Impacts of coastal flooding on watersheds of Hampton Roads, VA

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Abstract (academic)

Coastal communities face threats of flooding associated with episodic storm events and high tides that are increasing in severity and frequency due to climate change and sea level rise (SLR). The Mid-Atlantic U.S. is experiencing SLR at rates faster than the global average, especially in Hampton Roads, Virginia where the rate of SLR is accelerating due to land subsidence. Adaptation plans for coastal flooding are mostly made at the municipality level, ignoring the propagation of water across its administrative boundaries. Impact assessment at the watershed scale identifies areas where municipalities will need to collaborate to mitigate the flood impact. The main purpose of this project was to evaluate the impact of flooding among watersheds in Hampton Roads and identify those most at risk that overlap one or more municipal boundary. Additionally, this research assessed the impact on land use/cover and population throughout the Hampton Roads region and within a case study watershed. To meet these objectives, we used U.S. Army Corps of Engineers 50-year floodplain and NOAA intermediate SLR scenarios for 2030, 2060, and 2090 to calculate the percent land area inundated for each watershed in Hampton Roads. Further, we assessed the flood impact on populations and specific land use/covers throughout the region for each SLR scenario, as well as within the Elizabeth River watershed. Key findings show that five watersheds will see a greater increase in inundated area than the surrounding watersheds, with two that overlap multiple municipalities. The anticipated land use impacts indicate significant inundation of land occupied by military, followed by commercial, industrial, and wetland covers both in Hampton Roads and within the Elizabeth River watershed. These findings not only highlight the need for more synchronized collaboration on adaptation between municipalities in Hampton Roads, but also provide a framework for the impact assessments in similar settings globally.

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General Audience Abstract

Coastal communities face numerous threats of flooding due to storm events and high tides. These events are becoming more frequent due to climate change and sea level rise (SLR). The Mid-Atlantic U.S. is experiencing SLR at rates faster than the global average, especially in Hampton Roads, Virginia where the rate of SLR is accelerating due to sinking land. Water movement does not recognize administrative boundaries but rather reflects physical features of the land. At the same time most plans to combat rising water levels are often made within administrative boundaries. The main objective of this research is to evaluate the flood impacts at the watershed scale and identify areas where localities will need to collaborate to reduce flood impact. This research further explores answers the following questions: 1.)Which watersheds in Hampton Roads are most prone to flooding?; and 2.) How many people will be impacted by flooding, and what kinds of land uses will be impacted? To answer these questions, we used floodplain data and SLR scenarios for 2030, 2060, and 2090 to determine land area inundated for each watershed in Hampton Roads. Further, we summarized population and land use impacts within the floodplain for the entire region, as well as within a case study of the Elizabeth River watershed in Norfolk and Portsmouth. Key findings include five watersheds that will see a greater increase in inundated area with SLR than surrounding watersheds, two of which contain multiple municipalities. Finally, we identified significant impacts for military, commercial, industrial, and wetland land covers both in Hampton Roads and within the Elizabeth River watershed.

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Preface/ Attribution

Dr. Anamaria Bukvic was my committee chair and academic advisor for my thesis. She guided me through the research process, helping me through the development of research objectives and methodology. Her experience in the field of coastal resilience and adaption was important for this research.

Dr. Jennifer Irish provided the USACE flood hazard area data and sea level rise interpolations used to interpolate the water surface elevations as well as the background information regarding the models used by the USACE.

Dr. Daniel McLaughlin was a member of my thesis committee. His background in watershed hydrology and water resource management provided a key perspective vital during the formation of research objectives and methodology.

Dr. Yang Shao was a member of my thesis committee. His background in geospatial information technology was vital in the formulation of my geospatial analysis methodology. Primarily, He aided and guidance for the interpolation of the 2% AEP Hazard Area water surface elevations.

Each of my committee members brought a unique perspective, feedback, and encouragement throughout this research.

1. Introduction

Coastal environments are unequivocally changing and evolving mostly in response to human activities and climate change (Bukvic et al., 2020). Living near the water comes with the risk of flooding, especially in coastal areas that encounter many different types of inundation. In addition to precipitation-driven flooding, coastal areas experience tidal flooding that occurs during tidal cycles (Atkinson et al., 2013) and episodic storm surges (Wright & Nichols, 2019), both of which are exacerbated by sea level rise (SLR). The flooding from these different sources can occur simultaneously and lead to catastrophic flooding. For example, tropical cyclones can have devastating impacts on coastal areas when a storm surge occurs during a high tide or heavy rainfall causes flash and surface flooding. These flood events are projected to increase in frequency and severity over time due to climate change (USGCRP, 2018). The National Climate Assessment (USGCRP, 2018) identifies the Atlantic and Gulf coasts as the most at risk to climate change, with northeast and southeast regions having the highest projected increases in precipitation. Additionally, both the chronic and episodic flooding will increase with SLR that has been observed globally and is projected to continue in the future (IPCC, 2014; Parris et al., 2012). Coastal flooding and resulting socio-environmental and economic impacts on coastal communities will likely challenge the livability and resilience of coastal societies for decades to come. Hampton Roads, a region of 17 municipalities in the south-east region of Virginia along the Chesapeake Bay and Atlantic coast, is a coastal area particularly exposed to flooding.

Sea Level Rise (SLR)

According to the National Oceanic and Atmospheric Administration (NOAA), the mean sea level in 2018 was 8.6 centimeters above the levels observed in 1993 (Lindsey, 2019). Compared to 50 years ago, “nuisance flooding”, otherwise known as a high tide flooding (NOAA, 2018), occurs 300-900% more frequently (Lindsey 2019). According to a literature review, NOAA states there is a high confidence that the sea level will increase between 20 centimeters and 2 meters by 2100 (Lindsey 2019). The IPCC projections for 2100 (RCP8.5) narrows this range to 0.5-0.98 meters at a rate of 8 to 16 millimeters per year (IPCC, 2014). According to the IPCC AR5 report (2014), 70% of coastlines will experience some sort of SLR mostly due to thermal expansion and melting glaciers driven by climate change. Based on the projections, even if the greenhouse gas emissions were significantly reduced, increased sea levels are going to impact coastal communities (USGCRP, 2018).

While SLR is a global phenomenon, it is experienced differently in different parts of the world. In the Mid-Atlantic region, the rate of SLR is increasing beyond the global average (NOAA, 2012; Atkinson et al., 2013), largely due to land subsidence from sediment compaction, glacial isostatic rebound, and groundwater extraction (Parris et al., 2012; Engelhart et al., 2011; Atkinson et al., 2013). Other explanations include changes in ocean currents like the Gulf Stream in the North Atlantic (Parris et al., 2012). When the flow of the current is disrupted or weakened, water is displaced from the North Atlantic Gyre and causes the sea level to rise along the Atlantic coast. The Gulf Stream can be disrupted by tropical storm systems and climatic weakening (Parris et al., 2012; Atkinson et al., 2013; Ezer 2018). Flooding is projected to worsen over time in the Chesapeake Bay region. One study found that even the most conservative estimate of SLR would lead to an increase of flooding by a factor of four in Annapolis, Maryland, while a higher SLR scenario meant that the average monthly storm tide would surpass flooding levels by 2080 (Kriebel et al., 2015).The Sewell's Point tidal gauge in Norfolk, VA, a city within Hampton Roads, has recorded SLR at a rate of 45.72 centimeters per century since it started documenting tidal levels in 1928, but this rate is accelerating due to climatic change and Gulf Stream weakening (Atkinson et al., 2013; Ezer, 2018). This observation is supported by Habete and Ferreira's (2017) study that predicted the increase in rate of SLR in Virginia anywhere between 13.1-71%. Coastal Virginia is particularly at risk due to low-lying topography (Kleinosky et al., 2007), especially in urban centers (Liu et al., 2016). Many areas of already low elevation are sinking further, due to significant land subsidence (Atkinson et al., 2013). Subsiding land combined with SLR means an increased risk of coastal flooding, particularly in large urban settings. Indeed, Ezer (2018) noted that in the Hampton Roads region, seven out of the nine years on record with the highest flood frequency have occurred since 1998 and with longer duration than previously recorded, lasting multiple tidal cycles compared to just a few hours. For example, the number of hours where the streets within "The Hague" area of Norfolk are inundated has been increasing, with hours of street flooding reaching 300 in 2009 (Atkinson et al., 2013). This increase in flooding is coming from more than just the sea; during heavy precipitation events, surface flooding from overloaded storm drainage systems is fairly common (Bukvic & Harrald, 2019). For these reasons, there is a need to predict and adapt to flooding and its impacts in coastal Virginia.

Impacts of Flooding. Flooding can have detrimental impacts on the affected community, whether it occurs on a recurrent or episodic basis. The rising sea level will exacerbate existing flood hazards, thus increasing its direct and indirect impacts on the coastal built environments. For example, multiple studies have examined the impact of SLR- induced flooding on critical facilities, which provide vital public services to the community and serve as a necessary resource during an emergency situation (Kleinosky et al., 2007; Considine et al., 2017). Examples of critical facilities include schools, hospitals, emergency rescue squads, libraries, and fire and police stations. According to Kleinosky et al. (2007), a storm surge caused by a category one hurricane at 90 cm of SLR will increase the impact on critical facilities by 62.52% in the Hampton Roads region. Considine et al. (2017) analyzed the impact of SLR on four watersheds in Norfolk and Virginia Beach and found that 1.5 and 3 ft of SLR alone had little impact on critical infrastructure, but SLR combined with 100-year storm surge produced a "high threat" for critical infrastructure within the study area.

In addition to impeding critical services, flooding associated with SLR also has an economic impact on the region. A study conducted in Annapolis, Maryland examined the impact of flooding on the number of visitors to the City Dock business district and found that high tide flooding of parking lots is affecting accessibility to shops and adversely impacting local businesses (Hino et al., 2019). According to Hino et al. (2019), there was a 1.7% loss in business visitation during and after a flood event under current conditions, an outcome that is expected to increase to a 24% loss in visitation with 1.0 ft of SLR. Regarding the impact on business in Hampton Roads, the Hampton Roads Climate Report identifies businesses in Norfolk and Virginia Beach at the highest risk from SLR in the region (McFarlane, 2012). In addition to economic impact, some residents in Hampton Roads are concerned about the impact flooding has on their ability to commute to work (Bukvic & Harrald, 2019). For example, flooding in and around the military bases in Hampton Roads could block access routes, thus limiting the ability of employees and residents to navigate in and out of them, eventually affecting their readiness and operations. (Considine et al., 2017).

Another example of economic flood impact is the expansion of the Federal Emergency Management Agency (FEMA) Special Flood Hazard Areas (SFHA). Habete and Ferreira (2017) found that the expansion of the SFHAs to reflect the increased risk of flooding from SLR would place more areas within the floodplain, requiring more people to purchase flood insurance from the National Flood Insurance Program (FEMA, 2019). Recurrent or permanent inundation can also decrease the property values. The impact of flooding on the property value was one of the main concerns among the residents in Hampton Roads, with some homeowners even opposing the placement of flood-level warning signs in the vicinity of their homes to maintain the perception of safety (Bukvic & Harrald 2019).

In response to flooding, coastal communities have the following adaptation options: Protection, accommodation, and (planned) retreat (A.K.A. relocation; Bukvic, 2015; IPCC CZMS, 1990). Considering the complexity of circumstances in urban coastal settings, the best results can be achieved by implementing a combination of these options that reflect local contextual factors. Protection includes engineered (e.g., levees, seawalls) and natural (e.g., oyster reefs, forest buffers) solutions that defend against flood waters. Accommodation refers to adjustment in human behavior to minimize impact such as upgrading building codes and land-use planning. Planned relocation entails the strategic movement away from the coastline using policy solutions such as land use and zoning policies (Nicholls, 2011). One of the main mechanisms for implementing relocation is government buyout programs. While some decision-makers prefer this approach as it moves people away from the risk, the buyouts can have their own negative sociocultural and economic costs both on people who relocate and those who stay behind (Bukvic & Harrald, 2019). Usually, there is only enough funding to buy a few properties per year and in a dispersed spatial manner due to a voluntary nature of the program, which often leaves vacant lots throughout the community and results in a “swiss cheese effect” and lower social cohesion (Bukvic & Harrald, 2019). This example shows the complexity behind determining the best adaptation pathways for coastal locations.

Measuring Exposure and Risk. As the threat of coastal flooding continues to grow, much research has been dedicated to quantifying the risks in various communities, mostly through vulnerability assessments. Vulnerability is often defined as the susceptibility of a place to damage by a specific impact and often characterized by exposure, sensitivity, and adaptive capacity (Kleinosky et al., 2007). However, there is not much agreement on the exact definition of flooding vulnerability or how to quantify it. A review of 55 articles about coastal vulnerability mapping conducted by Bukvic et al. (2020) found that different research groups use various approaches to measure vulnerability of place. Some focus only on the exposure component, producing advanced flooding models, while others incorporate simplistic flood interpretations but center their attention on the socioeconomic elements. Interdisciplinary studies used more holistic approaches, incorporating both physical and social dimensions of coastal vulnerability.

Similarly, the vulnerability assessments conducted in Hampton Roads show a range of methodological approaches. For example, Kleinosky et al. (2007) and Liu et al. (2016) used an integrated approach aggregating physical and social vulnerability, while Stafford et al. (2016) focused exclusively on socioeconomic variables. Despite varying approaches, one of the common indicators of vulnerability is a place or household's financial capability to deal with repetitive flooding and resulting damages (Kleinosky et al., 2007; Liu et al., 2016, Stafford et al., 2016). Liu et al. (2016) suggested inclusion of considerations that are complementary to individual or small-scale factors such as road accessibility. The vulnerability assessments conducted by Kleinosky et al. (2007) and Liu et al (2016) identified different geographic areas in Hampton Roads as the most vulnerable highlighting the important role the selection of approach has on the assessment outcome. Kleinosky et al. (2007) used a higher number of socioeconomic indicators and based on their composite value concluded that the urban centers were more vulnerable. Liu et al. (2016) emphasized vulnerability of physical exposure and infrastructure, finding that rural areas are more vulnerable. The Hampton Roads Climate Report estimates that the population impacted by sea level rise will range between 60,000 and 175,000 by 2100 (McFarlane, 2012). Of the localities within Hampton Roads, the report identifies Virginia Beach as being at the highest flood risk in terms of affected area, population, and housing units. This example shows the limitations of vulnerability assessments and why it may be difficult to produce definitive results. The selection of spatial units and indicators can change the output and consequently affect policy decisions.

It is important to note that vulnerability assessments, as a methodological approach, do not always provide an absolute answer and rather serve as a broader indicator of areas that may need policy attention based on their specific approach, the selection of variables, and their aggregation and visualization approach. Rufat et al. (2019) evaluated the validity of four types of vulnerability indices and found that models were consistent with identifying the least and most vulnerable areas. However, they also found that their explanatory power varied, and suggested caution until more research on the best practices of vulnerability models becomes available before using them in high impact decisions (Rufat et al. 2019). A different study compared vulnerability to the impacts of Hurricane Katrina using the residents' rate of return relative to the intensity of the storm. They found that modeled vulnerability could only account for roughly half of the impact on population, often overestimating (Lein & Abel 2010). Lein & Abel (2010) propose that vulnerability assessments would be more accurate should they account for the local conditions and flood-prevention infrastructure.

Boundaries for Vulnerability Assessments. Climate change and SLR are expected to exacerbate existing flood hazards in coastal urban communities, such as Hampton Roads in Virginia. Current research and impact assessments in this region are typically limited to the case study locations within the administrative boundaries (e.g., cities or counties) or study the region as a single entity, and rarely acknowledge that the movement of water doesn't recognize political boundaries (e.g., McFarlane, 2012; City of Norfolk, 2016). Since flooding is a hydrologic hazard, using a hydrologic boundary (watersheds) would more appropriately capture the risks involved. Considine et al. (2017) used a watershed scale to study impacts on critical infrastructure in Hampton Roads but only applied it to a small section of this geographic area. Capturing this spatially explicit risk is crucial to develop optimal adaptation strategies for the affected area. Adaptation is not effective when done in a piecemeal fashion without a broader framing of synergistic actions that need to be taken to ensure that the whole region adapts in a coordinated manner. Thus, adaptation should be also explored on a wider geographic scale, especially to ensure that adaptive interventions in one municipality do not exacerbate flooding conditions in the neighboring communities and increase their vulnerability. Watershed-scale assessments not only make sense for studying flood-related impacts but are also ideal for identifying specific hydrologic systems at risk and the most effective regional adaptation strategies with co-benefits for neighboring municipalities. Focusing on watershed-level impacts while also using a specific region as a boundary of investigation will allow for regional synchronization, since the municipalities already cooperate and interact to form other regional policies such as those dealing with transportation and utilities. Finding the most effective way to adapt to SLR is especially important for coastal urban landscapes, such as Hampton Roads, Virginia where dense populations and various land uses are at risk.

Flooding does not conform to administrative or political boundaries but rather propagates based on topography and stormwater infrastructure. The majority of coastal vulnerability assessments use political boundaries as a unit of analysis (Bukvic et al., 2020), similar to the official flood impact study conducted by the Hampton Roads Planning District Committee (McFarlane, 2012). Multiple studies demonstrate why this may be problematic. John and Yusuf (2019) interviewed coastal stakeholders to learn that the most significant barrier to adaptation is a legacy of "Regional Conflicts" with jurisdictional and geographical boundaries perceived as deterrents to adaptation. (John & Yusuf, 2019, p. 161). Yet, many studies recognize climate change impacts on hydrologic systems and thus propose adaptation strategies at watershed scales (Cheng et al., 2017; Dudula & Randhir, 2016; Shannon et al., 2019, Choden et al., 2020), showing precedent for studying human systems at a natural scale. Additionally, Enrı´quez-de-Salamanca (2018) proposed that adaptation and resilience to flooding could be achieved through watershed management via land use practices. Considine et al. (2017) also recognized the importance of watershed-scale assessments and designed a flood impact study of four watersheds near the Norfolk-Virginia Beach boundary to study how risk and adaptation planning span across multiple jurisdictions. Such an approach across the larger Hampton Roads region is particularly important, where social and economic systems of multiple cities are both highly codependent and interconnected (Bukvic & Harrald 2019).

Problem Statement

While planning and zoning decisions are made within political boundaries, SLR and flooding will not conform to these boundaries. Even though it is implied that areas adjacent to the coast will be affected by SLR, storm surge flooding will also affect those living along the creeks and rivers in areas further inland, including in Hampton Roads, Virginia. Analyzing impacts on a watershed level will provide insight into which river systems challenged by flooding will have the most impact on the communities that surround them. Multiple studies have chosen to use watersheds as the spatial scale, as they more accurately show propagation of water-related hazards (Considine et al., 2017; Joyce et al. 2018; Kolok et al. 2009). However, the latter two studies were conducted outside Hampton Roads while Considine et al. (2017) studied just four sub-watersheds within Norfolk and Virginia Beach (Southeast Hampton Roads). Hampton Roads consists of multiple independent cities and counties that are dependent on one another but still strive to maintain their sovereignty, unique identity, and individual decision-making, making integrated regional adaptation planning more difficult. This issue is recognized by John and Yusuf (2019) where participants in their study identified jurisdictional and geographic boundaries as the main challenge of adaptation planning. Impact assessment on a watershed scale will help identify cross-jurisdictional areas that may require collaboration between local governments on adaptation planning, as well as the areas within a municipality that have a disproportionate amount of risk compared to the rest of the municipality.

Research Objectives. The overarching goal of this study was to evaluate potential coastal flooding from SLR and storm surges at a watershed-scale in the Hampton Roads area, as well as to determine how that risk varies between the municipalities within a case study watershed. This research further aims to assess how flood impacts on land use, land cover, and population across the Hampton Roads region and within the selected case study location. As such, this work will provide local and regional decision-makers with spatially explicit information to help inform their adaptation plans and priorities.

This study sought to answer the following research questions:

1. Which watersheds in the Hampton Roads area are the most prone to coastal flooding from SLR and storm surges over different temporal scales, and which of those most prone to flooding are within two or more municipalities?

2. To what extent are different land uses and populations impacted by coastal flooding over different temporal scales?

3. How are the impacted land uses, populations, and critical facilities distributed between municipalities within a case study watershed?

2. Manuscript

Assessing coastal flooding at watershed scales to inform collaborative adaptation

Allison Mitchell, Anamaria Bukvic, Yang Shao, Jennifer Irish, & Daniel McLaughlin,

Abstract

Coastal communities face threats of flooding associated with episodic storm events and high tides. These events are increasing in severity and frequency due to climate change and sea level rise (SLR). The Mid-Atlantic U.S. is experiencing SLR at rates faster than the global average, especially in Hampton Roads, Virginia, where the rate of SLR is higher mostly due to land subsidence. Generally, adaptation and resilience plans for coastal flooding are made at the municipality level, ignoring flooding impacts that can cross administrative boundaries. Consequently, impact assessments at watershed scales are needed to guide municipalities in collaborative flood mitigation efforts. To that end, we evaluated flooding impacts from SLR and storm surge among watersheds in Hampton Roads, Virginia U.S., a region in coastal Virginia containing 17 municipalities, identifying those watersheds most at risk that overlap one or more municipal boundary. Additionally, we assessed impacts on specific land uses provided by the Hampton Roads Planning District Commission and 2019 block group population estimates from the U.S. Census Bureau throughout the Hampton Roads region and within a case study watershed. To do so, we used USACE 2% AEP Hazard Areas and NOAA intermediate SLR scenarios for 2030, 2060, and 2090 to calculate the percent land area inundated for each watershed in Hampton Roads. Key findings demonstrate that five watersheds will see a greater increase in inundated area than their surrounding watersheds, with two that overlap multiple municipalities. The anticipated land use impacts indicate significant inundation of spaces occupied by military, followed by commercial, industrial, and wetland covers both in Hampton Roads and within the Elizabeth River watershed. Further, impacted populations are concentrated in urban areas along the Elizabeth River and in Hampton City. These results highlight the need for collaborative adaptation between municipalities. This watershed-based approach can be applied to similar coastal settings globally.

2.1 Introduction

Living in coastal areas means living with the risk of flooding. Coastal communities experience flooding from various sources including precipitation, high tides, and episodic events such as storm surges (Atkinson et al., 2013; Wright et al., 2018). Precipitation, tidal inundation, and storm surge are projected to increase in frequency and severity due to climate change, especially on the Atlantic and Gulf coasts in the United States (USGCRP, 2018). With changing precipitation patterns, severe rainfall events are likely to occur more frequently (IPCC 2014, USGCRP 2018). Sea level rise (SLR), which will further increase the frequency and severity of flood events, has been observed for decades globally and is projected to continue in the future (IPCC, 2014; Parris et al., 2012). Consequently, “nuisance flooding”, or high tide flooding, is 300-900% more frequent now than 50 years ago (Lindsey 2019). Based on a review of research conducted by NOAA, there is high confidence that SLR will increase between 0.2-2 meters by 2100 (Lindsey 2019). The IPCC projections for 2100 (RCP8.5) narrow this range to within 0.5 to 0.98 meters at a rate of 8-16 mm/year globally (IPCC 2014).

In the Mid-Atlantic U.S. region, the rate of SLR is increasing above the global average (Engelhart et al., 2011; Parris et al., 2012; Atkinson et al., 2013), largely due to land subsidence from sediment compaction, glacial isostatic rebound, and groundwater extraction as well as weakening Gulf Stream currents (Parris et al., 2012; Engelhart et al., 2011; Atkinson et al., 2013). Sewell's Point tidal gauge (Norfolk, VA), which has been documenting sea levels since 1928, recorded a rising rate of 45.72 cm per century, nearly twice that of the global rate (Atkinson et al., 2013; Boon, 2012; Ezer, 2018). Habete and Ferreira's (2017) further predicted that the rate of SLR in Virginia will increase anywhere between 13.1-71% by 2100. Coastal Virginia is particularly at risk due to its low-lying topography (Kleinosky et al. 2007), especially in urban centers (Liu et al. 2016) where already low elevations are gradually sinking (Atkinson et al. 2013). For example, Ezer (2018) found that seven out of the nine years with the highest number of nuisance flooding hours in Norfolk, VA have occurred since 1998. Further, the "The Hague" neighborhood of Norfolk is experiencing a positive trend in hours of flooded streets per year, with hours under water per year reaching 300 in the late 2000s (Atkinson et al., 2013). Norfolk and the 16 coastal cities and counties surrounding it make up the greater Hampton Roads area, a region recognized as highly vulnerable to SLR-induced flooding particularly coupled with storm surge events.

Rising sea levels will exacerbate flood risk from storm surges, particularly in urban coastal communities. Critical facilities, such as hospitals, schools, and rescue squads are crucial to provide daily essential services and emergency response. Flooding can interrupt the access to these facilities, causing delays in service acquisition, disruption in people's livelihoods, and public safety issues. In Hampton Roads, 90 cm of SLR is predicted to increase the impact on critical facilities affected by a category one hurricane storm surge by 62.5% (Kleinosky et al., 2007). This is supported by Considine et al. (2017) who analyzed the potential impact of SLR and storm surges on four watersheds in Norfolk and Virginia Beach and found that SLR (0.46 m. and 0.91m.) alone would have little impact on the critical infrastructure, but SLR combined with 100-year storm surge would likely produce "a high threat" for critical infrastructure within the study area.

Flooding associated with SLR also has a significant economic impact. The Hampton Roads Climate Report (McFarlane 2012) identified Norfolk and Virginia Beach as municipalities with the highest SLR impacts on the businesses in the region. Residents in Hampton Roads are also concerned with their ability to commute to work and access other travel routes (Considine et al., 2017). Another example of economic impact could ensue due to expansion of the Federal Emergency Management Agency (FEMA) Special Flood Hazard Areas (SFHA). Should the SFHAs expand to account for SLR, more homeowners would be obligated to purchase flood insurance from the National Flood Insurance Program (Habete & Ferreira, 2017; FEMA, 2019). Recurrent or permanent inundation will also reduce property values, an outcome that has been identified as a main concern among residents with some even opposing the placement of flood level warning signs near their homes (Bukvic & Harrald 2019).

Climate change and sea level rise will exacerbate existing flood hazards in coastal urban communities, such as Hampton Roads in Virginia. Flooding does not conform to the administrative or political boundaries in which planning and zoning decisions are made, but rather propagates based on the topography and stormwater infrastructure. The majority of coastal vulnerability assessments use political boundaries as a unit of analysis (Bukvic et al., 2020), similarly to the official flood impact study conducted by the Hampton Roads Planning District Commission (McFarlane, 2012). Multiple studies demonstrate why this may be problematic. John and Yusuf (2019) interviewed coastal stakeholders to learn what the most significant barrier to adaptation is a legacy of "Regional Conflicts" with jurisdictional and geographical boundaries perceived as deterrents to adaptation. (John & Yusuf 2019, p. 161). Yet, many studies recognize climate change impacts on hydrologic systems and propose adaptation strategies on the watershed scale (Cheng et al. 2017; Dudula & Randhir 2016; Shannon et al. 2019, Choden et al., 2020), showing precedent for studying human systems at a natural scale. Additionally, Enrı´quez-de-Salamanca (2018) proposed that adaptation and resilience to flooding could be achieved through watershed management via land use practices. Hampton Roads, as the urban center of coastal Virginia, is unique. While each jurisdiction is its own administrative entity , their social and economic systems are both highly codependent and interconnected (Bukvic & Harrald 2019). Considine, Covi, and Yusuf. (2017) also recognized the importance of watershed-scale assessments and designed a flood impact study of four watersheds near the Norfolk-Virginia Beach boundary to study how risk and adaptation planning span across multiple jurisdictions. Finding the most effective way to adapt to SLR is especially important for this coastal region, due to its dense population, presence of federal facilities, industrial ports, historic sites, and natural resources at risk.

Even though it is implied that areas adjacent to the coast will be affected by sea level rise, flooding will also affect those living along the creeks and rivers in areas further inland, including in Hampton Roads, Virginia. Analyzing impacts on a watershed-scale will provide insight into which river systems vulnerable to flooding will have the most impact on adjacent communities. Multiple studies have chosen to use watersheds as the spatial scale, as they more accurately show propagation of water-related hazards (Considine, Covi, and Yusuf 2017; Joyce et al. 2018; Kolok et al. 2009). However, two studies (Joyce et al., 2018; Kolok et al., 2009) were conducted outside Hampton Roads, while Considine et al. (2017) studied just four sub-watersheds within Norfolk and Virginia Beach (Southeast Hampton Roads).

Impact assessment on a watershed-scale will help identify cross-jurisdictional areas that may require collaboration between local governments on adaptation planning, as well as the areas within a municipality that have a disproportionate amount of risk. The overarching goal of this study was to evaluate the risk of flooding from SLR and storm surge at a watershed-scale in the Hampton Roads area, as well as to determine how that risk may change over time and vary among municipalities within a watershed. This research further measures the impacts of storm surge flooding on land use, land cover, and population on a regional level and within the selected case study location over different temporal scales. Additionally, the impact on critical facilities is detailed within the case study watershed. As such, this work provides local and regional decision-makers with spatially explicit information to help inform their adaptation plans and priorities as well as demonstrates an approach to apply in similar coastal, flood-prone urban landscapes.

2.2 Materials and methods

Study Locations. The study is focused on the Hampton Roads Planning District that contains 17 municipalities. Two of those municipalities, Southampton and Franklin, were excluded from the analysis as they are not prone to SLR and storm surge flooding due to their location further inland. Within the remaining 15 municipalities, there are 98 watersheds (12-digit HUC) that intersect with their boundaries (**Figure 1**). The impacts of storm surge flooding at different SLR scenarios were analyzed for all 98 watersheds in the Hampton Roads area to identify which ones are at the highest risk of future flooding. Substantial differences in risk were expected, as many of the watersheds overlap multiple municipalities with different land uses, populations, and administrative characteristics, creating unique socioeconomic circumstances within each watershed.

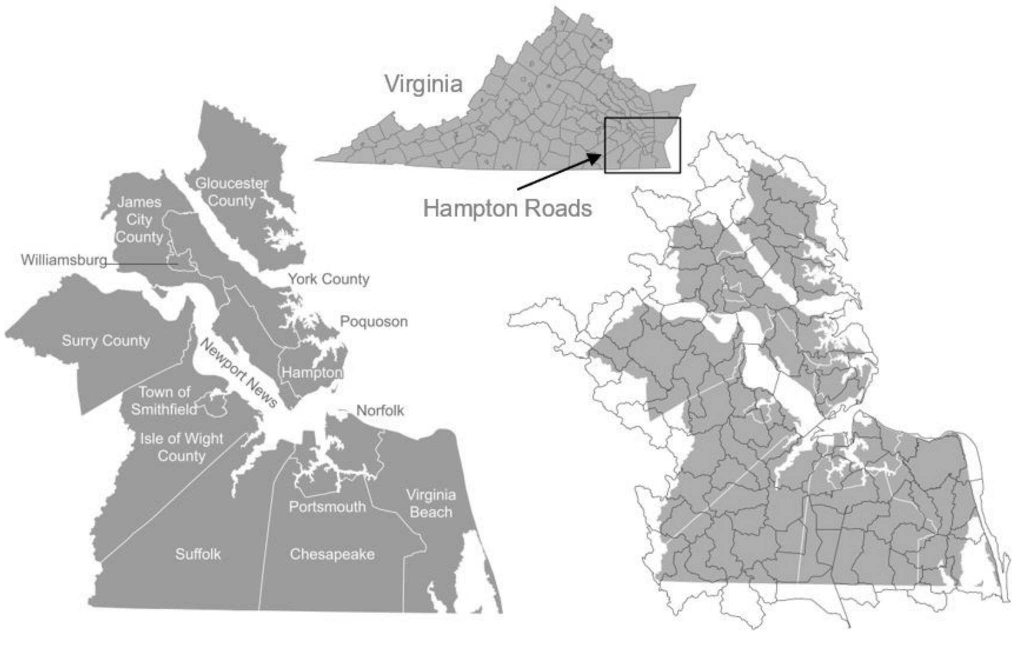


Figure 1. Hampton Roads Municipalities (left), the 12-digit HUC watersheds that intersect them (right), and location reference of study area within Virginia (top-center)

The municipalities differ in size, population density, and other sociodemographic and economic characteristics (**Table 1**). Population densities range from 190.9 people/km^2 in Isle of Wight County to 4,570.8 in Norfolk, showing the development range from more rural areas to denser urban centers. Some municipalities, like Williamsburg, have a small area coverage (23 km^2 , while others, like Suffolk have a much larger area (1036 km^2). Poverty rates tend to stay below 20% in this region, with the exception of Williamsburg and Norfolk with rates just above 20%. The majority of Hampton Roads municipalities have mostly white populations, with the exception of the urban core in Hampton, Newport News, Norfolk, and Portsmouth. Collectively, this region is a home for roughly 1.7 million residents (U.S. Census Bureau, 2019b).

Table 1. Socioeconomic characteristics of municipalities included in this study (Source: U.S Census Bureau, 2019b)

Municipalities	Population Density	Area (sq. km)	Median Income	Persons in poverty %	Race % White
Chesapeake	277	881	72,214	9.6	61.8
Gloucester County	64	583	63,881	8.7	87.7
Hampton	1,007	135	52,021	14.9	41.8
Isle of Wight County	46	818	67,767	10.3	72.5
James City County	191	396	80,772	7.5	80.3
Newport News	999	181	51,082	16.4	49.0
Norfolk	1765	139	47,137	21.0	47.4
Poquoson	297	41	88,328	4.9	94.5
Portsmouth	1,111	85	48,727	17.7	40.4
Town of Smithfield	326	26	72,308	14.2	68.3
Suffolk	89	1036	68,089	11.2	52.1
Surry County	9	723	54,656	13.6	52.5
Virginia Beach	706	642	70,500	8.0	67.2
Williamsburg	651	23	54,606	21.5	73.9
York County	250	275	86,781	5.2	76.3

Inundation Corridors. Inundation corridors are the areas that would be flooded under given SLR and storm surge scenarios. In this paper, our estimates are based on the 2% annual exceedance probability (AEP) hurricane flood hazard, i.e. the 50-year floodplain that represents a moderately frequent flood hazard. To represent the 2% AEP hurricane flood hazard, we used the U.S. Army Corps of Engineers' (2015) North Atlantic Coast Comprehensive Study's statistical coastal flood hazard data (NACCS; Cialone et al. 2015, Nadal-Caraballo et al. 2015). Joint probability, optimal sampling (Resio & Irish 2015 and references therein) and 1031 hurricane surge simulations (ADCIRC; e.g., Dietrich et al. 2011) support innovative flood modeling. The inclusion of joint probability allows for the addition of astronomical tides through superposition of 96 unique tidal phases with surge-tide nonlinearity adjustment. The nonlinearity refers to the divergence from a linear trend in SLR for each station. The simulated storm surges were based on the 1992 mean sea level with storm surge simulations based on the 1983-2001 tidal epoch (Cialone et al. 2015, M. Cialone personal communication). The 68% confidence interval for the NACCS 2% AEP is 0.5 m (Nadal-Caraballo et al. 2015). These methods are consistent with FEMA's methodology for Flood Insurance Rate Maps.

We projected the 2% AEP hurricane flood elevations for the year 2000 (base year) and for the years (and thus SLR scenarios) 2030, 2060, and 2090. Intermediate projections for SLR from NOAA (Sweet et al. 2017) were used for this study as they represent conservative scenarios, which is relevant for policy makers. Relative to the 2000 sea level, these SLR scenarios are 0.3 m. (2030), 0.7 m. (2060), and 1.2 m. (2090). Since SLR does not impact flood elevation linearly over a space, the NACCS study includes a nonlinearity assessment with the surge simulations added to the 1-m SLR scenario that is provided by the study (Cialone et al., 2015; Nadal-Caraballo et al., 2015). Variation of the normalized nonlinearities range between -12 to +5% departure from the linear trend at 90% of the stations. Using these SLR values, the 2% AEP flood elevations from NACCS were adjusted by multiplying the normalized nonlinearity with the sea level change from 1992 to the target year (starting with interpolation to 2000), and then adding the product to the sum of the flood elevation and sea level change value. This means the 2% AEP flood elevations were interpolated for 2000, 2030, and 2060 but were extrapolated for 2090 since the 2090 scenario is higher than the 1 m. scenario provided. These methods assume no change in coastal morphology over the selected time period.

The inundation dataset was in the point grid format, which was interpolated into a raster using inverse distance weighting with a resolution of 30 m. (**Figure 2**). The Digital Elevation Model (30 m resolution; USGS National Elevation Dataset, 2014) was then subtracted from the water surface elevation so that positive values would represent a flooded area. The resulting raster provides both area and depth of flooding under the given scenario.

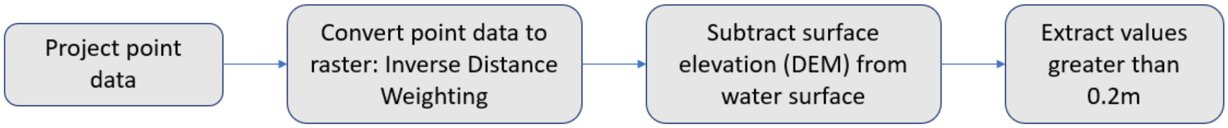


Figure 2. Flowchart of data transformation for inundation corridors.

Flooding is treated as a binary factor for the purpose of this study. An area is considered flooded at any depth above 0.2m. The value of 0.2m was chosen based on studies that identify this depth as a threshold where property damage and threats to safety begin (Dinh et al., 2012; Balica et al., 2013).

To ensure that only flooded land areas were included in the calculation, each of the datasets were delineated to exclude water areas. Water areas are mapped by the USGS in the National Hydrography Dataset (NHD; U.S. Geological Survey). The water body and water area layers were merged together, and the open water feature types were extracted. These feature types are defined by the NOAA GIS workflow (NOAA, 2019) for mapping open waters as bays/inlets, lakes/ponds, reservoirs, sea/ocean, stream/river, and estuaries. The workflow further recommends filtering out bodies of water with less than 10 acres of area, but water bodies with less than 5 acres of land were filtered out for this study. This is to ensure higher accuracy when recording flooded land areas while also excluding areas such as swimming pools. The delineated study area was created by deleting the water areas from the merged county and NHD layers. The inundation corridor raster layers were then masked using this delineated layer to ensure that only flooded land area was considered in all steps of the analysis.

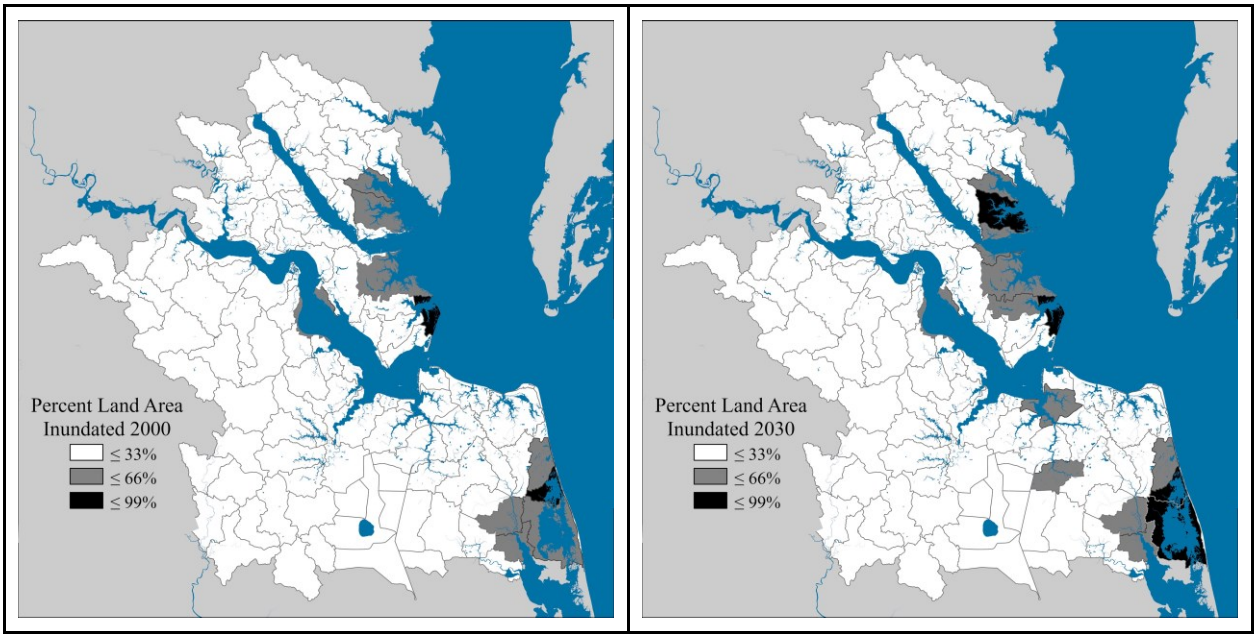
Flooding Impacts at watershed-scales. Area of land within the inundation corridor was calculated for each scenario within each HUC-12 watershed. Area of land inundated was calculated using zonal statistics by multiplying the sum of cells by the area of each cell. Additionally, only areas within watersheds within the boundaries of Hampton Roads were considered for these estimations. The inundated area was further broken down by parcel level land use type to determine the dominated land use category affected by flooding under each scenario within each watershed. Parcel level data in Hampton Roads for the land use types comes from the Hampton Roads Geospatial Exchange Online (Hampton Roads Planning District Commission, 2019a). These data are categorized in a uniform manner, ensuring land use categorization is consistent across the boundaries. Surry County was not included in the land use analysis due to lack of available data. The land use data were resampled into a 30-meter resolution raster layer to estimate land use areas within the same resolution of the inundation corridor. The land cover data in appropriate format and resolution (U.S. Geological Survey, 2011) within the inundation corridors were estimated for each scenario.

Next, an estimate of flooding impact on population was calculated for the study area based on the 2019 American Community Survey block group values (U.S. Census Bureau, 2019a). This procedure is based on the methodology used in the Hampton Roads Climate Report (McFarlane, 2012), which assumes uniform distribution of population within each census block and multiplies the percentage area inundated by the population, yielding a rough estimate of how many people live within the inundation corridors. Similar to the estimation of flooded areas within each watershed, zonal statistics were used to determine the percentage of each block group inundated in each SLR scenario.

The case study watershed was selected based on the percentage of land area inundated, the change in area inundated after SLR, and existence within two or more municipalities. The impacts described above were analyzed in more detail within the case study watershed. Additionally, critical facilities within the inundation corridors were summarized from the USGS National Structures Dataset (2020). The structures are typed according to the Homeland Security Infrastructure Program (HSIP; U.S. Geologic Survey, 2006). Structures considered critical by the HSIP fall under the categories of banking and finance, energy, emergency response and law enforcement, government and military, information and communication, health and medical, transportation, and water supply and treatment.. The SLR scenario that each critical facility became inundated was recorded.

2.3 Results

Coastal flooding at the watershed-scale. The majority (71 out of 98) of the watersheds within our study domain, including ones buffering the ocean and other waterways, exhibited inundated areas less than 33% for storm surge simulations via the 2% AEP flood hazard area (**Figure 3**), even with the addition of 2090 sea level projections. Yet, there were several notable watersheds that experienced large, flooded areas for current conditions. Before SLR (i.e., 2000 scenario), the 2% AEP inundation corridors indicate that five watersheds in the southeastern region of Hampton Roads would experience flooded areas more than 33%, as well as two low lying watersheds in York County, Poquoson, and Hampton (Middle Peninsula region). By 2090, the majority of the watersheds in Virginia Beach, Norfolk, Hampton, and Poquoson will be at least 33% inundated, making these the municipalities at the most direct threat of flooding in Hampton Roads. The watershed with the highest proportion of inundated land area across all four scenarios was the Back-River Frontal Chesapeake Bay watershed in Eastern Hampton and Poquoson. Without SLR, this watershed would be nearly 81% within the inundation corridor and would reach 98% after 2090 projected SLR. High levels of inundation from SLR and storm surge are not exclusive to coastal watersheds. Inland watersheds along the Elizabeth River in Portsmouth and Chesapeake exhibit inundation levels between 33-66% in the 2060 and 2090 scenarios.



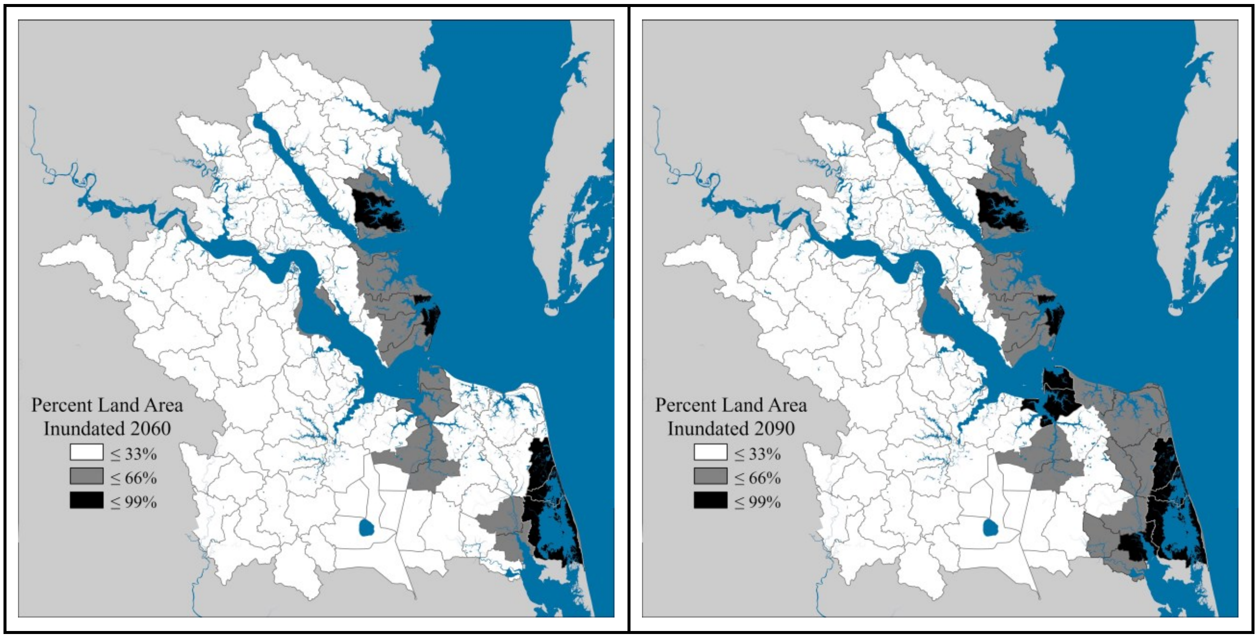
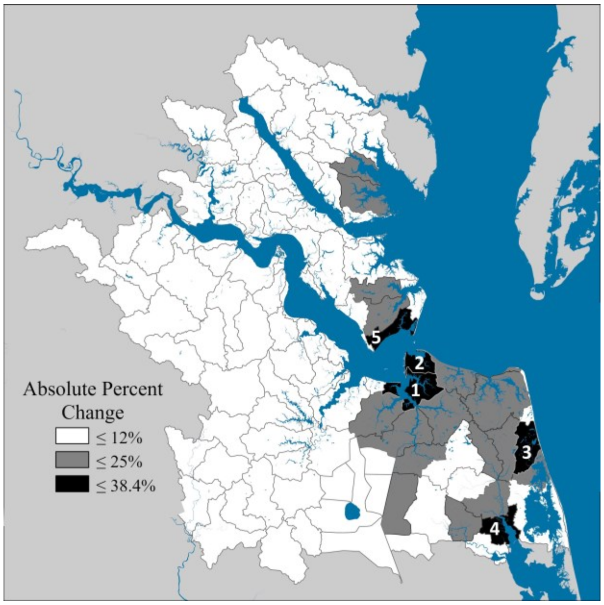


Figure 3. Percent land area within the inundation corridor (50-year floodplain) before SLR (2000) and after sea SLR for the 2030 (0.3 m), 2060 (0.7 m), and 2090 (1.2 m) scenarios for each Hampton Roads watershed (12digit HUC).

When the percent land area inundated in 2000 was subtracted from the percent land area inundated in 2090 (**Figure 4a**), five watersheds stand out as having the highest change in percent land area inundated, whereas changes in storm surge flooding with SLR were much smaller for the other watersheds. Even though the Back River- Frontal Chesapeake Bay watershed exhibited the highest proportion of flooded land area, it did not change much over time, making it among the lowest category of increased risk with time. The Elizabeth River watershed, located in Norfolk and Portsmouth (watershed 1 in Figure 4), is the watershed with the highest absolute percent change between 2000 and 2090 at 38.4%.



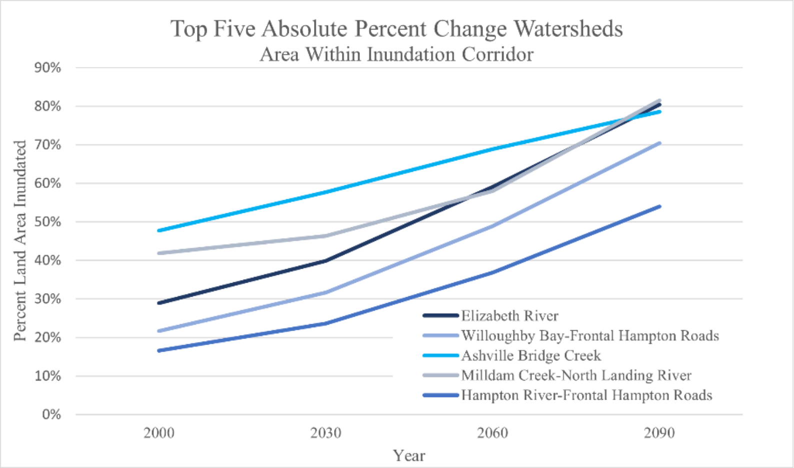


Figure 4a (left) Absolute change in percent of watersheds within 50-year floodplain from 2000 to 2090 and **4b (right)** the change in inundation over time for the five watersheds with the largest increases: 1, Elizabeth River; 2, Willoughby Bay-Frontal Hampton Roads ; 3, Ashville Bridge Creek; 4, Milldam Creek-North Landing River; 5, Hampton River-Frontal Hampton Roads.

Figure 4b shows that the change in percent land area inundated is not consistent over time and is not even across the watersheds. The Ashville Bridge Creek watershed is the only watershed of this group to increase at the constant rate in percent land area inundated with each scenario. The other four watersheds show acceleration after 2030. The Milldam Creek- North Landing River watershed, shows the most dynamic rate of change among the five watersheds, with a noticeable difference in slope for each segment of time. Additionally, watershed four, located in Virginia Beach, reaches the highest proportion of inundated land at 81%. Many of the watersheds with large increases in absolute percent change in inundation overlap multiple municipalities. Out of the 21 watersheds with at least a 12% absolute percent change, 11 of them overlap municipal boundaries (**Figure 5**). This occurrence is most common in the southeastern portion of Hampton Roads in Virginia Beach, Norfolk, Portsmouth, and Chesapeake. The remaining three watersheds in this category are along the boundaries of Hampton, Newport News, Poquoson, and York County.

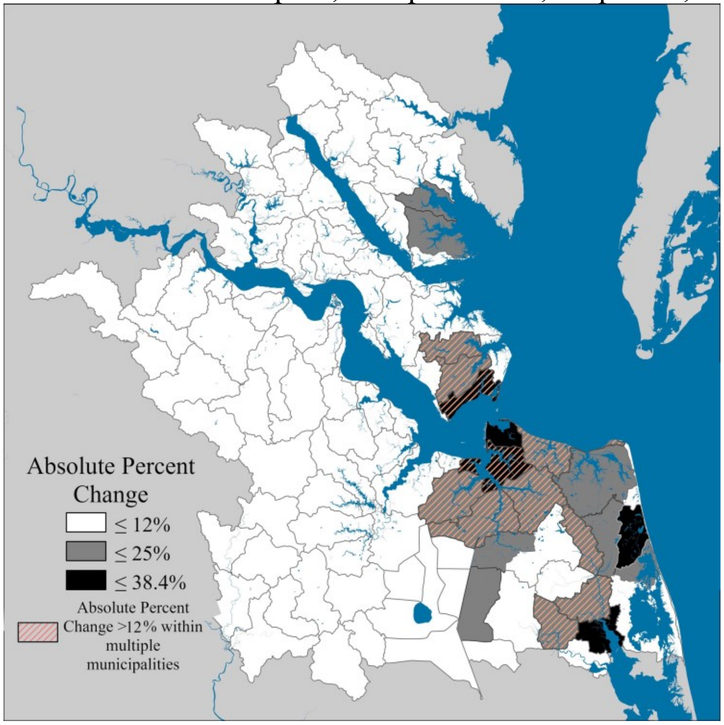


Figure 5. Watersheds with an absolute percent change of land area within the 50-year floodplain between 2000-2090 of at least 12% within multiple municipalities.

Flooding impacts at watershed-scales. Based on 2019 American Community Survey population estimates, 261,557 people would be directly impacted by storm surge flooding in the 50-year floodplain before the addition of SLR. With SLR, this number would rise to 332,556 in 2030, 449,554 in 2060, and 616,495 in 2090. The distribution of the impacted population in 2060 is shown in **Figure 6**. The impacted population is concentrated in Norfolk, Portsmouth, and Chesapeake along the Elizabeth River. Additionally, much of the City of Hampton population would be impacted by storm surge flooding. **Figure 6** also highlights that the higher numbers of impacted population are not always located in the areas with more flooding. Virginia Beach, for example, has more impacted population in watersheds that are less than 33% inundated compared to watersheds that are more than 33% inundated.

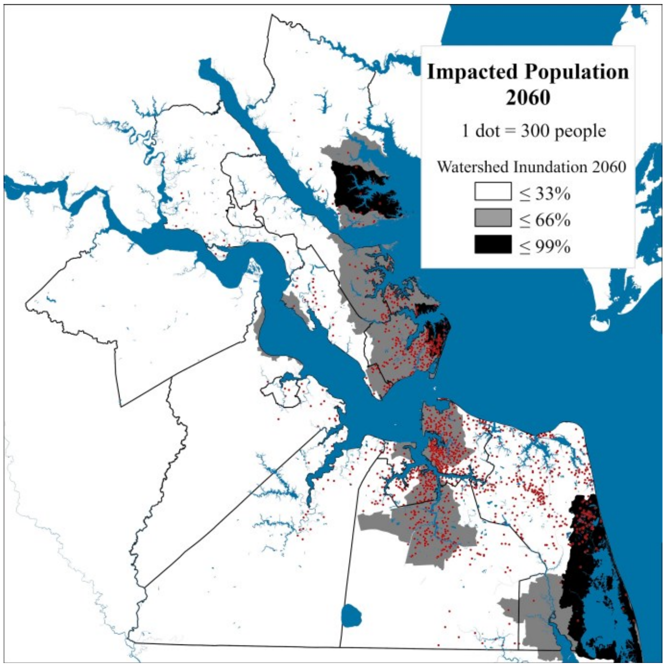


Figure 6. Population estimates within the 50-year floodplain for the 2060 SLR scenario (0.7m) with municipal boundaries and 2060 watershed percent land area inundated underlaid.

For the Hampton Roads region, excluding the Surry County, the land use category most impacted by SLR-driven storm surge flooding is military. Before SLR, 24% of all military land would be situated in the inundation corridor (**Table 2**). This impact increases to 38% by 2090. Residential areas are next with 31% area affected by 2090 and also with the sharpest increases in percent of land inundated from 2000 to 2090. Institutional land is the least affected land use category, with only 7% of it inundated even after the 2090 SLR scenario. Although vacant and open space land uses are similar, the vacant land still has the potential to be developed while open space is a designated open area. Even though as much as 34% of open space will be within the inundation corridor by 2090, damage to structures is not a concern. Conversely, the 18% of vacant land within the inundation corridor by 2090 may have structures that could be damaged if not converted to designated open space.

Table 2. Percent area within the 50-year floodplain for each major land use category before SLR (2000) and after SLR for NOAA intermediate projections for Norfolk, VA in 2030 (0.3 m.), 2060 (0.7 m.), and 2090 (1.2 m.).

Land Use Category	2000	2030	2060	2090
Vacant	12%	14%	16%	18%
Open Space	27%	29%	31%	34%
Residential	16%	19%	24%	31%
Military	24%	28%	33%	38%
Institutional	7%	7%	7%	7%
Mixed Use	6%	8%	10%	14%
Agricultural	7%	8%	9%	11%

Commercial and Industrial	10%	11%	14%	17%

Table 3 shows the percent area inundated for different land cover types in Hampton Roads. This analysis offers a different perspective from land use impact assessment because it shows a 30-meter resolution of what type of land is actually in a space, and not just the land uses a parcel is assigned to based on administrative categories. The land cover type that would have the highest proportion of its land area within the inundation corridors in 2090 are developed lands from low to high intensities. This is not surprising given the urbanization of this region. However, for the earlier three SLR scenarios, the most affected land cover is mixed wetlands (woody wetlands, herbaceous wetlands, and shrub/scrub). With the 2000 sea levels, 20% of wetlands in Hampton Roads would be within the inundation corridors, yet there is very little change over time. Given that wetlands in this area are generally located along the shoreline and river fringes, it is not surprising that the propagation of flooding further inland would not have an increased effect. However, the depth of this inundation could be increasing, which would change the impact of flooding on the existing wetland.

Table 3. Percent of area within the 50-year floodplain for different land cover types before SLR (2000) and after SLR for NOAA intermediate projections for Norfolk, VA in 2030 (0.3 m.), 2060 (0.7 m.), and 2090 (1.2 m.).

Land Cover Category	2000	2030	2060	2090
Developed, Open Space	10%	13%	17%	21%
Developed, Low-High Intensity	11%	15%	21%	31%
Mixed Agriculture	3%	4%	6%	8%
Non-Wetland Vegetated	2%	3%	4%	5%
Mixed Wetlands	20%	20%	23%	24%

Elizabeth River Watershed Case Study. To further illustrate the potential for a watershed-level analysis of flood impacts, the population, land use, land cover, and critical facilities impacted in the Elizabeth River watershed that encompasses two municipalities, Norfolk and Portsmouth, were analyzed. Further, how these impacts differ between the two municipalities in this watershed were described to highlight differences in priorities these municipalities might have when engaging in adaptation planning. This watershed was chosen because it had the largest absolute change in the percent land area inundated at 38.4%, meaning it will experience the highest impact from SLR. The drastic change in area inundated can be seen in more detail in **Figure 7**. Further, ~80% of this watershed is projected to be within the inundation corridor by 2090, making it one of the watersheds in the top category for both the land area inundated and the absolute percent change in land area impacted. Further, its placement within two municipalities will help demonstrate how this impact assessment is beneficial for cross-boundary adaptation planning.

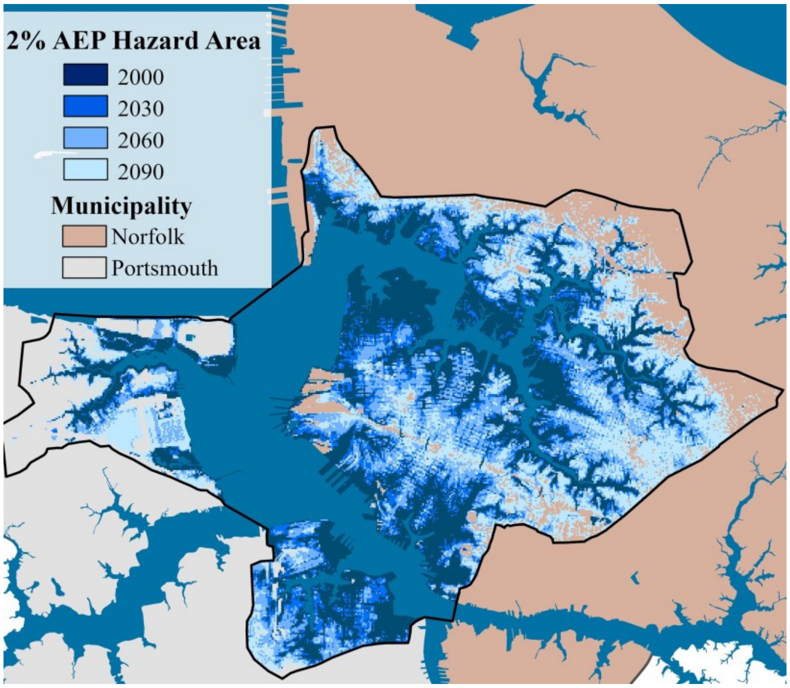


Figure 7. 50-year floodplain before SLR (2000) and after SLR for NOAA intermediate projections for Norfolk, VA in 2030 (0.3 m.), 2060 (0.7 m.), and 2090 (1.2 m.). in the Elizabeth River Watershed, with municipalities labeled.

Roughly 43,000 people in the block groups that intersect the watershed would be impacted by storm surge without the additional SLR. By 2060, this number increases to about 94,000. As many as 132,000 people could be impacted by 2090. The affected population in this watershed is mostly concentrated on the Norfolk side of the Elizabeth River. Even in the 2090 SLR scenario, only three of the block groups on the Portsmouth side reached over 4,000 people/km^2 of block group area, despite most of the lower portion being inundated by 2090 (**Figure 8**). The most densely populated block group is located in Norfolk along the Lafayette River and has an impacted population density of 3,266 people/km^2 with 2000 sea levels and 5,860 people/km^2 2090. In Portsmouth, the most densely populated block group did not reach 3,000 impact people/km^2 until the 2090 SLR scenario. Due to the size of these block groups, it is important to note that the population densities do not necessarily reflect the raw estimated population that would be impacted. For example, the most densely populated block group in this watershed has a density over 3,000 without SLR, but never reaches 3,000 non-normalized population impacted by the 2090 SLR scenario.

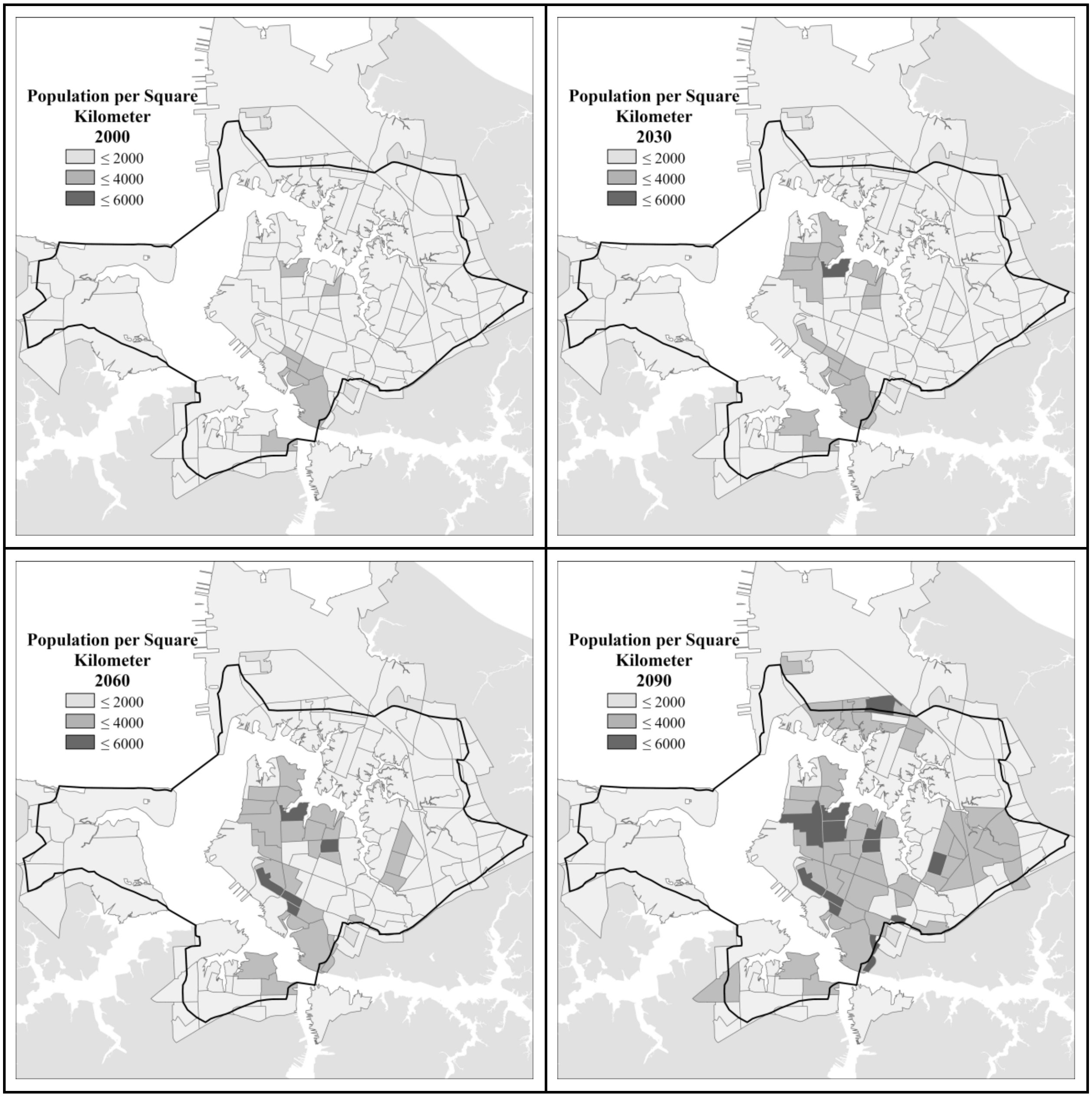


Figure 8. Estimated population per square kilometer of block group area within the 50-year floodplain before SLR (2000) and after SLR for NOAA intermediate projections for Norfolk, VA in 2030 (0.3 m.), 2060 (0.7 m.), and 2090 (1.2 m.).

The land use category that will be impacted the most in this watershed is open space between 31-82% from 2000 and 2090. Close behind are vacant areas and residential land at 82% and 80% by 2090, respectively. Before SLR, only 22% of the commercial and industrial land is within the inundation corridor. However, by 2090, this proportion increases to 74%. On the Norfolk portion of the watershed, the land use category with the most inundation is open space at 89% in 2090, followed by residential at 85%. On the Portsmouth side of the watershed, vacant land is the most impacted land use throughout all four SLR scenarios, topping out at 81% inundated by 2090. While as much as 57% of residential land may be within the inundation corridor by 2090, the population density maps in Figure 7 show that flooded residential land is not as much of a threat as it is on the Norfolk side. Instead, the main threat is inundated commercial and industrial land at 72% by 2090.

Table 4. Percent loss of land per land use and land cover categories within the 50-year floodplain before SLR (2000) and after SLR for NOAA intermediate projections for Norfolk, VA in 2030 (0.3 m.), 2060 (0.7 m.), and 2090 (1.2 m.)for the Norfolk and Portsmouth sections of the watershed, as well as the whole Elizabeth River watershed.

	Norfolk Section				**Portsmouth Section**				**Whole Watershed**			
Land Use Category	2000	2030	2060	2090	2000	2030	2060	2090	2000	2030	2060	2090
Vacant	31%	39%	58%	82%	34%	46%	70%	81%	31%	41%	62%	82%
Open Space	51%	60%	77%	89%	22%	30%	43%	49%	48%	56%	73%	84%
Residential	28%	39%	60%	85%	22%	29%	43%	57%	27%	38%	58%	80%
Military	15%	21%	35%	81%	31%	40%	50%	61%	29%	38%	48%	64%
Institutional	29%	44%	65%	82%	22%	29%	43%	57%	27%	39%	58%	75%
Mixed Use	8%	17%	24%	34%	22%	27%	30%	30%	12%	20%	26%	33%
Commercial and Industrial	22%	33%	51%	76%	22%	31%	50%	72%	22%	32%	51%	74%
Land Cover Category	2000	2030	2060	2090	2000	2030	2060	2090	2000	2030	2060	2090
Developed, Open Space	36%	46%	63%	80%	17%	25%	35%	47%	30%	40%	55%	71%
Developed, Low-High intensity	23%	34%	56%	81%	26%	39%	57%	71%	24%	35%	56%	78%
Non-Wetland Vegetated	52%	66%	76%	81%	29%	35%	46%	56%	41%	51%	62%	69%
Mixed Wetlands	67%	70%	75%	77%	31%	35%	44%	69%	46%	50%	57%	72%

In Elizabeth River watershed, 46% of its wetlands would be submerged in the 2000 inundation corridor (**Table 4**), making it the most impacted land cover type before SLR. However, by 2090, developed land would experience the largest flooded area at 78%. When we divided the watershed by municipality, a different pattern emerged. In Norfolk, 67% of its wetlands would be inundated under 2000 sea levels, but only 31% of Portsmouth's wetlands would be inundated, meaning the loss of wetlands is a much more immediate threat on the Norfolk side of the Elizabeth River. In terms of developed land, both the Norfolk and Portsmouth sections of the watershed show similar trends over time with Norfolk having a higher proportion of its developed land inundated by 2090 at 81% versus 71% in Portsmouth.

Out of the 19 critical facilities within this watershed, only two facilities would not be directly impacted by storm surge flooding with 2090 SLR scenario: a police department in Norfolk and a fire and rescue squad in Portsmouth. The majority of 17 critical facilities directly impacted by flooding in this watershed are medical services. Without SLR, the Tidewater Navy emergency medical services and a Norfolk fire station would be impeded by floodwaters on their properties with a 50-year storm surge event. By 2030, the Naval Medical Center in Portsmouth, Sentara Norfolk Medical Hospital, Sentara Heart Hospital, Norfolk Criminal Justice Services, and three other medical services in Norfolk would be impeded by flooding. By 2090, the remaining seven fire rescue and emergency services would have their properties impacted by storm surge flooding. Based on a visual evaluation, the emergency services that could assist the impeded facilities are scarce in areas outside of the floodplain, leaving many areas underserved by vital emergency response assistance.

2.4 Discussion

Watershed-scale impact assessment is a way for coastal communities to segment a region while recognizing movement of water. **Figure 4** visually demonstrates why it is difficult to study the impacts of SLR across a large geographic area, such as an entire region or a large municipality. The differences in percent land area inundated across different time horizons and between watersheds shows that the effect of SLR is location dependent. This methodology is consistent with meeting the resiliency goal for the State of Virginia of identifying which geographic areas should have a priority to achieve coastal resilience (Commonwealth of Virginia, 2020). While the Elizabeth River watershed was selected for further impact analysis in this report, there are several other watersheds where cross-boundary adaptation planning would be vital for optimal flood resilience. As seen in Figure 4, many of the watersheds surrounding the Elizabeth River watershed are projected to have elevated levels of inundation and are within multiple municipalities. Additionally, many of these watersheds are hydrologically connected by the Elizabeth River. This presents the opportunity for Norfolk, Portsmouth, and Chesapeake to work together to reduce the impact of flooding along this waterway. The municipalities may be limited in what they can achieve individually with their financial resources and political pressures (Hampton Roads Planning District Commission, 2017). Overlooking the political boundaries in favor of hydrological ones would allow municipalities to leverage their fiscal and technical capabilities and strengthen partnership between communities.

Impacted population densities can be used in tandem with the watershed level flooding information to set priorities for adaptation. Mapping products like in **Figure 5**, can help discern areas that have high rates of flooding and large impacted populations. Both this research and a report from the Hampton Roads Planning District Committee (McFarlane, 2012) found high rates of impacted populations in Hampton and Norfolk. Out of the three municipalities where watersheds are most affected (Virginia Beach, Norfolk, and Hampton), Hampton has the highest population density, highest rate of poverty, and highest proportion of minority residents, making its residents highly vulnerable to the impact of flooding. Vulnerability studies have previously identified Hampton as more vulnerable city than the surrounding localities that share the peninsula (Kleinosky et al., 2007; Liu et al., 2016). Further, with the exception of southern Virginia Beach, the overall vulnerability calculated by Kleinosky et al. (2007) shows that much of the flooded area identified by this study has socially vulnerable populations. Within the Elizabeth River watershed, the Norfolk side has more people at higher densities. Thus, it makes sense that the local officials want to discourage any new development within the floodplain and rather invest in neighborhoods at lower risk of flooding (City of Norfolk, 2016). Conversely, Portsmouth wants to increase their population and prioritized improvements of the stormwater management and other infrastructure to attract investors, new development, and more people (City of Portsmouth, 2018). These policies are especially relevant given the that roughly 80% of vacant land (18% region-wide), which could potentially be developed, would be within the 50-year floodplain by 2090.

The flooding of military land is a critical threat for this region, with up to 38% of military land within the inundation corridor by 2090. Not only do these facilities employ many Hampton Roads residents, but they also provide a labor force for the region through retirees who decide to stay in the region and military spouses (Hampton Roads Planning District Commission, 2017). In Norfolk, the Naval Station Norfolk is their largest employer (City of Norfolk, 2016). Should the federal government decide to either relocate or scale back operations in response to persistent flooding, there would be a significant impact on the Hampton Roads economy (Union of Concerned Scientists, 2016). Municipalities therefore have the motivation to work together with the military personnel to develop adaptation and resilience strategies to protect this land use. Based on the 2017 Hampton Roads Hazard Mitigation Plan, this joint effort is ongoing, as military representatives were present during the process of updating the document. Additionally, Chesapeake, Portsmouth, Norfolk, and Virginia Beach have been working with military personnel to evaluate the impact of SLR on assets critical to military function. The Norfolk-Virginia Beach Joint Land Use study focused on five main challenges associated with SLR and tidal flooding: commute accessibility, accessibility of community facilities and services, stormwater, utility services, and region coordination (Hampton Roads Planning District Commission, 2019b). The Portsmouth-Chesapeake JLUS is ongoing but will also focus transportation and land use surrounding military installation (Hampton Roads Planning District Commission, 2021).

While the inundation of commercial and industrial land is of concern for the whole region, it is particularly concerning for the Elizabeth River Watershed. This watershed contains major shipping and transportation hubs such as Virginia International Gateway (a shipping port) and the Norfolk Southern Lambert’s Point Yard. These and other industries could face a major economic impact from the sea level rise and storm surge. Additionally, the location of industries within the inundation corridors can be physically dangerous to the surrounding community. The Virginia Coastal Resilience Master Planning Framework (Commonwealth of Virginia, 2020) states, “Heavily industrialized areas along the Elizabeth River and other tidal rivers in the region create another layer of risk to flooding – environmental contamination.” (pg. 40). The Norfolk Vision 2100 (2016) divides the city into different zones based on the flood risk and location of assets with many major industrial areas being located within the “red zone”, the highest threat area. Norfolk’s plan to decrease vulnerability in this zone is to diversify the economy and increase flood protections. The Portsmouth comprehensive plan (City of Portsmouth, 2018), however, does not address these risks. Given Portsmouth goal of increasing population in waterfront areas, steps need to be taken to protect these populations from potential dangers caused by the flooding of commercial and industrial sites.

The loss of wetlands in Hampton Roads could mean the loss of natural protection from flooding, as well as important ecological functions and ecosystem services. The disproportionate effect on wetlands found in this research is consistent with the findings from Kleinosky et al. (2007), which estimated a 39% loss of wetlands with 90cm of SLR and a category one hurricane storm surge. However, the levels of wetland inundation reported in this study do not mean the permanent loss of wetlands. The dynamics of wetland loss and migration include many factors that were not addressed in this study. Herbaceous wetlands may be able to recover from a storm event, but the saltwater from a storm surge could permanently alter the landscape of other land cover types such as agricultural or forested areas. The preservation of wetlands is reliant on their ability to migrate inland, which is often restricted by the developed land (Kirwan & Gedan, 2019). In highly developed watersheds, like the Elizabeth River watershed, inland migration would not be a viable option. Norfolk and Portsmouth are both taking action to address this concern. Norfolk’s Coastal

Resilience Strategy (City of Norfolk, 2014) includes the placement of living shoreline buffers and Portsmouth plans to work with Elizabeth River Project to promote wetland conservation and living shorelines (City of Portsmouth, 2018).

The lack of critical facilities outside of the inundation corridor both within the Elizabeth River watershed and in the area surrounding it means the first responders will have to overcome additional obstacles to provide the assistance during a flood event. Further, many of the fire and rescue stations in Norfolk are in a need of renovations. Addressing the infrastructure needs of the city are listed as a priority for Norfolk, that plans to pursue those improvements and build new fire and rescue stations in less vulnerable areas (City of Norfolk, 2016). Similarly, Portsmouth aims to prevent the construction of new critical infrastructure in floodplains (U.S. Army Corps of Engineers, Norfolk Division, 2015). New construction of critical infrastructure presents the opportunity for the municipalities to work together to strategically select locations to serve the most people in the vulnerable areas. This type of municipal collaboration is an example of how improving one municipality can benefit residents in another.

Regional level planning is supported by the Virginia Coastal Resiliency Plan and is one of the primary goals of the master planning framework (Commonwealth of Virginia, 2020). The Hampton Roads Planning District Committee has also worked toward this goal of facilitating regional collaboration as evident from their publications such as the Coastal Resiliency: Adapting to Climate Change in Hampton Roads (McFarlane, 2013), the Hampton Roads Hazard Mitigation Plan (Hampton Roads Planning District Commission, 2017), and the Climate Change in Hampton Roads: Phase III: Sea Level Rise in Hampton Roads, Virginia (McFarlane, 2012). These documents provide a general guidance about incorporating sea level rise into municipality comprehensive plans as well as provide models of sea level rise, while the detailed impact assessments and the implementation of adaptation measures are left up for determination of the individual municipalities. There is still an opportunity to strengthen and align the adaptation efforts among municipalities to work together to achieve common resilience goals. Norfolk and Portsmouth are examples of two cities that could share resources and knowledge. Norfolk has conducted asset mapping and has provided a list of measures to be implemented across the city to protect those assets (City of Norfolk, 2016). Meanwhile, Portsmouth is still in the stages of evaluating the flood risks and vulnerabilities. Collaborating with Norfolk would be in line with Portsmouth's resiliency goal, "Work with regional, state, and federal agencies to mitigate the impacts of climate change" listed in their comprehensive plan (City of Portsmouth, 2018). It is in the best interest for municipalities to work across boundaries to achieve resilience to flooding, as increasing the adaptive capacity of the entire watershed will benefit each municipality. While this research focused on how the watershed-scale framework applies to the Hampton Roads region in Virginia, this framework can be applied to coastal regions globally.

Limitations and Future Work. There are several ways in which this research is limited. First, the delineation of the shoreline is not perfect, meaning estimations of inundated land area may not be completely accurate. Delineation of coastal areas is difficult due to the dynamic nature of tides. Additionally, the flood model used in this study is a bathtub model and does not reflect how hydrology and flood-protection infrastructure may impact flooding. Future research could more accurately model flooding by creating a higher resolution delineation and a hydrodynamic flood model that accounts for movement of water in a developed space. Another limitation of this study is that the projected impacts do not account for changes in population, land use, and land cover over time. While future land use data does exist, we elected to use the existing land use data to identify losses of potentially developable vacant land and to remain consistent over time, since the future land use data is not consistent across future time horizons and municipalities. The population estimation method used in this research does not account for the complexities of population distribution within the block group and changes over time. Future research could use dasymetric mapping and future population projections to predict impacted populations more accurately.

This research is limited in that it treats flooding and flood impacts as a binary: flooded or not flooded. In real life, the impacts of flooding can be shaped by the water depth, velocity of flow, and other factors not included in this study. Because of this, the degree of damage done cannot be assessed. Further, some impacts are cascading, meaning a population can experience a flood impact despite their properties not being flooded. Finally, this study modeled how SLR affects episodic flooding and not permanent inundation. Permanent inundation is more likely than a storm surge event to cause relocation of people and businesses and loss of wetland area.

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3. Conclusions and Summary

This study found that the rate at which the 2% AEP hazard area adjusted for different SLR scenarios is dependent on the location and not consistent over time. Many of the watersheds in Hampton Roads that will see the most change over time overlap with more than one municipality. The key impacts identified in this study include episodic inundation of military land, which had the highest rate of inundation throughout the Hampton Roads region. In urban watersheds, such as within the Elizabeth River watershed, the commercial and industrial land is at risk of high levels of inundation as well. The protection of these assets is key to maintaining the economic status of Hampton Roads. Additionally, the ecological resource of wetlands was found to be the land cover type most at risk of inundation throughout the region, risking the natural buffer from flooding. The urban Elizabeth River watershed does not have a lot of wetland area, so it is imperative that municipalities work together to protect these shared assets. Increased flood resilience in one municipality serves to benefit other municipalities within the same hydrologic system.

Despite the efforts on a regional scale to identify the risks of sea level rise and establish a framework for adaptation, there are disparities between municipalities in their progress towards the implementation of adaptation measures. While Norfolk has produced extensive advanced resilience plans all the way by the end of this century, Portsmouth is still in the flood risk evaluation stage. Implementation at a watershed scale would be more effective and equitable than the neighborhood-scale adaptation planning. It would also ensure that actions of one municipality do not worsen the adaptive capacity and risk of other neighboring administrative locations. Policy at this scale would not only achieve the Virginia Coastal Resilience Master Planning Framework's (2020) goal of regional cooperation but would also be consistent with the climate change research being conducted at the watershed scale (Cheng et al. 2017; Dudula & Randhir 2016; Shannon et al. 2019, Choden et al., 2020). While this research focused on impacts specific to Hampton Roads, Virginia, the framework used is applicable to coastal communities globally. This approach to flood risk assessment allows any coastal community to identify hydrologic systems within a given region are most exposed to flooding, which systems will experience the most change due to SLR, and to make adaptation strategies based on the impacts within a watershed. The watershed framework for the impact analysis and resiliency planning would encourage municipalities to work together to achieve a shared goal of adaptation and resilience.

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