I-87 Resiliency Study

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Contents

Appendices

Figures

Tables

Acronyms

AADD	Average Annual Disrupted Days
AADT	Average Annual Daily Trips
ACS	American Community Survey
ADCIRC	Advanced Circulation
B	Billion
BCSD	Bias-Corrected Spatially Dis-Aggregated
BOT	Board of Transportation (NCDOT)
CMIP	Coupled Model Intercomparison Project
CPI	Consumer Price Index
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FFE	First Floor Elevation
GCM	General Circulation Model
GCR	General Condition Rating
GIS	Geographic Information System
GHG	Greenhouse Gas
HAZUS	Hazards United States
INFRA	Infrastructure for Rebuilding America
LiDAR	Light Detection and Ranging
LOCA	Local Analog
LRS	Linear Route System
M	Million
MHHW	Mean Higher High Water
MPO	Metropolitan Planning Organization
NBIS	National Bridge Inventory System
NCDOT	North Carolina Department of Transportation
NCEM	North Carolina Emergency Management
NCFPM	North Carolina Floodplain Mapping Program
NOAA	National Oceanic and Atmospheric Administration
NPV	Net Present Value
OSM	Open Street Map
PAT	Project Action Team
PRI	Priority Replacement Index

QC	Quality Control
RCP	Representative Concentration Path
RMSE	Root Mean Squared Error
ROG	Rain-on-Grid
ROI	Return on Investment
SAP	System Analysis Program
SLR	Sea Level Rise
SR	Sufficiency Rating
STIP	Statewide Transportation Improvement Program
TAC	Technical Advisory Committee
TAZ	Traffic Analysis Zone
TPD	Transportation Planning Division
UNIPCC	United Nations Intergovernmental Panel on Climate Change
WHAFIS	Wave Height Analysis for Flood Insurance Studies

1 Executive Summary

1.1 Introduction

The North Carolina Department of Transportation (NCDOT) aims to connect people, products, and places safely and efficiently, with a focus on customer service, accountability, and environmental sensitivity. NCDOT oversees highways, public transit, aviation, ferries, bicycle and pedestrian facilities, and rail lines, maintaining the nation's second-largest state-owned highway system with approximately 80,000 miles of roads. The department's objective is to design, build, manage, and maintain a transportation system that is safe, effective, and resilient.

North Carolina's diverse geography and climate pose significant challenges to its transportation system, including hurricanes, coastal storms, flooding, geotechnical events, rising sea levels, coastal erosion, heatwaves, and droughts. To address these challenges, NCDOT continually adapts and enhances the resilience of its transportation infrastructure, incorporating future projections and sustainable engineering practices. The state has faced numerous catastrophic events, such as flooding from tropical storms and hurricanes, earning presidential disaster declarations.

Recent federal and state policies have significantly improved the environment for resilience initiatives.

Key developments include:

- **MAP–21**: Enacted in 2012, this federal transportation law emphasized a performance-based approach to transportation planning and investment, encouraging states to consider resilience in their transportation planning and asset management activities.
- **EO80**: Signed in October 2018, this executive order directed state agencies, including NCDOT, to integrate climate change considerations into their policies and operations, leading to initiatives like vulnerability assessments and the integration of sustainability and resilience considerations into transportation projects.
- **PROTECT Program**: Established as part of the Infrastructure Investment and Jobs Act (IIJA) in 2021, this program provides funding for planning, adaptation, and resilience projects, focusing on preparing transportation infrastructure for the impacts of climate change and other natural disasters.
- **EO266**: Signed in July 2022, this executive order established a process for determining if proposed non-highway state construction projects lie within a floodplain, implementing measures to reduce construction in floodplains, and setting resilience standards for projects within and outside floodplains.

On Sept. 27, 2021, NCDOT formalized its resilience policy (NCDOT Policy F.35.010), committing to actively managing risks and enhancing the resilience of the transportation system, considering both natural and human-made hazards.

To further identify potential solutions, NCDOT contracted AtkinsRéalis to conduct a resiliency study of Future I-87, a 182-mile transportation corridor from Raleigh, North Carolina, to Norfolk, Virginia. This corridor is home to major cities and towns and faces challenges due to changing extreme weather conditions.

1.2 Study Approach

The study used a scenario-based approach to simulate the corridor from 2020–2100. Using AtkinsRéalis' City Simulator tool, a high-detail digital twin of the corridor was created that contained 4,991 miles of road and 1,634 bridge, culvert, and drainpipe assets. The simulation was agent-based, meaning that the residents of the corridor were simulated moving throughout the transportation system, using it daily for commuting, commerce, and recreation. Further usage of the transportation system was also included in the simulation for activities such as freight transport through road and rail and pass-through trips through major conveyances like I-95.

An initial baseline scenario simulated the corridor with currently master planned capital improvements projects as well as asset condition-triggered maintenance events, with no additional action aimed at increasing resilience. A second scenario focused on resilience, elevating and hardening assets to the flooding levels resulting from the current 500-year 24-hour rainstorm. Results of the two scenarios were used to quantify the additional resilience provided and additional cost required to incorporate resilience into corridor operation in the future.

The study was run by a project action team (PAT) comprised of members from NCDOT divisions in the corridor and specialist divisions focused on hydraulics and planning. The PAT hosted a final technical advisory committee (TAC) workshop, where the TAC included stakeholders from NCDOT, corridor municipalities, counties, and municipal planning organizations, as well as state and federal-level agencies. Advice from the TAC was sought on defining the study scope and questions to be answered, describing the study findings, and preferred adaptation and mitigation actions.

Through advice from the TAC, the PAT defined a series of three study questions that focused on how changing extreme weather will impact the I-87 corridor. To answer the questions, the team developed a corridor simulator to simulate concurrent corridor growth and operations along with impacts from extreme weather, initially from 2020 to 2060. The time horizon was adjusted to 2020–2100 midway through the study. The simulation analysis domain was a 10-mile buffer on either side of the 182-mile stretch of I-87. The simulation included 4,991 miles of road with a focus on water-crossing transportation assets such as pipes, bridges, and culverts above 54 inches in diameter. Also included were rail crossings and buildings.

The simulation was driven by projections of rainfall, temperature, and sea level, which were derived from general circulation model (GCM) projections of these variables following the United Nations Intergovernmental Panel on Climate Change's Representative Concentration Path (RCP) 8.5 greenhouse gas control scenario. This so-called "business as usual" scenario posits that global governments maintain current greenhouse gas (GHG) control policies and generally predicts increasingly severe storms and steadily increasing extreme temperatures and sea level in the corridor. Recognizing uncertainty in future weather prediction, a probabilistic approach was used to generate thousands of projections of daily rainfall from 2020–2100; the 95th percentile most severe projection was used to drive the simulation to ensure proposed solutions would provide resilience in near worst-case conditions.

Through the simulation, key performance metrics such as storm damage, disrupted trips, and lost productivity were quantified and used to answer the study questions. The simulation baseline scenario did not include any adaptation, and mitigation measures and therefore exposes vulnerabilities in the corridor to future extreme weather if no resilience-focused action is taken. A second scenario added mitigation and adaptation measures to existing planned and asset condition-triggered maintenance events. For example, elevating bridges to the present-day 500-year flood water surface elevation when they are replaced. This resilience-focused scenario helped to quantify the value that additional spending on resilience would bring.

1.3 Study Goal and Objective Statements

Study goals were defined in the project scope, verified by the PAT, and reviewed by the TAC. The PAT consisted of key staff from NCDOT's Technical Services, Environmental Policy Unit and Transportation Planning Division (TPD) unit, as well as AtkinsRéalis staff.

Following NCDOTs existing goals and objectives on resilience, the goal of the study was to maintain NCDOT's high-quality transportation system during extreme weather events and ensure critical transportation infrastructure withstood harsher future conditions. Three study objectives were identified to achieve the goal.

Objective 1: Identify and explore ways to reduce failure risk: Keep key assets from failing due to extreme weather events.

Objective 2: Preserve continuity: Keep people moving following extreme weather events.

Objective 3: Foster equity: Make improvements to manage extreme weather event risks that are socially equitable and ensure vulnerable populations are served appropriately.

1.4 Study Questions

The PAT developed three questions for the study to answer. The questions specified the hazards to be simulated, the infrastructure of interest, the population, and the metrics of interest. The questions were:

Question 1: Future Disruption: Which assets (roads, bridges, culverts and pipes) will cause the most (and least) disruption to road and rail traffic if future extreme weather events (floods, storms, heat waves and sea level rise [SLR]) took them offline? Which assets or events are most likely to be impacted given their current condition?

Question 2: Critical Facilities: Which critical facilities (hospitals, emergency care, shops, schools, DOT facilities, fire stations, and police) are most at risk of being cut off from access through the transportation system? Which assets (roads, bridges, culverts, and pipes) are included in the transportation networks that serve these facilities?

Question 3: Disadvantaged Populations: How will disadvantaged populations be affected by climate change-influenced disruptions to the transportation system in the future?

1.5 Vulnerability Findings

1.5.1 Question 1 Findings: Future Disruption

Finding 1.1: Large Storms are Projected to Increase in Severity.

Large storms were found to have increased dramatically over the last several decades and were projected to continue increasing into the future. As **Figure 5-2** shows, the 100-year 24-hour rain depth was estimated by a sliding 40-year window, from 1922–1952 through 1992–2022 and evaluate the maximum 24-hour rain in each year in the window. A Weibull distribution was then fit to the maxima and the 1% (100-year) event was estimated from the resulting distribution.

Finding 1.2: Heat is Projected to be an Increasingly Disruptive Problem

The study projected maximum temperatures would rise steadily across the corridor and push the number of days above 90ºF to more than three times higher than in 2020. This is projected to increase disruption to road and rail traffic.

Finding 1.3: Sea Level Rise

The intermediate high mean sea level projection from the NOAA-led joint agency report was used as the projection for the study. This projection estimates an approximately 5.5ft rise in mean sea level from 2000–2100. The projected rise will cause both tidal flooding impacts and storm surge impacts in multiple locations in the I-87 corridor including Elizabeth City, Hertford, and Edenton/Hancock. For the most part, the disruptions will not impact NCDOT-maintained roads but will impact local roads in these communities.

Finding 1.4: Climate change impacts are projected to increase disruption to daily trips by approximately 19 times between 2020 and 2100, with heat impacts, tidal flooding, and acute flooding impacting from most to least.

Disruption to trips was selected as a key performance metric as it makes it possible to compare disruption from multiple causes. It was projected to increase substantially throughout the century, with the most pronounced disruption happening in the 2070–2100 period. The chronic disruptors — phenomena that happen on a near daily basis such as extreme heat — were projected to dominate disruption in the future.

Finding 1.5: The Cost of maintaining the system will steadily increase into the future with unpredictable future spending comprising approximately sixty percent of total spend on the corridor.

Predictable costs for maintenance estimated through decay-curve based models on each asset were projected to average around $8M per year, while unpredictable costs resulting from damage from hazards were projected to steadily increase, with median cost ranging from approximately $6.5M to $11M per year by end of century. The uncertainty in the hazards-based cost ranged from $8.5M to $15.5M per year by end of century.

Finding 1.6: Flood vulnerability occurs across the corridor with the highest disruption locations in the transportation network supporting I-87

I-87 has several locations that were projected to be vulnerable to future floods, though the highest vulnerability was in the road network connecting to I-87. Key locations were in Rocky Mount/Tarboro, Raleigh, and in Elizabeth City.

Finding 1.7 Locations of Special Interest

Seven locations of interest were identified for special review in the study. They included Tarboro/Princeville, Rocky Mount, Bear Grass, Hertford, Edenton/Hancock, Windsor, and Elizabeth City. Findings on each area are presented in the Vulnerability Chapter.

1.5.2 Question 2 Findings: Critical Facilities

Finding 2.1: Critical facility risk varies depending on overtopping risk and remoteness/redundancy in the facility service area.

General conclusions from the assessment related to critical facilities were:

- Inaccessibility peaks in multiple locations across the corridor with high-ranking facilities in both remote and urban areas. This is due to the inaccessibility index considering both remoteness/redundancy and overtopping risk.
- Overtopping risk is more of a factor in the parts of the corridor with flood risk. These locations include Tarboro, Rocky Mount, and the Raleigh suburbs. Flooding in these locations is likely due to potential riverine flooding during larger storms like hurricanes.

Finding 2.2: Climate change impacts will likely exacerbate inaccessibility for critical facilities.

Extreme weather impact on critical facilities was projected to be similar to the impacts described above for the larger corridor. Routes to the facilities that are supported by at-risk bridges, culverts, and pipes will have reduced accessibility. Remote facilities are particularly at risk because the lack of redundant routes makes them even more dependent on a single route.

1.5.3 Question 3 Findings: Disadvantaged Populations

Finding 3.2: Climate change is likely to exacerbate inaccessibility for disadvantaged populations.

Inaccessibility is a concern for disadvantaged populations across the corridor. Expected sea level rise compounded with storm surge, riverine, and pluvial flooding at the coast is projected to lead to significant increases in flood risk, while isolated disadvantaged populations in rural areas experienced increasing flood risk from pluvial and riverine sources.

Depending on location within the corridor, the projected increase in average annual trips disrupted from 2020 to 2100 ranged from five percent to more than eight times. This is because of both increased flood risk and increased travel on flood-prone roads, as population increased into the future.

1.6 Adaptation and Mitigation

The primary mitigation scenario explored included improving assets to achieve a higher design standard than they currently use. For bridges, culverts, and drain pipes, this included elevating their road decks to the level of the 2020 500-year flood, which is substantially higher than the current standard 50-year flood level.

The assets targeted for improvement included:

1. Assets specified for improvement by the statewide transportation improvement plan (STIP)
2. Assets that are triggered for maintenance by the decay-curve based models in the simulator.
3. Rail crossings, which were designated to be hardened to avoid damage — though not elevated as elevating sections of rail was deemed outside the practical scope of potential improvements.

Key findings included:

- Some locations may require an even higher level of protection than the 500-year flood level. These included primarily local roads in coastal communities, which face the double threat of increasing sea levels and intensifying storms.

- A sensitivity analysis that varied how proactively the corridor was improved in the future in terms of the timing of improvements showed that if an additional 6% of current budgets was spent each year on elevating roads, hardening bridges and culverts, 40% of the benefit of hardening the entire corridor could be gained by spending 25% of the cost.

A detailed list of the proposed improvement projects in each of the detailed study areas is presented in Chapter 6.

1.7 Recommendations

A list of recommendations in four categories was developed throughout the study. The categories include increased information and awareness, policy and planning enhancements, general infrastructure improvement, and physical countermeasures to climate change. Key recommendations include:

- Enhancing the design criteria for bridges, culverts, and drainpipes to recognize future extreme levels and built to them,
- Adjusting asphalt mix guidelines to handle future temperatures extremes,
- Improvements in both sensors tracking flood in the corridor and models and forecasts for corridor flooding, and
- Increasing the frequency of inspections of assets in the corridor.

2 Introduction

The I-87 transportation corridor forms a vital pathway from Raleigh, North Carolina northwest toward Norfolk, Virginia. Home to major cities and towns such as Elizabeth City, Edenton, Williamston, Tarboro, and Rocky Mount, the corridor is destined for continual economic and population growth. Challenging this growth are changing future weather conditions which may bring larger floods and longer and more intense heat waves over the next several decades.

To understand the potential vulnerabilities that will be exposed by continued growth along with future weather challenges, a holistic assessment of the transportation corridor and its various interacting systems is required.

This study used a scenario-based approach to simulate the corridor from 2020–2100. Using AtkinsRéalis' City Simulator tool, a high-detail digital twin of the corridor was created that contained 4,991 miles of road and approximately 1,634 bridge, culvert, and drainpipe assets. The simulation was agent-based, meaning that the residents of the corridor were simulated moving throughout the transportation system, using it daily for commuting, commerce, and recreation. Further usage of the transportation system was also included in the simulation for activities such as freight transport through road and rail and pass-through trips through major conveyances like I-95.

An initial baseline scenario simulated the corridor with currently master planned capital improvements projects as well as asset condition-triggered maintenance events, with no additional action aimed at increasing resilience. A second scenario focused on resilience, elevating and hardening assets to the flooding levels resulting from the current 500-year 24-hour rainstorm. Results of the two scenarios were used to quantify the additional resilience provided and additional cost required to incorporate resilience into corridor operation in the future.

The study was run by a PAT comprised of members from NCDOT divisions in the corridor and specialist divisions focused on hydraulic and planning. The PAT hosted a series of TAC workshops, where the TAC included stakeholders from NCDOT, corridor municipalities, counties, and municipal planning organizations, as well as state and federal-level agencies. Advice from the TAC was sought on defining the study scope and questions to be answered, describing the study findings, and preferred adaptation and mitigation actions.

This report lays out the study questions and objectives in Chapter 3, methods and assumptions in Chapter 4, vulnerability assessment results in Chapter 5, adaptation and mitigation results in Chapter 6, recommendations and conclusions garnered through the study process in Chapter 7, and further reading listed in Chapter 8. The other report appendices present links to and notes on the data used and supplemental information and more detailed descriptions of several of the modeling approaches used.

3 Study Objectives and Questions

An initial step in the study was to set clear study goals and objectives with consultation from the key stakeholders. Study goals were defined in the project scope and verified by the PAT. This team consisted of key staff from NCDOT's Technical Services and Statewide Initiatives Group, as well as AtkinsRéalis staff. Based on the study objectives, the PAT identified concise questions that were answered through the course of the study.

3.1 Study Goal and Objectives

Several existing plans were considered when developing the goals and objectives of this study. They included:

- NC MOVES 2050's objectives to:
  - Provide transportation access through building roads and bridges to withstand and endure major weather events,
  - Maintain a high-quality system through developing and mainstreaming risk/resiliency practices.
- The NCDOT Transportation Asset Management Plan's call to *"Perform predictive analysis to identify vulnerable areas within critical corridors."*

The goal of the study was to find actions to maintain NCDOT's high-quality transportation system during extreme weather events and ensure critical transportation infrastructure will withstand future conditions. Study objectives were:

Objective 1: Identify and explore ways to reduce failure risk: Keep key assets from failing due to extreme weather events.

Objective 2: Preserve continuity: Keep people moving following extreme weather events.

Objective 3: Foster equity: Make improvements to manage extreme weather event risks that are socially equitable and ensure that vulnerable populations will be served appropriately.

3.2 Study Questions

Based on the overall goal and three objectives identified, three study questions were identified by the PAT and agreed by the TAC.

3.2.1 Question 1: Future Disruption

Which assets (roads, bridges, culverts and pipes) will cause the most (and least) disruption to road and rail traffic if future climate change-influenced events (floods, storms, heat waves, and SLR) took them offline? Which assets or events are most likely to be impacted given their current condition?

3.2.2 Question 2: Critical Facility Accessibility

Which critical facilities (hospitals, emergency care, shops, schools, DOT facilities, fire stations, and police) are most at risk of being cut off from access through the transportation system? Which assets (roads, bridges, culverts, and pipes) are included in the transportation networks that serve these facilities?

3.2.3 Question 3: Disadvantaged Population Accessibility

How will disadvantaged populations be affected by climate change-influenced disruptions to the transportation system in the future?

4 Approach and Modeling Assumptions

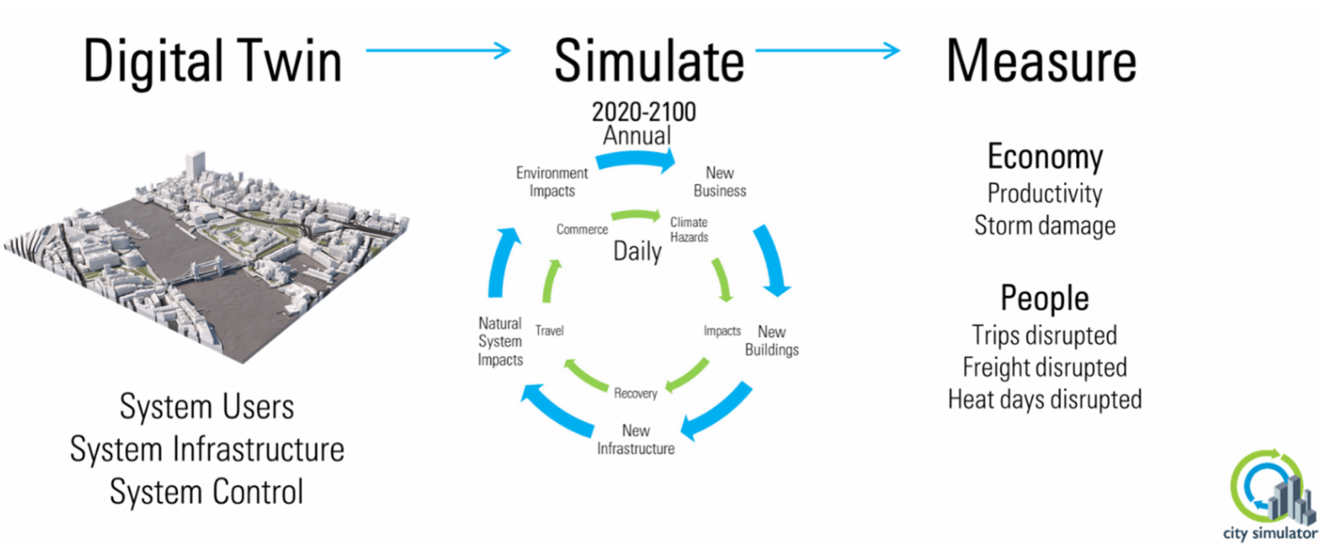
The findings and recommendations in the study required dynamic simulation of a digital twin of the corridor from 2020–2100. The approach, techniques, and assumptions involved are described in this chapter.

4.1 Using Dynamic Simulation to Measure Resilience

This study used AtkinsRéalis' City Simulator resilience modeling tool (see **Figure 4-1**). City Simulator is a Geographic Information System (GIS)-based tool that creates a digital twin of a city, county, state, or region and evolves it over the planning period (i.e., 80 years) to quantify future climate change impacts and find ways to mitigate and adapt.

A 3,800-square mile I-87 corridor digital twin was developed, consisting of the I-87 highway and all transportation infrastructure, buildings, and natural systems within a 10-mile buffer on either side of the highway (see **Figure 4-2**). The digital twin simulated growing, operating, and being hit with climate change-influenced disasters from 2020–2100.

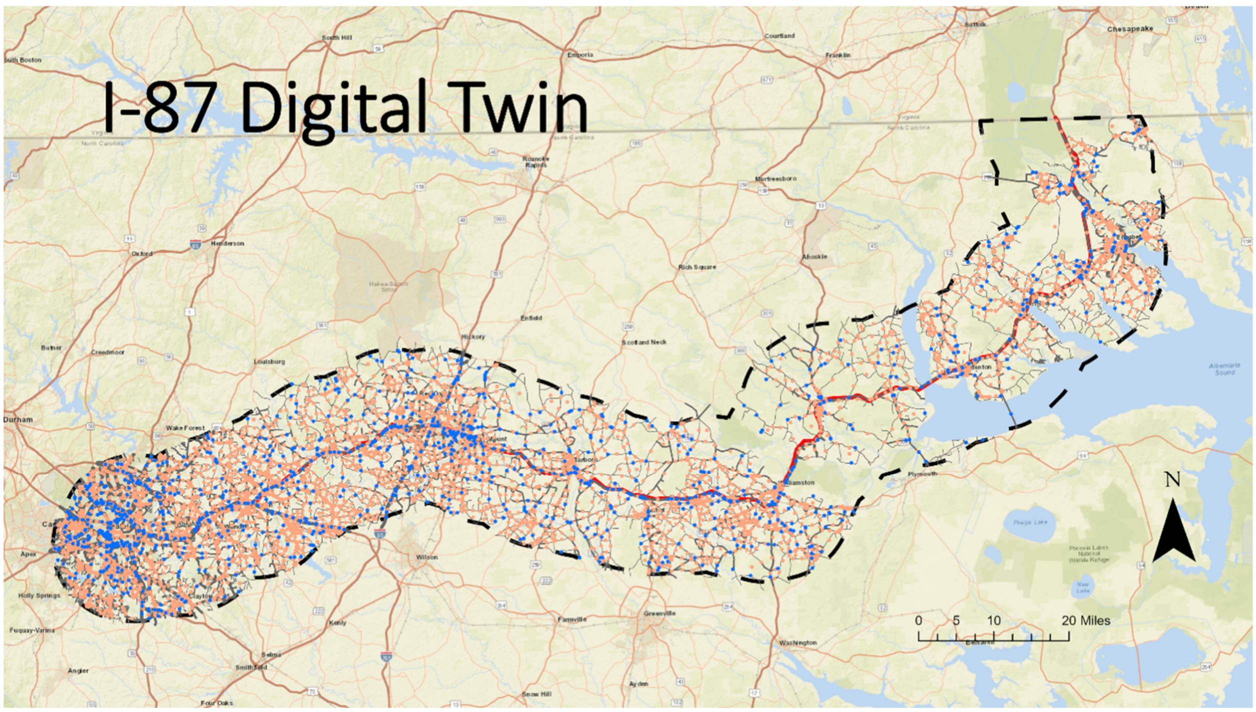
Figure 4-1: How City Simulator Works



How City Simulator Works*. A digital twin was created that included system users, infrastructure, and control. This digital twin evolved in a daily simulation from 2020 to 2100. The simulation included growth in infrastructure, population, and economy. Additionally, it included climate change-influenced disasters, like hurricanes and heat waves. Key performance metrics were evaluated throughout the simulation. A baseline simulation was conducted first without any adaptation and mitigation measures. Then, an adaptation/mitigation scenario was conducted that added actions like elevating bridges above the flood levels caused by the current 500-year, 24-hour rain event. The resulting key performance metrics were compared to quantify the increased resilience the adaptation/mitigation measures.*

City Simulator is an agent-based model, which means it creates a population of people in the corridor that is matched statistically to the real population. The I-87 simulator included avatars for the people that live within the buffer, plus agents moving into and out of the area along other highways. To simulate daily travel, residential and commercial buildings were added to the simulation to act as workplaces and homes for the avatars. Each day of the run, the avatars were simulated commuting from home to work and school. This allows for street-level estimating of future disruption from flooding and other disasters.

Figure 4-2: The I-87 Digital Twin, with Selected Statistics



The I-87 digital twin was compiled from multiple datasets of global climate model projections, historical weather and tide time series, flood models, digital elevation models, demographics data from the US Census, and GIS datasets of buildings, parcels, transportation, and rail systems.

4.2 Simulation Drivers: Projected Future Conditions

The simulation was driven by projections of daily rainfall, temperature, and sea level. The approaches used to incorporate these three drivers are detailed below.

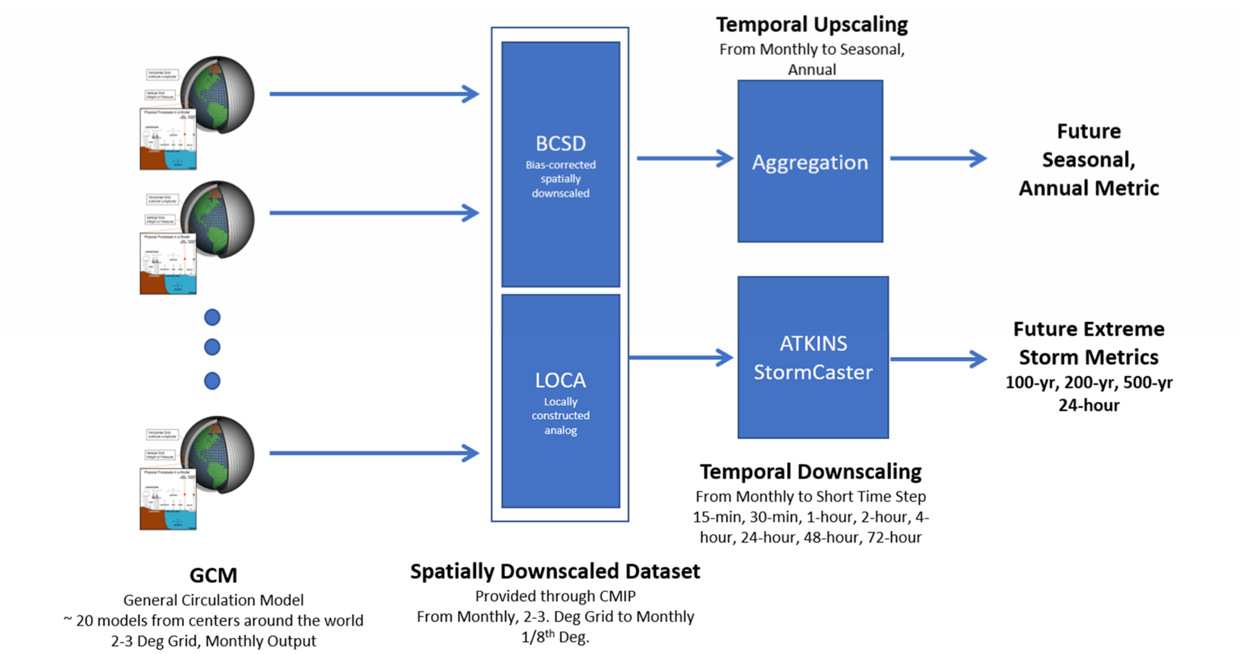
4.2.1 Rainfall

As **Figure 4-3** shows, rainfall projections started with an ensemble of monthly projections from the coupled model intercomparison project's (CMIP5) bias-corrected spatially dis-aggregated (BCSD) dataset. The BCSD process takes monthly (2020–2100) projections from 20 GCMs and converts them to a common grid at 1/16th degree latitude/longitude spacing, a process called spatial downscaling. (More information on the BCSD dataset.)

The assessment used the United Nations Intergovernmental Panel on Climate Change (UNIPCC)-defined representative concentration pathway (RCP)8.5 and RCP4.5 scenario results from each GCM. RCP scenarios define plausible global future conditions in terms of GHG emissions. The number designation — 4.5, 8.5 — is measured in watts per square meter and refers to the amount of energy retained in the atmosphere because of GHG emissions. (More details on RCPs.)

The RCP8.5 scenario is considered the "business-as-usual" scenario, where there is no attempt to control GHG emissions and global temperatures and extremes in weather continue to rise until the end of the century. The RCP4.5 scenario represents a concerted effort on the part of global governments to control GHG emissions which results in a stabilization of global temperatures and weather by the end of the century.

Figure 4-3: Future Rainfall Projection Algorithm



Future rainfall and temperature amounts were derived from CMIP5-based projections, which, in turn, were derived from GCM results. For rainfall, the spatially downscaled, monthly time-step BCSD dataset was used as input to the AtkinsRéalis StormCaster algorithm, which temporally downscaled the data to daily time-step. For temperature, the temporally and spatially downscaled LOCA dataset provided data in daily time-step.

Ensuring Extremes for Stress-Testing

With its short time-step requirement, City Simulator required daily rainfall projections. While daily projections were available from the CMIP5-based Local Analog (LOCA) dataset, a review of the extreme events in the projections in the I-87 corridor showed that 24-hour total rainfall projections were often not as large as recent events such as Hurricanes Florence and Matthew. Given an upward trend in historical 24-hour extreme event rainfall depths, it is unlikely that future events will become less extreme. As such, the AtkinsRéalis Stormcaster downscaling algorithm was used to temporally downscale the BCSD projections from monthly to daily time-step.

The StormCaster algorithm disaggregates projected monthly rainfall totals with a focus on:

1) extrapolating recent trends in historical variance in rainfall events from the prior 30 years, and
2) inflating/deflating daily extreme events (both high and low rain events — i.e., drought) such that monthly climatologies derived from projected future daily events match with projected monthly climatologies from the BCSD dataset.

This process ensures that extreme rain events in the projected future are at least as extreme as those seen in recent years and are often more extreme.

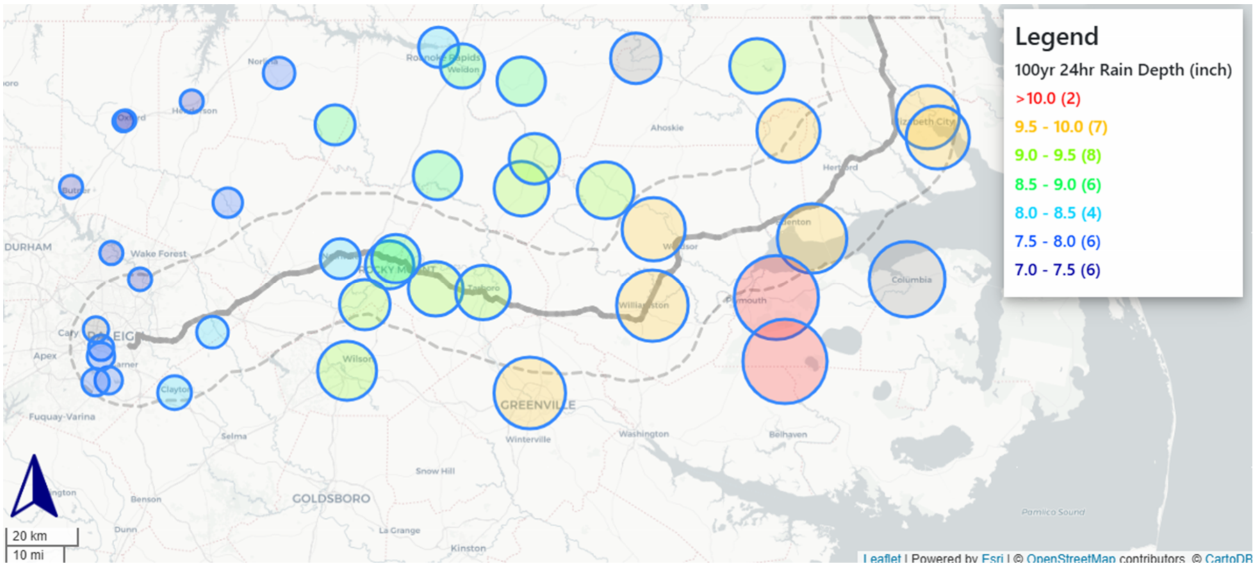
The rationale for this approach is that it is preferable to take a conservative approach, where plausibly higher extreme future realizations are better to stress-test the digital twin. Using the higher extremes will provide a higher level of confidence in future robustness and resilience if the results of the study are used to inform resilience planning.

Accounting for Regional Variability in Rainfall Totals

The maximum historical rainfall event in inches over 24 hours is shown in **Figure 4-4**. The northwest to southeast gradient from smaller maximums to larger reflects the change from higher elevation to lower and the attendant microclimates. To account for this regionality in the rainfall statistics, the gauge within the corridor with the maximum historical rain depth was found. This was the Edenton, NC gauge, where its 10.81-inch rain event was 82% of the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 500-year rain depth estimate for this location. A daily rain projection was then created for this gauge, which acts as the single rain projection for the corridor in the simulation.

Regional adjustment factors were developed for each Environmental Protection Agency (EPA) Level III eco-region (Piedmont, Southeastern Plains, Middle Atlanta Coastal Plains), where the factor was defined as the maximum 24-hour rain depth in the region divided by the maximum 24-hour rain depth at the Edenton gauge. The regional factors were then applied to the rain projection at each water-crossing asset (bridges, culverts, drainpipes, road low points) to produce a regionally adjusted rain projection specific to the asset.

Figure 4-4: I-87 Historical Max Rainfall (Inches)



Maximum 24-hour rain event (at all gauges) in the corridor region. The typical return-period event was at the Edenton, NC, gauge, which was 82% its 500-year, 24-hour estimate provided by NOAA Atlas 14.

Using this approach, when a rain event hits the corridor, it is assumed to impact the full corridor with an equal statistical impact. That is, if a 100-year 24-hour rain event is projected, infrastructure in each eco-region will be hit with a rain depth at the 100-year 24-hour rain depth specific to the eco-region.

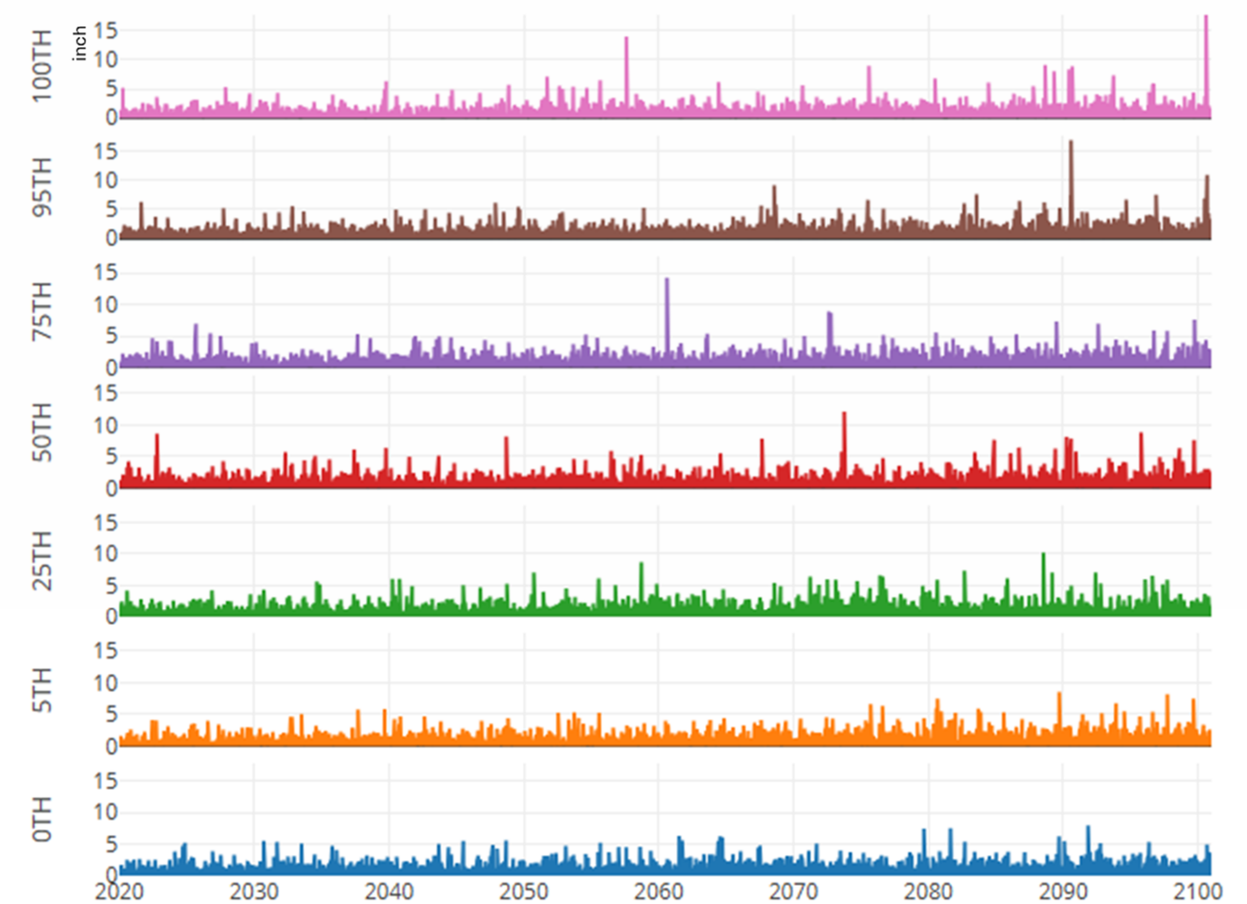
Generating the Corridor-wide Rainfall Projection

An ensemble of rainfall projections was created based on the maximum rainfall event gauge in the region (Edenton, NC, USC00312635) (see **Figure 4-5**). This ensemble included 1,000 realizations of future rainfall created through downscaling 20 GCM projections based on RCP8.5 with historical rainfall data at Edenton, NC. The realizations were ranked by their severity over the 80-year simulation timeline, where severity was defined as the cubed sum of daily rainfall depths over the timeline.

Figure 4-5 shows a series of projections corresponding to 0^{th}, 5^{th}, 25^{th}, 50^{th}, 75^{th}, 95^{th}, and 100^{th} percentile severity. Note, the 100^{th} percentile projection contains one very significant 24-hour rain event approximately 17 inches in depth (on the order of magnitude of a Hurricane Matthew- or Florence-size storm). In addition, there were several very large rain events from eight to nine inches. The current 100-year event at Edenton is 9.67 inches, according to NOAA Atlas 14. In the lower-percentile projections, the number of large events reduced steadily. The 0^{th}-percentile projection, for example, had no events over approximately five inches, which was approximately equivalent to the 5-year storm at Edenton.

It is important to note that each of these projections was based on a plausible future for the corridor. As the objective of this assessment was stress-testing the corridor for future extremes, more extreme projections were used in the analysis. The 95^{th}-percentile projection was adopted as the primary forecast for simulation.

Figure 4-5: Projection of Future Rainfall at Edenton, NC



The projections were generated using a combined temporal statistical downscaling and weather synthesizing algorithm that blended historical daily rainfall with monthly general circulation model projections of rainfall for the area. This procedure generated 1000 realizations of future rainfall from the 20 GCM projections. A severity index was calculated for each realization, which is the sum of rainfall depths to the fourth power. The realizations were then ranked by severity. The seven charts above are the 0th, 5th, 25th, 50th, 75th, 95th, and 100th percentile by severity from bottom to top. The 95th percentile "near-worst-case" realization was used in the simulation. It includes two Matthew-sized or higher storm events with 17 inches of rain in the largest event.

Enabling Comparison of Present-Day and Mid-Century to Quantify Climate Change Impact

One of the key questions of the study is how the impacts of climate change are changing over time. The majority of GCMs predict that extreme storms will become more extreme as the century progresses. This implies that the choice of weather projections used to drive the simulation should embed these changes in storm statistics over time.

The assessment of severity described above does not consider when in the timeline the severe events are occurring. This means that if a specific projection is selected to drive the simulation — say the 95th percentile projection — storms within the projection can potentially be early in the timeline, late in the timeline, or any combination in between.

This presented a challenge for answering the climate change impact study question. If the projection selected to drive the simulation is front-loaded (severe storms early in the timeline), it will show that climate change impacts are minimal if we simply compare the impacts in the period at the end of the simulation to the impacts in the period at the beginning. Comparing statistically similar impact levels at the start and end of the timeline is therefore required.

To solve this problem, the simulation was run with three rainfall projections focused on three planning years (2040, 2070, and 2100). The severity analysis was run with a focus on both the full 2020 –2100 timeline and on the21-year periods leading up to these planning years (2020–2040, 2050–2070 , and 2080–2100).

Estimates of climate change impact across the various metrics in the simulation (disrupted trips, storm damage, lost productivity, etc.) were then evaluated using the 95th percentile most severe realizations for each planning period.

Worst Case Scenario

A key modeling parameter is the rainfall severity percentile used in the final simulations. Within this study, the 95th percentile was used throughout. Like the logic of assessment using a design storm, the rationale is to use this near-worst case future realization to ensure vulnerabilities are exposed and solutions stress-tested under the more adverse conditions the corridor is likely to experience.

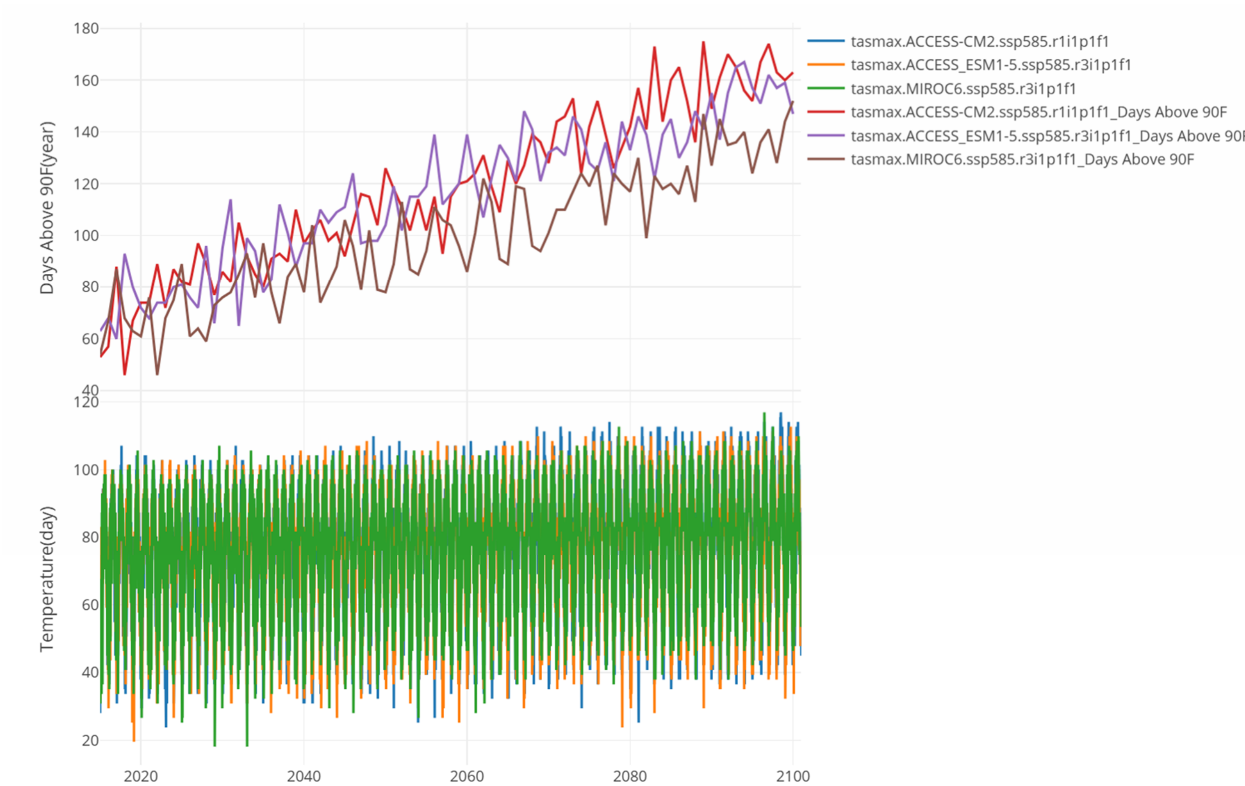
Discussion on Early vs. Late Severity Rainfall Projections

The choice of early or late severity rainfall projections raised considerations about which was a stronger stress-test for the transportation corridor. Intuitively, a front-loaded rain projection — with the most severe storms in the 2020s — will generally present a higher impact scenario, because NCDOT will not have had time to implement resilience measures before the storms occur. A back-loaded rainfall projection, given the impacts of climate change, will have more severe storms by magnitude than a front-loaded one, but by the time the storms occur, NCDOT will have had time to build a more resilient transportation system. These situations were observed in the simulation, particularly in the resilience-focused scenario described in the Adaptation and Mitigation section later in this document. Consult the results chapters for further discussion on this topic.

4.2.2 Temperature

Daily temperature projections used in the simulation were extracted from the LOCA2 dataset, as shown in **Figure 46** which is a spatially and temporally downscaled product derived from the CMIP6 GCM projections. The LOCA2 dataset is downscaled to 1/16th degree and daily time-step. Daily maximum temperatures from the UNIPCC RCP8.5 scenario version of the LOCA dataset were used in the study to estimate heat exposure impacts to corridor residents and travelers, as well as impacts on the railroads in the form of potential track buckling. The figure includes both the daily projected data from three GCM models for the ssp585 scenario as well as an annual days-above-90°F metric for these projections. The days above 90°F metric is a common metric used to clearly explain ambient temperature increase in the future. The 90°F threshold was selected as it is typically associated with a hot summer day. The figure shows that the number of above 90°F days is projected to increase almost three-fold, from 60 days per year to around 150.

Figure 4-6: Days Per Year Above 90° at Edenton, NC



An ensemble of three GCM-based projections of maximum temperature was used from the LOCA dataset. Here, the members of the ensemble at a single grid cell near Edenton, NC, were evaluated by the number of days exceeding 90° F each year. The upward, projected trend showed strong agreement among the models that future temperature increased dramatically over the coming century.

4.2.3 Sea Level

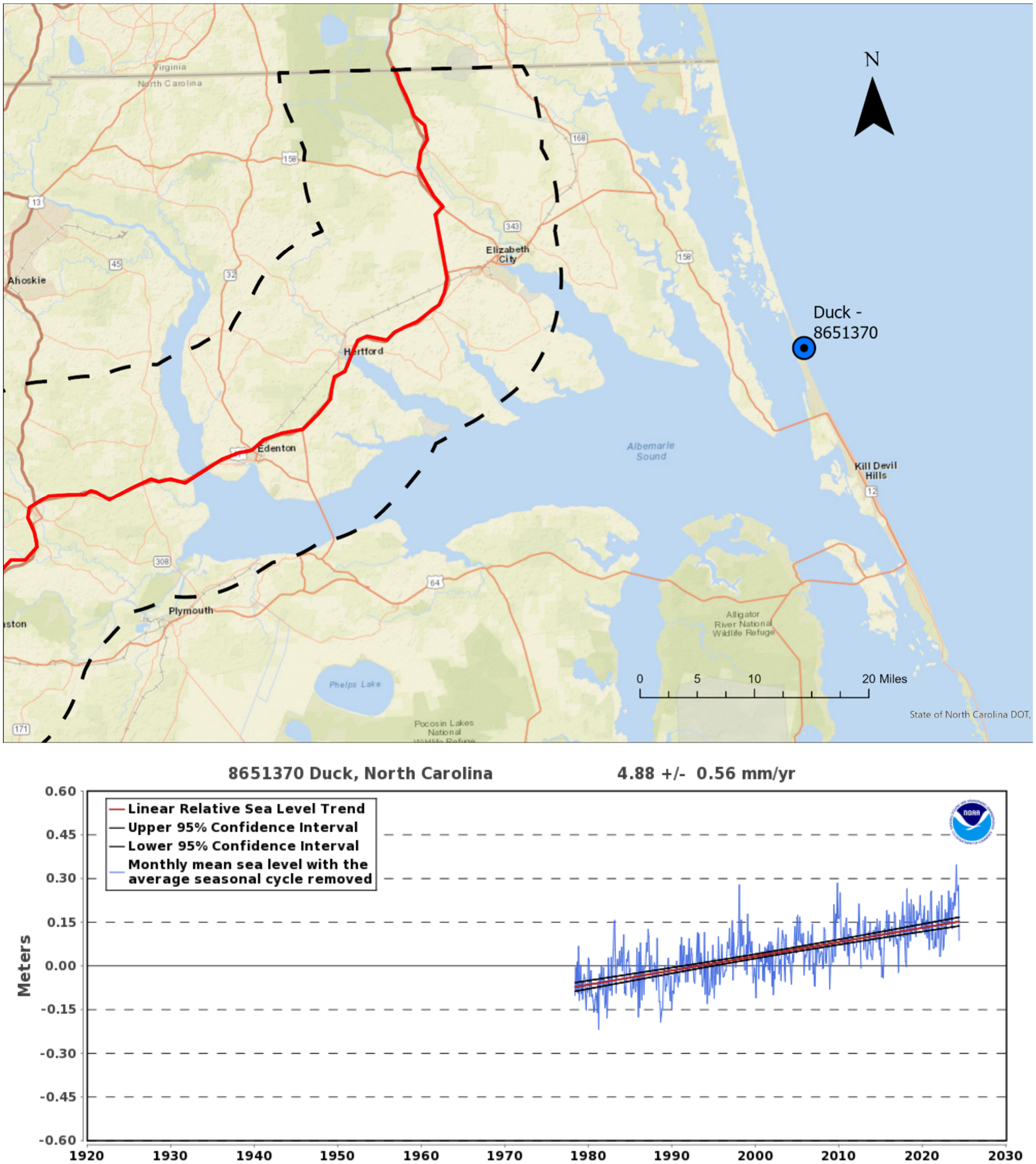
By 2060, mean sea level was projected to rise in Duck, NC between 1.57 feet and 2.53 feet relative to current mean higher high water (MHHW) (NOAA SLR Viewer). By 2100, this range varies from 2.62 feet to 7.05 feet. Rising sea levels will give rise to both chronic and acute disruption events, namely tidal or nuisance flooding and storm surges exacerbated by higher mean sea levels. To capture this disruption in detail, a high-detail sea level projection was needed that included tidal fluctuation.

Creating a Daily Projection of Sea Level with Tidal Fluctuation

Daily projections of three phenomena were developed and superposed to produce the tide projection. The three phenomena included:

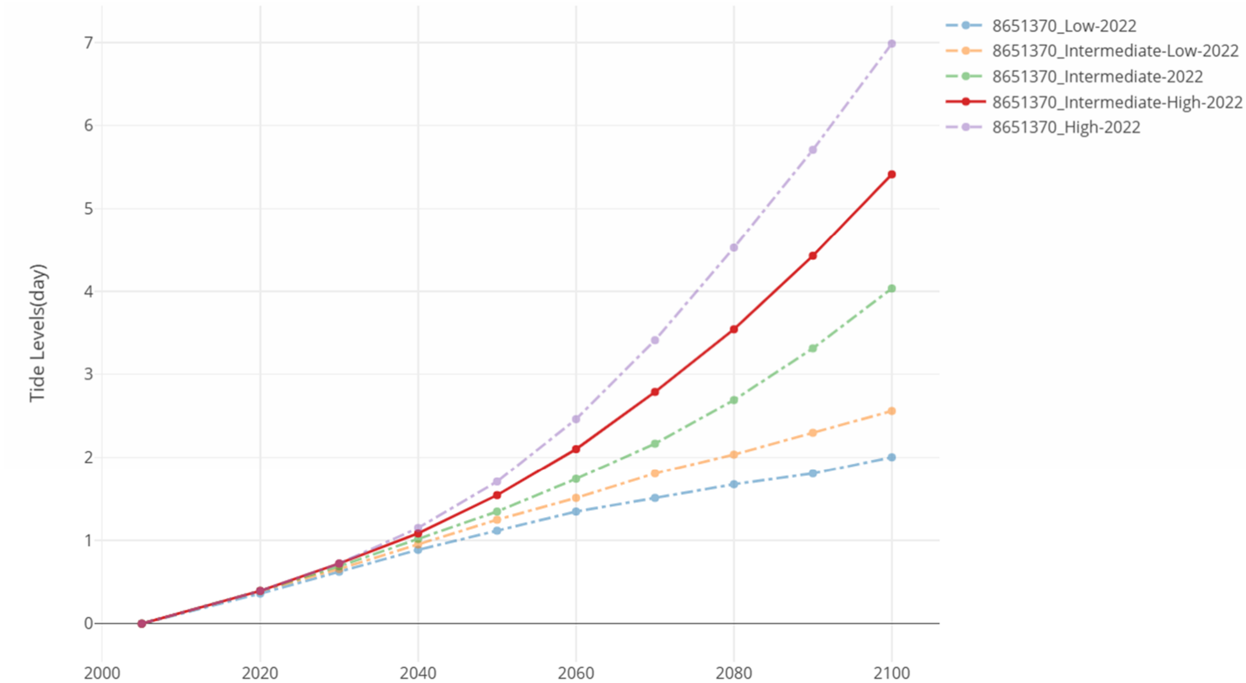
- **Mean Sea Level** – To reflect projected sea level rise, the NOAA intermediate projection of mean sea level at Duck, NC was used (**Figure 47**). The intermediate projection was selected from the array of projections by comparing the measured sea level increase in Duck, from 2000 to 2020, with the four projections for the same period. The lowest root mean squared error (RMSE) projection was intermediate-high. See **Figure 48** for a comparison. Under this projection, the mean sea level in the simulation is projected to rise by 4.99 feet by year 2100.
- **Tidal Predictions from Gravity Effects** – To reflect the effects of gravity on tides from bodies such as the sun and moon, 2020–2100 tidal predictions were downloaded from NOAA's water levels server for Duck, NC. These predictions provided estimates of daily high and low tides.
- **Tidal Prediction Residuals Based on Historical Residuals** – To reflect the impacts of phenomena like windstorms, rainstorms, and river flows on tide levels, a historical set of residuals was developed by subtracting actual tide levels at Duck, NC from the tidal predictions mentioned above. These residuals were used to calibrate a Markov probabilistic model that predicts the residual for a given day, based on the value of the residual from the previous day. The process used to generate the projection was embedded in City Simulator. The approach is, for this specific part of the analysis is considered proprietary. But Markov probabilistic models are used for stochastic weather, tide, and a host of other types of time series for decades. For an overview on the process, please refer to this reference.

Figure 4-7: Trends in Sea Level at NOAA 8651370 Station, Duck, NC



Notes: Upper panel – location map of the 8651370 tide station. Lower Panel – trends in sea level as provided by NOAA water levels site. Note provided by NOAA water levels site: "The relative sea level trend is 4.88 millimeters/year with a 95% confidence interval of +/- 0.56 mm/[year] based on monthly mean sea level data from 1978 to 2021 which is equivalent to a change of 1.60 feet in 100 years."

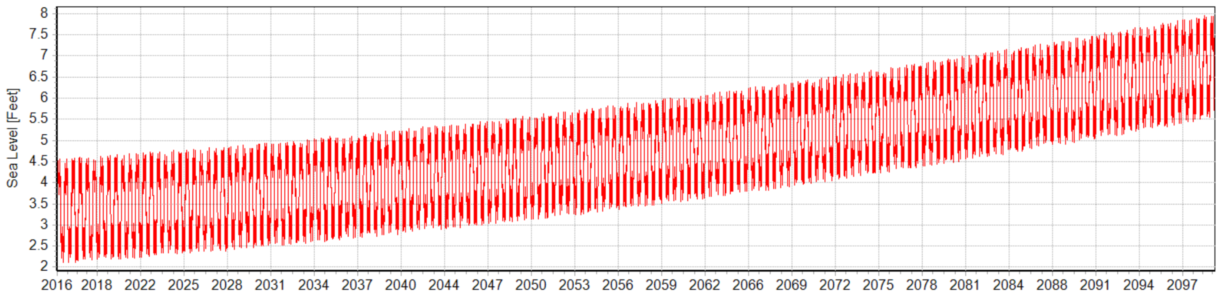
Figure 4-8: Projected Mean Sea Level at Duck, NC



Notes: Projections of sea level from NOAA, plus historical observed tide. In this study, the intermediate-high-2022 projected mean sea level scenario was used as it matched with an observed increase from 2000–2020. From the NOAA tide level site: "The projection of future sea levels that are shown below were released in 2022 by a U.S. interagency task force in preparation for the Fifth National Climate Assessment. The projections for five sea level change scenarios are expected to assist decision makers in responding to local relative sea level rise. The 2022 Sea Level Rise Technical Report provides further detailed information on the projections."

The resulting projected tide series is presented in **Figure 49**. The chart presents the full time series generated from 2018–2100. The portion used in the simulation was from 2020–2100. Note the upward slope in the projection, which reflects the NOAA intermediate mean sea level projection.

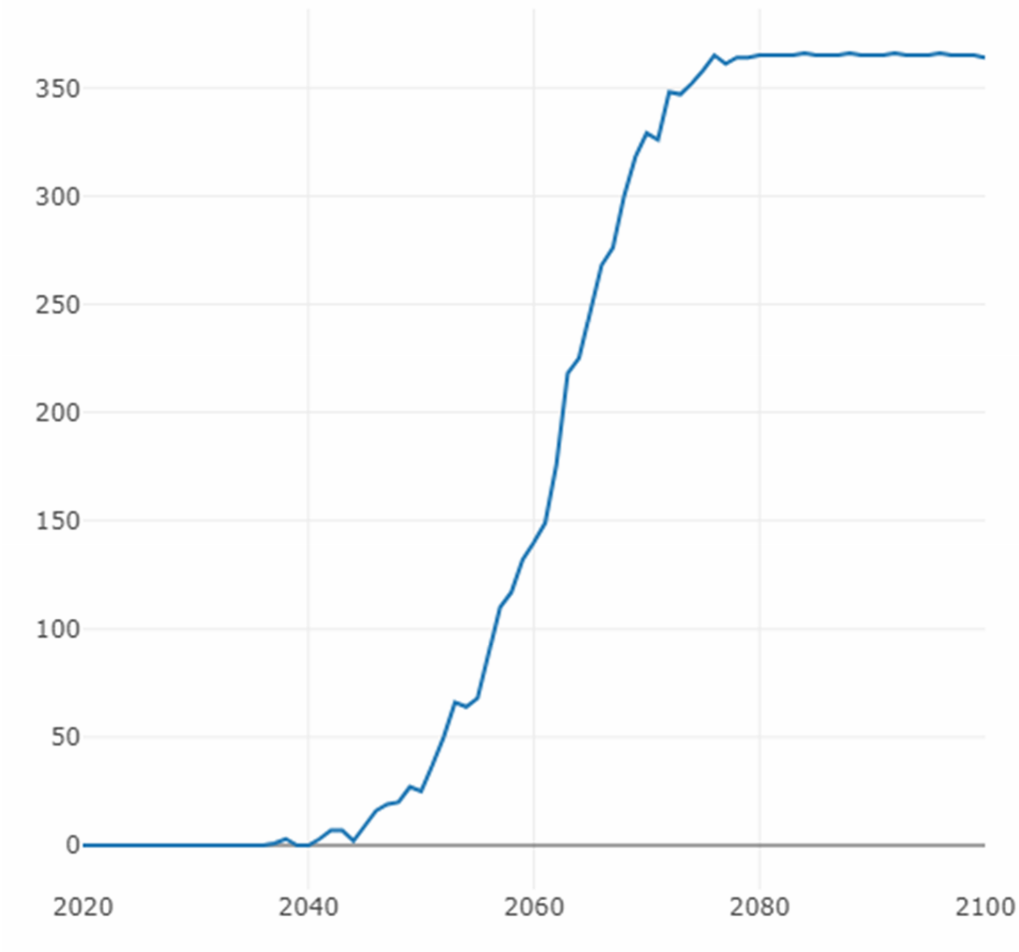
Figure 4-9: Projected Max Daily Sea Level at Duck, NC



The projection blended gravitational effect predictions of the tide at the gauge probabilistic-model-based projection of actual tide-predicted tide residuals and the NOAA intermediate mean sea level scenario projection described in the image above.

An assessment of the tide projection was conducted to evaluate the number of days above MHHW at the Duck station, as shown in **Figure 4-10**. The chart shows that from 2016 to mid-century (approximately 2050), there is a steady rise in the number of days above MHHW. After this point, tide levels are projected to reach MHHW every day of the year. This has important implications for disruption from sea level rise, as both nuisance flooding and elevated storm surge on higher seas will steadily become increasing disruptors.

Figure 4-10: Days above MHHW at Duck, NC When Using NOAA Intermediate SLR Forecast



The projected sea level time series was used to derive days above MHHW metric from 2020 to end of century at the location of the Edenton, NC gauge. The chart shows that by mid-century, tidal inundation will be an everyday occurrence.

Recommendations for Tide Simulation in Future Studies

The tidal projection developed could be improved in several ways to reveal even more detail on potential future tide-related flooding:

- **Incorporate uncertainty in the mean sea level projection** – the mean sea level projection has significant uncertainty, which grows into the future. The approach of selecting the scenario from the array of NOAA scenarios that best match the 2000–2020 actual tide levels provides confidence that the simulation matches conditions being observed in Duck. But the remaining scenarios from NOAA should be used to estimate the uncertainty in the projection — or some other suitable method for uncertainty estimation. This uncertainty should be propagated through the simulation to provide error-bars for tidal disruption estimates, which will improve decision support.

- **Improve tidal residual estimates** – the projection of tide residuals uses a Markov probabilistic model that is dependent on historical residuals. Implicit in this approach is an assumption of stationarity. That is, that the residuals will have the same distribution and dynamics they had in the past. As climate change proceeds, daily tidal behavior may shift statistically in response. As such, an investigation into methods to project the shift of the statistics of the Markov-based projections with time should be undertaken.

  Alternatively, a different approach could be taken for tidal projections that is more physically based, such as incorporating a 2D or 3D hydrodynamic model into the tide projection framework. While this would have a significantly higher level of effort, existing hydrodynamic models of the coastal region do exist and may be useful in taking this approach.

4.3 Building and Structure Modeling

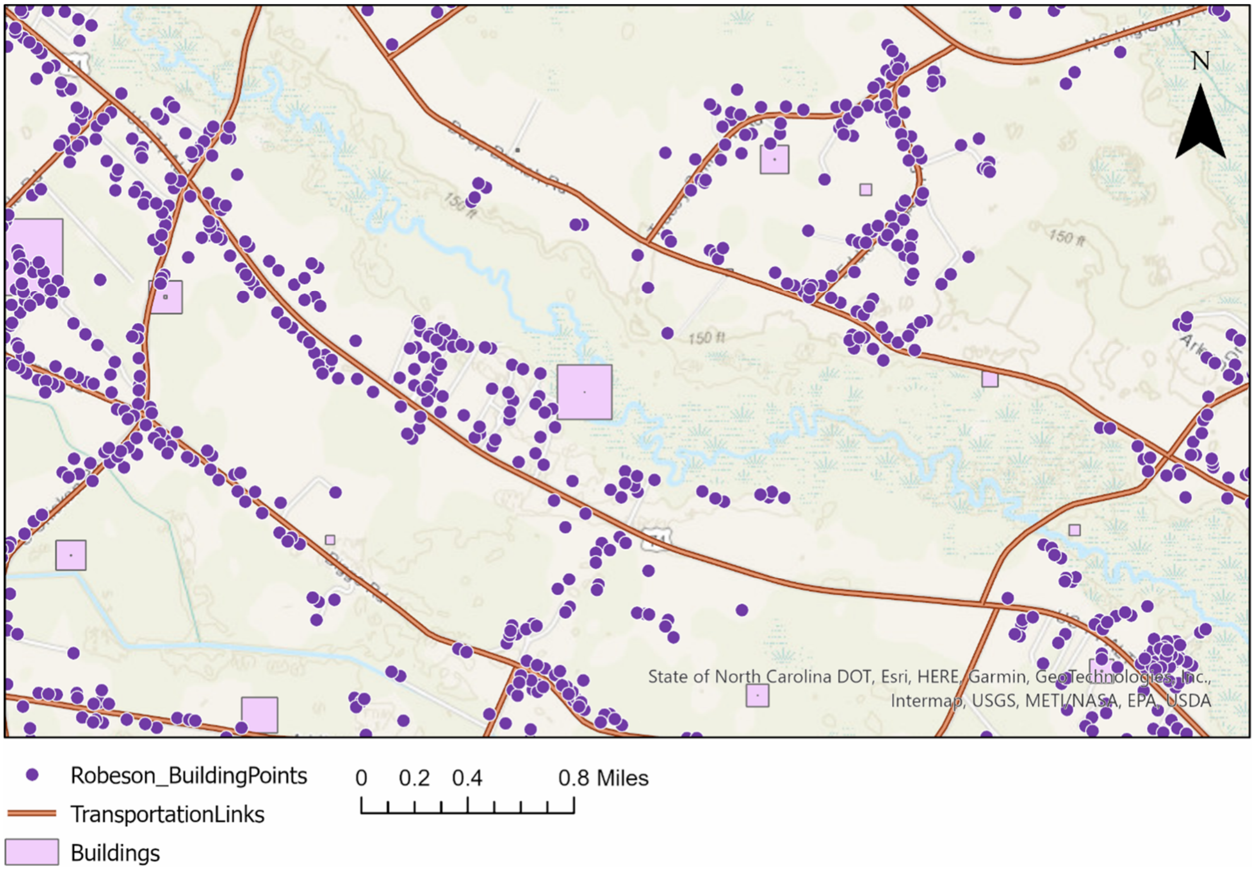
There were approximately 415,000 buildings in the I-87 study area. These buildings were partitioned into residential and commercial categories. The population in the corridor was represented as agents that live in the residential buildings and work in the commercial buildings. The process for synthesizing the agent population is described in the demographics section below.

The buildings were sourced from a joint building footprint/parcel GIS layer couplet. The building footprints were derived from a building footprint layer developed by Microsoft, and the parcels were derived from the statewide parcel layer prepared by North Carolina Emergency Management (NCEM). This joint GIS layer, developed by AtkinsRéalis before the start of the I-87 study, is stored as county-level geodatabases in AtkinsRéalis' servers. The geodatabases for the counties that covered the corridor were used.

4.3.1 MegaBuildings

Because the study questions focused more on the transportation system and less on the system of buildings, the buildings were converted to so-called "MegaBuildings" as shown in **Figure 4-11**. In this process, single buildings along each road segment were merged into an effective multi-family residential building and multi-tenant commercial building located at the geographic centroid of the road segment. This process also had the effect of speeding up simulation run times.

Figure 4-11: MegaBuildings



MegaBuildings (pink squares) were created at the centroid of each road segment. These structures were modeled as multi-family residential and multi-business buildings. The number of units/businesses in each MegaBuilding was evaluated as the number of real structures (purple circles) present on the road segment of interest. This figure shows an example set of road segments in Robeson County. MegaBuildings were created for all road segments in the corridor.

4.3.2 Controlled Access Road Segments

Because controlled access road segments (i.e., interstates, U.S. highways) do not typically support residential or commercial structures directly, these road segments were not assigned MegaBuildings in the simulation.

4.3.3 Building Flooding Not Simulated

The process of generating MegaBuildings necessarily eliminated building-by-building simulation of flood from the simulation. In other simulations conducted with City Simulator, each building's first-floor elevation (FFE) is compared to the riverine, pluvial and, where appropriate, storm surge and tidal flood levels when storm events occur. When the projected flood exceeds the FFE, building flooding is assumed to occur and storm damage is estimated by way of Hazards United States (HAZUS) depth/damage curves. With the MegaBuilding approach, building storm damage estimation was removed from the simulation.

4.4 Travel Modeling

The simulation integrated a travel model that simulated corridor residents and outsiders using the road system in daily activities, such as commuting, recreation, carrying freight and other activities. With the daily time-step used, travel was simulated as the usage of a set of road segments per day by each corridor resident. The specific road segments used were determined in the population synthesis step. See the section on agent modeling (following this section) for more details on this process.

4.4.1 Simulating Trip Disruption

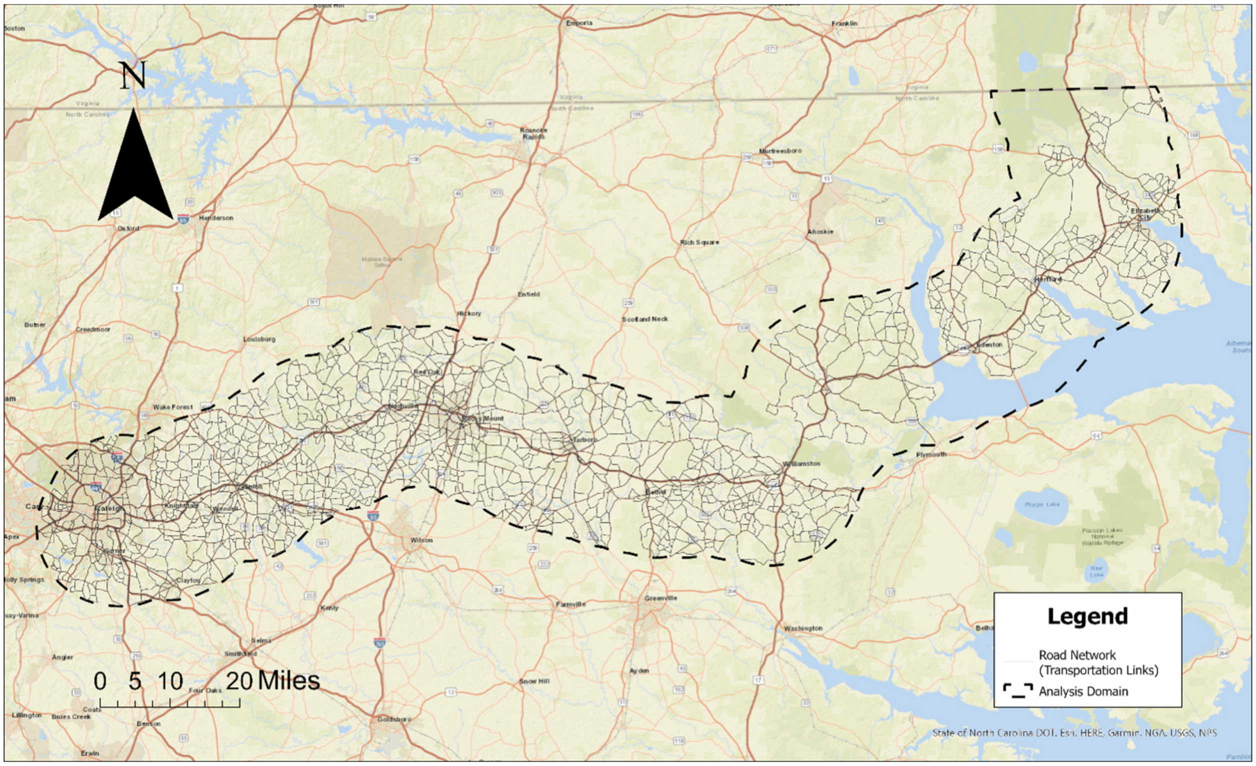
One of the key functions of the travel model was to pinpoint where disruption from climate change-influenced events occurred during the simulation. Road segments were impacted by both flooding events and heat events. When these events occurred, a disaster event was created and associated with the road segment. The disaster event had a recovery period that went from a single day for minor flood overtopping events and heat events to many months for major flooding events. The specific recovery duration rules for each disaster type are specified below in the sections on flood and heat modeling.

For each day of the recovery period, all trips that normally occurred on the associated road segment were recorded as disrupted. Therefore, disrupted trips become an important metric for understanding how climate change impacts transportation — both at hotspots in the road network and rolled up to the county, division, and full corridor level.

4.4.2 Creating the Road Network

The road network was a key GIS model component in the travel simulation. **Figure 4-12** shows the road network for this study. The network was held in the transportation links and transportation nodes layers of the City Simulator database. Each agent in the simulation was associated with two buildings: a workplace and a residence. The buildings were associated with the closest transportation node. As part of setting up the simulation, the complete set of shortest paths from each transportation node to each other transportation node was evaluated, a computationally intensive process that followed the well-known Dykstra algorithm.

Figure 4-12: Road Network



The modeling goal was to represent the transportation network in sufficient detail so the likely door-to-door path each traveler takes from origin to destination was represented explicitly for the majority of travelers. Furthermore, sufficient detail in the road network was needed to capture locations of flooding and the disrupted traffic accurately. The competing goal was to reduce the number of road segments in the network and to reduce the number of computations needed to define the commute paths. For this reason, the transportation network typically included interstates, ramps, state, and arterial route classes. Local roads were typically excluded, and the buildings they served were schematically connected to the higher volume road segments which connected the places to their local roads.

Additionally, the higher volume network was pruned to reduce the number of road segments. The pruning process included the following steps. Each step is described in general terms, and then a note is provided describing the specific actions for the I-87 study related to the step. Using a combination of these steps, plus careful quality control, a detailed but simplified network of road segments was created, minimizing the computational burden during simulation but also capturing the majority of locations of highly disruptive flooding.

Removing Danglers – This included finding road segments that were shorter than a threshold and were only connected to the network at one end. These segments were removed from the final network.

- **I-87**: Danglers shorter than one mile were removed. This was done after removing ring roads, a process that often resulted in and created danglers.

Removing Ring Roads – These were roads with an end point that was the same as their start point. Typically, these road segments represented the circuit route in a small neighborhood. They were also removed. Another road type classified as ring roads were roads with a start point and end point that connected to the same route. These were identified and removed as well.

- **I-87**: Ring roads were removed, which simplified the network. This process was run iteratively, combined with removing danglers to prune much of the high-density route networks, and represented non-local routes in subdivisions.

Unsplitting – Unsplitting means uniting two roads that have a start point and endpoint in common and no other road connecting at the same point. Used as a post-process after removing danglers, unsplitting typically achieves a large drop in the number of road segments.

- **I-87:** During the course of developing the network, a Quality Control (QC) process found multiple route segments that had opposing flow directions in the original data provided from the NCDOT linear route system (LRS). Using Esri's unsplit tool resulted in unsplit routes where the vertices of a portion of the segment flowed in one direction, while the vertices of the remaining route segment flowed in the other. This caused problems with transportation simulation because road segments are required to be single direction. To remedy this problem, a new unsplit tool was developed within City Simulator that corrected the direction of flow of one of the road segments before combining the two road segments. Unsplit was used repetitively in the network development process, typically after the removal of danglers and ring roads, as their removal by definition results in two road segments that qualified for unsplitting.

Planarizing – This process is one of the advanced editing tools in Esri ArcMap. It splits road segments where other road segments intersected them.

- Planarizing was used in sequence with unsplit, as unsplit occasionally joined two route segments where a joining route existed.

Merging Divided Highways – This Esri geoprocessing tool identified routes that ran parallel to each other within a set tolerance and merged them into a single line. This tool was used carefully in the pruning process, as often flooding had impacted one side of a divided highway and not the other.

- **I-87** – As the focus of the study was on I-87, which is a divided highway, the merge divided highway tool was not used. This preserved the main I-87 infrastructure, as well as I-95 and other interstate infrastructure, which was key to understanding flooding on these roads.

Removing Segments by Route Class – This step involved pruning road segments by identifying those that were not likely needed by route class and deleting them.

- **I-87** – All classes, except for interstate, U.S., and state highways and ramps were removed from the network. Notably, this meant no local roads were considered in the analysis.

The resulting set of tools and processes created during the road network creation will be a valuable resource in future City Simulator studies of other corridors in North Carolina. The process helped to identify the QC goals for future modeling. Additionally, the process developed unique tools that aided greatly in developing networks in other corridors. As the road network is the key geographic scaffolding for the study, ensuring high quality was essential in its creation.

4.4.3 Calibrating the Travel Model

Calibrating the travel model was completed with two datasets, recorded AADT on a subset of road segments and results data from the NCDOT Statewide 2045 Transcad travel demand model. All data was collected and provided by NCDOT.

The reported AADT data was used to set AADT in the simulation in the base year. The process of population synthesis created the simulation agents and assigned their commutes paths, resulting in a set of AADT for corridor residents. Where there was a discrepancy between the corridor AADT defined by the simulation and the reported AADT, it was assumed that outsider agents were making up the remaining trips. The agents were created and assigned homes and workplaces in phantom buildings on the border of the corridor analysis domain.

The Transcad models were used to corroborate the increase in trips throughout the simulation, which is driven by corridor population growth. The Transcad models results provided estimated trips on major roads in 2017 and 2045. These data were used to calculate a projected growth rate for each road segment. During the simulation, a growth rate was evaluated for each road segment and, where a Transcad estimate was available, compared to the projected Transcad growth rate. Where the simulated growth rate was lower than the Transcad growth rate, additional outsider agents were added to the phantom buildings during the simulation and given commute paths along the routes with under-projected trips.

4.5 Agent Modeling

The simulation represented users of the transportation system as agents. Agent activities that used the transportation system such as commuting were simulated daily. They typically followed the assumption that agents joined the transportation network at the node closest to their home and traveled to the transportation node closest to their destination (i.e., their workplace) using the shortest path, which was derived by the Dykstra algorithm as mentioned in the section on travel modeling above.

4.5.1 Calibration with Data from the U.S. Census American Community Survey

Population, jobs, households, and distribution of commute times at the census block group level were downloaded from the American Community Survey (ACS). These data were used to synthesize the population of agents, distributing them to the MegaBuildings so that the population, jobs, and households matched at the census block group level. Further, the agents' residences and workplaces were distributed, such that the estimated commute time distributions of agents in each census block group matched the reported commute time distribution.

The Transcad models provided by NCDOT (see Section 4.4.3) were used to set population growth rates in the simulation. The models provide population estimates at the traffic analysis zone (TAZ) level. A growth rate for each TAZ was defined using the 2017 and 2045 estimates provided. As new residential buildings were added to the corridor during simulation, the number of people in them was estimated using the growth rate of the TAZ in which they were placed. For example, if a TAZ was expected to grow in population 50% from 2017 to 2045 (29 years) and its initial population was 10,000 people, then in each year of the simulation, the additional population should be equal to 0.5 * 10,0000 / 29 years, or 172 people. In this case, when a new residential building was added in the simulation, the simulator would ensure there were 172 people multiplied by the number of years since the last residential building. This ensured that growth rates matched the Transcad models.

4.5.2 Calibration to Reported AADT

Residents within the corridor comprised some percentage of daily trips in the corridor. Out-of-corridor agents on trips that entered and left the corridor represented a larger percentage. As such, NCDOT's reported AADT in the first year of the simulation were used to further calibrate the model.

To match the trips to the reported AADT, phantom residential and commercial buildings were created, where roads entered/left the corridor. A portion of corridor residents was assigned to workplaces at phantom commercial buildings, while a population of phantom agents was created with residences at the border of the corridor that worked within the corridor. A third set of phantom agents was created that conducted pass-through trips in the corridor, which means that they did not stop in the corridor on their trips. For I-95, in particular, this population was large to match the tens of thousands of trips per day that passed through the corridor daily without stopping.

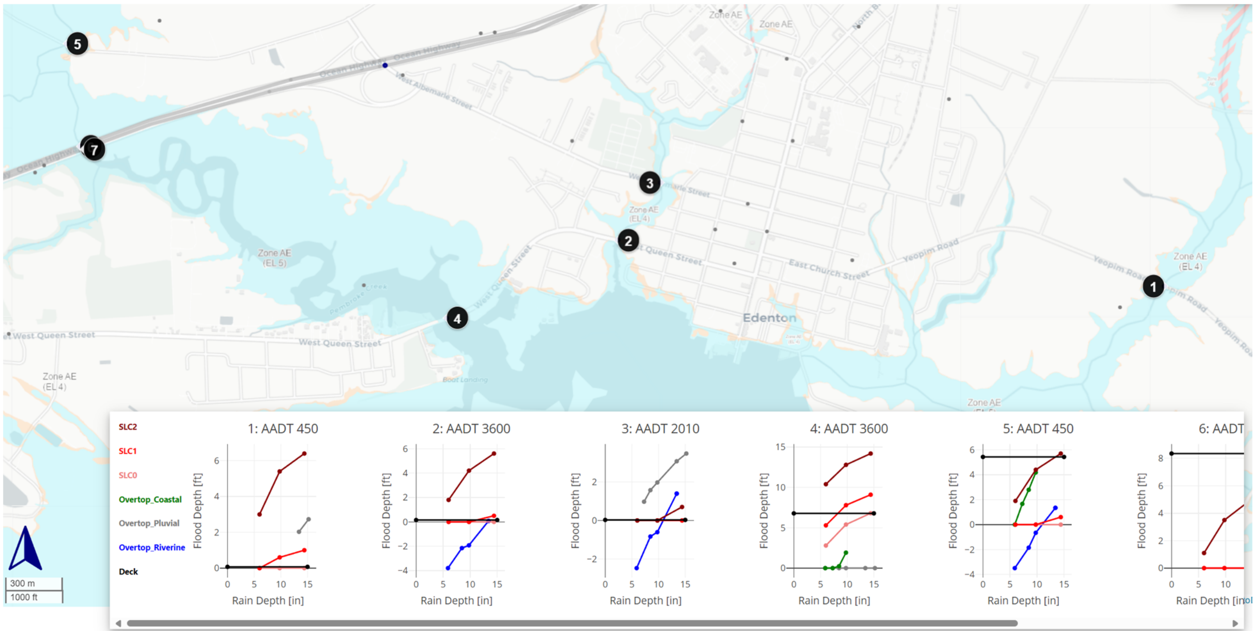
These populations of phantom agents and in-corridor agents that left the corridor daily were synthesized, such that the AADT at each road segment matched reported AADT, while commute time distributions for each census block group matched reported distributions.

4.6 Flood Modeling

Multiple flood modeling datasets were used in the study, accounting for the different types of flooding experienced in the corridor. The flood types included pluvial, riverine, coastal, and tidal. Each flood tracking point in the simulation — culverts, bridges, pipes, and other known flood points on the road system — was assigned flood response curves from each set of models, where applicable.

The flood response curves relate the depth of rainfall to the depth of flooding at the tracking point, assuming that the return period of the rain event matches the return-period of the resulting flood. When a rain event is simulated, the simulator uses the response curves to estimate the depth of each type of flooding at the tracking point. See **Figure 3-13** for an example of a flood response curve.

Figure 4-13: Flood Response Curve Example

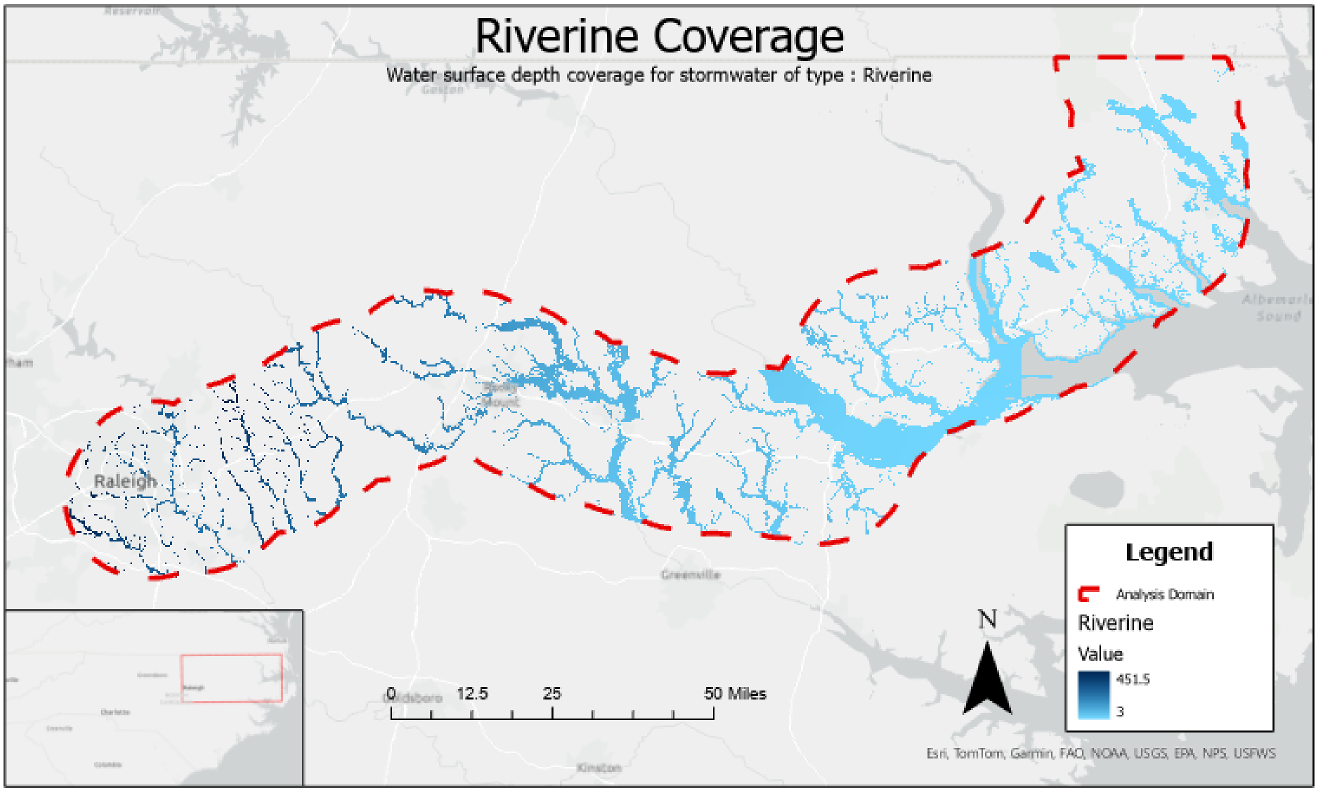


Screenshot of flood response curves in the City Simulator tool. The rain depth to road overtop curve was a key piece of data tying the GIS-based digital twin of the corridor to the modeled flooding response from pre-existing flood models. The curves provide an estimate of the level of overtopping at a specific location on the road network given a certain depth of rain from a storm. The curves were derived from a huge database of flood models described later in this section.

4.6.1 Riverine Flood

Riverine flood occurs when river flow becomes deep enough to overtop banks. A dataset of existing HEC-RAS 1D models was used to build flood response curves at the 1,263 bridges, culverts, and other tracking points in the simulation. The models were developed and maintained by the North Carolina Flood Mapping Program (NCFMP) and provided by NCFMP for use in this study. The return periods used were 10-, 50-, 100-, and 500-year. See **Figure 4-14** for a map of HEC-RAS 1D model coverage.

Figure 4-14: Coverage from HEC-RAS 1D Riverine Hydraulic Models



Riverine, pluvial, and coastal flood models covering the corridor were collected and sampled at the locations of the transportation assets (culverts, bridges, drainpipes, road low points) to create flood response curves that related rain depth to flood depth at each asset. There were HEC-RAS 1D models (gray areas), HEC-RAS 2D Rain-on-Grid models covering approximately 40% of the corridor, and an Advanced Circulation (ADCIRC) model combined with a Wave Height Analysis for Flood Insurance Studies (WHAFIS) model to estimate storm surge and wave action.

4.6.2 Pluvial Flood

Pluvial flood occurs when heavy rainfall ponds, causing localized flooding. Two datasets of pluvial flood models were used in this study:

AtkinsRéalis Pluvial – This is a nationwide set of Telemac-2D models with a 3-to-10-meter horizontal resolution produced by AtkinsRéalis. For this study, the models covered the full corridor and were used to create rain-to-flood response curves at 10-, 100-, and 1,000-year return-periods for each of the stormwater tracking points.

Rain-on-Grid (ROG) – These HEC-RAS 2D models were produced by the NCFMP. Each covers a HUC10 watershed, as shown in the map in **Figure 4-14.** These models are similar in nature to the AtkinsRéalis Pluvial Telemac-2D models but have higher accuracy in their terrain and rainfall input data. Further, they have a more accurate depiction of hydraulic structures, like bridges, which have a substantial impact on model accuracy. The available models covered approximately 52% of the I-87 corridor.

4.6.3 Coastal Flood

Coastal flood occurs with storm surge when heavy wind events push seawater inland. The total water level reached during these events includes both the surge component, as well as impacts of wave action. ADCIRC and WHAFIS models were used in this study to estimate the depth of flooding of these two components. See **Figure 3-14**, where the extent of the model is mapped.

4.6.4 Tidal Flood

The sea level projection mentioned above was used to estimate daily flood levels caused by tidal inundation. The section below covers sea level rise modeling and how tidal flooding was quantified in the simulation.

4.6.5 Summary of Flood Model Types Used in Simulation

When a flood occurs in the simulation, the multiple flood models provide a varying set of flood depth estimates at each water crossing asset, where a water crossing asset is defined as bridge, culvert, or drainpipe. The simulation was configured to take the deepest flood estimate as the expected flood level. The exception to this rule was the AtkinsRéalis pluvial flood model set, which was only used when no other flood models were available for the asset of interest. See the section on avoiding overestimation of flood below for more detail.

In reality, in situations where multiple flood types occur in the same location, compound flooding may be a concern. An example of compound flooding is at the coast in an estuarine environment, where storm surge from a tropical cyclone may meet riverine flood from a rainstorm occurring upstream. The resulting water surface elevation may be higher than any of the models of individual flood phenomena predict. For this reason, the analysis team recommends investigation of compound flooding more closely in future studies.

HEC-RAS 1D models were the majority model type used for flood depth estimation. This was expected because these models depict the collection of water in floodplains over the landscape and therefore likely provided the deepest flood estimates. The remaining models, ROG, AtkinsRéalis Pluvial and Coastal were used in the remaining flood estimates. Flooding outside the Federal Emergency Management Agency (FEMA) floodplain makes up a considerable portion of future floods.

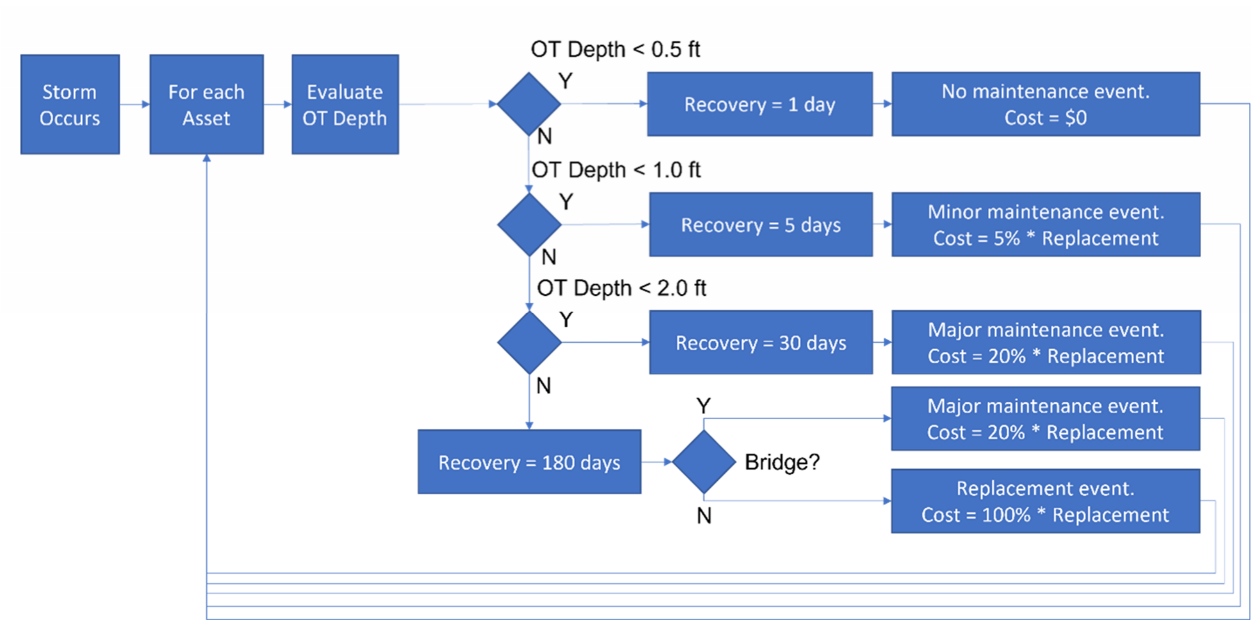
Avoiding Overestimation of Flood

Sensitivity analysis showed that very often the deepest flood estimate came from the AtkinsRéalis Pluvial models, and that when large events occurred, these models estimated upwards of 60% of water crossing assets were overtopped. Qualitative comparison between a simulation of an event similar to Hurricane Florence and drone footage of actual flooding during the same event revealed that 60% was likely a high overestimate. As a result, the simulation was configured to use only the AtkinsRéalis Pluvial flood estimate when no other flood type estimate was available.

4.6.6 Disruptions from Flood Events

When one of the flood models predicts overtopping at a tracking point, the simulator creates a disaster event associated with the tracking point. The level of overtopping determines the recovery duration — the length of time that the asset of interest is non-operational. The rationale is a small depth of flooding may cause perhaps a day or two of traffic disruption and will likely cause no physical damage, while several feet of flooding will likely cause severe damage and even destruction of a road, resulting in months of recovery before the road segment is restored.

Figure 4-15: Simulating the Impact of a Flood on Transportation Assets



The flowchart shows how the simulator assesses each asset when a flood event occurred. If the overtopping (OT) level, as estimated by the flood models described above, exceeds certain thresholds, then the asset is disabled and put into a period of recovery, and a maintenance event is created. The duration of the recovery period and the costs of the maintenance event increased with the depth of overtopping. Table 4-1 specifies the overtopping thresholds, recovery periods and maintenance event costs used in the simulation ***Figure 4-15*** *specifies the overtopping thresholds, recovery periods and maintenance event costs used in the simulation.*

The flowchart in **Figure 4-15** lays out the process the simulator uses for determining if an asset is in recovery and length of recovery. The parameters for the flowchart vary depending on the asset type (bridge, culvert, drainpipe). The specific parameters used for each asset type are shown in **Table 4-1**.

Table 4-1 lists the assets by type and the related overtopping thresholds that trigger each type of event (none, minor, major, replacement). As shown, the recovery period was set to increase with the level of overtopping and varies from one day to 180 days depending on asset type. Also listed are the type of maintenance event required to repair the flood damage and the cost of the work as a percentage of the replacement cost of the asset.

The set of model parameters were set so that the total cost for storm damage in a multi-year simulation that included major storms like Hurricanes Matthew and Florence matched the real spending during a period of the same duration. See the section on cost modeling below for details on this calibration procedure.

Table 4-1: Modeling Parameters for Flood Impacts on Transportation Assets

Simulation of Disaster Events in I-87 Resiliency Study

Asset Class	Overtop Threshold (ft) (ie. Level <= threshold)	Recovery Period (days)	Maintenance Event Type	Cost as percentage of replacement cost (%)
Bridge	0.5	1	None	n/a
	1.5	5	None	n/a
	4.0	30	Minor	3
	Max	180	Major	15
Culvert	0.5	1	None	n/a
	1.5	5	Minor	3
	4.0	30	Major	15
	Max	180	Replacement	100
Pipe	0.5	1	None	n/a
	1.5	5	Minor	3
	3.0	30	Major	15
	Max	60	Replacement	100

4.7 Asset Lifecycle Cost Modeling

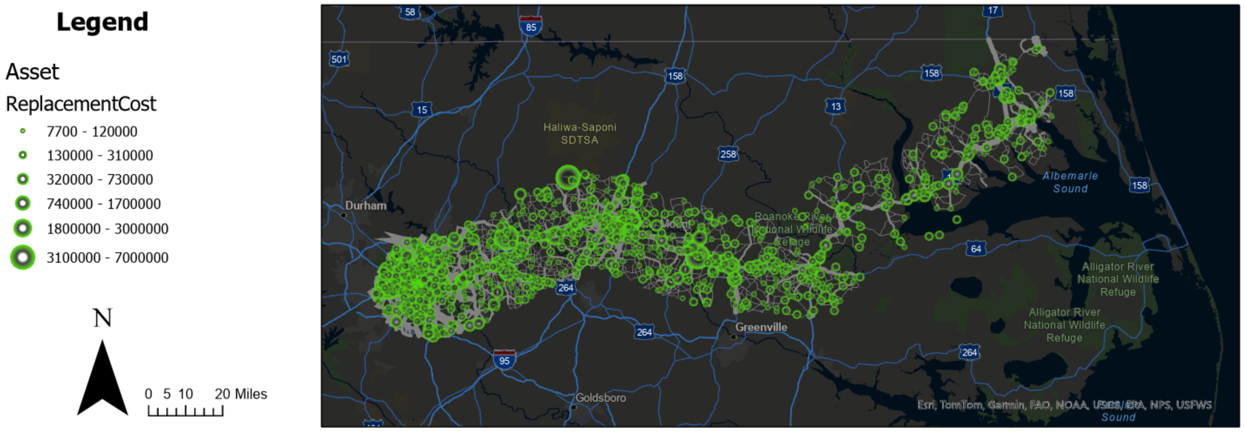
Asset cost modeling was implemented within the simulation using the following methods.

4.7.1 Asset Types

There were approximately 1,600 bridge, culvert, and pipe assets that were cost-modeled in the study. The asset data was provided by the NCDOT from their GIS-based National Bridge Inventory System (NBIS) and non-NBIS databases. For the simulation, assets at and above 54 inches in diameter were considered.

Note that while flood modeling was included for all tracking points, cost modeling was only done for water-crossing transporting assets (culverts, bridges, and pipes). Road maintenance and installation costs were not modeled. **Figure 4-16** shows these assets categorized by replacement cost.

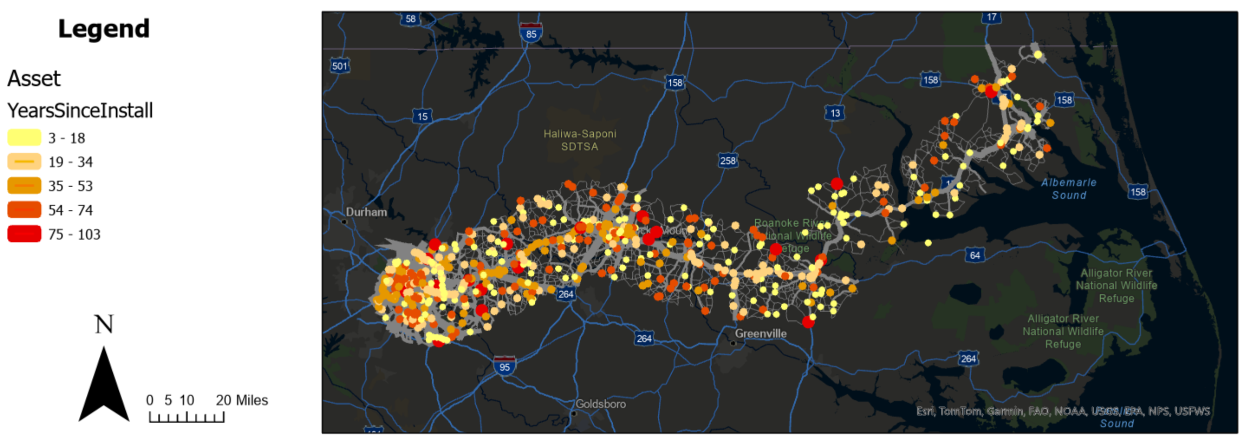
Figure 4-16: Replacement Value — Bridges, Culverts, and Pipes Greater Than 36" Diameter



4.7.2 Condition Decay

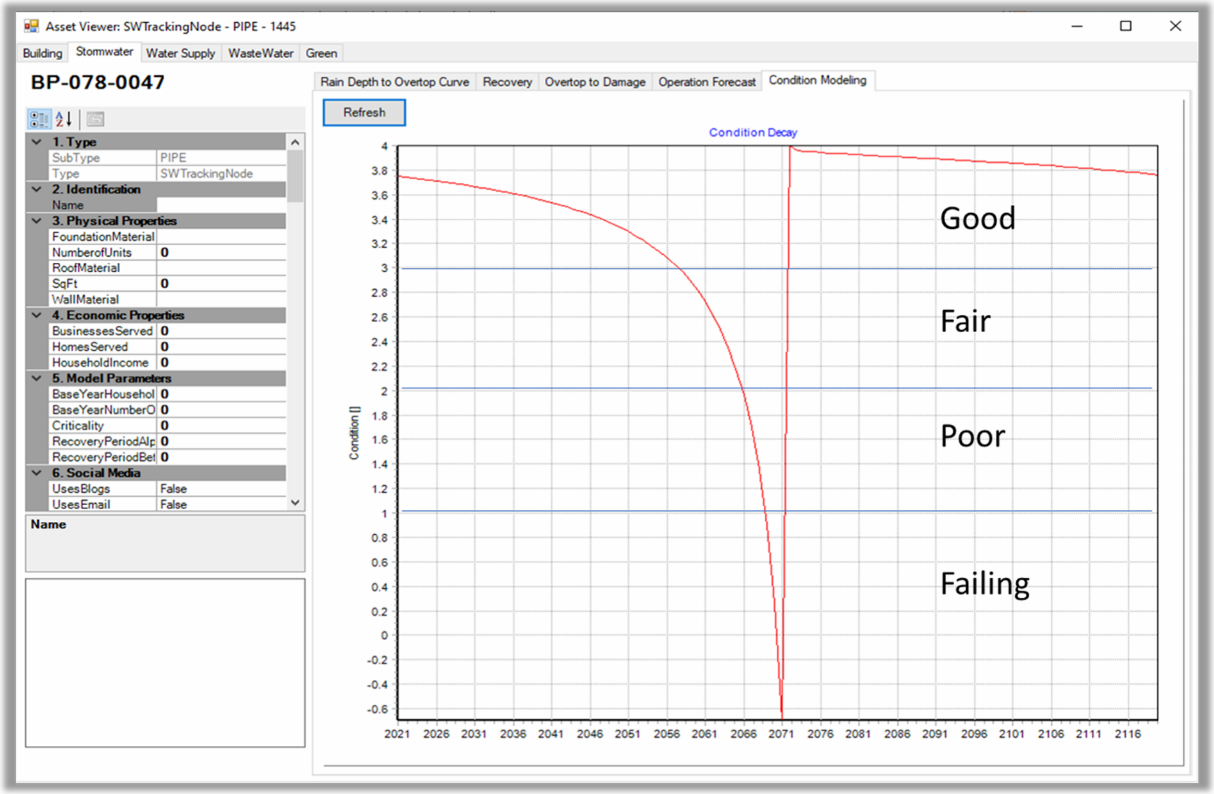
Bridge, culvert, and pipe assets were simulated within the digital twin as stormwater node assets. Each was fitted with a decay model that projects the condition of the asset in the future according to a logarithmic decay pattern. Condition categories included Good, Fair, Poor, and Failing, which are assigned numeric categories of 4, 3, 2, and 1, respectively. These categories were specified to match the existing condition category system used for the non-NBIS assets at NCDOT. **Figure 4-17** shows the assets categorized by their age.

Figure 4-17: Corridor Assets by Years Since Install



The logarithmic decay pattern reduces condition gradually at the beginning of the asset's lifespan and moves to increasingly faster decay toward the end of the lifespan. See **Figure 4-18** or an example.

Figure 4-18: Example of Asset Condition Simulated with a Logarithmic Decay Model in the Simulation



Each asset was fitted with a similar model, and the 2020 condition for the asset was used as an initial condition.

4.7.3 Condition Category System

To start the simulation, initial conditions of the assets were set using the current asset ratings at the time of the analysis (Summer 2022).

A challenge in the simulation was to convert the two different asset rating systems for NBIS and non-NBIS assets into a single rating system. While the non-NBIS assets are classified in a simple good/fair/poor/failing system that corresponds to the whole asset, the NBIS system is multi-part, assigning different condition ratings to the superstructure, substructure, and other systems that make up the bridge.

To solve this, the non-NBIS condition category system (good, fair, poor, failing) was adopted as the system the simulator would use and a method for cross-walking between the two systems was developed to categorize NBIS structures into the four-category system. The crosswalk method is shown below.

Each NBIS structure has the following attributes:

- SR = Sufficiency Rating
- PRI = Priority Replacement Index

- GCR = General Condition Rating: Deck Condition, Substructure Condition, Superstructure Condition, Culvert Condition

The 4-category rating for the NBIS structure was set using the following conditions:

- IF SR 60 OR #PoorGCR > 1 OR SUBSTR <= 4 OR Any GCR <= 3 THEN “FAILING”
- ELSE IF #PoorGCR = 1 THEN “POOR”
- ELSE IF Any GCR in (5, 6) THEN “FAIR”
- ELSE “GOOD”

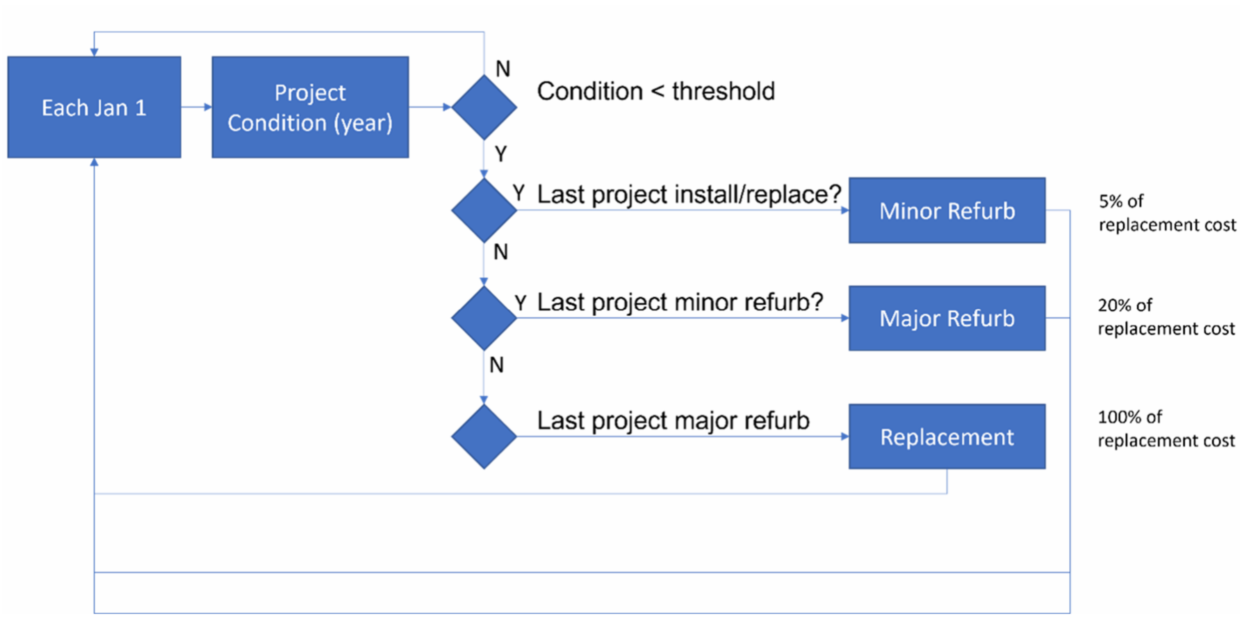
4.7.4 Maintenance Events

Maintenance events were simulated throughout the 80-year simulation. **Figure 4-19** provides a flowchart describing the procedure the simulator uses to insert these events. At the beginning of each year, the asset condition is projected. If the condition crosses into failing, i.e., is less than or equal to 1.0, a maintenance event is created and associated with the asset.

In the simulator, maintenance events can be of several types including minor, major, and replacement events. They are inserted in that order as the asset ages: first minor, then major, then replacement. If no storm-damage occurs on the asset prompting early repair, the simulator adds minor events approximately 30 years since installation/replacement, major events at approximately 60 years since installation/replacement, and replacement events at approximately 75 years since installation/replacement.

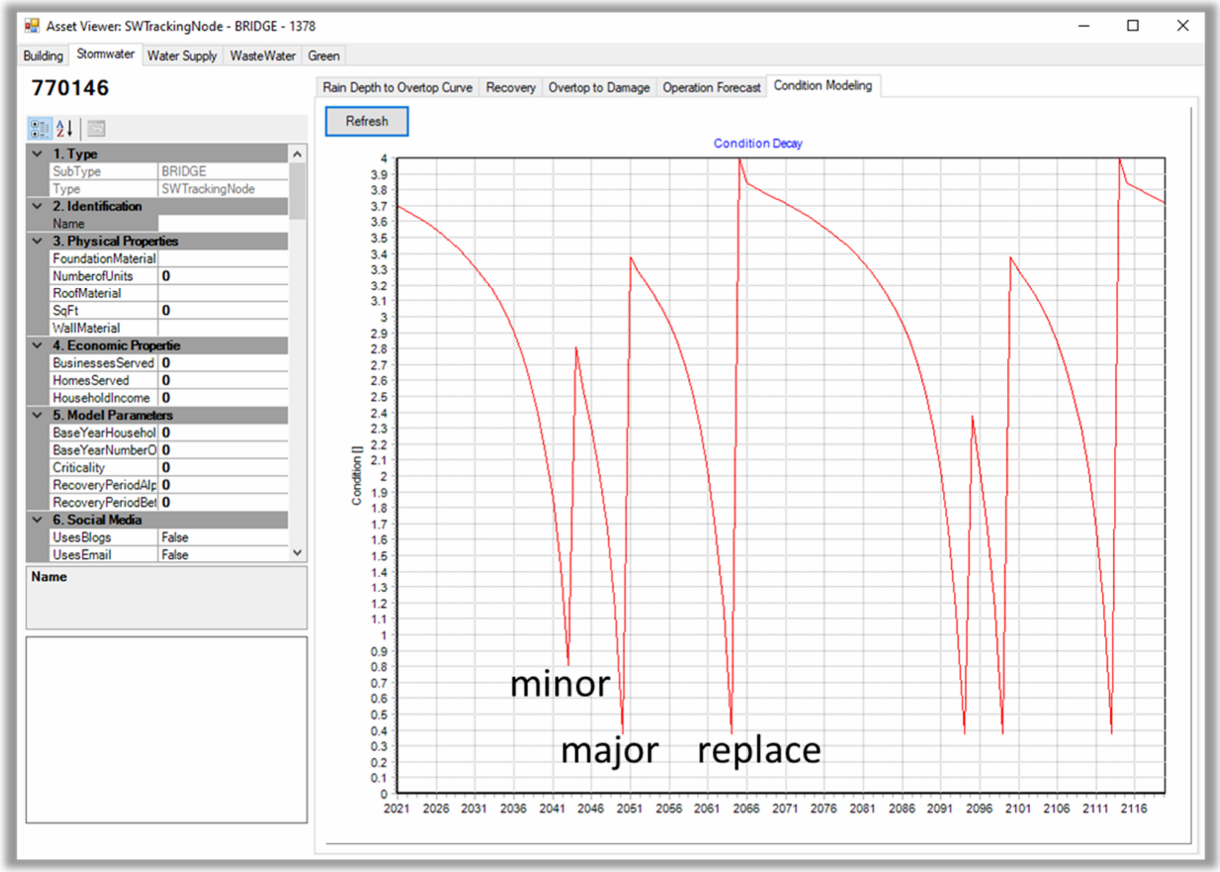
The cost for the event is determined by event type, the replacement cost of the asset, and the type of asset (bridge, culvert, drainpipe). **Figure 4-20** provides an example of the percentages of replacement cost for a generic asset. The actual percentages used are listed in **Table 4-1** above.

Figure 4-19: Maintenance Event Simulation Procedure



The percentages of replacement costs shown as examples of a generic asset. The percentages used were calibrated so that total spending matched actual spending reported in the NCDOT SAP database (see discussion below on calibration and Table 4-1 for a list of the percentages used in the study).

Figure 4-20: Water Crossing Replacement Events



The simulation inserts minor, major, and replacement events for each water crossing asset (bridge, culvert, pipe) in the corridor. These events occur when the projected condition of the asset falls below 1.0 or failing condition.

4.7.5 Cost Modeling

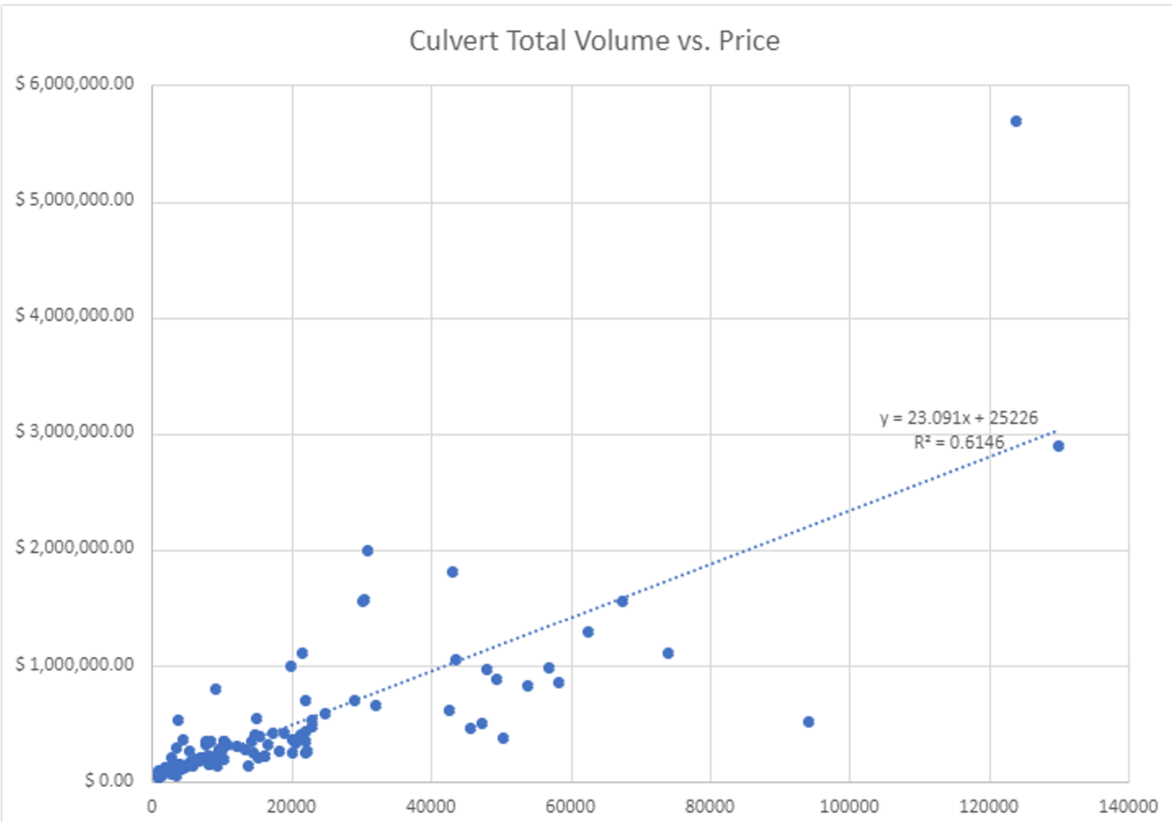
As described in Section 4.7.4, maintenance and replacement events were assigned costs as a percentage of the replacement cost of the asset. Multiple methods were used to estimate replacement costs depending on asset type:

- **NBIS asset replacement costs from Statewide Transportation Improvement Program (STIP)** – NBIS asset replacement costs were developed from a separate bridge study conducted as part of the NCDOT STIP.
- **NBIS asset replacements costs not estimated in STIP** – For those bridges where a STIP replacement cost was not provided, the deck area for the bridge was estimated by multiplying the bridge's length by its width (L x W). A per square foot value of $145 was used to convert the area of a replacement cost.
- **Non-NBIS assets** – A linear regression-based formula was developed for replacement costs of the non-NBIS assets (culverts and drainpipes) from a record of past bids for asset replacement focused on a subset of non-NBIS culverts and drainpipes throughout the state (see **Figure 4-21)**.

The analysis estimated the "total hydraulic volume" of each culvert and pipe as the product of the number of barrels and the hydraulic volume (hydraulic area multiple by the average barrel length). A linear regression of total hydraulic volume to proposed cost revealed a relationship of:

Replacement Cost = $25,226 + Hydraulic Volume (cu. ft.) * $23.091.

Figure 4-21: Regression of Past Bids to Estimated Replacement Cost of Culverts and Bridges vs. Hydraulic Volume



Culvert Volume = Length * Area * Num Barrels.

To estimate replacement costs for all non-NBIS assets in the corridor, a state-wide record of past bids on non-NBIS assets was used to estimate a relationship between hydraulic volume of assets and replacement cost.

4.7.6 Calibration of the Cost Model with Actual Costs from NCDOT SAP system

Both the projected maintenance costs and storm-caused costs were calibrated against a query from the NCDOT SAP system, which tracks actual historical spending in both categories of cost. A query was made of all costs on bridges, culverts, and pipes in the I-87 corridor for the years 2010–2022 (13 years).

In a previous study, these costs were summarized into average annual costs for master plan-triggered and condition-triggered maintenance ($3.97M per year) and repair of assets due to flood damage from storms ($1.32M per year). In the 2010–2022 period, storm damage costs including costs incurred during Hurricanes Matthew and Florence and were $17.1M total. Due to the similarities between the two studies, we chose to use this same methodology to guide our approach for I-87.

The implicit assumption made in this calibration was that the total non-disaster spending on bridge, culvert, and drainpipe assets at 54” and above in diameter is equal to the simulated minor/major/replacement-based spending in the simulation. Further, spending on storm-caused damage is implicitly assumed to match disaster funding spending rates reported historically.

To ensure this assumption is true within the simulator, the 2010–2022 historical rainfall was used to drive the simulator over a calibration period of the same duration. Model parameters including overtopping thresholds, types of maintenance events triggered by overtopping events and the cost of these events as a percentage of replacement cost were initially guessed and then adjusted until the average annual maintenance spending matched the historical and storm spending average. The calibrated parameters are listed in **Table 4-1**.

An important note is that a duration of maintenance events was introduced, which split spending on larger projects over several years. This mirrors how spending actually occurs and resulted in a closer match to the historical spending. The pattern used to estimate maintenance event duration specified:

- If triggered by master plan:
  - If the planned cost is greater than $100M, 10 years
  - If the planned cost is from $10M–$100M, eight years
  - If the planned cost is from $5M–$10M, six years
  - If the planned cost is from $1M–$5M, four years
  - If the planned cost is less than $1M, two years
- If triggered by flood:
  - Four years — assumes a replacement occurs
- If triggered by maintenance:
  - Two years

4.8 Sea Level Rise Modeling

As mentioned in Section 4.2.3 on projecting future conditions, the mean sea level is projected to rise in Duck, NC between 2.62 feet and 7.05 feet by 2100 (NOAA SLR Viewer). This will cause both chronic disruptions from nuisance flooding during high tides and acute disruptions from storm surges exacerbated by higher mean sea levels.

In the simulation, the rationale for modeling SLR was to produce a daily projection of high tide levels and use this to estimate the impacts of both tidally driven nuisance flooding and tidally influenced storm surges when these events occur.

4.8.1 Simulating Nuisance Flooding

In the simulation, each road segment was assessed against the projected high tide level each day to simulate nuisance flooding events. When flooding occurred, a disaster event was recorded for the affected asset.

Note that buildings were not assessed within the simulation, only road segments. Assessing impacts on buildings can be incorporated into future simulations, if desired.

A key measurement that impacted the simulation was deck elevation, the elevation of the road segment above which overtopping and road disruption occurs. To estimate this elevation, each road segment was measured for elevation at a 30-meter interval, or 98.4 feet. The minimum elevation along the road segment was retained as the overtopping elevation of the road segment. Through this approach, the simulation implicitly assumed that if any part of the road segment had overtopped, then all trips were disrupted along the road segment. This is most likely a conservative assumption, as a percentage of real trips are likely to use a portion of a road segment. However, to ensure that any level of disruption was captured in the simulation results, the assumption was retained.

The digital elevation model (DEM) used was the so-called “ribbon” provided by NCDOT, which is a high-detail (10-foot horizontal resolution) Light Detection and Ranging (LiDAR)-based DEM with data only along the road segments in the NCDOT Linear Referencing System.

Recognizing that high tide levels that do not overtop road segments still have an impact by inundating the road structure with seawater, a “freeboard flooding” metric was also introduced to the simulation. This metric recorded disruptions the same way as the overtopping metric but set the overtopping threshold as the road segment’s overtopping threshold minus two feet. The simulation results present both the nuisance flooding metric and the freeboard flooding metric. Disrupted trips presented in Chapters 5 and 6 include both metrics.

4.8.2 Simulating Sea Level Rise Impact on Storm Surge

Acute impacts of rising sea levels will happen in the future when storm surge sits atop elevated mean sea levels. As mentioned above, in the section on coastal flood modeling, an ADCIRC model was combined with an EPA WHAFIS model to estimate the depth of flooding in the coastal region of the corridor for 10, 50-, 100-, 500-, and 1,000-year events. NOAA Atlas 14 was then referenced to find the equivalent rainfall for each return period. See Section 4.2.1 for more detail on rain modeling.

The depth grids produced for each return period were then sampled at the low points of each road segment. The result was an overtopping curve for each road segment that related rain depth of an incoming storm with overtopping depth above the elevation of the top of road at the sampling point. When large storm events occurred during the simulation, these curves were used to rapidly estimate overtopping depths at each road and thereby estimate disrupted trips.

The ADIRC+WHAFIS model-based estimates were configured with the assumption of mean sea level in 2020 as a boundary condition. As the sea level rose in the simulation, this assumption causes the inundation estimates for both chronic and acute flooding to become less accurate — i.e., they are underestimated.

A more accurate estimate could be found by re-running the ADCIRC+WHAFIS models with a varying range of mean sea level and then using the appropriate version of the model based on the estimated mean sea level at the time of the future event. As running multiple ADCIRC+WHAFIS models was beyond the scope of this study, a more approximate method was used to estimate inundation during future storms. Namely, in each year, the projected increase in mean sea level was calculated. If a storm surge event occurred in that year, the depth of inundation in the flood response curve was augmented with the estimated SLR projection for the year.

4.9 Heat Impact Modeling

As temperatures increase with climate change, impacts on the road and rail system are expected. In the case of asphalt road segments, a common problem is flushing (see **Figure 4-22**), which occurs when temperatures are high enough during the day to destabilize the bitumen, allowing aggregate to move within the road. The threshold temperature is approximately 85°F.

When this situation occurs, vehicle tires then grab onto the aggregate. As the situation occurs over and over as the road asset ages, the ratio of bitumen to aggregate increases. High bitumen density is dangerous because it reduces skid resistance. To keep the road safe, roads with this problem often operate at reduced speed limits.

Figure 4-22: Flushing Impacts

https://www.abc.net.au/news/2018-01-06/how-heat-affects-roads-trains-and-planes/9308342)

High heat can cause other problems with transportation infrastructure as well. Concrete road segments, for example, expand in high heat and can buckle. While this is known and accounted for in current road design with gaps between the concrete sections, the gaps are designed for a certain maximum temperature, which is projected to be exceeded in future years. Appendix A. of this report provides links to multiple sites and articles that go into future detail on problems that can occur within increasing heat.

For the purpose of simulating disruption within this study, flushing was assumed to be treatable as a generic disruption event and applicable to all road segments, regardless of if they are asphalt, asphalt and concrete, or concrete only.

4.9.1 Probabilistic Heat Event Simulation

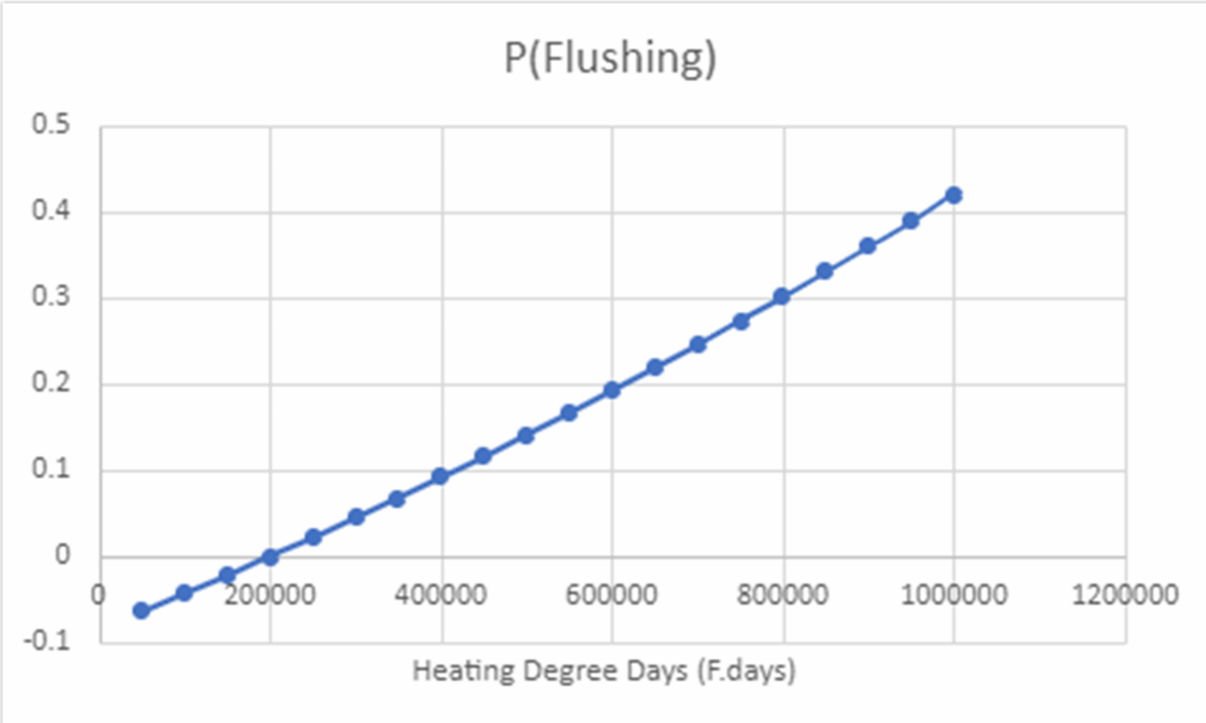
In each quarter, the heating degree days for each road segment were evaluated since the last maintenance event on the road segment. For example, if the last maintenance event occurred 10 years before the current time step in the simulation and the average atmospheric temperature was 85°F, the heating degree days are 10 years * 365 days/year * 85°F = 310,250 °F-days. The simulator includes projected maximum temperature from the LOCA dataset (see section above on climate stressor projections) and the latest maintenance event on each road segment. These were used to evaluate the heating degree days for the road.

A comprehensive literature review (see Appendix A) revealed multiple methods for simulating asphalt degradation over time, including methods that leverage artificial intelligence and machine learning. As one of the objectives of the study was to simulate disruption with minimized computational requirements, the simulator was configured with a probabilistic model, which linked cumulative heating degree days with probability of a flushing-related traffic slowdown initiated by NCDOT or other relevant DOTs.

The model assumes that if the trigger atmospheric temperature is 85°F, that flushing would start approximately 1/3 of the typical 20-year lifespan of the asphalt, or at about 6.66 years. This would give a threshold of 85°F * 6.66 years * 365 days/year = 206,833 °F days. A probability function was then developed that assumes that when the road reaches this threshold the probability of flushing becomes non-zero and increases as a power function until, at lifespan of 20 years, the probability of flushing is approximately 20%. **Figure 4-23** shows the function. The formula for the function is:

P(Flushing) = 3 ^ ((Cumulative Deg Days - 200000) / 100000/25) - 1

Figure 4-23: Probability of Flushing as a Function of Cumulative Heating Degree Days



4.9.2 Disruptions from Heat Events

The following example illustrates how the probabilistic heat event simulation proceeds. In the first quarter of 2040, for a single road segment, the simulator might find that the last maintenance event occurred on 1/1/2027, or 13 years prior. With increasing maximum temperatures, the cumulative heating degree days at this point are 425,000 °F-days. The probability function says that the probability of an unsafe road due to flushing at this point is 12%. The simulator then uses a random number generator to generate a uniformly distributed random number between 0 and 1, say 0.05. Since the number is less than 0.12 (i.e., 12%), the road segment is assumed to be unsafe, and a disruption event is recorded for the road segment.

An important note is that the probability model allows for road segments to age beyond the 20-year typical lifespan, with probability of flushing increasing with age. This accommodates any simulation scenarios where maintenance budgets are reduced and need to be stretched in the future.

4.9.3 Potential actions to reduce flushing risks

The literature review and discussions with pavement subject matter experts found multiple actions that can create resilience to flushing. They include:

- **Adjusting binder in asphalt mix:** the primary approach is to design the asphalt mix with a binder that will enable the mix to stand up to expected maximum temperatures. NCDOT uses the so-called Superpave asphalt mix design method to develop asphalt mixtures, where the binder added to the mix is designed to a target design temperature. To adapt to climate change and related increasing temperatures, projected maximum temperatures from global climate models should be used in each pavement design process into the future. Steadily increasing the robustness of the asphalt mix by using higher temperature binder in each successive replacement will likely incur higher costs, but these costs are expected to be manageable particularly as they will allow avoidance of traffic disruption related to flushing.

- **Replacing asphalt more frequently:** as flushing tends to occur as the asset ages, earlier replacement will provide a way to avoid flushing problems and related traffic disruption. This approach will result in higher costs, of course, but these costs are expected to be manageable when compared to disruption costs that may result from flushing. It is worth noting that discussion with NCDOT pavement experts revealed that often replacement occurs more frequently than the 20-year period used to define the flushing probability model, indicating that NCDOT is likely avoiding flushing in its primary route systems already.

4.10 Freight Impact Modeling

For the purpose of this study, only truck disruptions were analyzed however, this study can be expanded to analyze the impact of extreme weather factors such as heat, sea level rise etc. on other modes of freight delivery like ports, rail and aviation. Of particular interest in the simulation was the tonnage of freight disrupted by future climate change. Trips were disrupted within the simulation by flood and heat events (as described above in the flood modeling and heat modeling sections). The rationale for estimated freight disruption was to use the reported AADT specifically for trucks and then convert this to a tonnage by using an average tonnage per truck estimate. Note that these calculations did occur in the simulation as part of the standard simulation configuration, but as freight movement was not included in the final set of study questions, the specifics of the freight simulation were not reported in the findings of this report. These results can be explored in future studies.

4.10.1 AADT Truck Metric

In the same way total trips disrupted were estimated using the NCDOT AADT metric for each road segment, freight trip disruption was estimated by using the AADT truck trip estimates provided in the same dataset. This method was determined preferable to an assumed percentage of total trips because freight was transported on a specific set of roads within the corridor.

The tonnage of freight was estimated by multiplying the number of missed truck trips by the estimated average tonnage of freight in a truck. For this study, an estimate of 20 tons of freight was used per truck. This was taken from the Truck Geeks website (Truck Geeks, 2021).

4.10.2 Adaptation Approach

The resilience-focused adaptation actions implemented in the adaptation/mitigation scenario described in the Adaptation section of this report largely focused on general improvement of the transportation for all trips. As such, the improvements made such as elevating bridges and culverts proportionally reduced disruption to freight as well. On the roads supporting freight travel, reductions in disruption carried over to freight transportation as well and is reflected in the final results.

4.11 Disruption to Disadvantaged Populations

Disadvantaged populations exist throughout the I-87 corridor. A primary concern is the level of access these populations have to sustenance facilities. Within this study, these facilities included gas stations, stores, emergency care, and emergency shelters.

Ideally, disadvantaged populations have access to multiple options for each of these facility types, through multiple redundant routes. The rationale in this study was to investigate the level of accessibility disadvantaged populations had at a detailed scale, thereby allowing for pinpointing road segments that should be improved to increase access. This information can be used by NCDOT planners and engineers for prioritizing future expenditures aimed at increasing robustness of the transportation system.

4.11.1 Approach

The 2019 ACS poverty and minority data — at the census block group level — were used to define the census block groups with disadvantaged populations. The method outlined in the NCDOT community impact assessment guidance method was followed. This method specifies that a disadvantaged population census block group is one with more than 25% of the population at or below the poverty level (**Figure 4-24)**, and/or 50% of the population or more are in minority groups (**Figure 4-25**) as shown in **Figure 4-26**.

Figure 4-24: Percent of the Population in Poverty

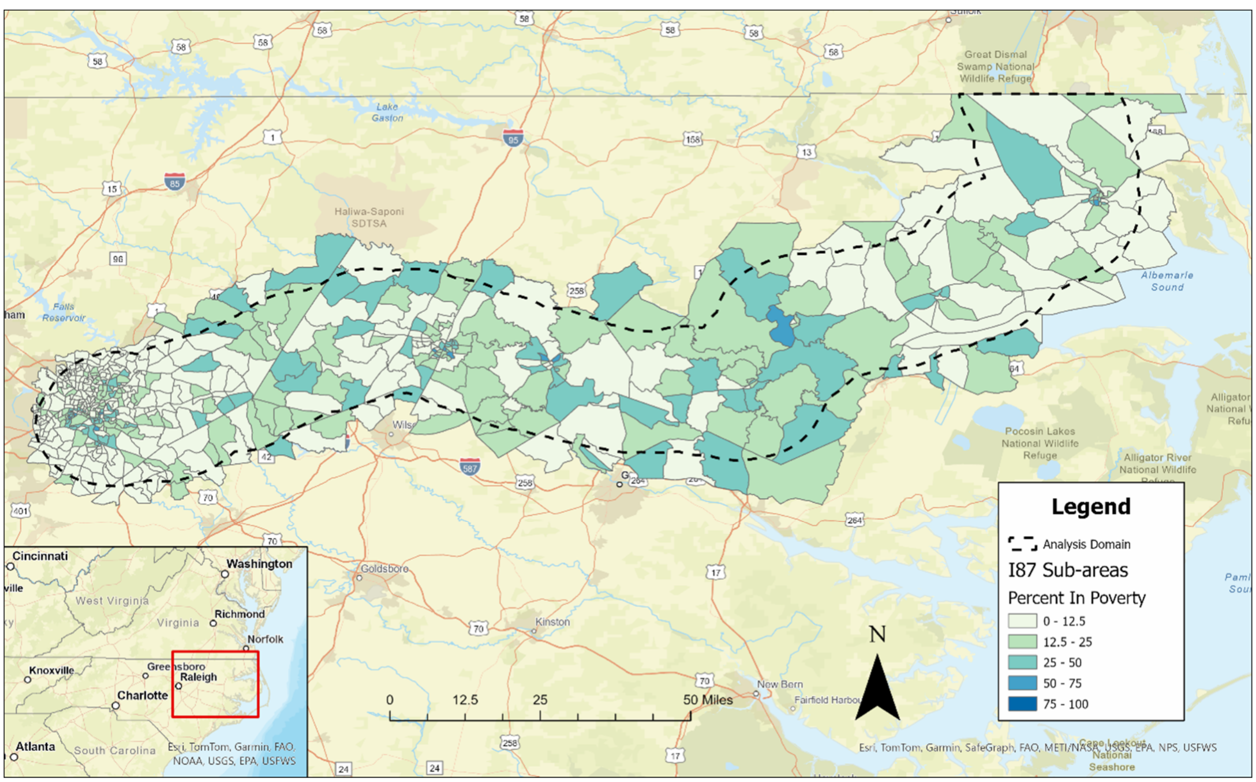


Figure 4-25: Minority Percentage

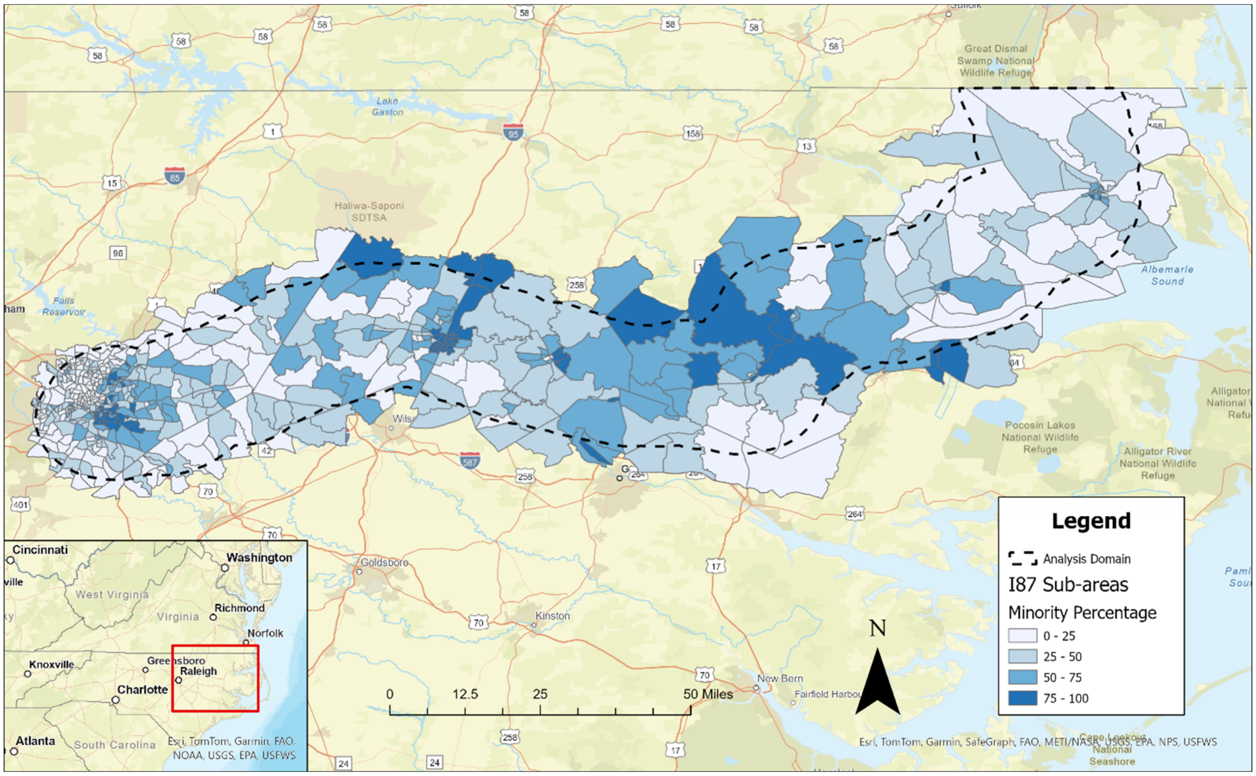
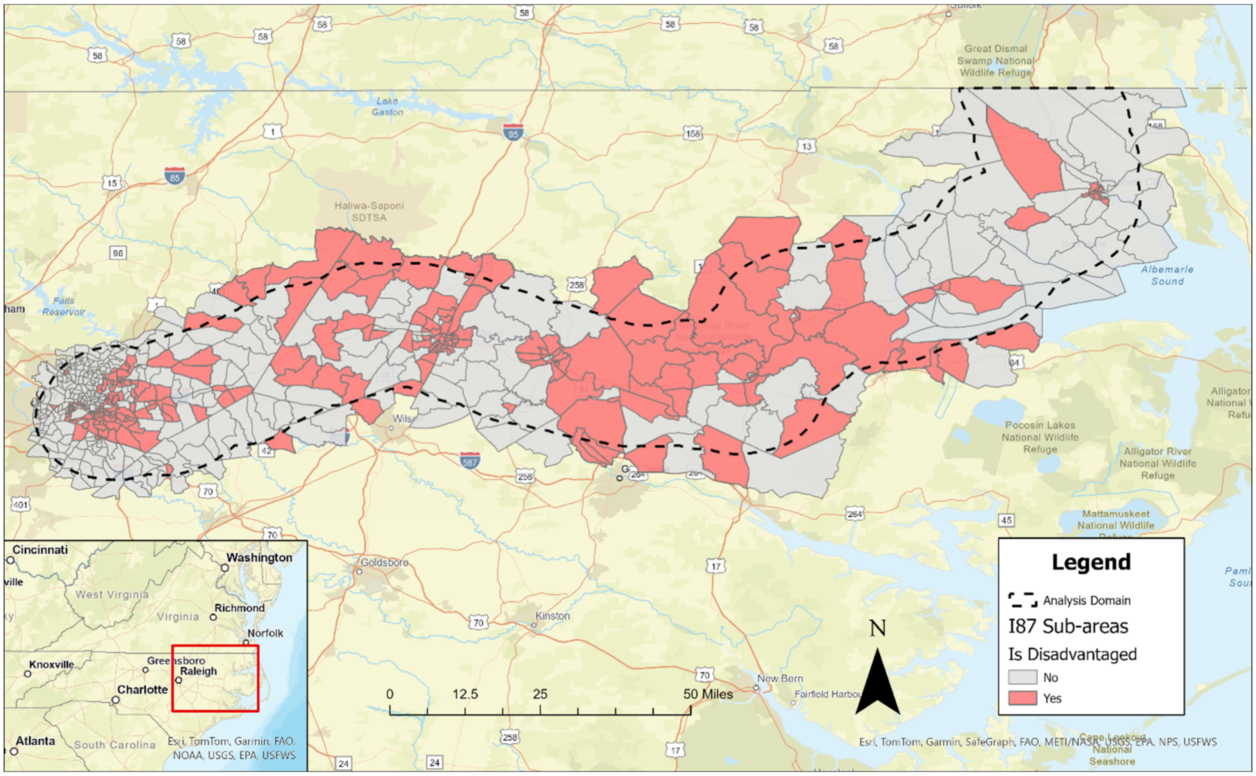


Figure 4-26: Disadvantaged Census Blocks



4.11.2 Inaccessibility Index

A sustenance inaccessibility index was developed to quantify the level of access census block group populations had to the road system when flooding occurred (see **Figure 4-27** and **Figure 4-28**).

As described above in the section on MegaBuildings, each road segment in the corridor had a residential building created at its geographic centroid that represented the people who lived on the road. Further, a set of sustenance facilities of category: shop, gas station, emergency care, and emergency shelter — using schools as a proxy— were acquired from the open street map (OSM) buildings dataset. These structures were reported by individuals to this open-source dataset and comprised of an incomplete but valuable approximation of all commercial buildings in the corridor.

Routes from each MegaBuilding to the closest three sustenance facilities of each category were defined. Then, the water crossing assets along these routes (bridges, culverts, pipes) were found. With these relationships established, the sustenance inaccessibility index could be calculated.

The index was then evaluated for each road segment as the product of a redundancy factor and a flood risk factor summed over the four sustenance facility categories.

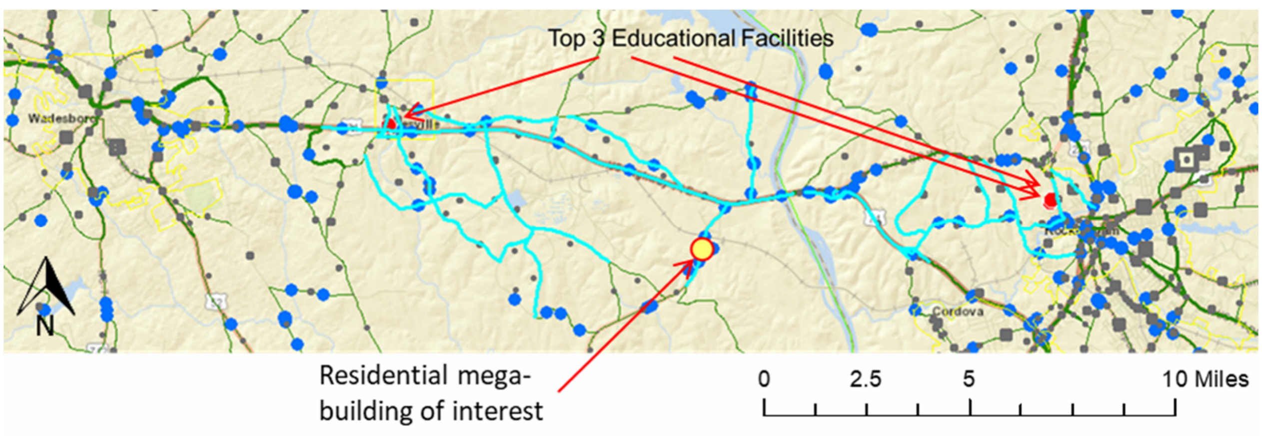
The redundancy factor was defined as the total road length from the MegaBuilding to sustenance facilities divided by the number of road segments. This factor increased as the total road length to sustenance facilities increased and as the number of road segments decreased. Therefore, if a MegaBuilding was far from sustenance facilities and only had single road segments pathways, then inaccessibility is extremely high. Conversely, if the MegaBuilding was close to sustenance facilities and there were comparatively many road segments (implying high redundancy of routes), then inaccessibility is very low.

The second factor was the flood risk factor, which estimated the potential for overtopping the routes had during major flood events. The average overtopping level for the 2020 500-year event was evaluated across all of the water crossing assets on the routes to sustenance facilities. Higher overtopping potential had the effect of increasing the inaccessibility index (**Figure 4-27** and **Figure 4-28**).

Valid Road Segments

The inaccessibility index was evaluated for each valid road segment, where a valid road segment was defined as roads with open access. As mentioned, in the MegaBuildings section above, controlled access roads such as interstates did not have a representative MegaBuilding, and their accessibility was therefore not considered.

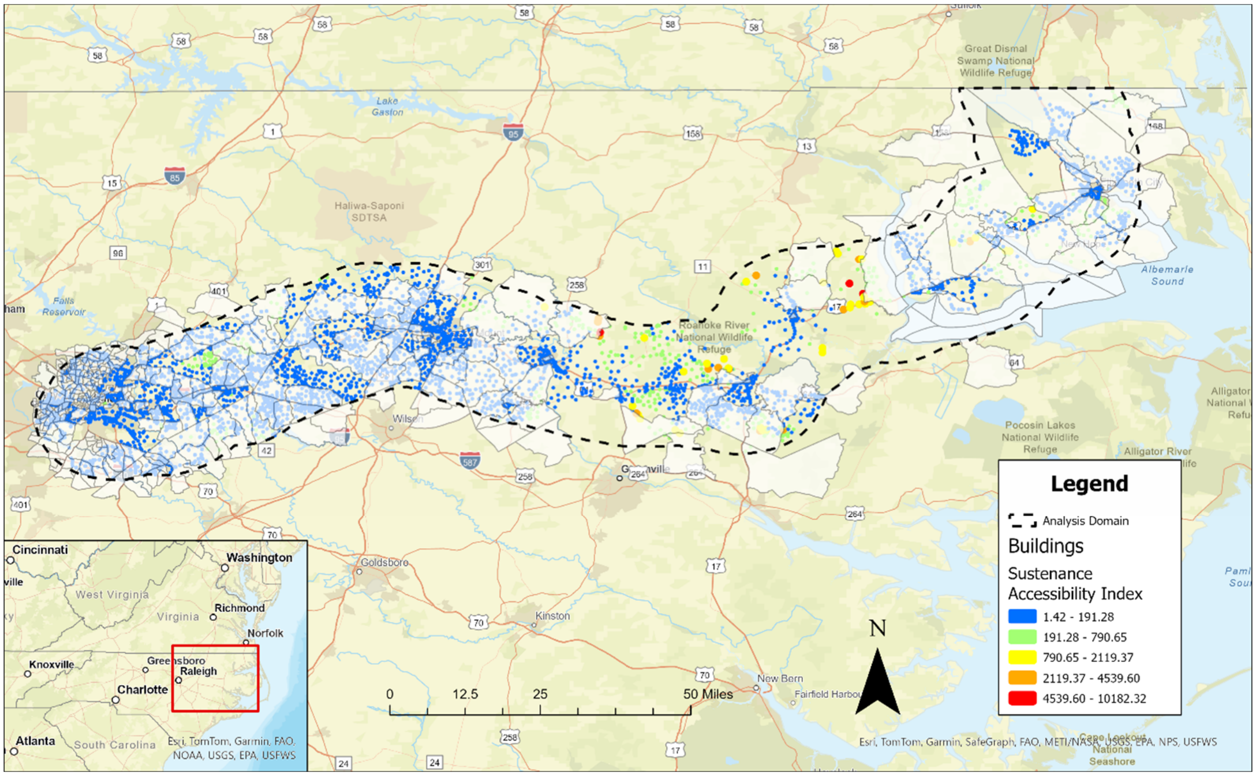
Figure 4-27: Sustenance Inaccessibility Index



$$Sustenance\ Inaccessibility\ Index = \sum_{Categories} \frac{1}{N} \sum_{N\ Facilities} \frac{1}{M} \sum_{M\ Routes} \frac{Road\ Length}{Num\ Road\ Segments} * \frac{OT_{500year}}{10}$$

Notes: Inaccessibility was evaluated for each residential building in the disadvantaged population census block groups across the corridor. Sustenance facilities (red dots in figure) were identified for each residential building (yellow dot in figure) and the routes from the residential building to the sustenance facility were identified (cyan lines). The sustenance inaccessibility index was then defined as the average of a remoteness/redundance index multiplied by a flood risk index for each route to each facility over the sustenance facility categories. The index was low when there were many sustenance facilities close by with many redundant routes and few flooding locations (blue dots) along the routes. High inaccessibility occurred when there were few sustenance facilities close by with few routes to them and high flood risk along those routes.

Figure 4-28: Sustenance Inaccessibility Index — Larger View



Inaccessibility across the corridor in disadvantaged population census block groups (the unmasked areas) shows that the rural areas and areas on perimeters of municipalities are the primary concern. See Figure 4-27 for detail on the method for calculating the index.

4.11.3 Simulating a 500-year Storm Impact on Disadvantaged Populations

The inaccessibility index was used to rank disadvantaged population road segments by their level of inaccessibility. The top 10 least accessible road segments in each division are presented in Chapter 5.

To provide a better understanding of how NCDOT can improve the situation for disadvantaged populations, the specific water crossing assets (bridges, culverts, drainpipes) with high flood risk that impact accessibility were identified.

Chapter 5 presents the results of this assessment. The mapping for the top disruptive assets in each division and listing of the disrupted trips for the top 10 by category along with their joint disrupted trips index is included as part of the web app deliverable. This set of metrics and those for all assets in the simulation is available through the City Simulator database provided as a deliverable for the project and through the Esri StoryMap.

4.12 Impacts to Critical Facilities

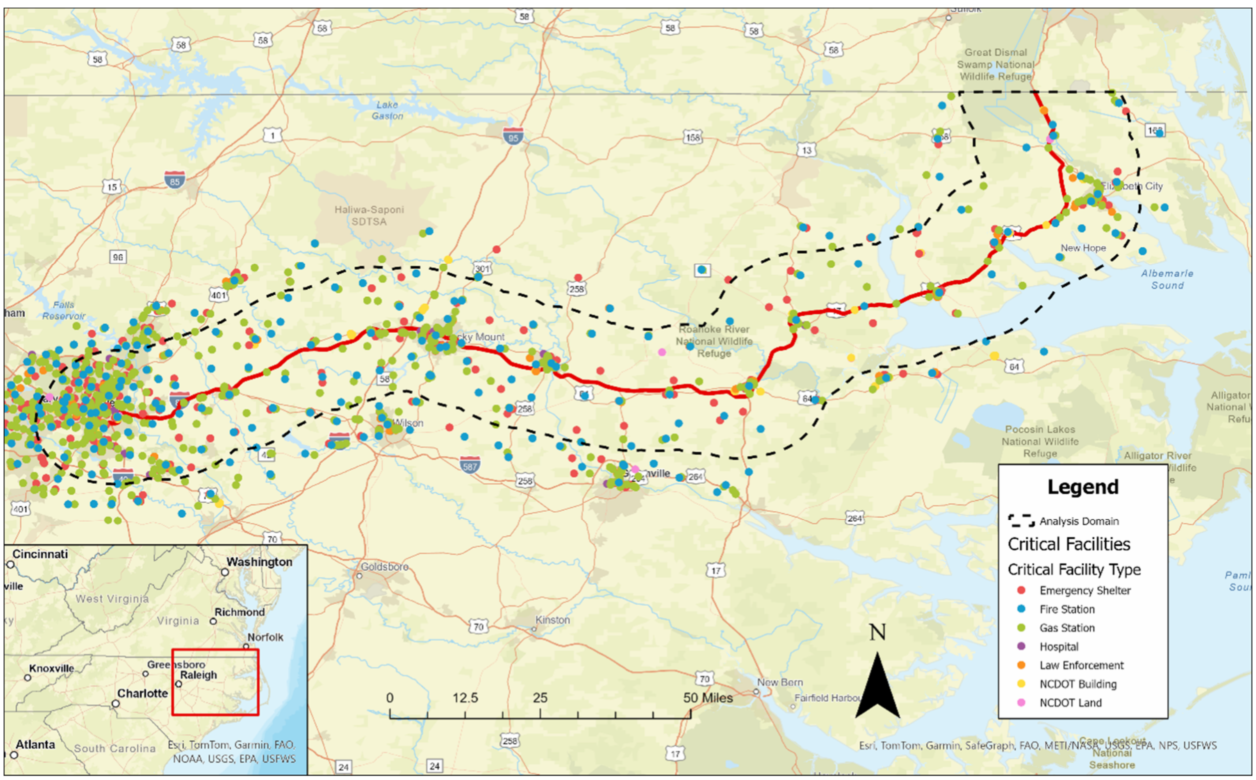
In this study, critical facilities considered included hospitals, emergency care, stores, schools, NCDOT buildings and land, fire stations, and police stations within the study area. These facilities encounter climate change impacts in the sense that the transportation paths providing access to them can become compromised as floods and heat events become more extreme.

The rationale was similar to the approach taken that assessed disadvantaged populations. That is, an inaccessibility index was used to quantify redundant routes and their flood risk to each facility from surrounding streets. The climate change impact to the water crossing assets supporting the routes evaluated the degree to which the facilities will become even less accessible in the future.

4.12.1 Approach

Critical facility locations were found through the open street map buildings (OSM Building) as shown in **Figure 4-29**. Point locations were downloaded for the full corridor for each of the facility types. A crosswalk was developed to aggregate OSM business and occupancy types to the target categories. NCDOT assets including NCDOT-owned land and NCDOT major facilities were also included in the analysis as critical facilities.

Figure 4-29: Critical Facilities



Critical facilities across the corridor were compiled from a combination of the open street map (OSM) publicly available dataset and several GIS datasets provided by NCDOT.

In addition to the OSM data, GIS data specifying the locations of police and fire stations, emergency care, and NCDOT facility and building assets were included. **Figure 4-29** presents all facilities used in the assessment.

4.12.2 Inaccessibility Index

The critical facilities were assessed for two factors, remoteness-redundancy, and overtopping risk.

Remoteness-redundancy was defined as the length of road within the critical facility's service area divided by the number of road segments. For critical facilities with short roads and high network density in their service area, the remoteness-redundancy factor is therefore low. Conversely, for critical facilities with relatively long access routes and low density the factor is high.

Overtopping risk was defined as the average overtopping depth above the top of road during the 2020 500-year flood level across all water crossing assets (bridges, culverts, pipes) in the critical facility's service area.

The two factors — remoteness/redundancy and overtopping risk — are similar to the factors used in the disadvantaged population assessment. The difference in the approach is that the focus is on routes from surrounding residential buildings to the critical facility in question, as opposed to routes from each residential building to multiple sustenance facilities.

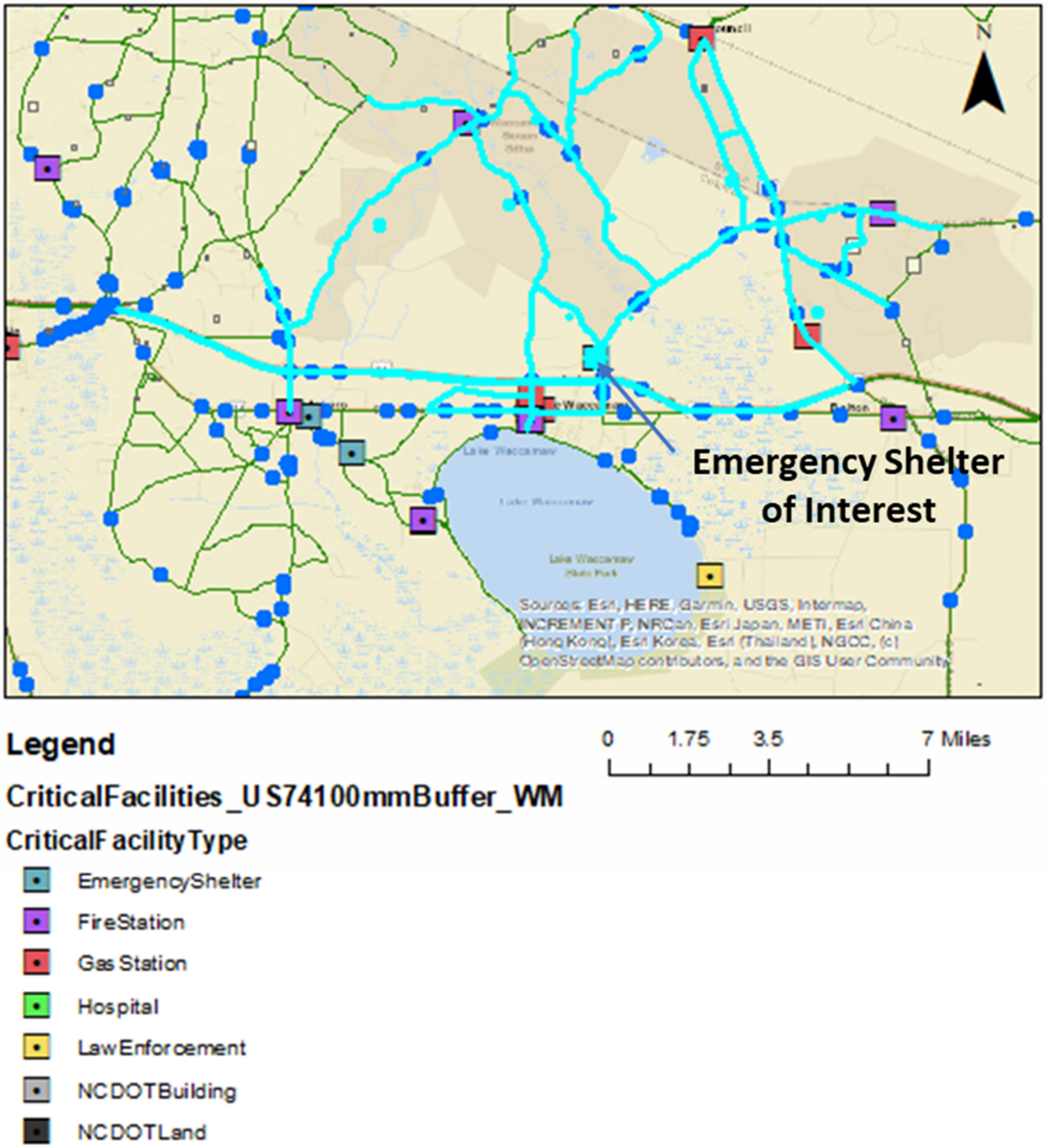
The service area for each critical facility (see **Figure 4-30**) was defined by selecting nearby residential buildings such that the total number of households in the buildings meets or exceeds set threshold for the facility type. The thresholds of households were set as follows:

- Hospital/Emergency Care — 100,000 households,
- Emergency Shelter — 5,000 households,
- Fire Station — 5,000 households,
- Gas Station — 5,000 households,
- Law Enforcement — 50,00 households,
- NCDOT Building — 1,000 households,
- NCDOT Land — 1,000 households.

The households' thresholds were estimated based on the prevalence of the facility category in the corridor and the nature of the service being provided. For example, there are many gas stations in the corridor, which implied that gas stations should have a lower number of households being served. Conversely, there were relatively few emergency care facilities in the corridor, implying that these types of facilities are likely serving a much larger population.

The set of residential mega-buildings was selected by progressively expanding a search radius until sufficient households were included to exceed the relevant household threshold. The road network used to transport individuals to/from the critical facility was then identified using the commute paths defined for travel modeling.

Figure 4-30: Example Service Area for a Critical Facility



An example critical facility service area is shown as selected roads (cyan lines), mega-buildings (cyan squares), and water crossing assets (blue circles). Each critical facility in the corridor had a service area defined in this way to facilitate calculating the critical facilities index.

The water crossing assets on the road network were then identified and their risk estimated as the average overtopping level during the 2020 500-year flood. The total length of road within the service area network was then found, as well as the number of road segments; these parameters were used to evaluate the remoteness/redundancy factor.

Figure 4-30 shows an example of a service area for a selected emergency shelter (i.e., school). The figure shows the mega-buildings (cyan squares), roads (cyan lines), and water crossing assets (blue circles) used to evaluate the remoteness/redundancy and overtopping risk factors.

To understand relative weights of remoteness/redundancy and overtopping risk, both against each other and across the corridor, each factor was normalized from one to 10, with one indicating low inaccessibility and 10 indicating high inaccessibility. These two categorized factors were then added to provide a 1-20 score for each critical facility. The results are presented in Section 4.2.

4.12.3 Opportunities for Improvement

The approach taken above should be considered a first pass at estimating critical facility climate change impact. This method provides multiple opportunities for enhancement. They include:

- Specifying service areas more accurately:
  - Contacting the larger service area entities such as the emergency care facilities to find if they have a specific estimate for the service area or number of households they serve. This data could be used to better calibrate the service area and related transportation network for each facility.
  - Literature review to refine the category-based estimates of households typically served by each category of critical facility. This could also partition the facilities into urban, suburban, and rural, which may serve significantly different numbers of households on average.
- Breaking facilities by travel required to provide service: the method specified above assumes all critical facilities serve a population. While this is true of facilities like hospitals, gas stations and shops, it is not true for all facility types, such as the NCDOT lands and buildings. These facilities are likely accessed by a comparatively minimal number of people. Yet, access to the facility 100% of the time is critical. As such, a closer look that splits the groupings of critical facilities into groups that serve populations that require travel to the facility, and critical facilities that require travel only by service personnel, should be undertaken.

4.13 Addressing Future Inflation

The rationale for including inflation in the simulation was to conduct the full simulation in base year (2020) dollars and inflate to future value as a post process. Three percent was used as an inflation rate, as specified by the NCDOT. This was the percentage used on the current STIP. The rate was adopted on December 8, 2021, by the NCDOT Board of Transportation (NCDOT BOT December 8, 2021, meeting minutes).

4.13.1 Approach

The cost of each maintenance event, storm damage event, and lost productivity were all calculated as present value (PV) estimates — that is in 2020 dollars across the 2020–2100 timeframe. When the simulation was complete, a future value (FV) for each of these metrics was calculated in each year that used the following formula, where N was the number of years since 2020 and i is the inflation rate.

$$FV = PV * (1 + i)^N$$

4.13.2 Comments on Inflation Approach

Inflation is uncertain. In the past five years (2021–2025), the year-on-year change in the consumer price index (CPI) has ranges from 2.9 to 7% (U.S. Inflation Calculator). Though changes in costs for transportation infrastructure capital expenditures had not tracked exactly with consumer prices, if we considered the CPI (a suitable proxy), this created questions on whether the three percent inflation rate used in the simulation was realistic. Given just a year before, the year-on-year CPI inflation was considerably lower than three percent, the U.S. 74 study assumed an average annual inflation rate of three percent was suitable for the purposes of the study. Based on this, we have chosen to do the same with the I-87 study.

Further, the future value approach used only reflects future value of expenditures in the simulation. A net present value (NPV) approach would consider the risk in the investments reflected through a discount rate. In future simulations, an NPV approach is recommended for a more comprehensive assessment of future investments.

4.14 Citations

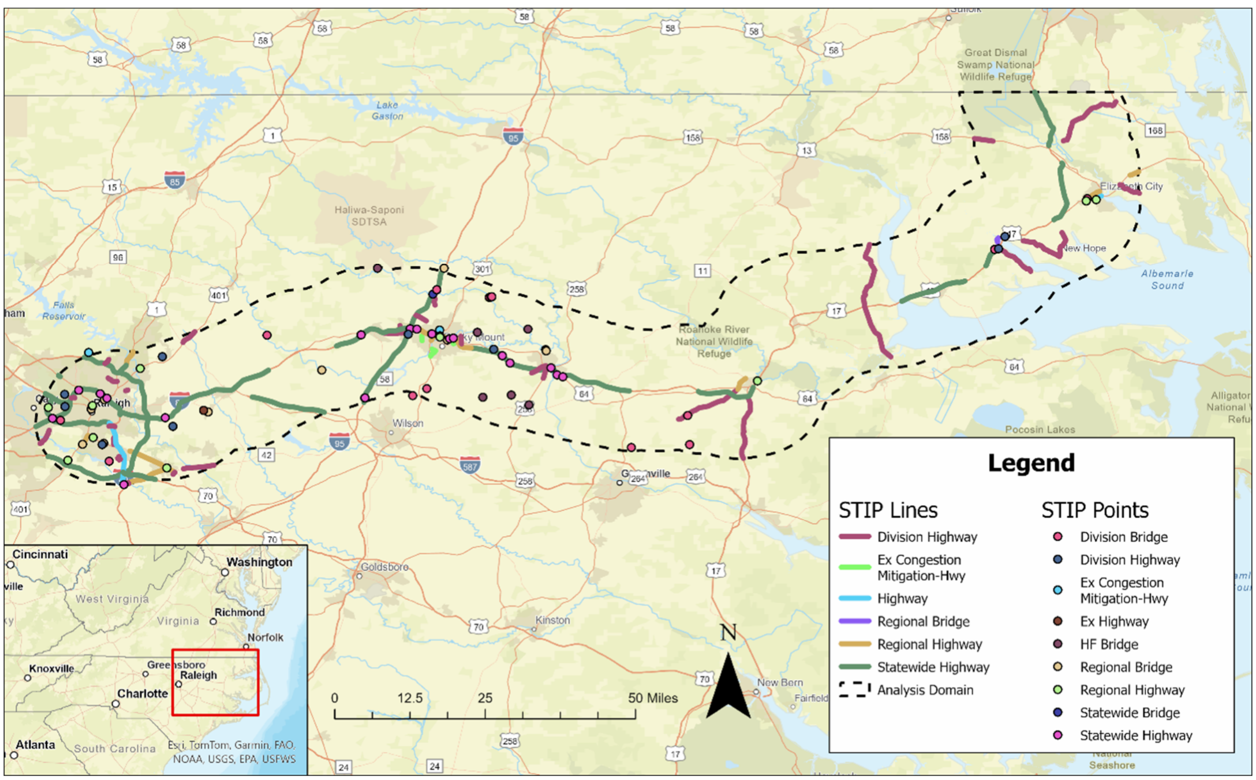
U.S. Inflation Calculator.com - Consumer Price Index Data from 1913 to 2025 https://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/

How Much Weight Can A Semi Truck Pull - Truck Report Geeks - https://truckreportgeeks.com/how-much-weight-can-a-semi-truck-pull/

5 Vulnerabilities

This chapter presents the vulnerability study findings. These findings were derived from the baseline scenario. In this scenario, no adaptation and mitigation measures were attempted. The transportation system was maintained as planned, with the 2020–2030 STIP projects implemented alongside automated asset maintenance projects governed by the asset condition forecasting model described in Chapter 4. When these projects occurred in the simulation, they did not include future climate change as a design guideline. Rather, they were implemented to simply refurbish and/or replace existing assets, returning them to good condition. Each finding presented below is related to one of the three main study questions that guided configuration of the simulation.

Figure 5-1: STIP Projects Included in the Mitigation Scenarios



5.1 Study Question 1 Findings: Future Disruption

Eight findings were made in answering the question:

"Which assets (roads, bridges, culverts, and pipes) caused the most (and least) disruption to road and rail traffic if future climate change-influenced events (floods, storms, heat waves, and SLR) took them offline? Which were most likely impacted given their current condition?"

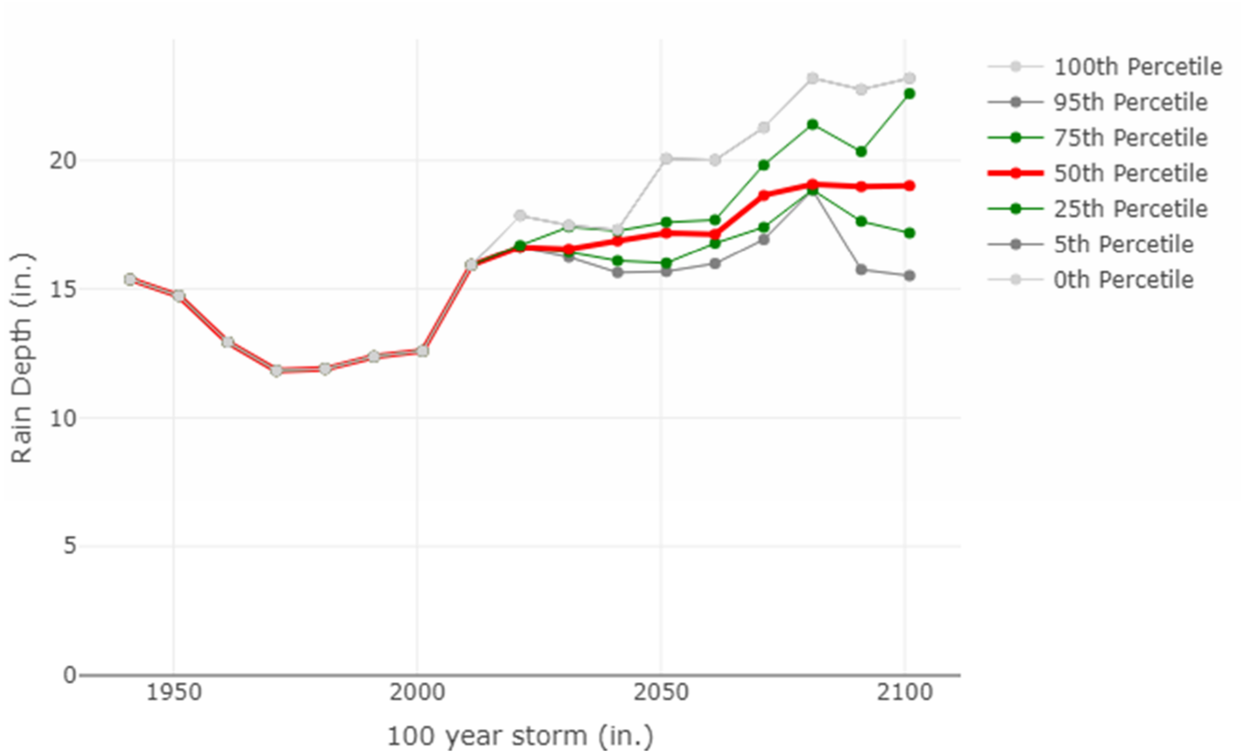
The findings focus on projections of how extreme weather will change, how those changes will disrupt trips across the corridor, and the locations within the corridor where disruption has the highest impact. Finally, they focus on asset maintenance cost, and how the simulation projects costs will change with climate change in the future.

5.1.1 Finding 1.1: Large Storms are Projected to Increase in Severity.

Large storms were found to have increased dramatically over the last several decades and were projected to continue increasing into the future. As **Figure 5-2** shows, the 100-year 24-hour rain depth was estimated by a sliding 40-year window, from 1922–1952 through 1992–2022 and evaluate the maximum 24-hour rain in each year in the window. A Weibull distribution was then fit to the maxima and the 1% (100-year) event was estimated from the resulting distribution.

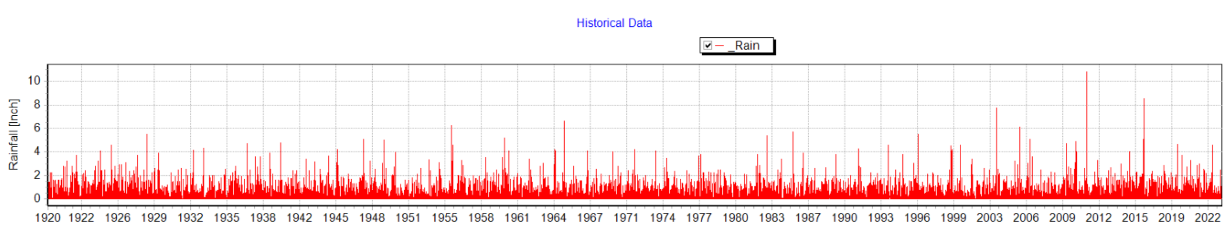
The results show a pronounced increase in the 100-year 24-hour storm over the last 40-year period (ending 2022, see **Figure 5-3**) and a projected continued increase into the future.

Figure 5-2: 100-Year 24 Hour Storm Event at Edenton, NC



An ensemble 1922–2100 daily rainfall projection was created by concatenating historical rainfall at Edenton with projected rainfall at the same location. Using a sliding 40-year window, the 100-year 24-hour event was estimated in each decade (i.e., 1923–52, 1933–62, etc.) The results showed a pronounced increase in the 100-year, 24-hour rain storm depth over the past 40 years, with the ensemble global climate models projecting the increase will continue into the future.

Figure 5-3: Edenton, NC Historical Rainfall



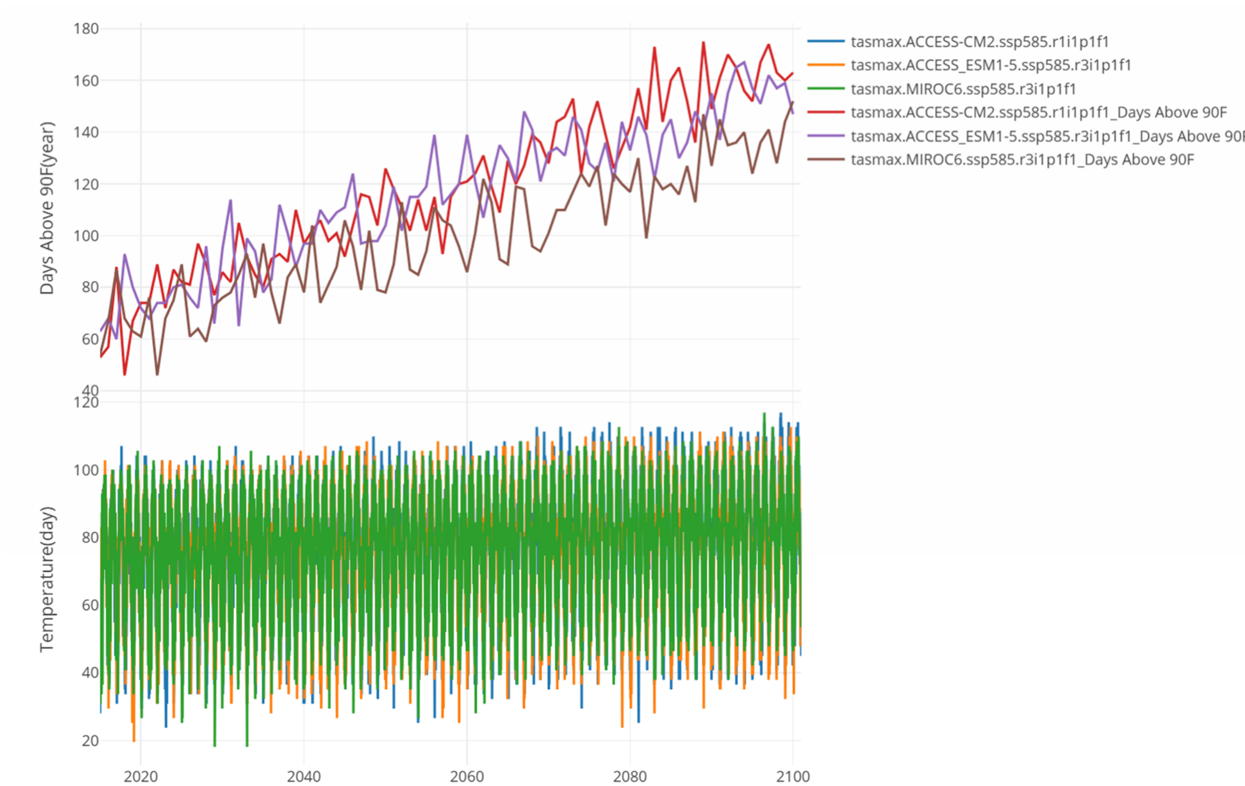
Historical rainfall in Edenton showed an increase in extreme rainfall events over the past 40 years, when compared to the whole record.

5.1.2 Finding 1.2: Heat is Projected to be an Increasingly Disruptive Problem

Using the LOCA2 dataset, which is a statistically downscaled dataset of maximum temperature based on the CMIP6 ensemble projections from a series of global climate models (GCMS), and following the ssp585 scenario, the study projected maximum temperatures would rise steadily across the corridor and push the number of days above 90^{o}F to near three times higher than in 2020. This is projected to increase disruption to road and rail traffic. Note that the ssp585 scenario refers to a situation where world governments focus on increasing economic prosperity over reduction in greenhouse gas emissions, and GHG therefore remains uncontrolled.

As figure 5-4 shows, ensemble projected maximum temperatures at Edenton NC rises steadily over the 21st century and results in a projected increase from approximately 60 days per year exceeding 90°F to 150 days.

Figure 5-4: Max Temperature Projection and Days above 90F at Edenton, NC



An ensemble of three GCM-based projections of maximum temperature was used from the LOCA2 dataset. Here, the members of the ensemble at a single grid cell near Edenton, NC, were evaluated by the number of days exceeding 90^{o} F each year. The upward, projected trend showed strong agreement among the models that future temperature increased dramatically over the coming century.

Note that the 90^{o}F threshold was used as it is a common threshold used in ambient temperature studies. The rationale is that 90^{o}F represents a warm summer day and exceeding it represents uncomfortable conditions. The metric measuring how often this threshold will be exceeded therefore provides an estimate of the level of discomfort that will be felt in future decades. The 85^{o}F threshold used in the assessment of road asphalt flushing (see section 4.9) was the threshold proposed in the study from which the method is based. The two thresholds are not comparable as one refers to ambient temperature and the other is used to evaluate heating degree days — the cumulative heat impacts felt — by the asphalt over time.

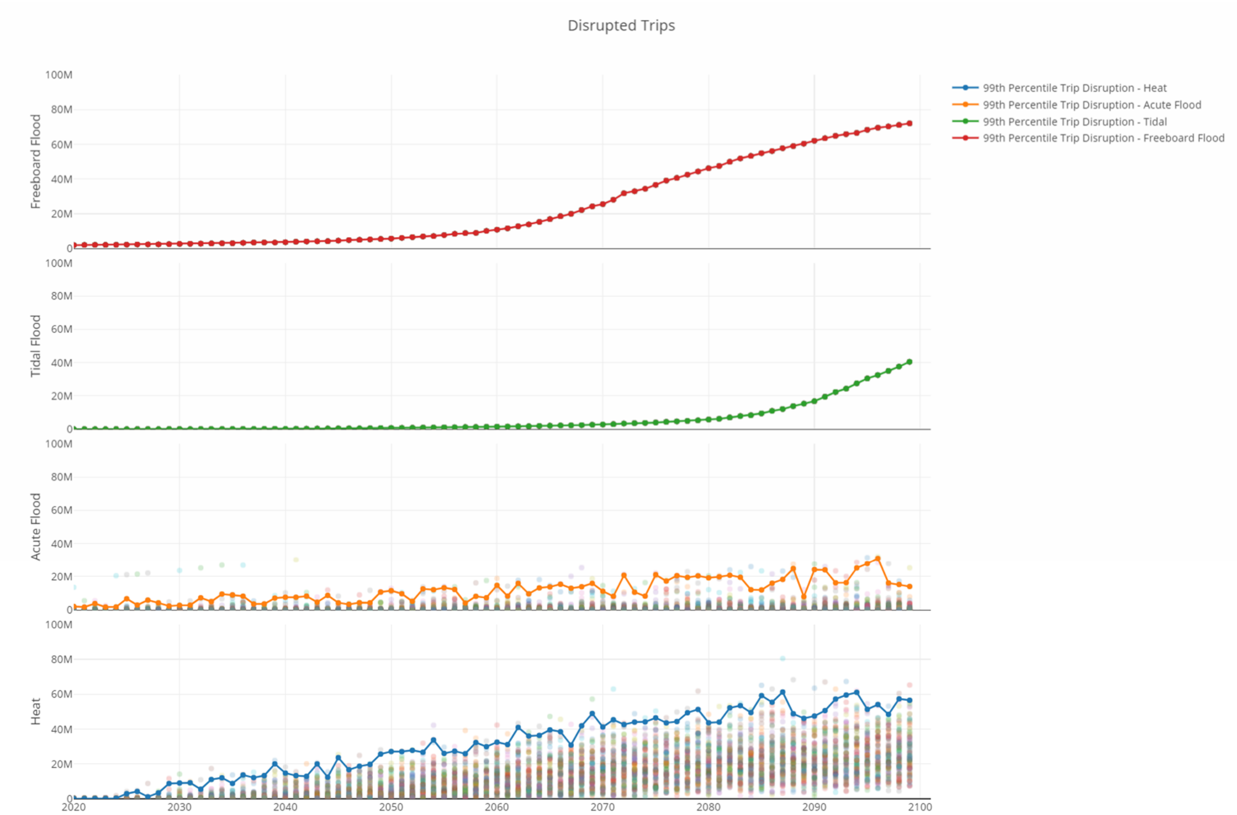
5.1.3 Finding 1.3: Sea Level Rise

The intermediate high mean sea level projection from the NOAA-led joint agency report was used as the projection for the study. This projection estimates an approximately 5.5-foot rise in mean sea level from 2000–2100. The projected rise will cause both tidal flooding impacts and storm surge impacts in multiple locations in the I-87 corridor including Elizabeth City, Hertford, and Edenton/Hancock. For the most part, the disruptions will not impact NCDOT-maintained roads but will impact local roads in these communities.

5.1.4 Finding 1.4: Climate change impacts are projected to increase disruption to daily trips by approximately 19 times between 2020 and 2100, with heat impacts, tidal flooding, and acute flooding impacting from most to least.

As **figure 5-5** shows, disruption to trips will increase substantially through the century. The four stacked charts from top to bottom show 1) trips happening during tidal flooding events within 2 feet of the road deck, 2) trips disrupted when tidal flooding tops the road deck, 3) trips disrupted when acute flooding (riverine, pluvial, storm surge) occurs, and 4) trips disrupted due to flushing of roads from excess heat.

Figure 5-5: Disruption Metrics



Disrupted trips for a single future weather realization with a large storm event late in the timeline. The simulation over time showed how chronic disruption like heat events and sea level rise (red, orange, and blue bars) compared to acute events (green bars), like riverine and pluvial floods. Though acute events had a substantial impact when they occurred, chronic disruption was far more damaging in the long run.

The latter two charts show the estimated disrupted trips from 600 realizations of future rainfall and temperature as dots on the chart in each year. The line is at the 99th percentile estimate in each year, i.e., the estimate of disrupted trips at 0.99 * 600 = 594th highest ranked dot. This method was used to estimate the worst-case condition.

The disruption is largely due to two factors. First, steadily increased usage of the transportation system as populations and business activities increase imply that each successive disaster will have a higher impact farther into the future. An equivalently disruptive hurricane in 2100, therefore, will have a much larger impact in terms of disruption than one in 2020.

The second factor is that climate models project that future extreme storms will be larger than today's storms, implying that the same return period storm in 2100 could cause substantially more damage than the storm in 2020.

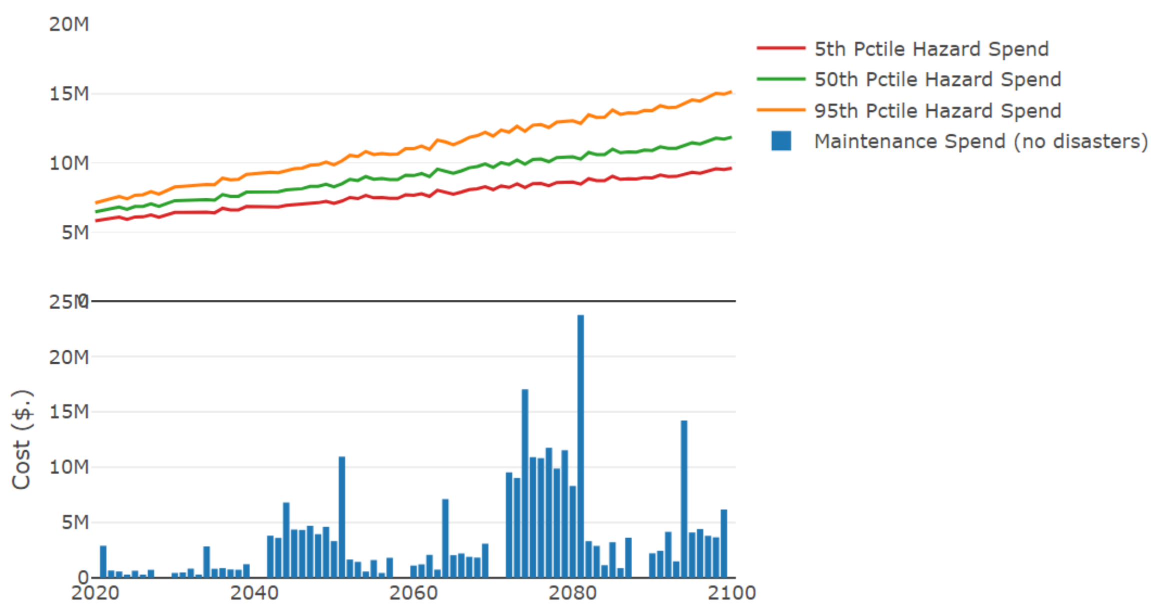
Causes for average annual disrupted trips include storm/flood, heat, nuisance flooding overtopping roads, and nuisance flooding coming within two feet of road overtopping — a hazardous zone in which the presence of seawater can increase the pace of deterioration in road condition. Disruption increases for all causes across the simulation with the highest increases for heat and nuisance flood. The leading source of disruption is flood, though heat approaches the same level of disruption as flood toward the end of the simulation.

An important note is that the simulation considers all of these disruption events as disruptions to travel. For example, a major flood that completely damages a road and stops travel is considered in the same light as nuisance flooding that enters the freeboard zone, or a heat event that slows down travel due to a flushing event. It is recommended that in future studies, the disruptions are partitioned into those that stop travel all together, those that cause inconvenience, and those that hasten transportation asset decay.

Another factor considered was chronic versus acute disruption. As the chart shows, storm and flood events have comparatively high impacts in terms of disrupting trips when compared to other disruptors. But the year-after-year steadily increasing impacts of heat and SLR cause arguably more disruption over the simulation timeframe. As the simulation approaches mid-century, disruption from heat and SLR is comparable to a major storm or flood event. This oncoming chronic climate change impact should be carefully considered when approaching adaptation and mitigation.

5.1.5 Finding 1.5: The cost of maintaining the system will steadily increase into the future with unpredictable future spend comprising approximately 60% of total spend on the corridor.

Figure 5-6: Projected Spending on Transportation Asset System



Predictable costs for maintenance estimated through decay-curve based models on each asset were projected to average around $8M per year. The figure above shows the predicted costs in the lower chart. The costs vary by year because of the distribution of the most recent maintenance date of the 1,634 assets simulated. The large grouping of costs starting around 2045, for example, occurs because many of the assets were last maintained around 2015, and the average recurrence interval (time to move from good to failing condition) for asset maintenance is around 30 years.

The upper chart presents unpredictable costs resulting from extreme weather events causing damage. The unpredictable costs were projected to steadily increase, with median cost ranging from approximately $6.5M to $11M per year by end-of-century. The uncertainty in the hazards-based cost ranged from $8.5M to $15.5M per year by end-of-century. It is important to note that the upper and lower estimates in the chart represent the 5th and 95th percentile costs

5.1.6 Finding 1.6: Flood vulnerability occurs across the corridor with highest disruption locations in the transportation network supporting I-87.

I-87 has several locations that were projected to be vulnerable to future floods, though the highest vulnerability was in the road network connecting to I-87. Figures 5-8 through 5-10 show the flooding hotspots in 2040, 2070, and 2100, with dots colored according to the projected average annual trips disrupted at each location. Key locations were in Rocky Mount/Tarboro, Raleigh, and in Elizabeth City.

Figure 5-7: Locations with Trip Disruption in the I-87 Corridor for the 2040 Planning Period

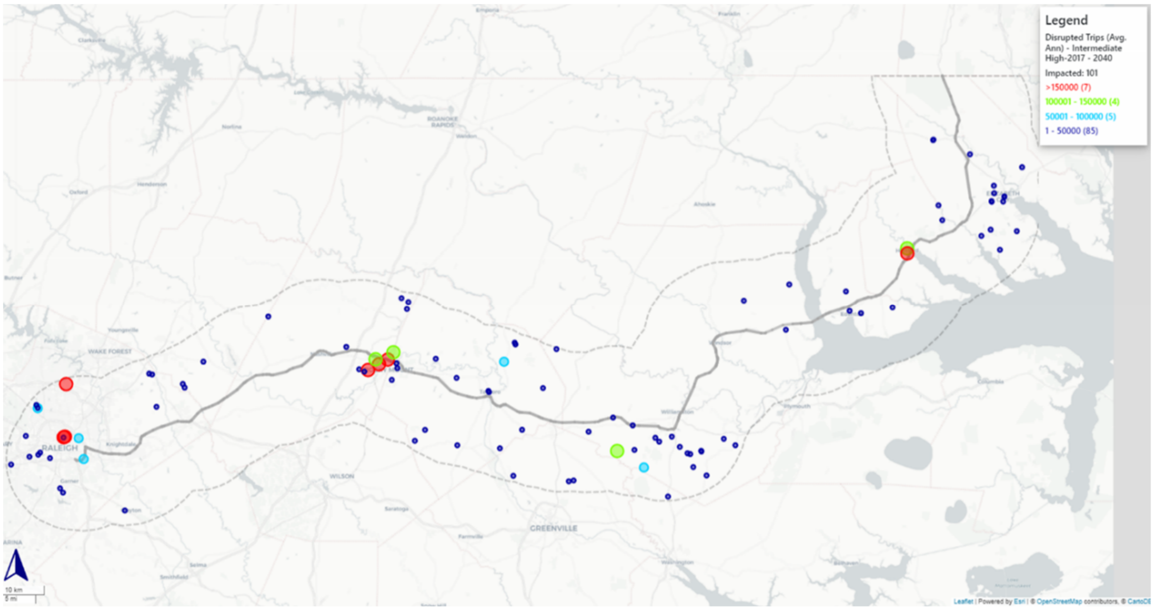


Figure 5-8: Locations with Trip Disruption in the I-87 Corridor for the 2070 Planning Period

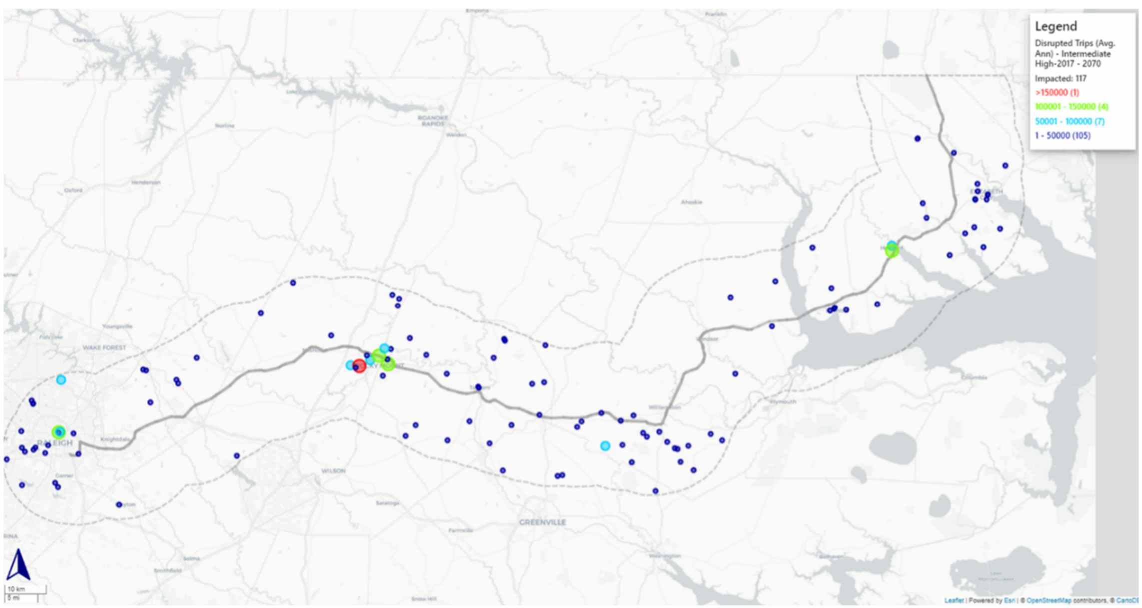


Figure 5-9 shows the key flood hotspots in the corridor. The locations are listed in **Table 5-1**, with their source ID, rank, division, the street that overtops the asset, the projected average annual trips disrupted and the asset latitude/longitude. The source ID is the NCDOT system ID.

Figure 5-9: Locations with Trip Disruption in the I-87 Corridor for the 2100 Planning Period

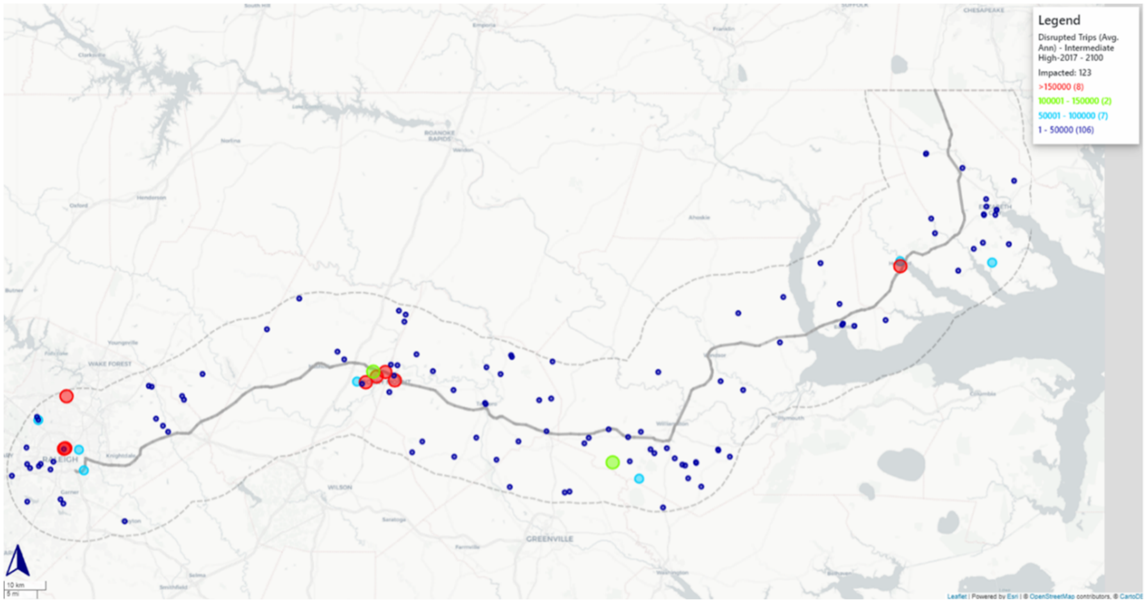


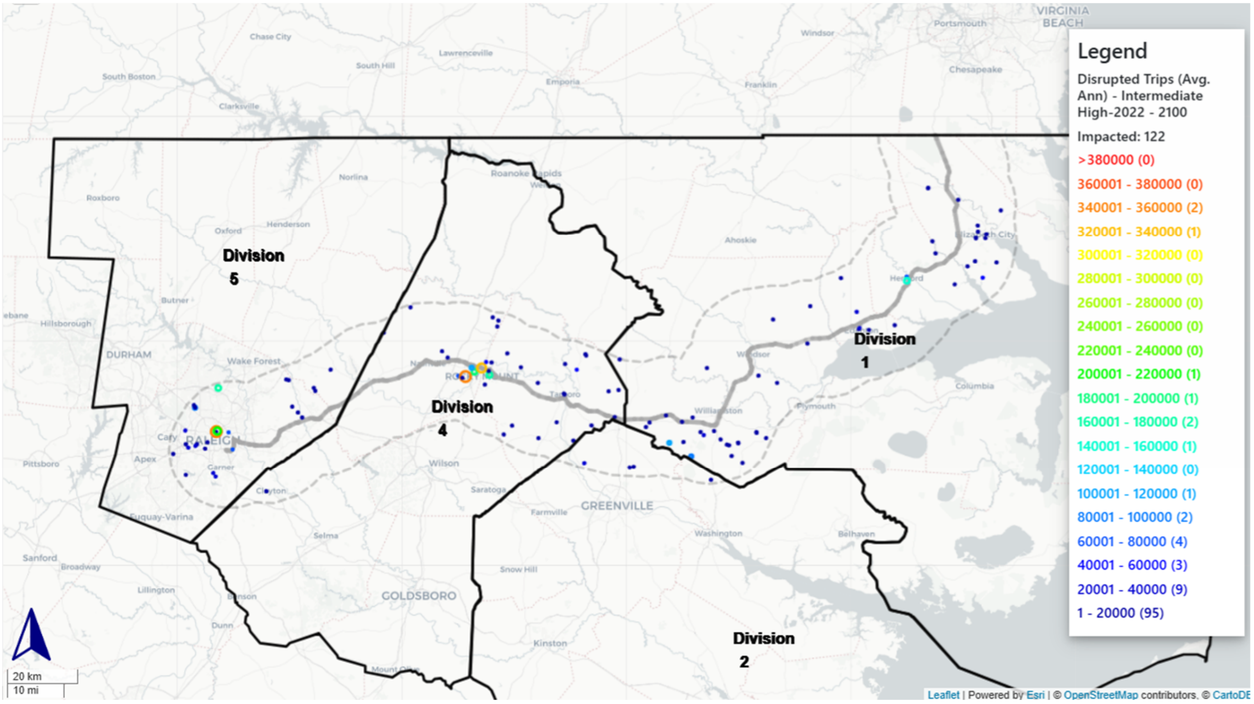
Table 5-1: Highest Trip Disruption Locations

Index	Division↕Σ	Rank↕Σ	CitySimID↕Σ	Type↕Σ	SourceID↕Σ	Route/Road↕Σ	Trips Disrupted (Ann Avg)↕Σ	Latitude↕Σ	Longitude
4911	1	1	8	BRIDGE	70014	S King St	54000	35.99358	-76.94249
5625	1	2	722	BRIDGE	710031	S Church St	51429	36.18392	-76.46588
5606	1	3	703	BRIDGE	710008	N Church St	35143	36.19413	-76.46643
5230	1	4	327	BRIDGE	570011	Bear Grass Rd	34571	35.73909	-77.14142
5260	1	5	357	BRIDGE	570053	Prison Camp Rd	31714	35.77342	-77.21004
5570	1	6	667	BRIDGE	690021	Creek Rd	16376	36.32377	-76.24405
4933	1	7	30	BRIDGE	70046	Woodard Rd	13714	35.94469	-76.93045
4944	1	8	41	BRIDGE	70066	Woodard Rd	13714	35.94366	-76.93076
5556	1	9	653	BRIDGE	690004	Nixonton Rd	12857	36.19136	-76.22844
5290	1	10	387	PIPE	570235	Bear Grass Rd	11829	35.79289	-77.10226
5661	2	1	758	BRIDGE	730198	Holland Rd	7714	35.72176	-77.47626
4903	**2**	**2**	**0**	**BRIDGE**	**60056**	**US** 17 Hwy N	**900**	**35.67856**	**-77.07966**
5662	2	3	759	PIPE	730302	Hollowell Rd	10	35.71214	-77.32167
5663	2	4	760	PIPE	730400	Tetterton Rd	3	35.71045	-77.33401

Index	Division↕Σ	Rank↕Σ	CitySimID↕Σ	Type↕Σ	SourceID↕Σ	Route/Road↕Σ	Trips Disrupted (Ann Avg)↕Σ	Latitude↕Σ	Longitude
5527	4	1	624	CULVERT	630289	US 64 E	317143	35.96301	-77.79802
5540	4	2	637	CULVERT	630311	S Winstead Ave	123101	35.94143	-77.84874
5542	4	3	639	CULVERT	630315	Country Club Rd	102857	35.96364	-77.8294
5026	4	4	123	BRIDGE	320015	N Raleigh St	55714	35.94543	-77.77361
5496	4	5	593	BRIDGE	630205	Sunset Ave	43136	35.95348	-77.82064
5536	4	6	633	CULVERT	630300	N Church St	41143	35.97832	-77.78373
5372	4	7	469	PIPE	630058	S Halifax Rd	25286	35.94288	-77.87152
5102	4	8	199	CULVERT	320129	Leggett Rd	24857	35.95546	-77.77595
5083	4	9	180	PIPE	320094	US 258 North	20914	35.95871	-77.50003
5075	4	10	172	BRIDGE	320085	US 258 North	20571	35.95421	-77.49965
5754	5	1	851	CULVERT	910193	Capital Blvd	347143	35.8019	-78.62896
5880	5	2	977	CULVERT	910509	Capital Blvd To Wake Fore Ramp NB	184286	35.80327	-78.62592
5886	5	3	983	PIPE	910531	Durant Rd	74595	35.91235	-78.62268
5691	5	4	788	CULVERT	910040	W Millbrook Rd	60667	35.86229	-78.69562
5929	5	5	1026	CULVERT	910600	I 440 EB	23238	35.79992	-78.59066
5674	5	6	771	CULVERT	910013	I 87 NB	23048	35.75663	-78.57781
5950	5	7	1047	CULVERT	910633	Gorman St	21429	35.76558	-78.69432
5845	5	8	942	BRIDGE	910318	Avent Ferry Rd	18471	35.76144	-78.71687
5742	5	9	839	BRIDGE	910180	Riley Hill Rd	18000	35.83756	-78.35999
5748	5	10	845	BRIDGE	910187	Lizard Lick Rd	14571	35.85025	-78.37334

**Source ID is the NCDOT System ID. Some Source IDs may be “n/a” because they are a tracking location at a road low point, as opposed to a water crossing asset like a bridge, culvert, or drainpipe. Only water crossing assets had NCDOT system IDs.*

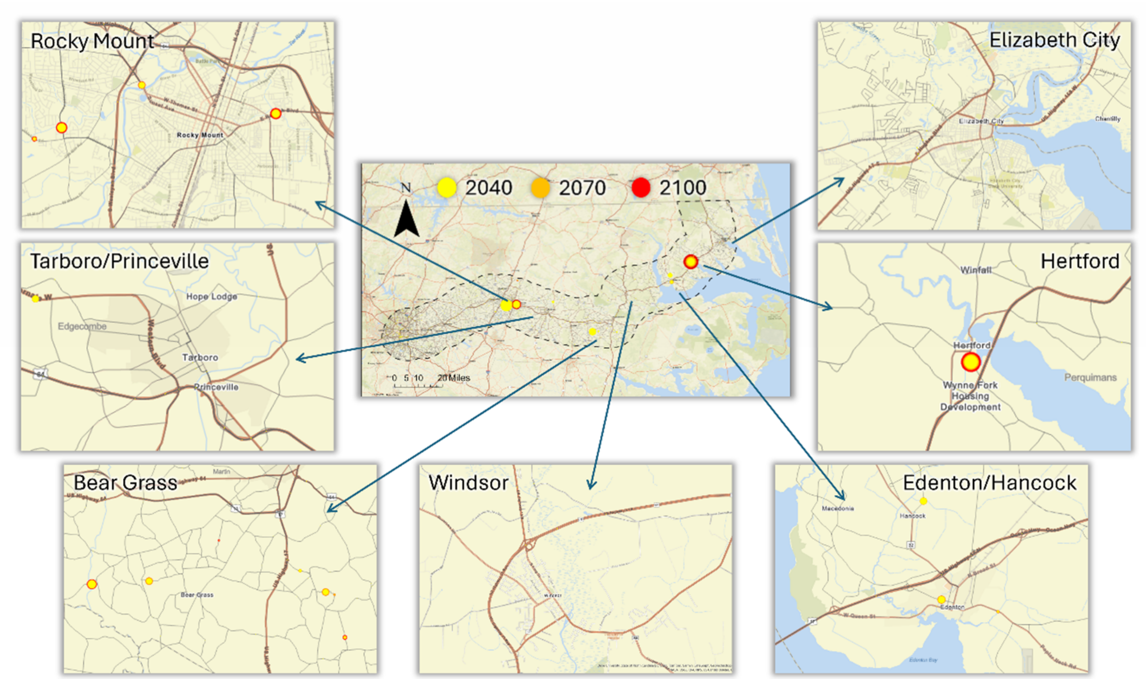
Figure 5-10: Disrupted Locations by Division for Base Run



5.1.7 Locations of Special Interest

Seven locations of interest as seen in **Figure 5-11** were identified for special review in the study. They included Tarboro/Princeville, Rocky Mount, Bear Grass, Hertford, Edenton/Hancock, Windsor, and Elizabeth City. This section will present findings on each area in respect to vulnerabilities.

Figure 5-11: Locations of Interest



Tarboro/Princeville

Vulnerability Findings:

- While there is significant flooding in the Tarboro/Princeville area, disruption of trips in the transportation network is projected to be relatively low compared to other parts of the corridor.
- The 500-year riverine flood at Princeville is substantially more extensive than the 100-year. NC33 and local streets in Princeville are estimated to experience disruption during above-100-year events.
- Disruption on U.S. 64, which has 22,000 trips per day in 2020, is estimated to be zero due to the high elevation of the deck and approach.
- Disruption on U.S. 258, with 2,400 AADT in 2020, is estimated at 2,475, 4,510, and 4,460 trips per year in 2040, 2070, and 2100, respectively.

Figure 5-12: Typical Overtopping Curves – Tarboro/Princeville

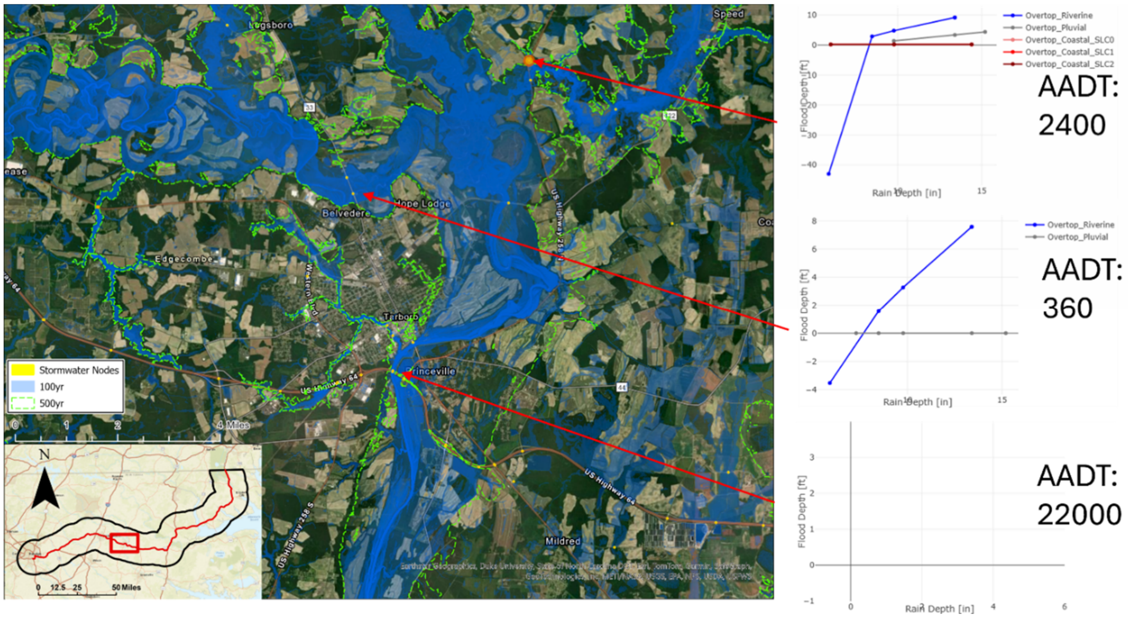
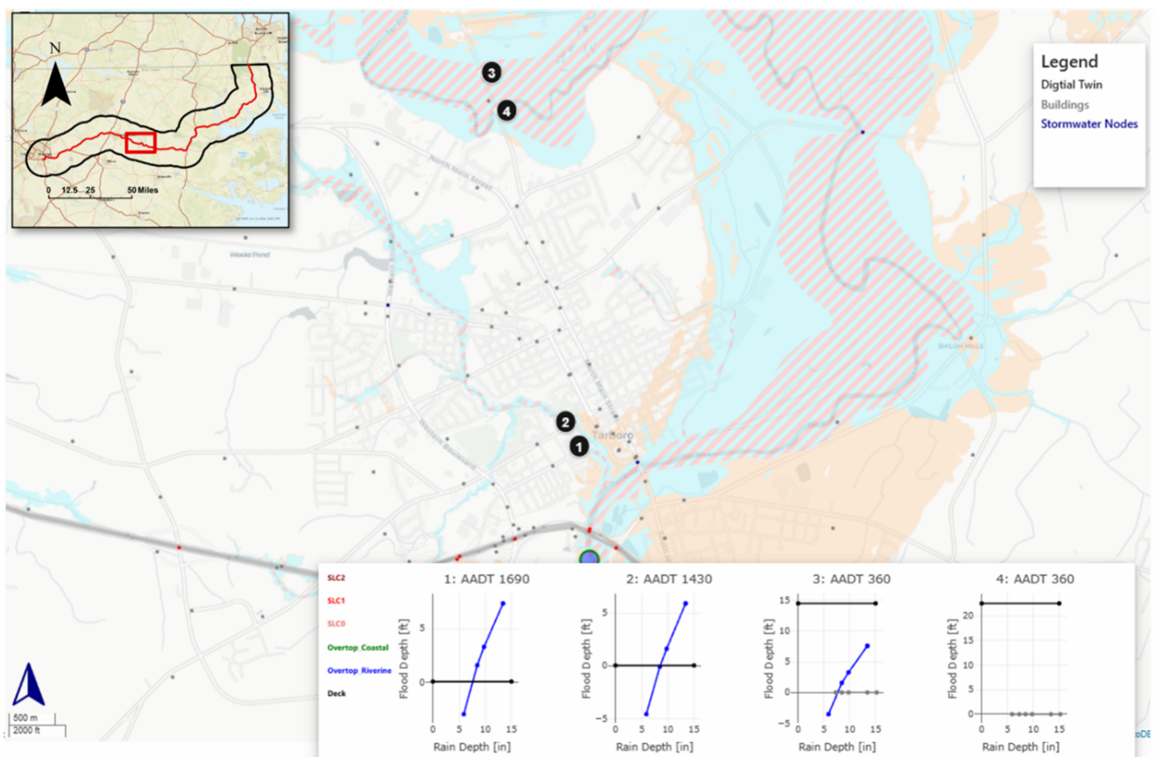


Figure 5-13: Online City Simulator View of Multiple Curves in Map Display – Tarboro/Princeville



Rocky Mount

Vulnerability Findings:

- Trip disruption in the Rocky Mount area is projected to be high relative to other parts of the corridor.
- U.S. 64, which has 13,000 AADT in 2020, will experience from 7,800 to 22,492 disrupted trips from 2040 to 2100 at Cowlick Branch.
- S. Winstead Avenue, with 12,080 AADT in 2020, will experience from 12,800 to 22,800 disrupted trips from 2040 to 2100 at Maple Creek.
- Sunset Ave with 14,000 AADT in 2020, primarily driven by off- and on-ramp traffic from U.S. 301 will experience from 4,200 to 5,000 disrupted trips from 2040 to 2100 at the Tar River.

Figure 5-14: Typical Overtopping Curves – Rocky Mount

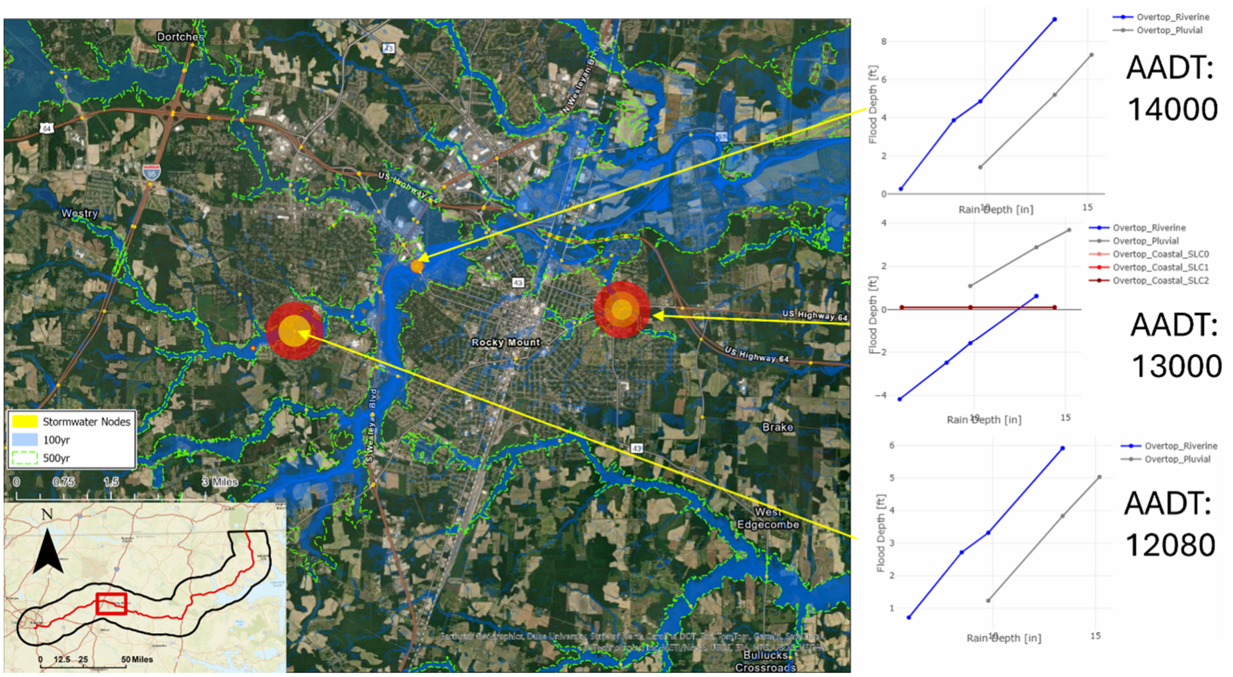
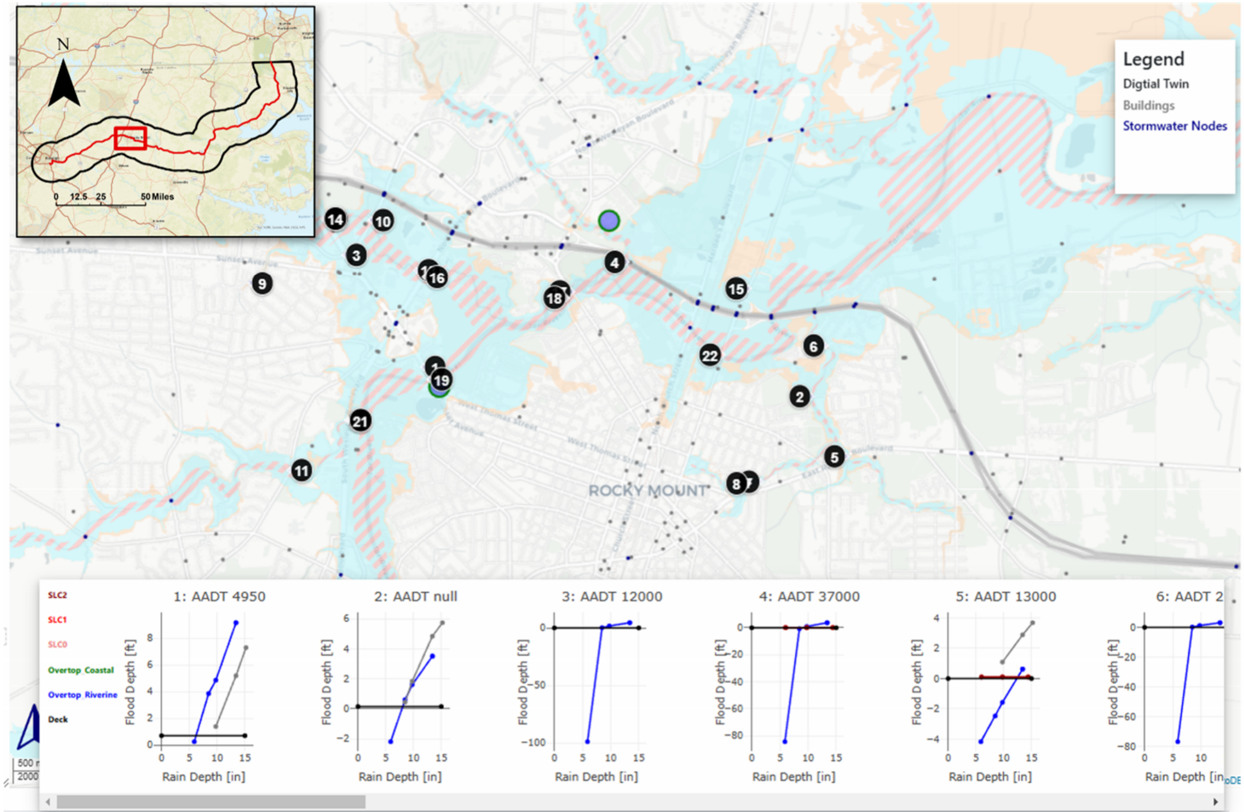


Figure 5-15: Online City Simulator View of Multiple Graphs in Map Display – Rocky Mount



Bear Grass

Vulnerability Findings:

- Trip disruption around Bear Grass is highest on Prison Camp Road, which conveys 3,700 trips per day on average. Trips disruption is projected to grow from 7,651 in 2040 to 13,207 trips per year by 2100.
- Jack Roberson Road at Turkey Swamp is projected to be disrupted from 1,300 trips per year in 2020 to 3,200 in 2100. With a relatively low AADT of 350 trips per day, this represents a significant level of disruption.
- Meadow Branch Road at Meadow Branch is projected to be disrupted from 1,300 trips per year in 2020 to 2,300 in 2100. Given AADT at Meadow Branch Road. is 230 trips per day, this represents significant disruption.

Figure 5-16: Typical Overtopping Curves – Bear Grass

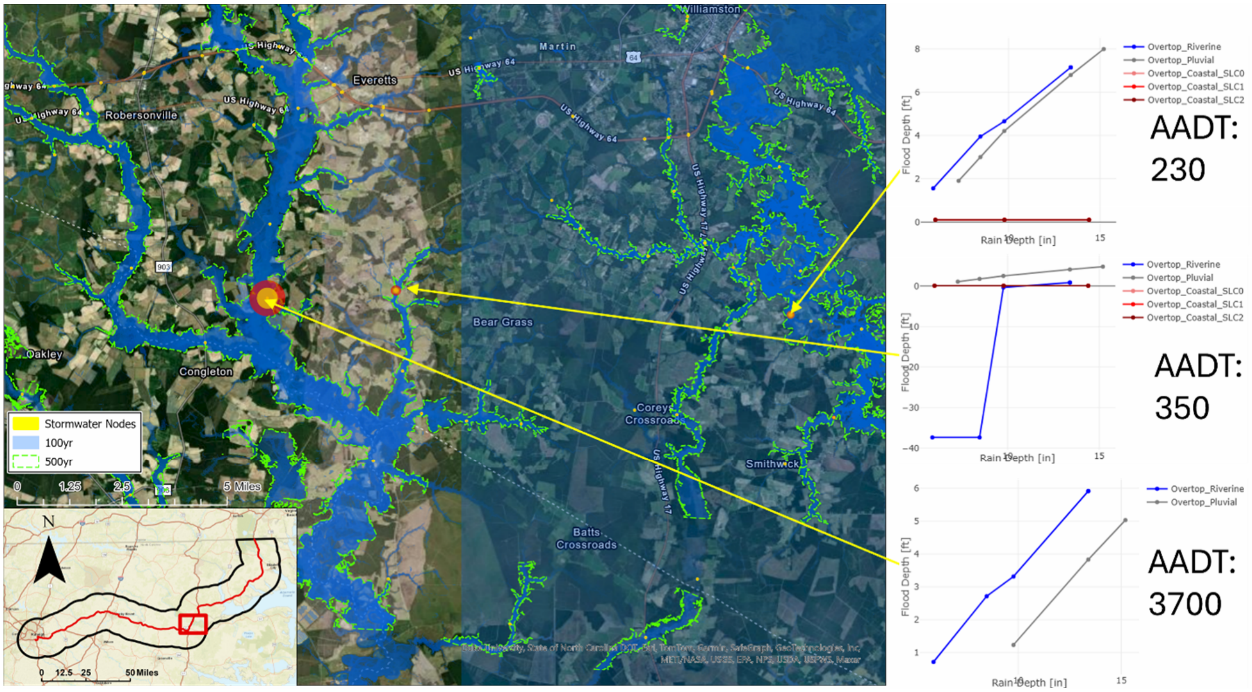
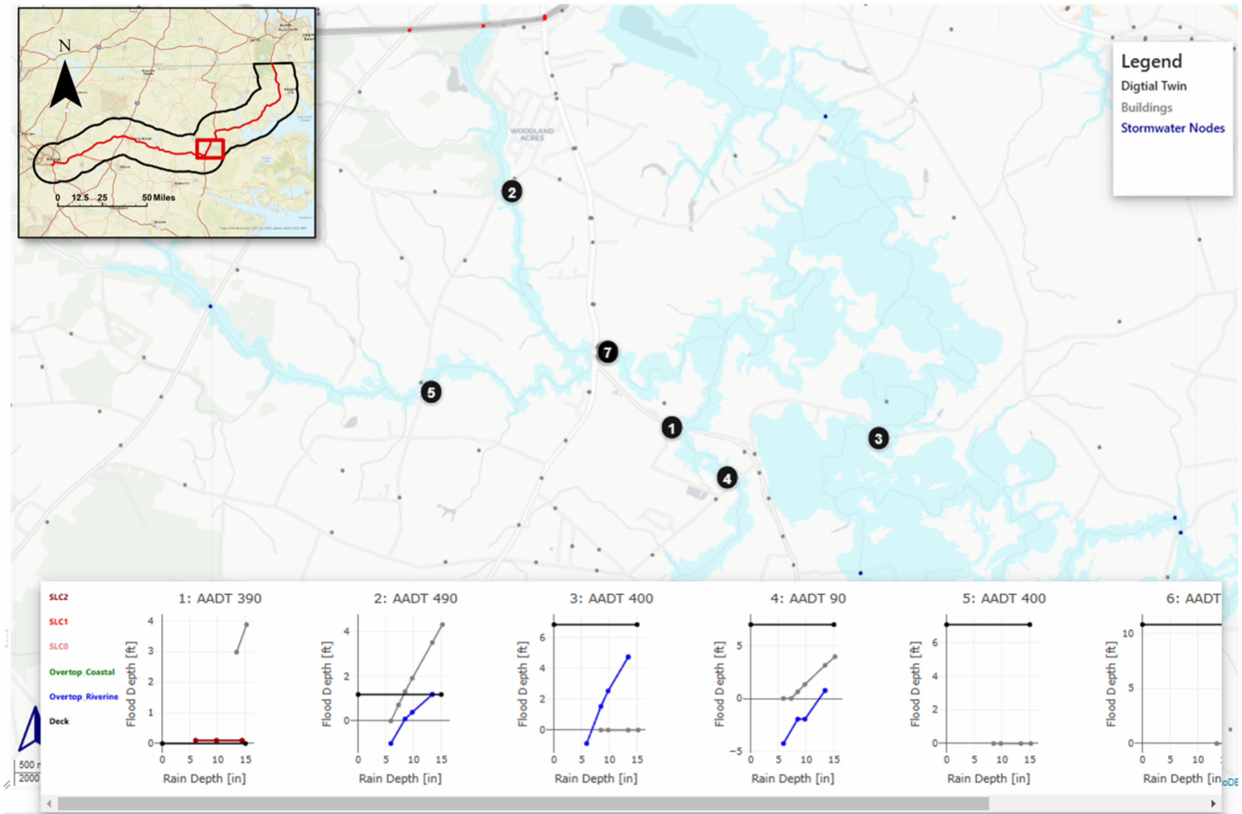


Figure 5-17: Online City Simulator View of Multiple Curves in Map Display – Bear Grass



Hertford

Vulnerability Findings:

- Trip disruption in Hertford is most pronounced at South Church Street on Racoon Creek. The 6,000 average daily trips are projected to be disrupted from 8,000 trips in 2040 per year to 36,000 trips per year by 2100. The marked increase is due to the joint impact of increasing traffic, rising sea levels, and more intense surge and riverine flooding in future years.
- Peak traffic (19,500 trips per day) in the area on U.S. 17 as well at North Church Street (4,100 daily trips) is not projected to be impacted by future flooding due to its high elevation.
- The 1,700 daily trips at Wynne Fork Road. are projected to be impacted by flooding at Racoon Creek during extensive storms with higher than the 2020 100-year return period. Disrupted trips are expected to range from 1,800 in 2040 to 2,500 in 2100.

Figure 5-18: Typical Overtopping Curves – Hertford

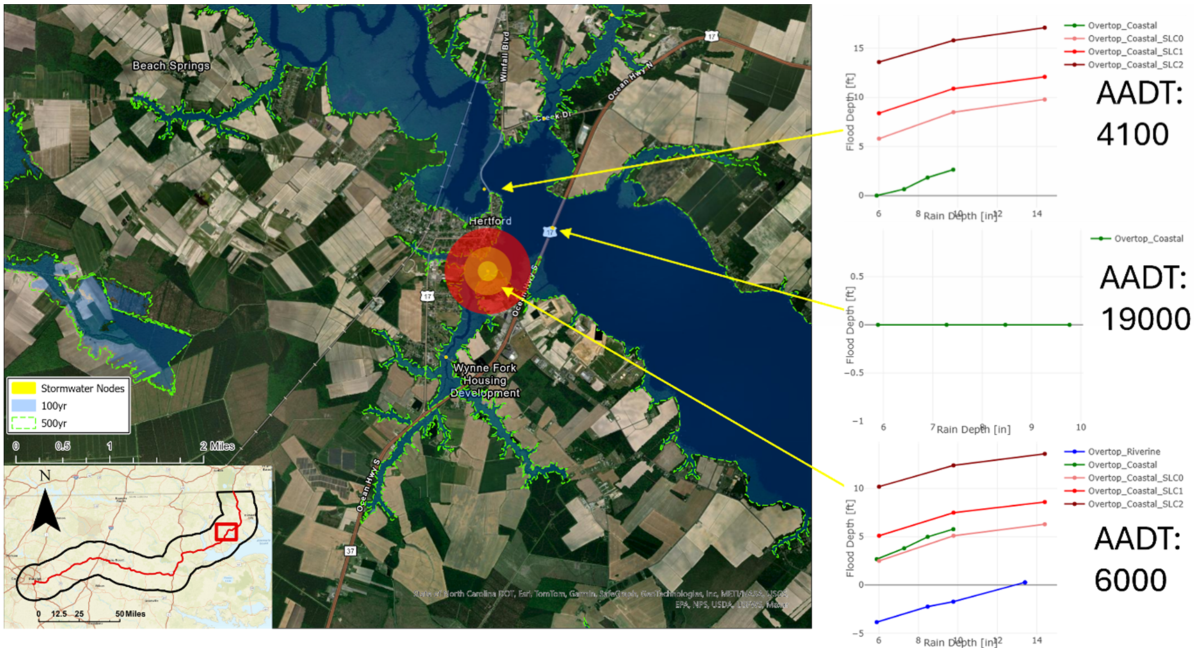
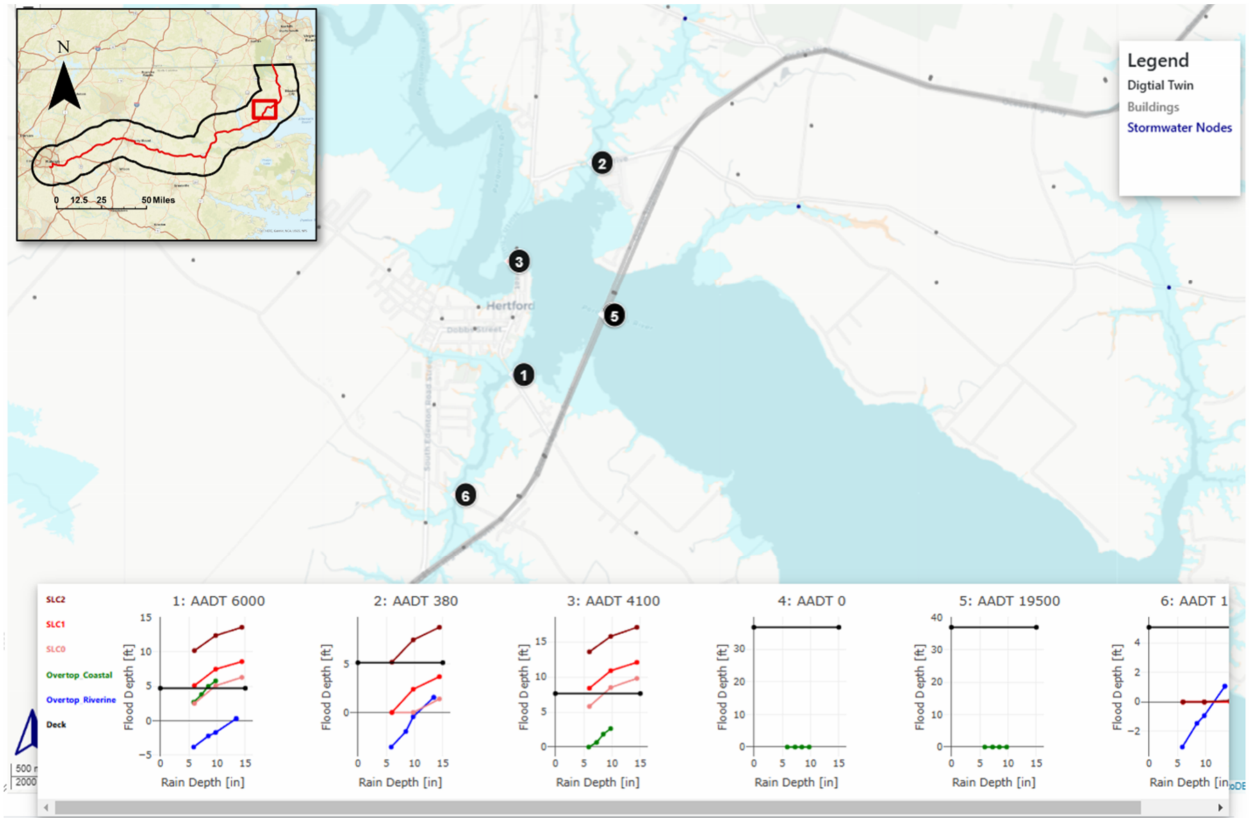


Figure 5-19: Online City Simulator View of Multiple Curves in Map Display – Hertford



Edenton/Hancock

Vulnerability Findings:

- Trip disruption in Edenton is most pronounced at Dr. Martin Luther King Jr. Avenue on an unnamed channel. The 2,000 average daily trips are projected to be disrupted from 3,342 trips in 2040 per year to 7,436 trips per year by 2100. The marked increase is due to the joint impact of increasing traffic, rising sea levels, and more intense surge and riverine flooding in future years.
- Peak traffic (9,500 trips per day) in the area on U.S. 17 is not projected to be impacted by future flooding due to its high elevation.
- The 500 daily trips at Greenhall Road. are projected to be impacted by flooding at an unnamed tributary of Pollock Swamp. The expected 4,500 disrupted trips by 2100 are significant compared to the number of trips per day.

Figure 5-20: Typical Overtopping Curves – Edenton/Hancock

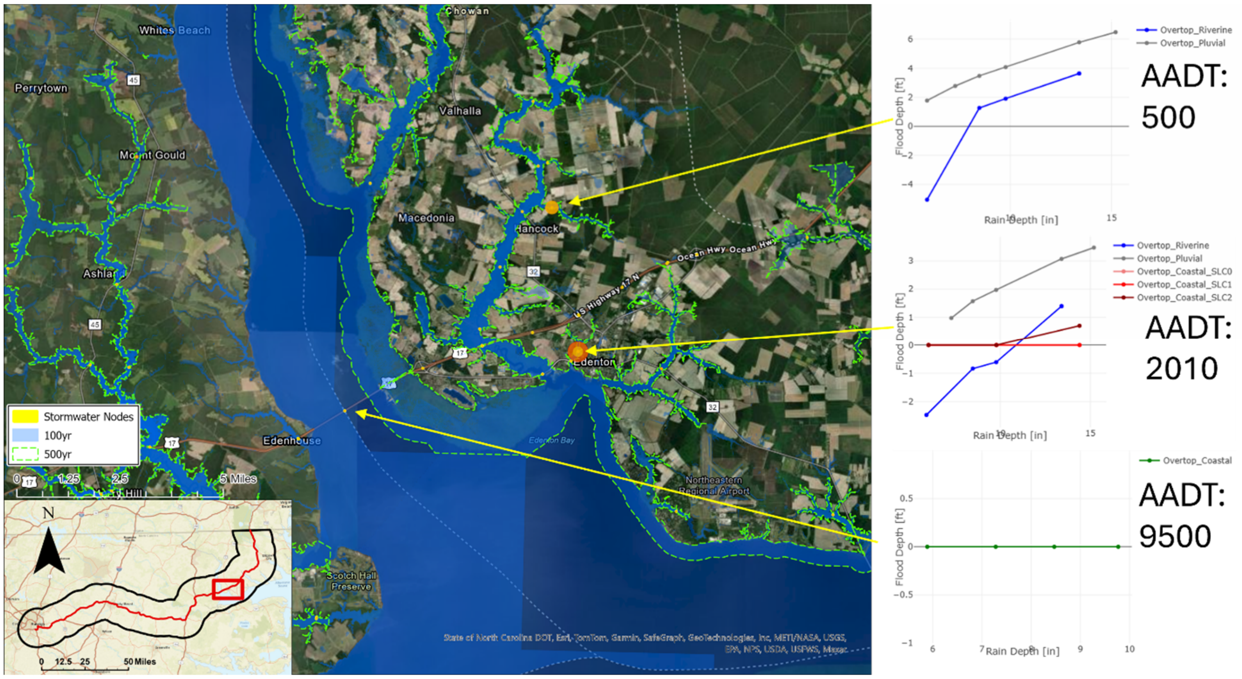
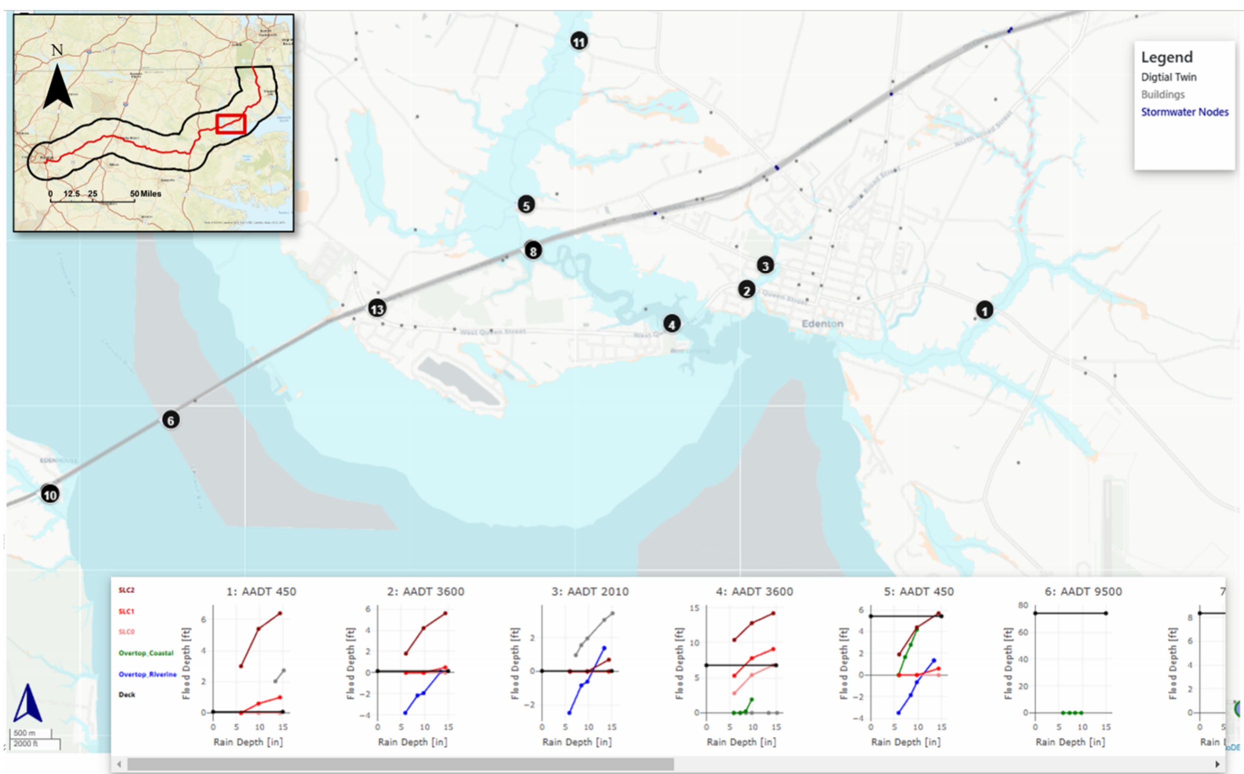


Figure 5-21: Online City Simulator View of Multiple Curves in Map Display – Edenton/Hancock



Windsor

Vulnerability Findings:

- U.S. 13 near Windsor is likely to see minor flooding at high return period storms. The 5,600 daily trips will be disrupted by flood depths near 0.7-feet, which occur within the 500-year return period in 2020. In the future, these events will become more frequent, and their heightened intensity will cause longer disruptions.
- Traffic on South King Street in Windsor will likely be significant disrupted by future flood. The 6,300 average daily trips will experience extended disruption by flood depths of more than 5 feet during 2020 500-year return period storms.

Figure 5-22: Typical Overtopping Curves – Windsor

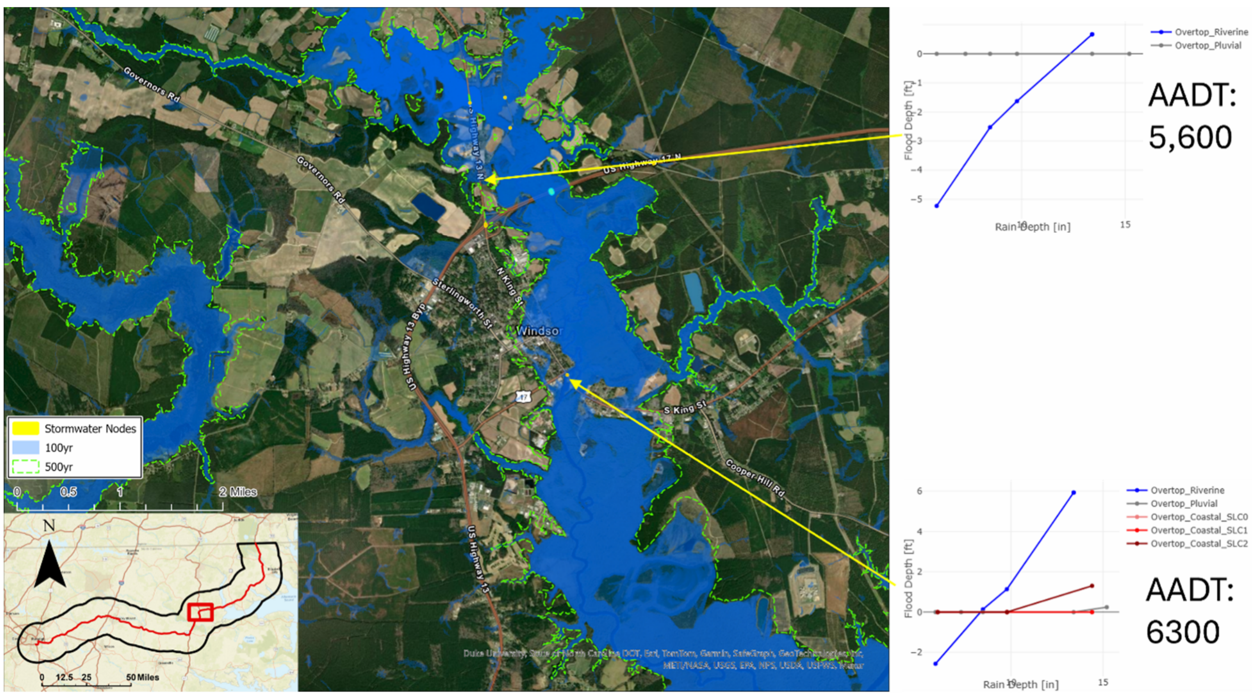
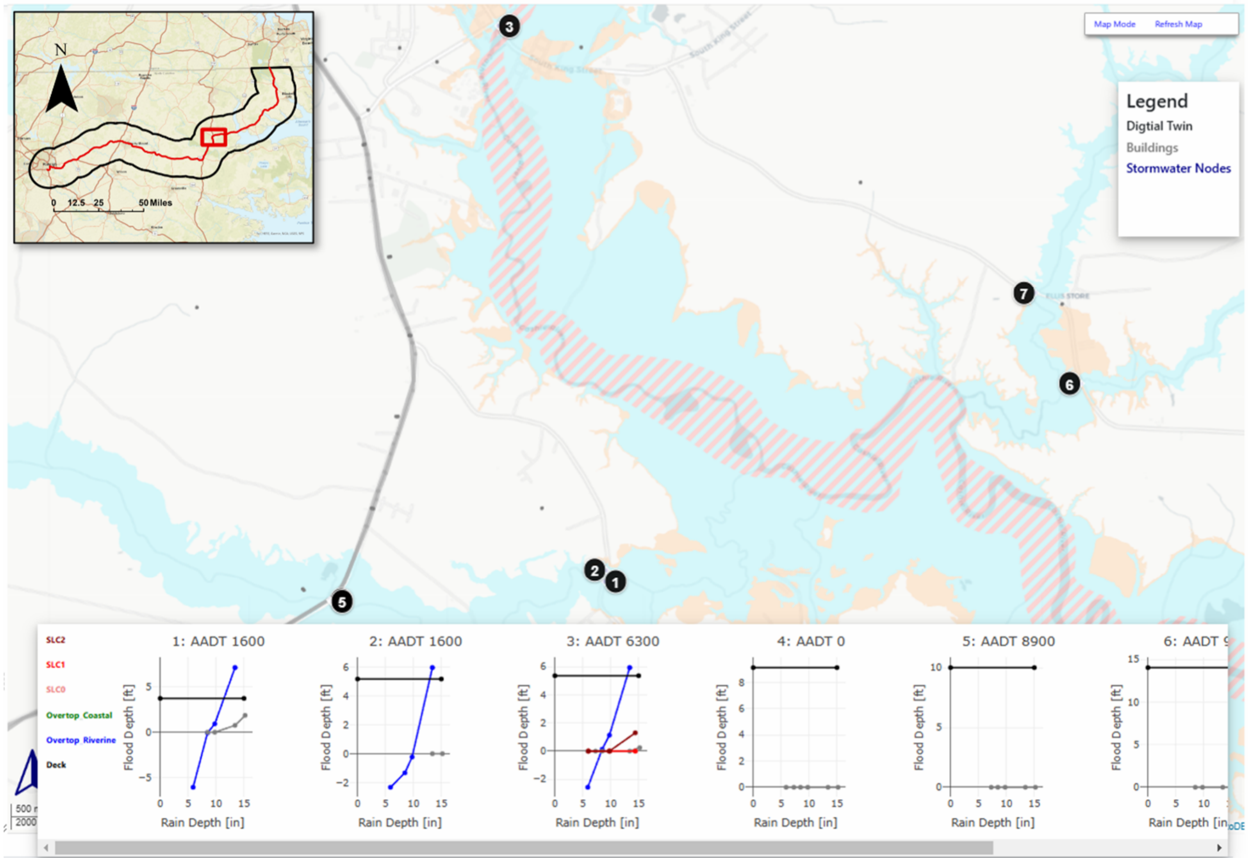


Figure 5-23: Online City Simulator View of Multiple Curves in Map Display – Windsor



Elizabeth City

Vulnerability Findings:

- In general, flooding in Elizabeth City from the Pasquotank River is not projected to cause disruption on the major highways (U.S.158, U.S.17, NC 344). However, flooding on local roads on tributaries to the Pasquotank will be significant and increasingly more disruptive in the future.
- South Road Street at Charles Creek, West Main Street and Providence Road. at a tributary to Knobbs Creek, are all expected to have overtopping depths at 1-2 feet during the 2020 500-year flood event.

Figure 5-24: Typical Overtopping Curves – Elizabeth City

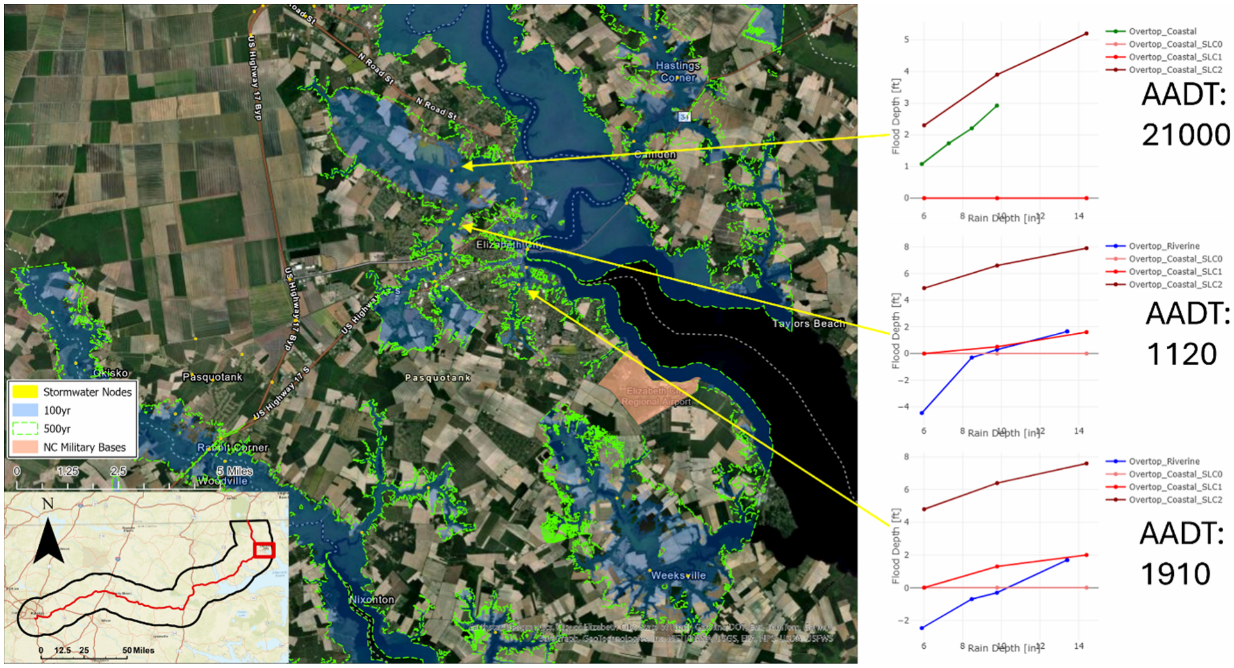
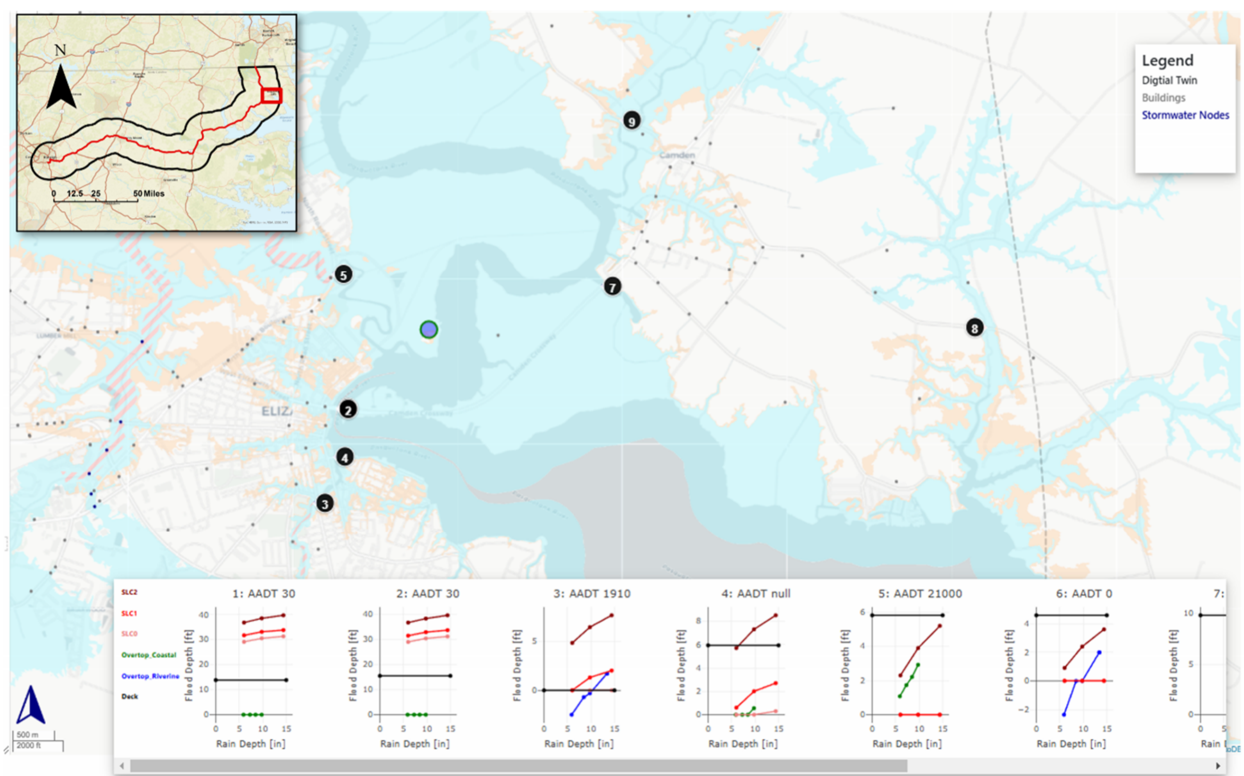


Figure 5-25: Online City Simulator View of Multiple Curves in Map Display – Elizabeth City



5.2 Study Question 2 Findings: Critical Facilities

The second question focused on critical facilities asked:

"Which critical facilities (hospitals, emergency care, shops, schools, NCDOT facilities, fire stations, and police stations) were most at risk of cutoff from access? Which assets (roads, bridges, culverts, pipes) were involved?"

The findings focused on identifying the remoteness, redundancy, and flood overtopping risk of the transportation network in each critical facility's service area and on how these factors are projected to change with climate change.

5.2.1 Finding 2.1: Critical facility risk varies depending on overtopping risk and remoteness/redundancy in the facility service area.

Figures 4.27 through 4.29 present the remoteness/redundance index, overtopping risk index, and total inaccessibility index respectively.

General conclusions from the assessment were:

- Inaccessibility peaks in multiple locations across the corridor with high-ranking facilities in both remote and urban areas. This is due to the inaccessibility index considering both remoteness/redundancy and overtopping risk.
- Overtopping risk is more of a factor in the parts of the corridor with flood risk. These locations include Tarboro, Rocky Mount, and the Raleigh suburbs. Flooding in these locations is likely due to potential riverine flooding during larger storms like hurricanes.

The remoteness/redundancy, overtopping risk, and inaccessibility indexes are stored in the I-87 City Simulator geodatabase provided as part of the deliverables of this project. Readers can view this data in a standard GIS software package or use the web app, also delivered as part of this project.

Figure 5-26: Critical Facilities by Remoteness/Redundancy

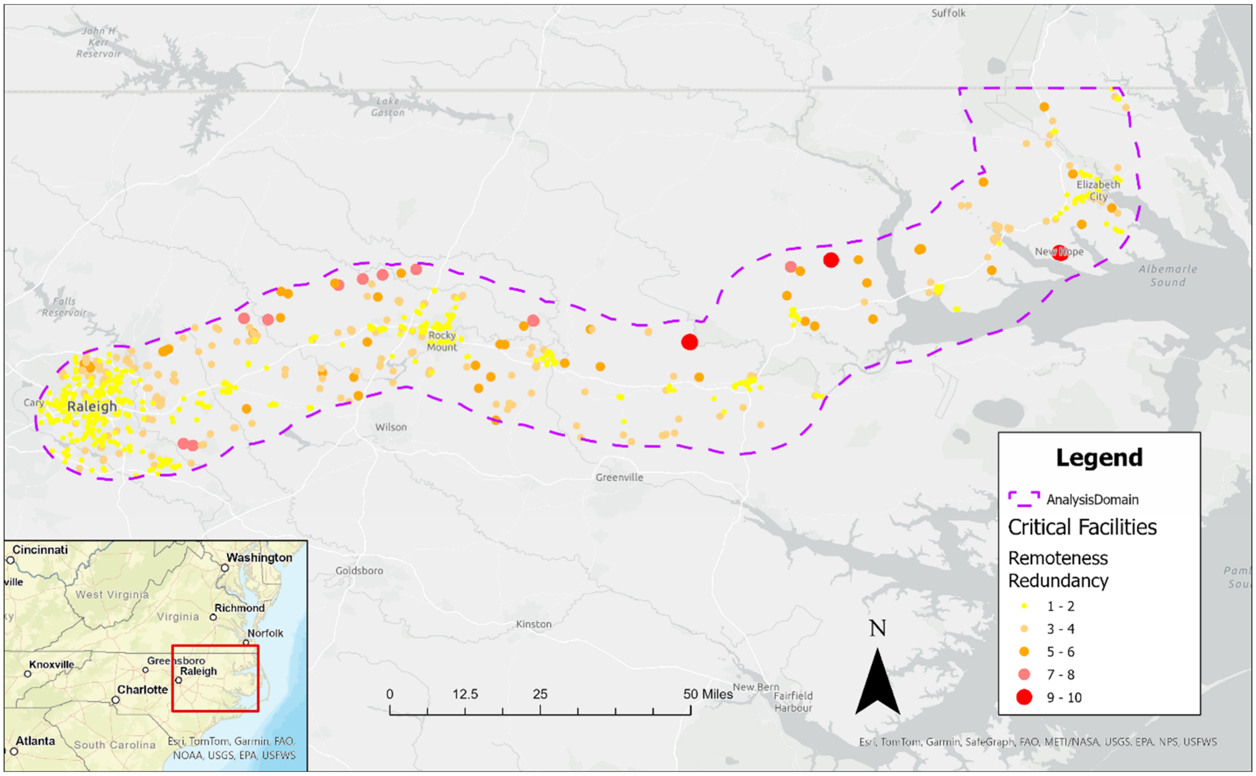


Figure 5-27: Critical Facilities by Overtopping Risk

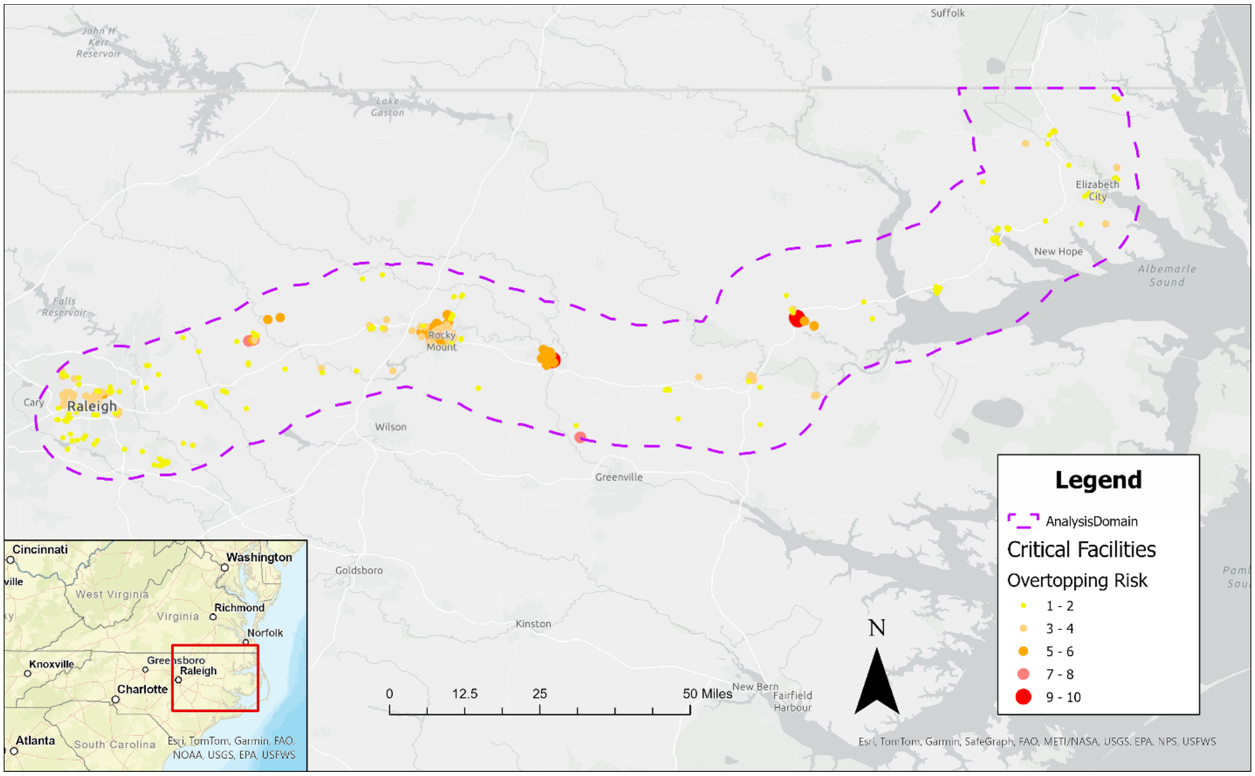
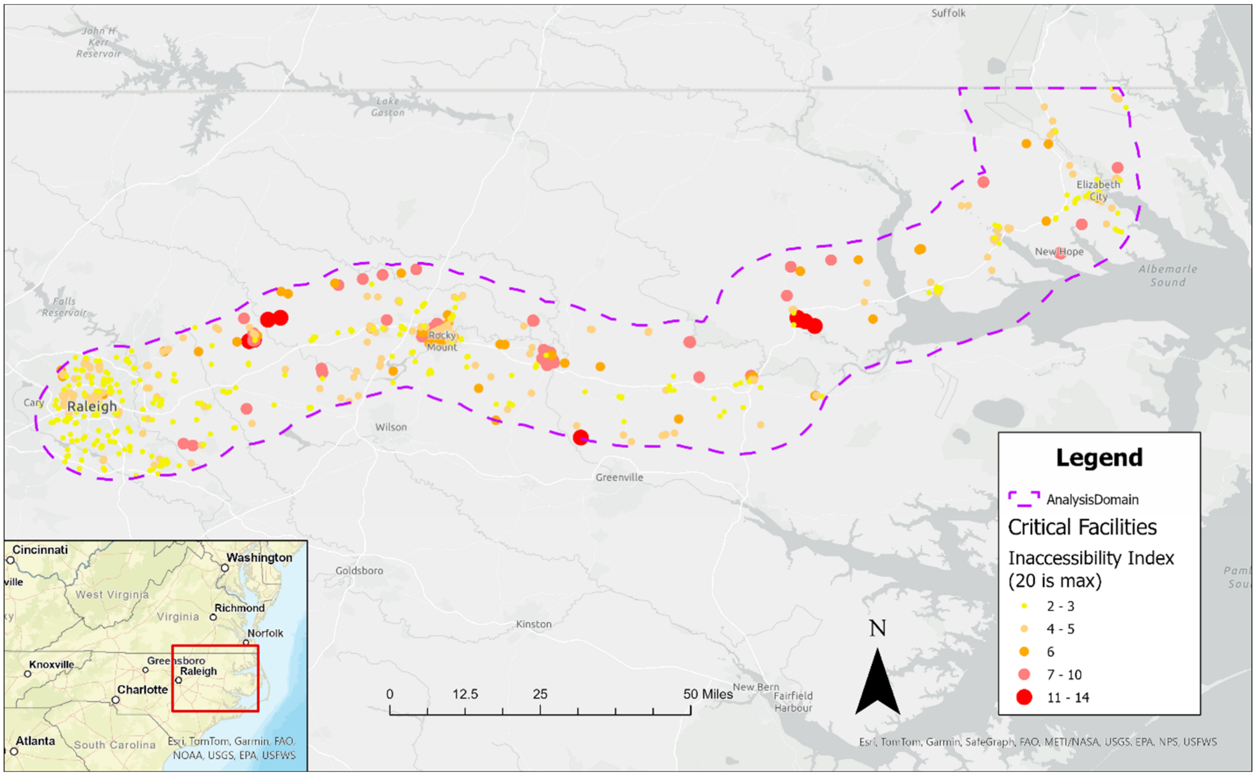


Figure 5-28: Critical Facilities Inaccessibility



5.2.2 Finding 2.2: Climate change impacts will likely exacerbate inaccessibility for critical facilities.

The climate change impact on critical facilities was projected to be similar to the impacts described above for the larger corridor. Water crossing locations such bridges, culverts, and pipes will encounter increasingly intense floods that threaten the reduction of accessibility in already remote and low route-redundancy critical facilities. The facilities with large service areas were found to be most at risk, because they often had a single route for access, a route that experienced severe flooding in future decades.

5.3 Study Question 3 Findings: Disadvantaged Populations

The third question focused on disadvantaged populations, asking:

"How were disadvantaged populations impacted by climate disruptions to the transportation system?"

The findings focused on current levels of access for disadvantaged populations to sustenance facilities (gas stations, stores, emergency care, emergency shelters), and how the level of access will change with climate change.

5.3.1 Finding 3.1: Climate change is likely to exacerbate inaccessibility for disadvantaged populations.

Disadvantaged populations were defined through the NCDOT Title VI-based guidelines as census block groups with high poverty and minority populations. See Sections 4.12 and 4.13 for details on how the populations were defined. Once defined, the roads within the disadvantaged census block groups were evaluated for their level of inaccessibility by an index that integrated the length of travel, road network density and flood risk along routes in nearby sustenance facilities. Sustenance facilities were defined as stores, emergency health care, emergency shelters, and gas stations.

Average annual trips and days disrupted were calculated for the early period of the simulation. Both the early period estimates and the late period estimates were 95^{th} percentile — or near worst case — estimates of disruption in their respective five-year periods.

Refer to figure 4-28 for a corridor-wide depiction of sustenance inaccessibility for disadvantaged populations. The analysis showed that Inaccessibility is a concern for disadvantaged populations across the corridor. Expected SLR compounded with storm surge, riverine, and pluvial flooding at the coast is projected to lead to significant increases in flood risk, while isolated disadvantaged populations in rural areas experienced increasing flood risk from pluvial and riverine sources.

Depending on location within the corridor, the projected increase in average annual trips disrupted from 2020 to 2100 ranged from five percent to more than eight times. This is because of both increased flood risk and increased travel on flood-prone roads, as population increased into the future.

6 Adaptation and Mitigation

6.1 Rationale

The simulator was used to test reducing the vulnerabilities identified in the previous chapter with adaptation and mitigation actions. These actions included the elevation of bridges and the roadways that overtopped culverts, hardened rail crossings, elevating roads at the coast, and increased redundant routes in inaccessible areas.

The study used a scenario-based approach, where a portfolio of actions was introduced in a single resilience-focused scenario. This scenario was simulated, and the subsequent performance metrics were compared to the same metrics evaluated in the vulnerability assessments' baseline run scenario.

Resilience-focused improvements were pursued on all future projects in the corridor, both documented STIP projects and automated maintenance projects initiated by asset condition decay. The type of improvement implicitly varied with the asset type. For example, if the asset was a bridge and a replacement was projected, then the improvement was to design and construct the asset with a higher protection level than the level used to design the current asset.

In the baseline scenario, a 2020 50-year event protection level was assumed as the design criterion — implying that any new bridge, culvert, or drainpipe is designed so that the road deck is above the water surface elevation projected to occur during a 2020 50-year flood event.

In the resilience-focused scenario, the protection level was increased to the 2020 500-year level. This increase resulted in increased cost as a percentage of asset replacement cost, as summarized in **Table 6-1:** Protection Level and Percent of Replacement Cost below. For this study, it was assumed that all current assets are designed to the 50-year protection level in the baseline scenario, and that in the resilience-focused scenario the protection level was at 500-year, which increased cost for replacement by 50%.

Table 6-1: Protection Level and Percent of Replacement Cost

Protection Level	Percent of Replacement Cost
50-year 24-hour	100%
100-year 24-hour	125%
500-year 24-hour	150%
1,000-year 24-hour	200%
All Storms	250%

An initial simulation of the resilience-focused scenario increased the protection level to the 500-year, while other factors such as the scheduling of maintenance events remained the same as the baseline scenario. In this initial scenario run, the level of investment was not limited, and return on investment (ROI) was not used as a guide. Often, this approach led to a reactive approach to improving resilience by only replacing and improving assets in the wake of storms.

Further, as many of the assets in the transportation system were installed around the same time, the approach led to “clumping” of maintenance projects, where years of relatively little spending were followed by heavy spending years. The findings on asset spending above underscored this effect. (See Finding 1.5 which shows relatively little asset spending in the 2030s followed by high very high spending requirements in the 2040s and 2050s.)

A sensitivity assessment was then conducted to refine the resilience-focused scenario to reduce post-disaster spending and achieve the highest resilience ROI given limited spending per year**. Figure 6-1** summarizes the resilience-focused scenario runs. The subsequent sections summarize the results of the initial resilience-focused run and sensitivity analysis.

Figure 6-1: Base Run and Resilience-Focus

Base Run	Resilience-focus	
• Ground-truthed Maintenance • Current Plans (2020-2030) • No Adaptation • No Mitigation	• Same as Base Run • Add resilience actions at each opportunity • Elevate Bridges/Culverts to 2020 500-year WSEL • Harden Rail Crossings • Increase Route Redundance	**Timing** • All at start • Annual Steady Improvement • Post-Disaster

6.2 Resilience-Focus Scenario

6.2.1 Improved Protection Level from 50-Year Storm to 500-Year Storm

Increasing the protection level from 50-year to 500-year in all future projects resulted in a substantial reduction of disruption in the corridor.

An important note is that this assessment focused generally on adaptation and mitigation actions that controlled flooding. For this reason, the improvements from the resilience-focused scenario improved the disruption because of flood and storm metrics, while having no substantial impact on heat-related and SLR-related disruption. Future studies should evaluate more adaptation actions that address these impacts.

6.2.2 Balance Between Improvements and Increased Risk and Level of Service

Despite protecting assets to the 500-year level, significant damage was found to still occur in the transportation system and grow in the future. This disruption is due to a steady, heightened demand on the road system by travelers and an increased intensity in storms. By the end of the simulation, the 95th percentile storms were substantially larger than in the early period, which meant that even if the transportation assets had been improved up to the 2020 500-year storm, the assets will continue to be damaged, resulting in disrupted trips.

The simulation projected that when large storm events occur around mid-century, the high level of overtopping will likely destroy the road deck, resulting in a recovery period of 180 days. As this highway transports thousands of trips per day now and will potentially carry approximately 60% more by 2100, the long-duration recovery event had a larger impact event on disrupted trips than a similar event that happens in 2020, regardless of the protection level.

6.2.3 Varied Asset Improvement Timing to Increase Resilience

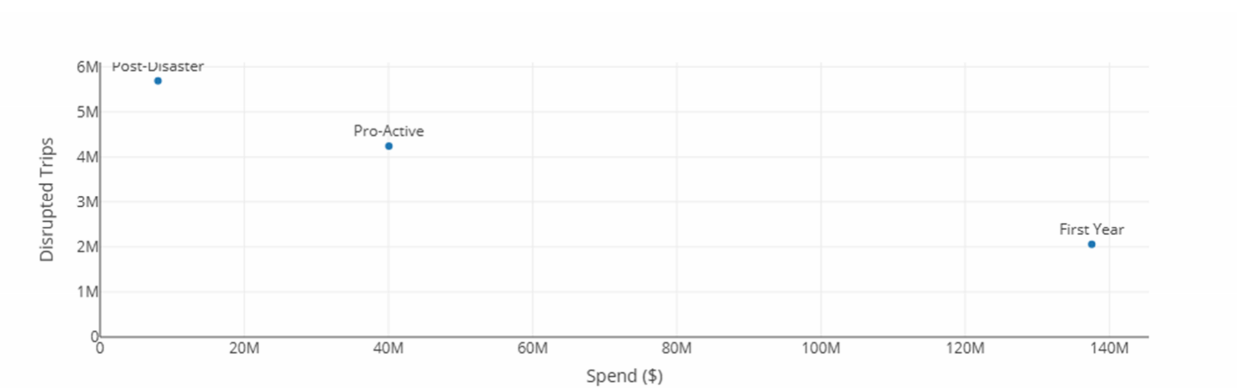
The initial resilience-focused scenario ran similarly to the baseline in terms of scheduling. That is, the 2020–2029 STIP projects were implemented along with asset condition-based maintenance events. This approach largely ignored resilience as a priority for scheduling asset improvement, beyond any focus on resilience built into the STIP.

A sensitivity analysis was conducted that focused on adjusting the scheduling of resilience-focused projects to explore methods to reduce disruption further. The three schemes compared were:

- **Post-disaster** — This was the initial resilience-focused scenario, where improvements only occurred post-disaster, or when an asset's condition hit failing and initiated maintenance.
- **Annual Improvement Investment** — This followed a set annual expenditure on improvements of $500K (or approximately 6%) of the current average maintenance budget. The budget was used to improve as many of the highest flood-risk assets as possible each year. The run was conducted with a rolling balance, meaning that funds not spent in any given year would accrue and be accessible in the following year.
- **Improve all assets at start of simulation** — This unrealistic approach aimed to quantify the attainable minimum level of disruption and assumed no limit of funds in the first year of the simulation.

Figure 6-2 shows the results of the analysis. Post-disaster and maintenance triggered improvements resulted in approximately 5.8M trips disrupted per year. If the whole system is improved in the start year, the resulting disrupted trips were around 2M trips, a 69% reduction in disrupted trips. However, this approach required spending $137M, an impracticable approach.

Figure 6-2: Sensitivity to Scheduling of Improvement Projects



The sensitivity analysis showed that 40% of the benefit in terms of disrupted trips could be gained by spending 25% of the cost of doing a full system replacement with more resilient assets.

Locations of Special Interest

Seven locations of interest as seen in **Figure 5-11** were identified for special review in the study. They included Tarboro/Princeville, Rocky Mount, Bear Grass, Hertford, Edenton Hancock, Windsor, and Elizabeth City. This section will present findings on each area in respect to adaptation and mitigation.

6.2.4 Tarboro/Princeville

Recommendations and high-level view for Adaptation and Mitigation in Tarboro/Princeville Region:

- Bridge Rehabilitation and Replacement: Prioritize the rehabilitation and replacement of multiple bridges along U.S. 64 (Future I-87) to ensure structural integrity and safety.
- Lane Improvements: Enhance the number of lanes on roads feeding into or near Future I-87 to accommodate increased traffic and improve connectivity.

The table illustrates specific Transportation Improvement Projects (TIPs), while the map provides precise locations to address these adaptation and mitigation-oriented projects.

Figure 6-3: Tarboro/Princeville Master-Planned Projects Map

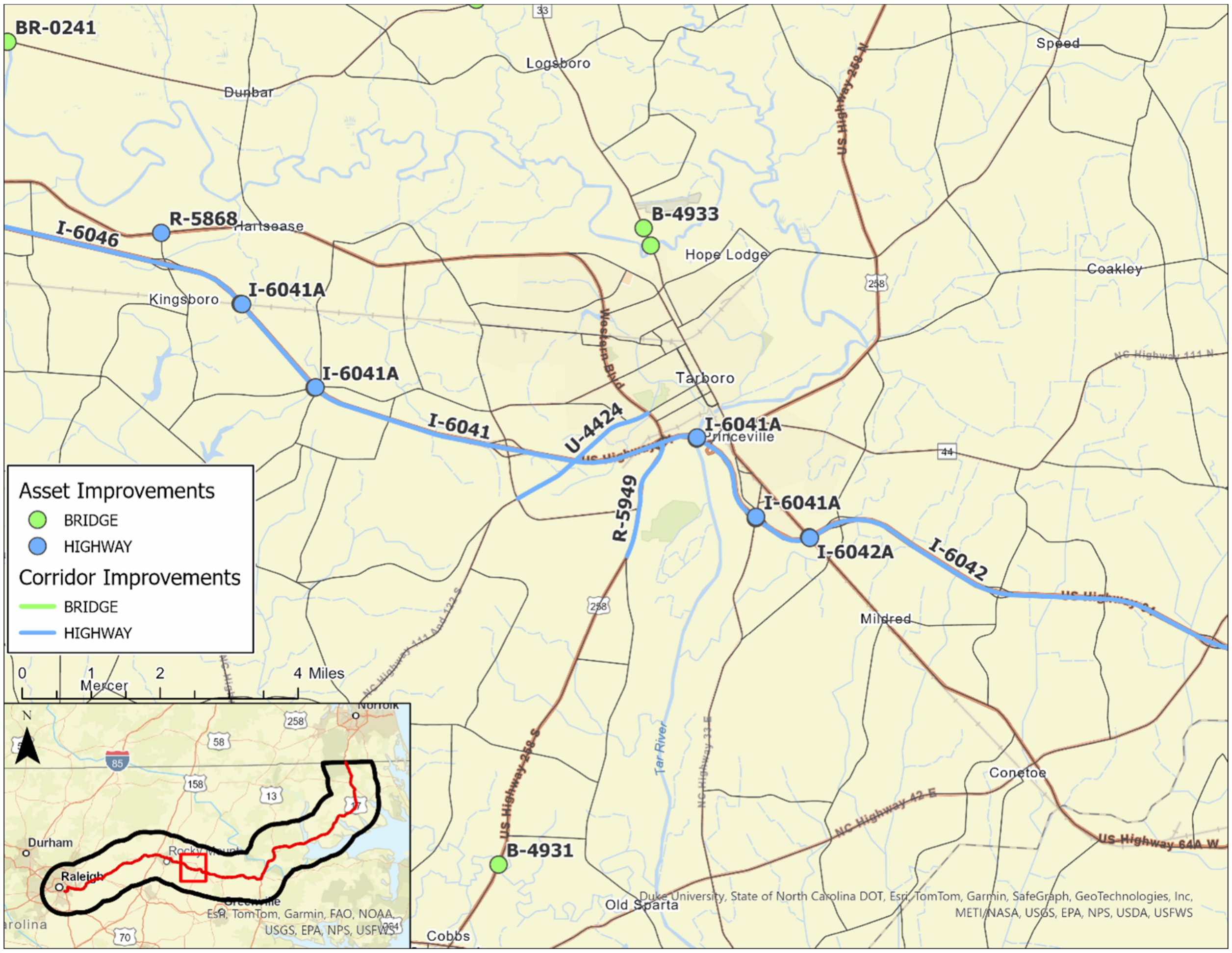


Table 6-2: Tarboro/Princeville Master-Planned Projects

TIP	Route	Description
R-5868	NEW ROUTE	SR 1252 (DUNBAR ROAD) TO SR 1225 (KINGSBORO ROAD). CONSTRUCT TWO LANE ROAD ON NEW LOCATION AND IMPROVEMENTS TO SR 1225 TO SERVE KINGSBORO MEGASITE.
B-4931	US 258	REPLACE BRIDGE 320022 OVER TOWN CREEK.
B-5655	NC 111 / NC 122	REPLACE BRIDGE 320011 OVER TOWN CREEK.
B-5671	NC 97	BRIDGE 87 OVER SWIFT CREEK ON NC 97.
B-6002	SR 1126 (FAITH BAPTIST CHURCH ROAD)	REPLACE BRIDGE 320064 OVER TOWN CREEK.
BR-0241	SR 1243 (LEGGETT ROAD)	REPLACE BRIDGE 320054 OVER TAR RIVER.
I-6041A	US 64 (FUTURE I-87)	REHABILITATE BRIDGE 320104, 320155, 320148, 320153, 320154, 320156, 320157, 320320, 320325, AND 320326.
I-6042A	US 64 (FUTURE I-87)	REHABILITATE BRIDGE 320327 AND 320328.
B-4933	NC 33	REPLACE BRIDGE 320080 OVER TAR RIVER. REPLACE BRIDGE 320049 OVER TAR RIVER OVERFLOW.
I-6041	US 64 (FUTURE I-87)	SR 1233 (THOMAS ROAD) OVERPASS TO NC 33. PAVEMENT REHABILITATION.
I-6042	US 64 (FUTURE I-87)	NC 33 TO MARTIN COUNTY LINE. PAVEMENT REHABILITATION.
I-6046	US 64 (FUTURE I-87)	SR 1603 (OLD CARRIAGE ROAD) TO SR 1225 (KINGSBORO ROAD). PAVEMENT REHABILITATION.
R-5949	US 258	SR 1601 (COLONIAL ROAD) TO US 64. WIDEN ROADWAY.
U-4424	NC 111 (WILSON STREET)	US 64 ALTERNATE (WESTERN BOULEVARD) TO NC 122 (MCNAIR ROAD). WIDEN TO THREE LANES.

6.2.5 Rocky Mount

Recommendations and high-level view for Adaptation and Mitigation in Rocky Mount:

- Infrastructure Enhancements: Construct roundabouts to improve traffic flow and safety. Rehabilitate bridges and pavement to ensure structural integrity and smooth travel and replace aging bridges to enhance reliability.
- Safety and Accessibility Improvements: Install pedestrian signs and other necessary signage to improve safety and navigation. Develop streetscapes that accommodate sidewalks and bicycle lanes, promoting safer and more accessible routes for pedestrians and cyclists.
- Multi-Use Path Development: Convert an old railroad into a multi-use path to provide recreational opportunities and alternative transportation options, enhancing the overall adaptability and resilience of the corridor.

These projects, both directly along U.S. 64 (Future I-87) and in its vicinity, aim to make the entire corridor more adaptable and resilient. The table illustrates specific Transportation Improvement Projects (TIPs), while the map provides precise locations to address these adaptation and mitigation-oriented projects.

Figure 6-4: Rocky Mount Master-Planned Projects Map

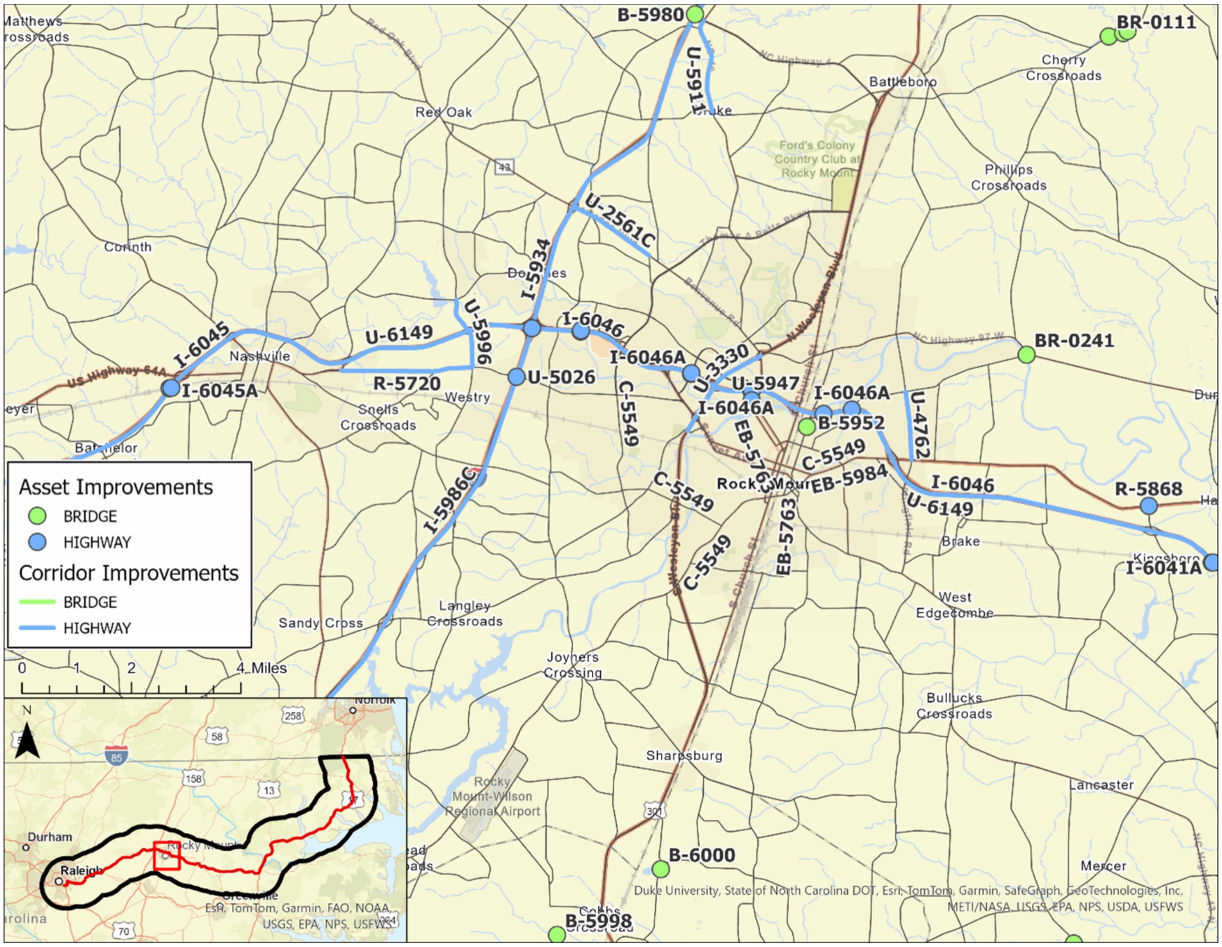


Table 6-3: Rocky Mount Master-Planned Projects

TIP	Route	Description
B-5998	SR 1339 (SHARPE SHORE ROAD)	REPLACE BRIDGE 970092 OVER TOWN SWAMP.
B-6000	SR 1400 (ROCK QUARRY ROAD)	REPLACE BRIDGE 970096 OVER TRIBUTARY OF TOWN CREEK.
BR-0111	SR 1404 (SEVEN BRIDGES ROAD)	REPLACE BRIDGE NO. 320003, 320004, 320005 OVER SWIFT CREEK ON SR 1404 (SEVEN BRIDGES ROAD).
R-5868	NEW ROUTE	SR 1252 (DUNBAR ROAD) TO SR 1225 (KINGSBORO ROAD). CONSTRUCT TWO LANE ROAD ON NEW LOCATION AND IMPROVEMENTS TO SR 1225 TO SERVE KINGSBORO MEGASITE.
U-5026	I-95	SR 1770 (SUNSET AVENUE) IN ROCKY MOUNT. CONVERT GRADE SEPARATION TO AN INTERCHANGE.
B-6002	SR 1126 (FAITH BAPTIST CHURCH ROAD)	REPLACE BRIDGE 320064 OVER TOWN CREEK.
BR-0241	SR 1243 (LEGGETT ROAD)	REPLACE BRIDGE 320054 OVER TAR RIVER.
I-5933A	I-95	BRIDGE REHABILITATION FOR 630009 AND 630012.
I-6041A	US 64 (FUTURE I-87)	REHABILITATE BRIDGE 320104, 320155, 320148, 320153, 320154, 320156, 320157, 320320, 320325, AND 320326.
I-6045A	US 64 (FUTURE I-87)	BRIDGE REHABILITATION FOR 630072 AND 630074.
I-6046A	US 64 (FUTURE I-87)	SR 1603 (OLD CARRIAGE ROAD) TO SR 1225 (KINGSBORO ROAD). REHABILITATE BRIDGE 630162, 630209, 630210, 630216, 630217, 630172, 630176, 320135, 320138.
B-5952	NC 97	REPLACE BRIDGE 320051 OVER TAR RIVER.
U-5947	NC 43 (BENVENUE ROAD)	US 64 BYPASS OFF RAMP. CONSTRUCT ROUNDABOUT.
B-5980	SR 1522 (HALIFAX ROAD)	REPLACE BRIDGE 630203 OVER I-95.
C-5549	ROCKY MOUNT	WINSTEAD AVENUE. CONSTRUCT SIDEWALKS.
EB-5711	US 64 BUSINESS (SUNSET AVENUE)	SR 1836 (MAY DRIVE) TO US 301 BUSINESS, NORTH BOUND (CHURCH STREET). INSTALL PEDESTRIAN SIGNALS.
EB-5729	NC 97 (ATLANTIC AVENUE)	US 64 TO EAST RALEIGH BOULEVARD IN ROCKY MOUNT. PEDESTRIAN IMPROVEMENTS.
EB-5761	US 301 BUSINESS (CHURCH STREET)	US 64 TO NC 97 (RALEIGH BOULEVARD) OVERPASS. CONSTRUCT STREETSCAPE IMPROVEMENTS. ADD SIDEWALK AND BICYCLE LANES.
EB-5763	ROCKY MOUNT	US 301 BUSINESS, RIVER DRIVE TO MONK STREET IN ROCKY MOUNT. CONVERT ABANDONED RAILROAD TO MULTI-USE PATH.
EB-5984	EAST RALEIGH BOULEVARD	US 64 TO ARLINGTON STREET IN ROCKY MOUNT. PEDESTRIAN IMPROVEMENTS.
I-5933	I-95	WILSON COUNTY LINE (MILE MARKER 124.6) TO THE NORTH OF NC 97 (MILE MARKER 127.6). PAVEMENT AND BRIDGE REHABILITATION.
I-5934	I-95	SR 1770 (SUNSET AVENUE) (MILE MARKER 137.4) TO SR 1544 (NORTH HALIFAX ROAD) (MILE MARKER 142.1). PAVEMENT AND BRIDGE REHABILITATION.
I-5986C	I-95	INSTALL BROADBAND FIBER ALONG I-95 FROM SOUTH CAROLINA LINE TO VIRGINIA STATE LINE.
I-6041	US 64 (FUTURE I-87)	SR 1233 (THOMAS ROAD) OVERPASS TO NC 33. PAVEMENT REHABILITATION.
I-6045	US 64 (FUTURE I-87)	SR 1306 (SOUTH OLD FRANKLIN ROAD) TO SR 1603 (OLD CARRIAGE ROAD). PAVEMENT REHABILITATION.
I-6046	US 64 (FUTURE I-87)	SR 1603 (OLD CARRIAGE ROAD) TO SR 1225 (KINGSBORO ROAD). PAVEMENT REHABILITATION.
R-5720	SR 1770 (EASTERN AVENUE)	SR 1003 (RED OAK ROAD) TO SR 1603 (OLD CARRIAGE ROAD) IN ROCKY MOUNT. WIDEN TO MULTI-LANES.
U-2561C	NC 43	SR 1613 (WOODRUFF AVENUE) TO I-95.
U-3330	US 301 BYPASS	NC 43/NC 48 (BENVENUE ROAD) TO SR 1836 (MAY DRIVE) IN ROCKY MOUNT. ADD AN ADDITIONAL LANE IN EACH DIRECTION.
U-4762	SR 1250 (SPRINGFIELD ROAD)	US 64 ALTERNATE TO SR 1243 (LEGGETT ROAD). WIDEN TO MULTI-LANES.
U-5911	NC 48	SR 1524 (RED OAK/BATTLEBORO ROAD) TO NC 4. WIDEN TO MULTI-LANES.
U-5996	SR 1603 (OLD CARRIAGE ROAD)	GREEN HILLS ROAD TO SR 1770 (EASTERN AVENUE). ADD CENTER TURN LANE AND WIDEN US 64 BRIDGE OVER SR 1603.
U-6149	US 64	NC 58 (WASHINGTON STREET), EXIT 459, TO SR 1233 (THOMAS ROAD) OVERPASS. UPGRADE TO INTERSTATE STANDARDS.

6.2.6 Bear Grass

Recommendations and high-level view for Adaptation and Mitigation in Bear Grass:

- Future I-87 Projects: Address alternate routes to improve connectivity.
- State Routes and Highways: Focus on replacing bridges, managing access, and widening roads to multi-lanes.

Most projects are focused on state routes and highways near Future I-87, aiming to enhance the overall corridor. The table illustrates specific Transportation Improvement Projects (TIPs), while the map provides precise locations to address these adaptation and mitigation-oriented projects.

Figure 6-5: Bear Grass Master-Planned Projects Map

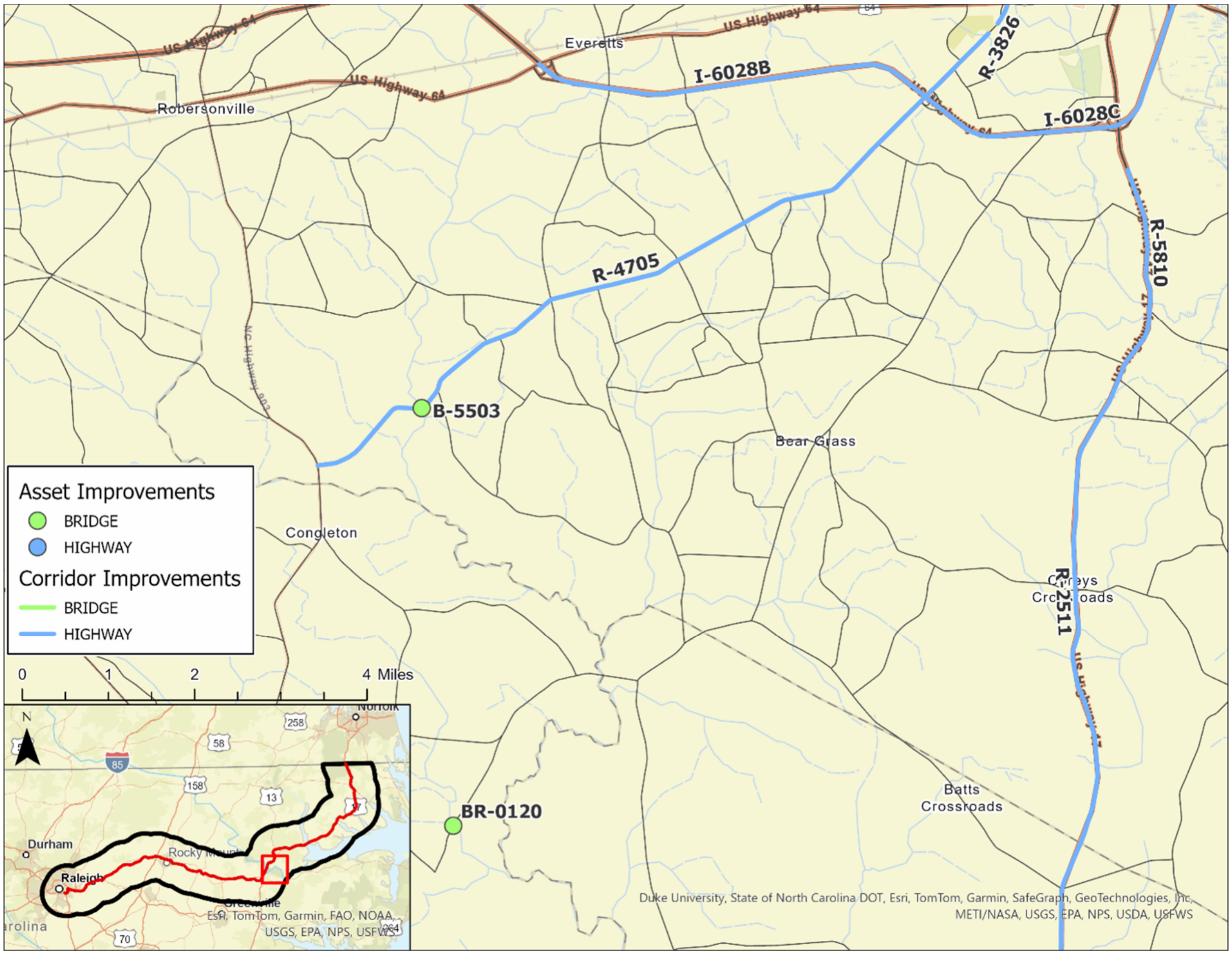


Table 6-4: Bear Grass Master-Planned Projects

TIP	Route	Description
B-5503	SR 1142 (PRISON CAMP ROAD)	REPLACE BRIDGE 570053 OVER COLLIE SWAMP.
BR-0120	SR 1551	REPLACE BRIDGE NO. 730123 OVER MEADOW BRANCH ON SR 1552.
I-6028B	US 64 (FUTURE I-87)	US 64 ALTERNATE TO NC 125.
I-6028C	US 64 (FUTURE I-87)	NC 125 TO US 13/17 AND US 64 INTERCHANGE.
R-2511	US 17	WASHINGTON BYPASS NORTH OF NC 171 TO MULTI-LANES SOUTH OF WILLIAMSTON. WIDEN TO MULTI-LANES.
R-3826	NC 125	SR 1182 (EAST COLLEGE ROAD) TO NC 125 NORTHWEST OF WILLIAMSTON. TWO LANES, PART ON NEW LOCATION.
R-4705	SR 1142 (PRISON CAMP ROAD)	NC 903 TO SR 1182 (EAST COLLEGE ROAD). UPGRADE FACILITY.
R-5810	US 17	SR 1119 (RALPH TAYLOR ROAD) TO SR 1205 (HOLLY CREEK ROAD). ACCESS MANAGEMENT.

6.2.7 Hertford

Recommendations for Improvement Near Future I-87:

- Future I-87 Projects: Address alternate routes to improve connectivity.
- State Routes and Highways: Focus on replacing bridges, managing access, and widening roads to multi-lanes.

Most projects are focused on state routes and highways near Future I-87, aiming to enhance the overall corridor. The table illustrates specific Transportation Improvement Projects (TIPs), while the map provides precise locations to address these adaptation and mitigation-oriented projects.

Figure 6-6: Hertford Master-Planned Projects Map

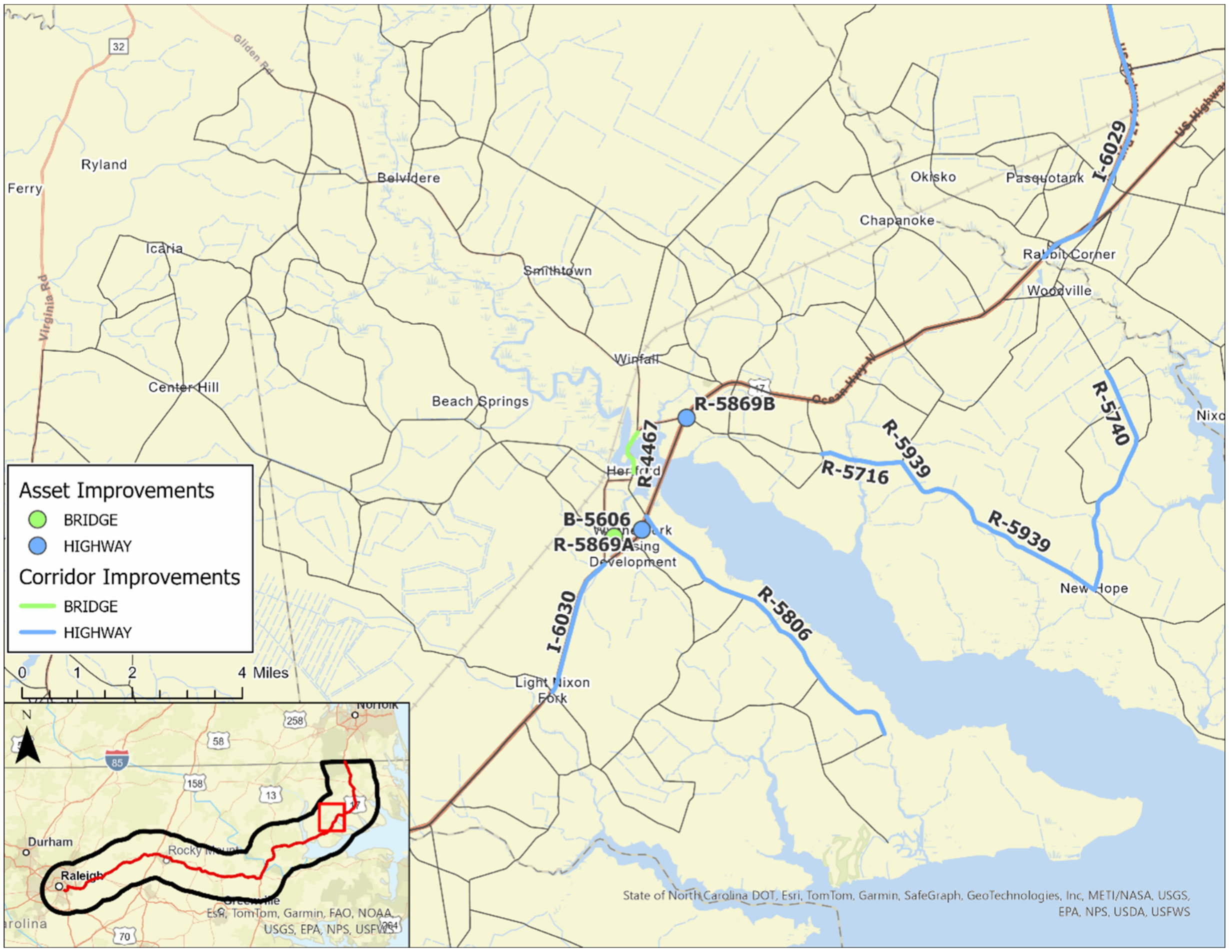


Table 6-5: Hertford Master-Planned Projects

TIP	Route	Description
B-5606	SR 1338 (WYNNE FORK ROAD)	REPLACE BRIDGE 710011 OVER RACOON CREEK.
R-5869A	US 17	SR 1336 (HARVEY POINT ROAD) AND SR 1338 (WAYNE FORK ROAD). CONVERT AT-GRADE INTERSECTION TO AN INTERCHANGE.
R-5869B	US 17	SR 1300 (NEW HOPE ROAD). CONVERT AT-GRADE INTERSECTION TO INTERCHANGE.
I-6027	US 17 (FUTURE I-87)	BERTIE COUNTY LINE TO PERQUIMANS COUNTY LINE. PAVEMENT REHABILITATION.
I-6029	US 17 (FUTURE I-87)	PERQUIMANS COUNTY LINE TO NORTH END OF US 17 (ELIZABETH CITY) BYPASS. PAVEMENT REHABILITATION.
I-6030	US 17 (FUTURE I-87)	SR 1101 (EAST BEAR SWAMP ROAD) TO US 17 BUSINESS NORTH OF HERTFORD. PAVEMENT REHABILITATION.
R-4467	US 17 BUSINESS/ NC 37 (NORTH CHURCH STREET)	FROM SOUTH OF PERQUIMANS RIVER BRIDGE TO NORTH OF NC 37. REPLACE BRIDGE 710008.
R-5716	SR 1300 (NEW HOPE ROAD)	SR 1302 (UNION HALL ROAD) TO SR 1303 (WOODLAND CHURCH ROAD). WIDEN AND RESURFACE.
R-5740	SR 1329 (WOODVILLE ROAD)	SR 1331 (RED BANK ROAD) TO SR 1300 (NEW HOPE ROAD). UPGRADE ROADWAY.
R-5806	SR 1336 (HARVEY POINT ROAD)	US 17 TO SR 1350 (CHURCHES LANE). MODERNIZE ROADWAY.
R-5939	SR 1300 (NEW HOPE ROAD)	WOODLAND CHURCH ROAD TO WOODVILLE ROAD (SR 1329). MODERNIZE ROADWAY.

6.2.8 Edenton/Hancock

Recommendations and high-level view for Adaptation and Mitigation in Edenton/Hancock:

- Pavement Rehabilitation: Focus on rehabilitating pavement directly on Future I-87.
- Bridge Replacements and Interchanges: Address bridge replacements and the creation of new interchanges.

The table illustrates specific Transportation Improvement Projects (TIPs), while the map provides precise locations to address these adaptation and mitigation-oriented projects.

Figure 6-7: Edenton/Hancock Master-Planned Projects Map

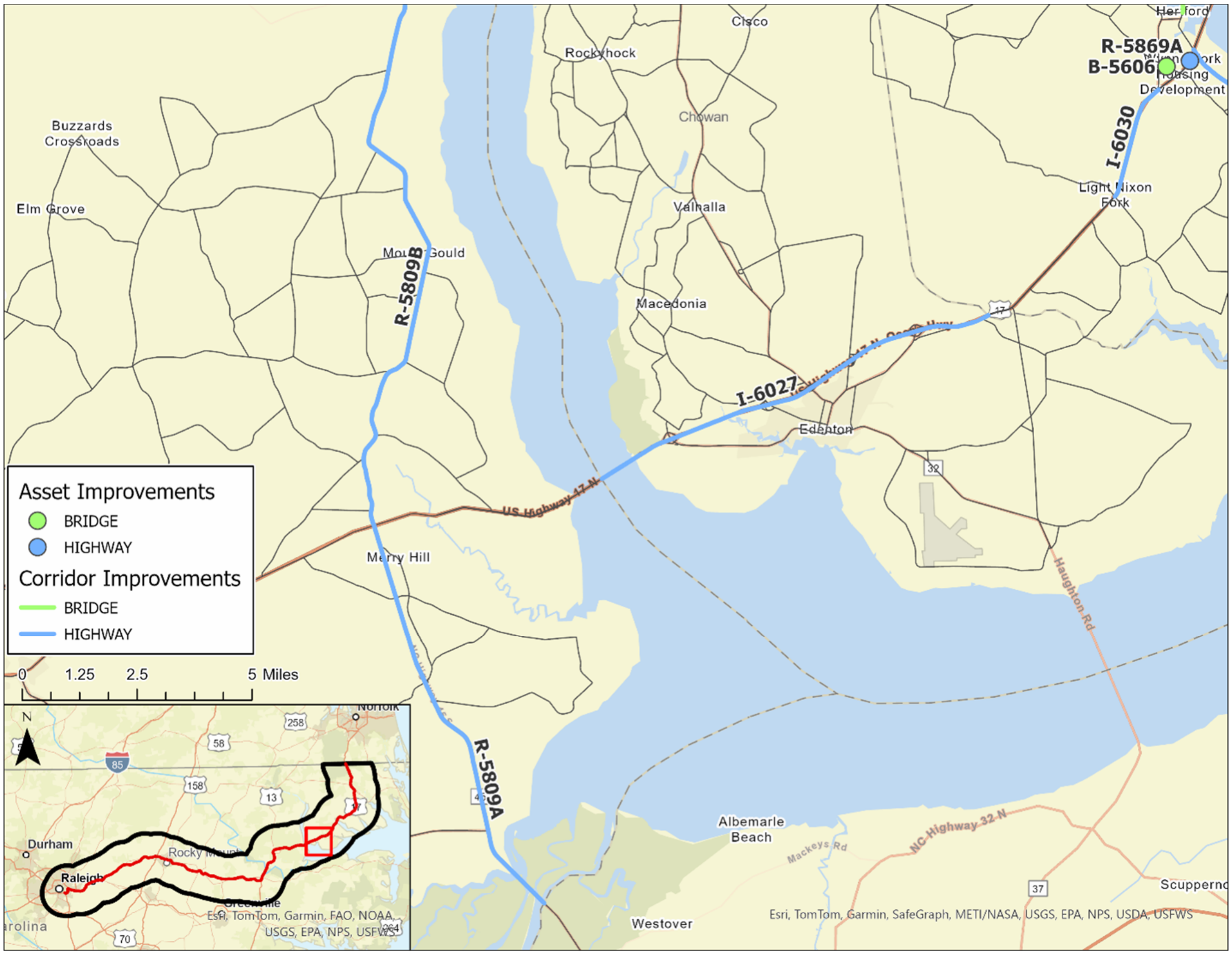


Table 6-6: Edenton/Hancock Master-Planned Projects

TIP	Route	Description
B-5606	SR 1338 (WYNNE FORK ROAD)	REPLACE BRIDGE 710011 OVER RACOON CREEK.
R-5869A	US 17	SR 1336 (HARVEY POINT ROAD) AND SR 1338 (WAYNE FORK ROAD). CONVERT AT-GRADE INTERSECTION TO AN INTERCHANGE.
I-6027	US 17 (FUTURE I-87)	BERTIE COUNTY LINE TO PERQUIMANS COUNTY LINE. PAVEMENT REHABILITATION.
I-6030	US 17 (FUTURE I-87)	SR 1101 (EAST BEAR SWAMP ROAD) TO US 17 BUSINESS NORTH OF HERTFORD. PAVEMENT REHABILITATION.
R-5809A	NC 45	WASHINGTON COUNTY LINE TO US 17 AT MIDWAY.
R-5809B	NC 45	US 17 AT MIDWAY TO SOUTHERN CITY LIMITS OF COLERAIN.

6.2.9 Windsor

Recommendations and high-level view for Adaptation and Mitigation in Windsor:

- Pavement Rehabilitation: Focus on rehabilitating pavement directly on Future I-87.
- Addition of curbs, ramps and sidewalks
- Expansion of lanes in certain areas along with the overall upgrading of facilities

The table illustrates specific Transportation Improvement Projects (TIPs), while the map provides precise locations to address these adaptation and mitigation-oriented projects.

Figure 6-8: Windsor Master-Planned Projects Map

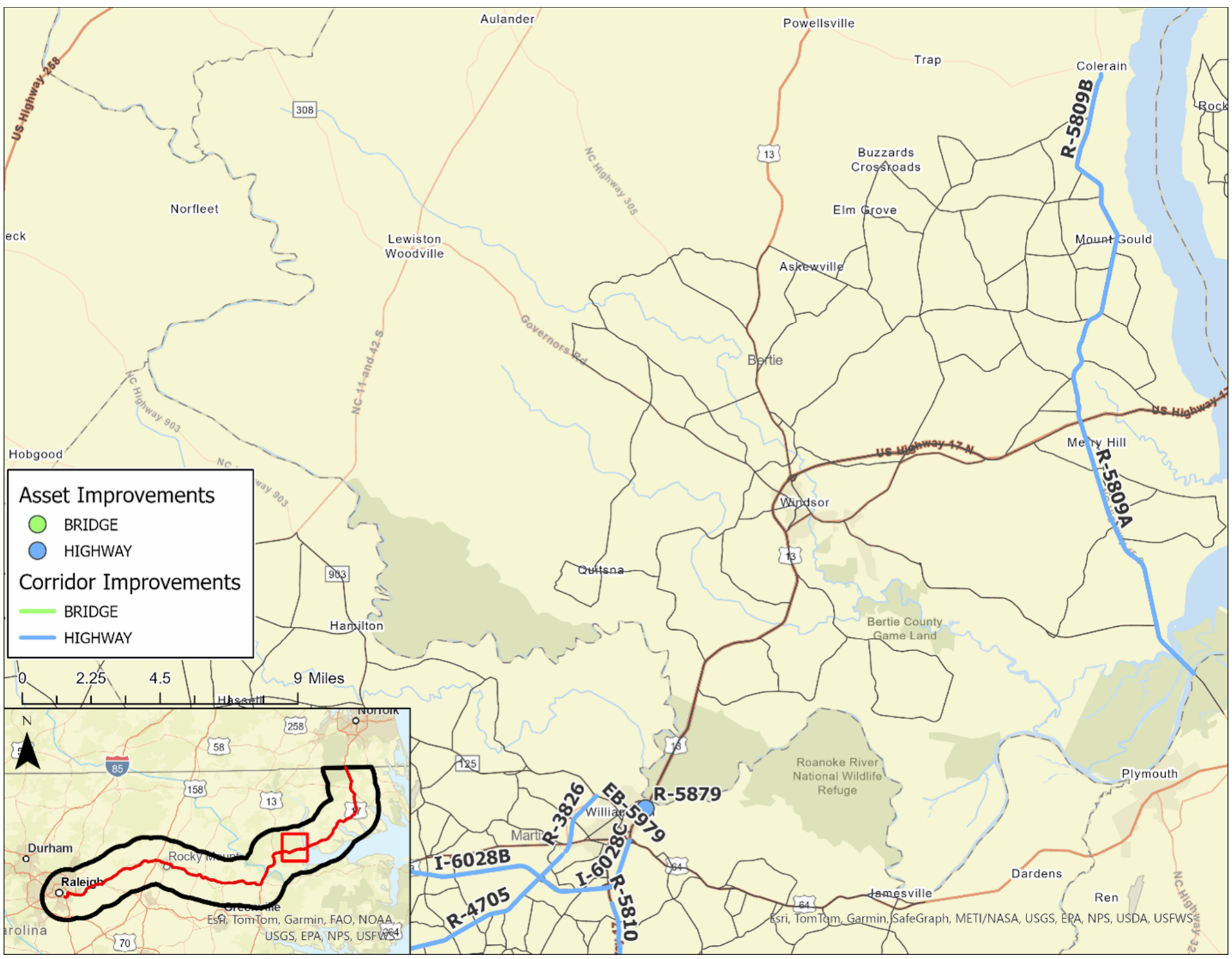


Table 6-7: Windsor Master-Planned Projects

TIP	Route	Description
R-5879	US 13/US 17	MAIN STREET IN WILLIAMSTON. IMPROVE INTERSECTION.
EB-5979	EAST MAIN STREET	BOULEVARD STREET TO RIVER ROAD IN WILLIAMSTON. INSTALL SIDEWALKS AND CURB RAMPS.
I-6027	US 17 (FUTURE I-87)	BERTIE COUNTY LINE TO PERQUIMANS COUNTY LINE. PAVEMENT REHABILITATION.
I-6028B	US 64 (FUTURE I-87)	US 64 ALTERNATE TO NC 125.
I-6028C	US 64 (FUTURE I-87)	NC 125 TO US 13/17 AND US 64 INTERCHANGE.
R-3826	NC 125	SR 1182 (EAST COLLEGE ROAD) TO NC 125 NORTHWEST OF WILLIAMSTON. TWO LANES, PART ON NEW LOCATION.
R-4705	SR 1142 (PRISON CAMP ROAD)	NC 903 TO SR 1182 (EAST COLLEGE ROAD). UPGRADE FACILITY.
R-5809A	NC 45	WASHINGTON COUNTY LINE TO US 17 AT MIDWAY.
R-5809B	NC 45	US 17 AT MIDWAY TO SOUTHERN CITY LIMITS OF COLERAIN.

6.2.10 Elizabeth City

Recommendations and high-level view for Adaptation and Mitigation in Elizabeth City:

- Bridge Replacement in areas near the Future I-87
- Intersections and signal systems need to be updated or installed
- Pavement and widening of roads need to be updated

The table illustrates specific Transportation Improvement Projects (TIP), while the map provides precise locations to address these adaptation and mitigation-oriented projects.

Figure 6-9: Elizabeth City Master-Planned Projects

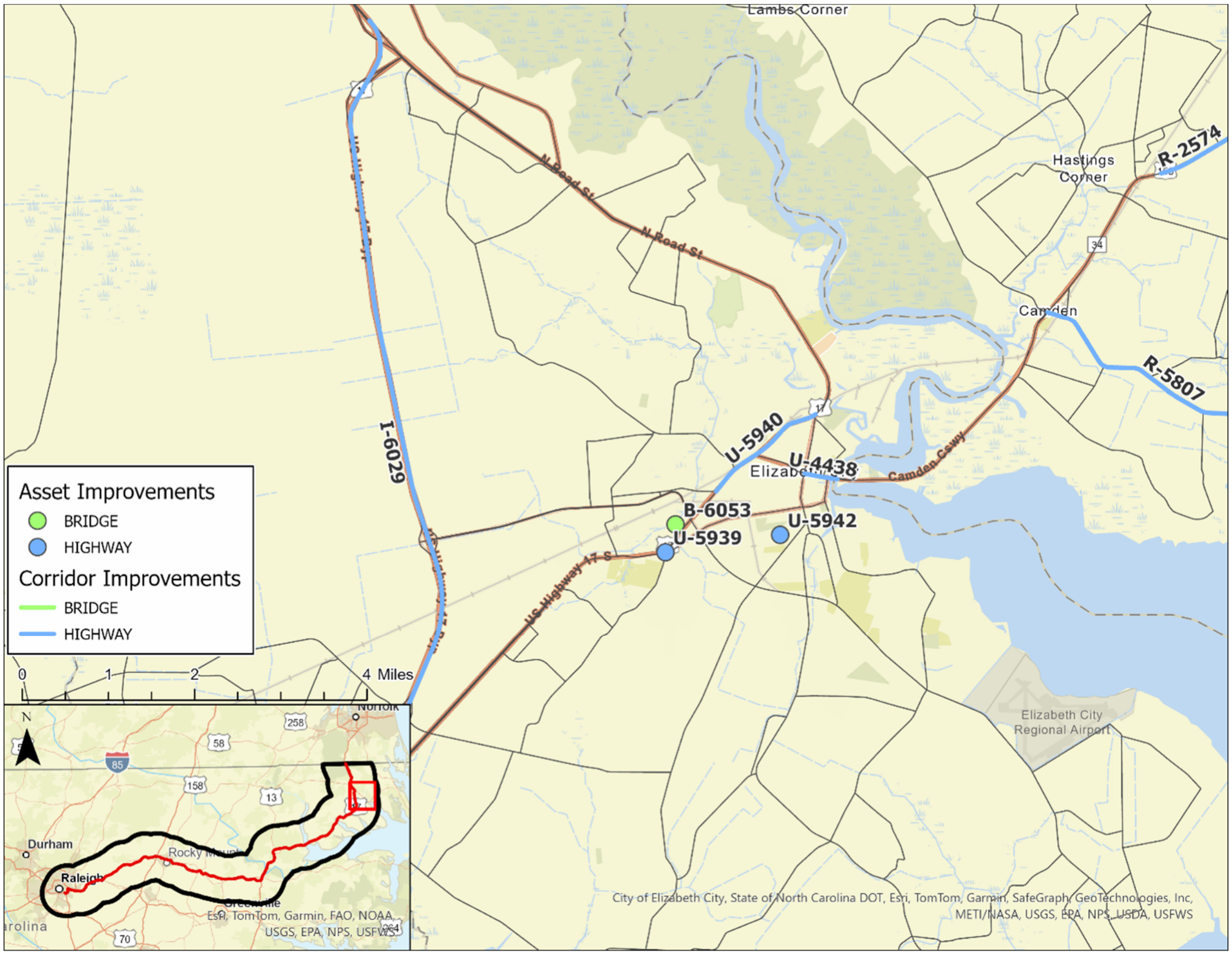


Table 6-8: Elizabeth City Master-Planned Projects

TIP	Route	Description
B-6053	PROVIDENCE ROAD	REPLACE BRIDGE 690034 OVER KNOBBS CREEK TRIBUTARY IN ELIZABETH CITY.
U-5939	US 17 BUSINESS	SR 1145 (OAK STUMP ROAD). IMPROVE INTERSECTION.
U-5942	ELIZABETH CITY	ELIZABETH CITY SIGNAL SYSTEM.
I-6029	US 17 (FUTURE I-87)	PERQUIMANS COUNTY LINE TO NORTH END OF US 17 (ELIZABETH CITY) BYPASS. PAVEMENT REHABILITATION.
R-2574	US 158 (SHORTCUT ROAD)	EAST OF NC 34 (SHAWBORO ROAD) AT BELCROSS IN CAMDEN COUNTY TO US 158/NC 168 (CARATOKE HIGHWAY) IN CURRITUCK COUNTY. WIDEN TO MULTI-
R-5807	NC 343	US 158 IN CAMDEN TO SR 1119 (SOUTH TROTMAN ROAD) IN SHILOH. MODERNIZE ROADWAY AND REPLACE BRIDGES 140017 AND 140018 IN
U-4438	US 158	US 17 BUSINESS (NORTH ROAD STREET) TO EAST OF PASQUOTANK RIVER IN ELIZABETH CITY. RECONSTRUCT ROADWAY AND REPLACE BRIDGE 690019.
U-5940	US 17 (HUGHES BOULEVARD)	SR 1308 (CHURCH STREET) TO US 17 BUSINESS (NORTH ROAD STREET).

7 Recommendations and Next Steps

The study revealed vulnerabilities throughout the I-87 corridor with future climate change. Also, multiple opportunities for adaptation and mitigation were revealed in the assessment of adaptation and mitigation options. They are listed below and categorized into one of four groupings: increased information, policy and planning, general infrastructure improvement, and physical countermeasures to climate change.

7.1 Increased Information and Awareness

- NPV Asset Investment Calculations.
- Add Benefit to Cost Ratio to Assessment.
- Increase the number of flood sensors (stream gauges, rain gauges, gauges of road overtopping) on I-87 and supported transportation infrastructure.
- Expansion of Rain-on-Grid Flood Models to the whole corridor.
- Improve Compound Flood Modeling.
- Inclusion of Real-Storm Models in Simulation.
- On-going cost calibration between SAP and Digital Twins.
- Simulator Training for NCDOT staff.
- Increase accuracy and understanding of service areas
- Improve definition of critical facilities against the populations they serve

7.2 Policy and Planning

- Adjust maintenance schedules and maximized preparedness.
- Integrate Master Planning across NCDOT/MPOs/Municipalities.
- Upgrade design guidelines with climate change and asset lifespan awareness — projected design levels matched preferably to lifespan of the asset. For example, if the asset is projected to provide a service life of 75 years, then the design guidelines should match storm levels 75 years after the install date of the planned asset.
- Introduce periodic vulnerability assessments and evaluate efficacy and update projections. For example, repeat this study on a five-year basis.
- Require future planning studies and engineering design processes include climate change influence.
- Adjust to a climate-infrastructure interaction model.
- Incorporate additional natural hazards and their impacts in vulnerability studies, such as wildfires and drought.
- Incorporate carbon footprint and net-zero assessment into studies.

7.3 Incorporate habitat and natural system concerns into future studies. General Infrastructure Improvement

- Prioritize Improvement Scheduling to Maximize Resilience.
- Improve Alternate Routes.
- Avoid Disaster Response-Driven Capital Improvement.
- Increased Inspection Rates to Identify Potential Problems.
- Improved Simulation of How Floods Impact — Road Structure Below Deck.
- Defined and Adopted Resilience-focused Standards.

7.4 Physical Countermeasures to Climate Change

- Harden roads.
- Adjust binder in asphalt mix and replace asphalt more frequently.
- Road Elevation.
    - Including the use of alternative materials (i.e., porous asphalt).
- Harden rail crossings.
- Harden freeboard areas against SLR Impacts.
- Evaluate and make improvements to Drainage Systems]

7.5 Locations of Special Interest

Seven locations of interest as seen in **Figure 5-11** were identified for special review in the study. Opportunities to improve the simulator in several of these areas were found and are noted here should additional simulation studies be carried out. Examples of opportunities include adding flood tracking nodes. The areas included Tarboro/Princeville, Rocky Mount and Windsor.

7.5.1 Tarboro/Princeville

- Crossing of Tar River North of Tarboro as seen in **Figure 7-1**: Tarboro/Princeville
    - Centered in FP
    - Existing SW node
- N.C. 111 coming into Princeville
    - No major structure at this location, no stormwater node previously

Figure 7-1: Tarboro/Princeville

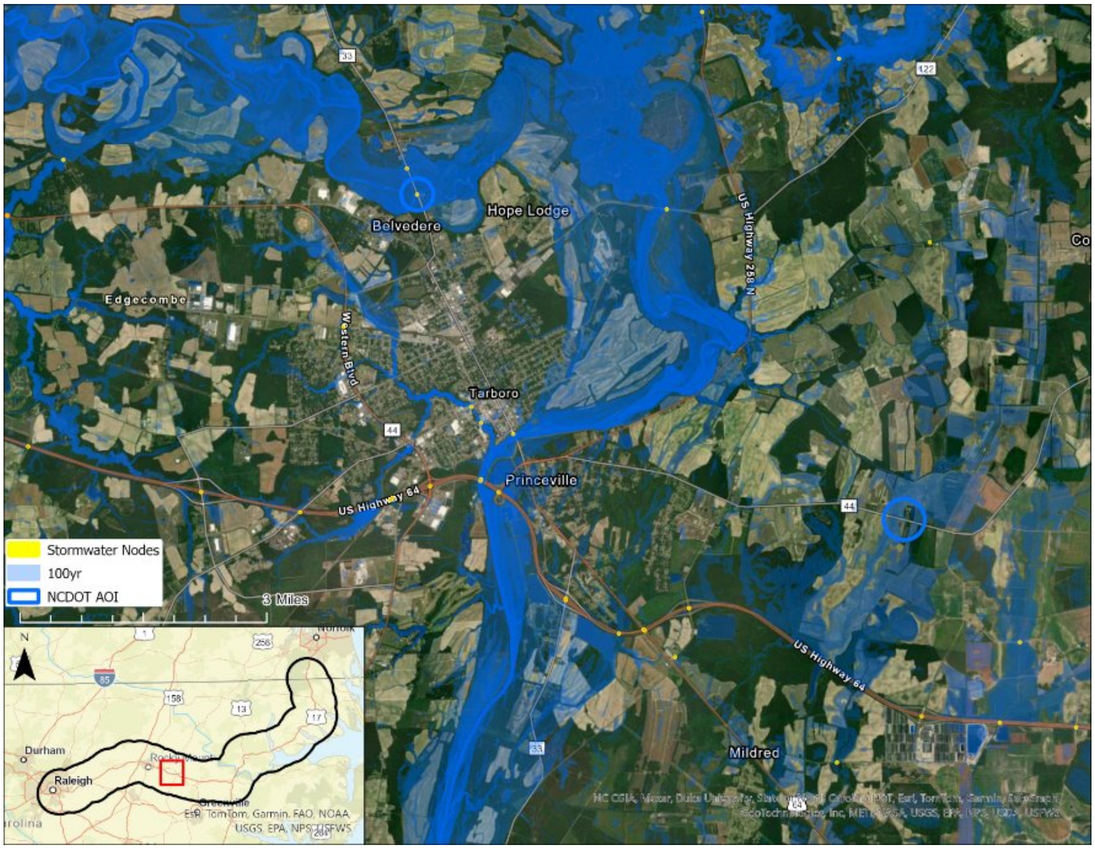


Figure 7-2: Crossing of Tar River North of Tarboro

7.5.2 Rocky Mount

- East of Rocky Mount along N.C. 97
  - No Stormwater node previously, but node directly to East and West.
  - Centered in FP
  - No major bridge or culvert located here

Figure 7-3: Rocky Mount

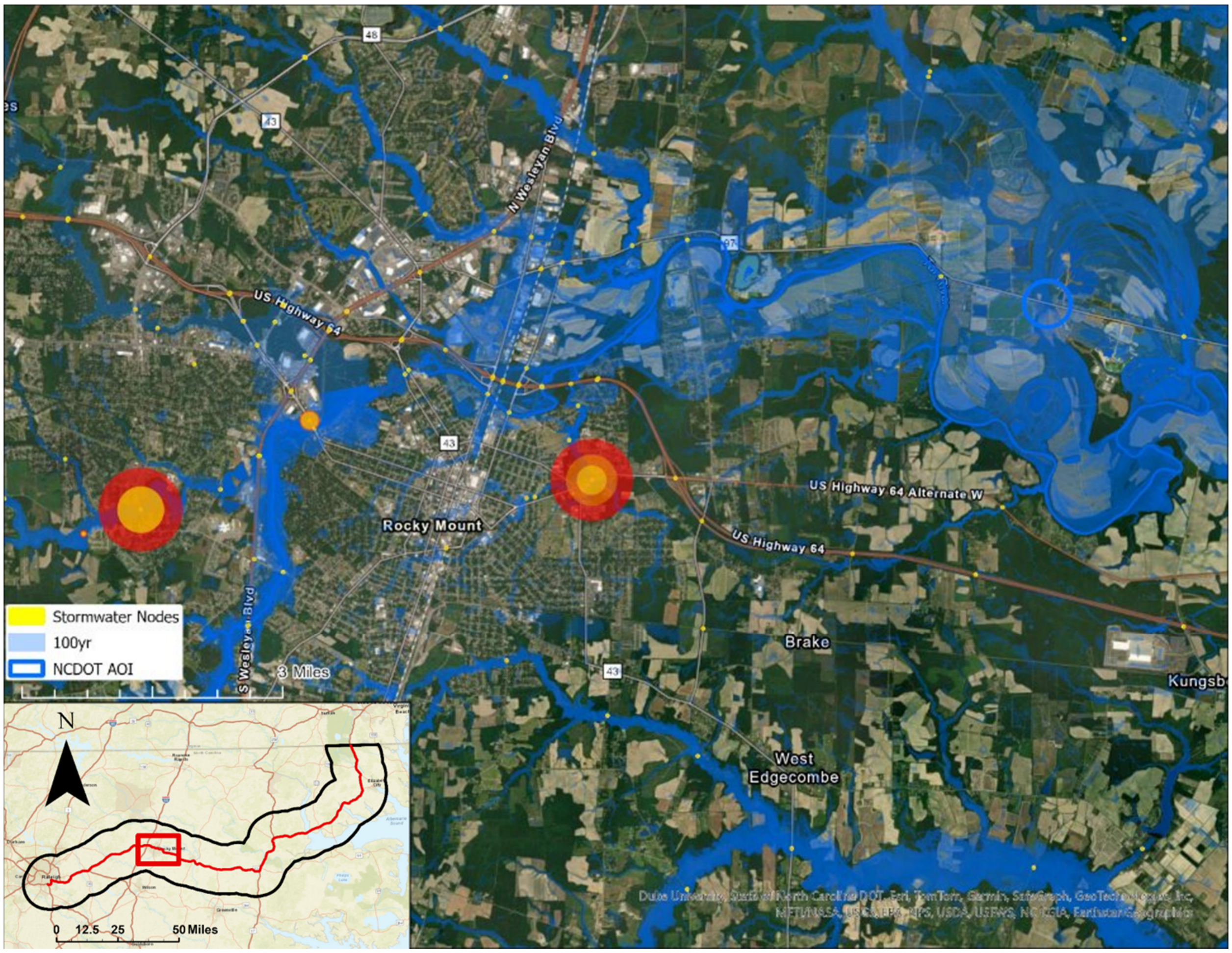


Figure 7-4: East of Rocky Mount

7.5.3 Windsor

- Near Windsor-North (pictured at crossing of road)
  - No stormwater node previously at this location
  - Small tributary floodplain shown crossing road
- Near Windsor-South
  - No stormwater node previously at this location
  - No flooding shown for this area from H&H model near this location

Figure 7-5: Windsor

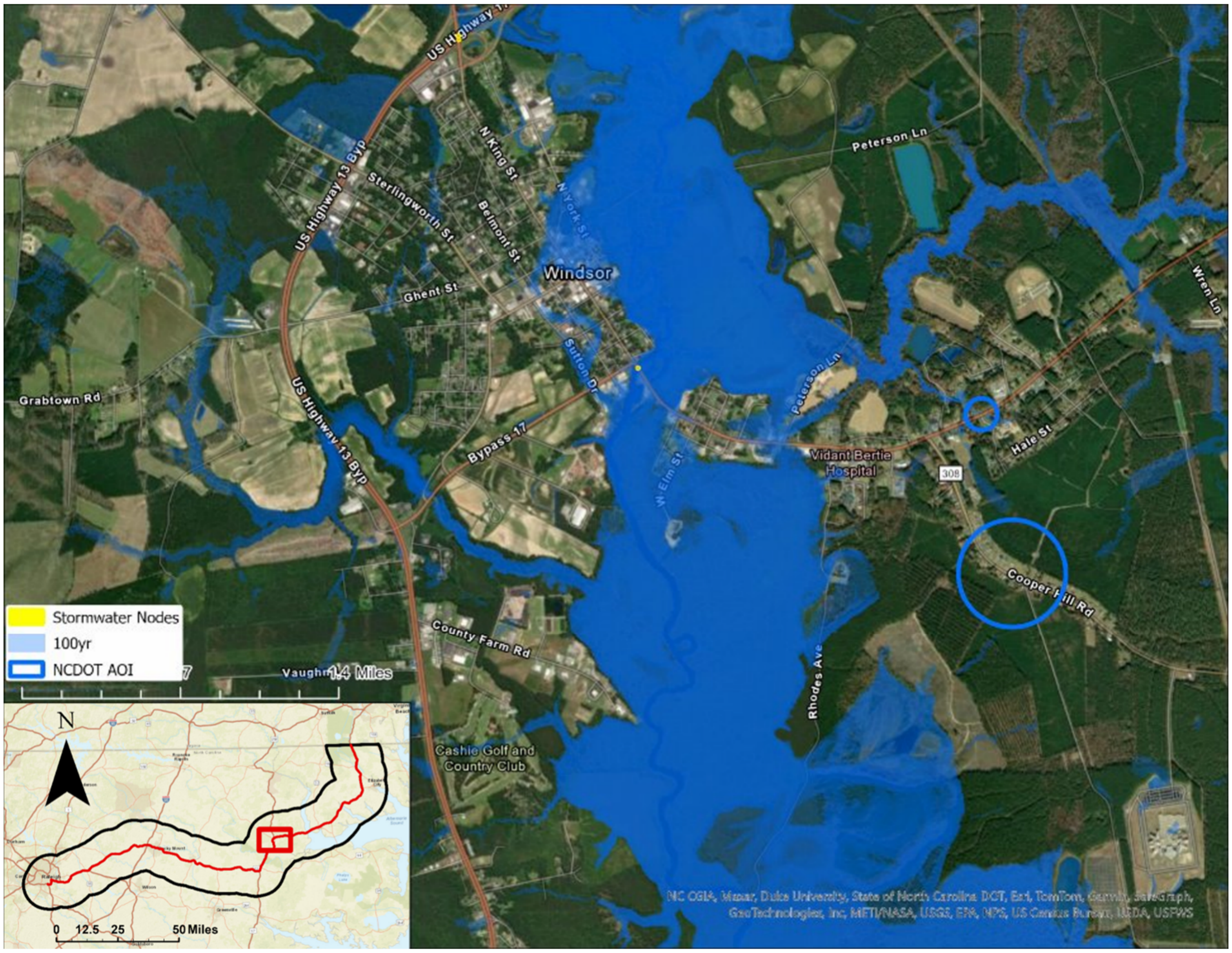


Figure 7-6: North of Windsor at Crossing of Road

8 Further Reading

The study included integrated climate science, flood modeling, agent-based travel modeling, economical modeling and GIS-based digital twin technology in a dynamic simulation. While the study stretched the bounds in terms of the level and details of this integration, further work was conducted both within NCDOT and externally that improved our ability of analyzing potential climate change impacts and developing an action plan. The following list of resources provides a broader perspective on recent studies and research. The reader is encouraged to use these resources for their knowledge on the topics studied.

2022 - NOAA - Sea Level Rise Technical Report: Download and FAQs (noaa.gov)
https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

2018 - National Climate Assessment 4 - Vol II. Impacts, Risks, and Adaptation in the United States.
https://www.globalchange.gov/nca4

2016 - Kipp, Max. Nationwide (USA) Pluvial Flood Modeling via Telemac2D
https://www.nrc.gov/docs/ML2106/ML21064A445.pdf

2007 - Bourne, Stephen. Microsoft PowerPoint -ARC TAZ Disaggregator.ppt (ampo.org)
https://www.ampo.org/assets/604_arctazdisaggregator.pdf

2022 - NASA SVS: CMIP5: 21st Century Temperature and Precipitation Scenarios (nasa.gov)
https://svs.gsfc.nasa.gov/4110

2019 - Paul Chinowsky, Jacob Helman, Sahil Gulati, James Neumann, Jeremy Martinich. Impact of Climate Change on Operation of the US Rail System. Transport Policy, 2019.

2018 - Extreme heat causes pavement buckling issues across the state -Radio Iowa
https://www.radioiowa.com/2018/05/29/extreme-heat-causes-pavement-buckling-issues-across-the-state/

Appendices

Appendix A. Data

This chapter provided links to the datasets used in the study, where possible. Where the data was not served for download, a reference was provided for further reading on the dataset.

A.1. Weather

A.1.1 Historical Rainfall and Temperature

- Menne, Matthew J., Imke Durre, Bryant Korzeniewski, Shelley McNeill, Kristy Thomas, Xungang Yin, Steven Anthony, Ron Ray, Russell S. Vose, Byron E. Gleason, and Tamara G. Houston (2012): Global Historical Climatology Network - Daily (GHCN-Daily), Version 3. NOAA National Climatic Data Center. doi:10.7289/V5D21VHZ

A.1.2 Projected Future Rainfall and Temperature

- 2022 - NASA SVS: CMIP5: 21st Century Temperature and Precipitation Scenarios - https://svs.gsfc.nasa.gov/4110
- https://cida.usgs.gov/thredds/dodsC/cmip5_bcsd/future_2.html
- https://cida.usgs.gov/thredds/dodsC/loca_future.html

A.1.3 Eco-Regions

- US EPA Ecoregions Site - https://www.epa.gov/eco-research/ecoregion-download-files-region

A.2. Flood Models

A.2.1 Riverine: HEC-RAS1D

Flood Risk Information System (nc.gov)

A.2.2 Pluvial: Rain-on-Grid

NCEM Rain on Grid models (enquire with NCEM for access)

A.2.3 Coastal: ADCIRC Plus WHAFIS

NCDOT coastal data (enquire with NCDOT for access)

A.2.4 Pluvial: AtkinsRéalis Pluvial

- 2016 - Kipp, Max. Nationwide (USA) Pluvial Flood Modeling via Telemac2D https://www.nrc.gov/docs/ML2106/ML21064A445.pdf

A.3. Sea Level

A.3.1 Mean Sea Level Projection

- 2022 - NOAA - Sea Level Rise Technical Report: Download and FAQs (noaa.gov) https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html

A.3.2 Tidal Dynamics

- NOAA Water Levels Server - https://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels

A.4. Transportation Infrastructure

A.4.1 Assets

- NCDOT's NBIS Geodatabase (enquire with NCDOT for access)
- NCDOT's Non-NBIS Geodatabase (enquire with NCDOT for access)

A.4.2 Routes

- NCDOT's Linear Referencing System (LRS) Dataset (enquire with NCDOT for access)

A.4.3 Geographic Divisions

- NCDOT Division layer (enquire with NCDOT for access)

A.4.4 Railroads

- NCDOT Rail Crossing Layer (enquire with NCDOT for access)

A.5. Asset Costing

A.5.1 Historical Opex and Capex

- NCDOT's SAP Asset cost tracking system (enquire with NCDOT for access)
- NCDOT Project Bid Spreadsheet (enquire with NCDOT for access)

A.5.2 Expenditure Models

- NCDOT Board of Transportation - December 2021 Meeting Minutes - Inflation Rates

A.6. Travel Demand Models

A.6.1 RPO/MPO

- Charlotte Regional TPO 2050 Transcad model - (enquire with Charlotte MPO for access)
- Wilmington MPO 2045 Transcad model (enquire with Wilmington MPO for access)

A.6.2 NCDOT

- NCDOT Statewide 2045 Transcad model (enquire with NCDOT for access)

A.7. Demographics and Disadvantaged Populations

A.7.1 Population/Jobs/Household

- ACS - TIGER/Line Geodatabase with Selected Geographic and Statistical Data -
- https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-data.html

A.7.2 Poverty/Minority

- ACS - TIGER/Line Geodatabase with Selected Geographic and Statistical Data
- https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-data.html

A.8. Land Use and Buildings

A.8.1 Buildings and Buildings

- Parcels and Building Footprints were merged into a single-related feature dataset for each county prior to the start of the project. The data was a part of AtkinsRéalis' National Building Database. The source data for this dataset included:
  - Parcels - NC OneMap's NC Statewide Parcel Geodatabase.

    https://www.nconemap.gov/pages/parcels

  - Building Footprints - NC Floodplain Mapping Program.

    NC Buildings Footprints (2010) | NC OneMap

A.8.2 Parcels

- See buildings discussion

Appendix B. Heat Modeling

This appendix is an extension of the section in Chapter 4 on heat modeling. It includes a citing of each literature reviewed as well as the abstract/website text for each citing. For ease of reading, the section on heat modeling in Chapter 4 is repeated here and the literature review notes follow.

In each quarter, the heating degree days for each road segment were evaluated since the last maintenance event on the road segment. For example, if the last maintenance event occurred 10 years before the current time step in the simulation and the average atmospheric temperature was 90°F, the heating degree days are 10 years * 365 days/year * 90°F = 328,500 °F-days. The simulator includes projected maximum temperature from the LOCA dataset (see section above on climate stressor projections) and the latest maintenance event on each road segment. These were used to evaluate the heating degree days for the road.

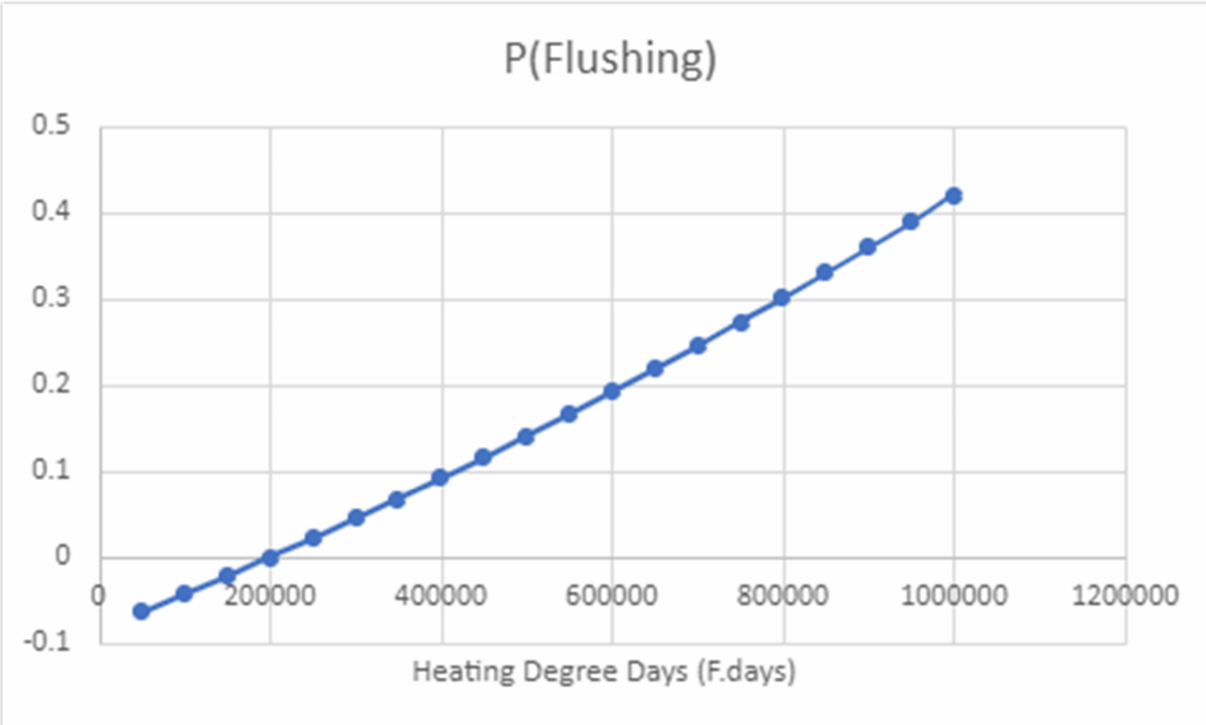
A comprehensive literature review (see Appendix A.) revealed multiple methods for simulating asphalt degradation over time, including methods that leverage artificial intelligence and machine learning. As one of the objectives of the study was to simulate disruption with minimized computational requirements, the simulator was configured with a probabilistic model, which linked cumulative heating degree days with probability of a flushing-related traffic slowdown initiated by NCDOT or other relevant DOTs.

The model assumes that if the trigger atmospheric temperature is 85°F, that flushing would start approximately 1/3 of the typical 20-year lifespan of the asphalt, or at about 6.66 years. This would give a threshold of 85°F * 6.66 years * 365 days/year = 206,833 °F days. A probability function was then developed that assumes that when the road reaches this threshold the probability of flushing becomes non-zero and increases as a power function until at lifespan of 20 years, the probability of flushing is approximately 20%.

Figure B-1 shows the function. The formula for the function is:

P(Flushing) = 3 ^ ((Cumulative Deg Days - 200000) / 100000/25) - 1

Figure B.1: Probability of Flushing as a Function of Cumulative Heating Degree Days



Note that the relationship used allows for extrapolation, so road segments that go beyond 20 years are estimated to have higher than 20% probability of having slowdown events.

B.1. Adaptation & Mitigation

Literature mentions

Sealing

Adding polymer to bitumen

Cooling via leaf canopy and building shadow

Cooling with water

B.2. Proposed Improvement to Heat Modeling Approach

Additional discussions with AtkinsRéalis pavement subject matter experts provided a possibly enhancement to the basic heat model implemented in the simulator. This method is recorded here and is recommended for use in future studies.

The method focuses on adding more variables, primarily expected traffic condition. In the current simulation, the heat model assumes that the road is performing at design level (i.e., design AADT). But, future traffic levels may vary substantially from design levels, particularly with growing population increasing levels, or adaptation/mitigation reducing AADT. As such, including measured or estimated travel in the heat model will provide more accurate estimates of flushing potential.

The flow chart below illustrates the proposed model. The primary differences between the current heating degree days only model and the proposed are:

Each road's AADT will be used to classify if the road is low or high volume.

The volume will be used to assign a binder that was/will be used in the Asphalt mix.

NCDOT likely uses the "superpave" asphalt mix design method, as most DOTs use. These mixes include a binder for increasing the roads' ability to stand up to heavy and repeated traffic in high temperatures. The numeric part of the binder name (e.g. PG64) refers to the design temperature in Celsius. The temperature is actually a 7-day maximum temperature average. That is, when designing the mix, the 7-day historic average maximum temperature is found, and the mix is designed to accommodate this temperature. The 7-day max atmospheric temperature is then converted to pavement temperature, which is significantly higher than atmospheric. The binder number chosen should be higher than the resulting pavement temperature.

During the simulation, two items will be checked:

Exceedance of design AADT — where simulated AADT increases in the model as the simulation proceeds

Exceedance of design temperature — where the past 7-day avg max pavement temperature will be evaluated from the 7-day avg max atmospheric temperature.

The simulation will accumulate exceedance of design trips and temperature each day and multiply them to make a combined cumulated exceedance index.

When the accumulated combined index goes above a threshold, the probability of flushing will go above zero as with the first heat model.

The proposed model will use the assumed 1/3 of 20 year life span and evaluate the threshold as the value of the combined index given constant 85F and the design AADT on the road of interest.

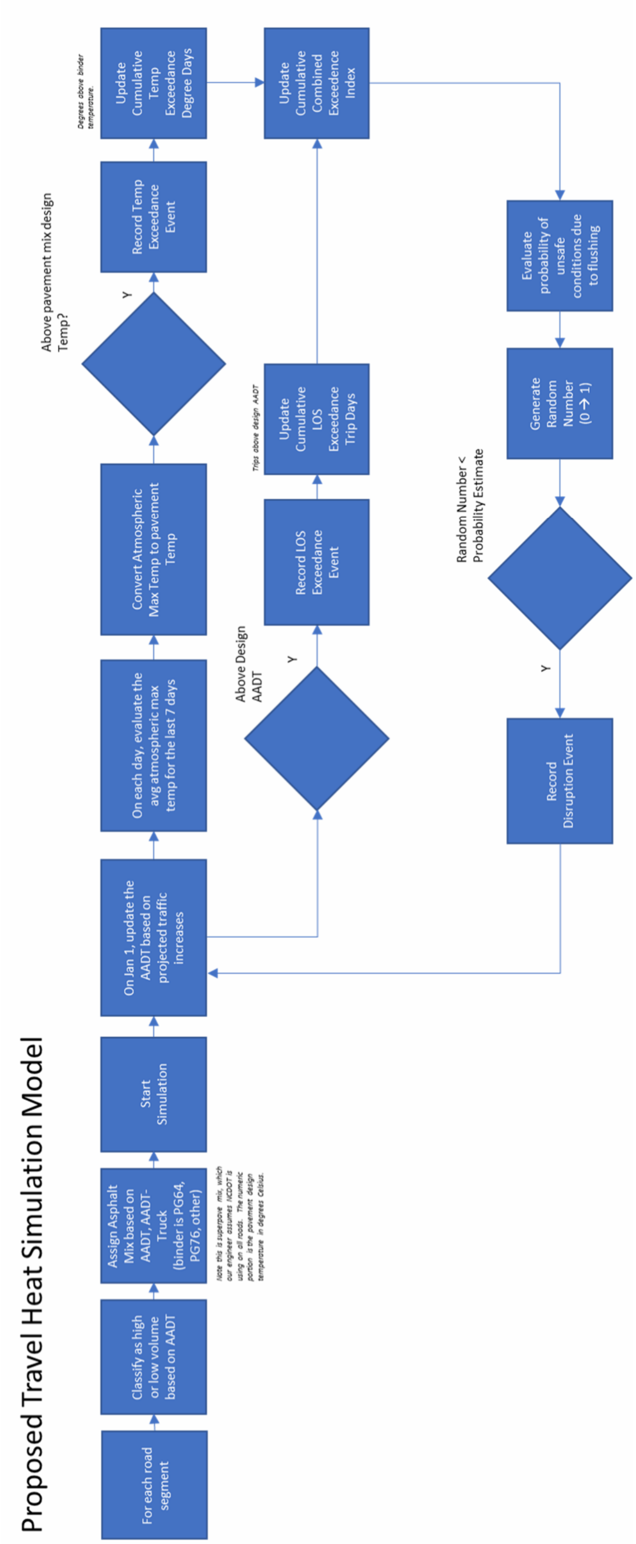
If a random number falls below the probability, then the simulation will assume a disruption occurs, and a disruption event will be recorded.

Notes:

This model will provide higher accuracy than the temperature-only model, primarily because it includes road usage in the calculation.

This model will essentially estimate the heating component the same as the first model, but it will add the component of increasing usage of roads over time, which is a new factor.

Figure B-2: Proposed Heat Model Flow Chart



B.3. Heat Modeling Literature Review

Links to literature reviewed are provided below.

http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0123-21262015000200006

https://www.ntnu.no/ojs/index.php/BCRRA/article/download/2743/2806/11505

https://www.researchgate.net/publication/279467078_Maintenance_Solutions_for_Bleeding_and_Flushed_Pavements_Surfaced_with_a_Seal_Coat_or_Surface_Treatment/figures?lo=1

https://www.ayresassociates.com/the-long-and-short-of-it-lifespans-of-paved-roadways/

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6416576/

https://aip.scitation.org/doi/pdf/10.1063/1.5042946

https://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP09-54_InterimReport-Submitted6-16-15.pdf

https://journals.sagepub.com/doi/abs/10.3141/2507-03

https://www.tandfonline.com/doi/full/10.1080/14680629.2016.1266739

https://www.tandfonline.com/doi/full/10.1080/14680629.2016.1266739?scroll=top&needAccess=true

https://scholar.google.com/scholar?q=asphalt+road+failure+prediction+model+with+temperature&hl=en&as_sdt=0&as_vis=1&oi=scholart#d=gs_qabs&t=1666777647114&u=%23p%3DYukmUkNQLsAJ

https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6746-01-1.pdf

https://journals.sagepub.com/doi/full/10.1177/0361198118822501

https://www.ntnu.no/ojs/index.php/BCRRA/article/download/2725/2788

https://ops.fhwa.dot.gov/publications/fhwahop20062/fhwahop20062.pdf

https://www.hindawi.com/journals/jat/2022/7783588/

https://www.tandfonline.com/doi/abs/10.1080/10298436.2013.828839

https://www.tandfonline.com/doi/full/10.1080/16742834.2019.1608791

https://transportgeography.org/contents/applications/climate-change-transport-infrastructure/climate-change-impacts-transportation/

https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm

https://www.bloomberg.com/news/articles/2022-08-18/the-world-s-roads-and-highways-aren-t-built-for-a-hotter-climate

https://www.plsofflorida.com/how-do-potholes-form/

https://www.washingtonpost.com/climate-environment/2022/07/20/heat-wave-road-railway-buckling/

https://www.roadbotics.com/2022/06/08/hot-weather-effects-on-roads/

https://www.researchgate.net/publication/230320048_Quantifying_the_effects_of_high_summer_temperatures_due_to_climate_change_on_buckling_and_rail_related_delays_in_south-east_United_Kingdom

https://rmets.onlinelibrary.wiley.com/doi/10.1002/met.1910

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6416576/

https://heatisland.lbl.gov/sites/default/files/cuhi/docs/211420-mallick-doc.pdf

https://www.tac-atc.ca/sites/default/files/conf_papers/shafieem-climate_change_and_asphalt_binder_selectio.pdf

https://urldefense.com/v3/__https://www.pavemax.com/how-hot-weather-affects-concrete-asphalt/__;!!OepYZ6Q!5y2nKpmUtvDDjoh8-4tSiR2KJD0Vx6gcDK0SRAnhAByFvJT2yOdrafWltIPBXD3_gsjE33JkxpXYKG6XLUVrD4ZRYtk_6sjXgQ$

https://www.ipcc.ch/apps/njlite/srex/njlite_download.php?id=6159