Toward Collaborative Adaptation: Assessing Impacts of Coastal Flooding at the Watershed Scale

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Abstract
The U.S. Mid-Atlantic coastal region is experiencing higher rates of SLR than the global average, especially in Hampton Roads, Virginia, where this acceleration is primarily driven by land subsidence. The adaptation plans for coastal flooding are generally developed at the municipal level, ignoring the broader spatial implications of flooding outside the individual administrative boundaries. Flood impact assessments at the watershed scale would provide a more holistic perspective on what is needed to synchronize the adaptation efforts between the neighboring administrative units. This paper evaluates flooding impacts from sea level rise (SLR) and storm surge among watersheds in Hampton Roads to identify those that are most at risk of coastal flooding over different time horizons. It also explores the transboundary implications of flooding on the municipalities within the watershed, and on the land uses and land covers throughout this region and within the case study watershed. The 2% Annual Exceedance Probability (AEP) storm surge flood hazard data and NOAA's intermediate SLR projections were used to develop flooding scenarios for 2030, 2060, and 2090 and delineate land areas at risk of combined flooding. Findings show that five out of 98 watersheds will see a substantial increase in inundation, with two of them intersecting multiple municipalities. They also indicate significant inundation of military, commercial, and industrial land uses and wetland land covers. Flooding will also impact residential areas concentrated in urban areas along the Elizabeth River and in Hampton City, supporting the need for collaborative adaptation planning on hydrologically influenced spatial scales.

Keywords: coastal, flooding, sea level rise, watershed, adaptation

1. Introduction

Coastal communities are increasingly experiencing 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 will

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likely occur more frequently and lead to surface flooding (IPCC 2014, USGCRP 2018). Sea level rise (SLR), which will further augment the frequency and severity of coastal flood events, has been observed globally and is projected to continue in the future (IPCC 2014; Parris et al. 2012). Consequently, nuisance or high tide flooding is 300-900% more frequent now than 50 years ago (Lindsey 2019). Based on the literature review conducted by the National Oceanic and Atmospheric Administration, there is high confidence that SLR will increase between 0.2-2 meters by 2100 (Lindsey 2019). The IPCC 2100 projections suggest that Global Mean Sea Level (GMSL) will increase between 0.43 (RCP2.6) and 0.84 (RCP8.5) meters at a rate of 15 mm/year globally (Oppenheimer et al. 2019).

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, Virginia, have occurred since 1998. Further, the "The Hague" neighborhood of Norfolk is experiencing an increase in hours of flooded streets per year, with hours under water per year reaching 300 in the late 2000s (Atkinson et al. 2013).

Rising sea levels will exacerbate flood risk from storm surges, particularly in urban coastal communities. Critical facilities, such as hospitals, schools, and police and fire stations 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). Similarly, Considine et al. (2017) analyzed the potential impact of SLR and storm surges on four watersheds in Norfolk and Virginia Beach and found that SLR (0.46 and 0.91 meters) alone would have little impact on the critical infrastructure, but SLR combined with 100-year storm surge would pose a high threat for critical infrastructure within the study area.

Flooding associated with SLR also has a significant economic impact on coastal communities. 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. Some of those impacts stem from the ability of the workforce to commute to work and access alternative travel routes (Considine et al. 2017). Economic impact could also 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 required to purchase flood insurance from the National Flood Insurance Program (Habete and Ferreira 2017; FEMA 2019). Recurrent or permanent inundation will also reduce property values, an outcome that has been identified as one of the main concerns among residents living in flood-prone areas (Bukvic and Harrald 2019).

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, built features, and stormwater infrastructure. Yet, the majority of coastal vulnerability assessments use political boundaries as a unit of analysis (Bukvic et al. 2020), such as the flood impact study conducted by the Hampton Roads Planning District Commission (McFarlane 2012). Multiple studies demonstrate why this approach may be problematic. For example, based on the stakeholder interviews, John and Yusuf (2019) found that the most significant barrier to coastal adaptation is a legacy of "regional conflicts" with administrative boundaries being perceived as deterrents to implementation of effective adaptation strategies (p. 161). Many studies recognize climate change impacts on hydrologic systems and propose adaptation strategies on the watershed scale (Cheng et al. 2017; Dudula and Randhir 2016; Shannon et al. 2019, Choden et al. 2020), showing precedent for studying human systems at a natural system scale. Additionally, Enrı´quez-de-Salamanca (2018) proposed that adaptation and resilience to flooding could be achieved through watershed management of land use practices. Hampton Roads, as the urban center of coastal Virginia, is unique. While each jurisdiction is its own administrative and governance entity, their social capital and economic infrastructure are highly codependent and interrelated (Bukvic and Harrald 2019). Recognizing the importance of watershed-scale approach, Considine et al. (2017) conducted a flood impact study of four watersheds near the Norfolk-Virginia Beach boundary to study how risk and adaptation planning span across neighboring jurisdictions within that area. Finding the most effective and comprehensive way to adapt to SLR is especially important for this coastal region, due to its dense population and presence of vital federal facilities, ports, historic sites, and natural resources.

Even though the areas adjacent to the coast often receive disproportionate attention in the flood risk research, flooding will also affect populated areas along the creeks and rivers further inland, especially with the increase in extreme rain events. Assessing impacts on a watershed-scale will provide insights into which river systems vulnerable to flooding will have the most impact on adjacent communities. Among studies using watersheds as the spatial scale of analysis, two studies (Joyce et al. 2018; Kolok et al. 2009) were conducted outside the Hampton Roads area and one studied just four sub-watersheds within Norfolk and Virginia Beach (Considine et al. 2017). Therefore, this study evaluates both extent and impacts of storm surge flooding at different SLR scenarios and time horizons at an all-inclusive watershed scale in the Hampton Roads area. It also provides estimates of permanent SLR inundation to indicate which areas would become inaccessible over time. However, SLR represents only a water level baseline and does not capture compounding risks stemming from the anticipated changes in the storm surge dynamics that would more accurately capture aggregate impacts on the coastal communities (Rezaie et al. 2021). The paper further measures the impacts of storm surge flooding on land use, land cover, and population on a regional level and within a selected case study location to produce spatially explicit information to help inform adaptation planning in this geographic location and other similar coastal, flood-prone urban landscapes.

2. Materials and methods

Study Locations. The study is focused on the Hampton Roads Planning District that encompasses 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 administrative boundaries (**Figure 1**). The impacts of storm surge flooding at different SLR scenarios were analyzed for all 98 watersheds 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, population densities, and socioeconomic and institutional characteristics, creating unique circumstances within each watershed.

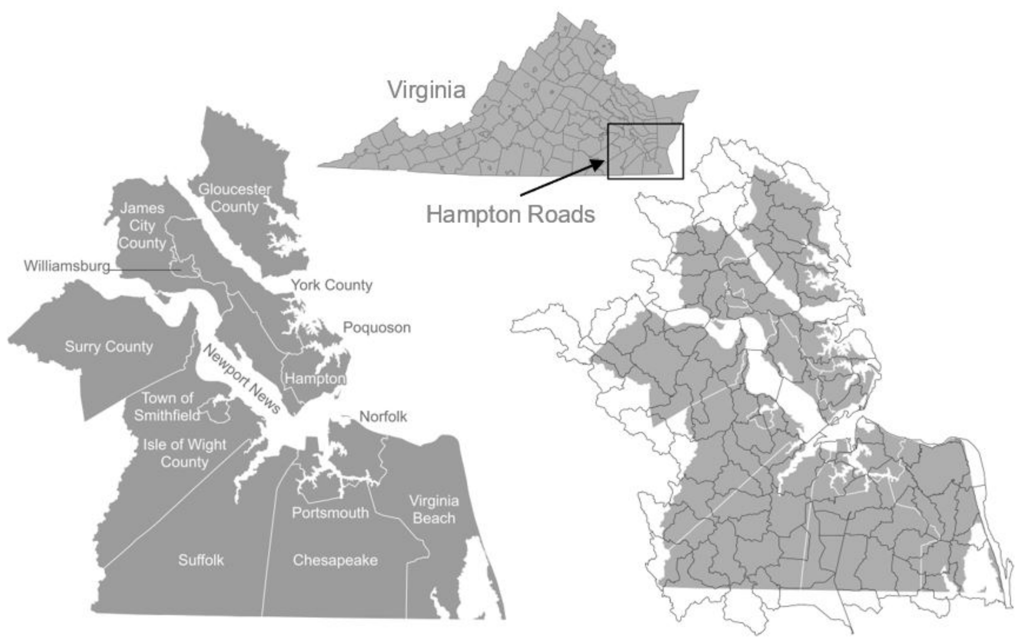

Figure 1. Hampton Roads municipalities (left), the 12-digit HUC watersheds that intersect them (right), and the location reference of study area within Virginia (top-center).

Table 1 shows population densities that range from 190.9 people/km^2 in Isle of Wight County to 4,570.8 in Norfolk, capturing the spatial extent from more rural areas to densely populated 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 Hampton Roads municipalities in this study (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. To characterize the spatial extent of coastal flooding, we first assessed the spatial extent of permanent inundation extents using different SLR scenarios. We then applied detailed evaluations of combined storm surge and SLR flooding and its impacts. Inundation corridors are the areas projected to be flooded under given SLR and storm surge scenarios. In this paper, our estimates are based on the 2% annual exceedance probability (AEP) storm surge flood hazard due to tropical cyclones (inclusive of tropical storms and hurricanes) and extratropical storms (popularly known as Nor'easters), 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, Nadal-Caraballo personal communication). The methods employed in the NACCS study are consistent with FEMA's methodology for Flood Insurance Rate Maps.

The NACCS tropical cyclone surge hazard characterization uses the joint probability method with optimal sampling (Resio and Irish, 2015 and references therein) and 1031 synthetic tropical cyclone surge simulations (ADCIRC; e.g., Dietrich et al. 2011) where astronomical tides are incorporated through superposition of 96 unique tidal phases with surge-tide nonlinearity adjustments. Nonlinearity here refers to the divergence from a linear trend in SLR for each station. The NACCS extratropical storm surge hazard characterization is based on dynamic astronomical tide and storm surge simulations of historical Nor'easters. Flood elevations were simulated atop a mean sea level represented by the 1983-2001 tidal epoch mean sea level datum; this level is assumed to represent mean sea level in 1992, namely the middle of the tidal epoch (Cialone et al. 2015, M. Cialone personal communication). The NACCS-reported 2% AEP flood elevations in the study area are characterized by a median value of 2.39 m, NAVD88 (1992 mean sea level), with 90% of the stations between 1.29 to 2.88 m, NAVD88 (1992 mean sea level).

We projected the 2% AEP flood elevations for the year 2000 (base year) and 2030, 2060, and 2090 (reflecting corresponding SLR scenarios). Intermediate SLR projections from NOAA (Sweet et al. 2017) were used as they represent scenarios that are more relevant for policy making. Relative to the 2000 sea level, these SLR scenarios in Hampton Roads are 0.3m (2030), 0.7m (2060), and 1.2m (2090). The impact of SLR on flood elevation is not linear, where the sum of present-day flood elevation and projected future SLR may not be correct and will likely be substantially biased high or low (e.g., Smith et al. 2010, Mousavi et al. 2011). Thus, the NACCS study includes a nonlinearity assessment with the surge simulated dynamically with a 1 m SLR scenario (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 (considered to have a base year of 1992) 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 this product to the sum of the 1992-basis 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 SLR scenario is higher than the 1 m scenario. 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 30m. 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. 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).

Permanent inundation due to SLR was mapped by selecting all cells on the DEM under the new MSL (NAVD88; 0.25 m, 0.65 m, 1.15 m., respectively). To ensure hydrologic connectivity, cells that did not intersect with bodies of water were excluded from the analysis. 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 the 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 (Siverd et al. 2019). 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 (USGS NLCD 2011) within the inundation corridors were estimated for each scenario. 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 (USGS NSD 2020). The structures are typed according to the Homeland Security Infrastructure Program (HSIP; U.S. Geological 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.

3. Results

***Coastal flooding at the watershed scale*.** Watersheds around the Back Bay and in Hampton will have 63% of the area permanently inundated by 2090 SLR (**Figure 2**). This type of flooding would lead to permanent land loss or the loss of functions due to saltwater submergence. The areas of highest SLR exposure include watersheds in the City of Hampton (i.e., Fox Hill and Grandview residential neighborhoods), parts of the Plum Tree Island National Wildlife Refuge in Poquoson, and areas around the Back Bay in Virginia Beach (i.e., mostly open space within the Natural Area Preserves, National Wildlife Refuge, and the State Park). Even though SLR serves as a valid indicator of permanent spatial impacts, it only represents a water level baseline. Focusing solely on this climatic driver would underestimate the comprehensive flood risk stemming from the compounding effects of high tides, storm surge, and fluvial inundation (Moftakhari et al. 2017). Therefore, we are using combined storm surge and SLR flooding for a more detailed impacts analysis on land use and land cover in selected case study areas.

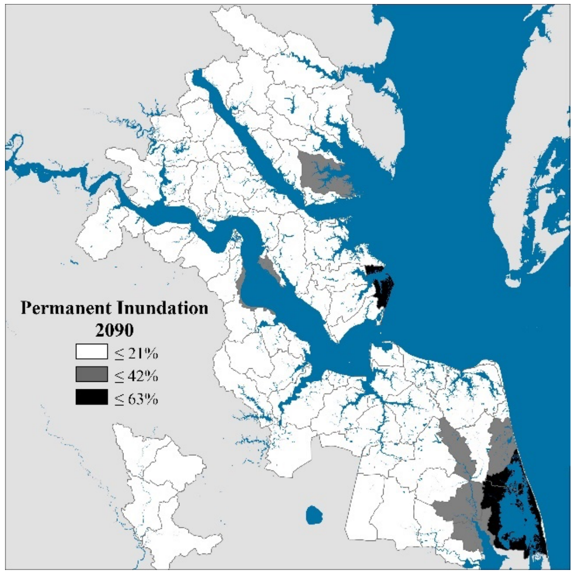

Figure 2. Percent watershed area permanently inundated under the 2090 SLR scenario of 1.2m.

The majority (71 out of 98) of the watersheds within our study area, including the ones adjacent to the ocean and other waterways, have less than 33% of area within the 2% AEP flood hazard area, even with the addition of 2090 sea level projections (**Figure 3**). Other watersheds have more extensive flood exposure, even for current conditions. For the 2000 baseline scenario, the 2% AEP inundation corridors indicate that five watersheds in the southeastern region of Hampton Roads would experience flooding in more than 33% of area, 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 have 33% of the area within the inundation corridor, making these municipalities at the highest risk 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. Under current-day conditions, this watershed would be nearly 81% within the inundation corridor and would reach 98% after 2090 projected SLR. High exposure to inundation from SLR and storm surge is not exclusive to coastal watersheds. Inland watersheds along the Elizabeth River in Portsmouth and Chesapeake exhibit inundation exposure levels between 33-66% for the 2060 and 2090 scenarios. Even though these watersheds have the highest percentage of area within the 50-year floodplain, they have low levels of permanent inundation, even with 1.2m of SLR.

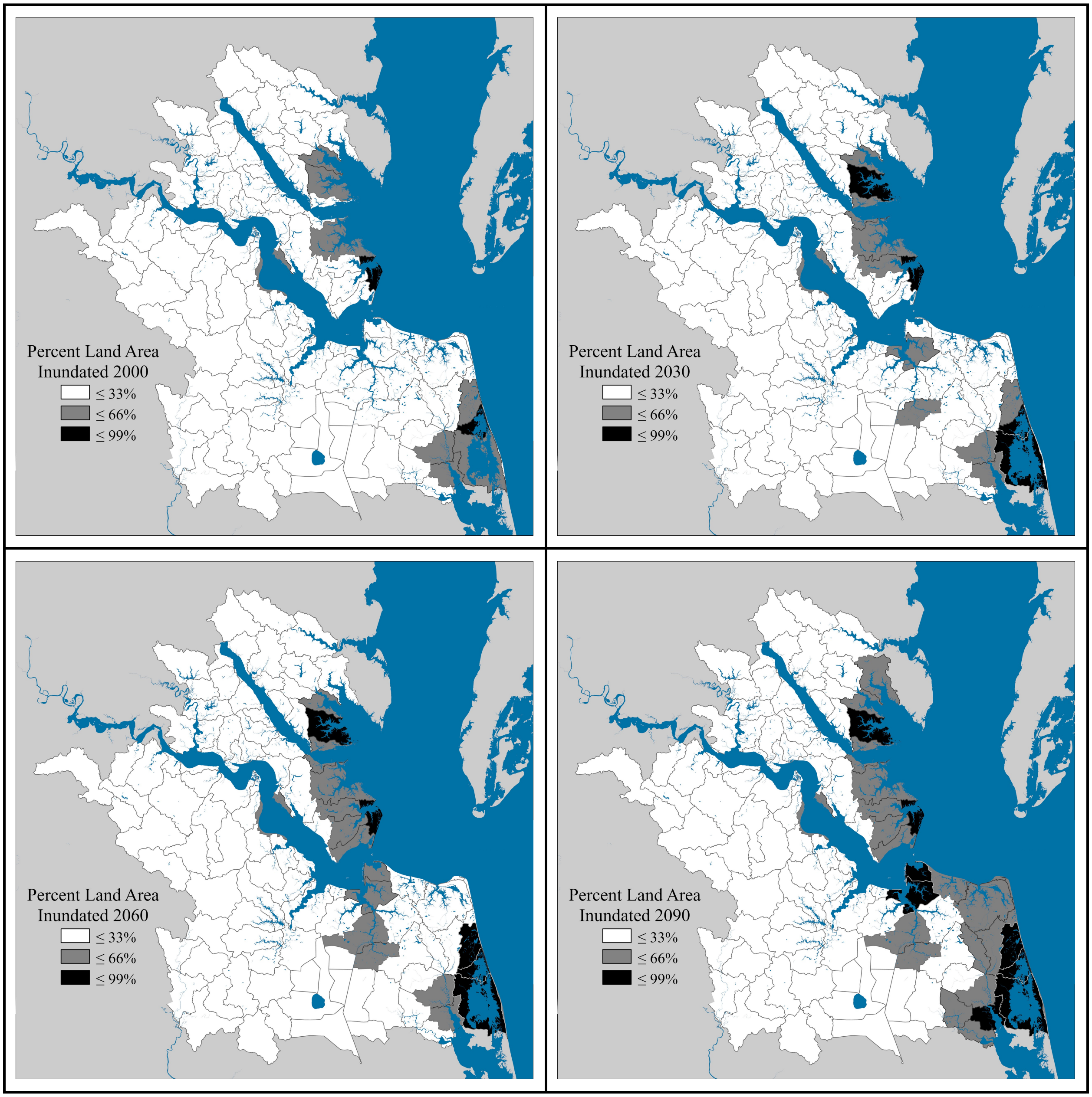

Figure 3. Percent of watershed area within the inundation corridor (50-year floodplain) before SLR (2000) and after SLR for the 2030 (0.3 m), 2060 (0.7 m), and 2090 (1.2 m) scenarios for Hampton Roads watersheds (12digit HUC).

Moreover, some watersheds have almost 99% of the area within the 50-year floodplain by 2090, with the substantial portion of this area that will be permanently inundated. Five watersheds have the highest change in the percent land area prone to storm surge flooding compared to other watersheds (**Figure 4a**). Even though the Back River- Frontal Chesapeake Bay watershed exhibited the highest proportion of flooded area, the percentage of land area inundated did not change much over time. In contrast, the Elizabeth River watershed, located in Norfolk and Portsmouth (watershed 1 in Figure 4a), is the watershed with the highest absolute percent change between 2000 and 2090 at 38.4%. **Figure 4b** shows that the change in percent of 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.

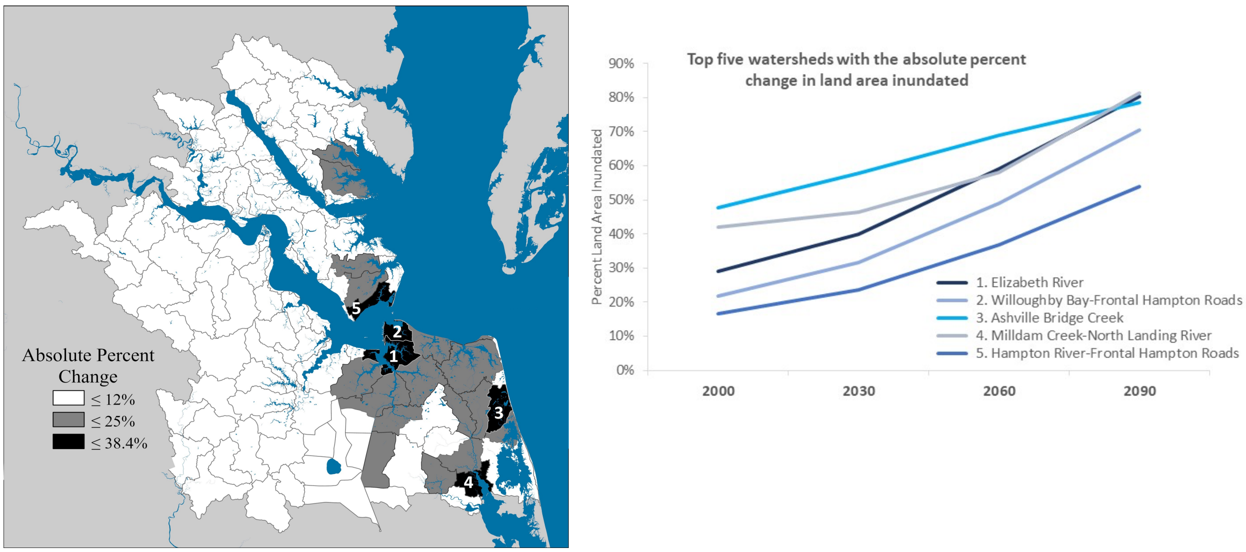

Figure 4. Absolute change in percent of watersheds within 50-year floodplain from 2000 to 2090 (4a map on the left) and the change in inundation over time for the five watersheds with the largest increases in area subjected to storm surge: increases: 1. Elizabeth River; 2. Willoughby Bay-Frontal Hampton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

***Land use-specific flood impacts*.** As for the land use impacts in the Hampton Roads region, excluding Surry County, the land use category most impacted by SLR-driven storm surge flooding is military. Before SLR, 24% of all military land is situated in the inundation corridor (**Table 2**). This impact increases to 38% (9% permanently inundated) by 2090. Residential areas will be also significantly impacted by storm surge with 31% area affected by 2090 (3% permanently inundated) and also with the sharpest increase in percent of land inundated from 2000 to 2090. Institutional land is the least affected land use category, with only 7% within the inundation corridor, even after the 2090 SLR scenario. Although vacant and open space land uses may have similar extent of impacts, the vacant land still has the potential to be developed while open space is designated as an open area and valued as such.

Even though as much as 34% of open space will be within the inundation corridor by 2090 (25% permanently inundated), damage to structures is not a concern. However, flood-driven physical loss of open space and its utility may still have significant adverse effects on the communities. For example, open space provides many benefits, especially in waterfront coastal settings (Dahal et al. 2018), such as esthetic appeal, ecosystem services, environmental and flood control protection, mitigation of heat island effect, health and recreational opportunities, and psychosocial support (Lee et al. 2015). Conversely, 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 impacted by storm surge (i.e., within the 50-year floodplain) and permanently inundated percent from SLR alone [in brackets] for each major land use category before SLR (2000) and after SLR for NOAA intermediate projections for Norfolk, VA in 2030 (0.3m), 2060 (0.7m), and 2090 (1.2m).

50-Year Floodplain [Permanently inundated]				
HRPDC Land Use Category	**2000 (%)**	**2030 (%)**	**2060 (%)**	**2090 (%)**
Vacant	12	14 [1]	16 [5]	18 [7]
Open Space	27	29 [2]	31 [19]	34 [25]
Residential	16	19 [0]	24 [2]	31 [3]
Military	24	28 [0]	33 [5]	38 [9]
Institutional	7	7 [0]	7 [2]	7 [3]
Mixed Use	6	8 [0]	10 [0]	14 [0]
Agricultural	7	8 [1]	9 [4]	11 [5]
Commercial and Industrial	10	11 [0]	14 [1]	17 [2]

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 m resolution of what type of land is actually in a space, and not just the assigned land uses to parcels based on the administrative categories. The land cover type that would have the highest proportion of its land area within the inundation corridors in 2090 includes developed areas with low to high intensities. This is not surprising given the level of urbanization of this region. However, across the first three SLR scenarios, the most affected land cover is mixed wetlands (woody wetlands, herbaceous wetlands, and shrub/scrub). With 2000 baseline inundation estimates, 20% of wetlands in Hampton Roads are located within the inundation corridors with very little change over time. Given that wetlands in this area are generally located along the shoreline and rivers, it is not surprising that the propagation of flooding further inland would not have an increased effect. However, the depth of inundation could increase, which would change the impact of flooding on the existing wetlands. The land cover types most affected by permanent inundation with SLR are developed open space (up to 10%) and mixed wetlands (up to 25%).

Table 3. Percent of area impacted by storm surge (i.e., within the 50-year floodplain) and permanently inundated percent from SLR alone [in brackets] 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).

50-Year Floodplain [Permanently inundated]				
NLCD Land Cover Category	**2000 (%)**	**2030 (%)**	**2060 (%)**	**2090 (%)**
Developed, Open Space	10	13 [5]	17 [8]	21 [10]
Developed, Low-High Intensity	11	15 [0]	21 [0]	31 [1]
Mixed Agriculture	3	4 [0]	6 [0]	8 [2]
Non-Wetland Vegetated	2	3 [0]	4 [0]	5 [1]
Mixed Wetlands	20	20 [3]	23 [18]	24 [25]

Elizabeth River Watershed Case Study. To further illustrate the benefits of watershed-level analysis of flood impacts, the additional analysis of impacts on the land use, land cover, and critical facilities was conducted in the Elizabeth River watershed. This watershed was chosen because it had the largest absolute change in the percent land area inundated at 38.4% and the highest projected flood impacts. Approximately 80% of this watershed is projected to be within the inundation corridor by 2090, making it one of the most vulnerable watersheds to both the land area inundated and the absolute percent change in land area impacted. Further, its overlap with two neighboring municipalities, Norfolk and Portsmouth, highlights how watershed-scale assessments can inform cross-boundary adaptation planning.

The land use category that will be impacted the most in this watershed is open space (48-84% from 2000 to 2090), closely followed by the vacant areas and residential land at 82% and 80% by 2090 respectively (**Table 4**). Before SLR, only 22% of the commercial and industrial land is within the inundation corridor. However, by 2090, this proportion will increase to 74%. On the Norfolk portion of the watershed, the land use category with the most area at risk of flooding 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 with 81% of areas within the inundation corridor by 2090. Further, 57% of residential land and 72% of commercial and industrial land will be in the inundation corridor by 2090.

In the Elizabeth River watershed, 46% of its wetlands will be located within 2000 inundation corridor, making it the most impacted land cover type before SLR. However, by 2090, developed land would experience the largest extent of flood-prone area at 78%. When compared between municipalities, 67% of wetlands in Norfolk will be flooded under the 2000 inundation scenario and only 31% of Portsmouth's wetlands, meaning potential wetland impacts are 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.

Table 4. Percent of impacted land area 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, and 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 & 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%

Out of the 19 critical facilities within this watershed, only two facilities would not be directly impacted by the storm surge flooding with the 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. Addressing the infrastructure needs of the city are listed as a priority for Norfolk, which 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.

4. Discussion

Our analysis shows that watershed-scale flood impact assessment is an effective approach to generate policy-relevant information to support adaptation of coastal communities based on the spatial movement of water and its implications for the municipalities and region as a whole. 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 one of the resiliency goals for the Commonwealth of Virginia of identifying which geographic areas should have a priority for coastal resilience interventions (Commonwealth of Virginia 2020). While the Elizabeth River watershed was selected for further impact analysis in this report, there are several other watersheds where transboundary adaptation planning would be vital for effective flood resilience. 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.

Even though this paper is not focused on assessing the impact of flooding on residents, 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 a more vulnerable city than the surrounding localities on 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/redevelopment within the floodplain and rather invest in the neighborhoods at lower risk of flooding (City of Norfolk 2016). Conversely, Portsmouth wants to increase its population and has 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 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 located 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 retirees who decide to stay in the region and military families (Hampton Roads Planning District Commission 2017). In Norfolk, 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 or permanent inundation, there would be a significant impact on the Hampton Roads economy (Union of Concerned Scientists 2016). Therefore, municipalities have the incentive to work together with the military to develop adaptation and resilience strategies to protect this land use. One such example of effective partnership is evident from the cooperation between Chesapeake, Portsmouth, Norfolk, and Virginia Beach and the military on evaluating the impact of SLR on assets critical to military operations. The Norfolk-Virginia Beach Joint Land Use study focused on five main challenges associated with SLR and recurrent flooding: commuting, accessibility to facilities and services, stormwater infrastructure, utilities, and region national security coordination (Hampton Roads Planning District Commission, 2019b). The Portsmouth-Chesapeake JLUS is ongoing but also focuses on transportation and land use impacts surrounding military installations (Hampton Roads Planning District Commission 2021).

While the inundation of commercial and industrial land is of concern for the whole region, it is particularly troubling for the Elizabeth River Watershed. This watershed contains major shipping and transportation hubs such as a shipping port, Virginia International Gateway, 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 lead to Na-tech events where natural hazards lead to technological disasters (e.g., accidental releases of hazardous materials) 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's 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.

Flooding impacts to wetlands in Hampton Roads could mean potential stress to or even loss of specific wetland types and their flood protection and other ecosystem services. The disproportionate effect on wetlands found in this research is consistent with the findings from Kleinosky et al. (2007), which estimated that 39% of wetland area would be impacted with 90cm of SLR and a category one hurricane storm surge. However, storm surge extents 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. For example, salt marsh wetlands may be able to recover from a storm event, but saltwater from a storm surge could lead to conversion of freshwater, particularly forested, wetland types. Further, the preservation of wetlands is reliant on their ability to migrate inland, which is often restricted by the developed land (Kirwan and Gedan 2019). In highly developed watersheds, like the Elizabeth River watershed, inland migration would be substantially limited, highlighting the value of adjacent open space there and in other flood-prone watersheds.

5. Conclusions

Many of the watersheds in Hampton Roads that will see the most change in flood exposure within the 2% AEP hazard area and different SLR scenarios overlap with more than one municipality. This finding reinforces the importance of impact assessment at a watershed-scale that can help identify transboundary flooding issues and foster cross-jurisdictional collaboration among local governments on adaptation and resilience planning. Such an approach will ensure that adaptive interventions in one municipality do not exacerbate flooding conditions in the neighboring communities and increase their vulnerability. Watershed-scale flood assessments are not only useful for studying flood-related impacts but are also helpful for identifying specific hydrologic systems at risk and the most effective regional adaptation strategies with co-benefits for all neighboring municipalities.

The main impacts identified in this study include episodic inundation of military assets, which will experience the highest rate of storm surge inundation throughout the Hampton Roads region. In urban watersheds, such as within the Elizabeth River watershed, the commercial and industrial land is also at high risk of repetitive flooding. The protection of these assets is key to maintaining the economic status of Hampton Roads. Among land cover types, wetlands will have the highest exposure to flooding throughout the region. Sea level rise can affect wetlands' important role as an ecological resource and flood buffer and eventually lead to their permanent loss (Blankespoor et al. 2014). However, wetlands can adapt to SLR if there is sufficient sediment input and accommodation space to support their landward migration (Schuerch et al. 2018; Borchert et al., 2017). Otherwise, wetlands risk becoming permanently submerged subtidal ecosystem or experiencing conversion to either mangrove or pond environments (Andres et al. 2019). Despite the efforts to identify the long-term risks of sea level rise on a regional scale and establish a framework for adaptation, there are notable disparities between municipalities in their progress towards the implementation of adaptation measures. While Norfolk has produced advanced resilience plans over long-time horizons, neighboring 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. Policy at this scale would not only align with the Virginia Coastal Resilience Master Planning Framework's (2020) goal of regional cooperation but would be also consistent with the growing body of research centered on the watershed scale (Cheng et al. 2017; Dudula and Randhir 2016; Shannon et al. 2019, Choden et al. 2020). While this research focuses on the impacts specific to Hampton Roads, Virginia, the approach used is transferable to other coastal communities to inform transboundary collaboration and resiliency planning.

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