Sea Level Rise Inundation Modeling Using Stormwater Infrastructure

In Norfolk Virginia

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Executive Summary

Climate change is impacting coastal communities worldwide as global sea levels rise. Portions of the east coast of the United States, including the city of Norfolk, Virginia, experience rising seas at almost three times the global rate. Norfolk specifically has the highest rate of sea-level rise among east coast cities in the United States. Climate variability and land subsidence related to Glacial Isostatic Adjustment (GIA) cause the high relative sea-level rise rates in this region (Bekaert et al., 2017). Sea level rise exacerbates nuisance flooding, also referred to as sunny-day high tide flooding, the cumulative effects of which can make more of an impact over time than the less likely extreme event. Near-term sea-level rise is already impacting day-to-day operations in coastal cities, specifically at high tide and with the increase in the frequency of nuisance flooding events. These impacts will continue to grow as sea levels rise.

The methods for this study in part follow the National Oceanic and Atmospheric Administration (NOAA) *Detailed Method for Mapping Sea Level Rise Inundation* for the creation of sea-level rise inundation grids. The NOAA method uses elevation data, sea-level rise values, tidal variation of the mean higher high-water mark, and the evaluation of hydrological connectivity to map inundation. This study uses geospatial analysis to show that adapting the digital elevation model (DEM) with stormwater infrastructure improves the accuracy of inundation modeling at low levels of sea-level rise. The stormwater infrastructure used in this analysis includes stormwater ditches, culverts, and pipes. Inundation grids are created for three sea-level rise scenarios: 0.5-meters, 1.0-meters, and 1.5-meters. The results of each scenario were overlayed with NOAA's designated low-lying areas to detect whether the stormwater infrastructure impacted the inundation of those areas.

The results suggest that including stormwater infrastructure in sea level rise inundation modeling has the potential to change the connectivity of inundated areas, even at low levels of sea-level rise. Many low-lying areas were impacted by inundation, at the 0.5-meter and 1.0-meter sea-level rise scenarios. This has near-term applicability as Norfolk may see 0.5-meters of sea-level rise by 2050. Impacts to the infrastructure itself include the inundation of structures like inlets and outfalls, which could make the city's stormwater system ineffective daily at high tide under these sea-level rise scenarios. Cities like Norfolk can use the results of this study to aid in resiliency planning, prioritizing stormwater infrastructure updates, and modeling future storms with the new inundation grid in mind. This work can be replicated in other coastal cities and will

also be useful for resiliency planning on military installations such as the Naval Station Norfolk. Building off current results by including precise elevations and slopes of the pipes will allow for modeling more accurate inundation amounts for each sea-level rise scenario. Fine-scaled inundation modeling is crucial for planning for sea-level rise-related impacts.

Acknowledgments

I would first like to thank my advisor, Dr. Pat Halpin, for all of his guidance throughout this process, and for helping this idea turn into a well-rounded project. I'd also like to thank Jesse Cleary for his advice and assistance with the geospatial portion of this project. Thank you to my peers, my fellow CEMs, for always listening and offering advice and words of encouragement. And thank you to my family for supporting me in everything that I set out to accomplish.

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Background

The impacts of climate change are seen worldwide and are becoming more severe. One of the main effects of climate change is rising sea levels due to melting glaciers and ice sheets, land subsidence, and thermal expansion. Global mean sea level (GMSL) is both rising and accelerating, but not uniformly across the globe; some areas are more affected than others. According to the Intergovernmental Panel on Climate Change (IPCC), GMSL will rise between 0.29 meters and 1.1 meters by the end of this century (IPCC, 2019). Recorded average global sea-level rise rates reported by the IPCC include a 1.9 mm/year rate from 1971 to 2006, increasing to 3.7 mm/year between 2006 and 2018 (IPCC, 2022). Records show the most notable increases in sea level rise rates since 1990.

Portions of the east coast of the United States see rising seas at almost three times the global rate (Union of Concerned Scientists, 2016). A combination of physical land processes such as land subsidence and a low elevation above sea level has led to different rates of sea-level rise. Subsidence is a local phenomenon exacerbated by depleting groundwater sources faster than they are replenished. Further, Glacial Isostatic Adjustment (GIA), the rebound of the Earth after the melting of glaciers, is still impacting vertical land movement across the east coast of the U.S, which used to be covered in ice (Sweet et al., 2022). Sea level rise exacerbates nuisance flooding, also known as sunny-day or high-tide flooding (NOAA, 2019). Nuisance flooding is often categorized as minor flooding, but the cumulative effects can make more of an impact over time than the less likely extreme event (Li, 2021). According to the 2022 Sea Level Rise Technical Report, written in partnership between NOAA, the US EPA, NASA, USACE, USGS, FEMA, and others, within the last 20 years, minor high tide flooding has more than doubled. It may do so again as soon as 2030 (Sweet et al., 2022). This type of coastal flooding disrupts daily life by making roads impassable, disrupting other transportation systems, and can impact emergency routes. Along with many others across the globe, these areas will only continue to suffer the consequences of sea-level rise over time. Nuisance flooding events will become more frequent and severe as sea levels continue to rise. As city managers look to try and respond to these events and plan for the future, they must have accurate sea level rise inundation maps to make informed decisions.

Models looking at sea level rise above the mean higher high-water mark (MHHW), tidal variability, and the influence of land subsidence on sea-level rise inundation helped provide background for this study (Shirzael, 2018). Studies show that sea-level rise will adversely affect transportation infrastructure. The National Oceanic and Atmospheric Administration Office of Coastal Management's (NOAA-OCM) Sea Level Rise Viewer shows the inundation model's results. The NOAA sea level rise inundation method uses a modified bathtub approach that includes tidal variability and hydrologic connectivity. The bathtub approach looks at sea level rise like water filling up a bathtub; the areas with lower elevation will flood first, while the higher elevations follow behind. So, the NOAA method is mainly a function of elevation and the amount of sea-level rise, and then an analysis of connectivity to produce an inundation surface that is connected to the ocean. However, this model and others do not include engineered infrastructure, such as stormwater culverts and ditches, which may impact the connectivity of the inundated surface. These structures are often hidden beneath roads, i.e., culverts, and are not resolved as barriers to flow paths by the digital elevation model (DEM).

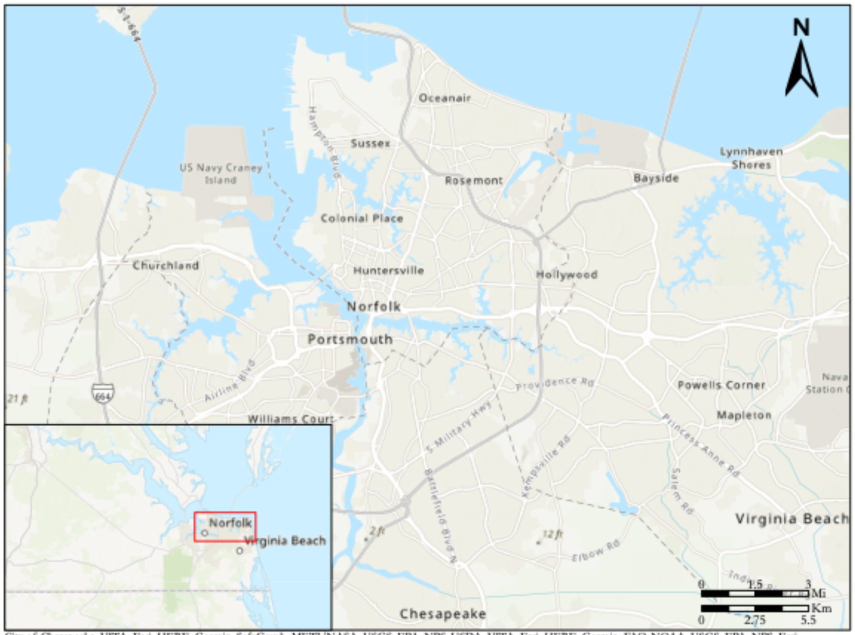
A culvert is typically an open-ended pipe or channel that allows water to move past an obstacle, typically under roads. Another essential stormwater structure is the open end of a stormwater pipe, typically designated as an outfall. Stormwater discharges into bodies of water like creeks, canals, or the ocean through these structures. Stormwater infrastructure exists to move water away from populated areas and off roads. However, it could also be a pathway for rising seas to inundate the very areas where the infrastructure is supposed to keep dry. Including stormwater infrastructure in the NOAA sea level rise model may result in a different inundation output, specifically at a fine scale. Sea level rise, along with the occurrence of nuisance flooding, is no longer an issue for the future; it is occurring now, and thus, modeling inundation needs to be at as fine a scale as possible.

Introduction

This study aims to understand the effect of stormwater infrastructure on the connectivity of inundated areas under low levels of sea-level rise. Comparing the results of each scenario to the NOAA OCM Sea Level Rise Viewer's inundation results will indicate the effects of stormwater infrastructure on inundation. A second priority within this study is to highlight vulnerable stormwater infrastructure that may be inundated because of sea-level rise. Assessing inundated stormwater infrastructure will aid in prioritizing potential infrastructure updates for the city. A third goal is to highlight other vital areas that may not directly be inundated under each scenario but are very close to being at risk. The findings of this pilot study should be helpful for future analyses in other regions.

Study Site

The city of Norfolk, Virginia is the site for this study, due to the high rate of sea-level rise and nuisance flooding occurring. The Virginia Institute of Marine Science (VIMS) reports that Norfolk saw a 5.4 mm increase in sea level in 2021, about a 0.5mm/year increase from 10 years prior (Malmquist, 2021). This is the highest rate of sea-level rise among east coast cities in the United States. Climate variability and above-average subsidence rates related to GIA cause the high relative sea-level rise rates in this region (Bekaert et al., 2017). Nuisance flooding in Norfolk, Virginia has increased 325% since 1960 and ranks in the top 10 U.S cities that have seen increases in coastal flooding events (Burgos, 2018). Surrounded on three sides by water, including the Chesapeake Bay, Elizabeth River, and the Atlantic Ocean, Norfolk is one of the more vulnerable cities on the east coast when it comes to sea-level rise. The city is home to about 250,000 residents along with the world's largest naval base, Naval Station Norfolk (Burgos, 2018). Bekaert et al., 2017 found exceptionally high rates of subsidence occurring at the Naval Station from 2007 to 2011, with more research needed on why. Detailed flood modeling is crucial to planning for the resilience of the nation's military bases as well as the cities that they inhabit.



City of Chesapeake, VITA, Esri, HERE, Garmin, SafeGraph, METI/NASA, USGS, EPA, NPS, USDA, VITA, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, Esri, NASA, NGA, USGS, Esri, USGS Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Figure 1: City of Norfolk, Virginia.

Methods

Literature Review

A literature review revealed the breadth and depth of current inundation modeling. Loftis et al., 2018, conducted an analysis of a sub-grid modeling approach that removed overpasses from the DEM to more effectively model Hurricane Sandy storm surge in New York City (Loftis, 2018). Another publication discussed creating a detailed high-resolution inundation model for modeling storm surge and precipitation-related flooding events at Langley Research

Center in Hampton, Virginia (Loftis, 2015). This model included the predicted tide and storm tide, along with wind and pressure atmospheric forcings, and infiltration through the soil as a fluid sink. They then used tide gauge data to compare to their simulation. Wang et al., 2015 used a LiDAR-derived DEM and resolved flow issues where bridges crossed the Potomac River (Wang et al., 2015). This source, although it is simulating storm tides, had helpful methods for resolving features like bridges. Loftis et al., 2018 reviewed current data sources for flood resilience planning, as well as gaps in the data (Loftis, 2018). This was a great resource for identifying potential data sources. Overall, the results of the literature review emphasized modeling storm surge and large flood events, without much emphasis on the modeling of day-to-day high-tide flooding because of sea-level rise alone.

Data

Data availability was a determining factor for the selection of the study site, as stormwater infrastructure data is openly available on the City of Norfolk's Open GIS website (City of Norfolk GIS, 2021). The Open GIS platform provides stormwater ditch, stormwater pipe, and stormwater structure shapefiles. The stormwater structures file is a point shapefile that contains locations of manholes, outfalls, ditch entrances and exits, pipe entrances and exits, and catch basins, among other features (City of Norfolk GIS, 2021). The Virginia Department of Transportation (VDOT) website also provides a culvert and bridge shapefile (VDOT, 2020). The culvert data is used in this analysis, as bridges were resolved in the DEM. This study also uses data from NOAA's Sea Level Rise Viewer, including the low-lying area shapefiles for different sea-level rise scenarios, and the DEM for Virginia (NOAA OCM). The DEM is a combination of multiple lidar datasets from sources including the United States Geologic Survey (USGS) and The Federal Emergency Management Agency (FEMA). The DEM was obtained from the NOAA OCM website and has a resolution of approximately 3 meters. The vertical datum is the North

American Vertical Datum of 1988 (NAVD88), and the horizontal datum is the North American Datum of 1983 (NAD83). Another piece of data used was a combination of features from the National Hydrography Dataset (NHD) and the National Wetland Inventory (NWI). The result of this combination is a hydrographic overlay that essentially shows hydrological connectivity for Virginia (USGS).

Analysis

This study follows NOAA's *Detailed Method for Mapping Sea Level Rise Inundation* for the creation of sea-level rise inundation grids (NOAA OCM, 2017). The method uses elevation data, sea-level rise values, tidal variation of MHHW, and the evaluation of hydrological connectivity to map inundation. This includes the creation of a tidal surface using the VDatum approach with NOAA's vertical datum conversion software to get the tidal surface elevation values in the North American Vertical Datum of 1988 (NAVD88). Creating a grid of points using a Virginia address points shapefile from VGIN clipped to Norfolk County, and then adding and calculating fields for latitude, longitude, and elevation fields, with elevation set to 0 meters completed the preprocessing required before using NOAA's vertical datum conversion software. The output was an excel sheet that had corrected elevation values for each point, elevation above the MHHW. The data was converted back into a grid of points in ArcGIS Pro, and various interpolation methods were used to find the smoothest surface to use as the tidal surface. Sea level rise values were then added to the chosen tidal surface to create a sea-level rise grid for each scenario. The stormwater infrastructure was incorporated into the existing DEM by first adding an elevation component to each infrastructure shapefile. Elevation was calculated as 0 meters for each infrastructure component, as most of these features are at the ground surface or beneath roads. The stormwater ditch data did not require any preprocessing, but the culverts and stormwater pipes data required data conversions. The culvert data needed to be converted from point to polygon format. For this study, not all the stormwater pipes were necessary, as not all sections of pipes would impact surface water flow. For this reason, the stormwater structures point data was used to select only certain portions of the stormwater pipes. Specifically, outfalls and pipe entrances and exits to ditches structure points were used to select stormwater pipes within 30 meters of the original inundation grid.

Exploratory flow analysis using the infrastructure data exhibited disconnected features and flow paths. The pipes data was buffered by 1 meter to ensure that all the infrastructure data was properly connected in the adapted DEM. Once the preprocessing analysis was complete, the stormwater pipes, ditches, and culverts data were converted into a raster format. In raster format, the infrastructure components were assigned a pixel value of 0 meters, and the No Data values were reassigned a value of 1 meter. This was to allow for multiplication of the infrastructure rasters by the existing DEM, therefore only changing the elevation values where the stormwater infrastructure exists. The cell size had to be set at 0.8-meters for the raster component, again so that the infrastructure was fully and accurately represented.

Similar preprocessing steps were taken to include the hydrographic overlay data into a second version of the DEM. For this study, the hydrographic overlay was included in the DEM that also had the stormwater infrastructure data, to show a more complete connected surface with both natural and manmade systems for water transport. The hydrographic overlay data was first edited so that two specific locations would not be represented as hydrologically connected to the rest, due to a flood gate and similar structure protecting those two features. Then an elevation value was calculated for the data, and it was converted into a raster, and combined with the infrastructure DEM. The result was two separate DEMs, one with infrastructure included, and the other with both infrastructure and the hydrographic data included. This will allow for further comparison of the effects of these man-made and natural structures on the connectivity of inundated areas under each sea-level rise scenario.

The creation of the inundation grid for each sea-level rise scenario followed NOAA's *Detailed Method for Mapping Sea Level Rise Inundation*. This approach maps sea level rise above the MHHW mark and evaluates the hydrologic connectivity of the inundated area (NOAA OCM, 2017). One of the results produced by the NOAA OCM method is the designated low-lying areas dataset. These low-lying areas have elevations below sea level under a specific sea-level rise scenario but have been deemed not hydrologically connected to the rest of the inundated area. Overlaying the low-lying areas data with the inundation results helps to show where infrastructure caused the inundation of these areas.

Multiple sea level rise scenarios were assessed using the NOAA method and the infrastructure adapted DEM. Scenarios were conducted at 0.5 meters, 1.0 meters, and 1.5 meters of sea-level rise in Norfolk, Virginia. The first scenario, 0.5 meters, is the amount of sea-level rise projected by the VIMS report for Norfolk by 2050. The other scenarios were conducted to investigate how the impact of stormwater infrastructure on inundation changes as sea levels increase. The same three scenarios were run using the DEM adapted to include both the stormwater infrastructure and the hydrographic overlay data as well.

In addition to mapping inundation under multiple sea-level rise scenarios, a vulnerability assessment of the stormwater infrastructure itself was conducted. The stormwater structures data was used along with the final inundation grids to see how much of the infrastructure overlapped with each scenario's inundation grid. These counts were divided into percentages for each type of stormwater structure.

Results

Inundation and Low-lying Areas

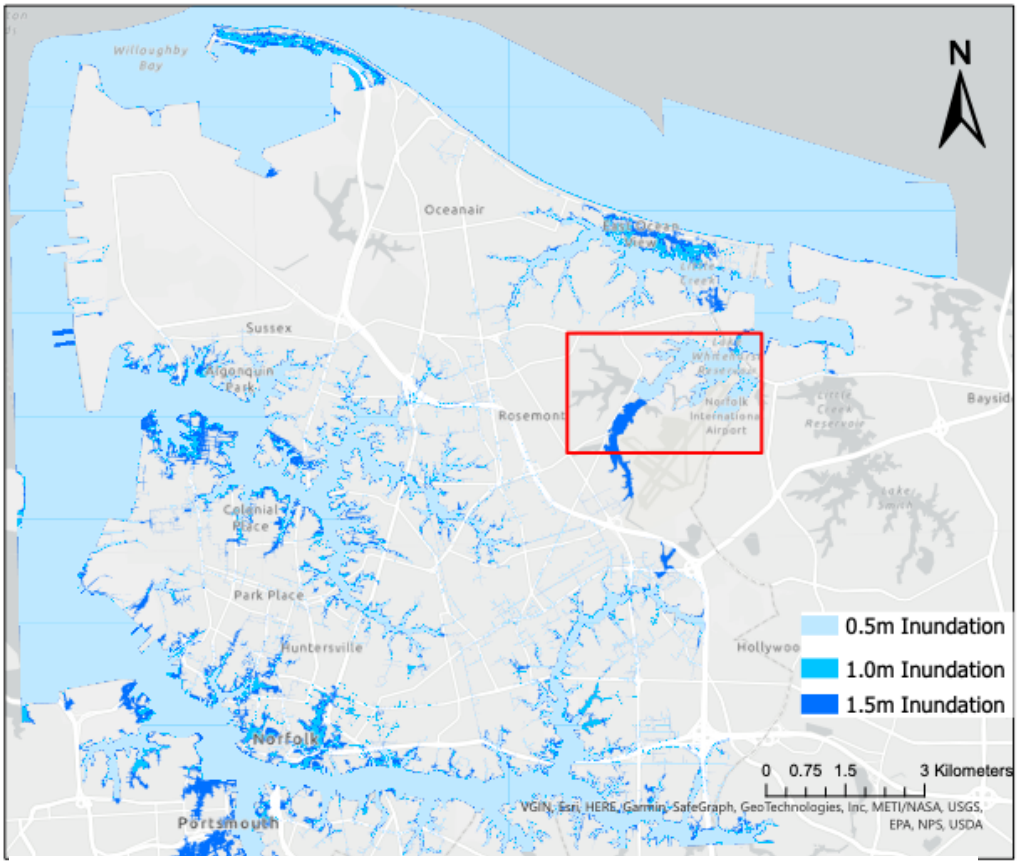


Figure 2: Inundation scenario results for Norfolk. Result of scenarios incorporating stormwater infrastructure into the model. Red box indicates location of Lake Whitehurst Reservoir, where connectivity may be stopped by manmade infrastructure.

The results of each scenario are shown in Figure 2. The inundation for each scenario is represented by a solid color rather than a range of values, as the significance of the result is more about the potential for inundation and overall hydrological connectivity rather than exact inundation amounts. The results of each sea-level rise scenario were overlayed with NOAA's designated low-lying areas to detect whether the stormwater infrastructure impacted the inundation of those areas. Table 1 shows the percentage of low-lying areas that are impacted by inundation under each scenario. For the 0.5m scenario, 31% of the low-lying areas showed some level of inundation due to the inclusion of stormwater infrastructure in the model.

Table 1: This table shows the percent of low-lying areas impacted by inundation at each sea-level rise scenario, with infrastructure incorporated in the model.

Low-Lying Areas	**Percent Low-Lying Areas Impacted**
0.5-meter Low-Lying Areas	**31%**
1.0-meter Low-Lying Areas	**54%**
1.5-meter Low-Lying Areas	**6%**

A greater impact is found at 1.0 meters of sea-level rise, with 54% of the low-lying areas impacted. Notable low-lying areas that did not flood include the Lake Whitehurst Reservoir and the Oastes Creek. Lake Whitehurst Reservoir is used as a source of drinking water for Norfolk and the surrounding areas. It is separated from the tidally inundated area by a road that has

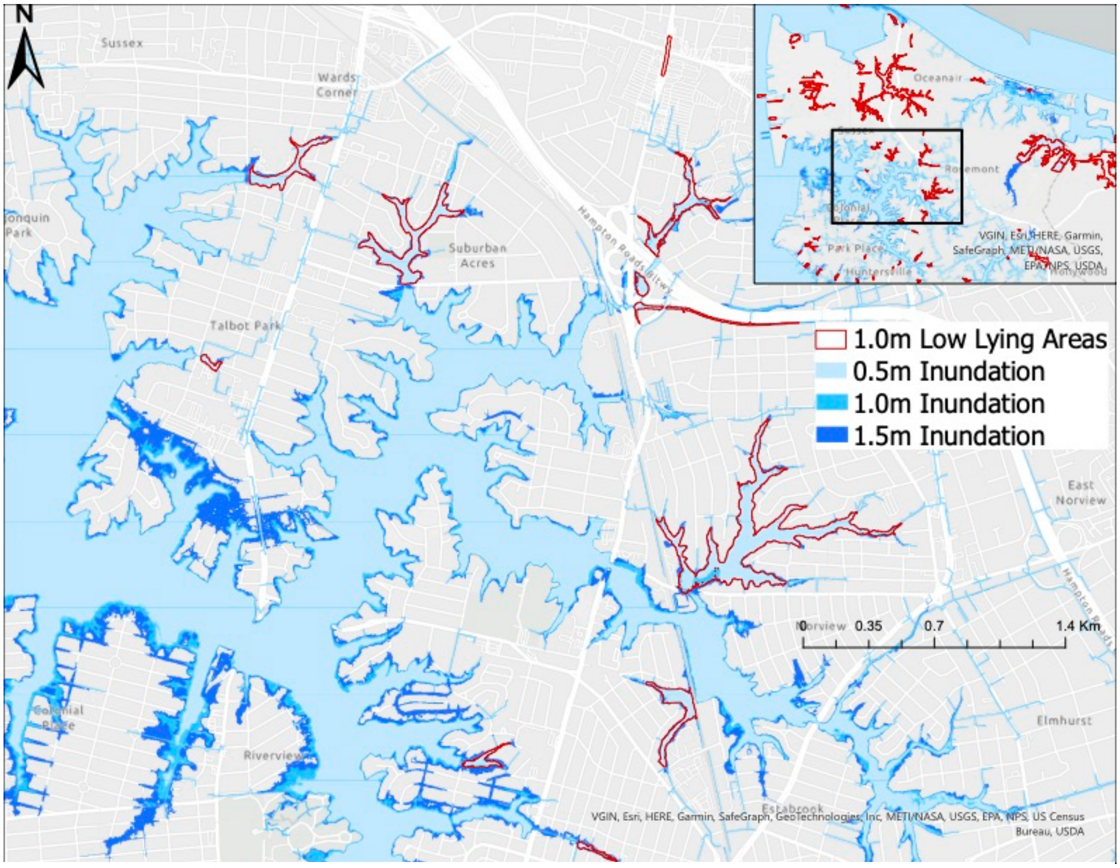


Figure 3: Zoom in of inundation results for each scenario, incorporating stormwater infrastructure. Low lying areas shown outlined in red.

drainage underneath it, most likely only allowing excess freshwater to drain, but not allowing seawater to enter the reservoir. Oastes Creek is hydrologically connected to the inundated area, and to the ocean itself, but there is a flood gate already in place, essentially disconnecting this Creek from the rest of the inundation grid. The 1.5-meter sea level rise result was different from the 0.5- and 1.0-meter results. When looking at the inundation grid and the corresponding low-lying areas for that sea-level rise amount, not many of the low-lying areas showed any inundation. This may suggest that the threshold for stormwater infrastructure's impact on the connectivity of inundation is between 1.0 and 1.5 meters of sea-level rise. Figure 3 shows a zoom-in of the inundation results after incorporating stormwater infrastructure into the model. Along with the three sea-level rise scenario results, the 1.0-meter low-lying areas are also shown. The figure shows all of the low-lying areas have the potential to be inundated, even at 0.5-meters

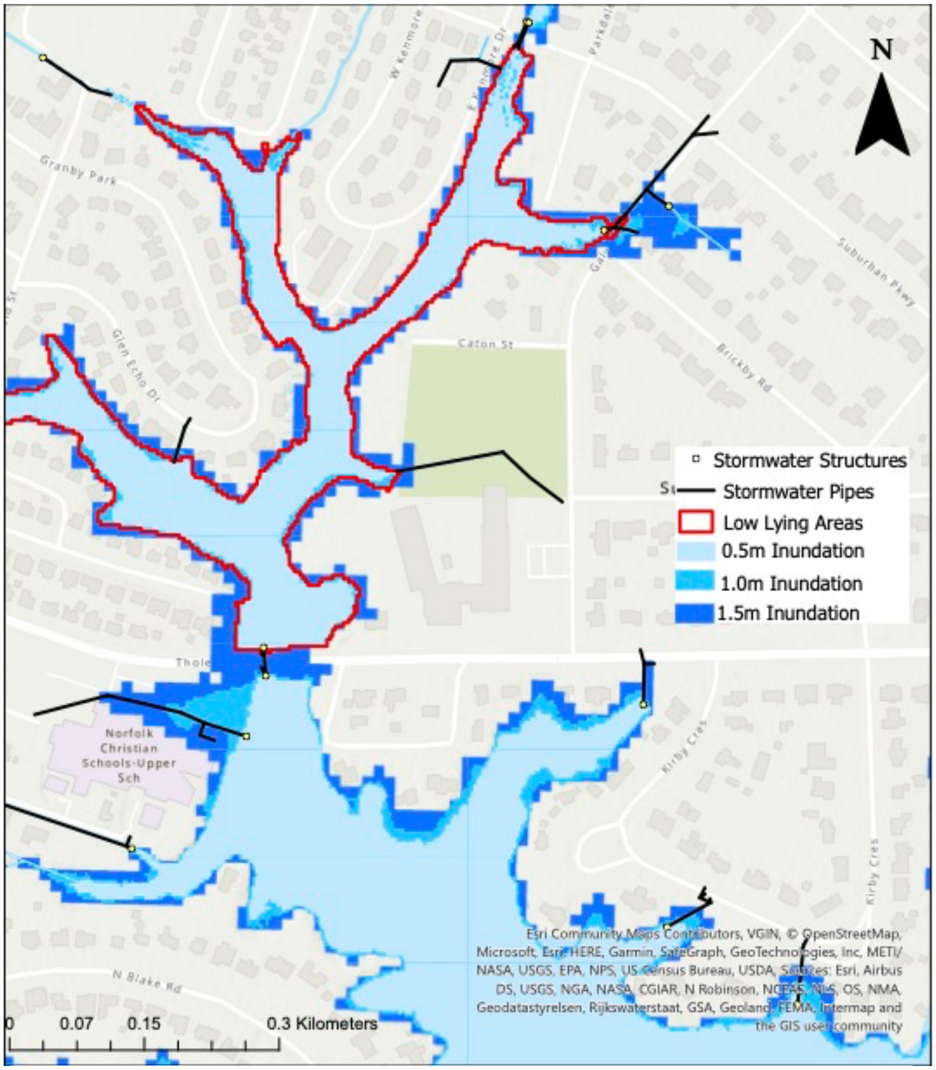


Figure 4: Example of how stormwater infrastructure impacts connectivity. This map shows inundation extent with stormwater pipes and low-lying areas included.

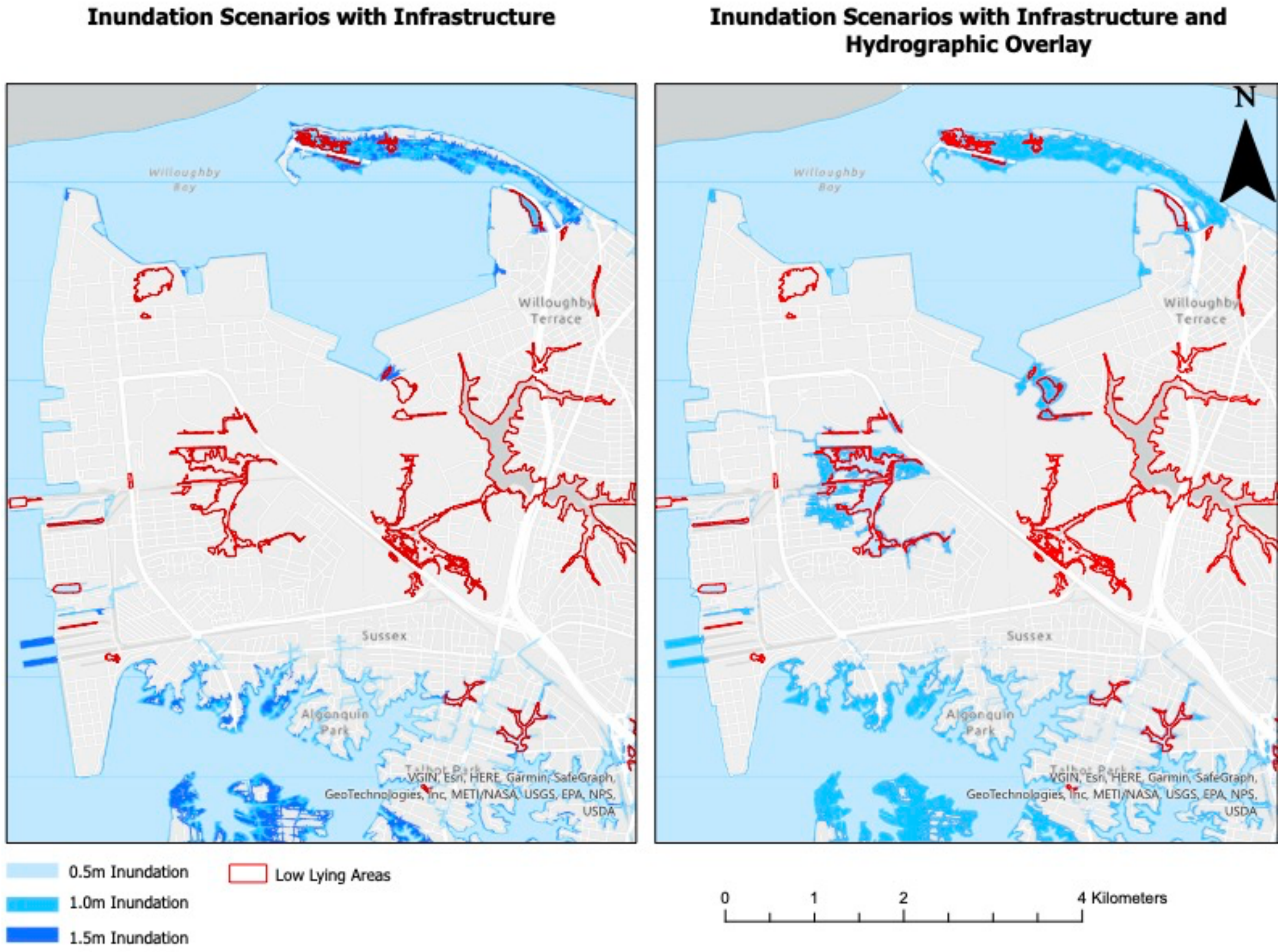


Figure 5: Comparison of infrastructure only scenario results(left) and infrastructure and hydro scenario results (right). Right map shows further inundation in additional low-lying areas.

of sea-level rise. Figure 4 shows the stormwater pipes and structures that hydrologically connect the inundation grid to the low-lying areas, essentially flooding them. On one end of the stormwater pipe connecting the original inundation grid to the low-lying area is an outfall, and on the other is the pipe entrance to a regulatory ditch. These two structures essentially make this length of pipe an open-ended culvert, which would allow water to pass through, under the road, and hydrologically connect the low-lying area. The results for the scenarios with the hydrographic overlay included show a few more of the low-lying areas having the potential to flood that the infrastructure only

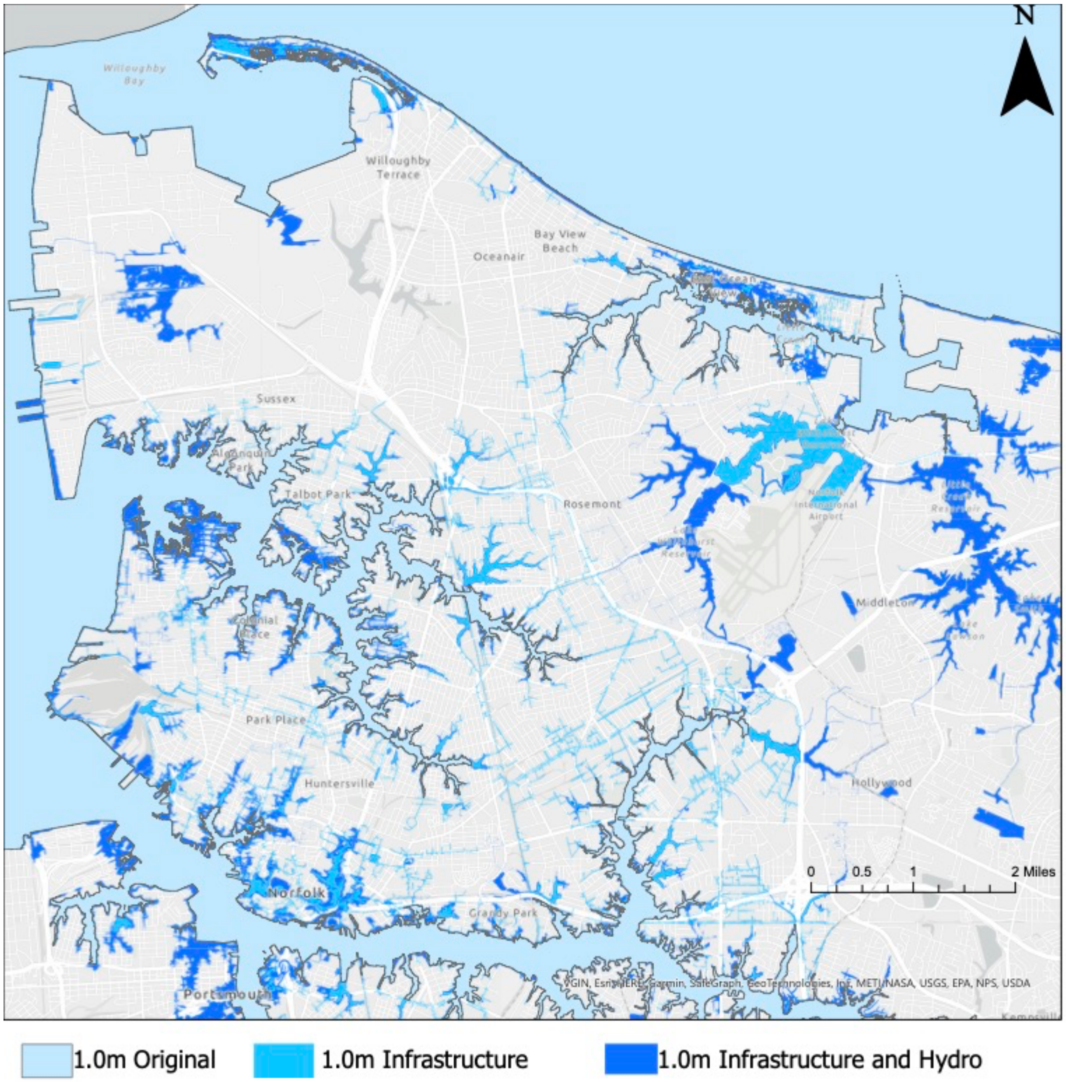


Figure 6: Comparison of original inundation results at 1.0-meters of sea level rise should no changes be made to NOAA model, stormwater infrastructure results, and infrastructure and hydro scenario results.

results did not. These differences are primarily in the Northwest portion of Norfolk, near the Naval Base. Another difference is that more area has the potential to be inundated under 1.0 meters of sea-level rise when the hydrographic overlay is included. Figure 5 shows the two sets of results side by side. Figure 6 shows three different results at 1.0 meters of sea-level rise. The lightest colored blue represents the results of the original method, with no changes, while the medium-colored blue shows the results of the method after incorporating stormwater infrastructure, and the darkest blue shows the inundation results after incorporating both the infrastructure and the hydrographic data. This figure exemplifies how each added layer of detail further expands the potentially inundated surface.

Stormwater Infrastructure Vulnerability Assessment

Stormwater structures, namely outfalls, manholes, ditch entrances and exits, and pipe entrances and exits, are heavily impacted by inundation under low levels of sea-level rise. In total, 49% of these structures face some level of potential inundation under 0.5 meters of sea-level rise. Under 1.0 meters of sea-level rise, the total percentage increases to 56% and rises to 60% at 1.5 meters of sea-level rise. Not surprisingly, outfalls are the most impacted structure of the structures studied. The number of outfalls impacted ranges from 81% to 88% under 0.5 meters and 1.5 meters of sea-level rise, respectively. Similarly, ditch entrances and exits are between 53% and 60% impacted by sea-level rise (Table 2).

Table 2: Results of stormwater structure vulnerability analysis, showing the total number and percentages of structures impacted by inundation under each sea-level rise scenario.

Structure Type	**# Impacted**			**% of Total Impacted**		
	0.5m SLR	**1.0m SLR**	**1.5m SLR**	**0.5m SLR**	**1.0m SLR**	**1.5m SLR**
Outfall	801	845	877	81%	85%	88%
Manhole	2451	3036	3347	48%	59%	65%
Pipe Entrance	1218	1483	1582	44%	49%	53%
Pipe Exit	1131	1322	1417	40%	47%	50%
Ditch Entrance/Exit	1106	1166	1240	53%	56%	60%
Total	**6807**	**7852**	**8463**	**49%**	**56%**	**60%**

Discussion

The results of this study suggest that including stormwater infrastructure in sea level rise inundation modeling has the potential to change the connectivity of inundated area, even at low levels of sea-level rise. Impacts to the infrastructure itself include the inundation of structures like grated manholes and inlets which could then not perform the drainage activities that they are responsible for. Outfalls will likely be inundated regularly at high tide so that if there is a precipitation event, water will likely become backed up in the stormwater system. In other words, the capacity of the stormwater system will be reduced, and the efficiency compromised during storms. This may lead to streets flooding more often and remaining flooded for a longer period while pumps work to push water out of the city. This could impact transportation infrastructure and emergency routes. The impact of this infrastructure appears to be at low levels of sea-level rise, specifically below 1.5 meters. These impacts will be seen in the near term, potentially within the next 30 years in Norfolk and other cities experiencing high rates of sea-level rise. The stormwater infrastructure vulnerability assessment suggests that the impact could be significant if mitigation measures are not undertaken. The results do not necessarily mean that all of the infrastructure will be incapacitated, but there is some level of risk involved. For example, an inundated outfall has a higher risk than a manhole, as outfalls are where water discharges, and if that can't occur, the rest of the system cannot work properly. Further, if there is a storm event on top of the daily inundation, the stormwater system may become overwhelmed more easily, leading to streets becoming flooded.

Planning for Resiliency in Norfolk

Norfolk, among other cities worldwide that are experiencing increasing impacts from climate change, is working to increase resilience. Norfolk has been a member of T*he 100 Resilient Cities (100RC) Network* since 2013, which aims to provide resources and guidance to cities facing threats due to climate change (ResilientVirginia, 2015). The State of Virginia has a resiliency strategy that in the first few years has begun publishing resiliency-related information on a website and in a newsletter, held two Resilient Virginia Conferences, and created a Comprehensive Resiliency Checklist which guides local governments towards achieving resiliency (ResilientVirginia, 2022). The city of Norfolk has outlined its own coastal resiliency strategy, using the terminology *plan, prepare, mitigate, and communicate* as the foundation for its strategy. To reduce impacts from flooding, community members are encouraged to help by planting trees and installing rain gardens, as well as restoring shorelines and wetlands (City of Norfolk, 2015). There are plans for flood walls, flood gates, and increasing the number of pump stations to improve stormwater capacity and therefore better protect the city during larger storm events such as hurricanes and nor'easters (City of Norfolk, 2015). The report mentions the construction of berms, and drainage improvements, along with structure elevations throughout the city (City of Norfolk, 2015). This work could help to reduce the impacts of increased nuisance flooding due to sea-level rise. The green infrastructure plan published in 2018 complements the coastal resiliency strategy, outlining more specific green infrastructure projects to help with both the stormwater retention issues as well as overall coastal resilience (City of Norfolk, 2018). One of the primary land goals states, "Install and maintain constructed green infrastructure to detain and retain stormwater and beautify areas where natural green infrastructure practices are less suitable" (City of Norfolk, 2018). This exemplifies the city's willingness to live with and work around rising seas by employing nature-based solutions in combination with other infrastructure updates. The green infrastructure plan also mentions how projects like those outlined in the plan will help to reduce the premiums on flood insurance through the National Flood Insurance Program (NFIP), and that a 15% discount is already available for NFIP participants in Norfolk each year (City of Norfolk, 2018). The city can receive points towards this discount through projects that will reduce flood damage and help with overall floodplain management. Although part of the city's plan for the future involves living with the water, the option for buyouts does exist and some residents have chosen that route as a result of recurrent flooding around their properties. In the Riverview neighborhood along the Lafayette River, some homes were bought by the City of Norfolk in partnership with FEMA; those homes were taken down and the land returned to marshland (Murphy, 2019). More of these projects are expected as a part of the coastal resilience plan and the green infrastructure plan.

Department of Defense Resiliency

The Department of Defense (DOD) has outlined plans for improving the resilience of military installations across the country. One such program, the Readiness and Environmental Protection Integration Program (REPI) aims to increase resilience and diminish the hazards posed to bases and installations by climate change (DOD, 2022). Like the projects and programs created by cities, REPI projects address climate change-related concerns by protecting critical infrastructure, personnel, and areas critical for everyday operations (DOD, 2022). For Naval Station Norfolk, and many other naval bases worldwide, rising tides will affect repairs happening at the dry docks, training, readiness, and access around the base itself. The Hampton Roads area, of which Norfolk is a part, has representation from every branch of the military, employs thousands of active-duty and reserve personnel as well as civilians, and provides a large economic value (DOD, 2021). Although the REPI program outlines some ongoing projects throughout the Hampton Roads area, there are not currently any proposed for Naval Station Norfolk, which could have negative implications for daily operations.

Data Constraints

Although the data available for the study site was robust, there were some data gaps that likely affected the outcome of the inundation grids. Specifically, there isn't any publicly available stormwater infrastructure data for the Naval Station Norfolk, which likely means inundation throughout the base was not accurately modeled. The area itself is flat, right next to the water, with a lot of area covered in concrete and other impermeable materials. This makes stormwater infrastructure even more important for the movement of water, as it won't be able to permeate the ground. If the stormwater systems are not able to operate properly due to rising seas and roads become impassable, the base may not be able to operate properly.

The stormwater pipe data posed many questions as well, as the depth below the surface wasn't known for the pipes, and the elevation at which the pipes met the surface was assumed. Components like the slope and diameter of the pipes could also impact the movement of water from the inundated surface to other areas. Because of these unknowns, it is difficult to pinpoint exactly how much of the pipes would be flooded, or if water would truly pass from one end of a pipe segment to the surface at the other end and impact a ditch or street where the pipe ends. For the pipes included in this analysis that were only crossing a road with openings on either end, essentially acting as a culvert, these questions likely wouldn't be an issue. The availability of all the stormwater infrastructure data from Norfolk's Open GIS site was critical to the success of this study.

Future Work

There are a lot of possible avenues for building upon the results of this study. The model could be run again, using just the known culverts and ditches, removing the pipe piece altogether. This would remove the need for additional data on pipe elevations and slopes, and it would be interesting to see how much the connectivity changes without the stormwater pipe data included. Building off current results by including precise elevations and slopes of the pipes would allow for more accurate inundation amounts to be modeled for each sea-level rise scenario. This additional information may also reveal that some of the pathways created in this study would not be inundated until a certain threshold of sea-level rise is met. Further, seeing how changing the diameter of the stormwater pipes and ditches data changes the inundated surface and the corresponding inundation amounts would reveal further insight into how different changes in stormwater infrastructure affects the capacity of the system overall. Building on that, changing the locations where these infrastructure updates are made throughout the city, and reviewing how connectivity and inundation changes, could be helpful in prioritizing locations where infrastructure updates should be prioritized.

Green infrastructure updates, both proposed and those already installed, could be incorporated into this model to see how inundation results change as well. Along a similar vein, adding the catch basin structures into the model as locations where water may collect would add another layer of detail and potentially positively affect the inundated landscape by increasing areas below ground where water can accumulate when need be. Then, similarly to testing changes in pipe and ditch infrastructure, the model could be adapted to include potential sites for additional catch basins, retention ponds, and berms to see where those additional structures would have the biggest impact on stormwater capacity. Another way that the current model and results could be expanded is by experimenting with seeing how inundation changes because of removing the potential for flow through outfall structures, mimicking flood valves.

The hydrographic overlay data brought an additional layer of detail to this study. Combined with the stormwater infrastructure data, the results hypothetically show a more detailed view of potential inundation for Norfolk as sea levels rise. It would be interesting to see the results of just the hydrographic data without the infrastructure piece and to compare the two. Further, using the NWI data, it would be interesting to do a vulnerability assessment of the wetland ecosystems that exist throughout Norfolk, by looking at the potential inundation of these areas and their ability to migrate inland as sea levels rise.

All the potential future work, and the replicability of this study in general, depend upon available data. The work outlined in this study as well as future work can be applied to other coastal cities and municipalities, as well as coastal military bases to understand the potential extent of inundation which can help prioritize planning and preparation.

Conclusion

Geospatial analysis tools including those used in this study can illustrate insufficiencies in coastal infrastructure. This study illustrates the potential for stormwater infrastructure to change the connectivity of the inundated landscape under low levels of sea-level rise if mitigation goals are not achieved. Engineered structures such as flood and tide gates can assist in keeping water out of areas. Updating outfalls to only allow the movement of water in one direction with another flood gate-type addition can keep seawater out of the stormwater system at high tide. As sea levels rise, the structural integrity of all stormwater infrastructure will become even more important, and drainage improvements should be a priority for cities like Norfolk. It is likely that a combination of engineered and green infrastructure will need to be incorporated into city planning to mitigate high water levels daily at high tide, as well as during heavy precipitation and storm surge events. Green infrastructure such as bioswales and rain gardens can help to return stormwater to the groundwater, and reduce the stress put on stormwater collection systems. In general, reducing the number of impermeable surfaces such as concrete is important for stormwater absorption and retention. Restoring and improving upon coastal wetlands is crucial for restoring natural flood protection for coastal areas.

The results of this study will be useful in prioritizing areas and infrastructure for improvements in the near term to protect the city from increasing nuisance flood events. This is a helpful starting point for the city of Norfolk to review its current stormwater infrastructure, as this study was conducted under the assumption that all the pipes, ditches, and structure points are currently in use. Further, the inundation surface results could be used as a worst-case scenario model, if flood and tide gates fail, for flooding at high tide under each sea-level rise scenario. From there, larger-scale events could be modeled using the existing inundation surface to get a more accurate model of flooding. Fine-scaled inundation modeling will be most useful in the near term as cities plan for impacts that are already occurring daily. The geospatial analysis tools such as those used in this study are valuable tools in the management of sea-level rise in coastal communities.

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Appendix

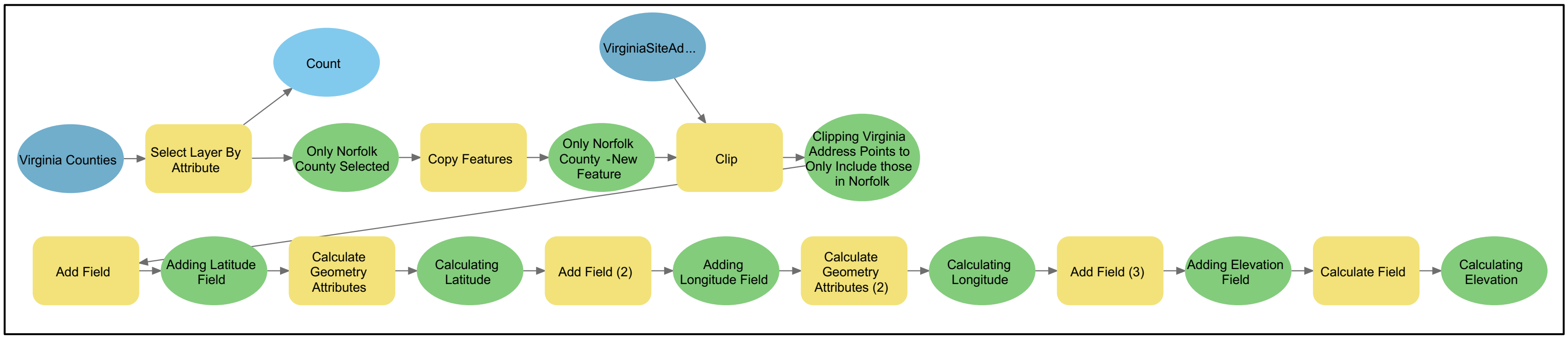

Figure 5: Preprocessing needed to prepare grid of points to be input into NOAA vertical datum conversion software.

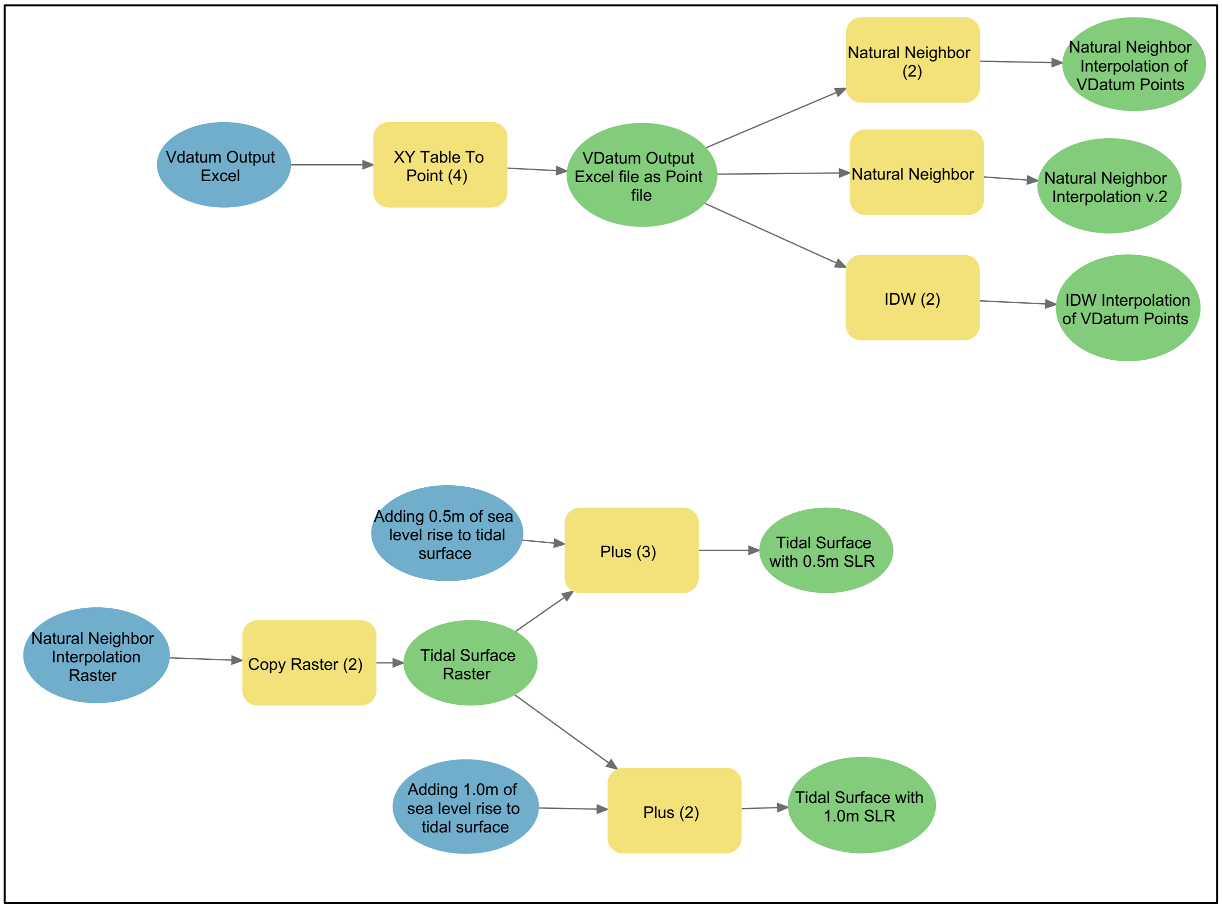

Figure 6: Top- Interpolation of VDatum software output grid. Bottom- Creating Tidal Surface with sea level rise amounts added.

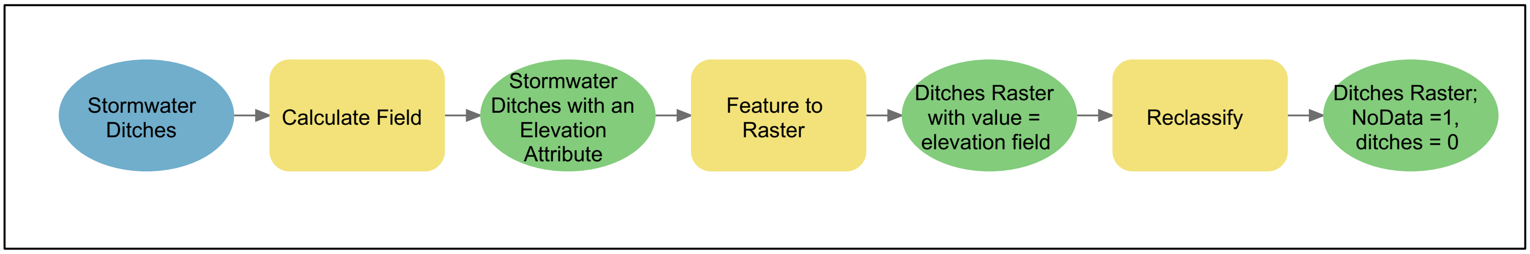

Figure 7: Example of preprocessing steps for each stormwater infrastructure piece, prior to including in the DEM.

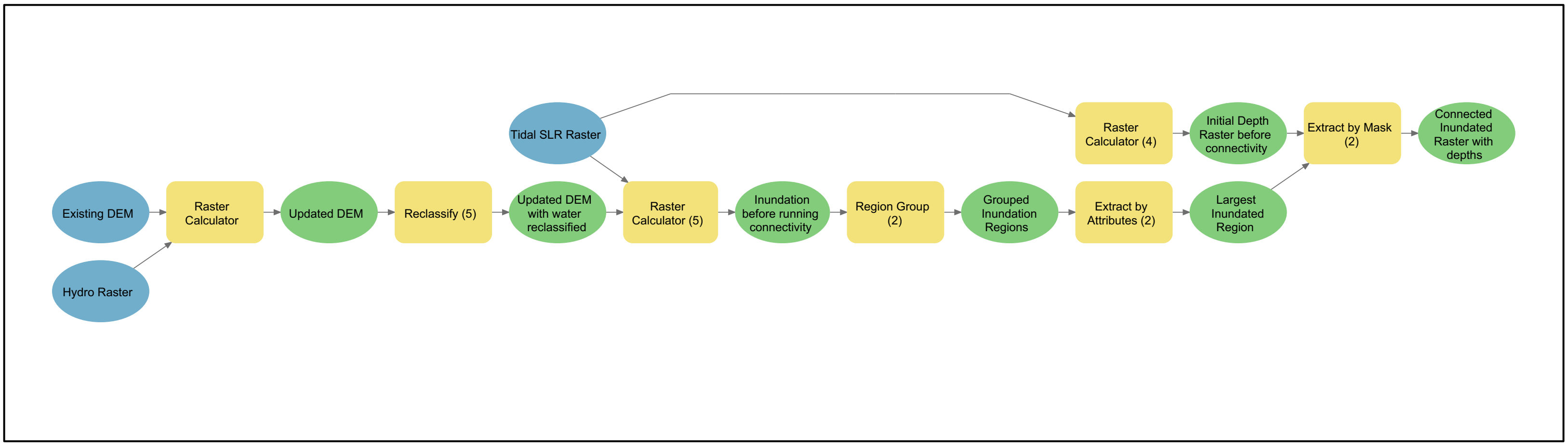

Figure 8: Example of steps for creating depth grids and running connectivity to get connected inundated grid.