Spring 2024

Coastal Virginia Ecological Conservation

Mapping Wetland Change Across the Coastal Regions of Virginia to Identify Areas Most Susceptible to Wetland Loss and Most in Need of Wetland Protection Advocacy

DEVELOP Technical Report
March 29th, 2024

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1. Abstract

Wetlands provide many ecosystem services to coastal regions, such as water quality improvement, carbon sequestration, and flood control. However, sea-level rise poses a threat to wetlands and coastal communities. Wetland areas are declining as they are forced to migrate inland, and communities are exposed to heightened risks of inundation and storm surge. We partnered with Wetlands Watch, an environmental non-profit that aims to protect wetlands through education, advocacy, and community engagement. This project used Landsat satellites, lidar-derived products, and tidal data to determine the vulnerability of tidal wetlands and predict migration patterns. We conducted a binary suitability analysis, using maximum wetland migration capacity, slope, future locations of the intertidal zone, and anthropogenic barriers to estimate the future extent of wetlands on a decadal scale from 2030 to 2100. By the end of the century, we estimated a 78% decline in tidal wetland area. We also identified developed land suitable for being re-naturalized to facilitate wetland migration. Minimally urbanized and agricultural lands that overlap with potential locations for tidal wetlands are the most optimal for being converted. However, re-naturalization does not mitigate the overall wetland loss observed through the end of the century. This data can be used by Wetlands Watch to communicate the rising threat that wetlands face in response to sea-level rise and underscores the feasibility of using remote sensing to study and predict this process. These preliminary findings highlight the need for further research to better understand wetland migration, loss, and prioritization for conservation efforts.

Key Terms

Sea-level rise, remote sensing, wetland migration, suitability modeling, predictions, Landsat, lidar

2. Introduction

2.1 Background

Wetlands typically regard highly biodiverse and productive ecosystems associated with seasonally or perennially wet growing environments (Dertien et al., 2020). They play a crucial role in maintaining ecological balance by aiding in nutrient and hydrologic cycling, acting as a carbon sink, regulating water quality, and serving as habitat for native species (Clean Water Act, 1972; Mitsch et al., 2015). Coastal wetlands also provide many regulatory ecosystem services to neighboring communities, such as being a natural buffer against storm damage to shorelines and coastal infrastructure by contributing to flood-flow desynchronization (Hovis et al., 2021).

However, climate change currently threatens the sustainability of wetlands, manifesting wetland decline and loss through rising temperatures, changing precipitation patterns, and sea-level rise (SLR; Blankespoor et al., 2014). The Hampton Roads area is among the most vulnerable regions in the United States to the effects of SLR, second only to New Orleans in terms of risk (Tompkins & Deconcini, 2014). Hampton Roads' low-lying coastal plain and proximity to the Atlantic Ocean and Chesapeake Bay expose it to heightened risks of inundation and storm surge events. Additionally, local land subsidence amplifies the impacts of rising sea levels. Regionally, Glacial Isostatic Adjustment (0.6–1.8 mm/year) and groundwater extraction (2–4.8 mm/year) are the biggest drivers of this subsidence (Ezer & Atkinson, 2015).

In response to SLR, wetland vegetation may accrete vertically or migrate horizontally. Wetlands have numerous methods of vertical accretion, which include plant growth, blue carbon accumulation, and inorganic sedimentation (Breda et al., 2021). Wetlands in Virginia are estimated to have a maximum vertical accretion rate of 5 mm/year (~1.6 feet/century; Morris et al., 2016). This rate is slower than the current rate of SLR, which estimates an additional 4.5 feet of sea level by 2100 (Figure 2; National Oceanic and Atmospheric Administration, 2017). This difference necessitates the ability of wetlands to migrate horizontally, expanding inland as new growth extends the wetland boundary.

One of the many concerns associated with SLR is the landward encroachment of the intertidal zone (ITZ). The ITZ, or littoral zone, is the area of shoreline exposed to air at low tide and covered with seawater at high tide, serving as the transition zone between terrestrial and marine ecosystems (Dai et al., 2022). As sea level rises, so does the ITZ. Shallow coastal areas, such as those found in Virginia, are especially vulnerable to this phenomenon. In these regions, the ITZ appears larger because there is less variation in elevation between high and low tides. The ITZ can extend further inland, and so even small changes in sea level can result in substantial alterations to the coastline (Archimedes, 287–212 BC). This migration threatens coastal communities by increasing the risk of inundation, flooding, and erosion, which can lead to property damage, loss of infrastructure, and displacement of residents (Intergovernmental Panel on Climate Change, 2022). Additionally, the encroachment of the ITZ may disrupt the ecological balance of wetlands or even drown them altogether (Morris et al., 2016). Therefore, protecting the resilience and sustainability of Virginia's coastal communities and wetlands necessitates identifying the future boundary of the ITZ.

2.2 Case Study: Poquoson, Virginia

One example of the consequences of sea-level rise and the encroachment of the ITZ is the formation of ghost forests, which are landscapes characterized by the stands of dead or dying trees. These forests emerge from saltwater intrusion into coastal areas, particularly in low-lying regions. As sea levels elevate, saltwater encroaches further inland, inundating previously freshwater habitats (Aguilos et al., 2021). Additionally, ghost forests can exacerbate coastal erosion and increase the vulnerability of adjacent communities to storm surges and flooding (Nordio et al., 2024). One major example of this within our study area is Poquoson, Virginia. As shown in Figure 1, over the past fifteen years, vegetation in Poquoson has largely died off, appearing less vibrant in 2023. This loss in vegetation is caused by saltwater intrusion and the subsequent emergence of a ghost forest, shown in the photograph on the right. While this is just one example of the effects of SLR, the majority of Viginia's coastline undergoing similar changes.

Summer 2008 Landsat Color Infrared	Summer 2023 Landsat Color Infrared	Poquoson Ghost Forest (Photo taken by Sean Asbrand)

Figure 1. Visualization of the change in vegetation near Poquoson, Virginia, using color infrared imagery from Landsat where bright red indicates vegetation and navy indicates water. The 2023 imagery in low-lying wetland areas is less vibrant, and some areas indicate surface water. Moreover, saltwater intrusion along the forest edge has led to dieback, shown in tan on the 2023 imagery. The photograph on the far right highlights the ghost forests that have emerged due to this dieback.

2.3 Research Framework: Objectives, Partners, and Study Area

Coastal wetlands, such as Virginia's salt marshes, tidal flats, and estuarine environments, are vulnerable to the effects of SLR, leading to increased inundation, erosion, and loss of habitat (Moomaw et al., 2018). Their degradation not only exposes vulnerable populations to increased risk of flooding but also threatens the integrity of infrastructure and regional ecosystems (Livingston et al., 2018). This project aims to prioritize conservation efforts and further explain why wetlands are both essential to Virginia communities and are at risk of being destroyed due to accelerated SLR. Specifically, the project includes the following objectives: (a) determine the feasibility of using remote sensing techniques to aid in understanding how wetlands have and will migrate because of SLR, (b) map the extent of current wetlands and how they have evolved over recent history, (c) develop a model that accurately calculates future ITZs accounting for subsidence and SLR, and (d) produce communication products that can be used to advocate change to lawmakers and educate the general public. To maximize the inclusion of vulnerable wetlands, the study area for this project includes coastal areas from Virginia's southern border to the Piankatank River in the north, as well as Virginia's Eastern Shore

(Figure 2). Furthermore, to understand how the extent of coastal wetlands has changed in recent years, and to estimate where wetlands may migrate in the future, this project employs a variety of relevant coastal wetland geographic data from 2008 to 2024.

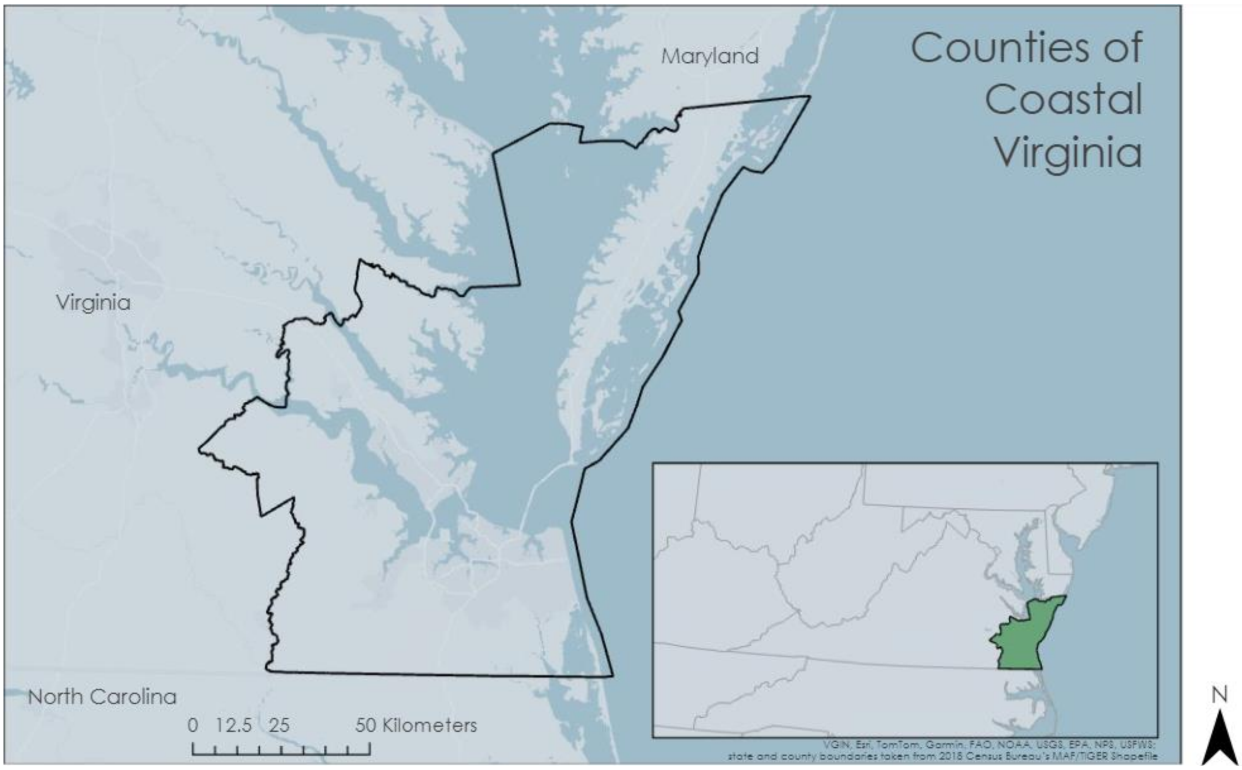

Figure 2. The study area includes the counties and cities of Accomack, Chesapeake, Gloucester, Hampton, Isle of Wight, James City, Mathews, Newport News, Norfolk, Northampton, Poquoson, Portsmouth, Suffolk, Surry, Virginia Beach, Williamsburg, and York. [Basemap: VGIN, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS].

This project's partner is Wetlands Watch, a nonprofit advocacy group based in Norfolk, Virginia, that works to protect Virginia's wetlands through education, legislation, and community engagement. Enhanced legal protection of wetlands at the state level is increasingly important in the wake of the *Sackett v. EPA* ruling, which removed federal protections of up to 63% of wetlands (*Sackett v. Environmental Protection Agency*, 2023; Frazer, 2023). Representatives of Wetlands Watch will be present at the 2024 General Assembly, allowing the opportunity to advocate for the protection of wetlands to state lawmakers. They can use maps, data, and deliverables from this project to foster a more engaging and beneficial discussion with legislators about the importance and the fate of wetlands in Virginia, ideally leading to more robust protections for wetlands in the state.

Remote sensing technologies provide an opportunity for wetland identification across larger areas and at a higher frequency when compared to traditional in situ methods. Moreover, remote sensing data products are becoming increasingly available for free to the public, enabling the potential for cheap, open-source, large-scale, and up-to-date environmental mapping applications and analyses. Most commonly, researchers have mapped wetland extent using publicly available satellite imagery in the visible, near-infrared, and short-wave infrared portions of the electro-magnetic spectrum processed via a combination of spectral indices, hydrological models, and pixel- or object-based AI classification (Hemati et al., 2023; Kaplan & Avdan, 2017; Molino et al., 2021; Rapinel et al., 2023). Similarly, a growing body of literature models historic instances of wetland loss, degradation, and migration (Fekri et al., 2021; He et al., 2022; Vanderhoof et al., 2020). However, the literature on predictive wetland mapping due to SLR is sparse, with existing studies focusing exclusively on forested wetlands (Doyle et al., 2009; Hughes et al., 2022). Moreover, as the rate of SLR is expected to accelerate during the twenty-first century—outpacing wetland accretion rates (Figure 3)—historical trends will become less effective at forecasting future wetland change and migration (Morris et al., 2016; National Oceanic and Atmospheric Administration, 2017). Unfortunately, satellite imagery is only available up to the present, requiring increased reliance on other more static factors such as slope, elevation, rate of SLR, and impervious surface maps for predictive mapping of future wetlands.

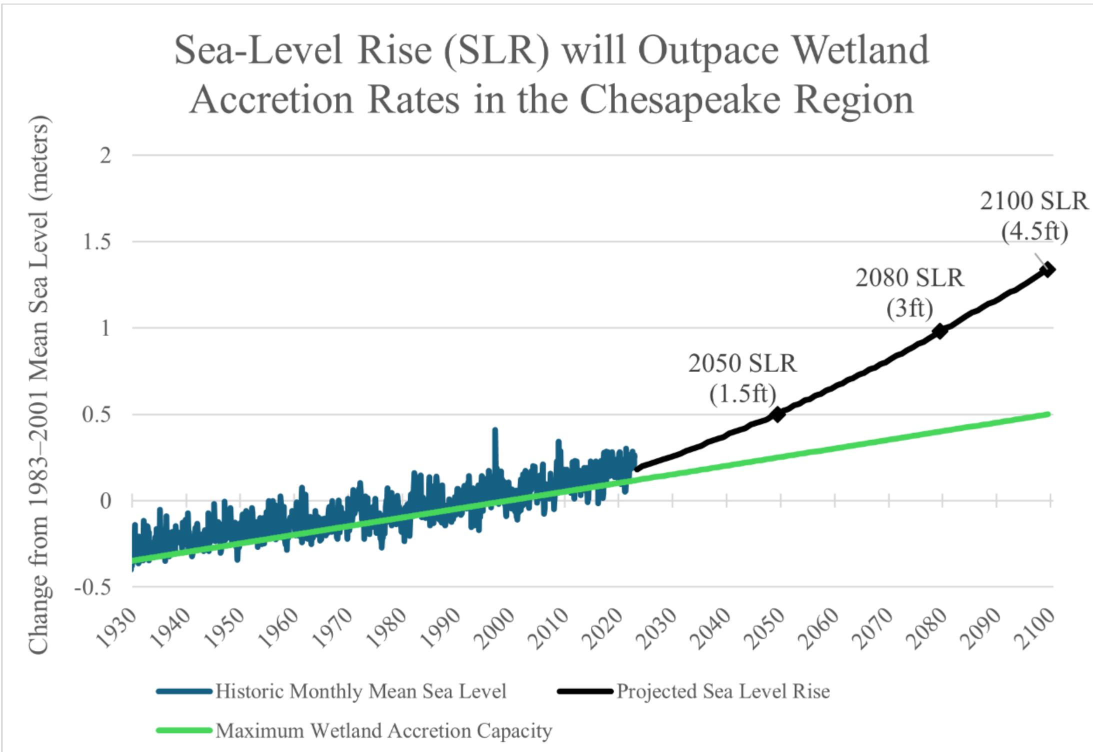

Figure 3. Based on the maximum wetland accretion capacity of 5mm per year and projected SLR, current intertidal wetlands will drown, forcing them to migrate landward (Morris et al., 2016; National Oceanic and Atmospheric Administration, 2017).

3. Methodology

3.1 Data Acquisition

3.1.1 Digital Elevation Model

Digital Elevation Models (DEMs) can be used for various geoprocessing tasks, such as finding the terrain's slope or determining how SLR impacts areas of different elevations. The DEM used in this project comes from the United States Geological Survey (USGS)'s 3-Dimensional Elevation Project (3DEP; United States Geological Survey, 2019). 3DEP provides lidar-derived DEMs at one meter resolution covering this project's entire study area. More important for SLR work, however, the 3DEP data covering our study area is quality level 2, having a vertical root mean square error of no more than 10 cm (~4 in; United States Geological Survey, 2019). Data of this quality enables, with significantly higher accuracy than other DEMs, predictions of which year individual pixels will become inundated with seawater.

3.1.2 Land Use/Land Cover

Next, we sought out data that will show where coastal wetlands currently exist within our study area. The extent of current wetlands comes from a layer produced by the Chesapeake Bay Program (Chesapeake Conservancy, 2018). Created through a collaboration of the Chesapeake Conservancy, USGS, and the University of Vermont Spatial Analysis Lab, this one-meter resolution land use and landcover (LULC) dataset is derived from the National Agriculture Imagery Program and lidar. Its most recent dataset provides spatial information from 2017/2018, classifying land use into 18 categories and 3 types of non-forested wetlands: tidal, riverine, and terrene.

Additionally, we utilized USGS's National Land Cover Database (NLCD) to identify anthropogenic barriers to wetland migration. This data is mainly derived from Landsat data and provides a map of current man-made and impervious land cover types at a 30-meter resolution (USGS, 2021). For our purposes, we defined anthropogenic barriers as urban land, pastures, and cropland.

3.1.3 Sea-Level Rise

The next dataset required for our analysis was SLR. The SLR data for this project was derived from the National Oceanic and Atmospheric Administration (NOAA)'s 2017 Global and Regional Sea Level Rise Scenarios. NOAA presents five estimations of SLR for every decade between 2000 to 2100 for a variety of data collection points in coastal Virginia and estimations range from relatively low to extreme change (National Oceanic and Atmospheric Administration, 2017). We selected the intermediate SLR forecast for Sewell's Point, a tidal data collection station in Norfolk, Virginia. We chose this point because it was used to determine the Hampton Roads Planning District Commission's (HRPDC) policy for SLR adaptation (McFarlane, 2018; HRPDC, 2023). The HRPDC represents local cities and communities in the Hampton Roads region, including large cities such as Hampton, Norfolk, and Virginia Beach, and is an authoritative source on policy and long-term planning.

3.1.4 Intertidal Zones

We wanted to collect data points that were evenly spaced temporally to determine an average high and low tide value for each section over 2023, the most recent year for which we have full tidal data. We started with the approximate dates of the spring equinox (3/20), summer solstice (6/21), fall equinox (9/22), and winter solstice (12/21) to discern representative tides throughout the year and create an average ITZ for 2023 within each section. However, the phase of the moon influences the strength of tides (Williams & Boggs, 2015). To standardize this effect when calculating the average high and low tides in our study area, we chose the date closest to these reference dates that were either first or last quarter moons, between 45 and 54 percent illumination (U.S. Naval Observatory, n.d.). Using this method, the four dates chosen from which to record the high and low tides at each station were 3/15, 6/10, 9/22, and 12/19.

Virginia tides are "semi-diurnal," meaning there are two high tides and two low tides per day, of approximately equal height (Rosen, 1977). To capture the full extent of the tidal range, we treated a day's worth of high and low tides as though it followed a mixed semi-diurnal pattern. Mixed semi-diurnal tides have two high tides and two low tides per day of *unequal* height; there is a higher high water, lower high water, higher low water, and lower low water (Figure 4; Nidzieko, 2010). For each date we chose at each station, we recorded the highest high tide and lowest low tide, giving us four data points for the high tide and low tide throughout 2023.

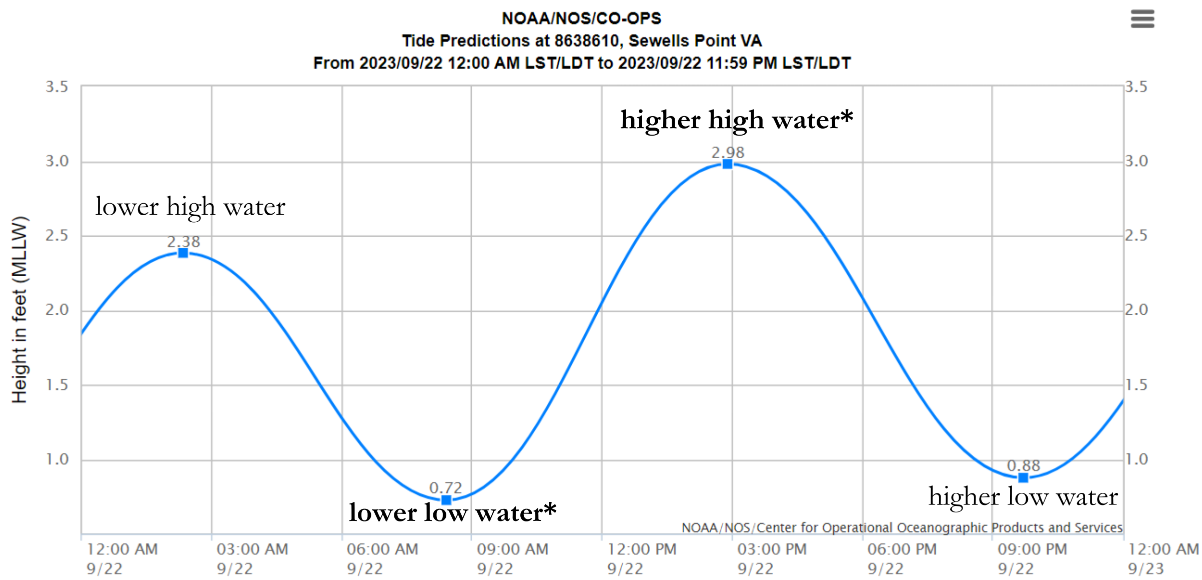

Figure 4. Tide chart of Hampton Roads (Sewell's Point) for September 22, 2023 (National Oceanic and Atmospheric Administration, n.d.b). Bolded points with an asterisk (*) indicate the values we recorded for the high and low tides of that day.

3.2 Data Processing

3.2.1 Maximum Wetland Migration Distance

Our base input is the boundary of total possible wetland migration. Since wetlands can horizontally migrate ~0.49 ±0.36 m/year (Schieder et al., 2018), this estimate creates an approximate upper threshold of wetland migration of 0.85 m/year, assuming there are no barriers to travel. For example, consider predicting the extent of wetlands in the year 2050 from our data acquisition in 2018. In theory, if wetlands migrated 0.85 meters every year for 33 years, they would migrate 27.2 meters by 2050, which is their maximum range of migration for that span of time.

We began data processing by determining the location of existing wetlands. The Chesapeake Bay Program's LULC data is county-based, which allowed us to use high-resolution LULC data for each of the seventeen counties included in our study area. Based on data provided by the National Wetlands Inventory and NOAA, the Chesapeake Bay Program delineated non-forested wetlands into three categories based on their water body proximity–riverine, terrene, and tidal. Because this project is concerned with wetlands in a broad sense, we used the ArcGIS Reclassify tool to dissolve these classifications into a binary layer, where we classified all wetland types as 1 and all other land uses as 0. To define the maximum migration range for each year of interest, we converted the binary wetlands layer to a polygon before creating a buffer of this maximum migration distance (Table 1). The buffer could then be converted back into a raster.

3.2.2 Slope

Using the 3DEP DEM, we used the Slope tool in ArcGIS to create a new layer visualizing topographic slope of the study area. We used the 16.7° slope threshold from Hemati et al. (2023)'s analysis of North American wetlands. Slopes below this threshold were classified as suitable (1) and slopes above it were classified as unsuitable (0; Table 1).

3.2.3 Anthropogenic Barriers

Emulating the methodology of Schieder et al. (2018), we defined anthropogenic barriers to wetland migration as developed lands classified by the NLCD as urban or agricultural. The land covers included in this classification were developed of any intensity, pasture/hay, and cultivated crops (Table A2). Anthropogenic barriers were classified as unsuitable (0), while all other land covers were considered viable for future migration and classified as suitable (1; Table 1).

Table 1
Summary of suitability criteria for tidal wetlands migration. Factors with an asterisk (*) indicate that suitable ranges change depending on the future year chosen for analysis.

	Suitable (1)	Unsuitable (0)
Maximum Wetland Migration*	Present	Not present
Slope	≤ 16.7°	> 16.7°
Anthropogenic Barriers	Not present	Present
Future Intertidal Zone*	Present	Not present

3.2.4 Future Intertidal Zone
To calculate ITZs across the Chesapeake Bay, we averaged higher high water and lower low water values to create one average high tide and one average low tide for each tidal station for 2023. NOAA divides these tide monitoring stations based on natural sections of Virginia's water bodies (Table A1). Six of these sections fell into our study area: Virginia – Outer Coast; Chesapeake Bay, Eastern Shore; Chesapeake Bay, Western Shore; Chesapeake Bay, Southern Shore, York River, and James River (National Oceanic and Atmospheric Administration, n.d.b). Because these regions experience unique tidal levels due to varying estuarine characteristics, we maintained this separation when collecting tidal data. For each section, we averaged all high tides and all low tides, which resulted in a single average high tide and low tide for each of the six estuarine sections of coastal Virginia. To utilize these divisions, we created polygons surrounding all stations that fell into each section and extended their boundaries to those of our entire study area, to include terrestrial environments that may become inundated by SLR and an accompanied encroaching ITZ (Figure 5).

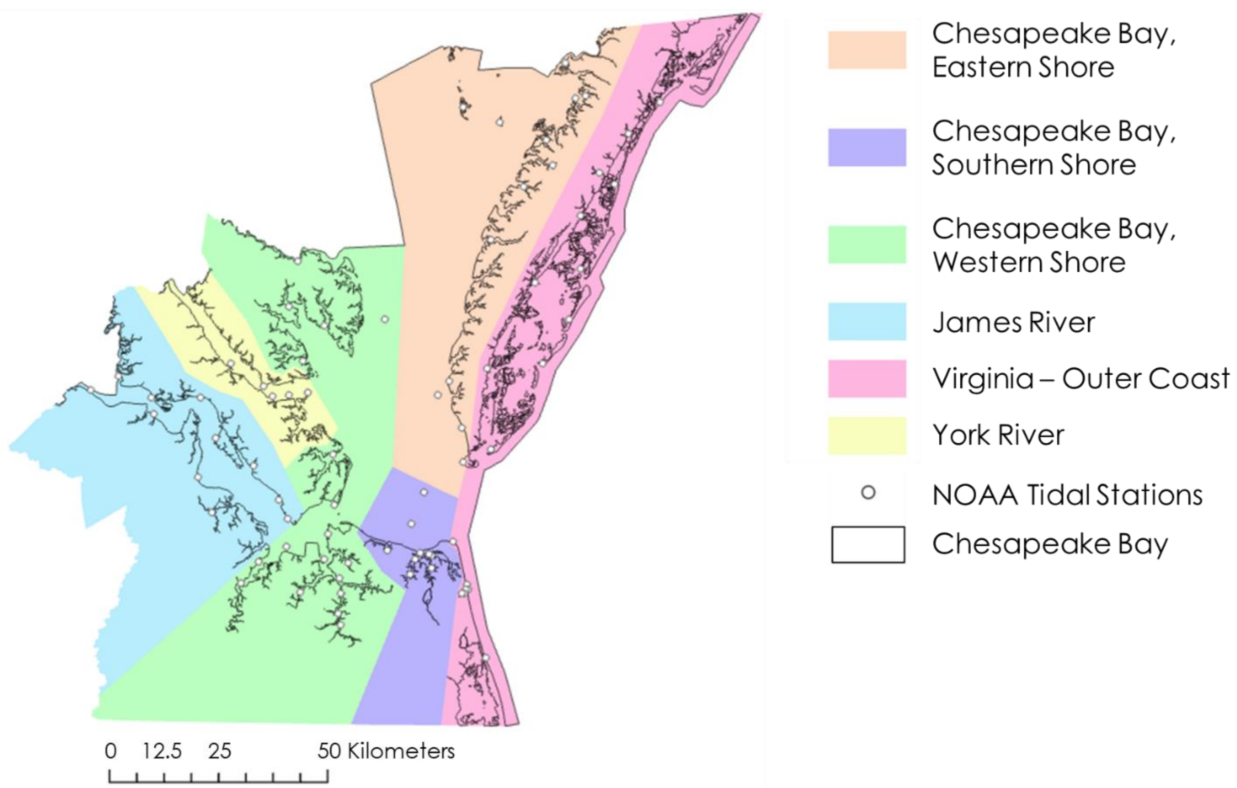

Figure 5. Six estuarine sections of coastal Virginia that are located in the study area, based on NOAA's Tide

Predictions webpage (National Oceanic and Atmospheric Administration, n.d.b; Virginia Department of Environmental Quality, 2022). Contains locations of NOAA's tidal monitoring stations (Table A1).

Using the decadal forecast of Sewell's Point SLR data, we interpolated linearly between points to obtain annual mean sea level estimates for our model. The result was relative mean sea level for every year from 2020 to 2100. These values were then subtracted from the original 3DEP DEM, creating new DEMs accounting for SLR in future years. Next, each 'future' DEM was split into separate rasters for each estuarine section so their ITZs could be calculated independently. For each section, mean higher high water and mean lower low water values were adjusted to account for elevation change due to different vertical datums used by USGS's 3DEP (North American Vertical Datum of 1988) and NOAA's tide sensors (1983–2001 National Tidal Datum Epoch; National Oceanic and Atmospheric Administration, 2018; National Oceanic and Atmospheric Administration, n.d.a.). 'future' DEM elevation values falling between the adjusted sectional mean higher high water and mean lower low water values represent the ITZ for that year. That range, representing the largest possible area suitable for tidal wetlands, was classified as suitable (1), while cells outside of the ITZ were classified as being unsuitable (0; Table 1). The exact model used to perform these steps is shown in the appendix (Figure A1).

3.3 Data Analysis

3.3.1 Binary Suitability Analysis

To determine where future wetlands may be located, we conducted a binary suitability analysis. This type of analysis focuses on determining the suitability of locations based on the presence or absence of specific criteria, rather than considering degrees of suitability characteristics of a weighted suitability analysis. Each input layer contained cells that were defined as either suitable (1) or unsuitable (0) for wetlands to exist in a given year. The four components used to determine suitability were maximum wetland migration, slope, ITZ, and anthropogenic barriers.

Once every layer was converted to a binary raster and projected in the correct coordinate system, we used the Raster Calculator in ArcGIS Pro to find areas of suitability for future wetland locations. Because we used four inputs for which being suitable was coded as a 1, a value of 4 indicated that the cell was a viable location for which a wetland might be in the future. Values of 1–3 indicated that one or more factors were not classified as suitable, rendering the entire cell as unsuitable. We repeated this process for every decade starting in 2030 and ending in 2100, generating eight unique maps for where wetlands may be located as sea level rises through the end of the century.

3.3.2 Urban Conversion for Wetland Migration

One component of advocating for the future protection of wetlands means advocating where urban environments might be removed to create land suitable for wetland migration. Our "urban conversion" suitability analysis reclassifies anthropogenic barriers into one of three categories based on how easy it might be to re-naturalize those land uses: (1) high potential for conversion, (2) some potential for conversion, and (3) no potential for conversion. For the 2021 NLCD dataset, we defined "high potential for conversion" as developed, open space; pasture/hay; and cultivated crops (<20% impervious surfaces). Developed, low intensity constituted "some potential for conversion" (20–49% impervious surfaces), while medium and high intensity developed land were defined as "no potential for conversion" (50–100% impervious surfaces; Table A2).

Developed, open space constitutes lands that are composed of less than 20% impervious surface. These spaces are commonly parks, golf courses, and vegetation planted for either erosion control or aesthetic purposes. These land covers are more easily removed than more developed land, reducing costs and displacement associated with urban conversion.

Agricultural land is another ideal candidate for conversion. As sea levels rise, coastal areas are increasingly susceptible to soil salinization, posing challenges for farmers. Elevated levels of saltwater intrusion into the soil can adversely affect crop yields by hindering plant growth and nutrient uptake (Gibson et al., 2021). Coastal farmers may experience reduced agricultural productivity and economic losses from declining crop yields. Moreover, salinization can compromise water quality in agricultural areas (Weissman and Tully, 2020). Recognizing that these lands may become increasingly unsuitable for traditional agriculture due to high salinity levels, transitioning them to wetlands may be beneficial, allowing room for wetlands to provide their vital ecosystem services to the coast. By facilitating wetland migration in response to the effects of SLR, such as soil salinization, coastal regions can foster ecological adaptation and long-term sustainability while maximizing the productive use of lands rendered unsuitable for conventional agriculture. Furthermore, cropland and pastures account for nearly 50% of all urbanized land cover in our study area, providing many avenues to explore conversion for wetland migration.

These suitability maps followed a nearly identical process to the binary suitability analysis, using maximum wetland migration, slope, and the future ITZ as binary inputs into the Raster Calculator. However, anthropogenic barriers were changed to reflect the possibility of urban conversion. "No potential for conversion" was classified as 7, "some potential for conversion" was classified as 17, and "high potential for conversion" was classified as 27; all other land covers were classified as 0. Combined with the binary inputs, the Raster Calculator yielded three outputs of interest. 10 indicated that the binary suitability criteria for maximum wetland migration, slope, and the future ITZ were met, but exist in highly developed areas that are not open to conversion. 20 meant that the same conditions were met in land covers that are possibly open to conversion. 30 indicated that all the binary suitability criteria were met and that these areas overlapped with land cover that is likely open to conversion. Areas with output codes of 30 are of most interest from a policy standpoint, as further research may be able to ascertain the specific localities that can be re-naturalized to make room for wetland migration. Like the binary suitability analysis, we created these maps on a decadal scale from 2030 to 2100.

4. Results & Discussion

4.1 Analysis of Results

4.1.1 Binary Suitability Analysis

Our binary suitability analysis yielded several important results. The projected area of tidal wetlands consistently and dramatically declines in the next 76 years. By 2100, the model estimates it will decrease from 491 square kilometers to 106 square kilometers, an approximate 78% decline in tidal wetlands by area (Figure 6a; Figure 6b; Figure 7). The largest declines take place between 2030 and 2060, where approximately 100 square kilometers of wetlands are lost every decade. This rate of loss decreases from 2060 to the end of the century, where it takes 40 years to lose another 100 square kilometers of wetlands.

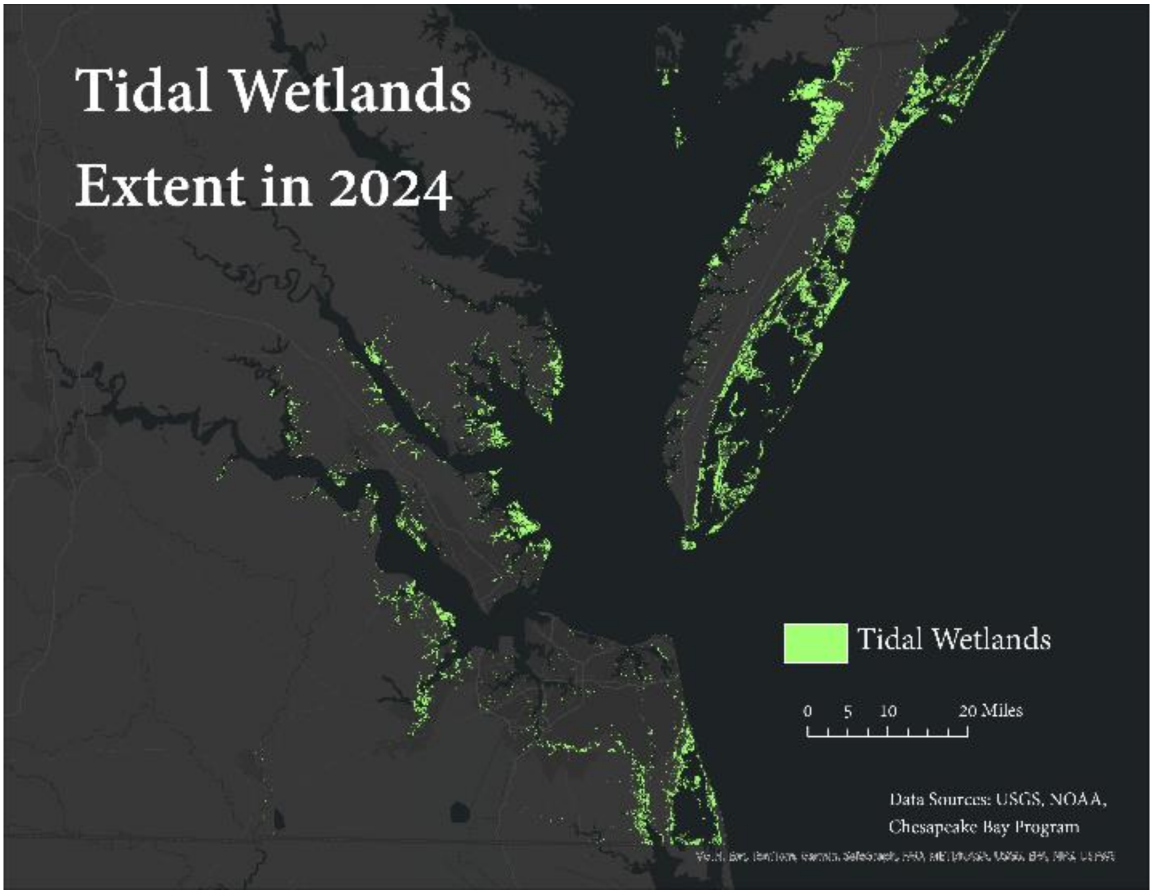

Figure 6a. Results of the binary suitability analysis. Green shows the predicted wetlands extent in 2024. [Basemap: VGIN, Esri, TomTom, Garmin, SafeGraph, METI/NASA, USGS, EPA NPS, USDA, USFWS]

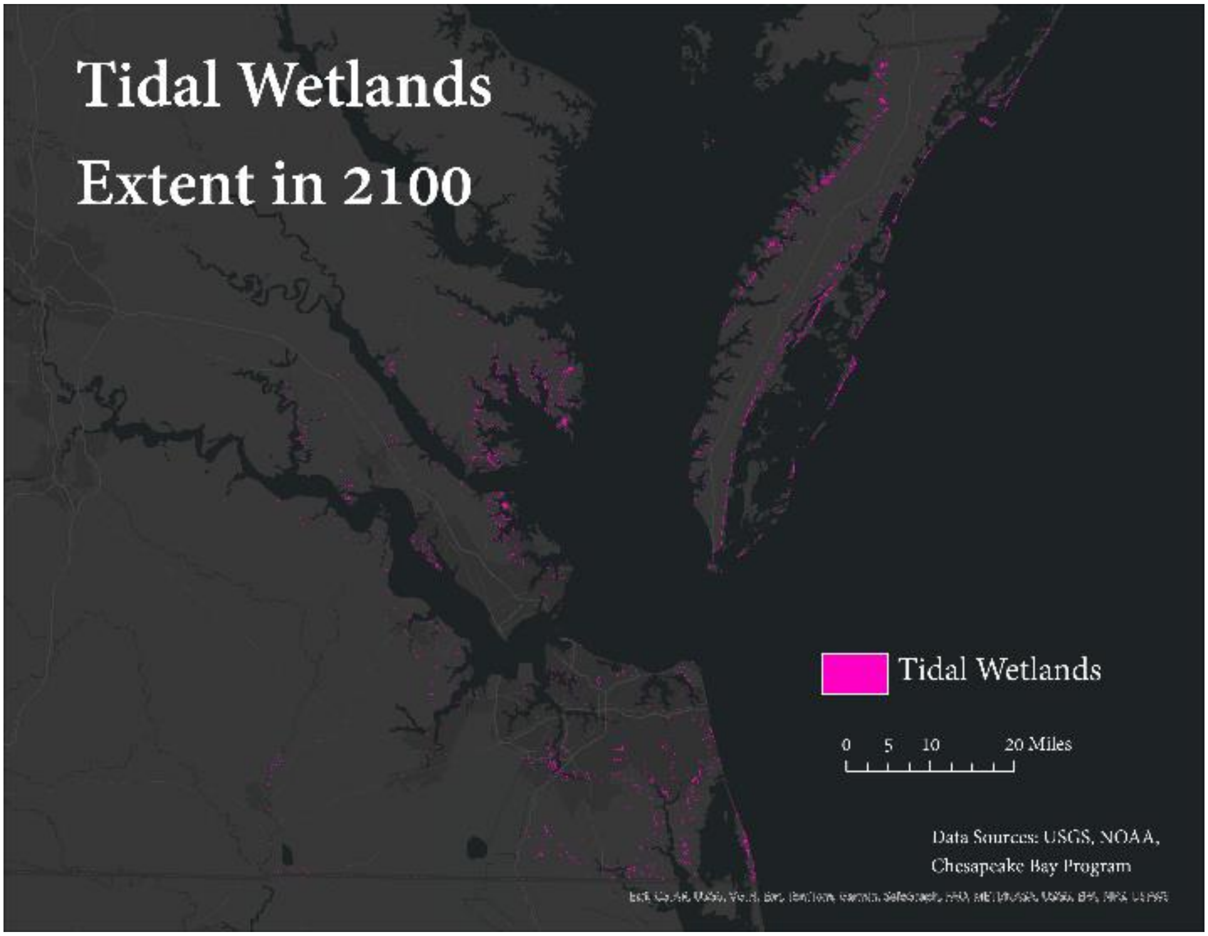

Figure 6b. Results of the binary suitability analysis. Pink shows the predicted wetlands extent in 2100. [Basemap: VGIN, Esri, TomTom, Garmin, SafeGraph, METI/NASA, USGS, EPA NPS, USDA, USFWS].

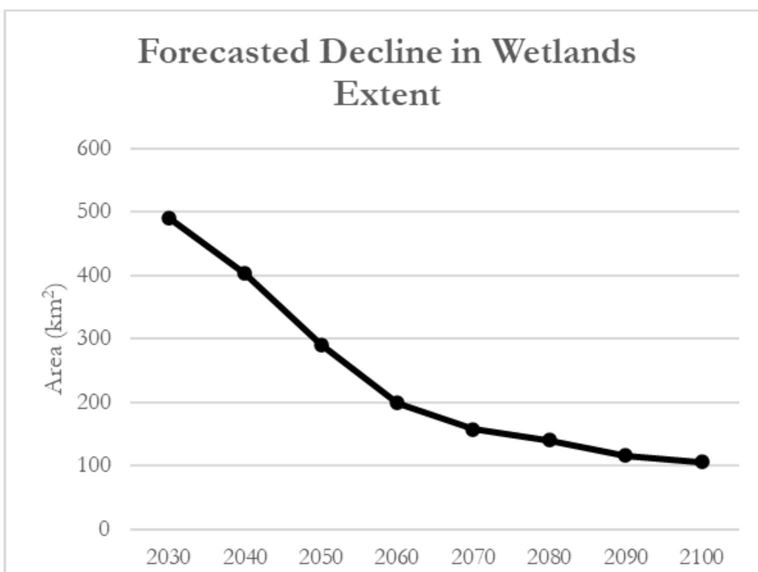

Figure 7. Forecasted decline in wetlands extent from our binary suitability analysis. This graph reveals a dramatic decline in area of wetlands, predicting a 78% loss in total area between 2030 and 2100.

Resources for the Future estimates that one hectare of wetland loss in developed areas costs society $8,290 in flood mitigation value, based on the National Flood Insurance Program's claims for Hurricane Sandy (Taylor & Druckenmiller, 2022). Between 2030 and 2100, our model estimates 385 square kilometers of wetlands to be lost. This means that within this 70-year period, approximately $319 million in flood mitigation value for coastal Virginia will be lost. In other words, every time a storm as powerful as Hurricane Sandy hits coastal Virginia, preserving those wetlands would save an additional $319 million in flood damage. Furthermore, this value is likely underestimated, since the National Flood Insurance Program's estimates do not cover properties outside the program (commercial, governmental, privately insured individuals, farm assets, and crop production) or account for the value of wetlands for recreation, habitat, water quality, and the fishing industry (Taylor & Druckenmiller, 2022).

4.1.2 Urban Conversion Suitability Analysis

Our urban conversion analysis focused on identifying areas within urban environments that could potentially be repurposed to facilitate the migration of wetlands, ensuring their long-term viability and ecological functionality. By categorizing anthropogenic barriers into distinct classes based on their suitability for conversion, we aimed to provide insights into feasible strategies for wetlands preservation amidst changing coastal dynamics. One notable aspect of our analysis is the trajectory of land suitability for urban conversion over time. From 2030 to 2100, there is a consistent increase in the proportion of land classified as suitable for conversion (Figure 8a; Figure 8b; Figure 9). This trend suggests a growing potential for repurposing man-made spaces to accommodate wetlands migration in response to SLR. For example, there appear to be many locations on the Eastern Shore that are highly suitable for conversion, due to its high concentration of agricultural land cover. Over time, this area may become unsuitable for agriculture, increasing the potential for tidal wetland migration.

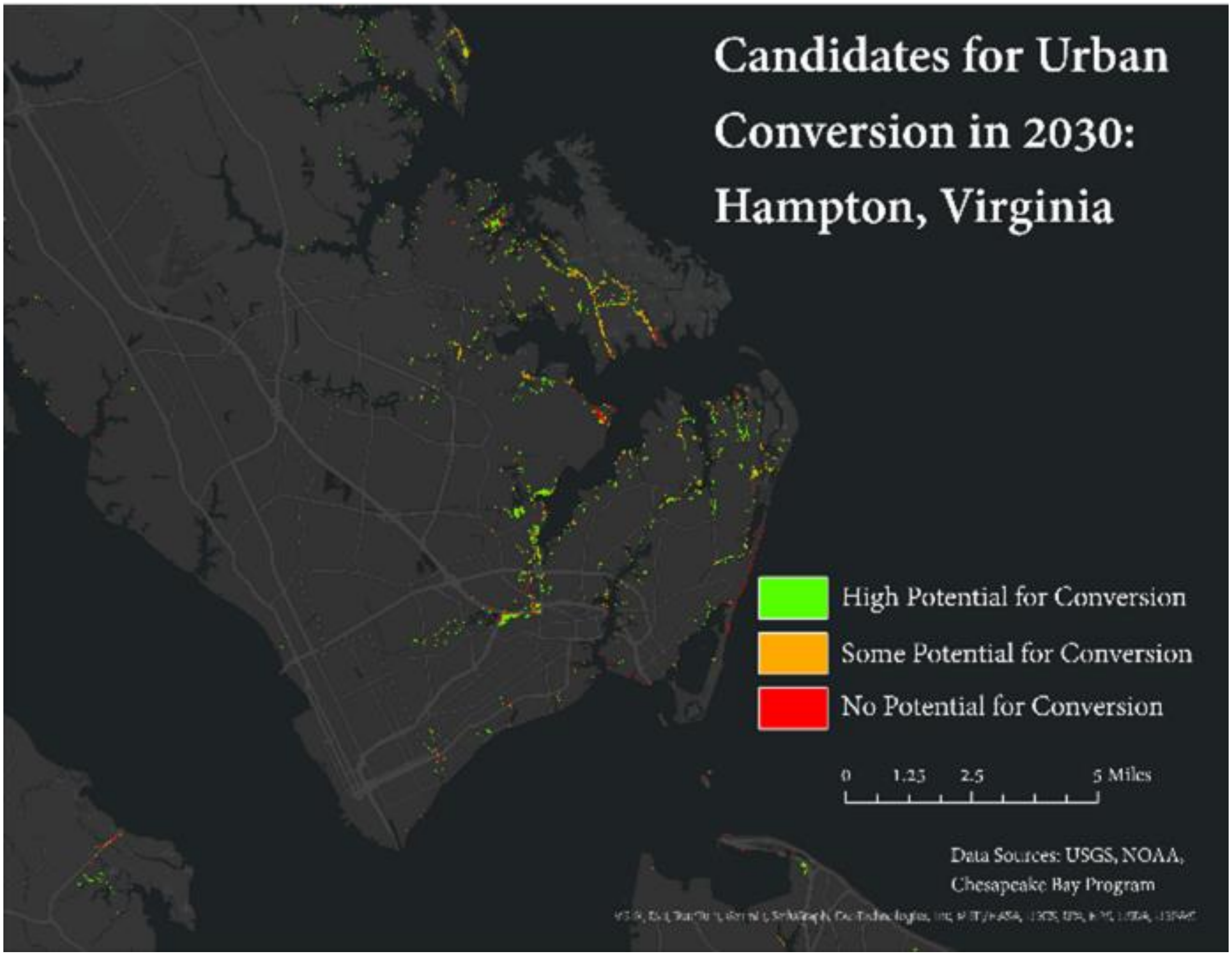

Figure 8a. Urban conversion candidates in 2030 in Hampton, Virginia. This map show locations that border wetlands suitable for conversion from anthropogenic barriers to wetlands. [Basemap: VGIN, Esri, TomTom, Garmin, SafeGraph, METI/NASA, USGS, EPA NPS, USDA, USFWS].

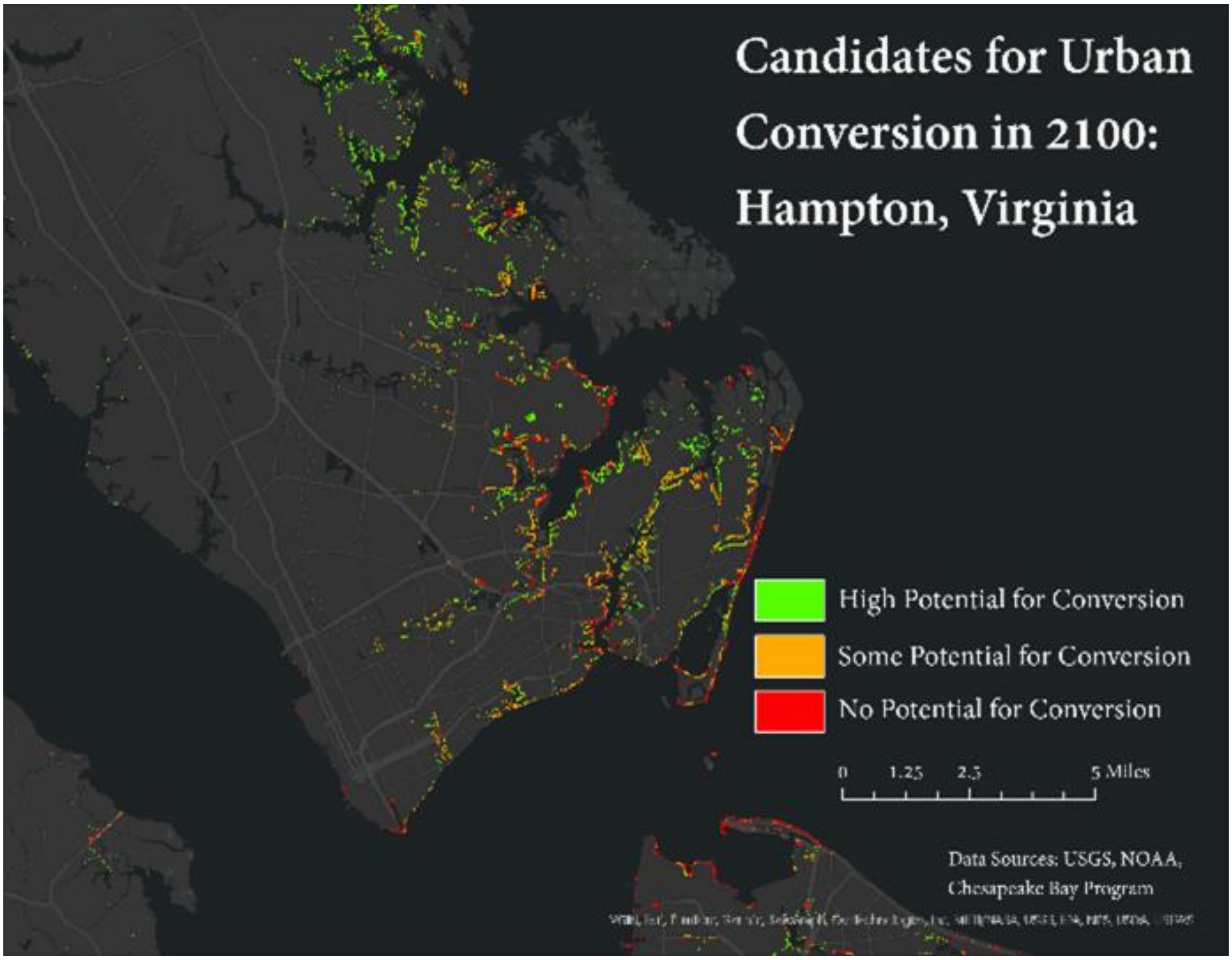

Figure 8b. Urban conversion candidates in 2100 in Hampton, Virginia. This map show locations that border wetlands suitable for conversion from anthropogenic barriers to wetlands. [Basemap: VGIN, Esri, TomTom, Garmin, SafeGraph, METI/NASA, USGS, EPA NPS, USDA, USFWS].

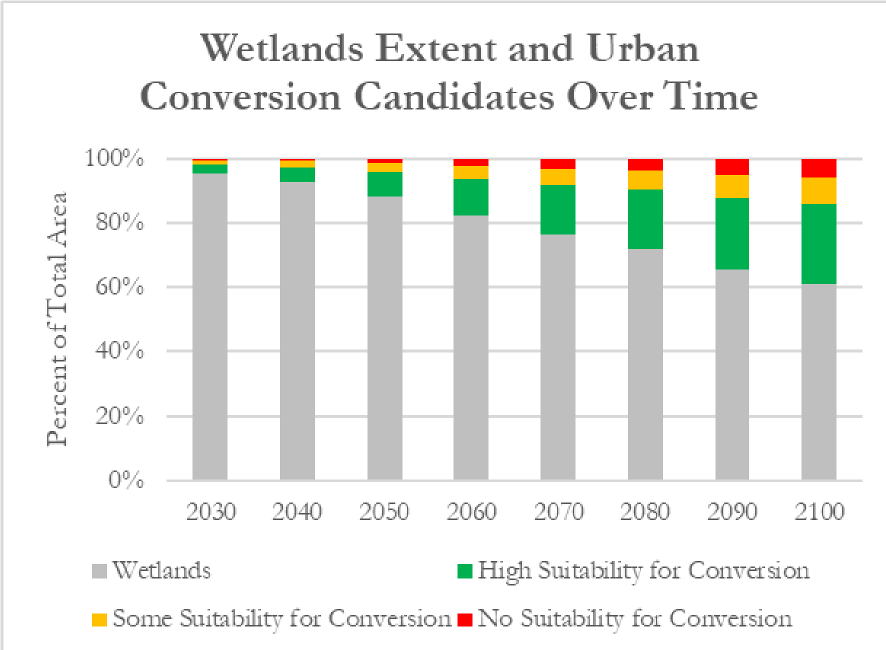

Figure 9. Wetlands extent and urban conversion candidates over time, by percentage of total area. This bar graph highlights the increase in proportion of land classified as suitable for conversion to wetlands through the end of the century.

Many of the most suitable lands for urban conversion may necessitate a lack of active intervention rather than proactive conversion efforts. All lands classified as having a high potential for conversion had less than 20% impervious cover, meaning that most of it is already green space. Transitioning maintained green spaces towards naturalized states is less intensive than removing urbanized land cover. This process may include actions such as refraining from traditional land management practices (i.e., mowing or landscaping), allowing vegetation to grow more freely and ecosystems to develop organically.

Despite these possibilities, urban conversion will not fully mitigate the loss in wetlands area caused by SLR (Figure 10). If every urbanized land cover, regardless of suitability, was converted to facilitate wetland migration, wetlands area could increase in 2100 by up to 68 square kilometers (Table 2). Also, it would increase projected cover in 2100 by 63%. However, this would still represent a 65% decline relative to the 2030 projection. Therefore, even large-scale efforts to maximize re-naturalization cannot fully offset the inevitable loss of wetlands area due to SLR.

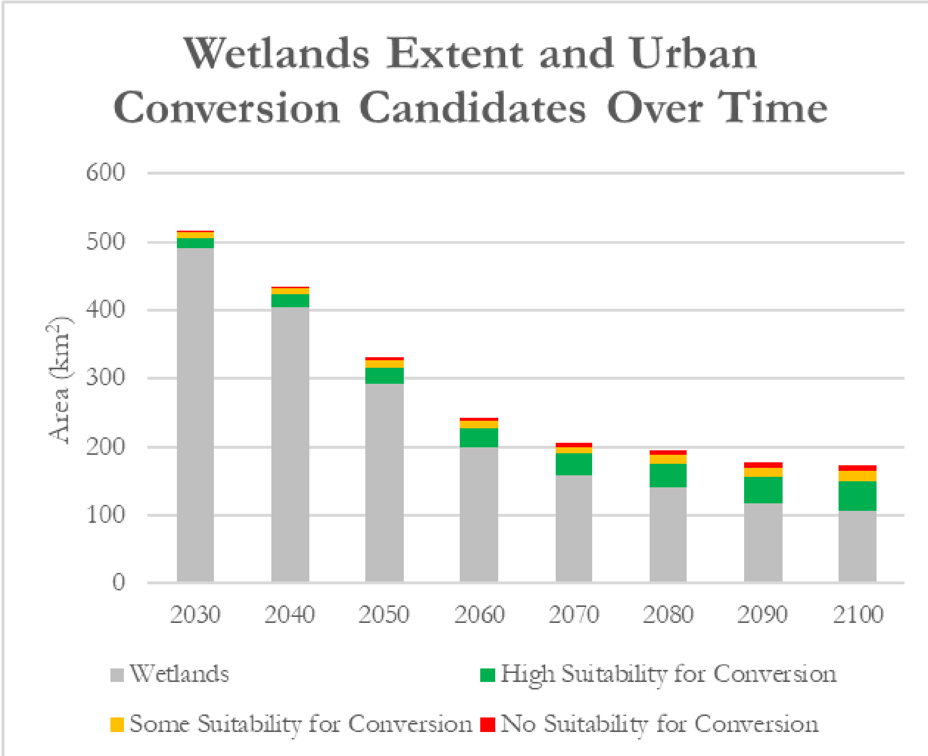

Figure 10. Wetlands extent and urban conversion candidates over time, by absolute area. This bar graph highlights the decrease in potential wetlands area through the end of the century and the idea that urban conversion alone cannot fully offset the loss of wetlands extent due to accelerated SLR.

Table 2.

Summary of projected area change over binary suitability analysis and urban conversion suitability analysis. Contains the projected area for wetlands extent, developed land that has "high potential for conversion," developed land that has "some potential for conversion," and developed land that has "not potential for conversion" for every decade from 2030 to 2100. All area values are expressed in square kilometers.

Year	Wetlands	High Potential for Conversion	Some Potential for Conversion	No Potential for Conversion
2030	491.34	15.46	7.05	2.69
2040	403.32	19.92	8.31	3.41
2050	291.04	25.36	9.38	4.36
2060	199.31	28.00	10.01	5.38
2070	157.56	32.01	10.75	6.51
2080	140.63	35.83	11.56	7.70
2090	116.64	39.50	12.88	8.91
2100	106.43	42.95	14.27	10.36

4.1.3. Errors

First, our binary suitability analysis is likely overestimating the future area of wetlands, since the model assumes that wherever wetlands *can* go, they *will* go. That assumption may not hold in the coming years as sea level continues to rise. Furthermore, our model was unable to account for jumping barriers to migration (Figure 11). It assumes that wetlands can "jump" over barriers such as urbanized land cover and steep slopes and migrate to otherwise suitable upland environments. However, because wetlands are blocked by those barriers, they will instead drown, serving as a source of overestimation in the model.

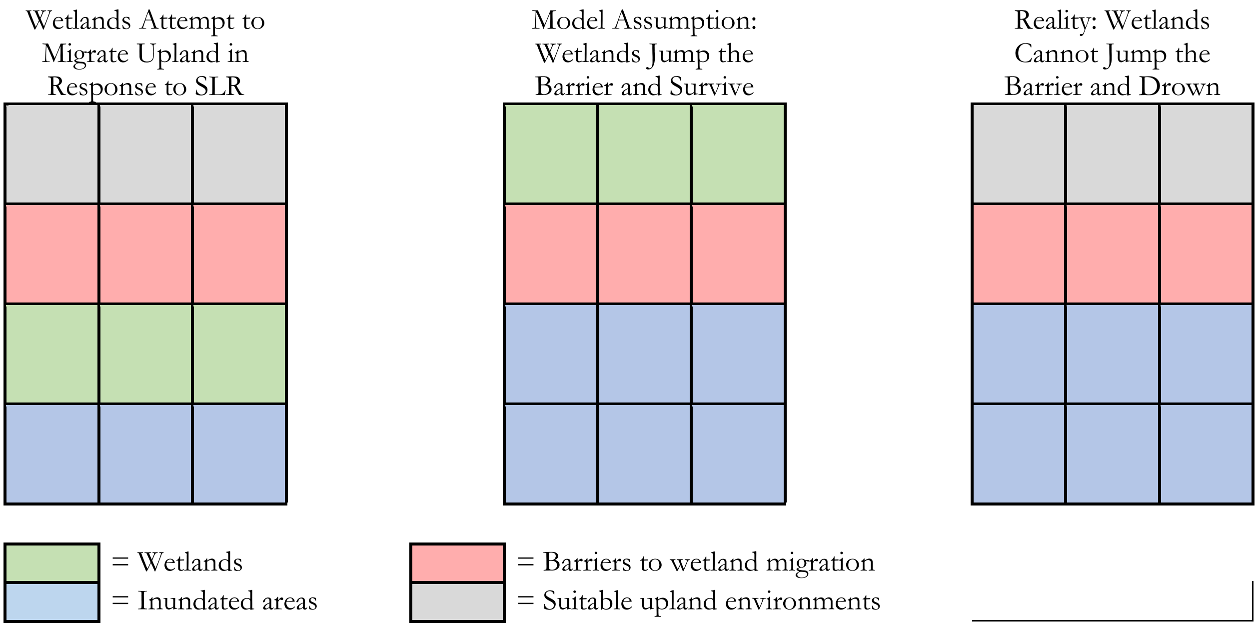

Figure 11. Visualization of the error of blocking migration paths, where green boxes represent wetlands, red boxes represent barriers to wetlands migration (i.e., anthropogenic barriers and steep slopes), blue boxes represent inundated land, and gray boxes represent upland environments our model classified as suitable for wetland migration.

Additionally, locations of potential future wetlands are dependent on the location of the ITZ. The projected ITZ may be incorrect due to the many uncertainties of predictions. One of the largest sources of error is the future rate of SLR. Though we used NOAA's intermediate estimate, there are many different possible outcomes for the future SLR rate. SLR projections come with a range of uncertainty due to various factors such as ice sheet dynamics, ocean circulation patterns, and greenhouse gas emissions scenarios (Durand et al., 2022). Only using one projection in the model may fail to capture this variability. If the chosen projection overestimates the rate of SLR, the model may exaggerate the extent of wetland loss. Conversely, if the project underestimates the rate of rise (which we believe is more likely given the chosen estimate), the model may underestimate the extent of loss.

Finally, our model does not factor in geographic variation land subsidence outside of the NOAA SLR forecast. In regions experiencing subsidence rates faster than 2.9 mm/year, the rate of apparent SLR is accelerated. Conversely, in areas experiencing less than 2.9 mm/year, the rate of apparent SLR is decelerated. Consequently, ITZs may expand more rapidly than predicted based solely on global SLR projections, underestimating the extent of wetland loss. Finally, our tidal data was dependent on the four recorded dates throughout 2023 to discern an average high and low tide for each tidal monitoring station. Tides are extremely variable both monthly and seasonally, and daily environmental changes can alter what the high and low tides will be. The calculated range may not be representative of regional tidal patterns, introducing error in the extent of the ITZ.

4.2 Feasibility for Partner Use

As a result of our analysis, we determined that it is feasible to use remote sensing techniques to estimate future wetlands extent. Our partner could reproduce our methods using data inputs from different sources to alter the estimation, but the process could remain the same and come to similar conclusions. Additionally, our partner focuses on community engagement. The maps created from these analyses could be used to communicate the risk that wetlands face in the Hampton Roads community (Figure 12a; Figure 12b).

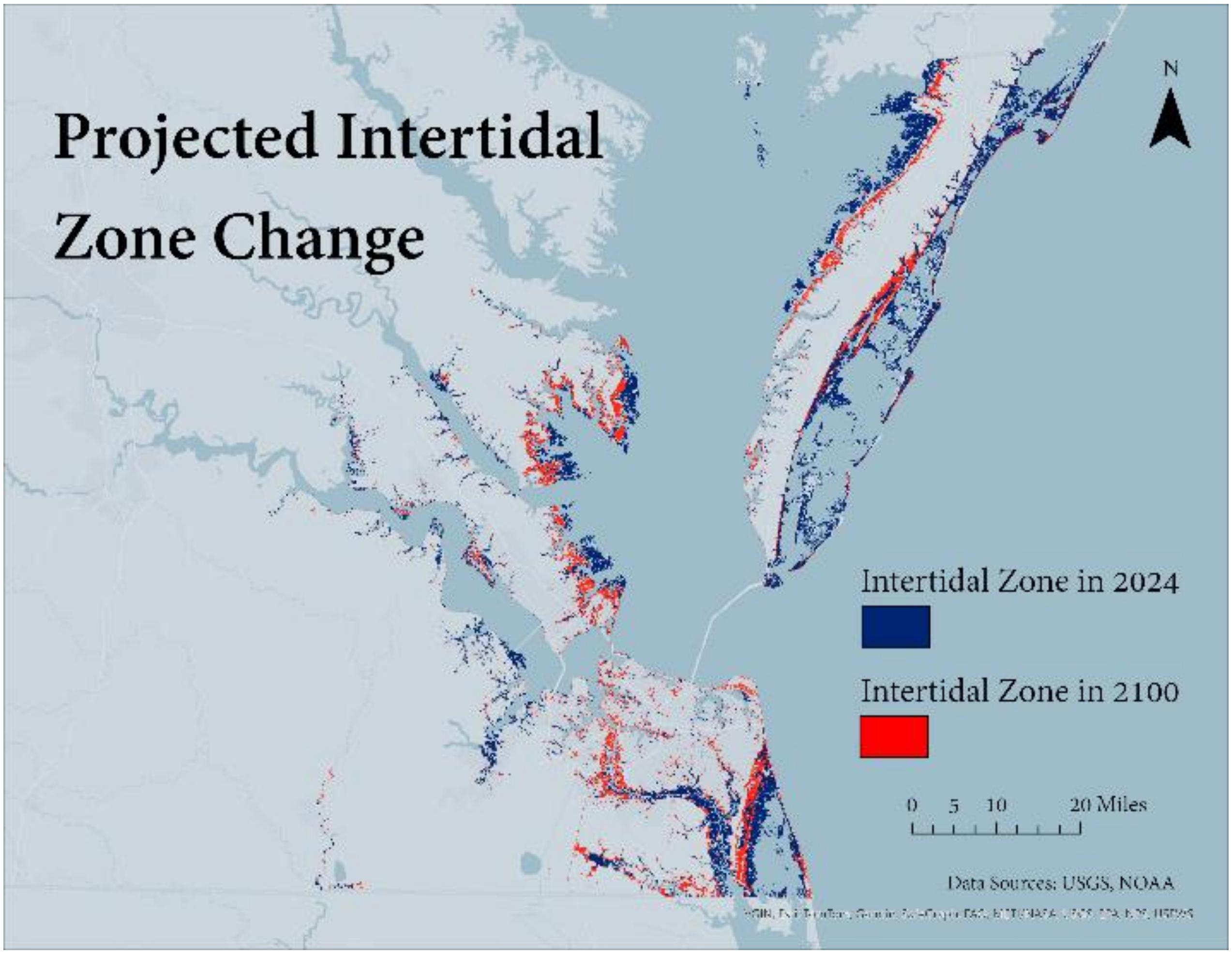

Figure 12a. Projected intertidal zone change from 2024 to 2100 for the entire study area. This image is an example of an impactful map we are providing to our partner. With maps like these, they can communicate our science to community members and policy makers. Basemap: [VGIN, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS].

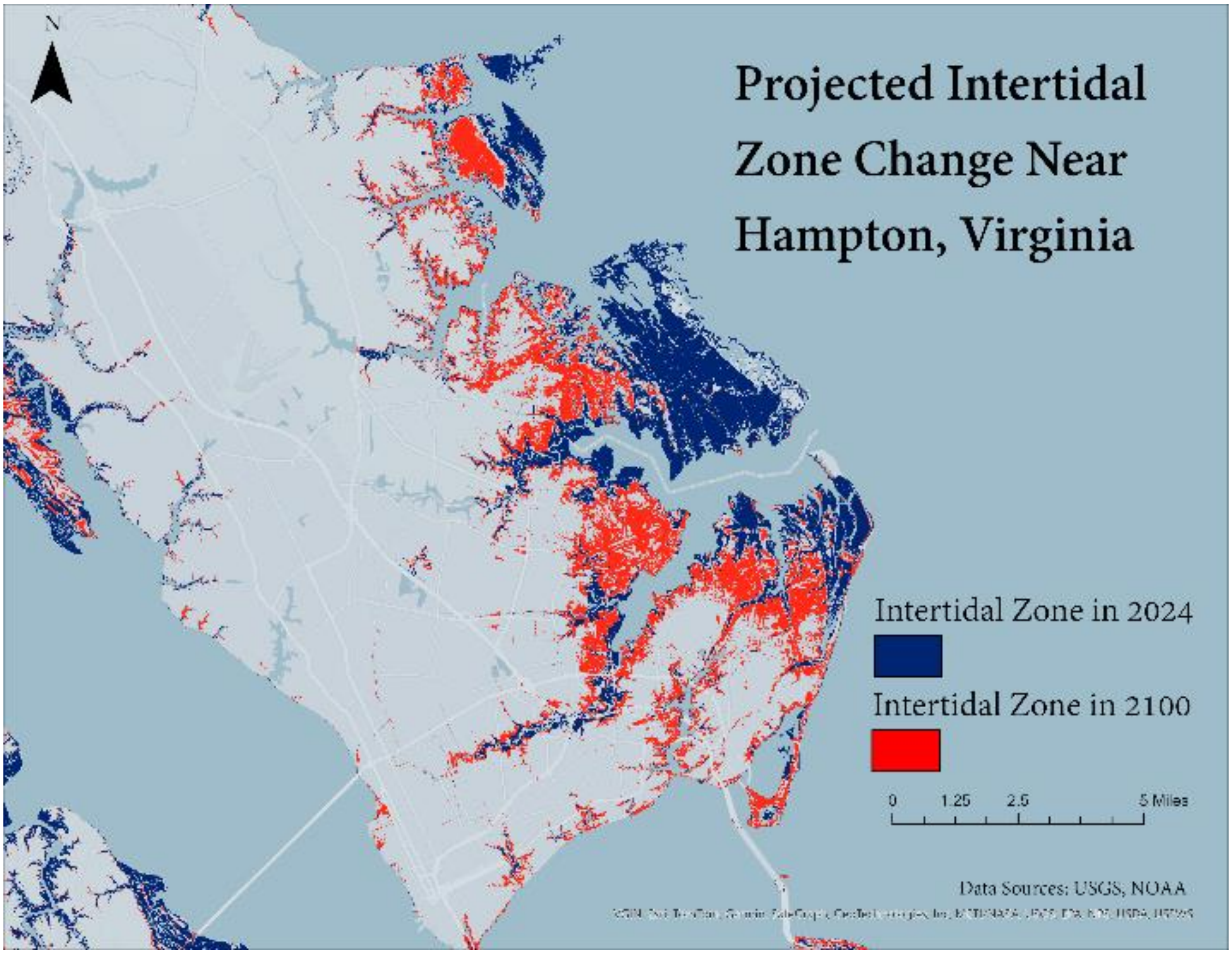

Figure 12b. Projected intertidal zone change from 2024 to 2100 near Hampton, Virginia. This image is an example of an impactful map we are providing to our partner. With maps like these, they can communicate our science to community members and policy makers. Basemap: [VGIN, Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS].

4.3 Future Recommendations

Wetlands Watch uses activism to influence local government land use and regulatory decisions, and advocate for state and federal policy. Therefore, their primary focus should be utilizing this research to most effectively advocate for their cause to lawmakers. Beyond presenting our deliverables to the public and General Assembly, one of our most open-ended conclusions is the idea of passive conservation derived from our urban conversion suitability analysis.

From a policy standpoint, adopting passive conservation measures can allow stakeholders to leverage existing land use patterns to facilitate wetlands migration, minimizing costs and potential social disruptions associated with active conversion initiatives. It is also crucial to recognize that all land, regardless of its level of conversion suitability, is projected to be in the ITZ by virtue of the model's structure, rendering it unusable to communities. Therefore, future focus for advocacy groups such as Wetlands Watch could be on determining where to strategically abandon land now, enabling submerged areas to become suitable for wetlands in the future. Such efforts would require further research and advocacy beyond geospatial analysis, integrating community dynamics, economic influences, and regulatory frameworks.

5. Conclusions

Our project highlights the increasing risk to wetlands through accelerated SLR. Through binary suitability analyses, we projected a significant decline in tidal wetlands area over the next eight decades, emphasizing the critical need for proactive conservation measures. Despite the potential for urban conversion to facilitate wetlands migration, our analysis reveals that such efforts alone cannot fully offset the inevitable loss of wetlands area. Even with maximum conversion of urbanized land cover, wetlands preservation efforts fall short of maintaining current wetlands extent. Our findings underscore the limitations of relying solely on conversion initiatives, emphasizing the importance of a multifaceted approach to wetlands conservation.

Our project provides Wetlands Watch with statistical data and visual aids with which to advocate for the protection of wetlands. It offers compelling and easy-to-understand data suitable for their goals of influencing local policy and educating the general public. This data can be used as a baseline source for advocacy efforts and serve as a bridge to developing regulatory strategies that integrate community dynamics and economic influences.

Our analysis also identifies several limitations and areas for future research. Uncertainties in sea-level rise projections and geographic variations in land subsidence underscore the need for refined predictive models. Additionally, our study emphasizes the importance of ongoing research to better understand the complex interactions between land use, sea-level rise, and wetlands dynamics.

Moving forward, our study provides valuable insights for policymakers, conservationists, and stakeholders involved in wetlands preservation efforts. By integrating our findings into advocacy strategies and policy decisions, we can work towards a sustainable future where wetlands continue to provide vital ecosystem services and contribute to the resilience of coastal communities.

6. Acknowledgements

The Coastal Virginia Ecological Conservation team thanks our project partner Wetlands Watch. We are grateful to Dr. Xia Cai and Dr. Joseph Spruce for advising this study, Olivia Landry, Marisa Smedsrud, and Laramie Plott for offering guidance, support, and feedback throughout this project.
Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

This material is based upon work supported by NASA through contract 80LARC23FA024.

7. Glossary

7.1 Definitions

Accretion – The accumulation of sediment and organic matter in wetlands, enabling them to grow vertically

Anthropogenic barriers – Any obstacle or structure that is created by human activity and impedes the migration of wetlands

Ghost forest – Coastal area where dead or dying trees stand among withered foliage, typically occurring because of saltwater intrusion into previously freshwater habitats

Intertidal wetlands – Usually tidal flats or salt marshes, defined as undeveloped land lying within the intertidal zone

Intertidal zone (ITZ) – Coastal areas that are inundated at high tide but exposed to air at low tide; they generally have an elevation between the mean higher high water line and mean lower low water line

Landsat – A system of NASA and USGS Earth-observing satellites providing continuous and archival open-access imagery at medium spatial, spectral, and temporal resolution

Land use/Land cover (LULC) – A dataset that combines land use (how humans use the land) and land cover (vegetative characteristics or manmade structures on the land's surface)

Lidar – A form of active remote sensing that reflects lasers off a surface to gain information about it, including texture and distance

Migration – The expansion and retraction of wetlands; primarily into formerly dryland habitats that become inundated as sea level rises

Remote sensing – Methods and technologies that enable the acquisition of information about a subject from a distance

Subsidence – The sinking of land, primarily associated with groundwater extraction

Urban conversion – The process of undeveloping land to reduce barriers to future wetland migration

Vertical Datum – A static reference (zero value) from which elevations can be compared; they are usually some measure of sea level

Wetland drowning – When a wetland becomes open water, usually due to SLR and subsidence outpacing accretion rates

7.2 Acronyms

DEM – Digital Elevation Model

ITZ – Intertidal Zone

NLCD – National Landcover Dataset

NOAA – National Oceanic and Atmospheric Administration

SLR – Sea-level Rise

USGS – United States Geological Survey

3DEP – 3-Dimensional Elevation Project

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9. Appendix

Appendix A: Supplemental Figures and Tables

Table A1.

Names of tidal monitoring stations used to calculate average high and low tidal values for the coastal regions of Virginia.

Virginia – Outer Coast	Chesapeake Bay, Eastern Shore	Chesapeake Bay, Western Shore	Chesapeake Bay, Southern Shore	York River	James River
Wallops Island Gargathy Neck Metompkin Inlet Folly Creek, Metompkin Inlet Wachapreague, Wachapreague Channel Revel Creek, Revel Island Great Machipongo Inlet (inside) Upshur Neck, south end Sand Shoal Inlet (Coast Guard Station) Oyster Harbor Smith Island (Coast Guard Station) Cape Henry Virginia Beach Rudee Inlet entrance Rudee Inlet, interior channel Rudee Heights, Lake Wesley Lake Rudee, south end Sandbridge	Fishermans Island Kiptopeke Beach Old Plantation Light Cape Charles Harbor Gaskins Point, Occohannock Creek Harborton, Pungoteague Creek Onancock, Onancock Creek Chesconessex Creek, Schooner Bay Watts Island Tangier Island Muddy Creek Entrance Guard Shore Saxis, Starling Creek	Jackson Creek, Deltaville Dixie Wolf Trap Light Mobjack, East River Belleville Browns Bay Messick Point, Back River Old Point Comfort Hampton Roads (Sewells Point) Pig Point Town Point Hollidays Point Craney Island Light Lafayette River Western Branch Norfolk Portsmouth, Naval Shipyard Money Point Deep Creek Entrance	Little Creek, NAB Chesapeake Bay Bridge Tunnel Chesapeake Channel Lynnhaven Inlet Bayville Buchanan Creek Entrance Brown Cove Broad Bay Canal Long Creek	Tue Marshes Light Yorktown, Goodwin Neck Yorktown, USCG Training Center Gloucester Point Cheatham Annex Roane Point West Point Wakema (Fraziers Ferry), Mattaponi River Lester Manor Northbury	Newport News Huntington Park Menchville Smithfield, Pagan River Fort Eustis (MARAD) Burwell Bay Kingsmill Scotland Jamestown Ferry Point (bridge) Wright Island Landing Lanexa, Chicahomny Claremont Tettington, James River Sturgeon Point Willcox Wharf, Charles City Jordan Point City Point, Hopewell Puddledock, Appomattox River Haxall Chester Meadowville Richmond Deepwater Terminal, James River Richmond (river locks)

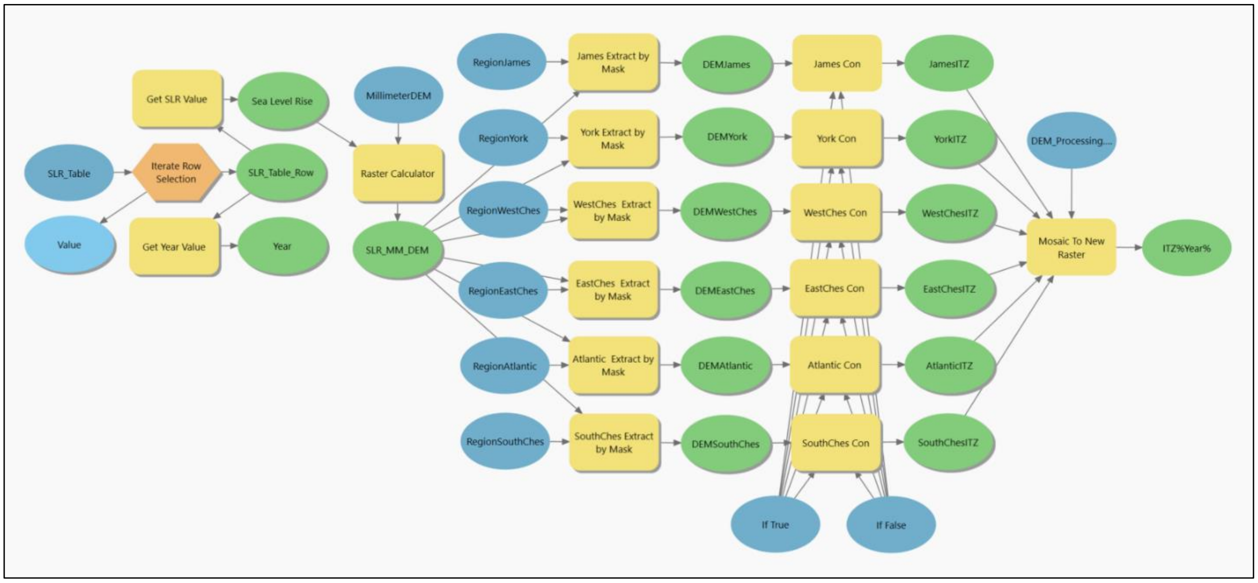

Figure A1. Model used to automatically calculate future ITZs in ArcGIS Pro ModelBuilder.

Table A2.

Land cover categories of the 2021 National Landcover Dataset. The second column includes source classification of different land use types. The third column includes their binary reclassification for defining anthropogenic barriers, where 1 is defined as suitable and 0 is defined as unsuitable. The fourth column includes their reclassification for urban conversion suitability; 7 is defined as no potential for conversion, 17 is defined as some potential for conversion, and 27 is defined as high potential for conversion.

Land Cover	**Source Code**	**Binary Reclassification**	**Urban Conversion Reclassification**
Open water	11	1	0
Perennial ice/snow	12	1	0
Developed, open space	21	0	27
Developed, low intensity	22	0	17
Developed, medium intensity	23	0	7
Developed, high intensity	24	0	7
Barren land (rock/sand/clay)	31	1	0
Deciduous forest	41	1	0
Evergreen forest	42	1	0
Mixed forest	43	1	0
Dwarf scrub	51	1	0
Shrub/scrub	52	1	0
Grassland/herbaceous	71	1	0
Sedge/herbaceous	72	1	0
Lichens	73	1	0
Moss	74	1	0
Pasture/hay	81	0	27
Cultivated crops	82	0	27

Woody wetlands	90	1	0
Emergent herbaceous wetlands	95	1	0