ABSTRACT

Water Infrastructure Vulnerability to Coastal Flood Hazards: A Space-Place Analysis of Manteo, New Bern, and Plymouth, North Carolina

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With the impending threat of sea level rise, as well as the recurring annual danger of storm surges during hurricane season and floods from heavy rain events, North Carolina's coast is especially vulnerable to coastal flooding, due mostly to large extents of low lying coastal areas. Water utility infrastructure is a vital resource to any community, while concurrently containing hazardous material that could be potentially devastating to the residents if parts are damaged. Unfortunately, they are commonly located in highly vulnerable areas along the coast. Hurricane Sandy illustrated how large magnitude natural hazards can damage vulnerable infrastructure, leaving municipalities burdened with enormous repair costs, as well as large parts of the city without running clean water.

To reduce the vulnerability of these important systems in several coastal North Carolina communities, New Bern, Plymouth and Manteo were assessed for their vulnerability to storm surge, sea level rise, and riverine flooding using downscaled surge flood models, and applying Geographic Information Systems techniques to improve the

accuracy of Digital Elevation Models used in flood mapping. A geospatial overlay of the water infrastructure assists in the computation of vulnerability of this resource to these risks, which will be used to promote proactive solutions to city officials in order to reduce their vulnerability. By modeling these different hazards for three different communities with different geographical contexts, we can observe how they differ within and throughout differing areas.

Water Infrastructure Vulnerability to Coastal Flood Hazards: A Space-Place Analysis of Manteo, New Bern, and Plymouth, North Carolina

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Zachary Oyer

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LIST OF ACRONYMS

CRC – Coastal Resource Commission

DEM – Digital Elevation Model

DFIRM – Digital Flood Insurance Rate Map

GIS – Geographic Information Systems

HECRAS – Hydrologic Engineering Centers River Analysis System

IPCC – Intergovernmental Panel for Climate Change

LiDAR- Light Detection and Ranging

MOM – Maximum of Maximums

NCFMP – North Carolina Floodplain Mapping Program

NC-SLRMS – North Carolina Sea Level Rise Management Study

NHD – National Hydrography Dataset

NOAA – National Oceanic and Atmospheric Association

NWS – National Weather Service

SLAMM – Sea Level Affecting Marshes Model

SLOSH – Sea, Lake, and Overland Surges from Hurricanes

USGS – United States Geological Survey

CHAPTER 1: INTRODUCTION

A variety of hazards threaten coastal communities in North Carolina, including sea level rise, storm surge, coastal riverine flooding, and shoreline erosion. With about 40% of the United States population on the coast, these hazards put many people's lives at risk, as well as many residential and commercial buildings, and critical urban infrastructure (U.S. Census Bureau, 2011). In order to help reduce risk and future disaster damage owing to these natural hazards, coastal communities are wise to assess their vulnerability and evaluate where they are at most risk of damage. With increasing availability and accuracy of Light Detection and Ranging (LiDAR) and associated geospatial technology, particularly accurate models can be created to simulate inundation arising from the different processes of coastal flooding. With these compounding effects influencing vulnerability to coastal flooding, some models predict an increase of up to 30 million people affected by this threat every year worldwide by the year 2080 (Nicholls *et al.*, 1999). Other modeling by Small and Nicholls (2003), predicts an increase in people living within a 100 year storm surge floodplain, from 200 million in 1990, to up to 600 to 800 million by 2100.

Water utility infrastructure, which involves the treatment and transportation of both clean water and sewage, is often located in low-lying areas along the coast, making these a highly vulnerable component of local utilities. A working definition of water utilities includes material infrastructure, or a public facility, which is physically comprised of canals, waterways, waterworks, reservoirs and pipelines for the purpose of supplying drinking water, industrial-use water, irrigation water, and wastewater disposal functions (Buhr, 2003). Flooding can cause pumping problems as the inundated water alters the hydraulic head of the system, as well as causing debris blockages and pipe failures (Titus *et al.*, 1987, Chughtai and Zayed, 2008). Additional concerns for water infrastructure damage include the intrusion of salt water, which may lead to pipe and valve corrosion (Fugro, 2012). Reduction or elimination of human and environmental exposure to dangerous materials, such as sewage, is very beneficial to at risk communities. Several studies have assessed the vulnerability of such utilities to storm surge or sea level rise in coastal communities and determined this infrastructure to be highly vulnerable (Burkett and Davidson, 2012, Heberger *et al.*, 2011). Burkett and Davidson concluded that clean water and sewage treatment utilities were at significant threat from the combination of sea level rise and storm surge in the United States.

The vast destruction Superstorm Sandy caused in the Mid-Atlantic in 2012 highlights our coastal vulnerability. Estimates for the cost of reconstruction from the damage caused by Sandy ranges between $140 to $240 billion (Bloomberg, 2012). With such critical and expensive infrastructure in highly vulnerable areas of coastal cities, expectations are for this trend to continue to increase if mitigation or adaptation measures are not undertaken to reduce our vulnerability and avoid ensuing damage. In the wake of Sandy's destruction, New York's Governor Andrew Cuomo vowed to rebuild and strengthen several aspects of water infrastructure to decrease its vulnerability to coastal hazards again (NY.gov 2100 Commission, 2013). Strategies that balance the investments in mitigating damages to existing infrastructure and seek to develop more adaptive, resilient infrastructure in the future are gaining serious consideration.

In order to contribute to our understanding of adaptation, mitigation and preparation for these increasing coastal hazards, this study evaluates vulnerability of water utility infrastructure to coastal flooding of North Carolina cities and towns, including the towns of Manteo and Plymouth and the City of New Bern (Figure 1.1). This study adopts a comparative approach to assess how local coastal geography can influence the risks posed by different hazards over space and time. We have the ability to not only assess how vulnerable the infrastructure is currently, but also to speculate how that may change over time as climate change and coastal processes interact with sea-level rise. In addition, the investigation can reveal differential spatial and time-evolving risks for communities, allowing them to prepare and plan for change into the future. Lastly, and most importantly, the goal is to approach hazards differently, by analyzing three separate flood hazards in three communities with different geographical settings. This type of approach will provide more context to true flood vulnerability that many other studies fail to assess. It is hoped that this study will encourage coastal communities to be proactive in seeking solutions to the ongoing and potentially increasing risk of flood hazards.

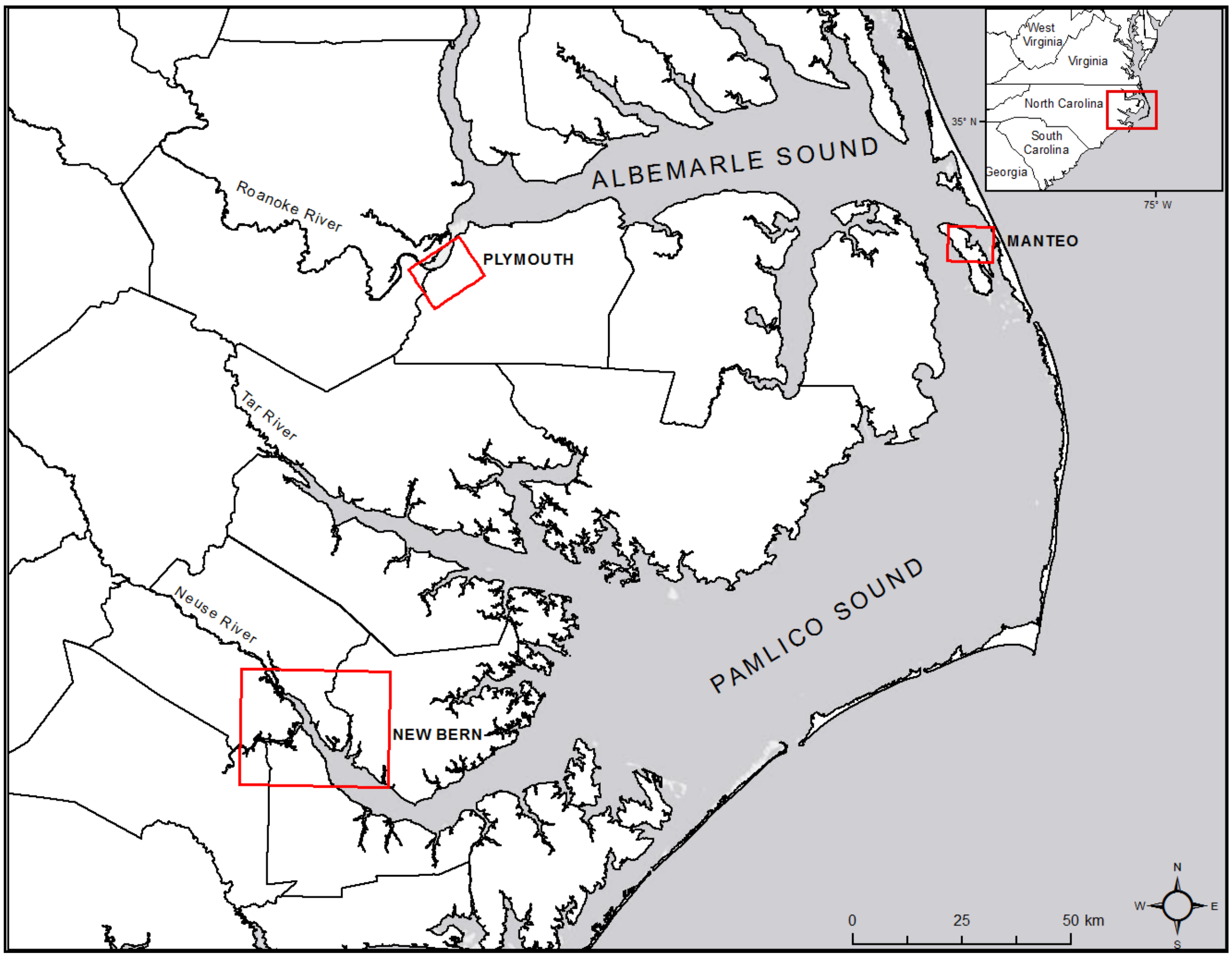

Figure 1.1: Study area and communities of interest in eastern North Carolina.

CHAPTER 2: RESEARCH QUESTIONS

1. *How do riverine flooding, storm surge, and sea level rise risks threaten the coastal communities of Manteo, New Bern, and Plymouth, North Carolina?*

While different geographic regions experience different risks and hazards, these hazards all contribute to the risk of all three communities. Vulnerability to hazards such as sea level rise and storm surge is increasing in coastal regions (Hecht, 2006). With North Carolina's low-lying coastal plain, storm surges are a continual threat, while the rise in sea level is a chronic, long-term threat facing the entire state's coastal region. Answering this question will elucidate the relative current threats of these hazards and allow for the comparison among the three locations being evaluated: 1) a river-dominated community (Plymouth), 2) a hybrid riverine-estuarine setting (New Bern) and 3) a coastal estuarine island community (Manteo).

2. *How vulnerable is the water infrastructure of Manteo, New Bern, and Plymouth to coastal flood hazards?*

While proactive planning efforts should keep important infrastructure out of flood plains, and away from harmful coastal hazards, wastewater treatment plants are often placed in highly vulnerable areas. The storm surges from larger storms will most likely encompass much of the infrastructure currently in vulnerable areas. With a continued rise of sea level, likely at an accelerated rate (Vermeer and Rahmstorf , 2009), there is an added long term flood hazard risk to this critical infrastructure, even if a large enough storm surge is not generated in the near future. As sea level rises, marshes and higher tidal zones begin to impact storm and wastewater outfalls, increasingly threatening the infrastructure with tailwater flooding and eventually outright flooding of facilities such as pump stations and underground pipes. Marshes may even invade facilities and reclaim transportation corridors. It is expected that all of these communities will have at least some vulnerability to all of these hazards, which can always be reduced.

3. *Which coastal hazard poses the greatest risk in the future for each of these communities' water resources infrastructure? How do these threats to infrastructure vary spatially and temporally among the study sites looking into the future?*

A cursory inspection of the spatial placement of the infrastructure, revelas high vulnerability to coastal floods. Larger storm surges should cause the most flooding and affect the most infrastructure since it has the quickest and largest influx of water. Regional sites should be differentially vulnerable to other hazards, depending on the geography of the coast. Greater exposure to open bodies of water will create more vulnerability to storm surges, while larger river basins will create more riverine vulnerability. By discovering which hazards are more of a threat to each community, this information could be useful moving forward with adaptation and mitigation efforts.

CHAPTER 3: REIVEW OF LITERATURE

Climate change and sea level rise have become topics of great interest in recent years. With almost 40% of the U.S. population living in coastal counties, which make up only 10% of the total land cover, these counties have a population density of 446 people per square mile (171 people per square km), versus the national average of 105 people (40 per square km) for the contiguous United States (U.S. Census Bureau, 2011). In North Carolina, Dare County comprises a large portion of the Outer Banks barrier island chain and was the fastest growing North Carolina county between 1970 and 1995 (Overton *et al.*, 1999). With such a high concentration of the population along the coast, and a high value of coastal property, some estimates predict that a large coastal storm could easily exceed $1 billion in damages on the North Carolina coast alone (Hondula and Dolan, 2010). The future risks such coastal communities face all over the world arise not only from coastal flooding from storms but from continued sea level rise as well.

3.1 Climate Change

Sea level rise is measured by two means, a global measurement of worldwide sea level, or "Eustatic" sea level, and a more local measurement termed "Relative Sea Level". The eustatic sea level rise rates have been measured at about 3.4 mm per year through altimetric means, with about 30% of that rise accounting for thermal expansion, and about 55% accounting for land ice melt (Cazenave and Llovel, 2010). The measured relative sea level rise of North Carolina has varied from 3.6 to 4.5 mm per year (Kemp *et al.*, 2009a, Kemp *et al.*, 2009b), exacerbated by strong local subsidence, particularly in the northeastern coastal plain and Outer Banks. Predictions for the rise in eustatic sea level have been generated in many reports, with many differing opinions on the rate of change. The Intergovernmental Panel on Climate Change (IPCC), which is recognized as one of the leading international organizations on climate change and sea level rise, predicts that by the year 2100, sea level will follow a linear rate of change, and will experience between about 20 to 60 cm of rise (IPCC, 2007). However, many studies suggest that the rate of sea level change will be an exponential rise. Vermeer and Rahmstorf (2009) point out that the IPCC report lacks an inclusion of dynamic ice processes, and predict that by the year 2100, sea level could be 1 to 1.5 m higher than it currently is. Concurrently, as sea level rises, not only will it continue to inundate more land, but it will also change the shape of the coast over time (Davidson-Arnott, 2005). With the rise of sea level expected to occur for a long period of time, there is much need for these coastal communities to assess the risk of coastal land loss, and to make preparations, mitigate or adapt.

In the short term, it is simplistically observed that more coastal inundation occurs annually from storm surges than annual sea level rise. North Carolina experiences strong thunderstorms, tropical cyclones, and nor'easters, with nor'easters creating the most wave energy on North Carolina's coast each year, bringing seven times the amount of total storm wave energy produced by hurricanes (Smith *et al.*, 2006). Storm surge flooding, coupled with heavy rainfall from these storms, causes extensive flooding and massive damage to the entire developed coast. One of the most famous nor'easters in North Carolina history, the Ash Wednesday Storm of 1962, impacted over 1,000 km of the Atlantic coast shoreline, causing over $300 million in property damage with over 10 m high waves (Davis and Dolan, 1993).

Tropical cyclones can be quite destructive as well, with the 2005 hurricane season being the most costly in recorded history. In that season, hurricanes were the cause of nearly 1700 deaths, and caused well over $100 billion in damages in the United States (Beven *et al.*, 2007). Hurricane Floyd brought some of the worst flooding in North Carolina's history in 1999, brought upon by torrential rainfall rather than extreme storm surges. Compounded by a wet summer and two preceding tropical storms, the flooding associated with Hurricane Floyd was categorized as a 500 year flood event, and over the next month drained a volume of water almost equal to the entire amount of the Pamlico Sound (Bales, 2003). Unlike many hurricanes associated with high death tolls and extensive flood damage, most of the flooding from Floyd was riverine, and 48 of the 56 deaths from Floyd were due to freshwater flooding (NWS, 2013). The transport of flood waters from Floyd into the Albemarle and Pamlico Sounds caused severe flooding for towns near river embayments and estuaries such as New Bern (Neuse River) and Plymouth (Roanoke River), but had comparatively very little effect on the Outer Banks at Manteo. This flood disaster highlights the spatial differences of some coastal flood hazards and stresses the importance of a comparative, multi-hazard approach.

Another recent storm that informs our understanding of the differences between flooding among these study sites is Hurricane Irene, which caused extensive damage in North Carolina as well. On August 20, 2011, Hurricane Irene was the first hurricane to hit the United States since Hurricane Ike hit the Texas coast in 2008, and was the 10^{th} billion dollar disaster in the United States, causing 300,000 people to evacuate in North Carolina alone (NOAA, 2011). The United States Geological Survey (USGS) has a database of high water marks (USGS, 2014), which were extracted to compare the three study locations, and the flooding that occurred differently among them (Figure 2.1). New Bern recorded the highest flood heights at over 2.2 m, while Manteo's highest recorded flood elevation was 2.1 m, and Plymouth only recorded a flood elevation of 1.98 m several kilometers down the Roanoke River. These differences illustrate the extreme variability of event impacts across a complex, extensive coastal plain and estuarine system such as eastern North Carolina.

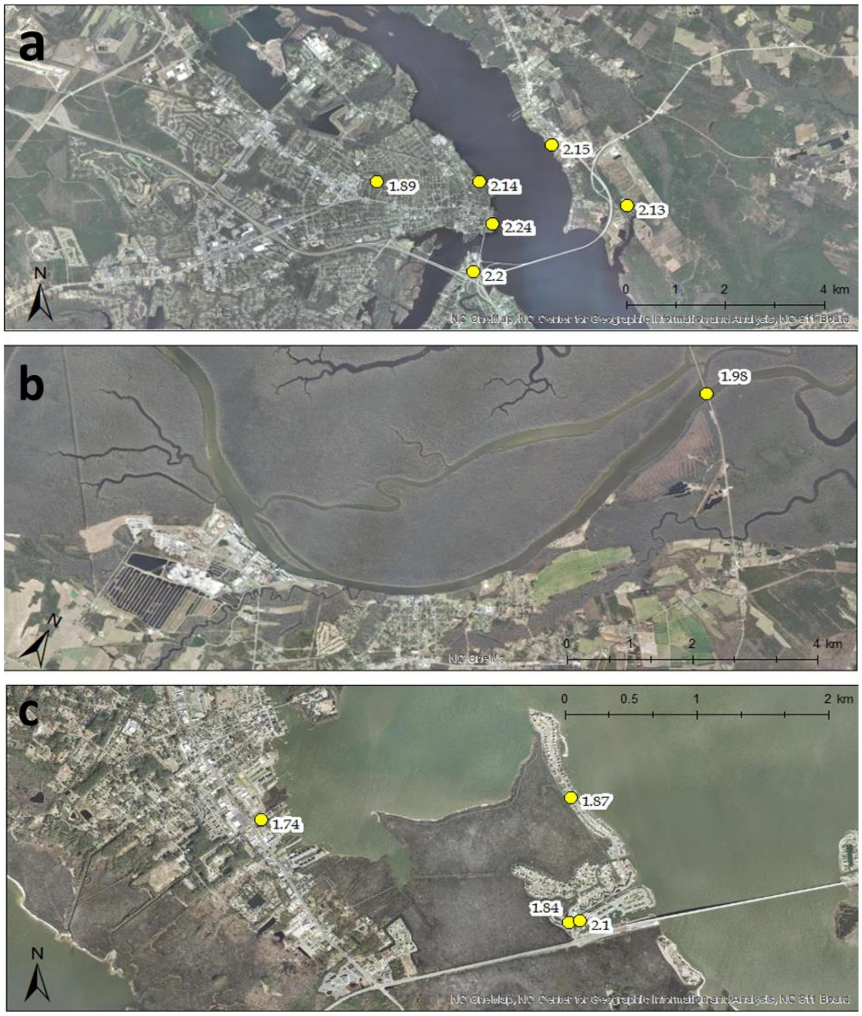

Figure 3.1: Heights of high water marks (meters) from Hurricane Irene in 2011 for A) New Bern B) Plymouth and C) Manteo overlaid onto orthophotography (composited of 2010, 2011 and 2013 imagery).

With climate change, the behavior of tropical cyclones is expected to change (IPCC, 2007). High resolution modeling is improving the ability to predict these changes of storms with warming temperatures and sea level rise. Most importantly, these models predict an increase in intensity of 2 to 11% by 2100, but yet also a decrease in total hurricane frequency by 6 to 34%. However, there may be an increase in the number of major hurricanes (Knutson *et al.*, 2010). An increase in hurricane intensity brings stronger winds, which will push more water onto shore at landfall and create higher storm surges. The combination of more intense hurricanes with larger storm surges, in addition to accelerated sea level rise makes predicting the extent of coastal flooding more difficult and could possibly result in under-estimations in the predictions.

3.2 Infrastructure Damage

For water infrastructure, coastal flooding causes many problems with pumping pressure and can also cause extensive damage to sewer pipelines from debris blockage (Titus *et al.*, 1987). Pumping pressure is determined by the "hydraulic head", which is the measured liquid pressure above a datum, which constitutes the water treatment plant's ability to pump water to its beneficiaries. The higher the water table rises above this datum, the more hydraulic pressure lessens, and the plant can lose the ability to pump water.

The integrity of the pipes may also be compromised due to coastal hydrologic processes such as groundwater infiltration (Chughtai and Zayed, 2008). Issues stemming from groundwater infiltration occur mostly with the soil surrounding the pipelines. The flowing of the groundwater around the pipes may erode the soils surrounding the pipes and undermine their support. With inadequate support from the ground, the pipes can come under too much stress, resulting in pipe failure. Additional damage to underground infrastructure can be incurred through the migration of saline water from tail water. The tail water is simply the elevation of the water downslope from a structure, such as a dam, or a coastal outfall for run off or treated wastewater (Figure 2.2). Once tail water elevations are high enough to reach the entrance of a coastal outfall, the slope of the water level landwards will push the direction of flow up the outfall, which can cause corrosion to pipes, valves and fittings (Fugro, 2012). The salinity of the water will also have an effect on the magnitude of corrosion, with rising water salinity causing corrosion to occur faster than before (Fink, 1960).

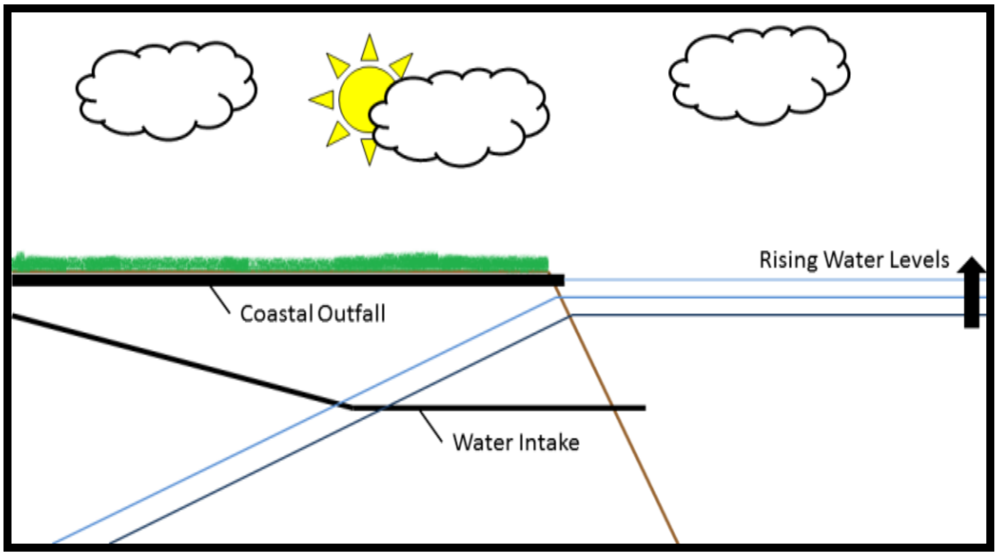

Figure 3.2: Diagram of raising tailwater elevations migrating upland and up coastal outfalls.

These processes involving saline groundwater will increase the risks for Manteo as compared to New Bern or Plymouth, owing to its location closer to the open ocean, and to its higher salinity surrounding estuaries by proximity to Oregon Inlet. The sounds of North Carolina contain brackish water, which can have a range of salinities as fresh water from tributaries meets the saline waters of the ocean. The salinity of these waters varies based on several processes, particularly proximity to fresh or salt water sources. However, as sea level rise increases, the higher salinity of the ocean will intrude into the estuaries, raising their salinity, and increasing their risk to corrosion as well. Some studies predict an increase of salinity of up to 4 ppt in drinking water with 100 cm of sea level rise in the Chesapeake Bay tributary rivers, far surpassing the EPA standards for dissolved solids in drinking water, which is 0.5 ppt (Rice *et al.*, 2012).

Preparation and mitigation for coastal communities can help reduce these costly repairs and environmental damage due to failing utility infrastructure.

3.3 Health Risks

In addition to the potential risk of increasingly saline water on infrastructure, flooding and relative sea-level rise also pose acute health hazards. With damage and possible failure of water infrastructure comes the possible spillage of dangerous material such as raw sewage, leading to associated health risks. There is no question that raw sewage in the public water supply is a health risk to the entire community (Lane *et al.*, 2013), however, there are serious negative effects to the entire ecosystem as well. The effluent release of this fecal matter floods the system with nutrients in coastal environments, causing massive algal blooms which create severe hypoxic conditions and substantial fish kills. While these contaminants may decline in the water column at an exponential rate through bacterial consumption, their presence in the sediment can last much longer, leaving the area contaminated for an extended period of time (Mallin *et al.*, 2007). Downstream ecosystem impacts can affect fisheries and livability and amenity value of coastal recreation and tourism. Fish kills, algal blooms, and reduced fishing are just a sampling of possible additional ecological impacts that could degrade the coastal economy.

Additional risks from flooding to humans, besides drinking water contamination from sewage, are direct exposure to sewage overflow, living in flood damaged homes containing mold or with utility outages for an extended period of time, and even drowning during flooding events (Lane *et al.*, 2013). These impacts to the well-being and quality of life of citizens should be among the top priority reasons for assessing risks and reducing the vulnerability of water infrastructure. While cost-benefit analysis should be considered for mitigation efforts, the effect on human lives and ecosystem goods and services should also be assessed.

3.4 Mitigation

As sea level rise becomes a more recognized threat to coastal communities, more cities have examined options to be more prepared to deal with these impending risks, in the form of policy and physical preparation (Munaretto *et al.*, 2012). The ability to act proactively to the anticipation of coastal flooding requires a combination of wise development and conservation of beaches and marshes along with considering potential hardened structures like levees, dams and bulkheads. Highly vulnerable and important infrastructure, such as sewage plants and pipelines should be moved to less vulnerable areas to prevent sewage backup and spills to save money in repairing damage. To accomplish these important and often expensive tasks, political cooperation and foresight are very important (Munaretto *et al.*, 2012).

To assess the need for proactive solutions to coastal inundation, many cities have evaluated their own vulnerability to future sea level rise and storm surges (Heberger *et al.*, 2011, Friedrich and Kretzinger, 2012). Assessments like these using GIS to model coastal inundation using high resolution digital elevation models (DEMs) with geospatial analysis of geographic locations of important infrastructure can provide important information to cities. While some studies focus more on vulnerability to sea level rise (Friedrich and Kretzinger, 2012), others combine risk assessment of floodplain inundation and surges with local estimates of sea level rise (Heberger, 2011). With information on thse hazards overlain, city planners and local government officials can consider how to move forward, improving the resilience of existing infrastructure, and designing for future projects with lower risks.

Resilience is the ability of a system to bounce back to its initial state after a disaster, such as flooding, which is a term adopted from physics, describing a material's ability to return to homeostasis after a disturbance (Norris *et al*., 2008). To improve resilience, communities can mitigate and adapt through several means. Mitigation and adaptation are both strategies to reduce a community's vulnerability to risk, but they differ by their goals in implementation. Kundzewicz and Matczak (2012) describe this difference as such: mitigation treats the causes of problems, while adaptation seeks to treat the symptoms. That is, mitigation aims to decrease the threat that causes coastal flooding, climate change, through measures such as reduction in carbon emissions, while adaptation attempts to decrease the damage that flooding causes, such as moving or elevating buildings.

3.5 GIS and Vulnerability Assessment

In order to create accurate assessments of flood inundation, it is necessary to correct digital elevation models used in geographic information systems (GIS) to portray the terrain in a more accurate manner than the publicly shared DEM. Hydro-correction is the process of editing the modeled terrain in order to adjust the hydrology of the system for more accurate flood models than before the correction. The use of hydro-correction can change the results of flooded areas drastically, in some studies changing the area of inundated regions by 760 km^2 (Poulter and Halpin, 2008). The change in the DEM creates flooding in areas that may be misrepresented by conventional LiDAR data, such as ditches, that may not have been captured by the models before the hydro-correction. Other forms of hydro-correction can be the addition of culverts, which along with ditches, can greatly affect the flow of water, hydrography, and delineation of watershed size and shape (Duke *et al.*, 2003).

To assess of vulnerability in this study, we must first define explain a working definition. Several studies have made attempts to create unified definitions of this term in order to help bring the scientific community into agreement on how to use and measure it. Wolf, *et al.* (2013), have defined vulnerability assessments dealing with climate change as the measured degree of effect a stimulus has on an entity. The IPCC has created a definition as well, which is "the degree to which a system is affected, either adversely or beneficially, by climate variability or change" (Parry *et al.*, 2007). Vulnerability can be calculated and represented through different measurements, such as a relative or absolute count. Relative vulnerability measures vulnerability based on a percentage of the total system affected, while an absolute vulnerability is based on a raw count of affected items. Relative vulnerability will tend to have higher values for communities with less infrastructure, such as towns with only one wastewater treatment plant. Meanwhile, absolute vulnerability assists in conveying vulnerability for larger communities with more infrastructure. For example, if you compare a town with one treatment plant with a city with four treatment plants, and both have one at risk treatment plant each, their respective relative vulnerabilities will be 100% and 25%, while both have an absolute vulnerability of 1. Relative vulnerability allows for comparison between communities of different sizes, while an absolute count will create bias on size, but will also give a different perspective on vulnerability.

3.6 Coastal Inundation Models

The Sea, Lakes and Overland Surge from Hurricanes (SLOSH) model was created by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA) to provide a fast, spatially universal, and relatively precise method to predict storm surge extents for oncoming storms (Zhang *et al.*, 2008). The model uses size, position and intensity of the hurricane to calculate the hypothetical inundation extent, excluding measurements such as wind parameters and tides (Jelesnianski *et al.*, 1992). It is a two dimensional model that uses a polar grid system and differing cell sizes to derive a predicted storm surge height with an accuracy of about ± 20% when tested against field-measured heights (Zhang *et al.*, 2008). The 20% rule is a conservative estimate, reflecting the NWS concerns for cascading errors from storm track and intensity variation as well as the fact that SLOSH does not explicitly include either astronomical tide, waves or wave run up. However, the SLOSH model has predicted with far greater accuracy than the standard 20% rule in some instances. For Hurricane Katrina, the predicted storm extent matched high water marks at ± 5% (Zachry *et al.*, 2012). SLOSH is used conservatively, usually with pre-run libraries of models for various storm tracks and intensities, and applicable tide and wave heights are added to the forecast and briefings from other model and observation sources. The SLOSH model uses simple meteorological parameters to compute the forces that drive the water onto land, using generalized and universal coefficients for variables such as surface friction to help make the model easier to use (Jelesnianski *et al.*, 1992). In addition, SLOSH remains the current operational model for the NWS, and it will allow for this study to evaluate the different hurricane categories to generate flood risk areas for each one.

There are several methods scientists use to project how raising sea levels will affect the coast, one of which is the Sea Level Affecting Marshes Model (SLAMM), which will help to assess the wetland response to inundation from sea level rise. The SLAMM model was created by Park *et al.* (1986) to simulate how coastal land cover will be affected by sea level, and has assisted in environmental decision making since its creation. This model uses sea level rise scenarios taken from the IPCC, and uses not only topography to compute inundation, but can also estimate changes in land cover, and relative changes in erosion based on the coastal geometry

(Clough *et al.*, 2009). The six processes it includes to determine how wetlands are affected are inundation, erosion, overwash, saturation, accretion, and salinity (Clough *et al.*, 2009).

Another, more simplistic method of modeling coastal inundation from sea level rise is with a simple "bathtub" model. This type of model involves a manual raising of the sea level by the modeler. In a typical bathtub model, hydro-connectivity to a water source, such as the ocean, is not accounted for, and cells are flooded solely on the basis of the being above or below the desired flood elevation. However, in order to create accurate sea level rise scenarios, studies have modified this approach to account for hydro-connectivity using the cost distance tool in ArcGIS (Allen *et al.*, 2013). As opposed to the SLAMM models, these models predict only direct inundation from sea level rise, rather than the effects of land cover type migration. Also, the SLAMM model is limited to the resolution of satellite land cover data, which is delineated at a coarse 30 m resolution. The bathtub scenarios, however, can be scaled to the size of the DEM, which in the case of this study, is a much finer scale than the land cover resolution.

Flooding by rainfall run off, or riverine flooding, is represented through FEMA Digital Flood Insurance Rate Maps (DFIRMs). The State of North Carolina conducted a project in 2001 called the North Carolina Floodplain Mapping Project to create a digital database of the existing FIRMs of both the 100 and 500 year floodplains. These floodplains are created using water inputs, discharge and topography to calculate areas of inundation. In one study, DFIRMs were tested against field-measured floodplain boundaries, and the 100 year floodplain DFIRMS captured about 67% of the true flooded parcels (Aycock and Wang, 2004). Another option for riverine flood models would be to create our own extents using the HEC-RAS model. This model uses one-dimensional energy equations using cross sections along a basin to calculate flooding, accounting for flow rates and friction with the bottom (Kelly *et al.*, 2007). However, the DFIRMs from the NCFMP represent the same type of models included in the HEC-RAS or other similar models, and will represent the extent of the floodplains in this study. Periodically, these DFIRMs are updated as new and higher resolution LiDAR data becomes more available.

CHAPTER 4: METHODOLOGY

This project was accomplished almost entirely with GIS, through which most of the spatial analysis, and modeling will be undertaken. The study will be divided into four main sections: 1) data acquisition, 2) compilation of high-resolution DEMs, 3) modeling of sea-level rise, flooding and storm surge, and 4) analysis and synthesis of results, including graphics and dissemination with community officials and planners for possible incorporation in mitigation and adaptation plans. The driving climate change scenario for future coastal evolution from sea-level rise used is the local relative sea-level change in the NC Sea-Level Risk Management Study (NC-SLRMS) as proposed in the 2010 NC Science Panel Task Force of the NC Coastal Resources Commission (NCCRC Science Panel 2010).

4.1 Data Acquisition

As with many GIS projects, acquiring all the data from different sources to pull together into one comprehensive map is not always an easy task. Several different sources were explored for GIS layers to represent utility water infrastructure such as water and sewage pipelines, water and sewage treatment plants, as well as pumping stations and service areas. Other data needed for this project are ditches and the high resolution (6.1 m or finer) DEMs for the three communities of New Bern, Manteo and Plymouth.

High resolution DEM data were acquired in prior work of the East Carolina University (ECU) Renaissance Computing Institute (RENCI) engagement center from NC Floodplain Mapping. Data acquired through other sources include sewer service areas, pipelines, pumping station, treatment plants, and ditches (Table 4.1). The ditches were found through the National Hydrography Dataset (NHD) provided by the USGS. The plants, pipelines, and service areas are accessible by the North Carolina One Map, an online dataset that provides GIS data to the public.

After contacting local professionals, more accurate data for New Bern than was previously found on OneMap, such as clean and wastewater lines, and pumping and booster stations were found through a published webmap provided by Kevin Gaskins (GIS technician, City of New Bern).

Table 4.1: Sources and publication dates for layers needed for vulnerability assessment.

Layer Name	Type of Data/ Resolution	Source	Pub. Date
Wastewater Service Areas	Polygons	NC One Map	3/6/2007
Treatment Plants	Points	NC One Map	3/21/2000
Pump Stations (Manteo, Plymouth)	Points	NC One Map	3/20/2000
Wastewater Pipelines (Manteo, Plymouth)	Lines	NC One Map	3/20/2000
Water Pipelines (Manteo, Plymouth)	Lines	NC One Map	3/28/2000
Pump Stations and Pipelines (New Bern)	Points and Lines	ESRI Map Publisher	1/3/2013
Riverine Floodplains	Polygons	NCFMP	4/16/2013
Dare County and Craven County DEM	20 ft (6.1 m) Raster	NCFMP	9/23/2002
Washington County DEM	20 ft (6.1 m) Raster	NCFMP	9/15/2004
Land Cover	30 m Raster	NOAA	2010
Census Block Groups	Polygons	Census Bureau	2/3/2011
NHD Canal/ditch	Lines	USGS NHD	

4.2 Dasymetric Mapping

Using the service areas of the wastewater treatment plants, it is necessary to estimate the number of people who would be affected by inundated treatment plants that could no longer serve the public. In order to derive this population count, the population was distributed spatially through dasymetric mapping. To do this, census block data from 2012, along with land coverage satellite data that has been reclassified into “high intensity”, “low intensity”, “cleared land” and “uninhabited” was used. The dasymetric mapping tool, provided publicly by the USGS, redistributes population totals for the census block groups based on the land coverage, and gives a population count in a pixel matching the resolution of the land cover data, in this case, 30 m. The totals are be placed into the categories of high, low and cleared land, while the uninhabited areas, such as water or swamps, get a population count of 0 (Figure 4.1). Using this, a zonal statistic tool was run to find the sum of all the pixels within each service area, and find the population affected by inundation.

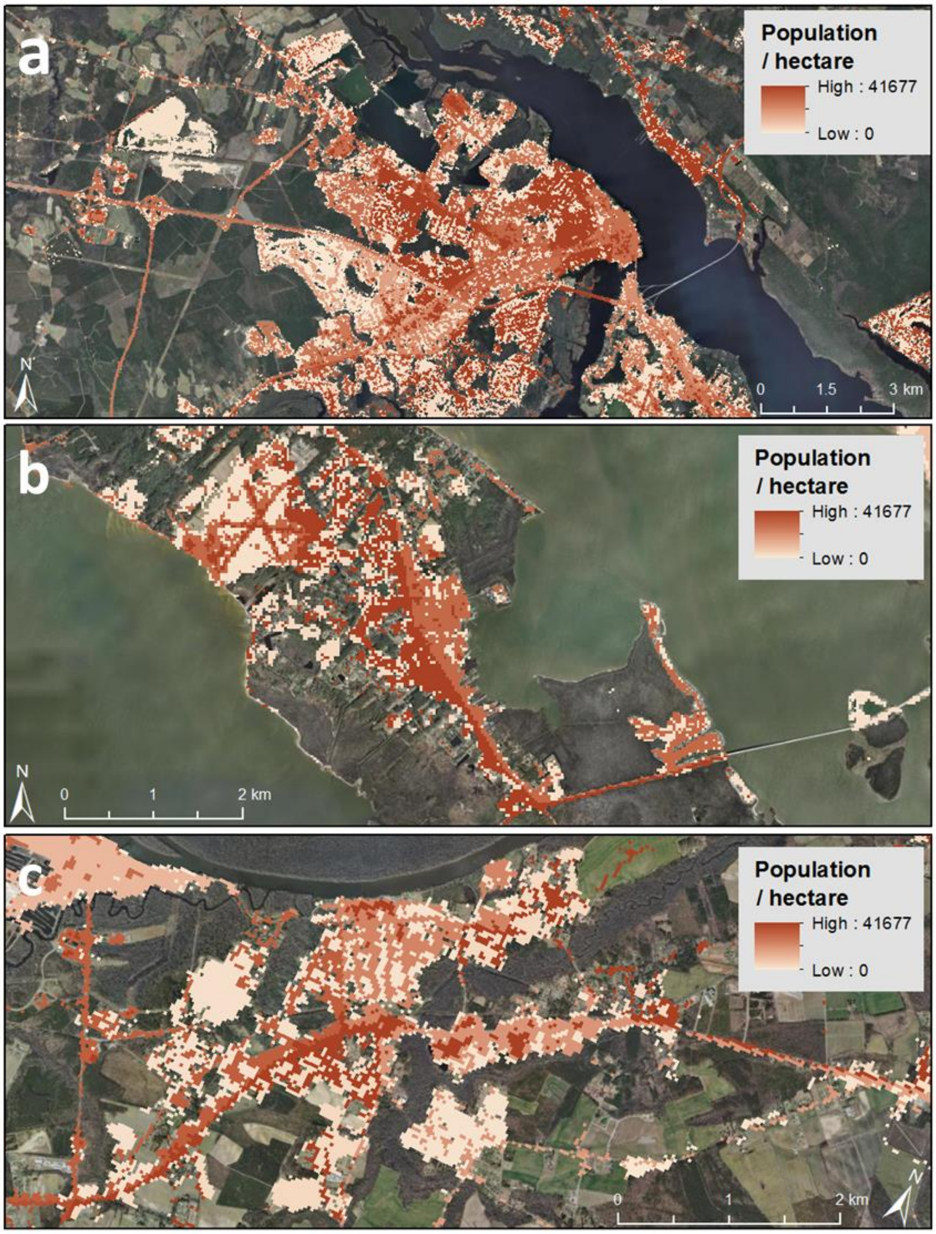

Figure 4.1: Example of dasymetric population mapping to show population redistribution for a) New Bern, b) Manteo, c) Plymouth. Population data provided by the 2010 Census, land cover data provided by the 2010 NOAA Coastal Change Analysis Program, and orthoimagery composited by NC OneMap with 2010, 2011, and 2013 imagery.

4.3 Compiling and Improving High-Resolution DEMs

Part of what makes this project distinctive is the accuracy of the DEM for water flow. While the resolution of the DEMs is high, important hydrologic features may still be excluded from floodplain LiDAR that may affect the direction of water flow drastically for different hazards. In order to solve this problem, the project aimed to improve the DEMs by additional hydro-correction to “burn” the ditches into the DEM to create localized areas of higher resolution hydrography than before. The ditch lines brought in from the NHD were overlaid on the DEM to show where the DEM needed to be updated, while additional areas, verified through orthophotographs as other ditches, were manually digitized. To burn the streams into the raster, the minimum elevation value in the ditch line is applied to all the remaining cells within that line. A conditional statement is then used to incorporate the ditch elevations where they are present, and the DEM values where they are not (Figure 4.2). With the flooding of ditches, the hydrography adjusts and lessens the flooding in other areas with higher elevation that are less likely to inundate in reality.

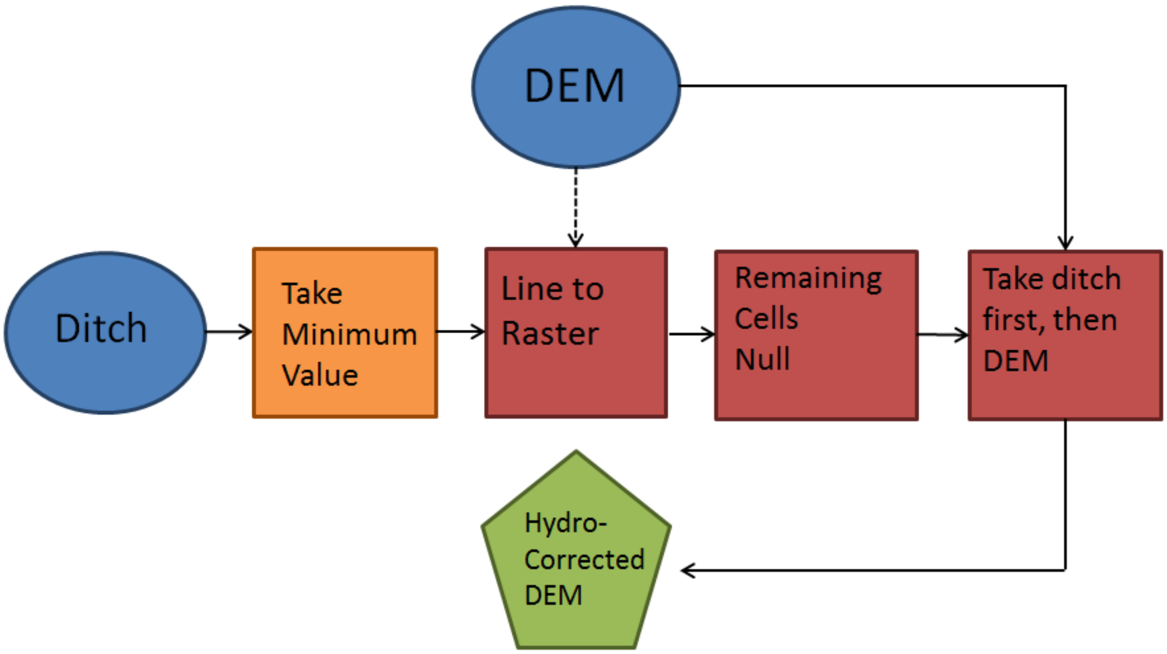

Figure 4.2: Flowchart describing the process of *hydro-correcting* the DEM. Blue ovals are data inputs, the orange box is a statistical calculation taken outside of ArcGIS, the red boxes are tools ran in ArcGIS, and the green pentagon is the output. The dotted line from DEM to the "line to raster" tool represents the input of the DEM's cell size for the rasterized ditch lines.

4.4 Modeling Coastal Inundation

This study incorporates three types of coastal flooding for these coastal communities: 1) riverine flooding, 2) storm surge, and 3) sea level rise. Each flood risk model is represented through different means. The riverine floodplains are models already generated through FEMA, while the sea level rise and storm surge downscale models are generated in this study.

4.4.1 Riverine model

The riverine floodplains are shown through DFIRMs created by FEMA, and show both the 100 and 500 year floodplains. To represent these floodplains in this study, they were acquired through the NCFMP and brought into ArcGIS to overlay the water utility infrastructure for geospatial analysis. The 100 and 500 year floodplain layers were extracted into two separate data layers, and were visualized through the definition query tool to represent the corresponding floodplain for vulnerability assessment.

4.4.2 Storm Surge model

The storm surge floodplains were generated using the SLOSH Maximum of Maximum (MOM) outputs for slow moving hurricanes in the Cape Hatteras/ Pamlico Sound basin. The MOM outputs give us worst-case hurricane inundation scenarios for all five categories of storms, excluding wave and tide elevations. However, the scale of these outputs for local communities is not precise enough to give real insight into their actual vulnerability. To adjust for this, we downscale the resolution of the SLOSH output grid to the resolution of the local DEM (Figure 4.3). After the resolution of the SLOSH is matched to the DEM, we then deem each pixel to be "floodable" or "non-floodable" based on the difference of the inundation calculation and the elevation of the DEM. Then, in order to generate more accurate flood zones, we must also account for hydro-connectivity from the ocean. To achieve this, a cost-distance function is used in the model to make unconnected raster cells too "expensive" to include (Allen *et al.*, 2013). These maps give a more direct map of actual inundated cells rather than a proxy of land cover changes from the SLAMM model for sea level rise scenarios.

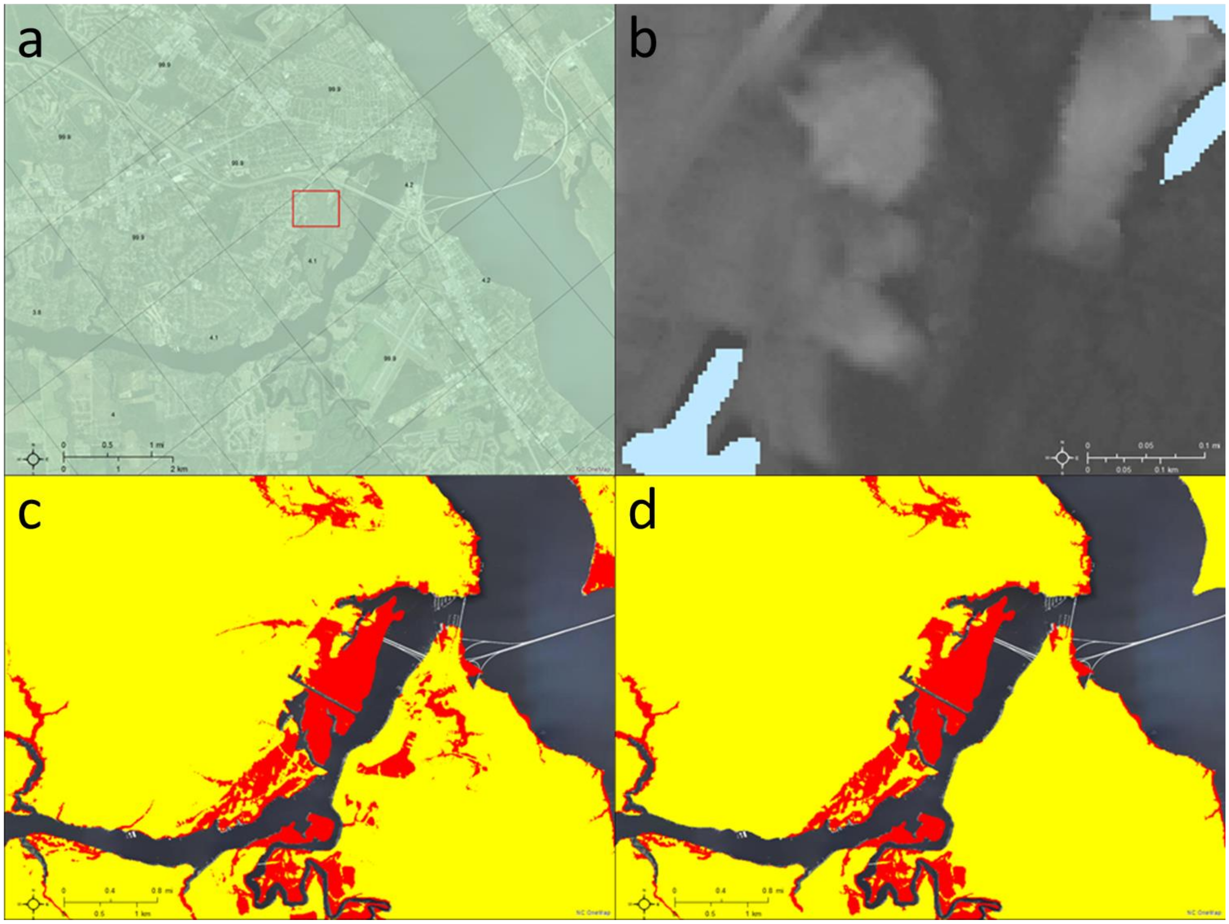

Figure 4.3: Methodology of downscaling SLOSH outputs to local DEM resolution at New Bern, NC. A) SLOSH output polygons with extent indicator for view shown in B, B) Inset in A, showing relative pixel resolution to SLOSH grid, C) SLOSH grid is converted to raster and matched with DEM pixel resolution, so that each DEM pixel has a corresponding SLOSH surge height calculation. The raster calculator can then calculate the difference between elevation height and surge height to find “floodable” (red) and “non-floodable” (yellow) pixels, D) After hydro-connectivity is simulated using the cost-distance tool, isolated flooded regions are excluded that would not flood in reality.

4.4.3 Sea Level Rise

Sea level rise is shown through a manually raised “bathtub” type scenario in increments of 40 cm, 60 cm, 80 cm, 100 cm, and 150 cm. This range of scenarios is derived from the North Carolina Coastal Resource Commission (CRC) Science Panel on sea level rise. The CRC is composed of North Carolina researchers who consulted several papers mentioned above, such as Kemp (2009), Vermeer and Rahmstorf (2009), and others, to generate sea level rise predictions for the state of North Carolina, rather than global estimations from the IPCC. The methodology for the sea level rise model is a similar, yet simpler version to the storm surge model described above. However, instead of using pre-run modeled outputs such as SLOSH, DEM pixels were simply reclassified as “floodable” or “non-floodable” based on being greater or less than the flood scenario ran, e.g. 40 cm, 60 cm, 80 cm, 100 cm, or 150 cm. Then, the same cost distance tool was used to simulate hydro-connectivity as was used in the storm surge downscale model.

4.5 Multi-Hazard Mapping

There are several methods available to potentially visualize inundation and vulnerability. Most simply, the infrastructure is mapped with each hazard type with all scenarios individually, creating nine inundation maps. These show the physical floodplains of each scenario modeled, which are the extents used to determine vulnerability. However, these nine different maps make it difficult to summarize which structures are actually experiencing the most vulnerability. To complement the initial single variable inundation maps, summary multi-hazard maps were created to more easily distinguished vulnerability within each of the communities using layered symbology.

There were several techniques that could have been used to visualize multivariate symbology, such as trivariate choropleth maps, however, trivariate choropleth symbology is usually reserved for attributes that add up to 100%, such as votes or grain size composition (Slocum *et al.*, 2005). Layered symbology, however, allows for separate attributes to be visualized in a more independent manner. Also, the trivariate choropleth maps have a stretched color scheme, rather than the classified color scheme used in the layered symbols, which does not allow the map reader to designate separate hazard vulnerabilities as well.

4.6 Vulnerability Assessment

Visual information graphics and a scoring system are used to assess the vulnerability of each type of infrastructure and place. Each hazard for each study area will have both a map of modeled inundation, and an associated bar graph with it as well to give the relative vulnerability of each structure type. The scoring system is based on normalizing the number of vulnerable features to the total gross count of that system component. The absolute vulnerability will be noted and discussed, but will not be included on the bar graphs. These bar graphs then will assist in comparing the differing amount of vulnerability experienced by each hazard for all three communities.

4.7 Hypsometric Graphs

Hyposometric graphs, which plot water level elevation versus the area inundated, are developed for each community and evolving time step of future risk. These graphs were developed in order to show how vulnerability may increase over time, as well as to reveal how elevation-area thresholds in the different hazards are possible where break points in flooded areas can occur at specific elevations of the water level (Zhang *et al.*, 2011). If higher elevations occur closer to the water source, but lower elevations exist behind this peak, once water has breached this point, it will suddenly flood everything lower behind it. These graphs aid in the assessment of how the topography affects the threat, and how the elevation gradient in a community affects flooding (Figure 4.4).

A steeper slope on these graphs represent a sudden increase in flood extents over a small increase in flood elevation, which corresponds to a gradual sloping, or flat topography. A gradual slope on the graph means there is very little change in the areal extent of the floodplain, while flood elevations continue to rise, which corresponds to a steeper topographic surface. Each study site has one graph showing this relationship for only storm surge and sea level rise, and does not include the riverine flood hazard. The rationale for this is that flood height has a different relationship with flood area for riverine floods since it is water runoff, draining towards the coast, rather than water rising from the coast, such as storm surges or sea level rise.

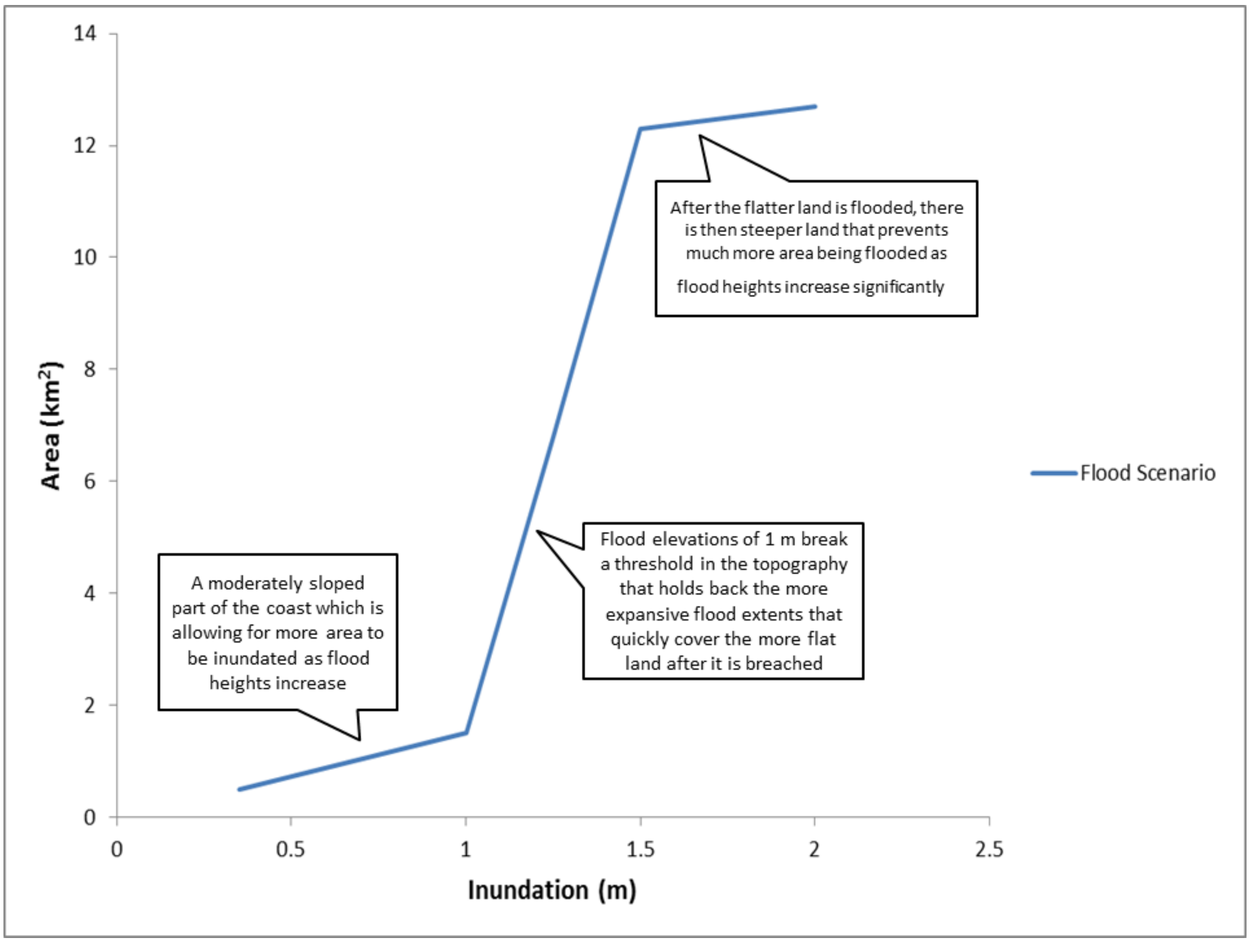

Figure 4.4: An example hypsometric graph with annotation to demonstrate how different slopes in the relationship of flood height and flood area help to illustrate coastal topography.

CHAPTER 5: RESULTS

The infrastructure for all three study sites is shown in figures 5.1, 5.2, 5.3, and the population served by wastewater systems found through dasymetric mapping is shown in table 5.1. As expected, New Bern, the only study site classified as a city rather than a town, has the highest population, the most treatment plants, most pump stations, the longest length of pipelines, and is the only locality with booster stations. Booster stations and pump stations are similar structures that are placed along pipelines that help move the fluid along the pipeline. Specifically, booster stations are for clean water pipelines, while pump stations are for wastewater. It should be noted that New Bern has four registered booster stations in the city, but one of them is currently offline, according to a local engineer who published the infrastructure data. It was thus excluded from this study. The population served, pump stations, and length of pipelines are an entire order of magnitude higher in New Bern than in Plymouth or Manteo. Manteo and Plymouth have much more comparable numbers, both containing only one treatment plant of each kind, but Plymouth possesses twice the number of sewage pump stations, and serves about 1,000 more people than Manteo. Population serviced by wastewater utilities were sometimes higher than the population of the city or town, which could be due to either the low precision of the dasymetric population distribution estimates, or that people serviced by the treatment plant live outside of the city or town limits.

Table 5.1: Water infrastructure and population served by wastewater services for all three study sites. Population within city/town limits provided by 2010 Census (Census, 2011).

	Manteo	New Bern	Plymouth
Wastewater Treatment Plant	1	4	1
Water Treatment Plant	1	1	1
Wastewater Pump Stations	7	104	14
Water Booster Station	0	3	0
Wastewater Lines (km)	22.38	652.37	55.10
Water Lines (km)	30.33	603.09	72.51
Population serviced by Wastewater	2,547	49,217	3,494
Population within city/town limits	1,434	29,524	3,878

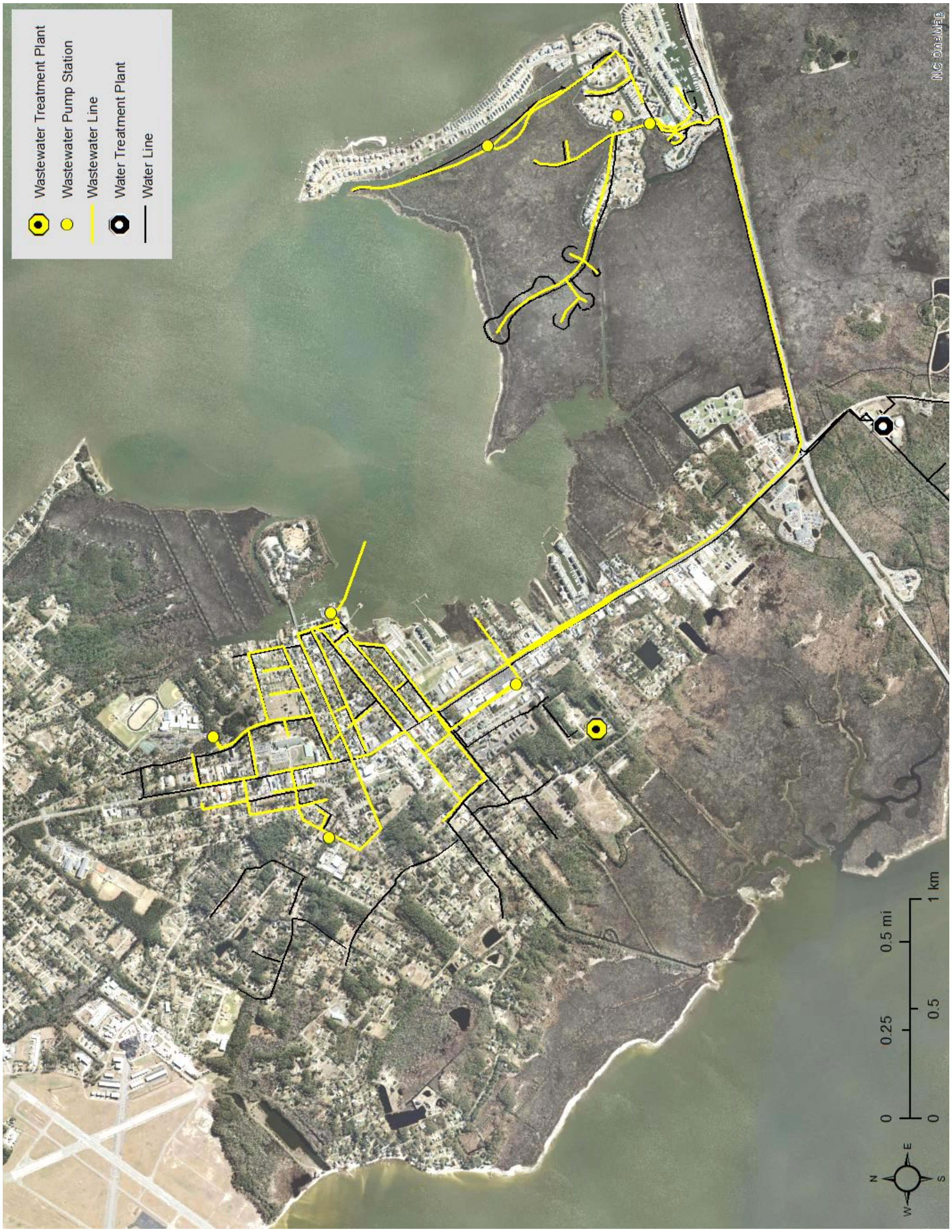

Figure 5.1: Water infrastructure for Manteo, NC overlaid onto orthophotography (composited of 2010, 2011 and 2013 imagery).

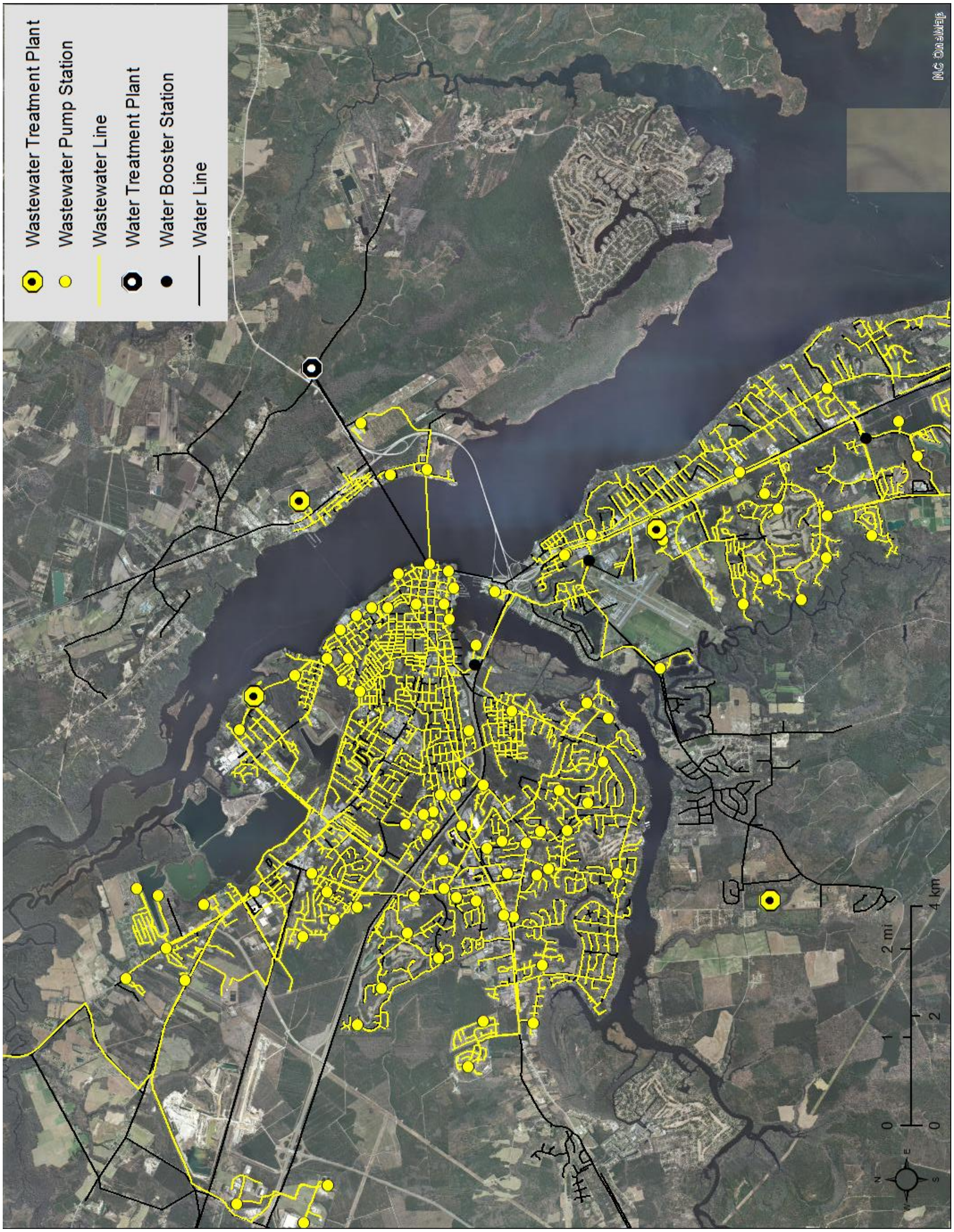

Figure 5.2: Water infrastructure for New Bern, NC overlaid onto orthophotography (composited of 2010, 2011 and 2013 imagery).

Figure 5.3: Water infrastructure for Plymouth, NC overlaid onto orthophotography (composited of 2010, 2011 and 2013 imagery).

Inundation maps are paired with bar graphs that show where inundation takes place spatially, along with how the infrastructure is vulnerable on a normalized basis, as explained previously. Each study site, Manteo, New Bern, and Plymouth, has separate maps for each hazard. Riverine flooding is in figures 5.4, 5.5, and 5.6, storm surge in figures 5.7, 5.8, and 5.9, and sea level rise in figures 5.10, 5.11, and 5.12, respectively.

5.1 Riverine Flooding

Riverine flooding creates the greatest vulnerability for both Plymouth and Manteo, and the second most for New Bern. While Plymouth experiences the most vulnerability from riverine flooding than it has from either of the other two coastal hazards, none of the hazards in this study put the clean water treatment plant at risk. The 100 year floodplain puts all of the types of infrastructure at risk, except for the aforementioned clean water treatment plant, with the clean and wastewater pipelines, wastewater pump stations and wastewater treatment plant at 9.2%, 18.5%, 35.7% (5 of 14), and 100% (1 of 1) vulnerability respectively. The 500 year floodplain increases the vulnerability of the clean and wastewater pipelines and pump stations to 18.7%, 33.4%, and 57.1% (8 of 14) respectively.

New Bern has the second greatest infrastructure vulnerability from riverine flooding, with all of the types of infrastructure at risk within the 100 year floodplain, except for the clean water treatment plant, which, like Plymouth, was not at risk by any of the modeled hazards in this study. The 100 flood put New Bern at about 25% (within 3%) vulnerability for all of these types of infrastructure, except for the booster stations, which are at 33.3% (1 of 3) vulnerability. The 500 year floodplain only increased the vulnerability of the the clean and wastewater pipelines to 30.4% and 27.6% respectively, and the wastewater pump stations to 30.8% (32 of 104). The wastewater treatment plant vulnerability did not increase, staying at only one inundated plant, but one more booster station became inundated, increasing the vulnerability from 33.3% to 66.7% (2 of 3).

Manteo experiences the greatest vulnerability from riverine flooding, with 100% (1 of 1) vulnerability for both treatment plants, and all seven pump stations, as well as 95% for wastewater lines and 82.7% in clean water lines, just in the 100 year floodplain. The 500 year floodplain slightly increases the vulnerability for both pipelines, from 95% to 98.3% and 82.7% to 84.8% for wastewater and clean water pipelines respectively.

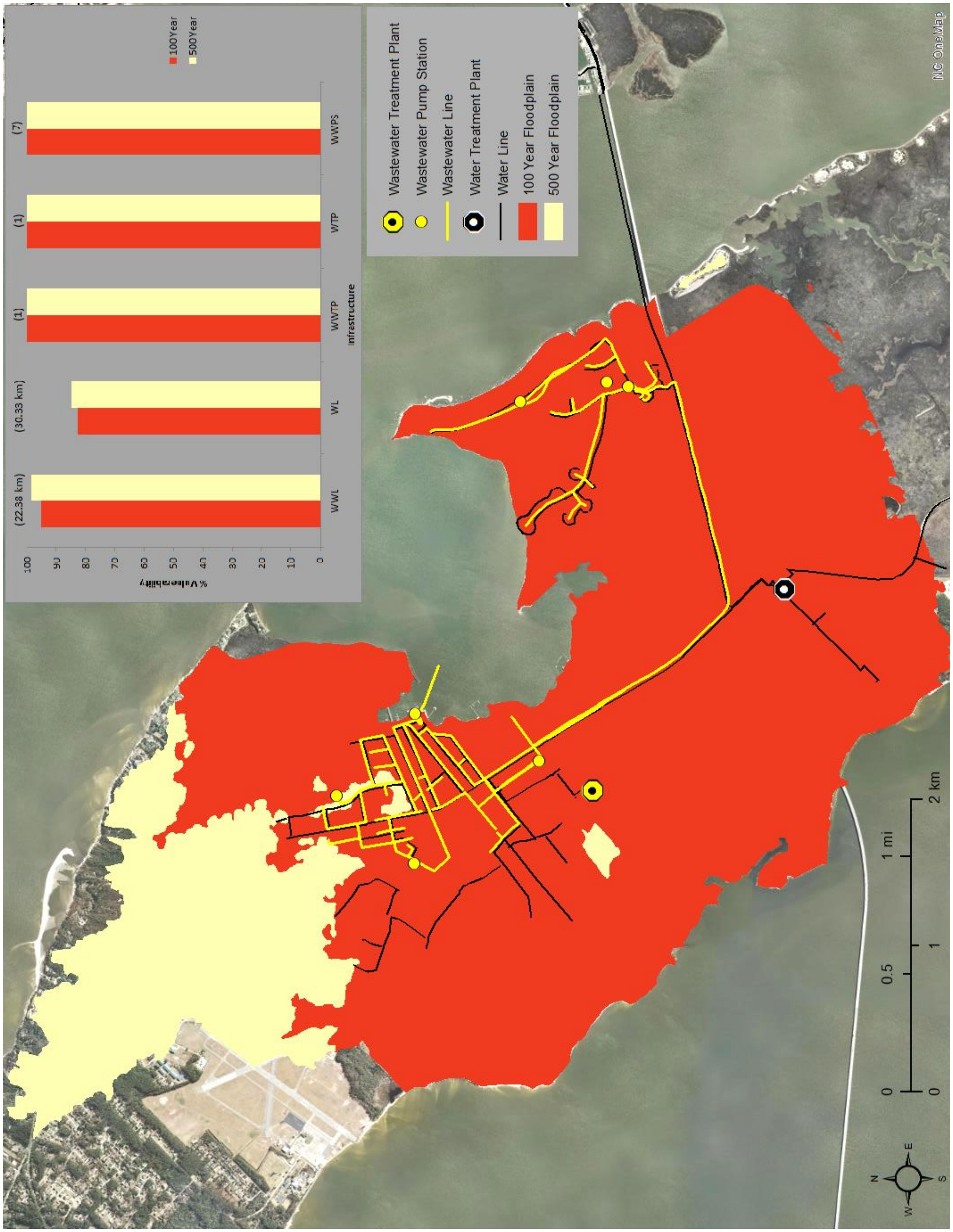

Figure 5.4: Riverine flooding vulnerability for Manteo, NC using FEMA modeled 100 and 500 year floodplains.

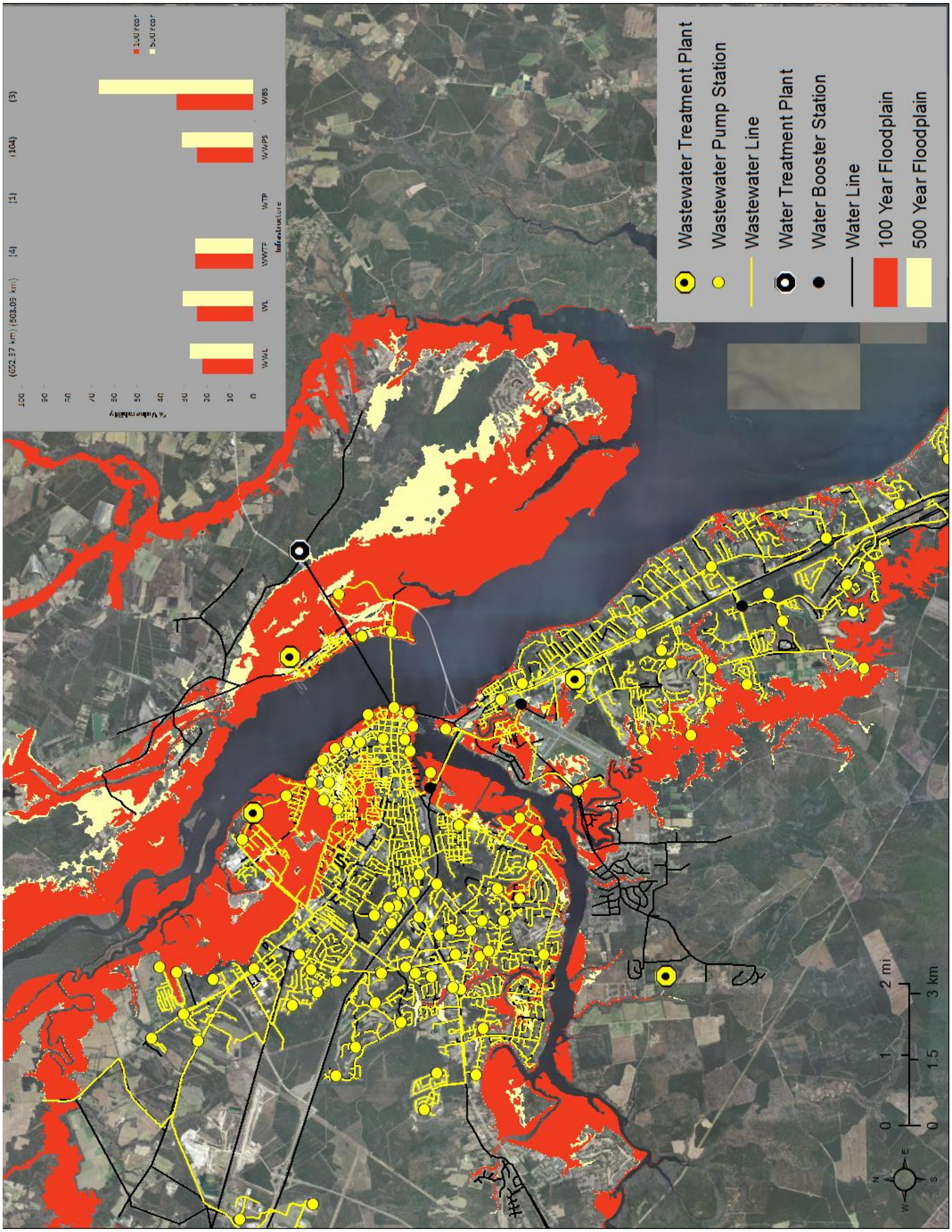

Figure 5.5: Riverine flooding vulnerability for New Bern, NC using FEMA modeled 100 and 500 year floodplains.

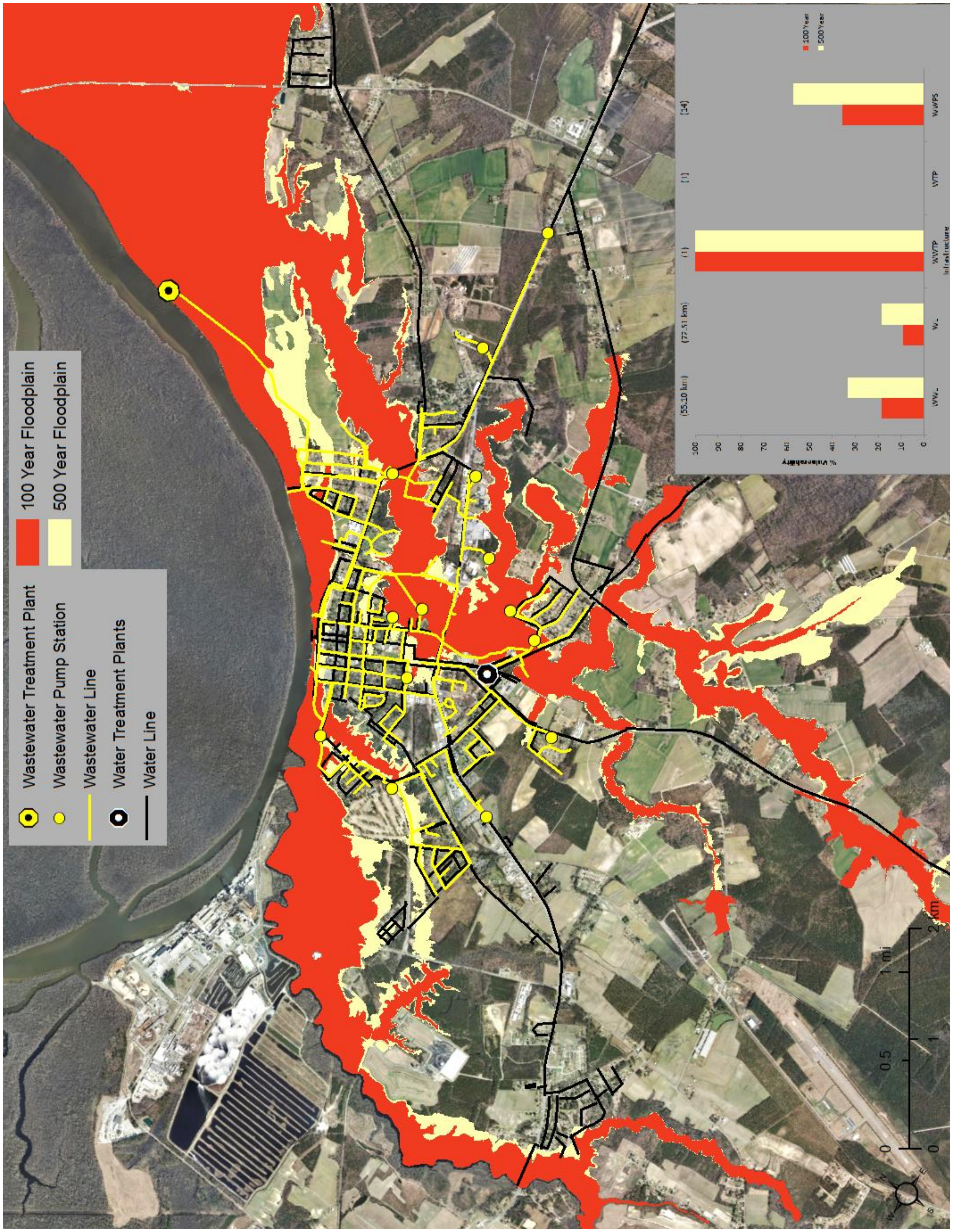

Figure 5.6: Riverine flooding vulnerability for Plymouth, NC using FEMA modeled 100 and 500 year floodplains.

5.2 Storm Surge

Storm surge creates the second highest vulnerability for Manteo, reaching 100% (1 of 1) vulnerability for both treatment plants, and pump stations for a category 5 hurricane, which also accounts for 94.2% and 80.8% vulnerability in wastewater and clean water pipelines respectively. While the pump stations and wastewater treatment plant do not reach 100% vulnerability until a category 5 hurricane, the clean water treatment plant reaches 100% with a category 2. Also, with a category 1 hurricane, pump stations experience 42.9% (3 of 7) vulnerability, wastewater pipelines 17.5%, and clean water pipelines 15.3% vulnerability.

New Bern experiences the greatest vulnerability from modeled storm surge than it does from either of the other two coastal hazards in this study. A category 1 storm put three types of infrastructure at risk, with clean and wastewater pipelines at 7.5% and 8% vulnerability respectively, and wastewater pump stations at 4.8% (5 of 104) vulnerability. A category 3 hurricane will put all of the other types of water infrastructure at risk, excluding the clean water treatment plant mentioned above, inundating 25% (1 of 4) of the wastewater treatment plants, increasing the vulnerability of clean water and wastewater pipelines, and wastewater pump stations to 33%, 32.2% and 35.6% (37 of 104) respectively, and inundating 66.7% (2 of 3) of water booster stations. A category 5 hurricane will theoretically create the same vulnerability for wastewater treatment plants and water booster stations, but will increase the vulnerability of clean water and wastewater pipelines and wastewater pump stations to 54%, 49.1% and 50% (52 of 104) respectively.

Modeled storm surge accounts for the second highest vulnerability for Plymouth, with a category 1 hurricane only inundating clean and wastewater pipelines and pump stations, generating a vulnerability for those structures of 0.1%, 3.8%, and 7.1% (1 of 14) respectively. The only wastewater treatment plant becomes inundated with a category 3 hurricane, which also increases the vulnerability of clean water pipelines to 3.1%, wastewater pipelines to 10.9% and wastewater pump stations to 21.4% (3 of 14). A category 5 hurricane theoretically will only increase the vulnerability of the clean and wastewater pipelines to 3.8% and 12.1%, respectively.

While all five categories were modeled in this study, it should be noted that a category 5 hurricane is exceedingly unlikely for North Carolina given the total energy requirement to generate such a storm and the latitude of this area. However, flooding can be exacerbated through compound flooding, such as simultaneous rainfall and rivereine discharge, which may add to the surge generated in the SLOSH model. Antecedent flooding may also increase flood extents as well, such as a flood event affecting the area and not returning to normal water levels before a hurricane strike. For example, the combination of these two effects is the amplified Hurricane Floyd's 500 year-flood event in 1999, despite being only a category 1 hurricane. While a category 5 hurricane is an unlikely scenario for North Carolina to experience, the flood extents modeled by it in this study could be reached through compounded or antecedent flooding.

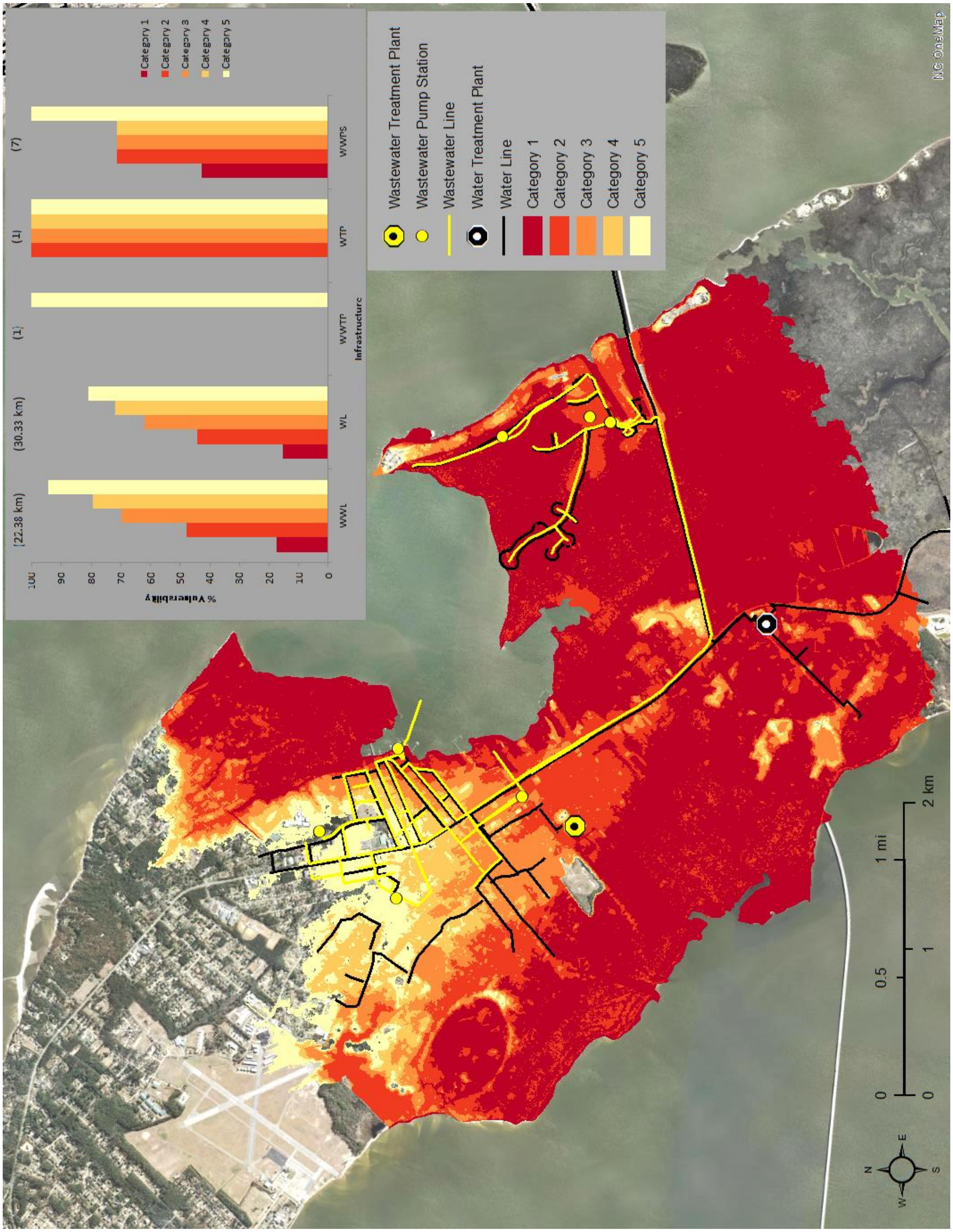

Figure 5.7: Modeled storm surge flooding for Manteo, NC generated from SLOSH MOM outputs downscaled to the local LiDAR DEM (6.1 m).

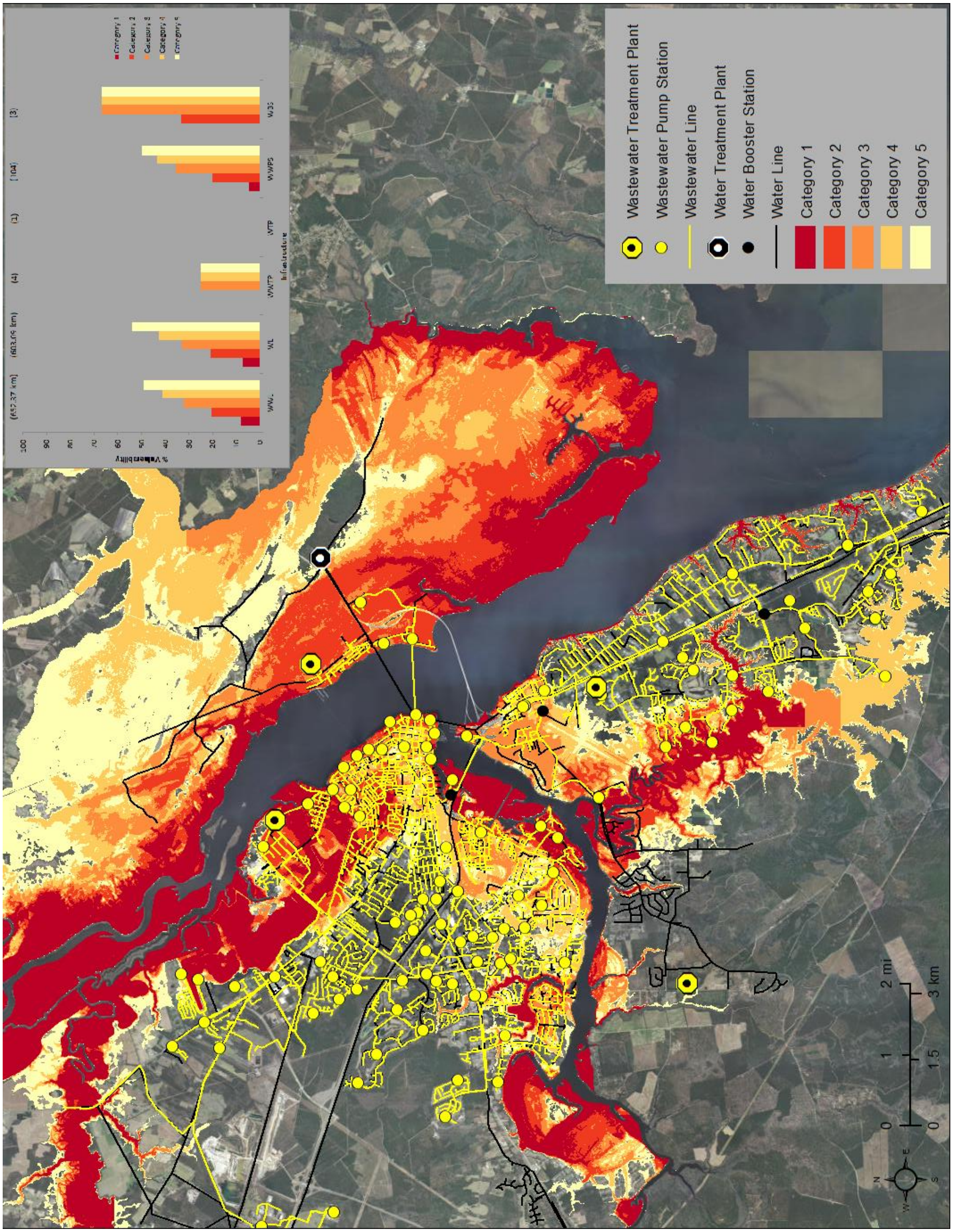

Figure 5.8: Modeled storm surge flooding for New Bern, NC generated from SLOSH MOM outputs downscaled to the local LiDAR DEM (6.1 m).

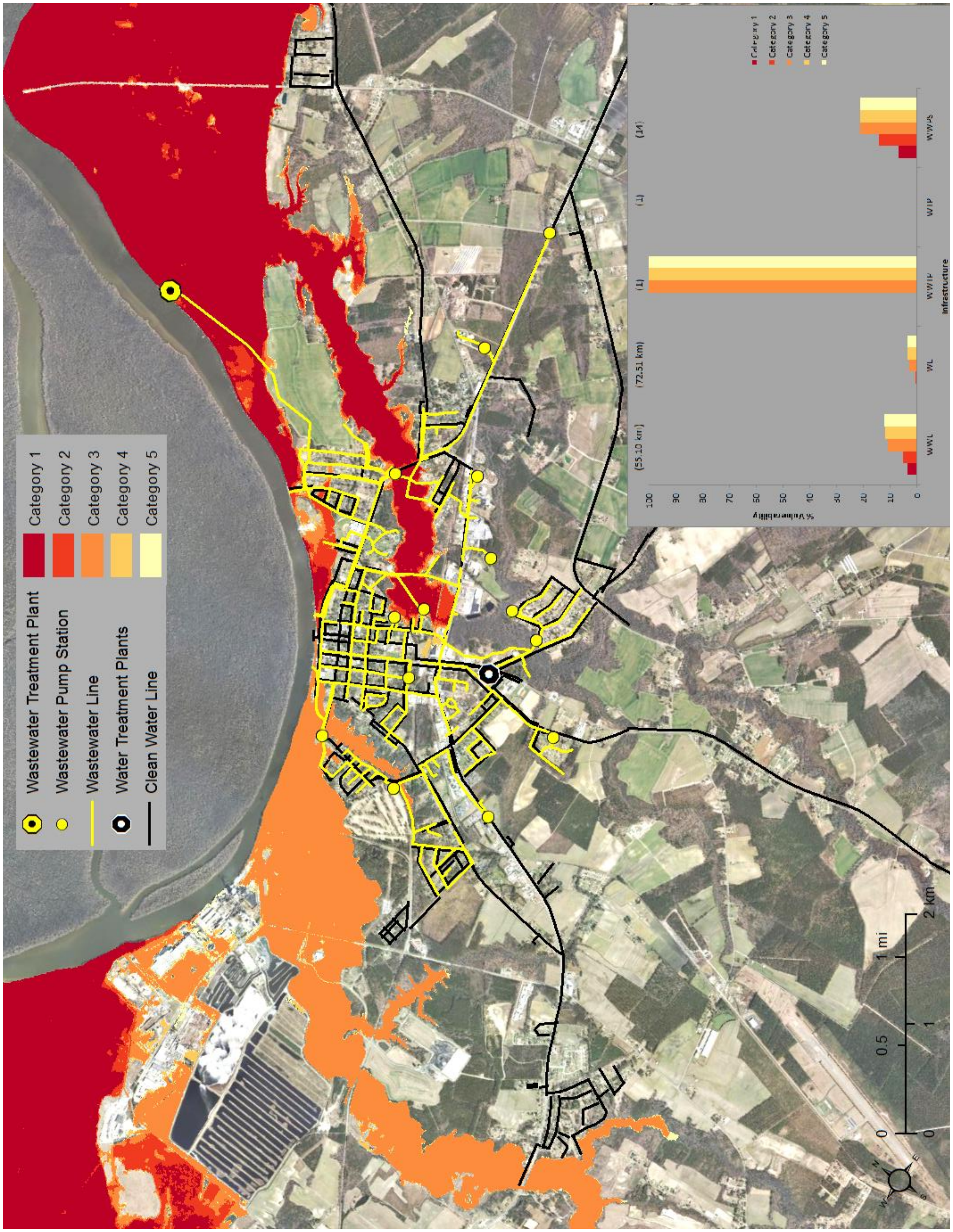

Figure 5.9: Modeled storm surge flooding for Plymouth, NC generated from SLOSH MOM outputs downscaled to the local LiDAR DEM (6.1 m).

5.3 Sea Level Rise

Sea level rise created the least amount of vulnerability for all three study sites. Manteo reaches 100 % (1 of 1) vulnerability for its wastewater treatment plant at 1 meter, and its clean water treatment plants at 80 cm of sea level rise. A rise in 1.5 m of sea level results in 60.3% vulnerability for clean water pipelines, 65.3% vulnerability for wastewater pipelines, and 71.4% (5 of 7) for pump stations.

Modeled sea level rise accounts for the least vulnerability in New Bern for water infrastructure, only inundating three types of structures: clean and wastewater pipelines and wastewater pump stations. These three structures are at risk for all five sea level rise scenarios, and at 40 cm of sea level rise, clean and wastewater pipelines, and wastewater pump stations show 3.8%, 3.5%, and 1% (104) vulnerability respectively. A rise in 1.5 m of sea level increases their vulnerability to 14.4%, 14.3% and 8.7% respectively.

Finally, in Plymouth, sea level rise only inundated the wastewater treatment plant at 1.5 m, which also puts the clean and wastewater pipelines at 1.6% and 7.6% vulnerability respectively, and wastewater pump stations at 14.3% (2 of 14) vulnerability. The wastewater pump stations first experience vulnerability at 80 cm of rise, with only 7.1% (1 of 14), which stays constant until doubling (2 of 14) at 1.5 m.

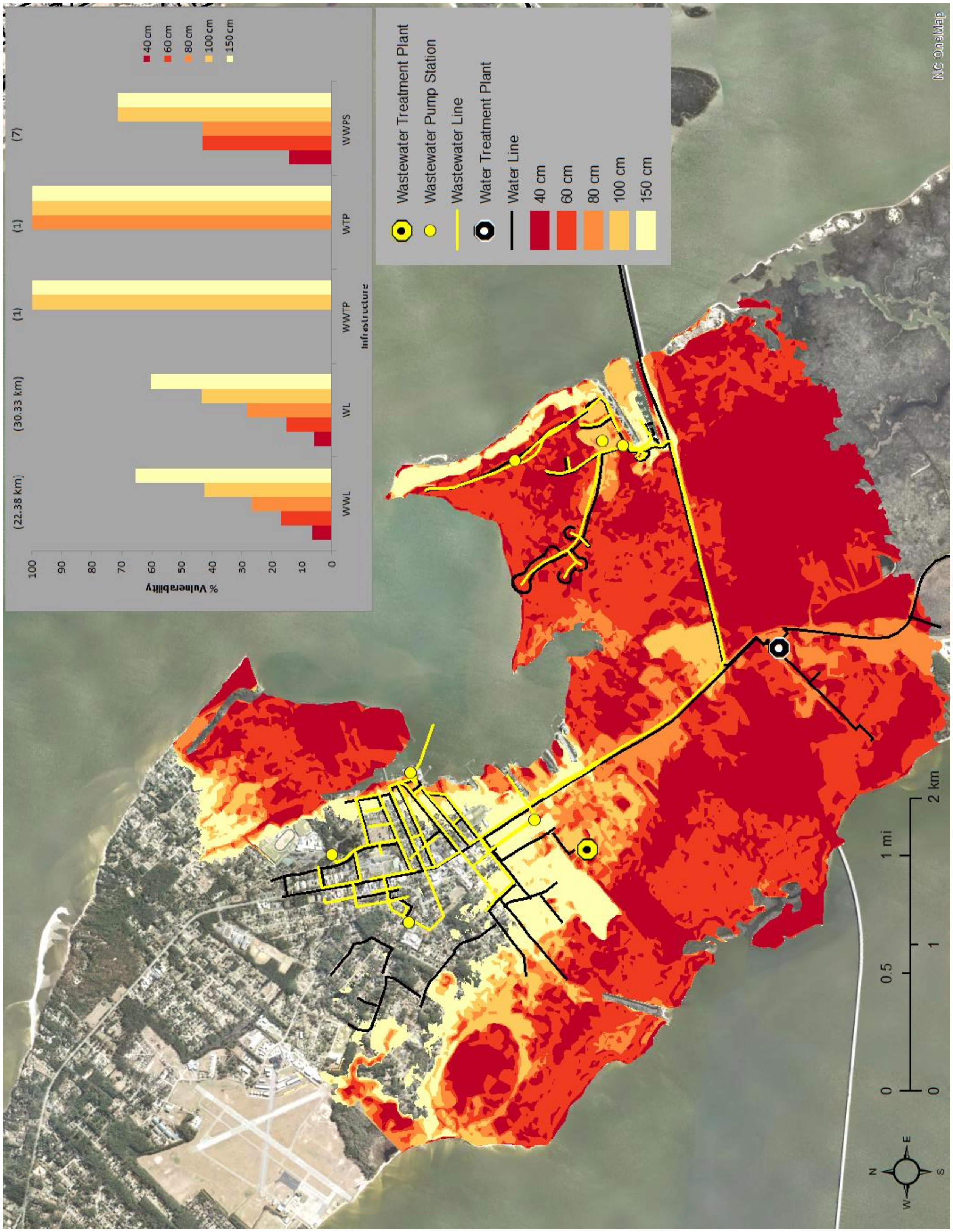

Figure 5.10: Modeled sea level rise flood potential for Manteo, NC.

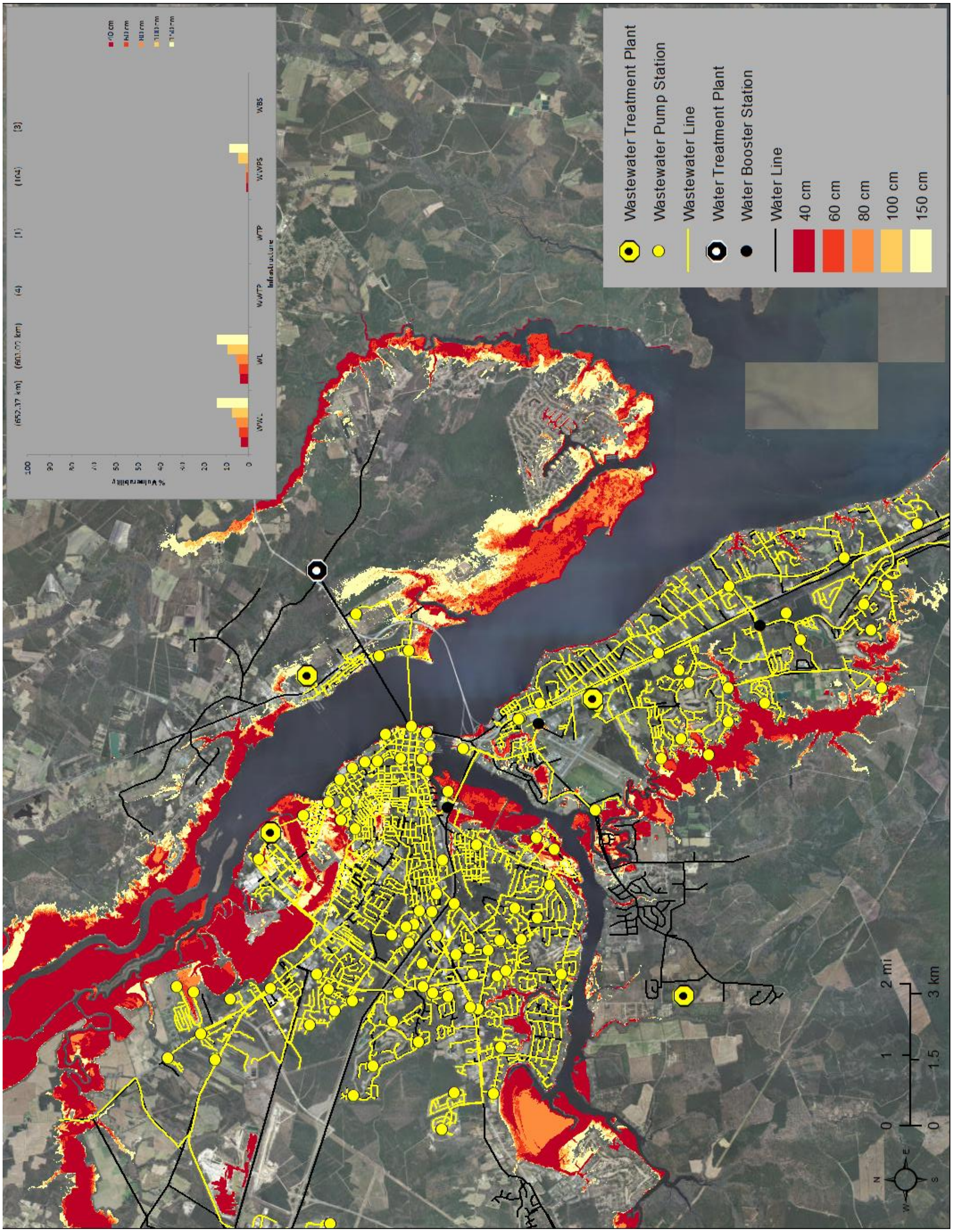

Figure 5.11: Modeled sea level rise flood potential for New Bern, NC.

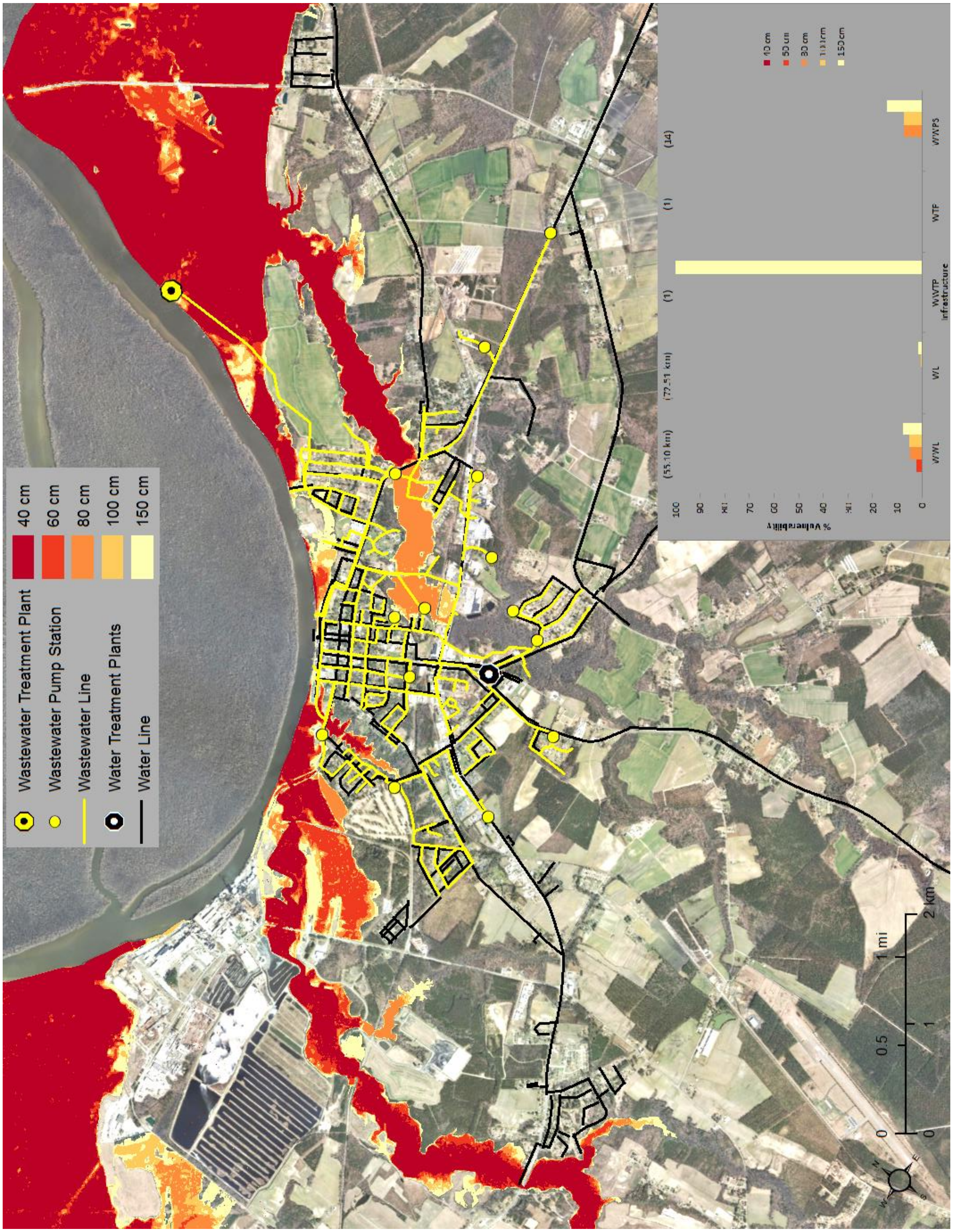

Figure 5.12: Modeled sea level rise flood potential for Plymouth, NC.

To assist in comparing the vulnerability across both hazards and communities, a small mutliples technique was used to display a comprehensive diagram to show all nine scenarios (Figure 5.13). This figure was organized so that vulnerability decreased from the top left to bottom right, and helped to distinguish how vulnerability varied across the board.

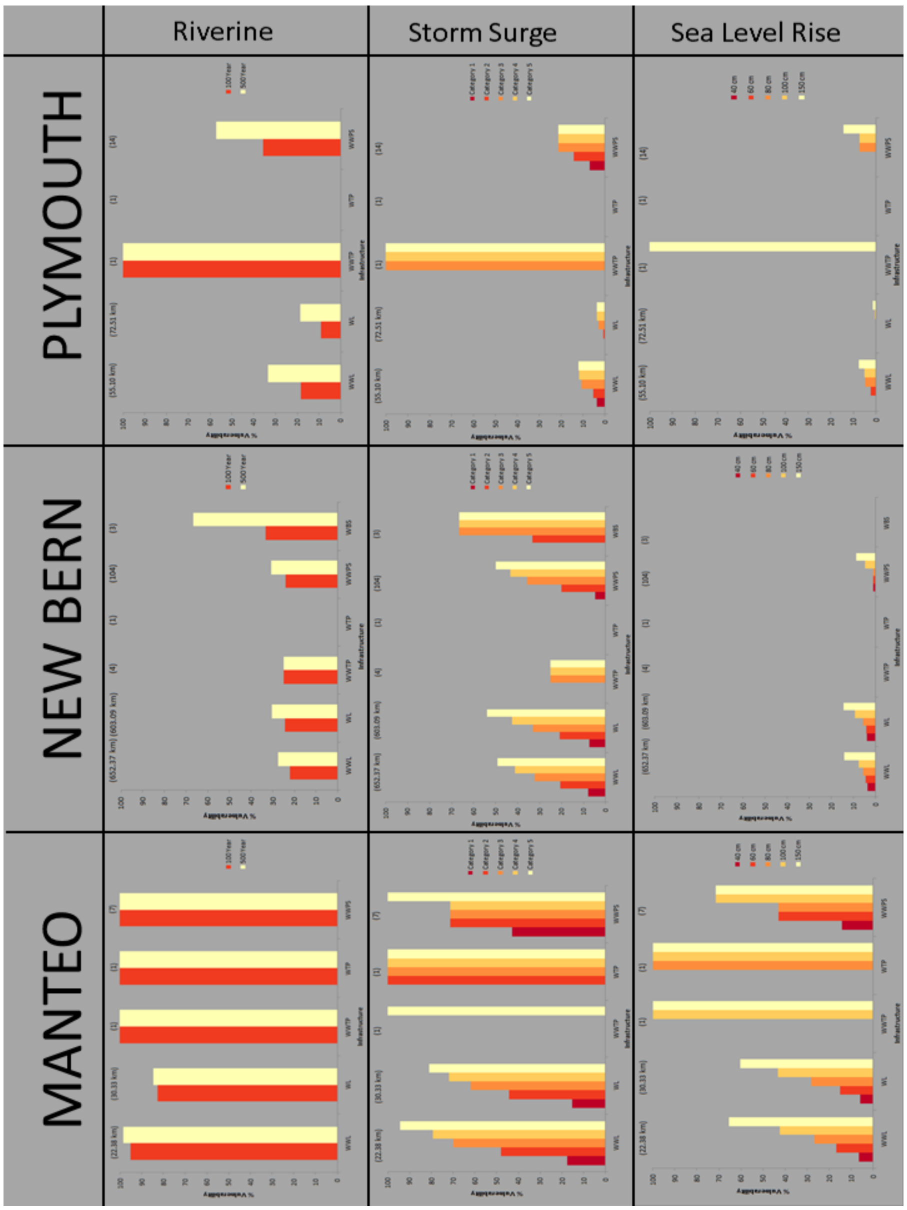

Figure 5. 13: Summary chart of all nine flood scenarios. This figure assists in comparing how vulnerability varied among the communities and hazards.

5.4 Hypsometric Graphs

5.4.1 Manteo

The hypsometric graph for Manteo (Figure 5.14) shows that storm surge reaches both a higher flood height, at 1.97 m, and creates a larger flood area, at 15.65 km^2, than sea level rise, which reaches a flood height of 1.57 m and creates a flood area of 13.36 km^2. The relationship for storm surge between flood height and area follows a pattern closer to a linear relationship, gradually increasing for both flood height, 0.7 m to 1.97 m, and flood area, 9.43 km^2 to 15.65 km^2. Sea level rise, however, increases gradually only for the flood height, 0.68 m to 1.57 m, but the flood area has a sharp increase initially from 0.54 km^2 to 9.72 km^2, and then gradually increases from there to 13.36 km^2.

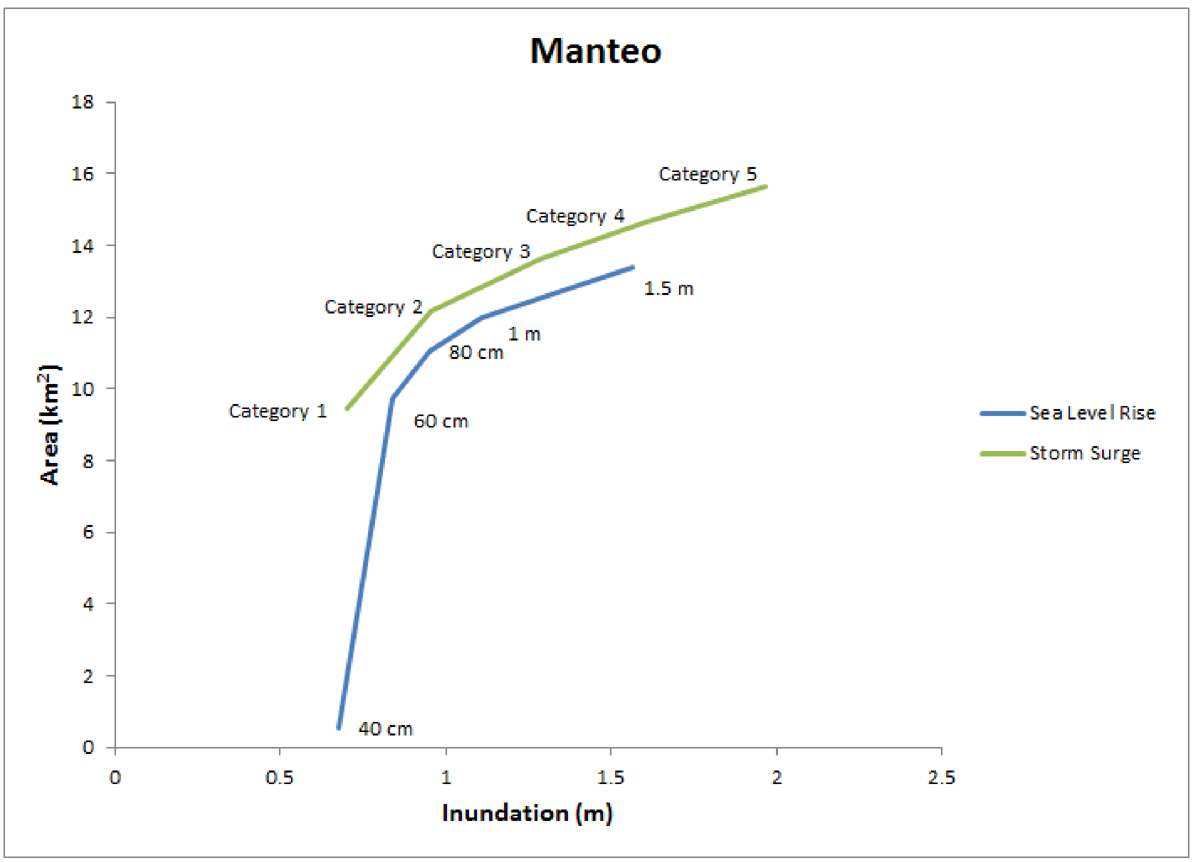

Figure 5.14: Modeled sea level rise and storm surge inundation and areas for Manteo, NC.

5.4.2 New Bern

New Bern has much larger differences between the sea level rise and storm surge hypsometric curves (Figure 5.15). Storm surge far surpasses sea level rise in both flood height and area, at 5.36 m of flood height which covers 191.28 km^2 for a category 5 storm surge, compared to sea level rise, which reaches a maximum 2 m flood height, covering 68.79 km^2 for a 1.5 m sea level rise scenario. Both hazards have a similar linear shape of gradually increasing flood area with an increase in flood height, but storm surge increases in both of these categories much more quickly than sea level rise. A category 1 storm surge generated a 1.3 m flood height which covered 54.79 km^2, while a 40 cm sea level rise scenario generated a 1.2 m flood height which covered 38.77 km^2.

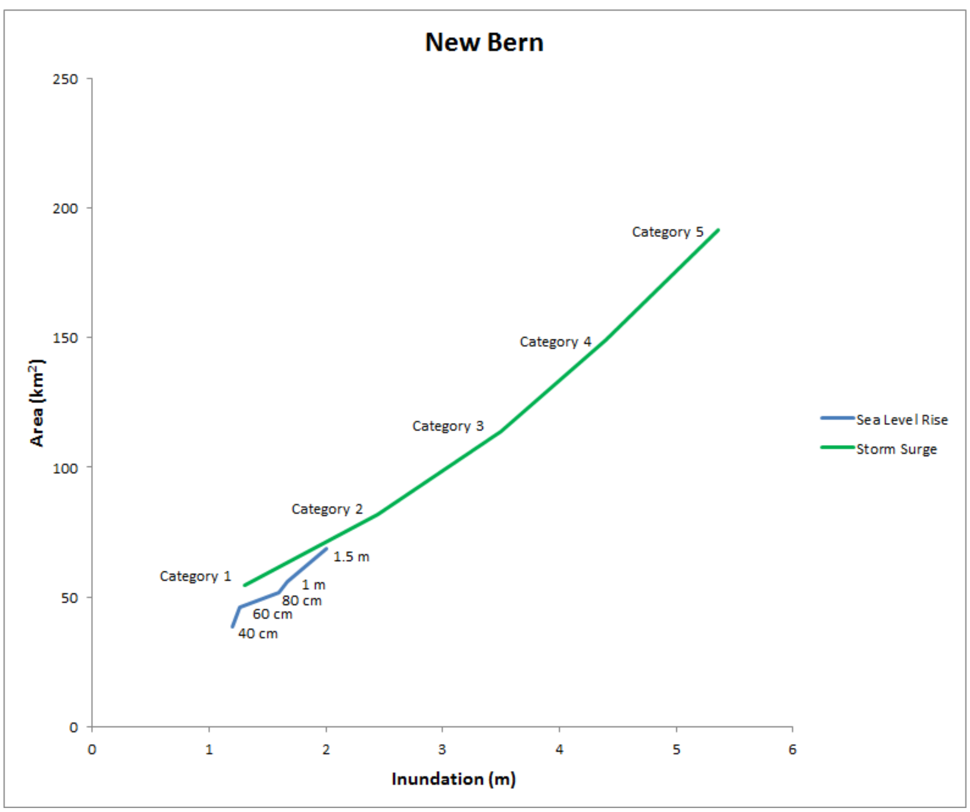

Figure 5.15: Modeled sea level rise and storm surge flood heights and areas for New Bern, NC.

5.4.3 Plymouth

The Plymouth hypsometric curves (Figure 5.16) have very similar shapes for both sea level rise and storm surge, with storm surge generating larger flood heights and flood area at 1.76 m and 11.95 km^2 for a category 5 hurricane, while a 1.5 m rise in sea level generates a flood height of 1.28 m which covers 10.74 km^2. Both hazards started with very similar flood height and extents, with 40 cm of sea level rise generating a 0.59 m flood height and 0.70 km^2 flood area, and a category 1 hurricane creating a 0.76 m flood height and 0.65 km^2 flood area. Both hazards went on to change very little in flood area with the next scenario, but also both show a sharp sudden increase in flood area, and eventually tapering off to a gradual increase again. For the storm surge scenarios, the sudden change came between the category 2 and category 3 hurricane, with a category 2 storm flooding 0.71 km^2, and a category 3 storm flooding 11.46 km^2. For the sea level rise scenarios, the sudden change occurred between 80 cm and 1 m of sea level rise, with 80 cm of rise covering on 0.92 km^2, and 1 m of rise covering 9.68 km^2.

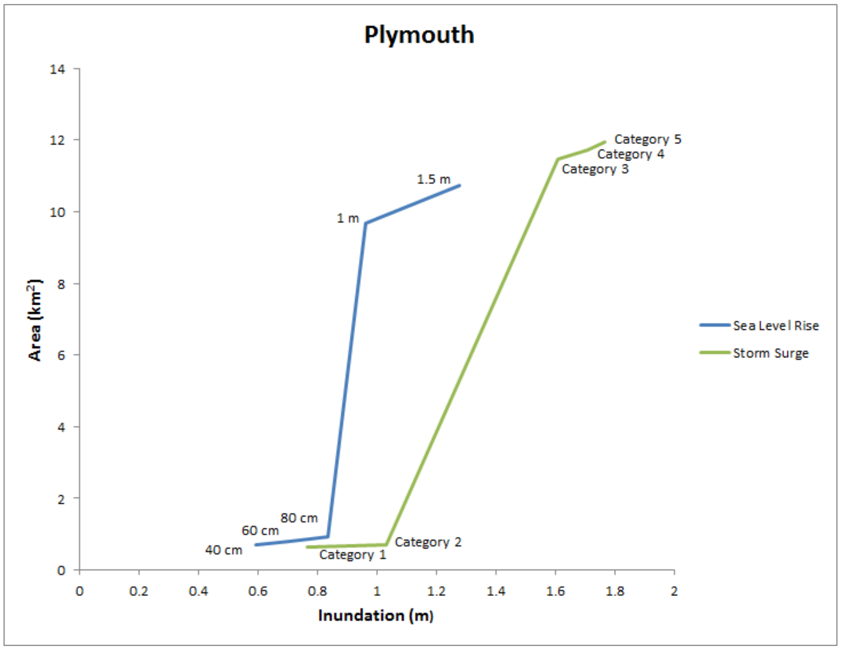

Figure 5.16: Modeled sea level rise and storm surge flood heights and areas for Plymouth, NC.

5.5 Multi-hazard Analysis

Summary maps were created to aid visual interpretation of vulnerabilities from all three hazards within a single map for all of the structures, excluding pipelines (Figure 5.18, 5.19, 5.20). Preceding these three figures is an example multi-hazard map with annotated text boxes to help interpreting the complex symbology (Figure 5.17). Pipelines were excluded since the layered symbology used would generate too much noise on the map, and degrade the legibility. Each symbol represents one structure, with up to three different vulnerability measurements, one for each hazard, with the center symbol representing riverine vulnerability, the middle symbol representing sea level rise vulnerability, and the outside symbol representing storm surge vulnerability. Color is used to visually represent the lowest scenario at which the structure could experience potential inundation. While all three hazards are represented, some of the structures are only vulnerable to one or two of the hazards rather than all three, so these points do not feature the layer that does not pose a risk for that structure.

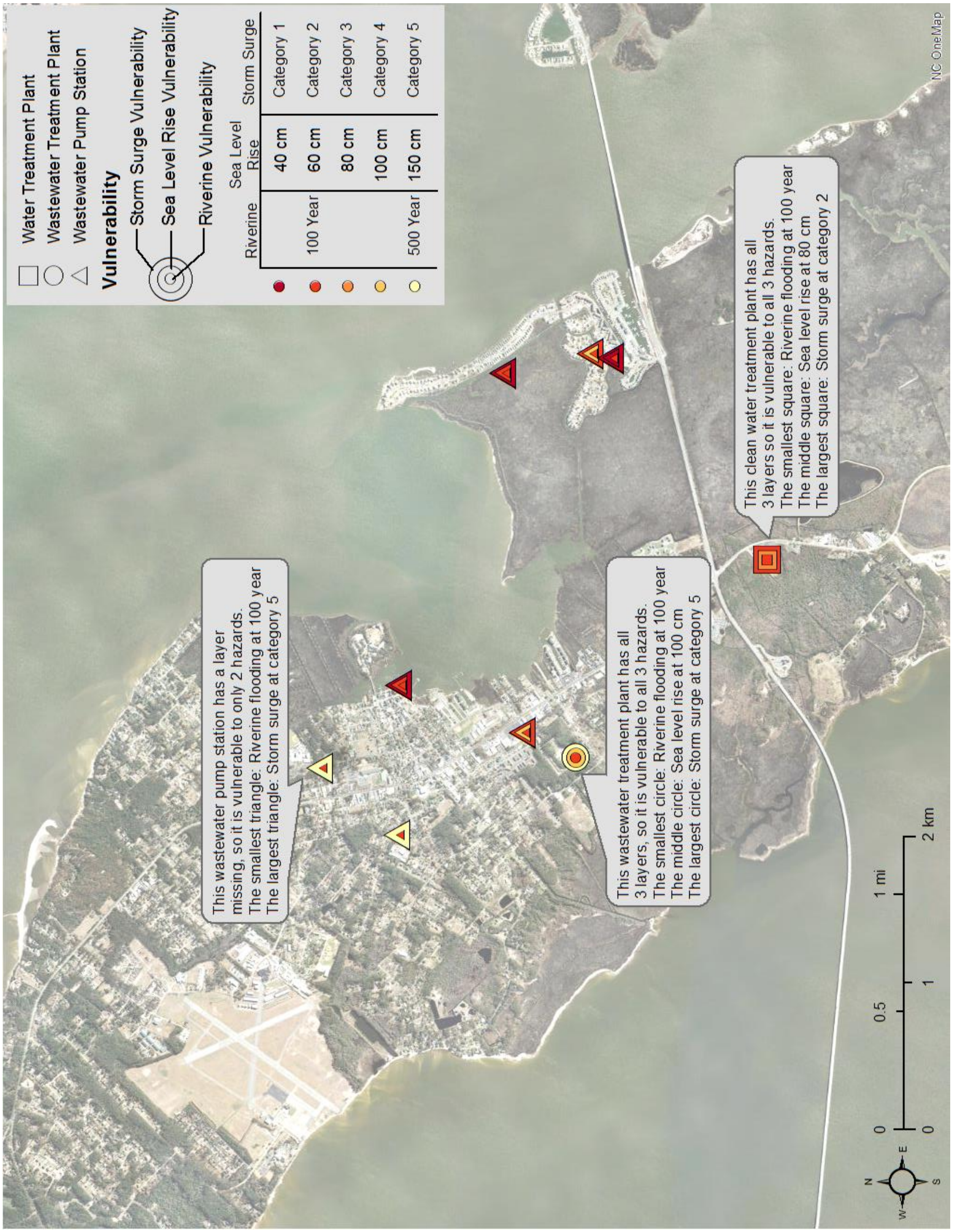

Figure 5.17: An example of the following multi-hazard maps, with explanations on how to interpret the symbology. Each type of structure is explained, with instructions on how to interpret all three layers of the symbol.

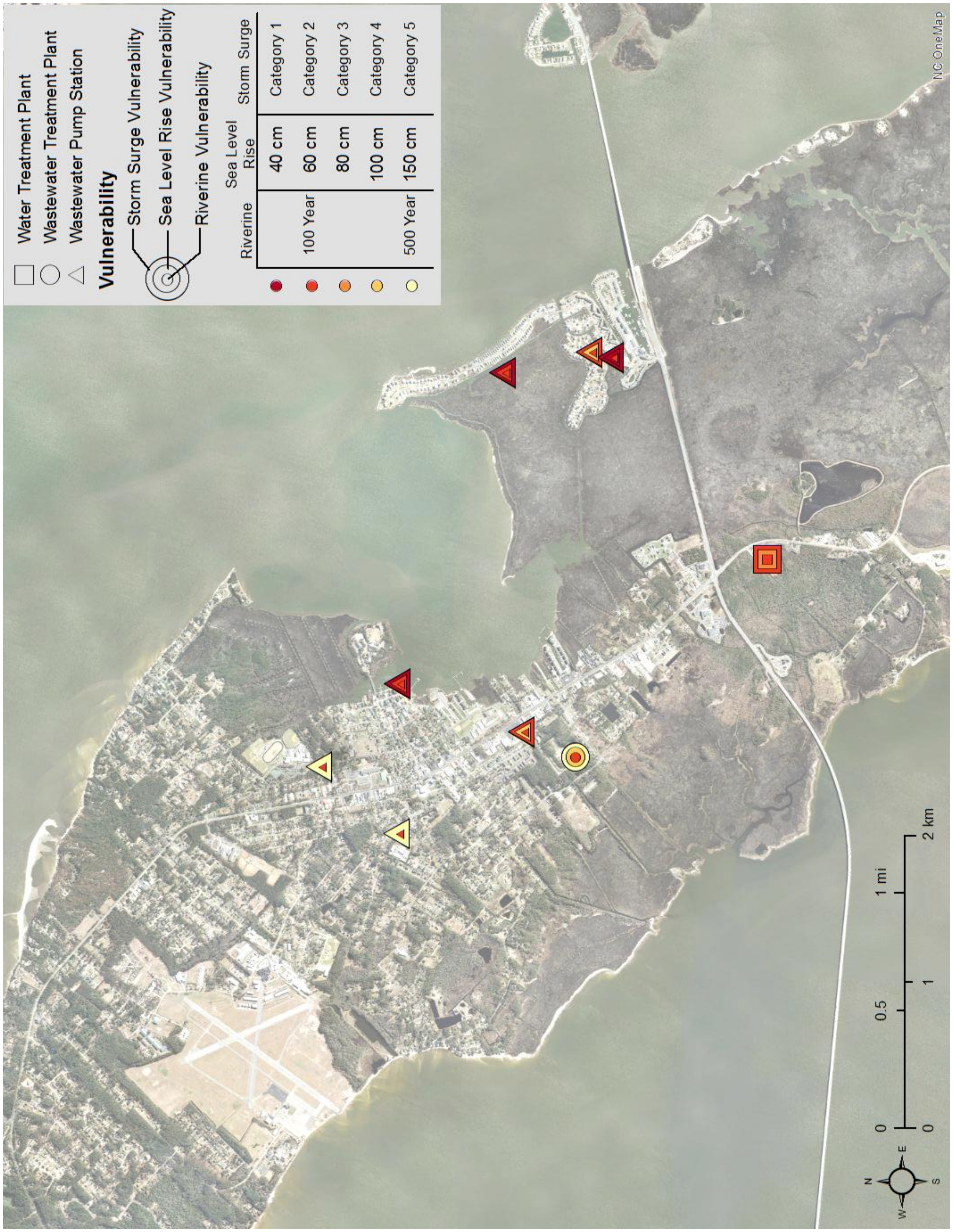

Figure 5.18: Multi-hazard vulnerability from modeled sea level rise, storm surge, and riverine flooding for Manteo, NC. Manteo contains the only clean water treatment plant of all three study sites, and all seven of their pump stations experience vulnerability at some point.

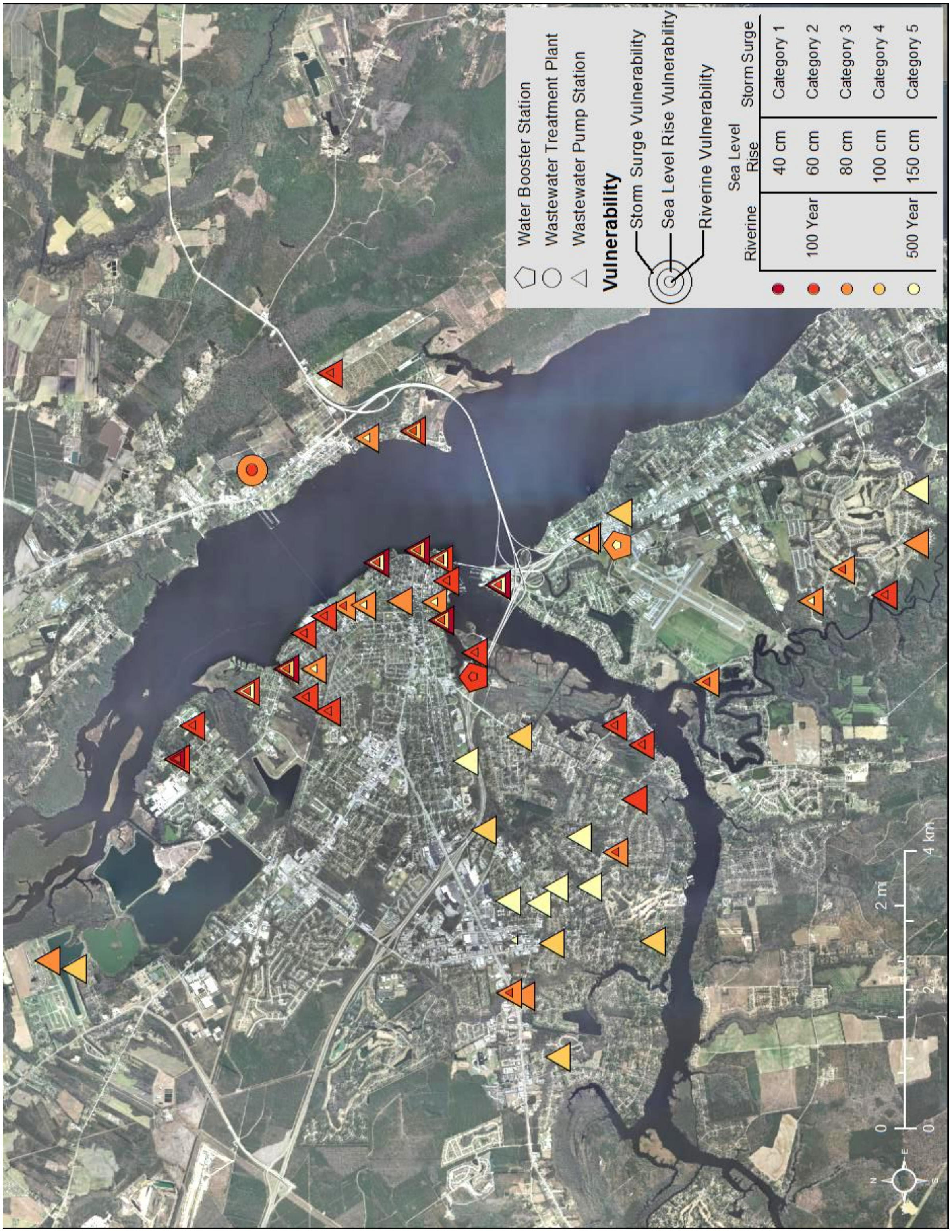

Figure 5.19: Vulnerability from modeled sea level rise, storm surge, and riverine flooding for New Bern, NC. New Bern has the highest count of vulnerable infrastructure, and has the only booster stations of all three study sites, all of which experience some vulnerability.

Figure 5.20: Vulnerability from modeled sea level rise, storm surge, and riverine flooding for Plymouth, NC. Plymouth's waterfront wastewater treatment plant is placed in a highly vulnerable area, as well as several pump stations placed along the Conaby Creek floodplain.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

6.1 DISCUSSION

Manteo generated the highest vulnerability percentages for its infrastructure across all three coastal hazards, making it the most vulnerable community in this study. All of the treatment plants and pumping stations potentially become inundated at some point in both the storm surge and riverine flood simulations, and it also has the only clean water treatment plant at risk of all three communities. Losing these treatment plants would not only be very costly to this community, but would also cut off the ability to flush sewage and would make fresh water inaccessible for the people of Manteo. Manteo experiences vastly larger flood extents than either of the other communities in response to such low changes in the water level. To explain Manteo's extensive flood vulnerability, the combination of a large area of low elevation, a gently sloping coastline, and being a coastal estuarine island, which allows flooding to occur on both the eastern and western shores of Roanoke Island, are important contributing factors.

Overall, New Bern is the second most vulnerable study site of the three, exceeding Plymouth in relative vulnerability in almost every category except for wastewater treatment plants, owing to one of four plants being at risk for New Bern, versus the sole plant serving Plymouth being at-risk. New Bern also certainly experiences the most absolute vulnerability of all three communities, with 53 pump stations at risk of at least one of the three hazards, and all three booster stations. In addition, while New Bern's clean water treatment plant does not apparently become at-risk, it is the only site that requires water booster stations to distribute fresh water to the community, and some of these structures experience inundation in some scenarios. This is an example of indirect, or cascading, vulnerability since losing the use of these booster stations will induce similar effects to losing the use the treatment plant itself. So, New Bern also has some population that is vulnerable to the loss of both of the ability to flush sewage and inaccessibility to fresh water. New Bern is also distinct from the other communities in that it covers a much larger area, so the potential flood inundation extents are much larger. Storm surge prone areal extent, for example, is an order of magnitude larger than any of the other hypsometric curves, and flood heights are over 3 meters higher than any of the others as well. In addition to being a larger study area, as hypothesized, New Bern's estuarine situation leads to these larger flood areas and heights. These curves illustrate that New Bern's coast has a gradual slope, which exacerbates New Bern's vulnerability.

Lastly, Plymouth's water infrastructure is the least vulnerable of all of the sites. While the wastewater treatment plant experiences some imminent vulnerability, it is the *only* site that does not experience vulnerability to either clean water treatment plants or booster stations. This means that, during a flood event such as a hurricane or heavy rainfall, there is no modeled risk of losing access to fresh water for the community of Plymouth. There are, however, some areas of clean water pipelines that are vulnerable to flooding. However, they experience a more long-term threat of failure, rather than failing from a single event. The hypsometric curves show that Plymouth initially has a steeper coast, but is surrounded by a shelf of flat land, that tapers off to higher ground. As hypothesized, Plymouth experiences the least vulnerability and flood area from storm surge than any of the other sites, which is mostly a function of its sheltered riverine situation just inland from the Albemarle Sound and the narrow mouth of the Roanoke River.

The ranking of these communities on their vulnerability is a difficult task due to the complexity of having both an absolute and relative vulnerability. Manteo does seem to be the most overall vulnerable of all three communities based solely on its extremely high relative vulnerability. However, both Manteo and Plymouth have the same number of at risk structures counting pump stations and treatment plants, with Manteo having slightly longer lengths of pipelines at risk. It is the combination of Manteo's vastly high relative vulnerability coupled with having both types of treatment plants at risk as well that make it considered the most vulnerable community. Similarly, it is the cumulation of these considerations that New Bern was ranked as the second most vulnerable compared to Plymouth, despite the 100% relative vulnerability that Plymouth experiences for its wastewater treatment plant. Plymouth's both low relative and absolute vulnerability, along with the lack of vulnerability to their clean water infrastructure makes them the least vulnerable.

6.2 Limitations and Improving Coastal Inundation Studies

There are several changes that could be made to this study to improve comparative coastal vulnerability assessments of flooding. First, the method used to determine flood heights within the hypsometric graphs were not easily obtainable through ArcGIS, so we created a methodology here that seemed to vary in accuracy with our own inputs. Ideally, for the flood heights in the hypsography for sea level rise, they would be equal to the input of sea level rise in the study (i.e. 40 cm, 60 cm, 80 cm, 1 m, and 1.5 m), however, the storm surge water levels were not always input as one value for the entire study site. Zonal statistics of the DEM were used as a proxy to estimate the highest elevation value within the DEM that was inundated. Then, to ensure comparability and consistency of methodologies to obtain these values, the same procedure was used with the sea level rise inundation models as well. In some cases, the output of this method for sea level rise was very similar to the inputs of sea level rise that we used, but in other instances, it may have overestimated inundation. So, the flood height values themselves may not be ideally reliable, however, they still graphically describe the elevation of the coast lines of these communities quite well. Verification stems from the fact that both sea level rise and storm surge hypsographs for Plymouth show the same shape of a steep coast line, followed by a large, flat shelf, and finally a gently sloping topography further away from the shoreline on the Roanoke River. Additionally, if a smaller storm surge flood height, such as a tropical storm, were modeled for Manteo, a similar drastic decline in flood area would be seen as the flood height decreased, much like the one seen from 60 cm of sea level rise to 40 cm.

For resolution consistency, it would also be fruitful to match the resolution of the models used to generate the DFIRM outputs (50 ft. / 15.25 m) with the resolution of the sea level rise and storm surge models (20 ft. / 6.10 m). This could be done by either running a dedicated hydraulic model, possibly the Hydrologic Engineering Centers River Analysis System (HECRAS) or another spatially explicit hydrologic model, or pursuing downscaling of existing models with similar methods to how the SLOSH storm surge model output was used. The wastewater treatment plant in Plymouth along the Roanoke River is on elevated ground which is seen by the higher resolution models, but it is uncertain if this treatment plant is truly in the 100 year floodplain, or if the small area is not represented well in the lower resolution DFIRM model. Other issues with misrepresentation may lie within the DEM itself. There will always be some error within the elevation values from the LiDAR point cloud, which is continually being improved as technology improves. Also, there may as well be adaptive structures already in place, such as berms or elevated platforms, that are not captured by the bare earth interpolated surface. Due to these issues, prior to any adaptive measures, there should be finer scale, individualized studies to verify the DEM for accuracy.

Perhaps the largest limitation in this study is the isolation of these hazards, rather than the ability to show compounding or antecedent flooding effects. All of the models in this study assume normal water levels, and base inundation by comparing a rise in water level with the

DEM. However, some flood events, such as that caused by Hurricane Floyd, have been shown to be far under-predicted because of heavy rainfall, and water tables that were still high from recent preceding storms, which are factors that are not included in our models. In addition, as sea level rises, water levels in these communities will be permanently higher, making 100 and 500 year floods much more frequent, and will likely make floodplains more extensive. Sea level rise also creates other future unknowns, such as how it will reshape the coast, and how that will affect the severity of coastal flooding. Rising water levels could eventually over-top the outer bank islands, which help protect the other coastal counties from large waves and tides. Without these islands, storms could generate larger surges due to larger fetches. With climate change and sea level rise models possessing so much uncertainty, mitigation efforts such as reduction in carbon emissions can help in ensuring a safer future for our coastal communities.

6.3 Contributions of This Research

It is hoped that this study will bring more attention to the dangers of coastal hazards, and to foster more progressive attitudes towards climate change and sea level rise. This approach of comparing hazards separately should inform coastal hazards researchers about the varying effects (spatially and temporally) of flood hazards in coastal communities. The vulnerability of this infrastructure is significant to the entire region, and more communities should be looking into the future to keep their citizens and environment in the healthiest condition as possible. Since there is a need for much of this infrastructure to be underground, its vulnerability will always be a complex issue, but the importance of thinking ahead for solutions where there is a clear and present danger is great. Many climate change projections reveal serious challenges for the United States’ coasts. Assessing and preparing for these increasing hazards will hopefully lead to fewer distasters, less costly response and recovery efforts, and a safer environment for coastal communities in the long run.

Much of this study has a clear basis using GIS for modeling and interpretations. While GIS is certainly a powerful tool that has some striking abilities to convey complex messages, it should be used with caution and a fine attention to detail. Some geographers are critical of how GIS has transformed the field of geography. For example, Peter Taylor believes that it drives a regression of knowledge from ideas to simply facts, calling it the very worst sort of positivism, and allowing geography researchers to ignore any broader questions in a social or political context (Taylor, 1990). However, studies like this one would be far more difficult without the powerful abilities of GIS, and in fact, geospatial information is critical to hazards identification, response and preparedness. With a strong background in attention to what geography is, an abundance of applied research can be empowered through its broad range of capabilities. Openshaw (1991) saw GIS for what it was early on, a way to bring geography to more people, and viewed it as a holistic approach to the space-time foundation of geography.

The rapid and accurate data processing of which GIS is capable of has much to contribute to the study of natural hazards. Hazards researchers like White, Kates, and Burton (2001) question why vulnerability to coastal floods has escalated, when our knowledge of how these hazards function has only increased. With our assistance in developing an understanding in coastal flood hazards, as well as encouraging mitigation efforts to decrease vulnerability, this project reaches the very core of geographic study. It brings together the physical behavior of coastal flooding, while focusing on the human impacts of hazards. This combination provides the necessary tools for future natural hazard management and adaptation.

6.4 Conclusions

The multi-hazard maps created for this study were very important in demonstrating the necessity for the mutli-hazard approach. Some of the structures had only one or two layers present, meaning they were only vulnerable to certain hazards rather than all three.This indicates that other studies that only assessed vulnerability to a single hazard, such as storm surge, may not recognize that structure as having flood vulnerability. By analyzing all three hazards, we have obtained a more full assessment of flood vulnerability to this infrastructure, and thus are approaching the reduction of this hazard in a more complete manner. By the color scheme and layering technique used, the map reader can get a quick assessment of the overall vulnerability to each structure by the number of layers and color hue. Additionally, using three different study areas allowed for supplementary context for how flood hazards differ in changing environmental scenarios.

While reviewing their vulnerability to coastal floods, communities studied here will have to decide on the steps they want to take to mitigate and adapt based on the benefits it can bring them and the cost it will take to make changes. Manteo may have a harder time adapting to change than the other two sites due to a lack of land space that would create a less vulnerable scenario. Since the topography of Manteo is lower and flatter than either Plymouth or New Bern, moving structures, such as a treatment plant, is a very limited option, and, since moving an entire treatment plant would be costly procedure, the new placement of that plant would have to outweigh those moving costs with enough benefits to justify it. Hence, mitigative engineering approaches, such as elevating and protecting the structures, may be the only short to medium range options. In the longer term, even beyond the scope of the scenarios included in this study, relocation and retreat alternatives are conceivable for Manteo and possibly fundamental to the community's sustainability.

New Bern and Plymouth, however, have more room to explore adaptation options. Both of these towns should weigh the options in moving their wastewater treatment plants that are at risk, because doing so would drastically decrease their overall vulnerability. Specifically, if Plymouth could successfully move their riverside wastewater treatment plant to adjacent higher elevated land, adaptation for several pump stations would almost eradicat any remaining coastal flood vulnerability except for pipelines. Pipeline adaptation strategies are different from pump station or treatment plant strategies, in that they can not simply be moved or raised, because their location is necessary to provide people with their service. However, there are other adaptation strategies, such as pipe coverings that protect from salt water corrosion, which may also help these communities reduce their vulnerability. Since New Bern has a much greater absolute vulnerability than the other communities, an emphasis on their adaptation strategies should be prioritizing more vulnerable structures in order to systematically lower their vulnerability over time. It is also notable that adaptation can accommodate risk reduction for multiple hazards, so the multi-hazard assessment here could assist the community with addressing long-term capital and adaptation planning.

While adaptation strategies should be weighed more on a cost-benefit analysis, mitigation through reduction of carbon emissions should be a goal for the entire country. Not only does it aim to make our communities more sustainable, but as sea level rise and climate change continue, their impacts are likely to worsen, and may be hard to predict. Sea level rise accounted for the least vulnerability in this study, but only because it was calculated as an isolated hazard, rather than being viewed as an added threat to storm surge or riverine flooding. Ultimately, accelerating sea levels will drive all the other coastal hazards and changes, compounding storm surges, rising water tables, changing coastal geomorphology and ushering the migration of wetlands. Sea level rise is more of a threat than is captured in the modeling used here, and will become the test of sustainable communities for generation to come.

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