilities (medical, police, fire, emergency centers, schools), induced physical damages (debris), direct social and economic loss, and shelter needs.

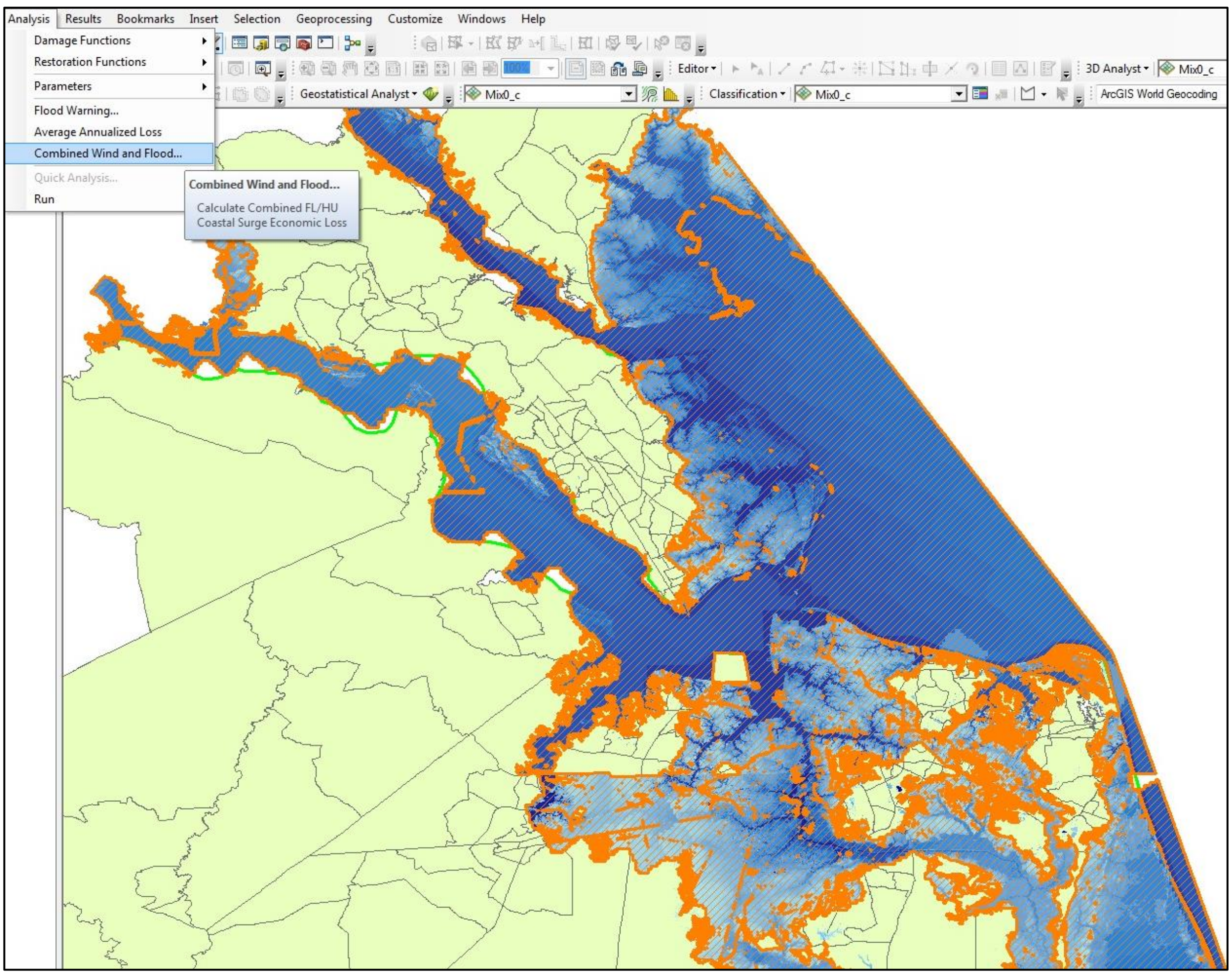


Figure 27. Hazus sotware example, floodplain for category 3 storm with +1.5 ft (.46 m) sea level

RESULTS AND DISCUSSION

Wind Damage

As neither the strength nor category of the storm were modified for this analysis, the Hazus model held wind damages constant for all sea level scenarios. If Hurricane Florence had made landfall in southeastern Virginia, it was predicted that 107,260 or 18% of all buildings in Hampton Roads would suffer some from wind damage. This number included an estimated 2502 buildings that would be either severely damaged and uninhabitable or entirely destroyed. Building-related economic losses were estimated to total nearly $5 billion (Table 7). Approximately 91% of these predicted losses were in the form of direct property damage with the remainder being business interruption-related costs.

Table 7. Predicted Building-Related Economic Loss Estimates in USD

Category	Residential	Commercial	Industrial	Others	Total
Property Damage					
Building	3,132,647,680	145,555,030	42,377,080	38,595,530	3,359,174,320
Content	996,107,790	50,136,380	29,453,780	12,883,350	1,088,581,310
Inventory	0	1,260,420	5,445,120	297,480	7,003,020
Subtotal	**4,128,754,470**	**196,951,830**	**77,275,980**	**51,776,360**	**4,454,758,650**
Business Interruption					
Income	130,410	18,849,060	584,680	4,004,140	23,568,290
Relocation	211,432,000	3,052,800	3,155,360	7,837,180	252,953,340
Rental Income	98,693,710	16,303,940	494,660	788,360	116,280,660
Lost Wages	305,380	18,998,010	970,510	18,800,100	39,074,000
Subtotal	**310,561,500**	**84,679,820**	**5,205,200**	**31,429,790**	**431,876,300**
Total	**4,439,315,970**	**281,631,650**	**82,481,180**	**83,206,150**	**4,886,634,950**

Losses were predicted for every locality in Hampton Roads, with many totaling in the hundreds of millions or billions (Virginia Beach) of dollars. When considering these losses as a percentage of the building stock for each municipality, the impact of Hurricane Florence's winds was the strongest in Virginia Beach (2.95%), Chesapeake (1.8%), Norfolk (1.5%), and Portsmouth (1.43%), with others trailing closely behind. Table 8 details the direct economic losses resulting from wind damages related to buildings for each municipality in the region. Capital Stock losses include building and contents damage as well as inventory loss. Income losses include relocation expense, lost capital, lost wages, and rental income loss.

Table 8. Predicted direct economic losses caused by wind damage for each municipality

Locality	Capital Stock Losses	Loss Ratio	Income Losses	Total Loss
Chesapeake	669,295,000	1.8	57,075,000	726,370,000
Franklin	6,653,000	0.57	392,000	7,045,000
Gloucester	78,313,000	1.09	3,082,000	81,395,000
Hampton	192,212,000	0.87	8,458,000	200,670,000
Isle of Wight	20,845,000	0.35	789,000	21,634,000
James City County	107,719,000	0.73	3,137,000	110,856,000
Newport News	133,610,000	0.53	10,057,000	143,667,000
Norfolk	544,955,000	1.51	69,961,000	614,916,000
Poquoson	23,857,000	0.94	618,000	24,475,000
Portsmouth	175,812,000	1.43	21,994,000	197,806,000
Southampton	16,789,000	0.68	568,000	17,357,000
Suffolk	69,411,000	0.56	3,262,000	72,673,000
Surry	6,695,000	0.65	232,000	6,927,000
Virginia Beach	2,287,843,000	2.95	248,559,000	2,536,402,000
Williamsburg	10,037,000	0.41	502,000	10,539,000
York	110,714,000	0.79	3,188,000	113,902,000
Total	**4,454,758,000**	**1.6**	**431,876,000**	**4,886,634,000**

Storm Surge Flooding Damage with Increased Sea Level

Flooding-related damages occur mostly adjacent to the ocean, bays, rivers, and other low-lying flood-prone areas. Hazus modeling predicted that flooding impacts from a Florence-like hurricane would progressively increase with sea level rise. This research compares damage estimates from three scenarios given current infrastructure and building stock. The baseline scenario is Hurricane Florence tracking over Hampton Roads at current sea level. Scenario 1 is equivalent to the baseline plus 1.5 feet (0.46 m) of sea level rise. Scenario 2 is equivalent to the baseline plus 3 feet (0.91 m) of sea level rise. Model estimates predicted for scenario 1 and scenario 2 illustrate how the damages from a major storm increase appreciably with sea level rise.

Flood depth grids created by the Hazus Flood model during floodplain delineation were employed for overlay analysis with Hampton Roads regional parcel data retrieved from the Hampton Roads Geospatial Exchange Online (HRGEO) (*61*). Table 9 provides an accounting of the number of parcels for each municipality and the entire region which are predicted to experience flooding at present day, +1.5 feet, and +3 feet sea levels (+0.46 and +0.91 m, respectively). While the cities of Virginia Beach and Chesapeake have the highest number of potentially impacted parcels in the study area, the impacts only represent a small percentage of their total number of parcels. By percentage of impacted parcels, the City of Poquoson appears to be the most seriously impacted with 100% of parcels predicted to be flooded during this storm at all sea levels. Norfolk, Portsmouth, and Hampton are predicted to suffer critical impacts with both high percentages and counts of impacted parcels.

Table 9. Parcels predicted flooded by a CAT 3 storm with increasing sea level (1 ft = .305 m)

Municipality	# of Parcels	% Flooded No SLR	% Flooded +1.5 feet SLR	% Flooded +3 feet SLR
Chesapeake	88,725	3	13	21
Franklin	5,029	0	0	0
Gloucester	27,334	28	28	29
Hampton	51,347	45	55	61
Isle of Wight	17,308	4	4	4
James City	35,054	2	2	2
Newport News	54,087	1	4	5
Norfolk	68,570	31	50	74
Poquoson	37	100	100	100
Portsmouth	36,513	33	40	68
Smithfield	4,222	0	0	0
Southampton	15,245	0	0	0
Suffolk	40,774	2	3	3
Surry	6,676	4	4	4
Virginia Beach	161,669	5	12	17
Williamsburg	4,752	0	0	0
York	27,247	21	22	22
Total	**644,589**	**13**	**20**	**27**

According to these estimates, the Hampton Roads region would experience an increase in the number of flood-impacted parcels by approximately 53% with 1.5 feet (0.46 m) of sea level rise and 106% with 3 feet (0.91 m) of sea level rise. These data also reveal that storm-flooding impacts will not be uniform throughout the region. Sea level rise presents a minimal threat from surge-related flooding to the cities of Franklin, Williamsburg, Smithfield, and Southampton County. Conversely, localities with greater exposure to open coastal waters show a trend of sharply increasing flooding with increasing sea level.

Examination of predicted flooding for the City of Norfolk provides ample evidence of this trend. Approximately 31% (21,305) of all parcels (68,403) in Norfolk would have been partially or entirely inundated if Hurricane Florence had made initial landfall at current sea level. With 1.5 feet (0.46 m) and 3 feet (0.91 m) of sea level rise, the percentage of impacted parcels would climb to 50% and 74%, respectively. Figure 28 illustrates this progression for the Ocean View–Willoughby area of Norfolk by highlighting the increasing extent of inundation and impacted parcels as sea level increases.

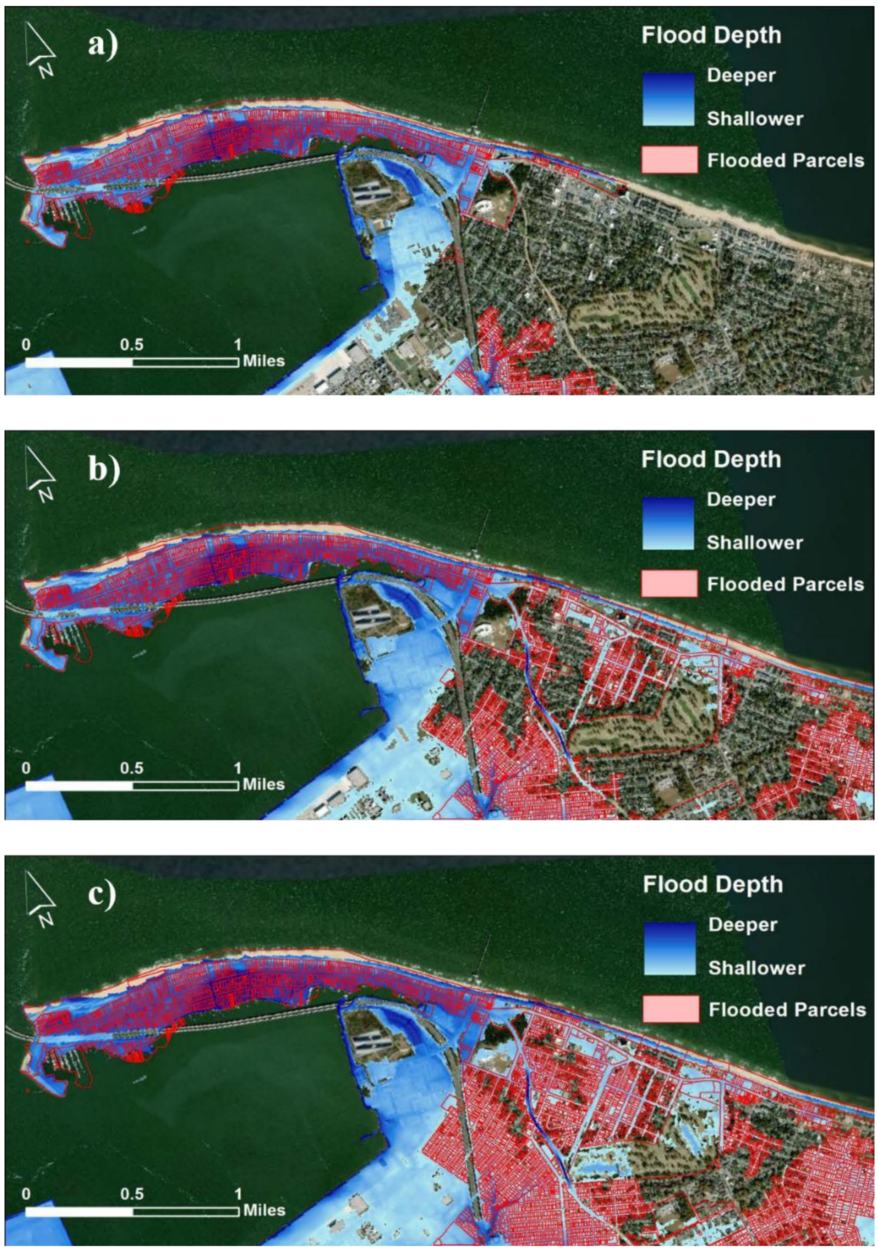


Figure 28. Flooded Areas and Parcels in Ocean View, Norfolk

a) current sea level, **b)** +1.5 feet (+0.49 m) sea level, **c)** +3 feet (+0.91 m) sea level

While more buildings experienced wind damage than flood damage in this simulation, loss estimates reveal that storm surge and flooding were far costlier on a per building basis. At present-day sea level, it was estimated that flooding from Hurricane Florence in Hampton Roads would cause approximately $16 billion in economic losses directly related to building damages.

Modeling of Florence's flooding with increasing sea level reveals that damage estimates will naturally increase as the base water level increases. An additional 1.5 feet (0.46 m) of sea level rise escalated direct economic loss revealed by flood damage modeling to approximately $26.3 billion. According to Virginia Institute of Marine Science forecasts, we should expect the +1.5 feet (+0.46 m) sea level scenario to be our present-day reality near the year 2050 (*57*).

Amplification of sea level to +3 feet (+0.91 m) above today's level inflated modeled flood damages for a Florence-like storm by another $10.3 billion, to approximately $36.6 billion. Table 10 provides a comparison of these direct economic loss at each increment of sea level and illustrates that, while physical damage to buildings is costly, approximately one third of all costs will result from business interruption factors such as lost income, rents, and wages.

Table 10. Direct Economic Loss Estimates from Flooding with ΔRSL (1 ft = .305 m)

Category	Present Sea Level	+1.5 Feet SLR	+3 Feet SLR
Property Damage			
Building	5,356,673,000	9,002,668,000	13,007,361,000
Content	5,125,881,000	8,476,029,000	12,135,917,000
Inventory	69,465,000	110,257,000	168,974,000
Subtotal	**10,552,019,000**	**17,588,954,000**	**25,312,252,000**
Business Interruption			
Income	1,227,714,000	2,073,942,000	2,812,123,000
Relocation	1,306,987,000	1,848,060,000	2,451,746,000
Rental	815,612,000	3,619,334,000	4,529,337,000
Wage	2,507,853,000	1,189,033,000	1,547,936,000
Subtotal	**5,858,166,000**	**8,730,369,000**	**11,341,142,000**
Total	**16,410,185,000**	**26,319,323,000**	**36,653,394,000**

In addition to direct economic losses resulting from building damage, an array of related impacts would be experienced. Among those most acutely felt would be the loss of emergency infrastructure such as, police, fire, hospitals, and shelters. Table 11 details high levels of predicted impairment of such facilities and services as a result of a Florence-like storm directly impacting Hampton Roads with increasing sea level. With an additional three feet of sea level, the model predicted that 25% of emergency operations centers, 24% of fire stations, 31% of hospitals, 29% of police stations, and 26% of all schools could be incapacitated.

Table 11. Emergency facilities impacted by flooding with increasing sea level (1 ft = .305 m)

		# Facilities Impacted		
Facility Type	**Total**	**Present Sea Level**	**+1.5 Feet SLR**	**+3 Feet SLR**
Emergency Ops Centers	4	1	1	1
Fire Stations	63	10	12	15
Hospitals	26	4	5	8
Police Stations	63	12	15	18
Schools	561	56	103	146

Furthermore, a hurricane of this scope will displace a significant number of households and require tens of thousands of individuals to seek short-term shelter during the storm and longer-term temporary residences afterwards (Table 12). Demand for shelter of this magnitude is certain to strain the resources available to potential evacuees. The Commonwealth's Annual Report on Emergency Shelter Capabilities and Readiness, released in 2018, identified a capacity to shelter 93,275 individuals in the Hampton Roads region (*62*). However, this accounting includes many facilities which may not be suitable or may be inoperable in high-wind and/or storm surge events. The report concluded that the *entire* Commonwealth would be unable to meet the shelter needs of

10,595 people during a CAT 2 storm, 45,000 people during a CAT 3 storm, and 96,000 during a CAT 4 storm (*62*). Hazus model predictions for escalating displacement and shelter requirements as sea level rises underscore the need for the Commonwealth to plan for additional shelters.

Table 12. Shelter Requirements caused by flooding with increasing sea level (1 ft = .305 m)

Shelter Requirements	Present Sea Level	+1.5 Feet SLR	+3 Feet SLR
Displaced Households	69,542	108,249	147,133
Shelter Required (# people)	15,821	25,309	35,279

Also noteworthy is the fact that the flooding impacts of a Florence-like storm would not be felt equally throughout the region. Municipalities having more shoreline exposure to water bodies and/or higher percentages of low-lying land areas show greater and more rapidly increasing damage estimates as sea level increases. Actual dollar damages for the City of Norfolk are predicted to be the greatest of any Hampton Roads municipality. However, economic losses for Newport News and Chesapeake are predicted to dramatically increase with sea level. Table 13 ranks the top five Hampton Roads cities by percentage increase of predicted direct economic loss from flooding as a result of a Florence-like hurricane striking with sea level rise. These findings are striking in that they highlight that Norfolk will consistently suffer the highest losses from a hurricane strike of this magnitude, and also that the cities of Newport News and Chesapeake, much less vulnerable in present day, could potentially experience well over 1000% increases in damage from storm events in the coming decades.

Table 13. Top 5 Localities Ranked by % Increase in Hurricane Flood Damage with SLR

Locality	Flood Damages ($) Present Sea Level	Flood Damages ($) +1.5 feet SLR	Flood Damages ($) +3 feet SLR	% Increase from Present to +3 feet SLR
Newport News	14,713,000	256,742,000	288,932,000	1864
Chesapeake	242,306,000	2,414,828,000	4,255,419,000	1656
Virginia Beach	850,437,000	2,636,480,000	4,164,771,000	390
Portsmouth	1,948,081,000	2,746,035,000	5,286,229,000	171
Norfolk	6,556,167,000	10,507,936,000	15,705,385,000	140

Combined wind and flood physical damage losses of over $20 billion for a Hurricane Florence-like storm directly striking Hampton Roads would rank the storm among the top ten costliest hurricanes to ever strike the continental United States, even with no increase in sea level (*56*). Furthermore, analysis of storm-related and ancillary impacts over the first year after landfall by McNab et al. (2019) revealed that the total impact could approach or exceed $40 billion (*55*).

Increasing sea level will only exacerbate the impact of such a devastating storm, resulting in total physical damages from wind and storm surge estimated at over $30 billion with 1.5 feet (0.46 m) of sea level rise predicted by 2050 and $40 billion with 3 feet (0.91 m) of sea level rise by the end of the century. These damages are calculated in present-day United States dollars (USD) without inflation and consider neither new infrastructure nor mitigation solutions which may be developed in the coming decades. While these and other variables, such as the tide level and timing of landfall, will determine the actual cost of storm-inflicted damages, it remains clear that rising sea level will dramatically increase the region's risk from storm flooding. Given the rapid increase in sea level in coastal Virginia relative to other communities in the United States, the consequences associated with a major hurricane making landfall are increasing.

CHAPTER IV

GEOSPATIAL RISK ASSESSMENT OF MARINE TERMINAL INFRASTRUCTURE TO STORM SURGE INUNDATION AND SEA LEVEL RISE

PREFACE

A modified version of this chapter was published on May 11, 2018, as Issue 11 in Volume 2672 of the Transportation Research Record, Journal of the Transportation Research Board (TRB). The right to reproduce this article in theses or dissertation is retained by the author under the author rights agreement with National Academy of Sciences: Transportation Research Board. https://doi.org/10.1177/0361198118774234

BACKGROUND

Prompted by recent planning activity at the Port of Virginia, this research examined and employed the most recent scientific information from several studies by federal agencies focused on the Hampton Roads port region of southeastern Virginia. Observations and trends from prior studies were synthesized with peer-reviewed literature relevant to vulnerability assessment, modeling, and risk management in ports across the world.

Numerous sea level rise vulnerability studies have been conducted in or near the Hampton Roads region. However, none has specifically evaluated site and infrastructure exposure to storm surge hazard and sea level rise in the marine terminals of the Port of Virginia. The USACE study (*63*) of the Norfolk Naval Station required several years and millions of dollars to evaluate systemic risks and provides the nearest analog with the nearby Port of Virginia marine terminal, both spatially and regarding specific facilities. Further, Titus and Cacela (*64*) implemented an analysis of regional vulnerability, although this was conducted at too coarse a scale for site-level inference. To the south, the North Carolina Sea Level Rise Risk Management Study (*65*) is a robust regional modeling assessment, but the focus on flood zones and future risks posed to the State and National Flood Insurance Program (NFIP) is markedly different than the concerns of a marine terminal. Other relevant studies have either tended to focus on economic and property vulnerability (*66*), specific sectors such as metropolitan public roadways, or utilized bathtub models lacking hydrologic connectivity or ambiguous tidal flooding (*67*), use static incremental water level changes (*68*), or are limited in spatial extent and temporally focused on near real-time prediction rather than long-term sea level rise (*69*).

The objective of this research was to answer two fundamental questions on the exposure of the Port of Virginia's Norfolk International Terminals South (NITS) facility to future storm surge flooding concomitant with relative sea level rise: (1) What is the magnitude and spatial extent of potential surge-related flooding that may be expected at the terminal, both currently and for specific future sea level rise scenarios?, and (2) What is the current and future vulnerability, in terms of flood risk exposure, of the structural assets to this surge-related flooding under these given sea level rise scenarios? It was hypothesized that modeling would reveal that, with increasing sea level, even moderate storm surges would impact critical infrastructure and impair future operations.

Given that discussion or presentation of the forecasted vulnerability of specific elements of terminal infrastructure is forbidden by a non-disclosure agreement (NDA), this report was designed to provide an overview of the spatial vulnerability of NITS to inundation from storm surge with ΔRSL and to detail the methods developed to offer guidance beyond this specific case, to facilitate study of other regional port facilities, and to suggest pathways for necessary adaptation and mitigation actions pertinent to planning, sustainable design, and facility resiliency.

Prior Sea Level Rise Studies

The Hampton Roads Sea Level Rise (HRSLR) Preparedness and Resilience Intergovernmental Pilot Project recommended that the region foster improved ways for agencies to work together and the adoption of regional sea level planning scenarios and standards (*70*). At the time of this research, the region had not yet adopted regional sea level planning scenarios and standards for this case study to use for guidance. The Norfolk International Terminal South (NITS) project did, however, leverage recent related efforts by Strategic Environmental Research and Development Program (SERDP) "Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide," (*71*) and two recent studies by NOAA focused on regionalizing sea level trends (*7*) and preparing for future non-linear increases in recurrent tidal or nuisance flooding (*16*). Key highlights from these studies include the HRSLR Intergovernmental Pilot study's recommendation that vulnerability of critical infrastructure to sea level rise impacts focus on the next 30 to 75 years. The same group noted interdependencies between private and public infrastructure systems, an externality that bears consideration for this project, which does not directly evaluate impacts on City of Norfolk or Navy properties and their infrastructure and transportation systems with significant connection to NITS. From outside the region, some specific best management practices can be drawn from Southeast Florida and New Orleans relevant to the Port, including:

- Strive for regionally consistent mapping methods and products for sea level rise planning.
- Develop consistent criteria for risk assessments.
- Evaluate management strategies for storm water and flood control/drainage structures.
- Include tidal flooding in risk assessment studies.

Port Response to Climate Change Risks

In reviewing the state of scientific study of the impacts of ∆RSL on ports, trends are evident in sectors and scale of analysis. There exists a core, traditional body of research that focuses on ports and their regional to global scale function. There is also a growing body of literature on the site-specific dimensions of port vulnerability to ∆RSL. Relatively few studies scale between these to the level of whole facilities or regions, creating a knowledge gap on what policies and best practices port planners and governing authorities can exchange and implement.

Some studies of individual ports have tended to focus on the ports in the context of urban metropolitan systems with vulnerabilities including infrastructure, transportation, economics, and social vulnerability. Akukwe and Ogbobo (*72*), for example, analyzed Port Harcourt, Nigeria, to evaluate exposure of the port's economic and social vulnerabilities to create indices for tracking vulnerabilities. Also working at the city-scale, Hallegatte et al. (*73*) focused on identifying economic impacts of sea level rise and storm surges in Copenhagen, cautioning that predictions in changes in storminess were indeterminate for Copenhagen.

At a coarse, global scale, Becker et al. (*74*), utilized social science surveys of port administrators to investigate preparedness for climate change. The study revealed that many ports acknowledge sea level rise and climate-related issues but have yet to address them. Hanson et al. (*75*) took a similar, global-scale approach to evaluating port cities and climate extremes. They estimated that about 40 million people are now exposed to the threat of 100-year coastal flood events and that population could triple by the 2070s owing to combined population growth in coastal cities and relative sea level change. In fact, Norfolk-Virginia Beach was noted as one of the global top-ranked metro areas (#19 globally in assets exposed by the 2070s, rising from $84.8B today to $581.9B in the future).

The Port of Miami, The Port Authority of NY and NJ, the Massachusetts Port Authority, Port of Seattle, Port of Corpus Christi, and Georgia Ports Authority are each mentioned for various initiatives. Nonetheless, common challenges were revealed, such as the region-specific climate information needs of ports requiring more data and research. Nicholls et al. (*76*) ranked the exposure and vulnerability of global ports to climate extremes. In summary, these coarse-scale studies suggest overarching issues for consideration by port administrators at the local level:

- Short- and long-term plans should benchmark climate change forecasts as the science improves, such as an interval of 5-years (with projections out 50 years).
- Port administrators should keep abreast of scientific developments, trends, and technologies for potential adaptation.
- Ports ought to ally with regional entities facing the similar challenges.
- Coordinated studies, such as state, regional and multi-nodal nature, would be fruitful.

At the site-level, port literature is often focused on engineering design in the face of increasing wave energy and flood impacts. Numerical modeling was demonstrated by Rajabalinejad and Demibilek (*77*) for engineering structures exposed to sea level rise (*77*). They recommended modeling for the capacity to inform uncertainties with current practices and designs for coastal flood protection. Finally, some ports exposed to wave-overtopping have demonstrated that scenario-based approaches were useful analyses (*78*). From a coastal risk management perspective, Hinkel et al.(*79*) concluded that it may be best to utilize lower probability, extreme (upper tail end) events rather than Intergovernmental Panel on Climate Change (IPCC) scenarios.

With specific relevance to this NITS study, Wood et al. (*80*) noted that local participants did not use GIS-based maps to the extent hoped, depending rather upon local experts, technical advisors, and aerial photo and static maps. Overall, Wood et al. recommended early engagement with a diversity of port stakeholders and capturing a wider range of community vulnerability.

Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Model

The SLOSH model was developed by the National Weather Service National Hurricane Center (NHC) to "estimate storm surge heights, resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data" (*81*). Composite storm surge modeling methods are available within SLOSH, specifically a Maximum of Maximum Envelopes of Water (MEOWs), abbreviated, MOMs, approach "which are regarded by the NHC as the best approach for determining storm surge vulnerability for an area since it takes into account forecast uncertainty" (*81*). This method incorporates storm simulations from thousands of model runs with the same category, forward speed, storm trajectory, and initial tide level. MOMs provide a worst-case scenario product as they are compiled based on the maximum storm surge height for all hurricanes of a given category. When assessing storm surge impacts, utilization of SLOSH MOMs for each Category (1-5) storm occurring at high tide, is most effective for identification of infrastructure vulnerability as a worst-case scenario for risk identification (*82*).

Relative Sea Level Rise Scenarios

Several studies note the need to consider future scenarios for sea level rise, considering a wide range of potential changes, emphasizing prudent, conservative estimates resulting from plausible consequences of ice sheet degradation, and localized uncertainty in subsidence. Sweet et al. (*7*) recommend using a scientifically plausible upper bound (worst case or extreme scenario) in addition to intermediate scenarios. Although lower probability, using higher forecasts reveals overall system risks and information for long-term strategies. A complementary mid-range scenario is appropriate for shorter-term planning. The two, in combination, can be considered as a "general planning envelope" (*7*). Accordingly, the sea level curves for potential consideration of the adopted scenarios were reproduced (Figure 29).

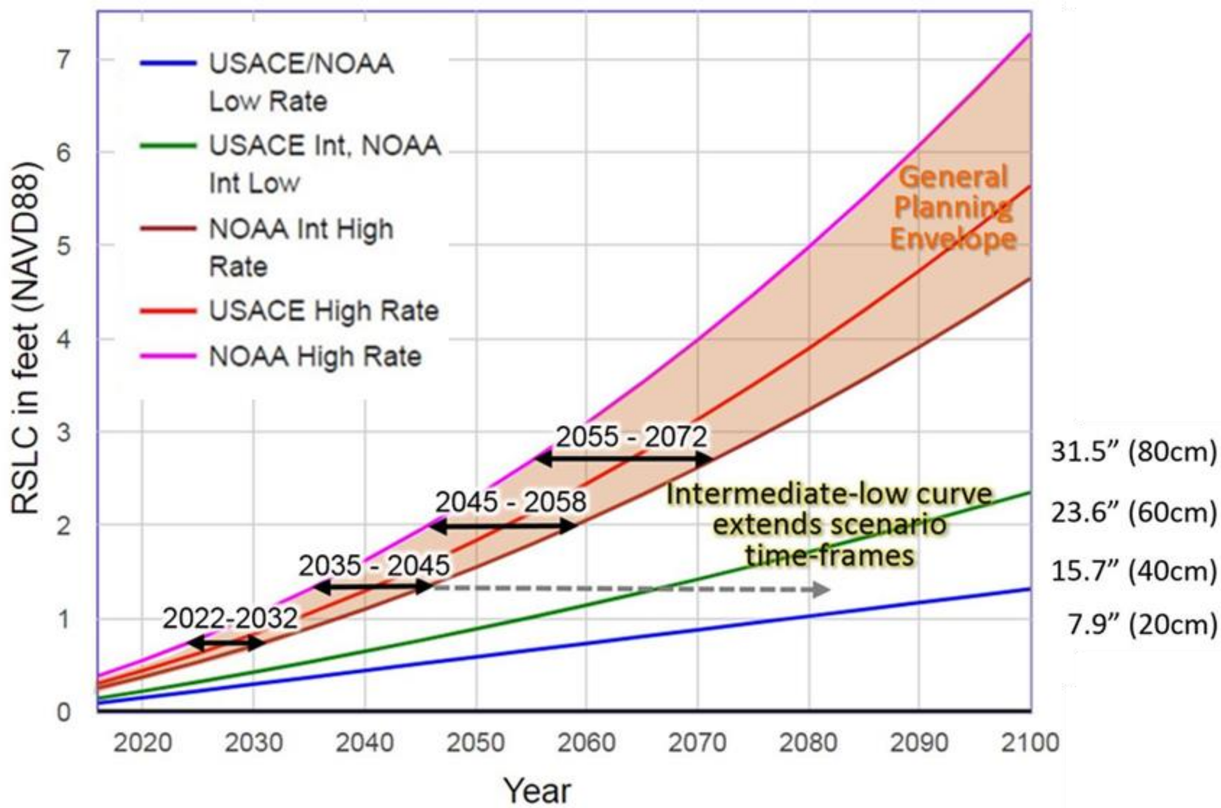


Figure 29. Relative Sea Level Projection Curves for Sewells Point, VA

NOAA and USACE curves and the general planning envelope between intermediate-high and extreme curves (orange fill) are shown. Arrows depict time ranges for relative sea level scenarios within the planning envelope between NOAA High and Intermediate-High SLR that were used in modeling storm surges and tidal flooding. Adapted from USACE Sea Level Curve Calculator.

Tidal Flooding

The rate of occurrence of nuisance events is increasing along the U.S. East Coast, such that nuisance events are becoming chronic, and tipping points for impacts in areas such as Norfolk, where relative SLR rates are themselves faster than other areas. Well before 2050, it is expected that the number of days of tidal flooding will increase with rising sea level. One study (17) predicted an accelerating trend of tidal flooding days per year specifically for Norfolk, VA. Another study (15) provided support for these claims by finding that tidal flooding in the Lafayette River watershed, which contains the NITS study area, is frequent and is expected to worsen over time as “mean sea level” rises. Nonetheless, as tidal flooding increases frequency, today’s nuisance or “extreme” becomes tomorrow’s “mean” (*83*).

APPROACH AND METHODS

Sea Level Rise Scenario Selection

To provide context for inundation maps and projected sea level rise and surge in time, the USACE Sea Level Rise Curve Calculator was utilized (*44*). The study includes inundation maps for the following four relative sea level rise scenarios for storm surge model simulations and tidal “nuisance” flooding with approximate years of potential realization, with the first year reflecting the fastest acceleration of SLR (NOAA extreme) and the latest the NOAA intermediate-high: 7.9” (20cm), 2022-2032; 15.7” (40cm), 2035-2045; 23.6” (60cm), 2045-2058; 31.5” (80cm), 2055-2072.

Study Area

Approximately 95% of Norfolk’s boundary is along water and the Lafayette River watershed is by far the largest in the City of Norfolk. The boundary of the study area for this research includes the Port of Virginia’s NITS facility and immediately adjoining areas located at the mouth of the Lafayette River (Figure 30). The NIT South Terminal comprises 272 acres of NIT, which is the Virginia Port Authority’s largest terminal (*84*).

Figure 30. Norfolk International Terminal South (NITS) study area location

Assumptions

In keeping with a conservative approach for risk identification, no engineering intervention or related landform changes that would mitigate storm surges under relative sea level rise were assumed. Similarly, no major shoreline modifications or fortifications around the facility were considered.

Elevation Data

This modeling endeavored to detail and mitigate data error and uncertainty as best possible, including potential error in DEMs, which were evaluated using hydro-connected storm surge modeling and Monte Carlo simulation in tidal flood modeling. A key descriptive metric of the accuracy of digital elevation data is fundamental vertical accuracy, which describes vertical accuracy at the 95-percent confidence level in open terrain where errors should approximate a normal error distribution (*39*). The fundamental vertical accuracy for the current best available lidar data for the NIT terminal study region used for this study was reported as +/- 0.129 m (*85*).

Storm Surge Inundation Mapping

This research applied a multi-hazard methodology for vulnerability assessment. This included applying the NOAA SLOSH model, superposition of SLOSH on fixed landforms and developed surfaces with ΔRSL, mapping surge inundation zones for three levels of storm severity, and estimating freeboard or potential depth of inundation of the critical structural elements. Storm surge modeling data was obtained from the SLOSH Display Program and used to map the extent and depth of inundation resulting from various storm surge levels with sea level rise. SLOSH relies on unique regional modeling grids to develop the most accurate storm surge data for a specific area. Accordingly, the "Norfolk" modeling basin grid that covers the entirety of the Chesapeake Bay and offshore waters of the Atlantic Ocean ranging from Delaware to North Carolina was used to provide the most accurate surge forecasts for the NITS study area (Figure 31).

A multi-step process was used to obtain surge water levels from SLOSH MOMs for storm categories 1-3. Polygon MOM surge zones aligned with the Norfolk modeling grid for storm categories 1, 2, and 3 were generated using SLOSH (Figure 32). Individual polygons in these MOM data layers were attributed with values representing the modeled surge at that location.

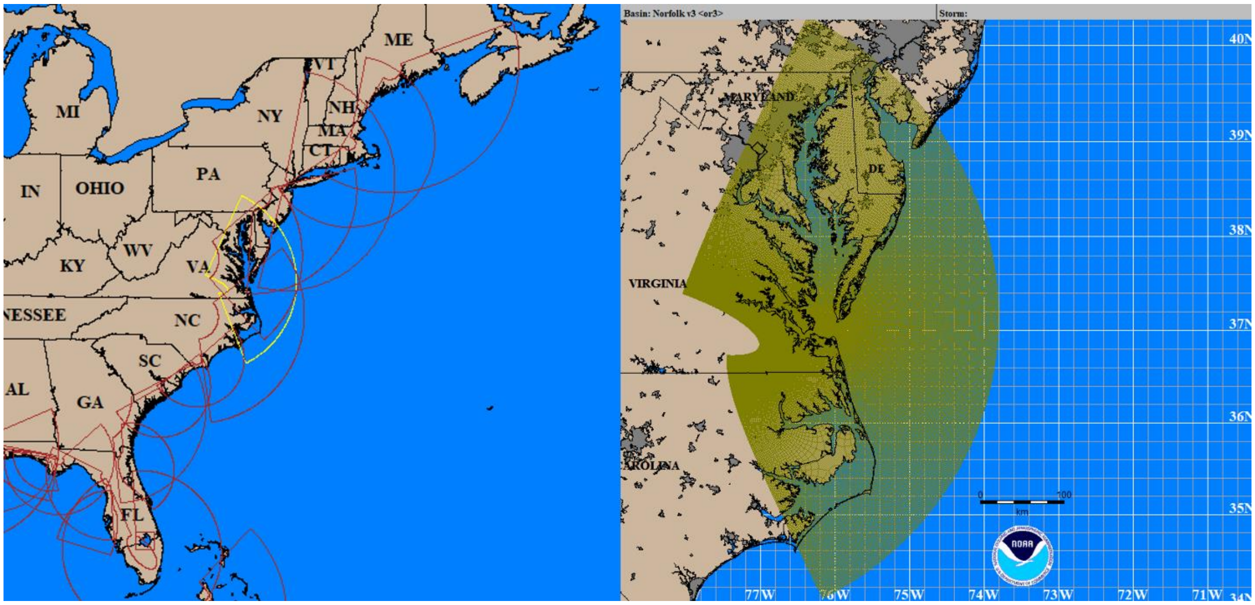


Figure 31. Atlantic SLOSH modeling basins with Norfolk outlined in yellow (left) and Norfolk SLOSH model grid (right**)**

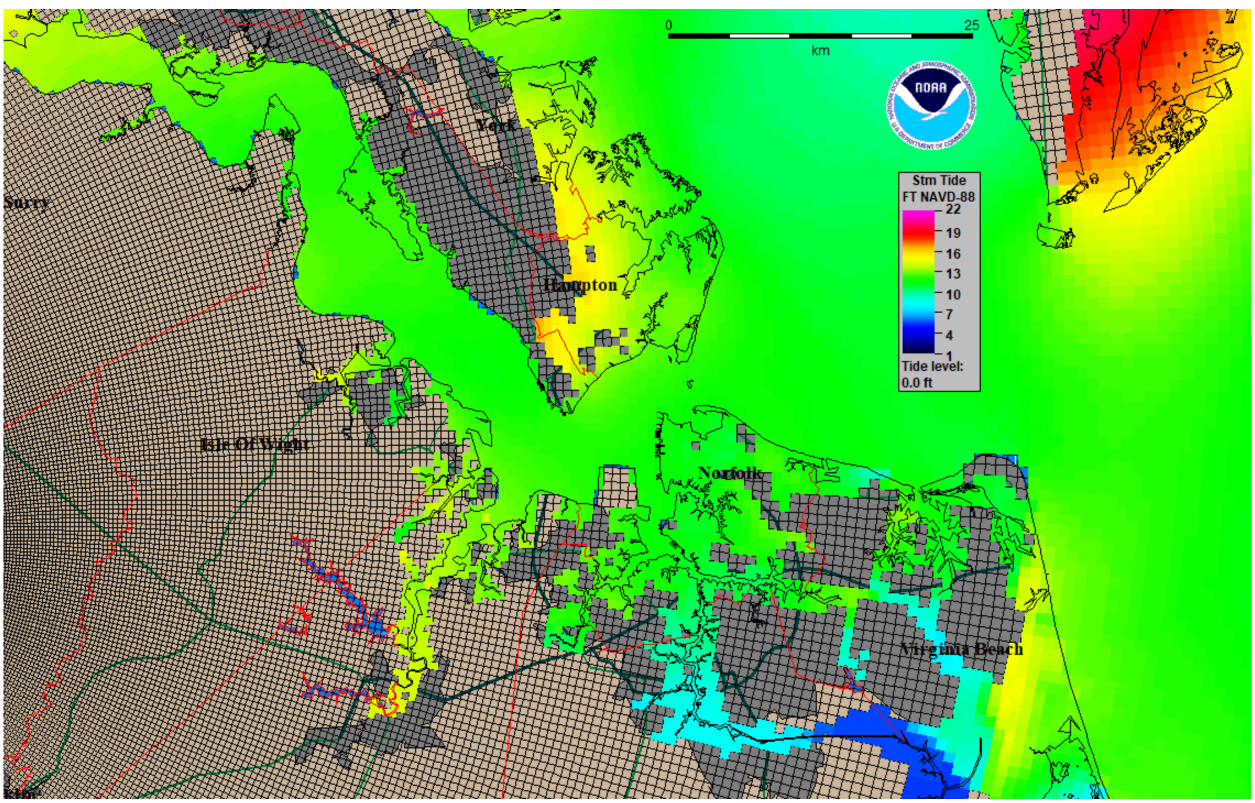


Figure 32. SLOSH modeled Category 3 MOM polygon surge grid layer example

For SLOSH polygon surge data to be used for inundation modeling, it was necessary to convert those data into raster surge grids. Using ArcGIS Pro, SLOSH polygon data were first converted to points, located at the centroid of each model grid polygon, that inherited the predicted surge height for each MOM layer and were then used to interpolate smoothed raster data surfaces representing storm surge water heights throughout the study region (Figure 33a-b).

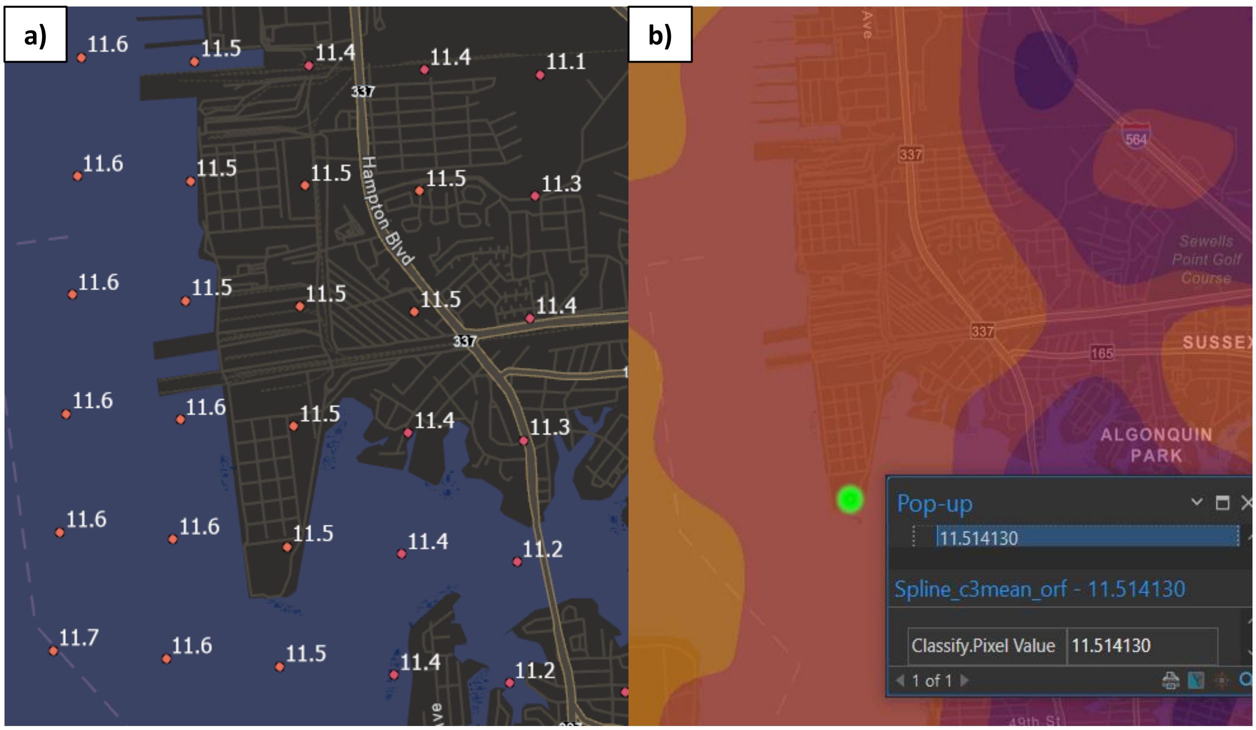


Figure 33. SLOSH storm surge data

a) Storm surge height points extracted from SLOSH, **b)** Smoothed storm surge raster surface interpolated from SLOSH points.

The NOAA SLOSH model contains inherent uncertainty owing to the coarse resolution of the model grid. In a conservative approach, this research rounded interpolated values to the highest adjoining SLOSH cells for areas that were not initially characterized as flooded. The research made use of existing and available data and incorporated ancillary data characterizing the present-day risk conditions in the Federal Emergency Management Agency's (FEMA) updated Special Flood Hazard Areas (SFHAs) published and provided in database form in mid-2016. Prior Virginia Department of Emergency Management (VDEM) flood zones are also used as reference to judge the conservativeness of inundation models developed in this research.

Inundation Model. For modeling hurricane surge inundation, Saffir-Simpson categories 1-3 were employed as surrogates for a range of hurricane surge severity. The Saffir-Simpson scale categorizes hurricanes into 5 classes which are determined by the velocity of sustained winds. Modeling of Category 4 and 5 hurricanes was not necessary as storms of these intensities produce surges which would completely inundate the study area and cause near-total destruction.

Inundation mapping implemented a hydrologically connected flood model, with existing baseline water at MHHW datum expanding in 8 possible directions (N, NE, E, SE, S, SW, W, NW) across the bare earth DEM for any cell less than or equal to the downscaled SLOSH surge height. Positive values yielded during subtraction of the land surface elevation surface from the SLOSH surge height surface signified depth of inundation (Figure 34). A raster depth grid was produced utilizing this cost distance method.

Figure 34. Flood depth equals land surface elevation subtracted from height of flood waters

Each structural element of NITS critical infrastructure was overlaid on the inundation grid for calculation of freeboard height (or depth in the case of complete inundation). An inundation map was created for each category 1 through 3 for the baseline (today) as well as each future scenario of sea level rise. A common symbology color ramp and classification scheme was created to allow for comparison of the expanding inundation zone, with an underplayed orthophoto basemap image and superimposed point and polygon features of the structural assets.

Freeboard Elevation. Structural elements of critical infrastructure were identified by the Port of Virginia and characterized by a critical elevation value provided by the Port. These elevations were subtracted from the surge height grid, resulting in positive (above flood elevation) or negative (inundated) values. Thus, resulting tables characterized depth or freeboard and allowed for ranking or classification of exposure. Tabular summaries were created by joining the measured freeboard-depth values to a master table containing the structural features' attributes. Tables were then symbolized and sorted by freeboard-depth for vulnerability analysis.

Tidal Flooding

For tidal flooding, the NOAA threshold value of 0.53 m was retained for the study area based upon the local elevation of street-level impacts (*7*).

Two contrasting methods were employed for modeling of potential tidal flooding areas at NITS. First, a cost-distance model simulated flooding only in land areas that were hydrologically connected to open water. Second, a bathtub model uniformly simulated flooding in all land areas with elevations below the defined flood surface elevation, regardless of connectivity and barriers. The benefit of this composite methodology was that it allowed for the identification of low-lying areas which are not hydrologically connected to open water, but which are immediately adjacent and/or separated by narrow barriers. Each sea level rise scenario was modeled to include an additional 0.53m of tidal inundation, the "nuisance" value calculated for Norfolk (*16*). Maps were created for comparison of the extents and both the cost-distance and bathtub modeled flood surfaces.

The impact of positional error in the lidar DEM was considered during the analysis of the potential for recurrent tidal flooding. This was accomplished through iterative Monte Carlo (MC) error distribution modeling. An MC error distribution model was created to generate 100 unique permutations of the DEM, using a pseudo-random number generator and the bounds of potential error. The model follows the current practice of flood mapping which assumes that lidar vertical errors follow a normal distribution with zero bias (*31*). Similar methods were used by Liu et al. (*86*) for studying the effect of elevation error on shoreline position and Bodoque et al. (*87*) for characterizing first floor elevation errors related to flood modeling.

For each increment of sea level rise, this study ran a tidal inundation model on each DEM permutation, and recorded differences between flood and elevation surfaces. The cumulative confidence of all inundation simulations was calculated by tallying the number of runs that resulted in each data cell being inundated. Grid cells were shaded in proportion to the number of simulations that produced flooding, providing a probabilistic delineation of potential error and flood vulnerability (Figure 35). Symbolizing pixel areas by consistency of predicted flooding allows for identification of areas with high and low inundation uncertainty for particular flooding scenarios.

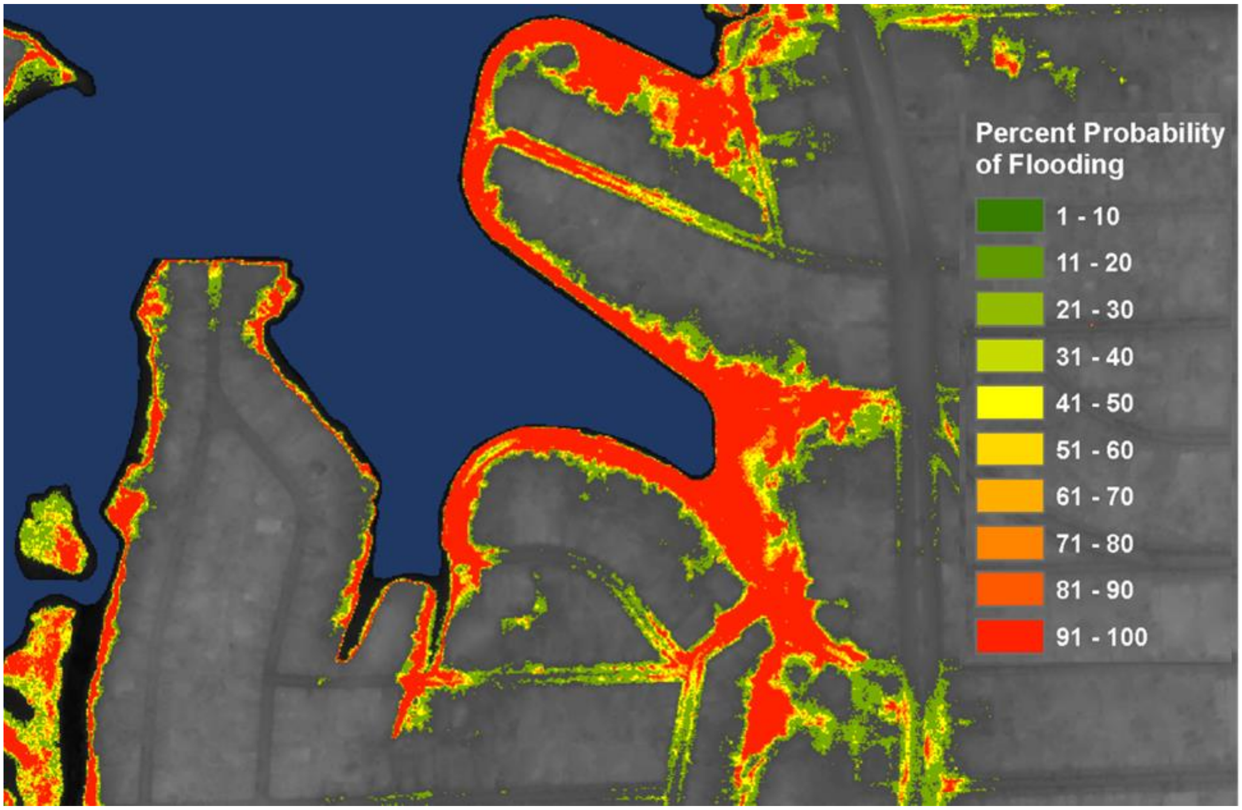


Figure 35. Example flood probability surface resulting from Monte Carlo uncertainty modeling Counts indicate the number of model runs out of 100 that a pixel was predicted to flood.

RESULTS AND DISCUSSION

The following sections summarize highlights and patterns of vulnerability for exposed assets at each sequential level of ΔRSL. Maps of inundation patterns and tabular summaries of freeboard elevation (or depths) were analyzed iteratively and cumulatively with each ΔRSL step.

Storm Surge Inundation Modeling and Mapping

Results for baseline surge at present day depicted a pattern of vulnerability extending along the lowest elevations on the outer fringe of the Lafayette River shoreline for category 1 storms. Stronger storms (category 2-3) exposed more extensive potential flooding around the pier and along reefer row and associated power substations. For low to moderate levels of surge (category

1-2), few critical elevations were reached by the surge MOMs. Although critical elevations are not attained by surge, wave action, wind and debris may nonetheless damage structures. In addition, a dozen assets may be inaccessible during peak surge (category 3). The percentage of area at NITS predicted to be inundated by storms of identical category progressively increases as sea level increases (Figure 36). Mapping of predicted storm inundation revealed a pattern of increasing floodwater encroachment into the NITS interior from the Lafayette and Elizabeth Rivers as sea level and storm category increase (Figure 37). Increases in flooding percent between scenarios are expected to be non-linear as they are driven by elevation and topography of the study area. However, NITS uniformly low elevation and slope resulted in near linear increases.

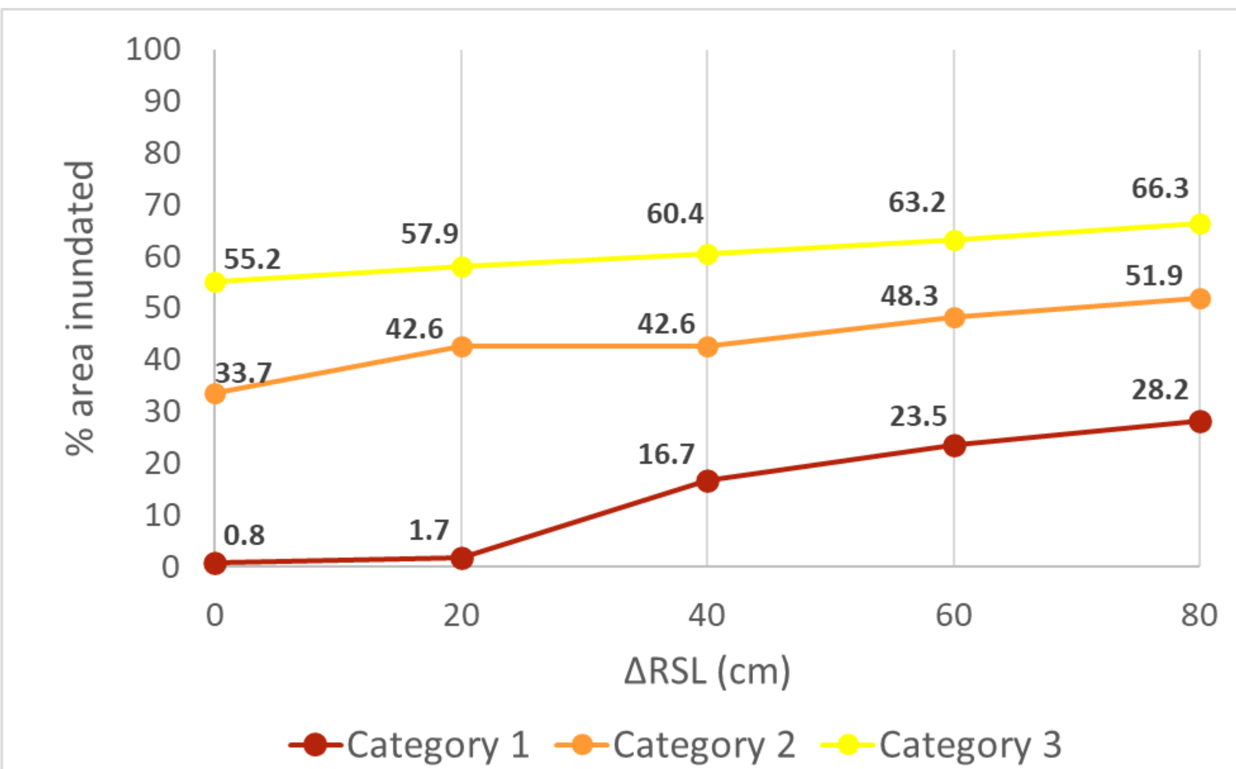


Figure 36. Percent of terminal potentially flooded by surge level for each SLR scenario Category 1 inundation area shown by red line, Cat 2 by orange line, Cat 3 by yellow line.

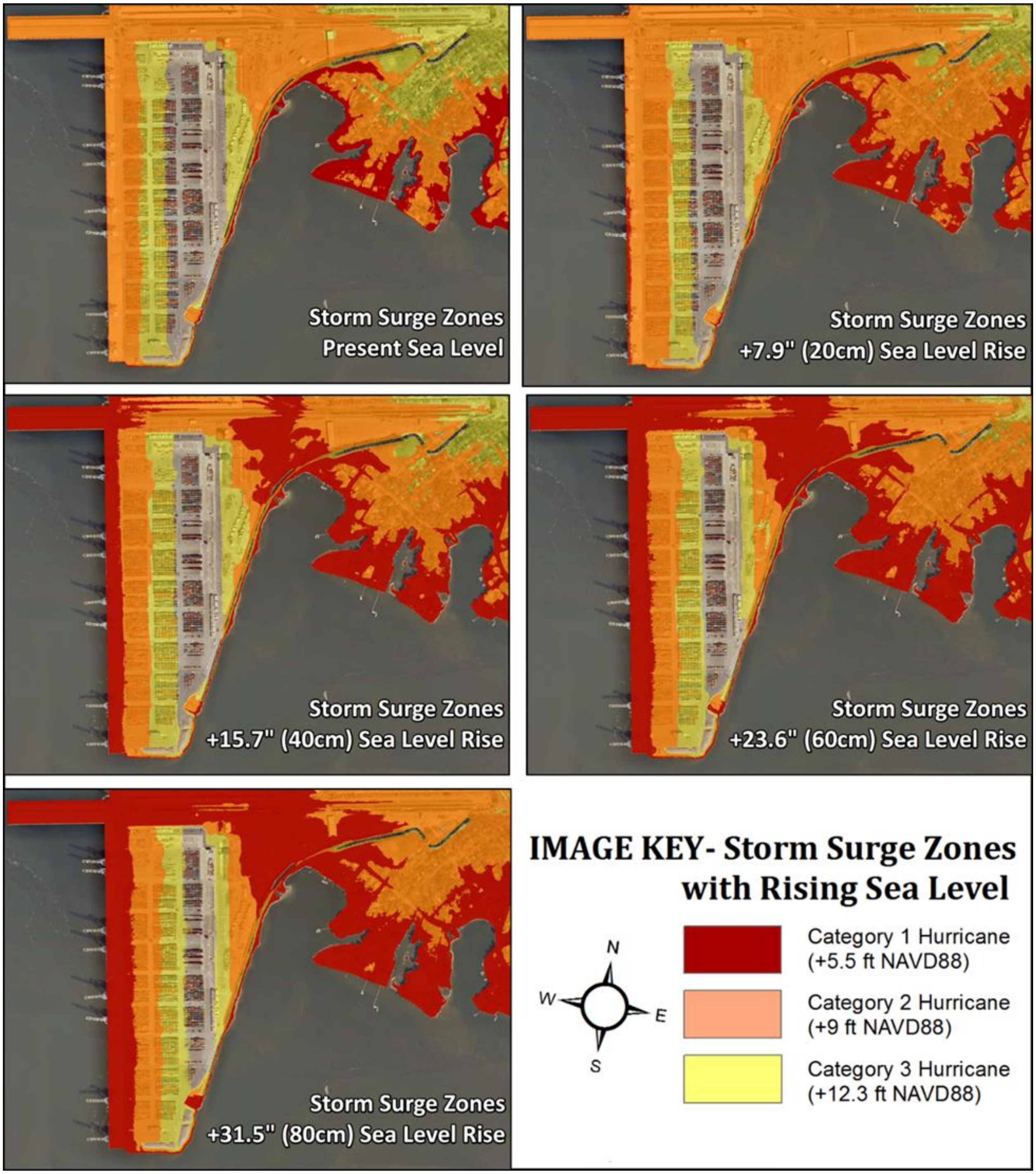


Figure 37. Potential inundation maps Port of Virginia NITS

Present day sea level (today), +7.9" (20cm) RSLR, +15.7" (40cm) ΔRSL, +23.6" (60cm) ΔRSL, and +31.5" (80cm) ΔRSL scenarios.

Tabulated Infrastructure Risk Exposure

Risk exposure summaries were tabulated for each item of critical infrastructure, a redacted example of which is shown in Figure 38. The tables were grouped by infrastructure type and then sorted by elevation to reflect risk exposure from most to least (descending risk as elevation increases.) Color ranges from yellow, light orange, medium orange, orange-red and dark red symbolize the relative risk (from most to least) in direct proportion to the freeboard elevation from the surge water level up to the critical elevation of each element.

Infrastr_Type	Crit_Infrastr_Name	Crit_NAVD88_ft	FB_c1	FB_c2	FB_c3
		9.848	4.348	0.958	-2.342

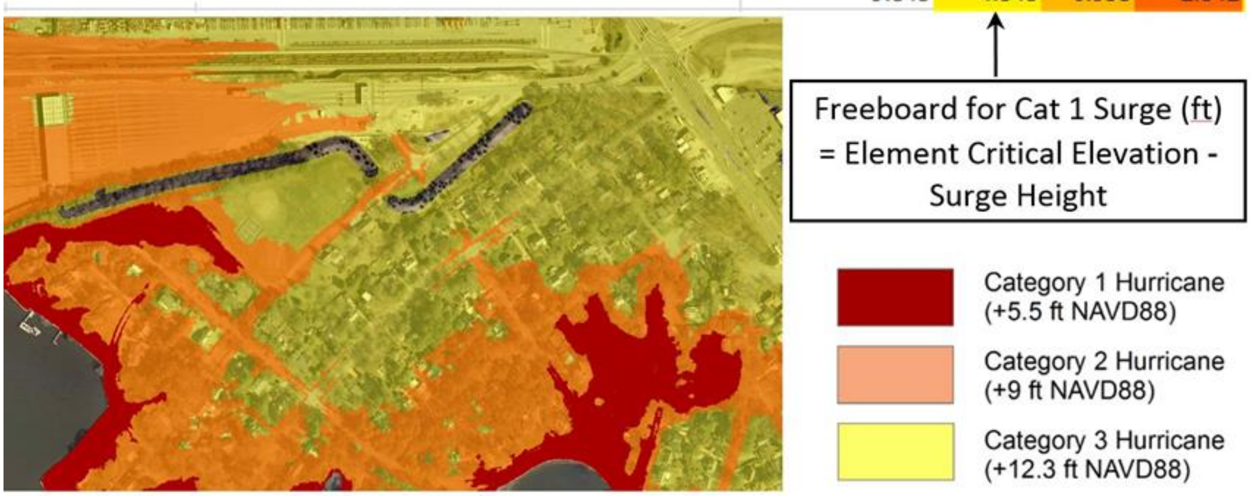


Figure 38. Example of infrastructure risk table usage (redacted due to NDA)

From left to right, columns FB_c1, FB_c2, and FB_c3 list the freeboard elevation in feet between the surge and the critical elevation of the structure. Positive values indicate critical elevation is not submerged and negative values indicate potential inundation depth. The tables also include the infrastructure type, name, and identification number, which is labeled in a series of inundation maps.

Results of the timing of potential exposure of each asset to surge inundation are complicated by uncertainty in future recurrence intervals of storm intensity. Nonetheless, assuming no stark increasing intensity, relative sea level rise will elevate the risk of exposure to storm surges. With time, less surge can cause the same exposure, owing to the rise of static water levels. The first possible year of exposure for each structural element at the terminal was calculated by adding surge values to the NOAA High scenario sea level curve value presented by the US Army Corps of Engineers Sea-Level Change Calculator, focusing on the level of critical elevation that a category 3 storm could impact.

Tidal Flooding

The current and future extent of predicted recurrent "nuisance" tidal flooding in concert with relative sea level rise were also mapped (Figure 39) to allow for identification and analysis of spatial patterns of inundation. Results depicted a pattern of pronounced impacts on adjoining shorelines and residential areas of the Lafayette River, yet demonstrated future tidal influence is confined by structures along the southern and southeast shore of the facility.

At all modeled sea level scenarios, recurrent tidal flooding was predicted to pose minimal risk to terminal infrastructure unless current barriers to tidal waters were removed or destroyed. Hardened structures that serve, increasingly, as levees during extreme tides could become susceptible to undermining and erosion or failure that could flood extensive disconnected low-lying areas. Development of elevation transect profiles for several locations along the interface between the terminal boundary and Lafayette River provided evidence of the critical importance of the elevated natural and fabricated barriers for flood mitigation. The map and accompanying transect profile graphs shown in Figure 40 reveal that these barriers are critically necessary to protect low lying areas of the terminal from ingress of future sea level and nuisance floods.

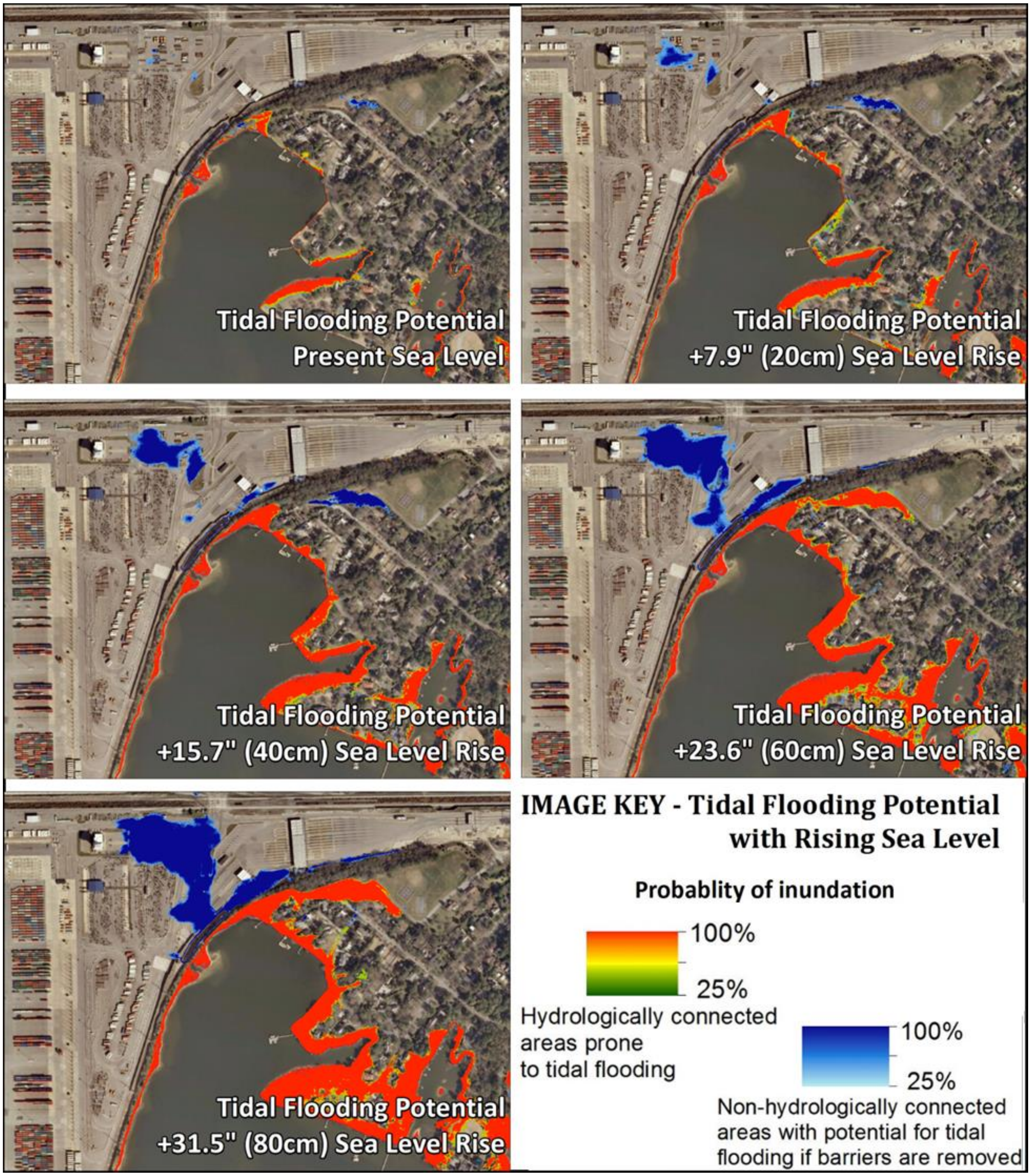


Figure 39. Tidal flooding simulations show the evolution of future tidal flooding from present (baseline) to potential future conditions with no human use modifications

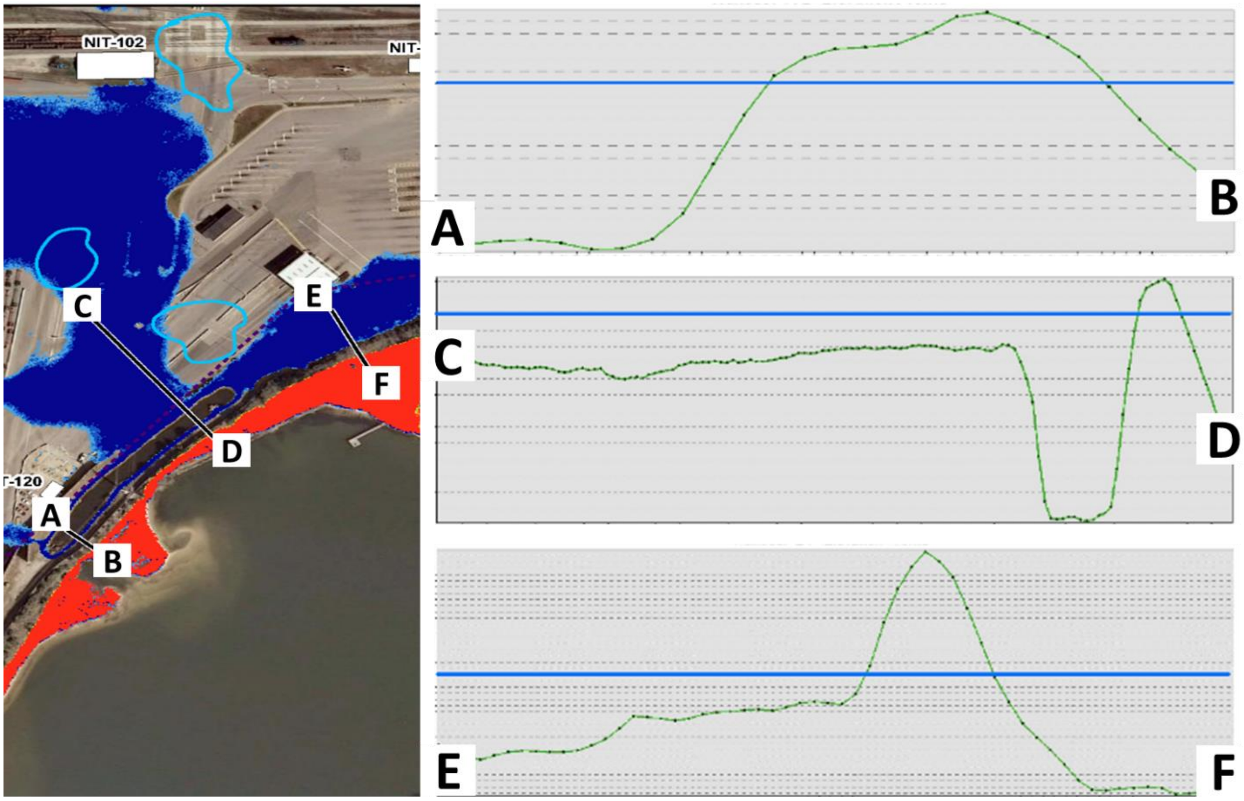


Figure 40. Southeastern NITS modeled with 31.5 inches (80 cm) of sea level rise

Blue gradients represent areas of low elevation prone to flooding, blue circles were identified by terminal staff as areas of concern, red gradient shows high probability of tidal flooding; black map transects labeled A-B, C-D, and E-F and corresponding profile graphs show topographic elevation along the transects.

Implications, Inferences, and Recommended Improvements

Several significant inferences resulted from this risk assessment. Identification of exposure of critical infrastructure is the first of four potential steps towards reducing the potential vulnerability of terminal assets. Second, the susceptibility of infrastructure is also an important ingredient to defining "vulnerability." Third, concise reporting of analysis results also precludes certain nuanced, specific differentiation of exposure of assets. For instance, use of a single critical elevation for a structure element may not capture exposure from submergence of adjoining terrain, which can prohibit access, emergency maintenance, or delay recovery. Cascading failures may also chain in sequences that were not considered in this assessment. Fourth, wave overtopping and velocity components, entrained debris and wind may also cause damage in addition to surge submergence. For the longer time horizon, the relative elevation of ships and cargo may also bear consideration, as extreme tides today become mean tides in the future (*83*).

Strategic Actions to Improve Preparedness. This research recommends that the port operators engage in several strategic data development and research actions to improve preparedness: (1) ensure that vertical elevations of all infrastructure are accurately collected in both horizontal and vertical dimensions, (2) examine cascading failures in a systematic analysis, similar to the risk assessments of SERDP (*63*) and Norfolk Naval Station, (3) investigate subsurface drainage and hydrologic connectivity, revealed here as ambiguous or incompletely determined, and (4) collate data within an enterprise GIS, connecting this system to both planning, operations, and emergency management.

Planning Activities to Improve Preparedness. It is also recommended that the ports facing these risks engage in planning activities which will improve preparedness and extend the utility of this case study: (1) explore wider area vulnerabilities (e.g., transportation corridors adjoining the terminal), to include multi-modal transport linkages, in collaboration with surrounding municipal organizations, (2) incorporate continual monitoring or benchmarking of sea level and flood hazards into ongoing short-term planning, (3) incorporate vulnerabilities into plans for future disaster response and emergency management (including Hazmat waste and spills), (4) engage with regional entities on wider community risk assessment, adaptation, and mitigation projects and participate continually in these efforts, and (5) track the progress and status of other ports regionally, nationally, and internationally as they plan and adapt. This may be accomplished, in part, by the Port engaging with professional organizations, continually reviewing peer-reviewed and government research, and engaging in strategic business planning.

In recent years, significant progress was made by the Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project to coordination communication activities (i.e., workshops, forums, town halls) which shared best practices in hazard mitigation and resilience between federal, state, local, and community organizations (*8*). Extending these efforts to focus on concerns specific to terminals and transportation corridors will be a critical step in improving port resilience.

CHAPTER V

CONCLUSIONS AND FUTURE WORK

CONCLUSIONS

The research presented here demonstrates the considerable utility of geospatial modeling, analysis, and visualization in the development of predictive data and information that provide critical insight into the potential location, extent, and severity of risk and impacts resulting from flooding induced by rising sea level, king tides, and both tropical and non-tropical storm events. At all geographic scales, the ability to provide estimates detailing the cascading impacts of flooding is foundational to the development of response, mitigation, and adaptation plans. This work helps to develop that foundation by providing an array of techniques for several different causes of coastal inundation that provide first order answers to questions, such as, "where and when will it flood? what infrastructure will be impacted? what is the cost of flooding?"

Coastal Virginia Inundation Modeling

At the spatial scale of the coastal zone of the Commonwealth of Virginia, spatial modeling and analysis using the best available water level, land elevation, and infrastructure data were successfully employed to answer *Research Question 1*, "What will be the extent of permanent flooding due to relative sea level rise for all coastal zone planning districts within the Commonwealth of Virginia in the years 2040, 2060, and 2080?" Affirmation of the hypothesis of non-linear expansion of flooding and related infrastructure impacts was supported by both mapping and tabulation. The maps and related digital data developed by this research promote sub-regional comparison and provide community organizations and municipalities a spatial product for first-order risk assessment and planning. Model results and supporting graphics clearly illustrate that the Hampton Roads, Accomack-Northampton, and Middle Peninsula planning districts will be the most severely and disproportionally impacted and that impacts are expected to increase approaching the end of the 21st century. In addition, recurrent tidal flooding will have impacts attributed to frequency and duration of flooding, particularly for wetlands and roadway not previously affected by increasingly higher tides and, especially, salinity.

Broad studies such as this should be used to inform and assist with the prioritization of more detailed, fine- scale analyses. The data developed by this research provide a starting point for localized impacts analyses that allow for the inclusion of comprehensive and highly specific asset inventories, which are unique to each study area. Highly developed asset inventories, combined with sea level and tidal flooding modeling, are necessary for identifying and quantifying the level of risk and potential cost of response.

An unanticipated result is that of the broad utilization of the results of this research and high demand by others for access to maps and data produced herein. Usage statistics for web maps, applications, and data made available in ArcGIS Online are tracked and available to the content owner. Review of these statistics for the web map and data developed in this study shows a high number of content requests. For example, during the 12-month period ending February 17, 2023, inundation data layers for the year 2040 were requested a total of 2,687,463 times with an average of approximately 7,363 requests per day (Figure 41). In the case of web maps and data, a “request” can come in the form of users viewing data in the original web mapping application developed in this study or from these data layers being embedded and viewed in other users’ applications and web maps.

The large number of content requests during this period provides evidence supporting broad utilization, adoption, and integration of these data into work being done by others. The maps and related digital data developed by this research can, and hopefully will be used to, promote sub-regional comparisons and provide community organizations and municipalities a reliable spatial product for first-order risk assessment and planning.

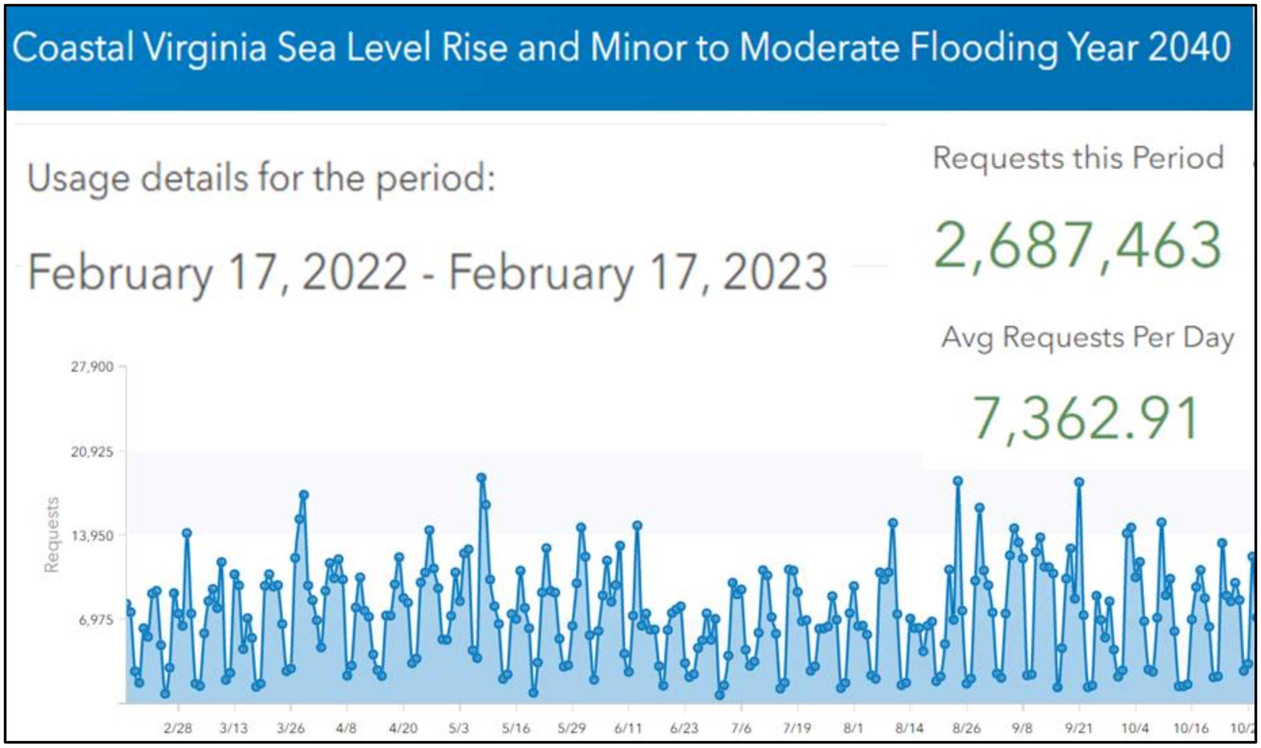


Figure 41. Graph of web views during the period of 2/17/22 – 2/17/23 of GIS inundation data layers for the year 2040 developed in this research

Hampton Roads Simulated Hurricane with ΔRSL

Geospatial modeling methods to examine the impacts, at a regional scale, of a theoretical hurricane making landfall at and travelling directly over southeastern Virginia, provided a first-look assessment of the increased severity of loss that hurricanes pose with sea level rise. Discovery that a hurricane like Florence, that made landfall at Wilmington, North Carolina in 2018, striking directly at the Hampton Roads, Virginia region would result in over $20 billion in combined wind and flood losses was significant in that it would rank as one of the ten costliest storms in history for the continental United States. Even more striking were the results discovered when addressing *Research Question 2*, "Under near-future increased sea level scenarios, what physical damages and related first-order socioeconomic costs will result from a Hurricane Florence-like Category 1 storm making landfall near Virginia Beach and travelling westward through Hampton Roads?" While it was hypothesized that modeling the same storm with increased sea level would produce large increases in damages and associated economic costs, it was not expected that sea level rise of 1.5 feet (0.46 m) expected by 2050, and 3 feet (0.91 m) expected before 2100, would result in 50% and 100% increases in losses totaling $30 billion and $40 billion, respectively. These values were calculated in present-day $USD without inflation and will likely be higher in future dollars. With regional building stock inventory and wind field parameters from this storm held constant, the model predicted, as hypothesized, a large increase of approximately $10 billion in storm surge damages for each additional +1.5 ft (.46 m) ΔRSL. Valuating risks at the region-scale is a must for ensuring that sufficient resources are allocated for mitigation, adaptation, and recovery efforts. Moreover, "big picture" analyses of this type often provide key insight into smaller-scale areas of vulnerability.

Sub-regional variation in the model results was also noteworthy. Low-lying, densely populated, and highly urbanized localities such as Virginia Beach, Norfolk, Newport News, Chesapeake, and Hampton were predicted to incur the highest damages, yet not always the highest percentage of damage of their parcel and building stock inventory. Owing to these sub-regional variations, modeling of potential physical damages and tightly coupled economic analysis and forecasting are invaluable for developing a clear picture of the risks posed to individual municipalities. The results of regional modeling should be used to target smaller geographic regions, such as watersheds or neighborhoods, which exhibit the highest vulnerability to the impacts of hurricane surge and flooding for further analysis. The coupling of Hazus damage estimates with other information, such as real estate records, transportation features, utilities, and economic and business data can be invaluable for highlighting which areas and potentially critical potential failures must be addressed before a major hurricane directly strikes southeastern Virginia.

Port of Virginia Hurricane Surge Impacts with ΔRSL

Modeling of multiple types of inundation (i.e., sea level rise, storm surge, tidal flooding) and related impacts on critical infrastructure at the scale of a single Port of Virginia terminal facility provided a template for other highly focused and localized analyses. By itemizing the vulnerability of individual elements of infrastructure of critical importance to the Port, geospatial modeling effectively answered *Research Question 3*, "How will sea level rise, coupled with hurricane storm surge, impact critical marine infrastructure of a single Port of Virginia container terminal facility?" The revelation that even moderate storm surges may impair future operations with as little as +15.7 inches (+20 cm) sea level rise aligns with the hypothesis. Furthermore, the finding that nearly all terminal infrastructure will be vulnerable to flooding by storm surge as sea level approaches +31.5 inches (+80cm) above present day underscores the importance of maintaining a GIS database inventory of assets and flood protection infrastructure at the NITS terminal and other similar facilities. A digital inventory of these important features will allow for future rapid scenario modeling and will provide valuable information for Port officials to employ when contemplating major capital infrastructure investments.

An important general conclusion is that marine terminal facilities should diligently plan for increased relative sea level and attendant increasing exposure to hurricane storm surges. Although there is marginal increased exposure of critical assets for smaller storm surges (using Saffir-Simpson category 1 and 2 as proxies) in the near-term, even moderate storm surges show potential to impact critical structures once relative sea level reaches +15.7-23.6" (20-60cm). Given that those levels of mean sea level could be attained as soon as the mid-to-late 2030s, prudence would dictate that major capital infrastructure investments ought to appropriately consider these findings.

High exposure of infrastructure is revealed by major hurricane surges (category 3 Saffir-Simpson scale as surrogate), and these lower probability events could nonetheless affect facilities sooner. As sea level rises, nearly all the infrastructure critical elevation thresholds become vulnerable to a worst-case category 3 surge with +31.5" (80cm) of relative sea level rise. Current precautionary (intermediate-high to extreme) sea level curves project this amount of rise could arise locally between the mid-2050s to early 2070s.

The approach used in this study does not evaluate future climate change insofar as it affects storminess, storm tracks and hurricane frequency. In addition, extreme rainfall and changing climate affecting non-tropical storms and storm water flooding are not evaluated. Nonetheless, a range of implications are inferred, and potential improvements undertaken to inform planning and operations. This preliminary assessment provides site- and element-specific data in map and tabular form. These data can be further leveraged if the Port were to develop a GIS database and integrate assets and vulnerabilities into enterprise planning and operations, along with regional observations (Sewells Point tide gauge sea level trends) and regional data repositories (university, federal agencies and city and regional government.)

In addition to storm surge and disaster preparedness, tidal flooding poses a creeping threat to this marine terminal through the nearby Lafayette River and potential shift of the mean higher high water tidal frame. The research's results point to undetermined subsurface hydro-connectivity between ponding on areas of the cargo tarmac and roads, the potential for "nuisance" flooding today to increase extent and frequency with moderate sea level rise, and external considerations of street-level flooding to transportation corridors surrounding this marine terminal.

Understanding and Reducing Uncertainty

It is important to note that uncertainty in modeling of flooding impacts increases as forecasts extend further into the future. This research considered landforms, infrastructure, populations, and other related features as they exist in the present day and did not speculate on any future change. However, we know that a multitude of changes will occur including, but not limited to, geomorphological change of landforms (e.g., shoreline migration, vertical land motion), removal or addition of infrastructure, population redistribution, variation in atmospheric conditions (e.g., increased intensity, frequency, duration of storms and rainfall), and changes in governing rules, laws, and codes. Combining inundation modeling with modeling of one or more of these other systems in a digital twin representation of a study area could be effective for reducing the potential error and uncertainty that is inherent in future risk forecasting.

Summary

There are two overarching and scale-independent conclusions of this research: (1) that geospatial modeling methods and analytical tools are critical and necessary for understanding the extent of flooding and quantifying the potential impacts resulting from sea level rise and future storm events, and (2) that the Commonwealth, regional government officials and planners, marine terminal facility operators, and all residents of Virginia's coastal zone should diligently plan for recurrent flooding and elevated storm surge risk as relative sea level increases. Examination of the problem of coastal flooding at multiple spatial and temporal scales provides the foundational data necessary to inform, guide, and prioritize future research, mitigation, and adaptation efforts.

FUTURE WORK

The methods and body of work developed in this research provide ample foundation for enhancement, refinement, and follow-on research. Collectively, these "next steps" are aimed at improving the accuracy, reliability, and utility of resulting data and information for their use in informing resilience planning and flood mitigation and adaptation. This work may be extended to quantify the regional impacts of ΔRSL in smaller geographic areas. Areas of potential critical impact (e.g., Ports, Department of Defense facilities, historical sites, high-value economic districts) should be identified for high-resolution development of asset inventories and focused analyses of physical and economic impacts of ΔRSL.

Several modes of extension of the inundation data developed for the Commonwealth are already underway or planned for the near future including the creation of dynamic web dashboards, development of enhanced 3-dimensional visualizations, and coupling of inundation data with socioeconomic data for human impacts analysis. Enhancements and new avenues of research provided below could increase resilience to coastal hazards associated with sea level rise.

Combined Flooding

Only a few very recent studies have quantitatively verified the increases in extreme rainfall, corroborating global and regional climate models. Few spatial risk assessments have been conducted that identify these risks and impacts. Extensive regional rainfall studies and climatology could inform stormwater engineering and drainage planning as well as coupling dynamic rainfall interactions with tidal flooding and sea level rise.

As flooding increases in extent, frequency, and duration with sea level rise, rainfall runoff co-occurring with storm and tidal flooding will exacerbate flood extent, depth, and impacts. Multiple recent studies also point to increasingly extreme rainfall events, evidenced in rainfall intensity and shorter return periods and affirming predicted regional climate change (*88; 89*). Thus, combined flooding bears further research and study, as rainfall hydrology is likely to co-occur and compound storm and tidal flooding. In order to meet the need for an expedited assessment, this study was unable to include the rapidly developing scientific understanding of combined flooding and the interaction of extreme rainfall and increasing tidal water levels.

Dynamic Web Dashboards

A subset of the inundation data for years 2040, 2060, and 2080 developed by this work was linked to property tax database records for the City of Norfolk. This linkage allows for the calculation of the value of property at risk from the three modes of flooding (SLR, minor, moderate) modeled for each year. Creation of a dynamic web mapping dashboard featuring these newly linked property risk data allows for a user of the application to pan and zoom to any location in Norfolk and be instantly presented with a summary of the potential losses and values by property type. Figure 42 provides a static depiction of the dynamic prototype dashboard for Norfolk. Provided that property tax data is made available for all coastal Virginia planning districts, this dashboard prototype could easily be extended and made available for the entire study area.

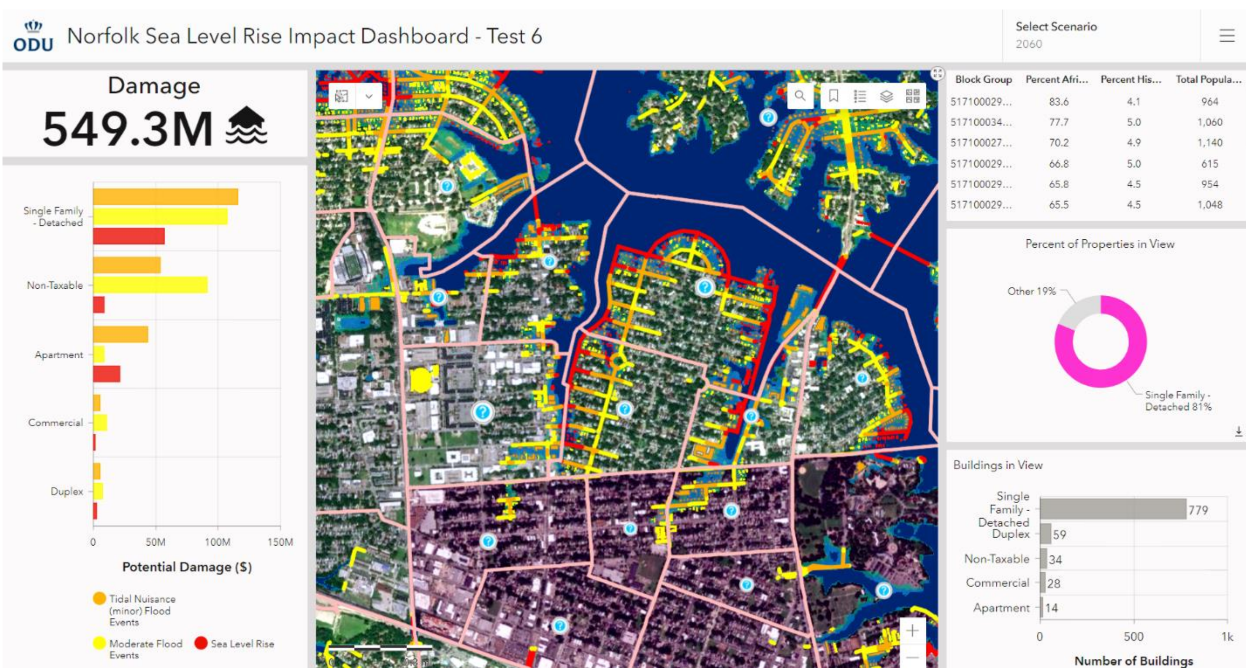


Figure 42. Example dynamic web mapping dashboard depicting potential $USD losses to property for any area displayed in the window or selected by the user https://www.arcgis.com/apps/dashboards/ee084a2186ac471294b1ba03f0c5ea68

3-dimensional Visualization

The same data are also being used to develop enhanced 3-d visualizations that show alternate views of future inundation that may potentially illuminate new potential risks and/or evoke stronger responses from viewers. In their recurring "Blue Line" project, Allen and Hutton endeavored to identify the appealing components of various types of visualizations and determine which images increase risk perceptions, contribute to the selection of adaptation or mitigation strategies, and elicit protective actions (*90*). They discovered that, although different techniques (i.e., maps, photos) possessed unique advantages, a combination of impacts visualizations was preferred for the realism conveyed to the viewer. Accordingly, lidar surface data for Norfolk are being used to explore techniques for to creating more realistic inundation visualizations. A coarse 3-d model of the city's buildings was constructed, linked to this work's inundation data layers, and embedded in an online 3-d web mapping application. The web application allows users to navigate anywhere in the city and visualize potential inundation from any perspective (Figure 43). Visualizations such as these may be further enhanced by improving the photorealism of the inundated area to included building, monuments, and other landmarks that are easily identifiable to citizens of the region. Towards this end, uncrewed aerial vehicles (UAV), commonly known as drones, have been used to systematically capture imagery of well-known structures for the purpose of employing photogrammetric techniques to construct 3-d facsimiles that can be embedded in web scenes and other visualizations. Figure 44 provides an example of a 3-d model of the Chrysler Museum of Art in Norfolk that has been constructed using several hundred aerial photos recorded by a UAV.

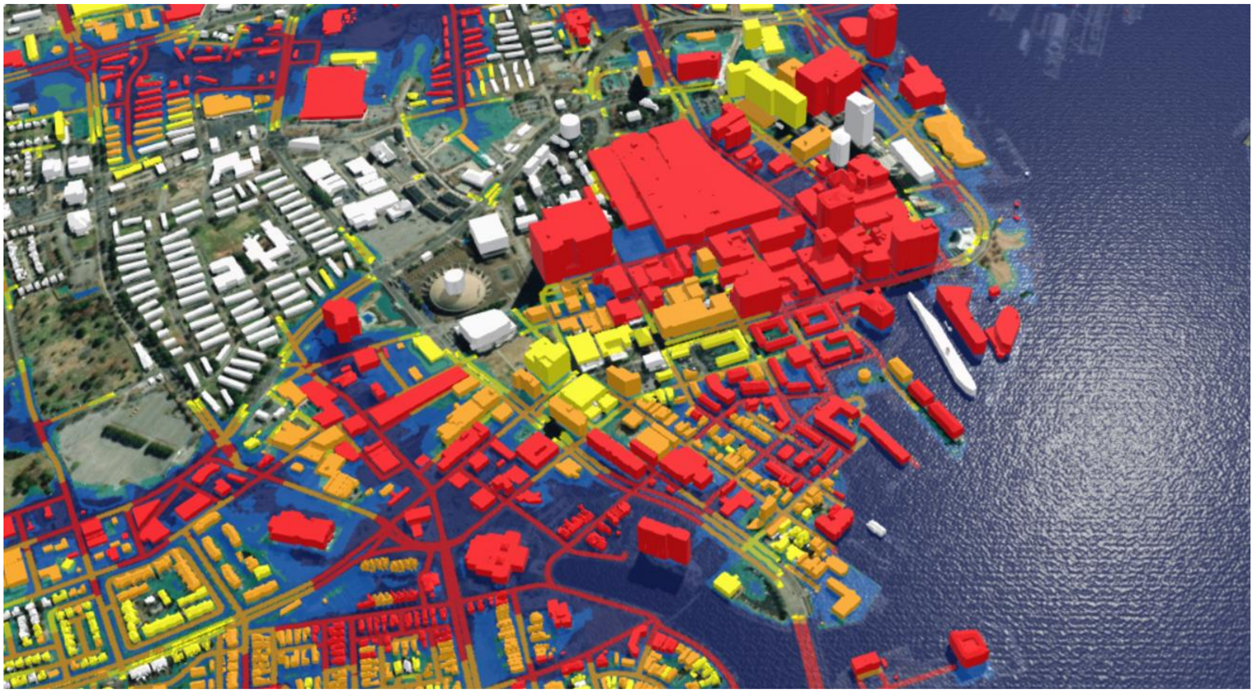


Figure 43. 3d web scene image showing inundation potential for downtown Norfolk

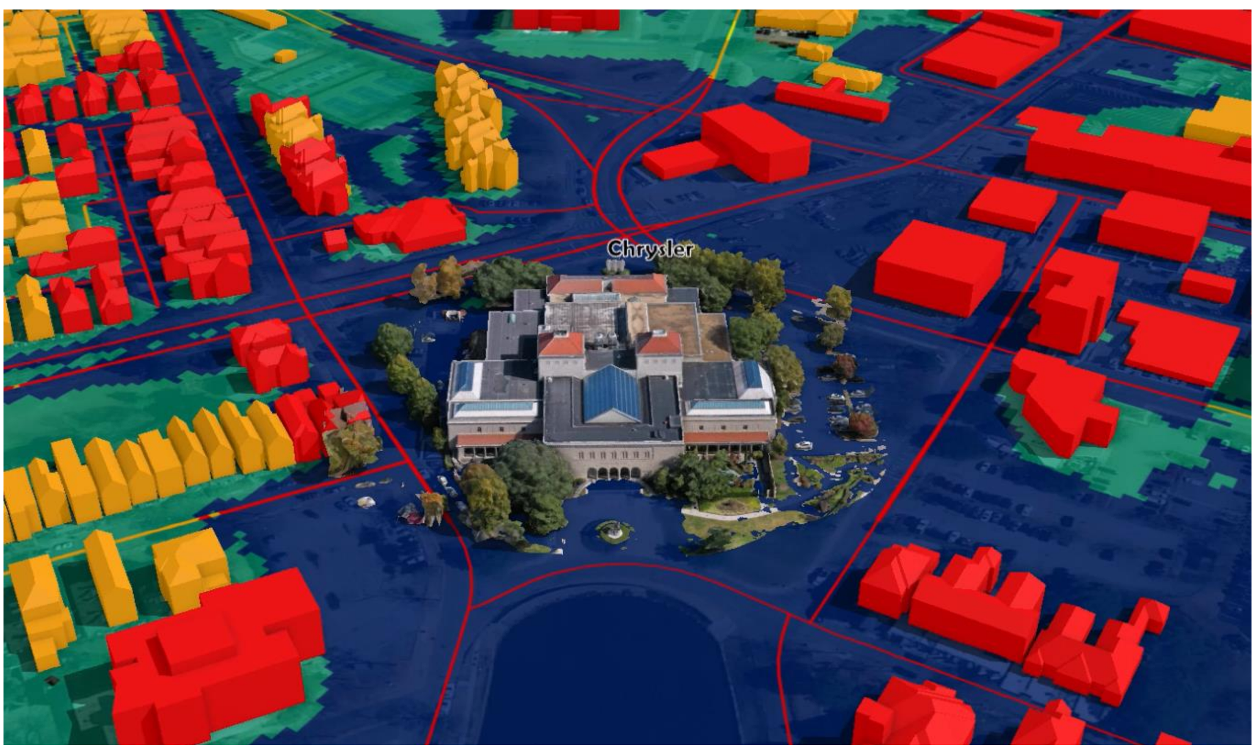


Figure 44. 3d model of the Chrysler Museum of Art embedded with Norfolk flooding data

Data Overlay, Comparison, and Combination

Beyond the development of enhanced visualizations, the data developed in this work may be analyzed in conjunction and comparison with a host of other information, such as real estate records, transportation features, utilities, socioeconomic and health data, facility/campus infrastructure, and business data to identify problems and potentially catastrophic failures in each of these areas. Examination of the impacts of flood levels predicted by this work on socioeconomically disadvantaged populations has already begun. Partnership with public television station WHRO on a web expose entitled "At A Crossroads" resulted in development of a dynamic online map that displays this work's future flooding data superimposed on historically redlined areas of high socioeconomic vulnerability (Figure 45) (*91*). Redlining refers to historical discriminatory lending practices in communities that were deemed undesirable.

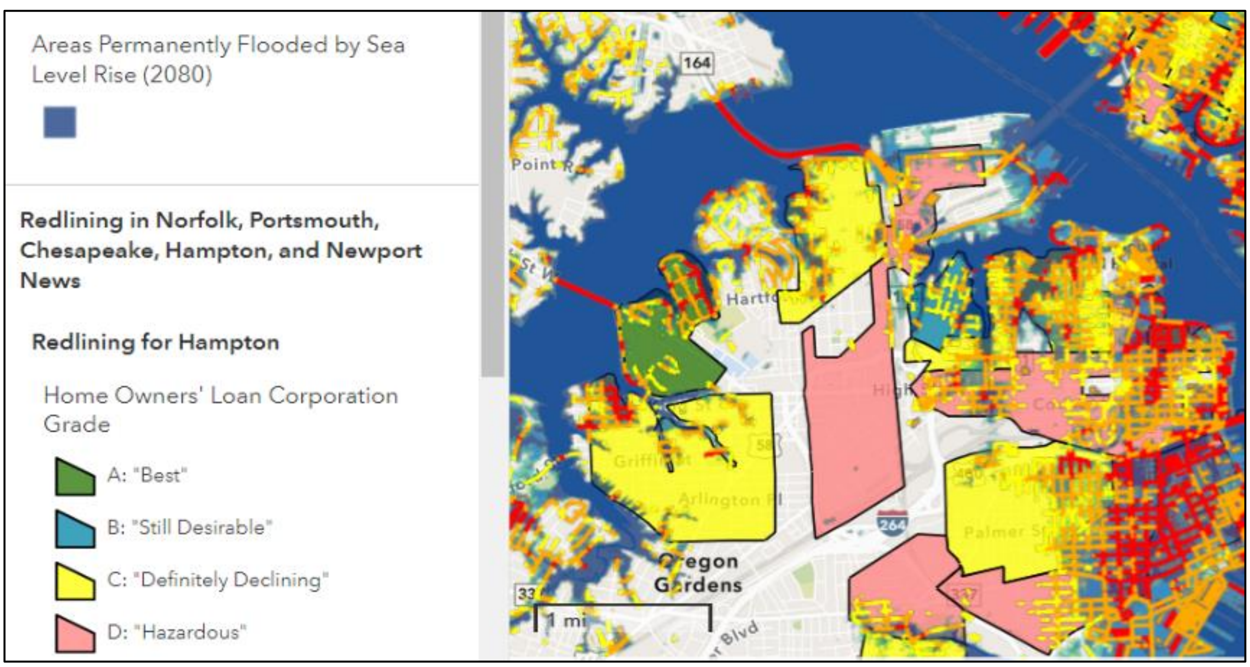


Figure 45. Example Web map developed for WHRO "At A Crossroads"

In addition to the numerous avenues of research flowing directly from the inundation modeling performed in this research, there are multiple related areas of investigation that would improve spatial flood modeling and/or provide alternate views of flood-related risk. Chief among these is the development of fine-scale elevation data and improvement of digital elevation models found at the core of all inundation modeling. Building on prior research by Allen and Howard, work has begun to conduct fine-scale hydrocorrection on study area elevation models and to refine and improve the methods for doing so (*49*).

Probabilistic Flood Modeling

Also of great interest is the further development of probabilistic flood modeling techniques used in Port of Virginia inundation modeling. As uncertainty in inundation modeling is largely a function of the accuracy of elevation data, this approach examines the fundamental vertical accuracy of lidar-derived DEMs for a study area, applies Monte Carlo simulation techniques to pseudo-randomly adjust surface elevations within the accuracy range, and iteratively models inundation for prescribed flood scenarios. For each model run, elevation adjustments will naturally cause the inundation zone to fluctuate either landward or seaward. The cumulative confidence of all inundation simulations (potentially hundreds) may then be calculated by summing the number of runs resulting in each cell being inundated. Whereas, even the best single-run hydrodynamic flood models do not account for elevation uncertainty, application of Monte Carlo analysis of inundation variability using error modeling provides greater fidelity of inundation zones while highlighting areas of moderate uncertainty.

Hypsometric Tipping Points

Finally, developing methods for utilizing study area hypsometry, area-elevation relationship, to identify elevation-based “tipping” points at which the impacts of sea level rise suddenly and dramatically increase is of keen interest (*92*). Techniques for evaluation of flood risk using hypsographs have been explored in the author's prior work with Allen and Hutt that compared U.S. east coast port vulnerability to sea level rise (*93*). Figure 46 (adapted) provides an example of how hypsometric data may be used to illuminate severity and timing of flooding from future sea level rise. Extending this work to identify critical points of inflection and large areas of low slope along these curves could provide key insight into the timing of widespread flooding for any given study area. Furthermore, plotting the vertical location of critical infrastructure and assets on a study area hyspograph may likewise provide a best approximation of the timing of significant, recurrent, or permanent flooding. The certainty and potential severity of the impacts of sea level rise on the natural environment, developed infrastructure, socioeconomic systems, and human health, provide ample support for further exploration of each of these techniques. If these research efforts undertaken individually or cumulatively can provide information and insight that mitigates or alleviates potential loss of natural resource, property, economy, and human life, then they are worthy of continued investment of time and resource.

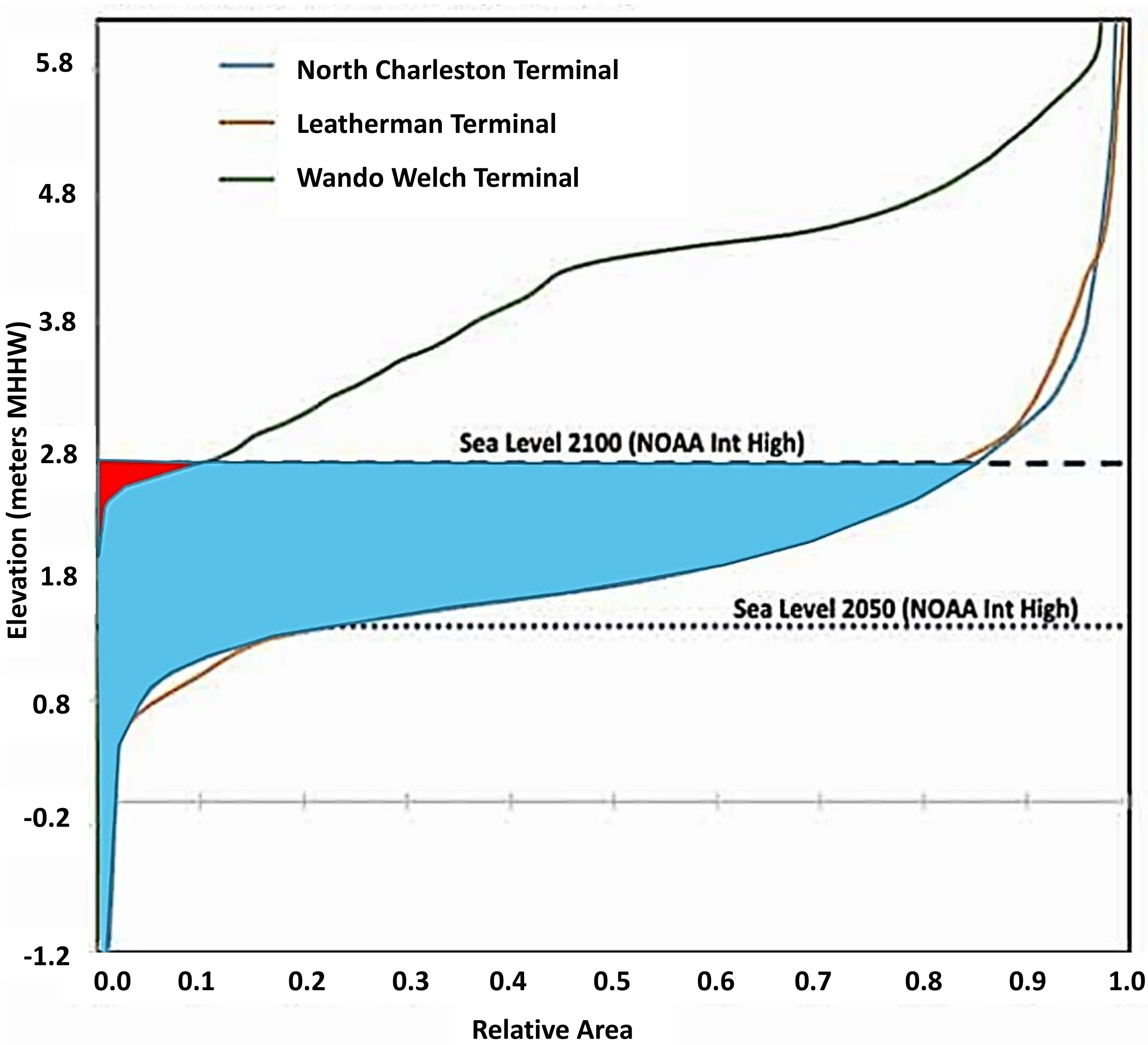


Figure 46. Example hypsograph depicting hypsometry of South Carolina port terminals to levels of future projected sea level rise

Blue shaded area represents relative area of North Charleston terminal, nearly 85%, impacted by sea level rise at the year 2100. Red shaded area indicates relative areas of Wando Welch terminal, less than 10%, impacted by sea level rise at the year 2100. Adapted from Allen, McLeod, Hutt. (*93*)

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VITA

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EDUCATION

Ph.D. candidate, Old Dominion University, Norfolk, VA	Expected May 2023
M.S. Oceanography, Old Dominion University, Norfolk, VA	December 2009
B.S. Geography, Old Dominion University, Norfolk, VA	December 2004
B.S. Business, Virginia Commonwealth University, Richmond, VA	August 1993

PROFESSIONAL EXPERIENCE

2004- Present	Director, Center for Geospatial Science, Education & Analytics, ODU
2019- Present	Senior Fellow, Commonwealth Ctr for Recurrent Flooding Resiliency, ODU
2010- Present	Adjunct Faculty, Department of Political Science and Geography, ODU
2016- 2018	Adjunct Faculty, GIS for Public Health, MPH Program, EVMS, Norfolk, VA
2005- 2015	Consulting Geoscientist, Continental Shelf Associates, Stuart, FL
2005- 2015	Adjunct Faculty and GIS Program Coordinator, TCC, Virginia Beach, VA

COURSES TAUGHT

Geospatial Field Techniques, Geographic Information Systems, Advanced GIS, Cartography, Understanding Geographic Data, 3-D GIS Analysis, Remote Sensing, Maps & Geographic Information, Geospatial Technology and Society, Modeling & GIS for Public Health

SELECTED PUBLICATIONS

McLeod, G., Allen, T., Hutt, S., Solano, M., Steinhilber, E., Burdick, K. Future Sea Level and Recurrent Flooding Risk for Coastal Virginia. Commonwealth Center for Recurrent Flooding Resiliency (CCRFR) Report #11. February 2020. 43pp.

McLeod, G., McNab, R., Hutt, S. Modeling of the Potential Impacts of a Hurricane Striking Hampton Roads with Increased Sea Level. Commonwealth Center for Recurrent Flooding Resiliency (CCRFR) Report #10. June 2019. 19pp.

McLeod, G., T. Allen, J. Behr. Geospatial Risk Assessment of Marine Terminal Infrastructure to Storm Surge Inundation and Sea Level Rise. Journal of the Transportation Research Record. https://doi.org/10.1177/0361198118774234. 1-11. Online publication May 11, 2018

McLeod, G., Allen, T., Daigneau, J., Collins, J., Swan, N. High Resolution Dune Complex Mapping for the Monitoring of Coastal Landform Change, First Landing State Park, Virginia. Virginia Journal of Science, 58(1): 17-27, 2007.

AWARDS

2019	NASA Space Grant Graduate Fellowship
2018	Special Achievement in GIS (SAG) Esri International User Conference
2012	Best Data Integration – Map Gallery (2nd) Esri International User Conference