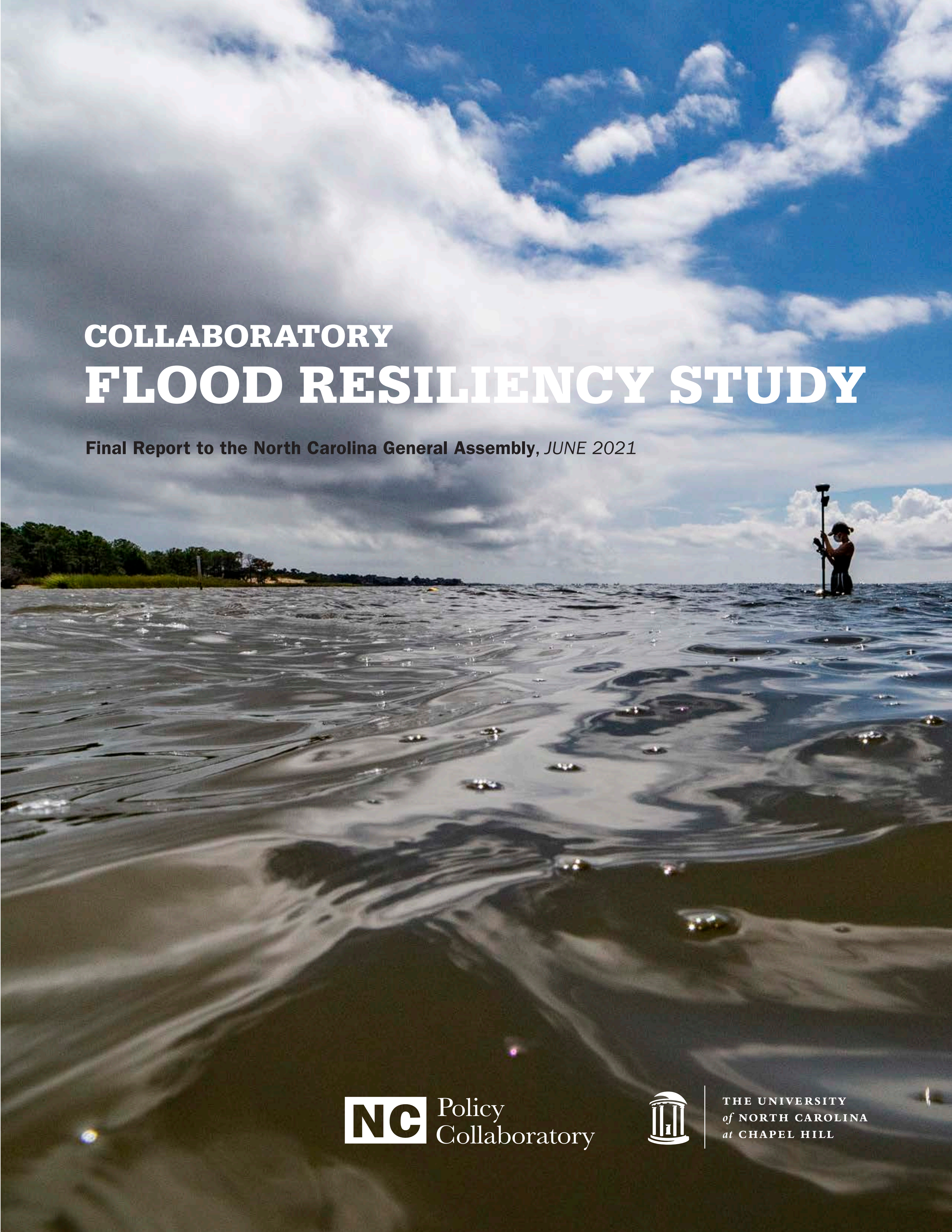

COLLABORATORY
FLOOD RESILIENCY STUDY

Final Report to the North Carolina General Assembly, *JUNE 2021*

NC Policy Collaboratory

THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

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Foreword

NC Policy Collaboratory

Legislative Charge

In September 2019, the North Carolina General Assembly (NCGA) passed Senate Bill 429, the "Disaster Recovery Act," (Session Law 2019-224) into law. Among its many provisions the bill appropriated $2,000,000 to the North Carolina Policy Collaboratory to conduct research related to flood resiliency in eastern North Carolina. The legislation called for submittal of the final report by December of 2020.

During the 2020 legislative session, in response to challenges faced by university researchers due to the ongoing pandemic, the NCGA passed House bill 308, which delayed the final report date until June 1, 2021. (Session Law 2020-74)

The additional time allotted for the study allowed researchers to develop more robust results and increased confidence in recommending the actions included in the Implementation Plan. In February 2021 the research team submitted an Interim Update to the NCGA to share some initial findings and recommendations that could potentially be acted on during the 2021 legislative session.

On April 13, 2021 the faculty lead for the study, Mike Piehler, delivered a presentation to the Senate Select Committee on Storm Related River Debris and Damage in North Carolina at which he outlined the framework of the study and identified some initial findings.

Rachel Noble, UNC Institute of Marine Sciences. Morehead City, NC. Photo courtesy of the University of North Carolina at Chapel Hill.

NC

Study Development and Focus

A research team comprised of experts in a wide range of fields was developed to evaluate flood resiliency from a comprehensive perspective. The flood resiliency study focused on five specific focal topics:

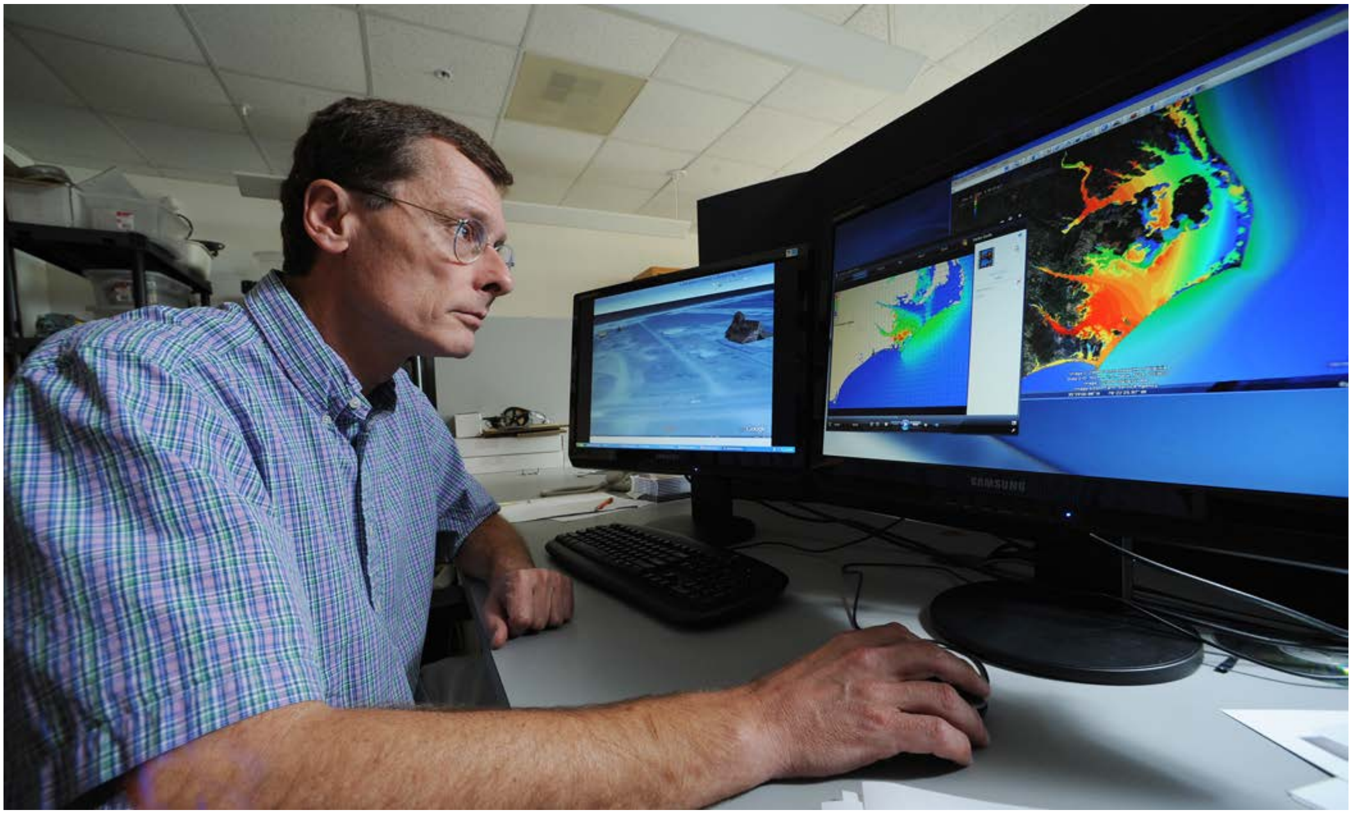
- Floodplain Buyouts
- Financial Risk
- Natural Systems
- Infrastructure
- Public Health

The study was a collaboration of many projects and researchers from the University of North Carolina at Chapel Hill and North Carolina State University as partner universities. The full study was overseen by Principal Investigator Mike Piehler, the Director of the UNC Institute for the Environment. The various lenses through which inland flood resiliency was analyzed coalesced on the shared goals of keeping North Carolinians healthy and safe, and improving the state's planning for, and response to, flood and storm events.

Study Principles

The research conducted as part of this study follows the guidelines of rigorous academic research, as is true of all North Carolina Policy Collaboratory funded projects. Using research designed by leading experts, the study's goal was to generate new information to inform decisions around flooding and storms. Identified information users included governments, non-governmental organizations, private organizations, and individuals.

Dr. Rick Luettich, Professor and Director, Institute of Marine Sciences. Photo courtesy of the University of North Carolina at Chapel Hill.



Study Activities

In the year and a half dedicated to the project, scientists have worked on several scientific and economic research sub-projects. Some of the specific research and project activities undertaken during the course of the study included:

- Assessing operational flooding risks for substations and the wider North Carolina electricity grid
- Evaluating the impact and challenges of stormwater control measures during floods
- Exploring the funding mechanisms available for floodplain buyouts
- Creating a dynamic model of flood damage and property values
- Modeling storm surge on coasts from Hurricane Florence
- GIS analysis of areas to implement natural infrastructure practices
- Storm sampling for pathogen tracing
- Engaging stakeholders throughout eastern North Carolina and state leaders

Outreach and Engagement

At the outset of the Study, members of the research team held meetings with the leadership of the NC Division of Emergency Management (DEM) and the NC Office of Recovery and Resiliency (NCORR). These meetings were designed to ensure that the research team was working with the most up-to-date data and not duplicating efforts underway at the state agency level. The cooperation of the DEM and NCORR were critical to the research plan developed for the study.

Research team members also met with a number of state agencies to solicit their feedback and share information about the study. These agencies included:

- Department of Agriculture and Consumer Services
- Department of Commerce
- Department of Environmental Quality
- Department of Health and Human Services
- Department of Insurance
- Department of Transportation

In addition to the engagement with state agency officials, project leaders also presented information about the Resiliency Study to other interested parties. This outreach work was intentional in sharing information about the project and listening to key stakeholder input that could inform the research. The input and guidance from local government officials, environmental organizations, and industry had a direct impact on identifying key issues that are being examined as part of the study.

By the Numbers

Recent Flood Impacts in NC

$22B damages from Hurricane Florence across NC.

35.93 inches of rainfall from Hurricane Florence in Elizabethtown, NC.

100,000 number of buildings in NC damaged by Hurricane Matthew.

$88M estimated water/wastewater/stormwater needs as a direct result of Hurricane Florence.

70% proportion of damages from Hurricane Florence estimated to be uninsured.

65 NC municipalities with road area impacted by high-tide flooding.

Study Actions and Findings

~9,600 flood-prone properties/structures have been purchased through state and local flood buyout programs.

+40,000 total properties have been acquired with federal grants funding flood buyouts.

18% of buyout projects spent a third or more of their total funding on costs beyond property purchases.

44% of financial risk is retained by residential property owners.

100 electric generators (1000s of installed MW of capacity) and hundreds of electrical substations in the areal footprint of severe flooding.

1.5 up to 1.5 feet water level reduction is possible with natural infrastructure implementation.

13-14% potential reduction in structural damages by utilizing natural infrastructure measures.

9000 jobs estimated to be generated overall from constructing natural infrastructure measures.

+250 samples collected and analyzed for microbial contaminants.

33% of sewer treatment plants and 23% of sewer pumps are in the 100-year flood plain.

Implementation Plan

The legislation establishing this study specifically called for an Implementation Plan as a component and deliverable of the study. What follows are implementation actions identified by the study team categorized into the five focal areas of the study. The actions include suggested time frames as well as a priority status of high, medium and low.

Summary Table of Implementation Action Items

Priority Level	Recommended Action	Areas of Intervention
High	Limit development in flood hazard areas	Buyouts, Financial Risk, Natural Systems
High	Optimize transaction costs	Buyouts
High	Track spending of federal grants	Buyouts
High	Calculate potential avoided loss	Buyouts
High	Incentivize use of flood insurance	Financial risk
High	Establish pre-disaster mitigation plans	Financial risk
High	Enhance role of wetlands in flood mitigation	Natural Systems
High	Initiate compound flooding pilot studies	Compound Floods
High	Develop comprehensive geospatial database	Compound Floods
High	Install storm drain tide gates	Infrastructure
High	Authorize pre-storm emergency pumping	Infrastructure
High	Convene electric grid working group	Infrastructure
High	Address infrastructure funding reliability	Infrastructure
High	Increase surveillance of flood water quality	Public Health
High	Determine health risks of flood borne pathogens	Public Health
High	Engage health-related stakeholders around flooding	Public Health
Medium	Explore alternative buyout processes	Buyouts
Medium	Investigate novel buyout funding mechanisms	Buyouts
Medium	Identify properties and communities most at risk	Financial Risk
Medium	Pilot flood mitigation via ecological restoration program	Natural Systems
Medium	Invest in water farming	Natural Systems
Medium	Increase funding for forest development	Natural Systems
Medium	Assess and optimize stormwater systems	Infrastructure
Medium	Consider innovative design features	Infrastructure
Medium	Utilize power grid research model	Infrastructure
Low	Conduct statewide flood risk assessment	Financial Risk
Low	Address wastewater infrastructure	Infrastructure

Actions to Improve the Floodplain Buyout Process

Limit Development in Flood Hazard Areas:

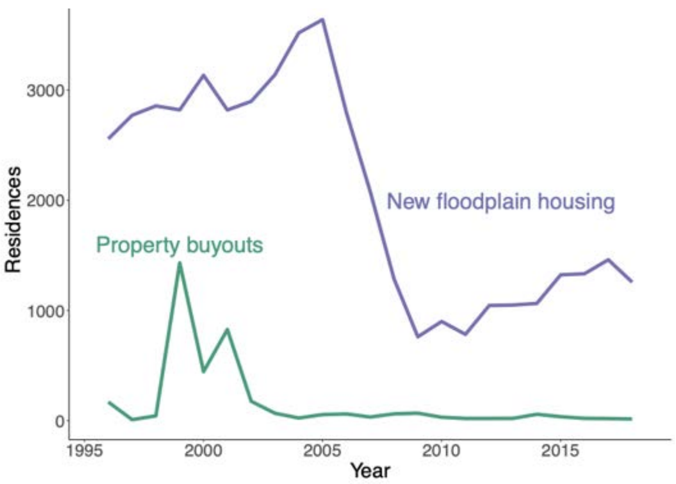
The State should incentivize communities that receive federal or state grants for buyouts to restrict future residential development in flood hazard areas.

Priority: High, Time frame: 2-3 years

Optimize Transaction Costs:

The transaction costs associated with buyouts vary widely across the State and around the United States, but they can be substantial. These costs are likely absorbed by municipalities and landowners under current buyout processes. The State's Office of Recovery and Resilience (NCORR) could be instrumental in helping to limit these costs, along with efforts to prioritize and plan for future buyouts across the State.

Priority: High, Time frame: Immediate



New floodplain construction far outpaces removal of floodplain property through buyouts in North Carolina.

Track Spending of Federal Grants:

All spending on federal buyout grants – by federal, state, and community sources – should be tracked in detail by the State to better understand transaction costs associated with buyouts and find ways of streamlining buyout processes. Researchers at UNC-Chapel Hill can help the state create database tools to accomplish this.

Priority: High, Time frame: Immediate

Calculate Potential Avoided Loss:

As part of exploring alternative buyout processes, the state should identify improved methods of calculating avoided loss that include aggregate risk (beyond project itself, e.g., downstream impacts) to determine whether buyouts lower flooding risk and damage nearby.

Priority: High, Time frame: Immediate

Explore Alternative Buyout Processes:

Additional work needs to explore the legal hurdles to implementing alternative buyout processes and evaluate how those processes would ensure stronger equitable and environmental outcomes.

Priority: Medium, Time frame: 2-3 years

Investigate Novel Buyout Funding Mechanisms:

The state of North Carolina should explore a wide variety of funding mechanisms that could smooth and speed buyout processes, including municipal/green bonds, revolving loan funds, local option sales taxes, and stormwater utility fees. Special attention should be paid to the inclusive and equitable use of these funding mechanisms at the state and local scale.

Priority: Medium, Time frame: 2-3 years

Actions to Minimize Financial Risk

Incentivize Use of Flood Insurance:

Flood insurance, essentially all of which is provided by the federal government via the NFIP, is the primary tool for managing financial risk of flood-related damages for property owners. Because flood insurance uptake in North Carolina remains very low, the state should target communities at risk to encourage insurance uptake through both education and provision of incentives, such as funding to assist property owners in paying NFIP premiums to cover future damages.

Priority: High, Time frame: 1-2 years

Establish Pre-Disaster Mitigation Plans:

Regardless of any achievable increase in flood insurance uptake, uninsured damages continue to be a reality in North Carolina. The state should initiate renewed efforts to develop pre-disaster mitigation plans via a "portfolio" approach that includes multiple strategies, including infrastructure (e.g., flood control, property elevation), buyouts of at-risk properties, zoning policy and financial instruments (e.g., flood insurance, disaster-based reinsurance).

Priority: High, Time frame: 1-2 years

Identify Properties and Communities Most at Risk:

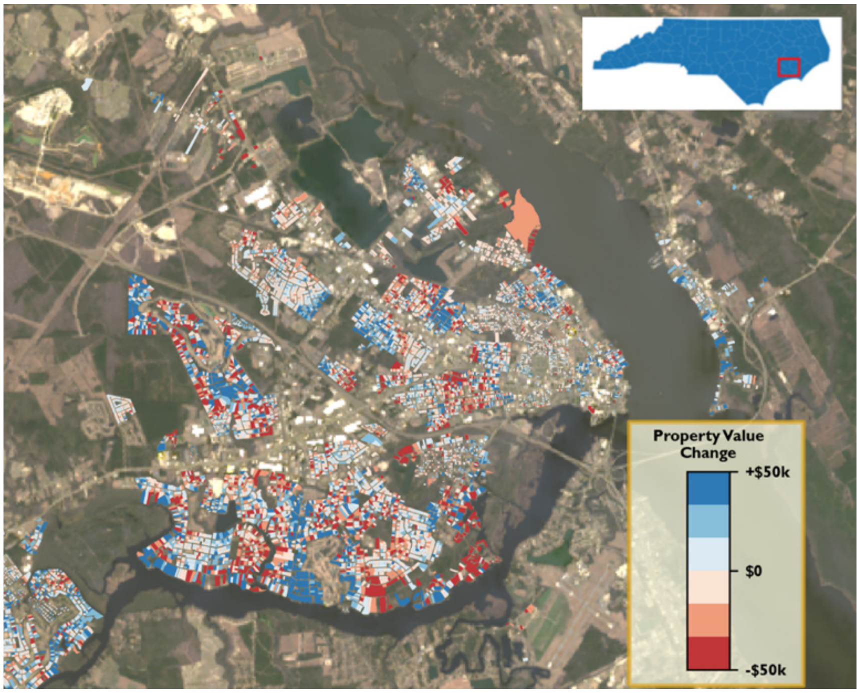
The impacts of severe flood events on property value and the ability of property owners to pay their mortgages represents a longstanding, but thus far unquantified source of risk to both lenders and local governments. A rigorous and detailed assessment of neighborhoods at highest risk of flood-related mortgage default should be conducted to identify which areas and lenders are most threated, and to inform actions designed to mitigate this risk (e.g., property buyouts, lines of credit to vulnerable banks).

Priority: Medium, Time frame: 3-5 years

Conduct Statewide Flood Risk Assessment:

Many parts of North Carolina, including urban areas and communities in western parts of the state, are largely unfamiliar with flood events but may be at greater risk in the future. A more comprehensive assessment of statewide flood risk and the attendant financial risk would give state agencies a better understanding of risk and improved ability to assess the feasibility of a range of risk management actions. Additionally, greater specificity with respect to who holds flood-related financial risk should be identified to inform preparation and mitigation strategies.

Priority: Low, Time frame: 5-10 years



Changes in property values in downtown New Bern, NC after Hurricane Florence.

Actions to Increase Use of Natural Systems for Flood Mitigation

Limit Floodplain Development:

Adopt policies that prevent future development and redevelopment within the 100-year floodplain and that severely restricts development in the 500-year floodplain. It should be noted that all encroachment into the floodplain (i.e., elevated structures) reduces the water storage capacity of the floodplain during extreme events.

Priority: High, Time frame: 1-2 years

Enhance Role of Wetlands in Flood Mitigation:

Maintain and enhance the role of wetlands in North Carolina's flood resilience strategy:

a) Ensure regulatory certainty by maintaining current protections and mitigation requirements.

b) Fund flood control projects authorized in the 2020 Water/Wastewater Public Enterprise Reform Act (HB 1087).

c) Expand opportunities for landowners and local governments to protect natural systems that contribute to flood mitigation.

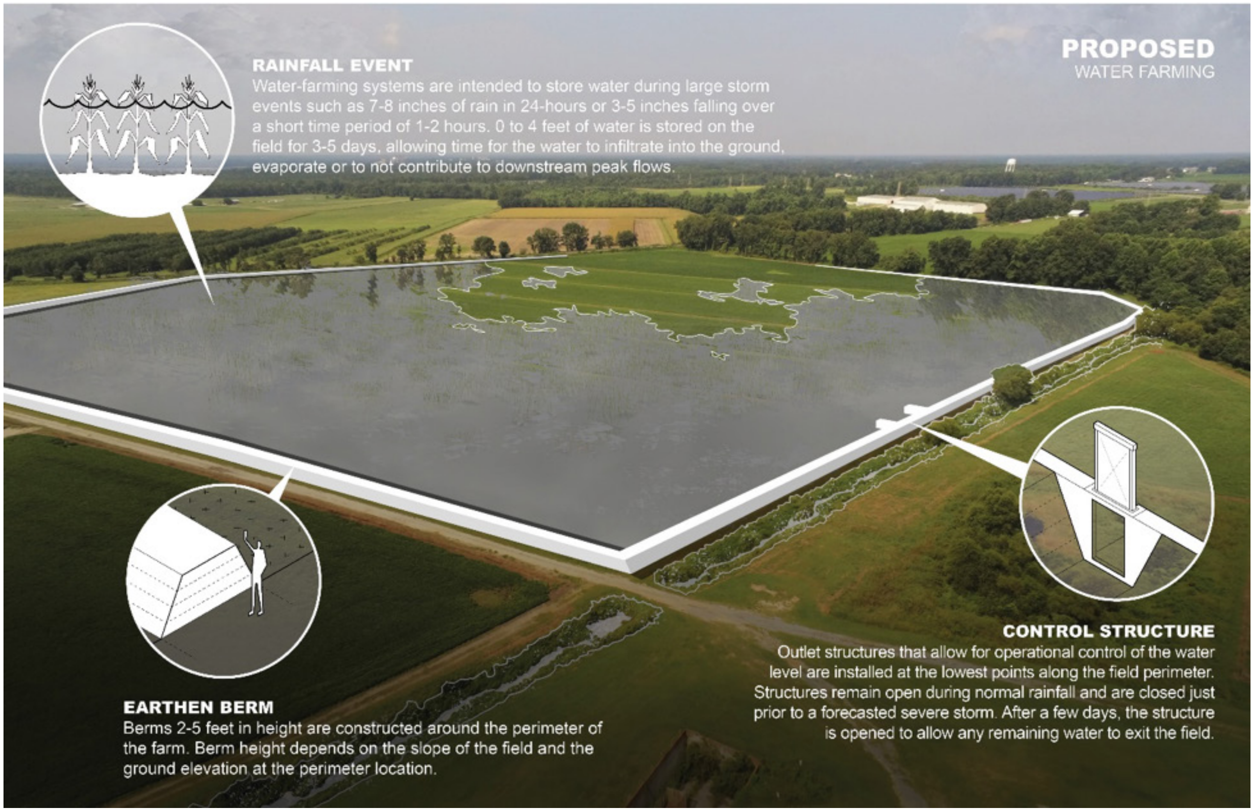
d) Provide local governments with capacity building and coordination support.

Priority: High, Time frame: Immediate

Pilot Flood Mitigation via Ecological Restoration Program:

Develop a pilot flood mitigation program for a targeted subwatershed with documented flooding issues. The program would allow the ecological restoration industry to implement flood mitigation projects. Flood storage benefits could be estimated by comparing model results of the peak flow reduction, peak flow delay and volume of water stored for existing and proposed condition during the several return interval storms (e.g., 50-, 100-year storm). Track the economic and employment impacts of this program.

Priority: Medium, Time frame: 1-2 years



Concept of Water Farming.

Invest in Water Farming:

Invest in research to develop and monitor a pilot water farming project. The research should focus on evaluating water management systems, storage and peak flow reductions, impacts to soils and crops and other agricultural management processes, and associated economic factors.

Priority: Medium, Time frame: Immediate

Increase Funding for Forest Development:

Increase funds for the NC Forest Service's Forest Development Program in order to convert lower productivity lands and other open lands to forests by targeting projects in flood prone areas.

Priority: Medium, Time frame: Immediate

Specific Action Items to Better Understand Compound Flooding

Initiate Compound Flooding Pilot Studies:

Initiate pilot studies to evaluate flood hazards when compound flooding is explicitly represented versus when hydrological and coastal surge hazards are considered separately and superimposed after the fact. Findings of these pilot studies will lend insight into the urgency of revising flood hazard calculations to include compound flooding across all of eastern North Carolina.

Priority: High, Time frame: 1-2 years

Develop Comprehensive Geospatial Database:

Create an integrated geospatial database that includes the state's LiDAR topography, georeferenced HEC-RAS cross-section data, and other remotely sensed and geographic information needed to accurately delineate channel location and bathymetry, and floodplain depth and extent in North Carolina's coastal plain. Gaps in the existing datasets, particularly where cross-sectional surveys may be outdated or lack resolution, should be identified, and filled.

Priority: High, Time frame: 1-2 years

Actions to Strengthen and Protect Infrastructure

Mitigate Stormwater Inundation

Install Storm Drain Tide Gates:

For stormwater network inundation in the short term, the most direct engineering solution is to install tide gates that prevent flow up-network when receiving water levels are elevated.

Priority: High, Time frame: 1-2 years

Assess and Optimize Stormwater Systems:

Addressing the long-term issue of coastal urban flooding will require substantial investment in planning and upgrading drainage systems. Examples include:

- Updating infrastructure to address network inundation (e.g., backflow prevention, pumping, fixing leaky pipes)
- Decentralized or low impact development practices to manage stormwater (e.g., stormwater harvesting and storage above ground)
- Landscape-scale planning to incorporate temporary surface storage of flood waters

Priority: Medium, Time frame: 3-5 years

Stormwater Control Measures (SCM)

Authorize Pre-storm Emergency Pumping:

Before impending events (hurricanes, nor'easters) the design and maintenance community has requested emergency authorization to pump down SCMs that hold water. Lowering the water level well below normal pool creates (often a lot) of additional storage capacity in the stormwater practice, allowing the SCM to better manage large floods. Jurisdictions can be encouraged to allow this specific emergency maintenance.

Priority: High, Time frame: Immediate

Consider Innovative Design Features:

Design features have been shown to enhance resilience, yet these functional versions of these features are not reliably included in SCMs. Key design features include:

- Emergency spillways. This is water's path of last resort and it needs to be stable and sufficiently broad and deep to convey emergency flows. Well-designed and maintained emergency spillways prevent berm or dam breaching.
- Forebay features. As water enters the forebay it should not be directed directly at the back berm. Having water flow directly into the back berm has caused the forebay to blow out.
- Consider back flow of brackish water into the SCM for practices along the coast.

Priority: Medium, Time frame: 1-2 years

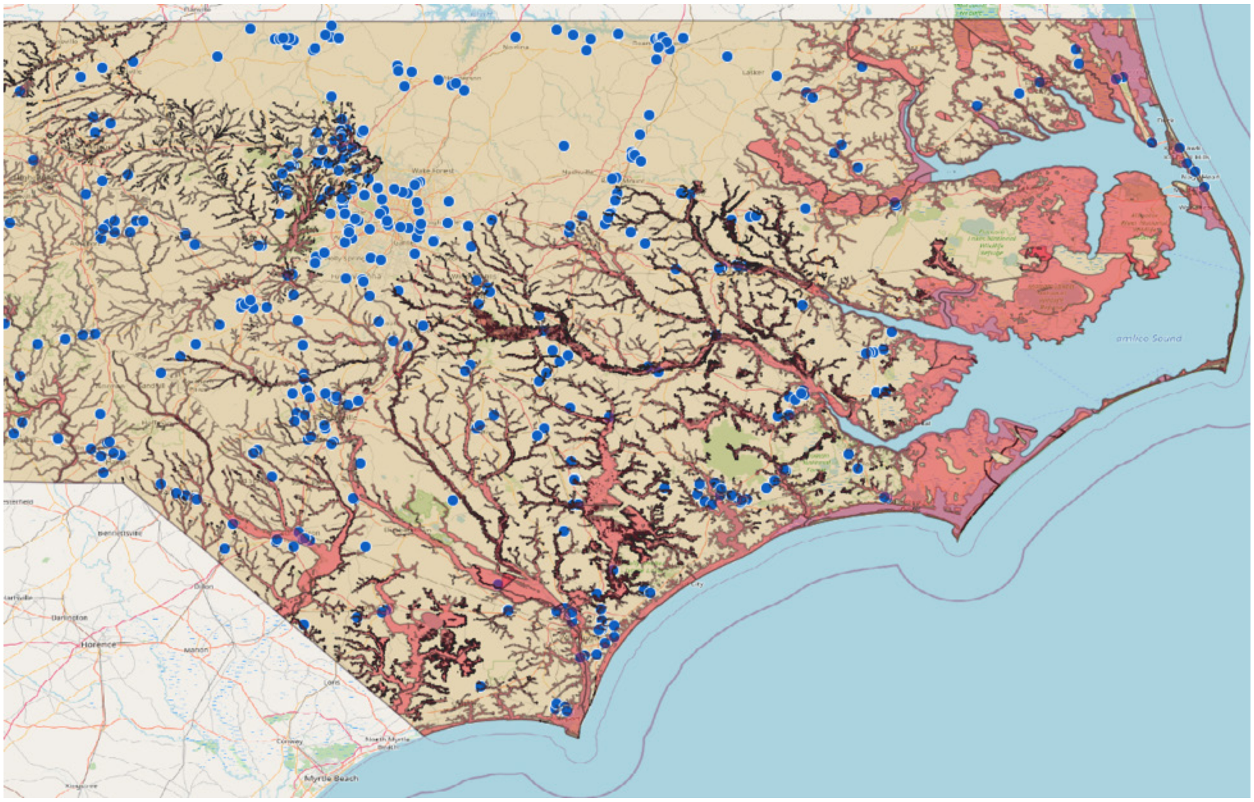
Electric Grid

Convene Electric Grid Working Group:

The state should convene a small working group or task force to:

- Identify the communities and sections of the grid in eastern NC most at risk of prolonged electric outages due to flooding.
- Prioritize the need for protective intervention based on likelihood of occurrence and potential for negative consequences.
- Gain knowledge about grid operators' contingency plans before and during severe, localized flooding events.

Priority: High, Time frame: 1-2 years



Maximum flooding extent from Hurricane Florence (red) shown alongside the locations of selected major electrical substations (blue dots) in Eastern North Carolina. Note: substations shown here are not a complete list of substations in North Carolina.

Utilize Power Grid Research Model:

The state should utilize the research team's model of the NC power grid to evaluate flooding and other resiliency impacts on the grid in connection with natural disasters such as hurricanes.

Priority: medium, Time frame: 1-2 years

Water and Wastewater Utilities

Address Infrastructure Funding Reliability:

The State should consider launching a bridge funding/financing program that allows utilities to borrow money to repair/replace critical infrastructure while waiting for FEMA money.

Priority: High, Time frame: 1-2 years

Address Wastewater Infrastructure:

Because wastewater infrastructure tends to be built at the lowest point in town, it is more likely to experience the impacts of flooding. As such, the state should consider drinking water and wastewater holistically, thinking about the connectedness of water resources when making legislative changes related to flood resilience.

Priority: High, Time frame: 5-10 years

Actions to Protect Public Health

Increase Surveillance of Flood Water Quality:

Now that we have developed advanced techniques for high throughput characterization and quantification of microbial contaminants in light of the COVID-19 pandemic, we recommend a stratified random sampling approach to characterize floodwaters and non-flood impacted waters with priority devoted to assessing the relative impact of sewage and hog fecal material on relevant systems. Improved system characterization of pathogens will benefit from a simultaneous assessment of the reports of GI pathogen, wound infection and floodwater related exposures and risks by analysis of the NC DETECT emergency room data.

Priority: High, Time frame: Immediate

Determine Health Risks of Flood Borne Pathogens:

Accurately quantifying pathogens and genes is a first step towards understanding whether water sources pose risks to human health. Especially during extreme events, it is important to efficiently determine health risks.

- Vibrio: This is a pathogen with outcomes in the NC Surveillance System (e.g., NC DETECT). We are working on improving methods for quantifying the known virulence sub-strains of Vibrio that can cause infection which may be more useful than past approaches to quantify Vibrio at the species level.
- Antimicrobial resistance genes: We are hoping to use more advanced molecular diagnostic approaches for quantification of combinations of antimicrobial resistance genes that may be more indicative of risk to humans.

Priority: High, Time frame: 1-2 years

Engage Health-related Stakeholders Around Flooding:

It is certain that engagement with relevant stakeholders, including municipal wastewater utilities, hog and livestock farming operations, and county health departments will permit a further assessment of the risks posed by floodwaters. Thankfully, we have already accomplished much of this stakeholder relationship building with WWTP utilities through the COVID-19 pandemic, so working with them to address flooding and flood/stormwater resilience strategies will be a valuable next phase of effort.

Priority: Medium, Time frame: Immediate

To review the full technical reports and publications on each of these research projects please visit the webpage:
https://collaboratory.unc.edu/current-projects/flood-resilience/

STUDY REPORTS

The following sections of this document are summaries of the individual projects conducted by distinct research teams addressing specific questions as part of the study. Each of these summaries contain a condensed version of the reports from each of the research teams.

To review the full technical reports and publications on each of these research projects please visit the webpage:
https://collaboratory.unc.edu/current-projects/flood-resilience/

Floodplain Buyouts

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Overview

Over the last 30 years, government-led acquisition and removal of flood-prone residential properties (known as “floodplain buyouts”) has become a popular method for reducing future flood damages in the United States. Buyouts are attractive as they are voluntary and permanently remove vulnerable homes from flood hazard areas, and homeowners typically receive pre-flood, fair-market value for their home. The downside is that buyout projects occur within a complex intergovernmental framework, which makes buyouts somewhat unpredictable and time-consuming. Generally, federally administered buyouts take 2-5 years to complete. In addition, buyouts are reactive, with most funding becoming available only after a major disaster.

Project Goals

The broad goals of this project were to: 1) estimate the full costs of implementing buyout projects, separating costs associated with a normal property acquisition process from uniquely those costs associated with conducting a buyout (i.e., transaction costs), 2) document the variety of buyout funding mechanisms adopted by federal, state and local governments, 3) explore the potential role of the private sector in financing and implementing buyouts, and 4) determine whether development in floodplains outpaced the removal of flood-prone homes in certain communities and how floodplain development patterns differ across communities in North Carolina.

Research Methods

We relied on literature and public budget reviews, interviews with key informants (buyout consultants and government officials), and a survey of local government hazard managers in NC and state hazard managers across the United States. Much of our time was also spent on the creation and analysis of a statewide database of buyouts, amalgamated from numerous local, state, and federal datasets.

Summary of Findings

- State and local governments have adopted a variety of mechanisms to fund buyouts, including bonds, stormwater management fees, grants, and sales taxes. We found 34 total funding programs, nationwide. Many of these funding tools aim to promote autonomy from federal mitigation programs, and ultimately, faster buyout processes.

- Local governments around the United States seldom maintain any accounting of their total expenditures on buyouts costs beyond the direct cost of acquiring homes. While literature helps us identify buyout activities that incur transaction costs, the absence of cost data inhibits targeted policy reform and adoption of best practices. More detailed and standardized data collection and reporting can inform more impactful and equitable buyout policy, as well as more efficient use of public resources.

- Private sector involvement, e.g., in the financing or management of buyouts, could lead to cost-savings and a more efficient buyout process. By distributing investment risks outside the public sector, it may be possible to re-structure programs in a manner that achieves hazard mitigation objectives and better aligns stakeholder interests. Attention must be paid to oversight and equity implications.

- Many communities that have implemented buyouts concurrently allow (or even facilitate) additional development in their floodplains, thus countering any reduction in vulnerability to flooding stemming from the buyout.

- Historical data on buyouts are unreliable and difficult to use. New data management structures need to be developed to accurately maintain buyout records for any policy analysis or evaluation purposes.

Research Questions Addressed

This project sought answers to the following questions:

1. What mechanisms have been used by federal, state, and local governments to fund buyouts?
2. What is the full cost of implementing a buyout project? Specifically, what are the transaction costs associated with buyouts?
3. In what ways could private sector involvement reduce the costs and improve the efficiency of implementing buyouts?
4. To what extent have the flood mitigation gains from buyout projects in NC been undermined or offset by new development in the floodplain?

To address these research questions, we developed two, multi-part projects, described below:

- Estimating the full costs of buyouts and identifying the range of buyout funding mechanisms,
- Assessing the overall or net physical risk reduction as a result of new development in floodplains in communities that have removed flood-prone homes through a buyout.

Estimating Full Costs of Buyouts and Identifying Funding Opportunities

Federal buyout programs have long been criticized as being time-consuming, lacking transparency, and not providing sufficient funding to acquire the total number of qualifying properties. Given these shortcomings, some local and state governments have created their own buyout funding programs, drawing on a variety of both established and innovative funding mechanisms. However, little work has comparatively documented the frequency and geography of these programs, the range of funding mechanisms used, or the number of buyouts they implement.

Similarly, compared to other natural hazard risk reduction techniques, there has been comparatively little research on the cost of implementing buyouts, particularly for local and state governments. Buyouts can be quite costly for federal, state and local governments. In addition to property purchases, surveys, appraisals, title searches, and other tasks generally associated with real property transfers, expenses that are uniquely part of a buyout process include outreach, administration, counseling, negotiation, closing, relocation and demolition (which we term the "transaction costs" of buyout programs). In addition, the entire process is time-consuming; buyouts frequently take two-five years to complete (and often longer). This lengthy processing time often discourages participation, as many homeowners opt to repair their homes rather than wait for it to be acquired.

Finally, there have been no studies on the potential benefits of private sector involvement in funding buyouts, e.g., to acquire homes on behalf of a local government. Private investors may look to buyouts as an opportunity to realize financial returns by providing efficiencies for buyout-related services, including partnering or managing buyout programs currently run by governments, or by negotiating with buyout funders to keep some portion of reduced transaction costs. Private financing mechanisms could allow the public sector to distribute the risks and uncertainty associated with achieving buyout success (roughly measured, from the perspective of governments, as accumulated avoided costs from future flood damage) beyond taxpayers.

Project A goals:

1. Identify the different mechanisms used at the federal, state and local level to fund buyouts.
2. Create a framework for estimating the federal, state and local costs attributed to designing and implementing a buyout project. Implement this model to estimate range of transaction costs in NC.
3. Explore the conditions under which private firms could productively engage in buyout processes to reduce buyout program costs or improve buyout program performance.

Buyouts, Physical Risk Reduction and Development in Floodplains

The implementation of buyouts is intended to help communities become more resilient to natural hazards. However, resilience improvements due to buyout projects can be offset by new development in floodplains. Even communities that have participated in buyouts, or who are taking other steps to reduce flood risk, might be allowing new development in floodplains. While some communities work to steer new construction away from floodplains and acquire existing flood-prone houses, others might ignore floodplains altogether in their decision-making. Yet, with little data available on how development in floodplains has changed over time, our understanding of which communities have effectively managed their floodplains – and how – has remained limited.

In recent years, the availability of data to measure development has dramatically expanded, creating new opportunities to assess empirically floodplain management performance. In this project, we measured floodplain development at the parcel scale to evaluate municipal performance in managing exposure to flood hazards, and identified which communities have avoided developing in floodplains while continuing to grow.

Project B goals:

1. Determine whether development in floodplains outpaced the removal of flood-prone homes
2. Assess how floodplain development patterns differ across communities, and;
3. Assess the extent to which other flood risk management activities were associated with limited floodplain development.

Findings

Estimating Full Costs of Buyouts and Identifying Funding Opportunities

On the federal level, we identified a total of nine buyout funding programs, including the FEMA and HUD programs discussed in the full report, as well as one lesser-used program, two now-repealed programs, and one proposed program. At the state level, we found six programs using three different financing mechanisms, including grants, revolving loan funds, bonds, and – to some extent – tax credits and incentives. At the local level, we found 19 programs in 17 municipalities using four financing mechanisms, including stormwater utility fees, local option sales taxes, and municipal bonds. Most (88%) of the state and local funding programs were aimed, at least in part, at creating a source of local or state funding that could be used as a federal cost-match (Figure below).

State and local funding programs nationwide have resulted in the purchase of some ~9600 flood-prone properties or structures. As most of these buyouts occur with funding from programs that share costs with FEMA, they represent nearly 25% of the over 40,000 total properties acquired with federal grants.

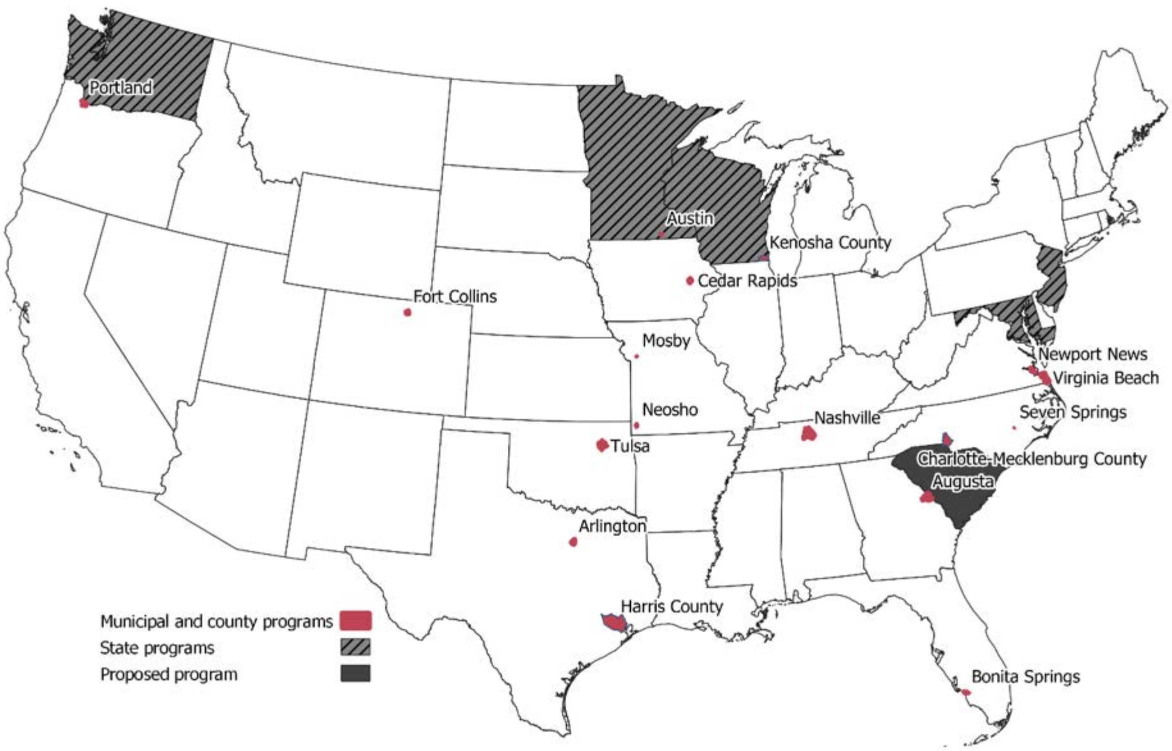

Figure: Map of state and local buyout funding programs in the United States. Municipal and county programs are labeled.

As state and local programs continue to emerge and evolve, they can address some of the shortcomings of federally funded buyouts identified here, namely: funding, flexibility and uncertainty. First, the inability to provide the local contribution for federal funds can discourage local governments from participating in a buyout (FEMA's grants generally require a 25% local match). State and local programs offer one path for streamlining cost matches to obtain federal funds.

Second, programs that are funded independently of federal programs can operate with more flexibility, buying homes more quickly than through federal programs: for example, six months in Charlotte versus five years for federally funded buyouts. Moreover, state and local governments can be proactive in acquiring flood-prone homes, rather than acting after-the-fact, as with federal grants.

Third, state and local buyout programs can reduce the complexity and uncertainty of federal programs; specifically, they can add certainty as to the timing and amount of funding availability, as well as which homes will be eligible. However, the extent to which these non-federal funding sources systematically increase the number of properties bought and reduce the timeline of buyout projects, are areas in need of further investigation. Additional research is needed to evaluate the relative cost-efficiency of state and local programs compared to federally funded programs. Such research is particularly timely given the projected increased changes in sea level and in the intensity of storms and frequency of flooding, which may increase the demand for buyouts.

Creating a Model for Estimating Costs of Designing and Implementing a Buyout

FEMA alone has spent more than three billion dollars on floodplain buyouts, yet we found limited sources with relevant cost information, none of which report transaction costs. Very few published documents (n = 23; 2% of reviewed documents) itemized the costs, either in terms of expenditures or person-hours, of specific activities comprising floodplain buyouts. Of the 23 documents, the large majority (n = 19; 83%) specified only property purchase prices, while three documents (13%) provided information on property purchase prices and another activity, and one document (4%) only described asbestos testing costs. Other itemized activity costs included site maintenance (4%); property purchase price and relocation costs (reported jointly; 4%); appraisal, property purchase price, and demolition (reported jointly; 4%), and asbestos testing (4%).

Similarly, our budget review found little on the specific costs of buyouts. Despite drawing our sample from budget-years in which we knew HMGP buyout grants were active, only a small proportion of budgets itemized buyout costs. Of those that did, many described their buyout activities with only a single line-item in the budget. None of the budgets that provided buyout cost information provided information on FTEs dedicated to buyouts or on how costs were broken down across various buyout activities.

We also examined two public FEMA datasets in an effort to quantify the costs incurred by different buyout activities. While the definitions of variables provided in these datasets were so vague as to limit our ability to draw high-confidence conclusions, our analyses supported the idea that buyout projects frequently incur significant costs beyond those associated with purchasing properties. Indeed, of the 936 we analyzed, 18% (n = 170) spent a third or more of their total funding on activities other than those encompassed by FEMA's "Actual Amount Paid" variable, which primarily reflected property purchase costs. In conjunction with the results of the systematic review and budget review discussed above, these findings suggest that, although property purchase prices receive the bulk of the attention in the discussion of floodplain buyouts and their costs, other activities may play an important and significant role in determining total buyout project costs.

Exploring Private Sector Funding and Implementation of Buyouts

We created a typology characterizing private sector involvement in buyout programs, including forms of public-private partnerships (with firms as service providers [common today] and as partners for running buyout processes), and forms where governments incentivize floodplain acquisitions through a fully privatized buyout market. We found that a variety of environmental finance mechanisms could be employed under each of these market structures.

To proactively move people out of harm's way, floodplain buyout programs need to be scaled up and expanded into high-risk areas. To expedite this process, in the context of buyouts, large investors could establish a "portfolio" of floodplain buyouts, where the conservation of floodplains is adequately capitalized and sufficient funds can be mobilized for the acquisition of new buyouts. The conservation of floodplains can be considered capitalized at a sufficient rate when all high-risk properties that are targeted by buyout programs (1) can be acquired in a timely manner, and (2) at buyout prices high enough to ensure buy-in from property owners.

We found that, under the assumption of variable transaction costs associated with implementing floodplain buyout programs, private market involvement can, in some circumstances, result in efficiency gains. However, it is clear that there would continue to be a need for coordination of the private sector with broader public sector infrastructure plans that may affect private buyout decisions. These considerations may include the locations of desired buyouts, acknowledging that these locations depend not only on flood risk, but also on plans for levees, drainage, and other flood control structures. Also, buyout programs must take into consideration new construction and land use policy such as zoning decisions. Furthermore, governments' unique abilities to help relocated households in ways the private sector cannot (e.g., tax abatements, temporary housing subsides) suggests that continued government involvement will be absolutely key in moving forward with any proposed alternative buyout program structures.

Finally, we discovered a variety of legal hurdles to implementing alternative buyout processes. For example, the US Stafford Act currently authorizes buyout grants to states, tribes, local governments, and certain nonprofit organizations (42 U.S.C. §5170c(b)&(C); 44 C.F.R. § 206.434) only after a presidential disaster declaration. The law does not provide for pre-disaster buyouts or the involvement of investors or other third-party intermediaries. Amendments to the statute and implementing regulations would be necessary to permit the use of federal funds to support privatized or semi-privatized markets for buyouts, provide guidance for private sector involvement, specify any limitations on the use of federal funds, and establish measures to protect property owners from fraud.

Although private sector involvement in floodplain buyouts would be new, improving efficiency and reducing administrative costs for buyouts would be consistent with other provisions in the Stafford Act. For example, a recent amendment required FEMA to develop a plan for administrative cost reduction for disaster assistance, and FEMA regulations define "hazard mitigation" as "[a]ny cost effective measure which will reduce the potential for damage to a facility from a disaster event." (42 U.S.C. § 5165e; 44 C.F.R. § 206.2)

Buyouts, Physical Risk Reduction and Development in Floodplains

In North Carolina, widespread development in floodplains has far outpaced removal of flood-prone property through voluntary buyouts. Since 1996, 3,721 properties were acquired in North Carolina as part of a buyout, while housing has been newly constructed on over 47,000 floodplain parcels. In fact, the sum total of state buyout efforts was offset by floodplain construction in a single year, with 3,639 floodplain parcels developed in 2005 (Figure below).

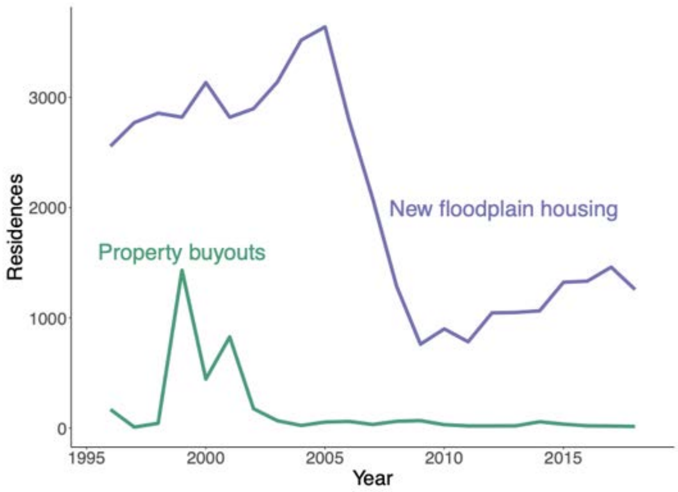

Figure: New floodplain construction far outpaces removal of floodplain property through buyouts in North Carolina. While floodplain housing construction dropped during the real estate market crash of 2008, floodplain construction rates are rising again. (these are preliminary findings that are subject to change upon peer review)

In addition, we found that the construction of housing in floodplains is more likely to occur in communities with small populations (under 5,000 people). Interestingly, our results indicate that the more flood-prone houses a community acquires, the less likely it was to observe development in floodplains. Many of the communities with disproportionately high amounts of floodplain housing have not done any buyouts, and several of them have done fewer than ten buyouts. Finally, floodplain housing patterns differed between inland and coastal communities and as a function of property values.

The complete Floodplain Buyouts report with a list of citations, figures and recommendations can be found at:
https://collaboratory.unc.edu/current-projects/flood-resilience/

Financial Risk of Flood Events in Eastern North Carolina

Greg Characklis, Department of Environmental Sciences and Engineering, UNC-Chapel Hill

Overview

North Carolina has been impacted by three “billion-dollar” flooding events since 2015, imposing financial burdens on many communities, particularly in the eastern part of the state. As a result, developing new strategies for mitigating and managing these financial losses has become more urgent, especially as climate projections suggest that flood events will become even more common in the future. Traditionally, estimates of the flood-related risk, as measured by losses, are quantified as either insured or uninsured, information that is useful, but often too general to develop targeted actions as it provides little information as to whom these losses accrue.

This research takes advantage of several unique, highly resolved datasets (e.g., parcel level information on flood insurance policies/claims, property values, outstanding mortgage balance) and a novel analytical method to quantify the fraction of flood-related financial risk distributed across four groups within 17 counties that lie within the Neuse River Basin: the federal government (through the National Flood insurance Program (NFIP)), property owners (in this case residential only), mortgage lenders, and local government (i.e. county and municipal).

Using Hurricane Florence (2018) as a case study, residential property owners are determined to retain the largest fraction (44%) of the financial risk, followed by the federal and then local governments, each of which hold roughly 25% of the risk, with mortgage lenders retaining the remaining 10%. It is important to note, however, that the relative fraction of risk accruing to each group varies considerably from county to county across the basin, information that will be important to targeting mitigation and management actions to increase community resilience.

Recommended resilience strategies include policy options that break the cycle of financial losses for flood-affected properties resulting in displacement, foreclosure, and abandonment. This may include subsidizing federal flood insurance premiums in vulnerable areas to shift risk away from local communities, identifying mortgage defaults risks for local lenders or offering mortgage relief directly to households after floods. Identifying communities that will benefit from these and other strategies is crucial for successful implementation, as the distribution of risk is largely dependent on specific vulnerability and flood hazard. Continued work should inform prioritization of these efforts.

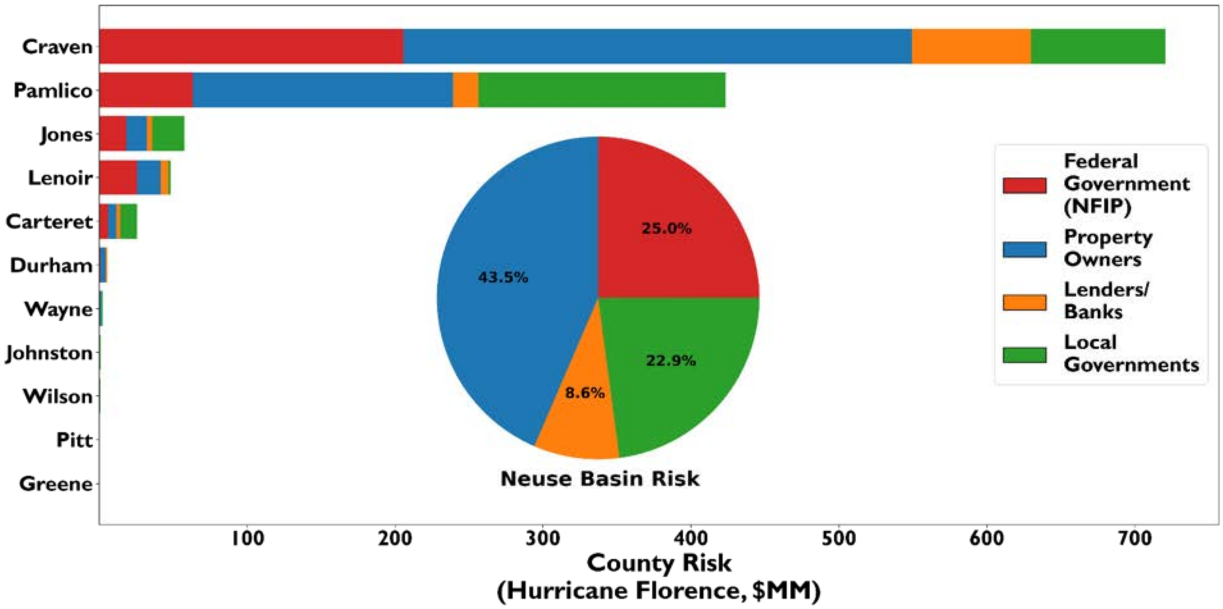

Figure: Modeled financial risk (>$20,000) of modeled counties within the Neuse Basin resulting from Hurricane Florence flood impacts on residential properties. Basin-wide risk is inset.

Research Questions

- When property damages due to flooding events occur, how is financial risk distributed between the federal government, local governments, mortgage lenders/banks, and property owners?
- How does this distribution of risk differ by community in North Carolina?
- How can analyses of these risks inform mitigation and management strategies that increase North Carolina's resilience in the face of future flooding events?

Introduction

Since 1980, flooding and hurricanes have collectively caused over $1 trillion in damages in the United States (NOAA 2020). In North Carolina, three extreme events (Matthew (2016), Florence (2018), and Dorian (2019)) have occurred since 2015 and imposed enormous costs on communities, particularly in eastern parts of the state. Flood insurance provides an initial layer of financial protection for property owners to recover from flood losses, but residential insurance uptake rates are estimated to be only 3.5% in North Carolina compared to the national average of 15%. Over 70% of the $24 billion in damages resulting from Hurricane Florence are estimated to be uninsured, a level consistent with similar storms, such as Hurricane Harvey (2017), that have made landfall in the United States in recent years.

Flood losses are expected to increase in North Carolina as a result of continued development, population growth, and projected increases in severe weather events due to anthropogenic climate change. Consequently, quantifying the financial risk of these events by characterizing the cost and distribution of flood losses is an important tool for increasing resilience to future flood events.

While attempts have been made to quantify flood losses at the regional or community scale, it is often less clear to whom the financial risk of these losses accrue, as well as how these risks could cascade through a community. Flood damages to residential properties expose property owners to significant financial risks arising from the direct costs of repairing damages and home equity losses resulting from reductions in property values. It is often these property owners, and residential homeowners in particular, that are assumed to carry most of the risk of flood-related losses, but the actual distribution of losses across different groups within a community is more complex and largely unexplored.

Individual property owners can, and do, pass some of the risk of flood recovery costs along to the federal government by purchasing coverage through the National Flood Insurance Program (NFIP). Nonetheless, most property owners do not buy flood insurance, even when their mortgage terms require coverage and those that do can only recover losses up to the NFIP cap of $250,000 for structural damage (and another $100,000 for losses related to the contents of the home), which maybe insufficient to cover damages.

Many uninsured or underinsured property owners seek to recover from flood events by borrowing funds against the equity they hold in their home, taking advantage of the relatively low interest rates, in order to repair and rebuild properties. If damages are substantial enough such that they exceed the amount of a property owners' equity, there is a tendency for property owners to walk away from their properties.

For properties with a mortgage, this can lead to default and foreclosure, such that the financial burden of the home is then transferred to the lender, who in many cases will attempt to sell the home to an organization willing to repair and then "flip" (i.e., resell) the property. For example, mortgage payments for damaged properties in Texas after Hurricane Harvey were more likely than non-damaged properties to be delinquent at least 90 days after the storm, with the fraction of those properties that were uninsured being even more likely to be delinquent, need loan modifications, or default compared to their insured counterparts. The risk of default is further elevated after a flood because flooded properties often see a reduction in property value.

If repair costs exceed the post-event market value of a home, lenders may be forced to take losses on any outstanding mortgage balance, as they are unlikely to undertake any lengthy and expensive foreclosure proceedings intended to recover value from the home. This can result in the property being abandoned, at which point responsibility for its maintenance or demolition, as well as the associated costs, are transferred to local government at the municipal or county level. In addition, the combined effects of home abandonment, community outmigration, and neighborhood blight can reduce a local government's property tax base, exposing the entire community (flooded and non-flooded alike) to even greater levels of financial risk as local governments are simultaneously trying to pay to repair damages to public buildings and infrastructure.

Thus, while property owners certainly retain a significant portion of the flood-related loss that impacts their property, these losses have cascading effects throughout a community. As a result, determining the best path by which to make an entire community financially resilient in the face of extreme events is critically dependent on understanding what fraction of flood risk is held by different groups, primarily the federal government, property owners, lenders (local or national), and local government. Quantifying the distribution of flood-related financial risk among these groups, and how this distribution changes across different at-risk regions of North Carolina, will aid in the development of targeted mitigation and relief strategies designed to promote greater resilience in the wake of future flood events.

This work represents an advance through its rigorous parcel-level (i.e., individual property level) estimation of the fraction of flood-related risk that accrues to these four groups, with the focus limited to residential properties in this investigation (consideration of commercial properties will come later). Environmental, financial, and built-environment data are used to model specific flood events and their impact on residential parcels in terms of both damages and declining property values.

Flood hazard areas are described via hydrologic variables; the financial data includes residential property sales values, outstanding mortgage balances, and parcel level data on both insurance coverage and claims; and the built environment is described using characteristics of the parcel and its building that influence both the flood exposure and the property value. Previous studies have adapted machine learning models for natural hazards, such as prediction of the footprint of historic floods, and the estimation of insured damages at specific parcels.

In this analysis, uninsured damages are also estimated over a broad spatial scale using sparse data on observed insured damages via a machine learning algorithm based on random forests. Property value changes are estimated over space and time using built environment variables and property sales data to interpolate property values for all. Combining estimates of flooding losses (i.e., uninsured damages and property value changes) with census tract level mortgage data allows estimation of a damage-adjusted “loan-to-value” ratio (LTV) and home equity at each parcel. The relationships between the outstanding mortgage balances, the built equity, property values and damages provide a basis for characterizing parcel-level financial risk which can then be aggregated to the county and regional scale.

Research Methods

This analysis benefits from access to several unique and highly resolved datasets that describe the environmental, financial, and built environment systems. This includes parcel level information on flood insurance policies, flood insurance claims and property sales, as well as mortgage information at the census tract level. Built environment variables are used to estimate both uninsured flood damages and property values, and so include both flood-relevant and sales-relevant variables such as first-floor elevation and square footage, respectively. Environmental data are used to estimate total expected damage at the parcel scale, and include soil characteristics, height above nearest drainage site, and other elements that affect local flood wave routing.

A schematic of the modeling framework is laid out in the figure below. The described variables are fed into three models focused on estimation of property values, estimation of uninsured damages, and estimation of outstanding mortgage balance. Methods and results are organized around these three distinct modeling efforts. The outputs from these models are then combined to estimate financial risk at the county and basin-scales. This combination is described by the “LTV analysis” in the Figure below, where a pre-storm equity amount and post-storm adjusted “loan-to-value” ratio (LTV) are calculated and then used to assign fraction of risk to potential risk-holders. Insured damages are retained by the NFIP. Property owners are unlikely to borrow additional funds to repair a home with an LTV greater than 1 (i.e., the outstanding loan on the home is greater than the home’s value), and lenders are unlikely to pay for repairs where flooding damages exceed the total value of the property, which can lead to abandonment. Local governments then assume the risk of properties abandoned by lenders through the costs of maintenance or demolition. This decision-making paradigm is discussed in further detail in the full report.

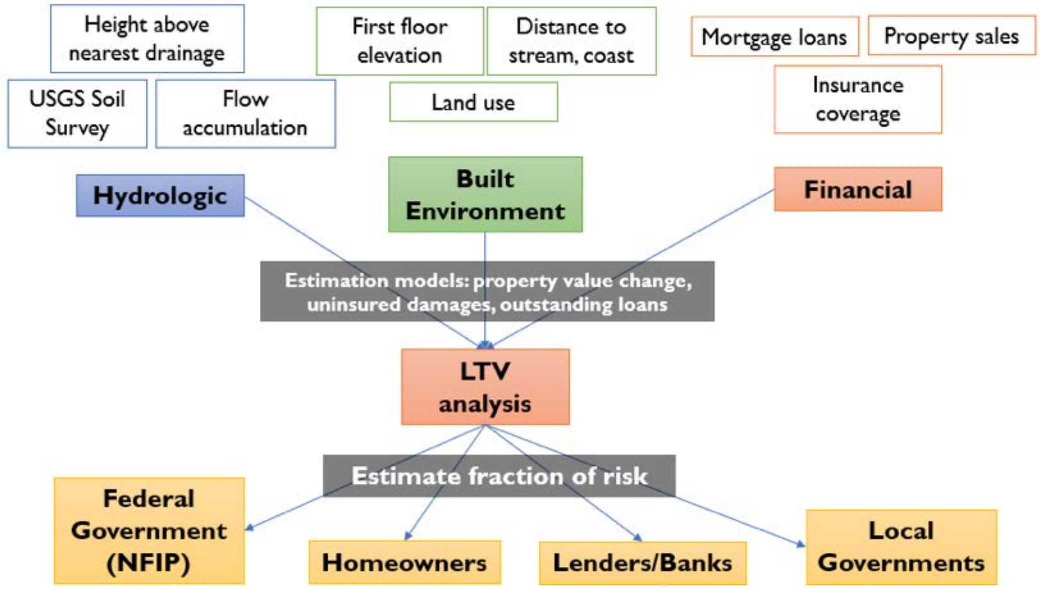

Figure: Process for estimation of systemic financial risk from flood events. Environmental/hydrologic components are in blue, built environment in green, and financial in orange. Parties holding financial risk in yellow.

Analysis was primarily conducted for select counties in the Neuse River basin (figure below) impacted by Hurricane Florence, chosen as an initial case due to widespread flooding and the magnitude of damages. The Neuse basin was selected as it contains counties such as Craven (home to the city of New Bern) that were highly impacted by Hurricane Florence; as of March 2021, New Bern alone has received over $40 million to address infrastructure and other damages (FEMA 2020). Importantly, multiple counties within the Neuse basin qualified for Individual Assistance from FEMA (direct funds for affected individuals and households, such as to support property repairs) following Florence, indicating losses extended far beyond those covered by insurance. For this analysis, 17 counties of the Neuse basin were included due to significant area within the basin; those excluded were Harnett, Sampson, Duplin, Onslow, Beaufort, and Edgecombe, though these counties will be considered in future analyses.

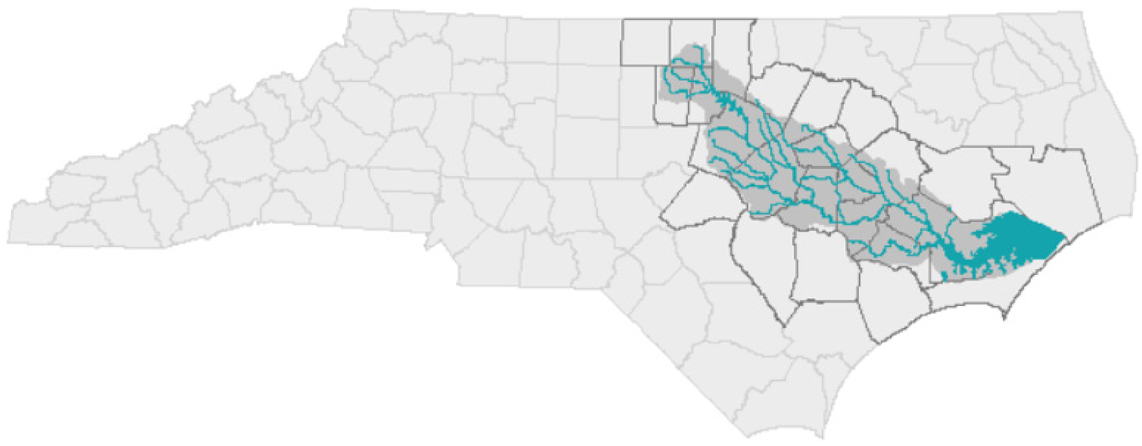

Figure: A county map of North Carolina with the Neuse watershed shown in darker grey and major rivers and streams in teal. Image credit: NC DEQ Water Resource Plans, 2010.

Findings

Results detailed below are specific to Hurricane Florence in the 17 included counties of the Neuse Basin. The results indicate the utility of these detailed and location-dependent analyses in making more highly resolved estimates of the financial risk of North Carolina communities to flood events.

Financial Risk Estimates

In this analysis, the federal government is determined to hold the financial risk of flood events through the NFIP and the payouts this program makes of flood insurance claims to insured properties. Property owners are assumed to hold the risk if the reduction in property value after the storm, uninsured damages, or the sum of the two are less than the equity the property owner maintains in the property. Once the sum of property value reduction and uninsured damages exceeds the equity, the property owner is assumed to forfeit that equity, default on the mortgage, and walk away from the property. For properties holding a mortgage, this results in the property becoming the responsibility of the mortgage lender. For properties in a similar situation without a mortgage, financial responsibility for the property reverts to the local government, which may either demolish, maintain, or repurpose it.

At the time of the flooding event, the simulated loan-to-value ratio and the interpolated property value provide an estimate of owner equity. As the mortgage balance remaining to pay is fixed post-storm, the property owner equity is effectively impacted with property depreciation and uninsured damages. This “decrease” in equity limits the capacity to borrow for repairs, as the low-interest loans offered to property owners by the Small Business Administration (SBA), Federal Housing Administration (FHA), or private lenders are contingent on the value of the mortgage (i.e., equity). Lowered borrowing capacity increases the likelihood of default and eventual abandonment (figure below). The conceptual framework used to assign risk in this analysis is shown succinctly in the rightmost column of the figure below, as increased flood damages relative to property value determines where financial risk is retained among the four parties.

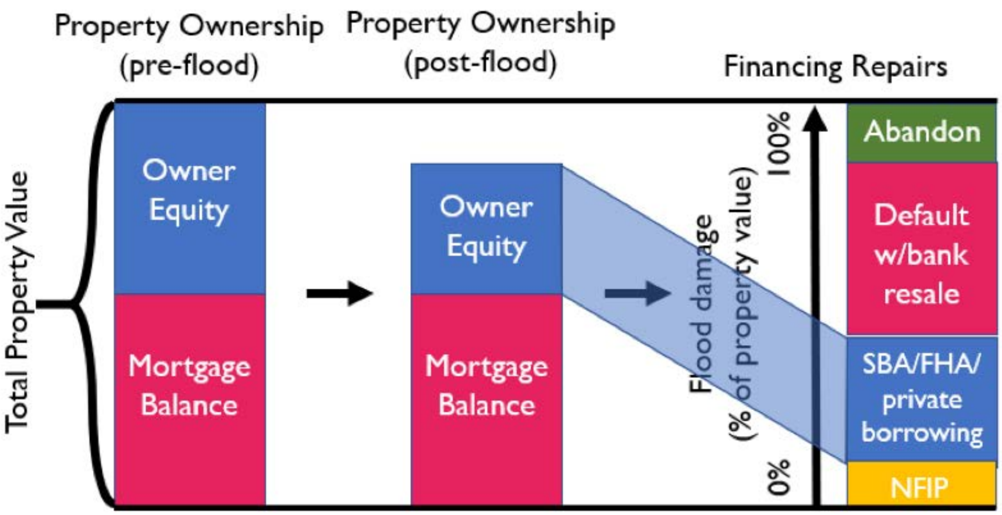

Figure: The impact of flood events on property ownership decisions related to repairing or abandoning the property. As mortgage balance remains fixed, decreases in property value reduces owner equity, which in turn affects the availability of low interest borrowing to repair damages. In the right-most bar, risk accrues to the federal government (yellow), the property owner (blue), the mortgage lender (pink), or the local government (green) depending on magnitude of damages.

Though the relation of the insurance coverage, property value, damage, and equity determines the “assigned” fraction of total financial risk accruing to each group, the risk itself is driven by the combination of uninsured damages and any reductions in property value. Addressing these two drivers of risk calls for different types of policy actions, so understanding their contributions is useful for resilience planning. For example, as reductions in property values in flooded neighborhoods can have a negative impact on both flooded and unflooded properties alike, detailing where post-flood property value decreases are more prevalent could be predictive of neighborhood-wide or community-wide property value losses. These areas could benefit from policies or programs that counteract these effects of the flood.

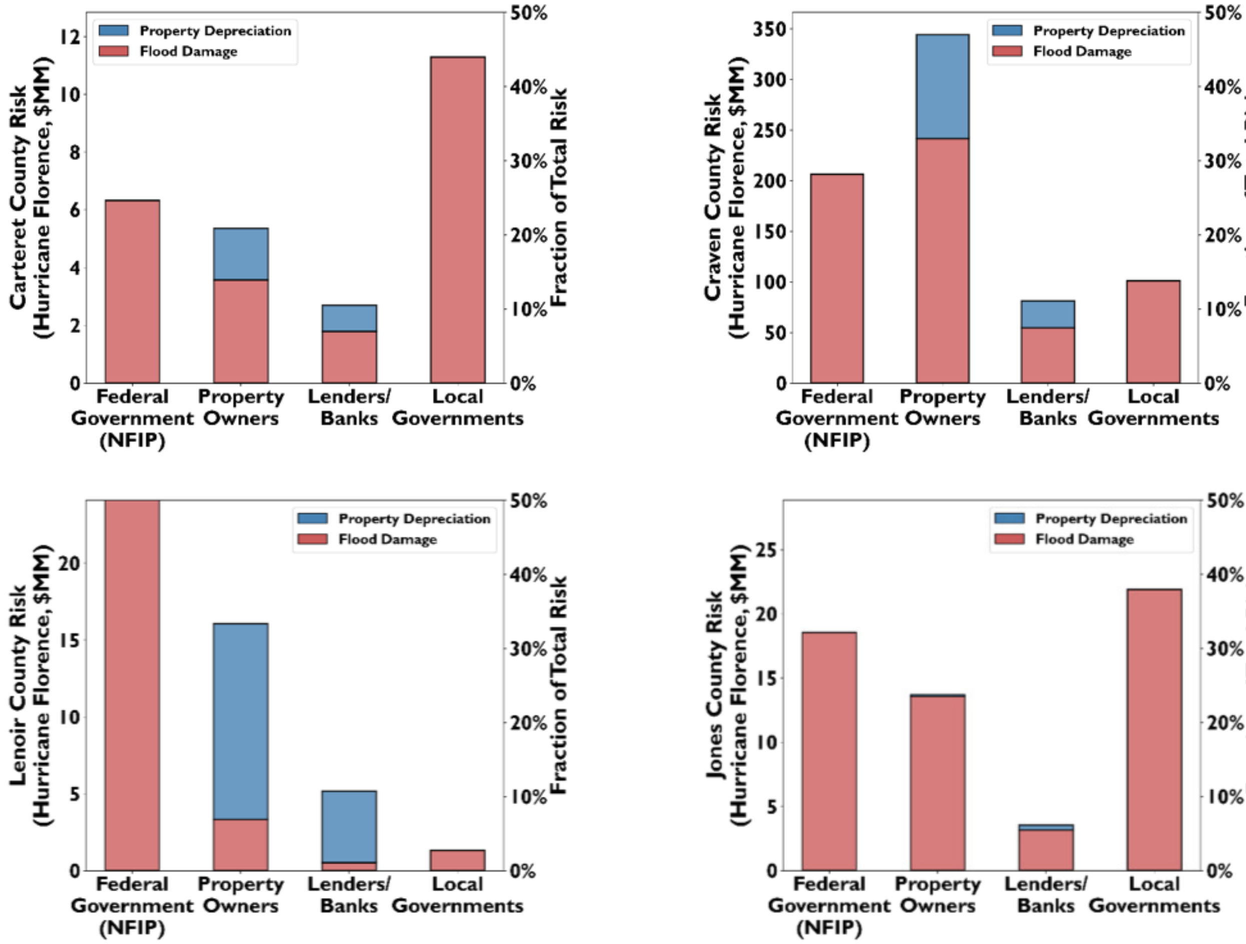

Figure: Modeled losses due to property depreciation and flood damages in (clockwise from upper left) Carteret, Craven, Jones, and Lenoir counties. Note the differing left-hand y-axis for each county to accommodate county specific levels of loss, and the consistent righthand y-axis indicating the fraction of risk to each risk holder, per county.

The risk to each party is also summed across the 17 counties in the Neuse basin to yield estimates of basin-wide risk (Figure below). Property owners carry the largest fraction of the basin-wide financial risk (44%), while the mortgage lenders retain less than 10%, with the federal government (via the NFIP) and local governments each holding roughly 25% of the risk each.

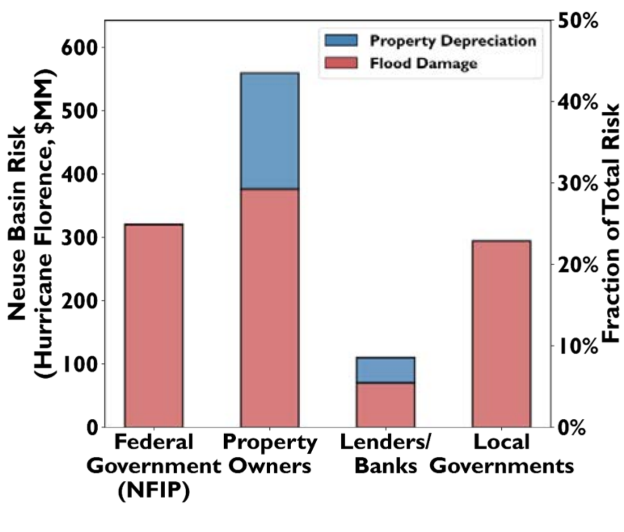

Figure: Hurricane Florence losses due to depreciation and damages across the Neuse watershed. Damages are only charted for counties classified as damaged by the random forest model.

These results provide a more detailed analysis of how financial risk from floods cascade through local communities in North Carolina. Though specific to the scenario that was modeled – historic flooding attributable to Hurricane Florence in the counties of the Neuse Basin—the results indicate that losses accrue to different groups in different proportions from county to county. Property owners bear the most risk at the basin-wide level, however, the risk held by other groups is substantial, in some counties exceeding 50% of the total, and the distribution varies greatly between counties.

Other counties, such as Lenoir, exhibit the protective nature of high levels of flood insurance uptake, as most damage losses accrue to the federal government through NFIP policies, and not to property owners, mortgage lenders, or the local government. Future work aims to explore additional flood events, expanded geographic areas, and the potential for these models to expand to provide predictive capacity related to future flood losses. These detailed, county-specific risk characterizations exhibit the complexity of flood impacts in North Carolina and can be used to inform future recovery and resiliency efforts.

Across the Neuse basin, property owners retained 44% of the flood-related financial risk, the majority due to directly to flood damages, with the remainder coming about as a result of reductions in property value following a flood event. Given the very low levels of flood insurance uptake across the basin, there is a significant opportunity to transfer some of this property owner risk to the federal government by encouraging more owners to purchase this insurance via the NFIP. This will require some effort from the state as flood insurance coverage is already required of properties purchased within a FEMA-designated Special Flood Hazard Area (SFHA) with the help of a federally insured mortgage (i.e., most mortgages). Even with these requirements, however, flood insurance policies only have an average tenure of 2-4 years, despite an average mortgage loan period of 30 years. By both enforcing existing rules and providing additional incentives to increase flood insurance uptake by property owners most at risk (i.e. those in the SFHA) considerable risk could be transferred from property owners, as well as lenders and local governments, to the federal government Even greater levels of risk transfer to the federal government could come by encouraging those most at risk of flooding, but outside of the designated SFHAs, from purchasing insurance via the NFIP,, as flood insurance uptake in these areas is even lower than in the SFHA. This would be particularly effective in urban and coastal areas that have a history of flooding, but are not within the mapped SFHA.

Increased enforcement of policies that make purchasing flood insurance the default when deemed required, such as keeping flood insurance in escrow, would increase insurance coverage within the SFHA. Multi-year insurance contracts are another proposed solution that are projected to increase coverage and satisfy property owners by locking in coverage at an acceptable price for longer periods. Finally, subsidizing flood insurance premiums in at-risk areas would increase coverage for those unable to pay premiums out of pocket and would contribute to not only reducing the risk to property owners, but also to lenders and local governments. If calibrated properly, these incentives could provide a positive return on investment to the state, as some financial risk would be shifted to the federal government via payouts of insurance claims and would provide more immediate relief to improve financial resilience in communities that have experienced flooding.

Mortgage lenders hold just under 10% of the basin's flood-related financial risk. The distribution of this risk between national lenders and local lenders will clearly be of importance to efforts to promote financial resilience in the basin, as local banks are an important source of lending to property owners seeking the resources to repair damages. Distinguishing between local and national lenders cannot, however, be determined with existing data, but will be the subject of future investigation. Nonetheless, understanding the potential losses accruing to lenders remains necessary to predict potential changes to community borrowing capacity and stability of local financial institutions.

To protect these parties, post-disaster relief could include policies that help to break the cycle of foreclosed properties, including state-administered individual assistance, mortgage relief packages, or post-disaster foreclosure moratoriums. For example, after Hurricane Sandy hit New York, FEMA and the Department of Housing and Urban Development (HUD) collaborated to provide rental assistance to households temporarily displaced by flood damages to their primary residences to ease short-term financial stress; mortgage lenders also coordinated foreclosure moratorium policies and allowed loan modifications to reduce confusion and financial burden for affected property owners. The coordination of these programs was facilitated by the Hurricane Sandy Rebuilding Task Force and is recommended for future disaster planning as well. An analysis of mortgages at risk of default (those with an LTV > 1), as performed in this work, could aid in providing more targeted outreach for post-disaster policies. Further research into the ability of mortgage lenders (both local and national), to absorb losses from flood events is recommended to prepare these institutions to survive these events and continue to provide borrowing resources to their communities in the post-event environment.

Local governments hold 22.9% of the financial risk of flooding in the Neuse basin experienced as a result of Hurricane Florence. First, any action that reduces the flood risk of property owners (e.g., increased uptake of flood insurance) will reduce the probability of local governments ultimately assuming this risk. Additionally, local governments may be able to prevent future flood impacts through alternative zoning rules. Requiring and supporting structural mitigation efforts, such as home elevations, should provide higher levels of protection for property owners already residing in the floodplain, reducing displacement, and encouraging safe neighborhood growth. If development continues in flood prone areas, those exposed to the related financial risk continues to grow; if flooded properties are repurposed and resold without both appropriate mitigation efforts made to the structure and disclosure of flood risk to the new property owner, the pool of property owners at risk is simply refreshed, and mortgage lenders and local governments do not gain any protection. Limiting development in current and future floodplains in North Carolina is one way to decrease the exposure to flood events and the potential of property owner financial risk being passed along to local government through abandoned properties. To assess total financial risk accruing to local governments, future consideration should also be given to the losses arising from reductions in the property tax base due to lower post-event property values, damages to local infrastructure, business disruptions, and the potential long-term effects of blight.

The complete Financial Risk of Flood Events in Eastern North Carolina report with citations, figures, and recommendations can be found at: https://collaboratory.unc.edu/current-projects/flood-resilience/

Natural Systems: Improving Resilience to Coastal Riverine Flooding

Barbara Doll, NC Sea Grant, NC State University

Overview

Three major storms during the past twenty years, Hurricanes Floyd (1999), Matthew (2016) and Florence (2018), have resulted in loss of life and billions of dollars in impacts to homes, businesses, transportation infrastructure, agriculture, and commerce and hundreds of millions of dollars in emergency response and recovery costs. The frequency and intensity of severe storms and associated flooding are expected to increase due to climate change. The large-scale implementation of strategically located natural infrastructure (NI) measures (e.g., wetlands, forests, water control systems) to increase water storage capacity and reduce flooding was evaluated in the middle Neuse River Basin.

Eighteen NI measures initially considered were reduced to three measures - reforestation, water farming and flood storage wetlands - based on a literature review, expert opinion, geospatial mapping of opportunity, and ground-truthing of three study subwatersheds. NI implementation was modeled in three subwatersheds– Little River, Bear Creek and Nahunta Swamp – and the results were extrapolated to the other sub-watersheds of the middle Neuse River Basin. Costs and secondary economic benefits of investing in these NI measures were also evaluated.

Approximately 112,737 acres, constituting 10.5% of the middle Neuse Basin that drains to Kinston, were identified as suitable for the NI measures. The greatest opportunity was in the lower portion of the basin where the land is flatter and less developed. In areas of high-density NI implementation, localized flooding could be substantially reduced (up to 45% peak flow reduction and up to 1.5 ft. water level reduction), even for larger storms. The degree of flood reduction was a function of the density and location of NI implementation in a watershed, with greater reductions occurring along smaller tributaries than on the mainstem of the rivers. Lower water levels (0.3 to 0.5 ft.) resulting from the full implementation of NI resulted in estimated reductions in damages to structures ranging from 7% to 21% for Goldsboro and Kinston, depending on the scale of the storm. The largest damage reduction percentages were estimated for the 50-year storm. In addition, water quality modeling indicated that widespread NI measures could reduce nutrients (6 to 18%) and sediment (16 to 30%) export from the three modeled subwatersheds.

The costs of establishing all of the identified NI measures in the middle Neuse River Basin was estimated at $726 million. Damage reductions to structures in the floodplain were estimated at 13% to 14% ($23 to $35 million) when NI practices were implemented compared to scenarios without NI implementation for two theoretical 30-year future scenarios. Direct employment and the economic response that would result from fully implementing the measures were estimated at 1665 jobs and $791 million. Economic multipliers for indirect employment were estimated at approximately 5.2 to 5.4 for all three measures and secondary economic impact multipliers were above 2.16. As a result, the direct, indirect, and induced impacts are estimated to generate almost 9000 jobs and $1.9 billion in total economic impacts during the construction period. Selling nitrogen credits at the value set by the NC Division of Mitigation Services could potentially offset about 20% of the construction costs for flood storage wetlands.

Because of the low cost of reforestation, combined with substantial water quality and modest flow reduction benefits, increased investments in forest conservation programs should be an immediate priority. Moderate flood reduction, especially at the local scale, combined with substantial water quality benefits and large economic multipliers associated with NI investment indicate that further investigation of the identified NI measures is warranted. Further study of the optimization of NI placement and density and a deeper examination of the ancillary and indirect benefits of NI adoption, through additional modeling studies and on-the-ground pilot projects is recommended. Because an NI implementation program will require installation and management on private working lands, landowners should be involved in the process early. Other state's conservation-based flood mitigation programs, such as Iowa and Minnesota, could serve as possible program models. Finally, because reductions in existing flooding impacts through NI are limited and future storms are projected to increase flooding, it is recommended that North Carolina restrict future development or redevelopment in floodplains to reduce future losses.

Introduction

Flooding, especially resulting from hurricanes, is the most frequent natural disaster globally and one of the most devastating in terms of both lives lost and economic damage. Riverine flooding is believed to affect more people than any other natural disaster by deteriorating infrastructure, damaging crops, displacing residents, contaminating local water supplies, and disrupting natural ecosystems. It is expected that the frequency and duration of riverine flooding events will increase in the coming years due to changing patterns in precipitation, continued urbanization, and other changes in land use that affect natural landscapes.

Nature-based solutions, also known as natural infrastructure, present advantages for water quantity and quality and is a more sustainable approach to flood management. When implemented as a series of distributed practices across a watershed, natural infrastructure is likely to be designed, approved and built more rapidly than large reservoirs, levees or other flood mitigation projects. Natural infrastructure uses natural land features such as wetlands and forests to slow down runoff from storms and store water for an extended period. The purpose of natural infrastructure practices is to increase infiltration and incorporate water storage through constructed natural land features.

Project Goals

The goals of this study were to determine the extent to which natural infrastructure can mitigate the impacts of flooding and improve water quality in the Neuse River Basin. A successful natural infrastructure-based flood mitigation program in eastern North Carolina should ensure that environmental, social and economic benefits are realized, and ensure that financial resources are spent wisely.

Study Approach

A multidisciplinary team of university faculty, staff and student researchers (NCSU, UNC-Chapel Hill) and non-government organization representatives spent 16 months evaluating the potential for natural infrastructure (NI) to mitigate riverine flooding in eastern North Carolina. NI refers to a strategically planned and/or managed network of natural lands (i.e., forests and wetlands), working landscapes and other open spaces that conserves or enhances ecosystem functions and provides associated benefits (e.g. flood control) to people.

The study team (23 people) conducted geospatial mapping analyses; hydrologic, hydraulic and water quality modeling; economic analyses; landowner and community outreach and a preliminary review of potential programs and measures for implementing a conservation-based NI program. The Middle Neuse River Basin from Johnston to Lenoir County, which has been heavily impacted by recent riverine flooding events, was the focus area of the study.

Through a literature review and exploration of 18 conservation, restoration and land management measures, eight key natural infrastructure measures were identified with the greatest potential to help improve flood resilience in Eastern North Carolina (Table below).

Measures	Descriptions
Agricultural	
Cover crops and no-till	Including cover crops on fields during winter
Hardpan breakup	Breaking up compacted hardpan layers to allow for soil water infiltration
Forests and Tree Planting	Planting bottomland hardwood or pine forests
Agroforestry	Combining mixed trees and pasture fields
Wetland and Stream	
Wetland Restoration	Restoring natural wetlands along streams or at a lower elevation with grasses and sedges and water control structures, or bottomland hardwood wetlands on prior converted agriculture land
Stream Restoration	Restoring previously straightened streams to the original configuration or expanding floodplains adjacent to existing agricultural ditches and stream channels
Structural	
Dry dams and berms	Creating catchment areas to store water during flooding (e.g., “water farming”
Land drainage controls	Installing simple drainage controls including terraces, tile underdrains, and flashboard risers

Table: Eight Categories of Natural Infrastructure Measures Suitable for Increasing Flood Resilience in Eastern North Carolina

Three subwatersheds (50 – 80 square miles; 32,000 to 51,000 acres) of the Basin – Little River, Bear Creek and Nahunta Swamp – were intensively modeled to estimate the peak flow reductions during large storms and water quality benefits resulting from implementing the NI measures. Geospatial mapping combined with ground-truthing of the subwatersheds resulted in the selection of three NI measures with the highest potential for implementation in the study area - wetlands, water farming and reforestation. Geospatial analysis and ground-truthing were conducted in three study subwatersheds (Little River, Nahunta Swamp and Bear Creek) to identify opportunities for the natural infrastructure.

Water Farming

Water-farming refers to constructing earthen berms with outlet structures around the edge of a field for the purpose of temporarily retaining runoff during extreme flooding events (see Figure below). Water-farming systems, implemented in areas of Florida, have been shown to improve water quality while reducing runoff from fields. During normal rainfall and weather conditions, the structure(s) remain open; prior to a large storm, the structure(s) are closed so that all water that falls on the field will be retained. After flood flows have receded (3-5 days), the structure(s) are re-opened to allow any remaining water to drain off the field.

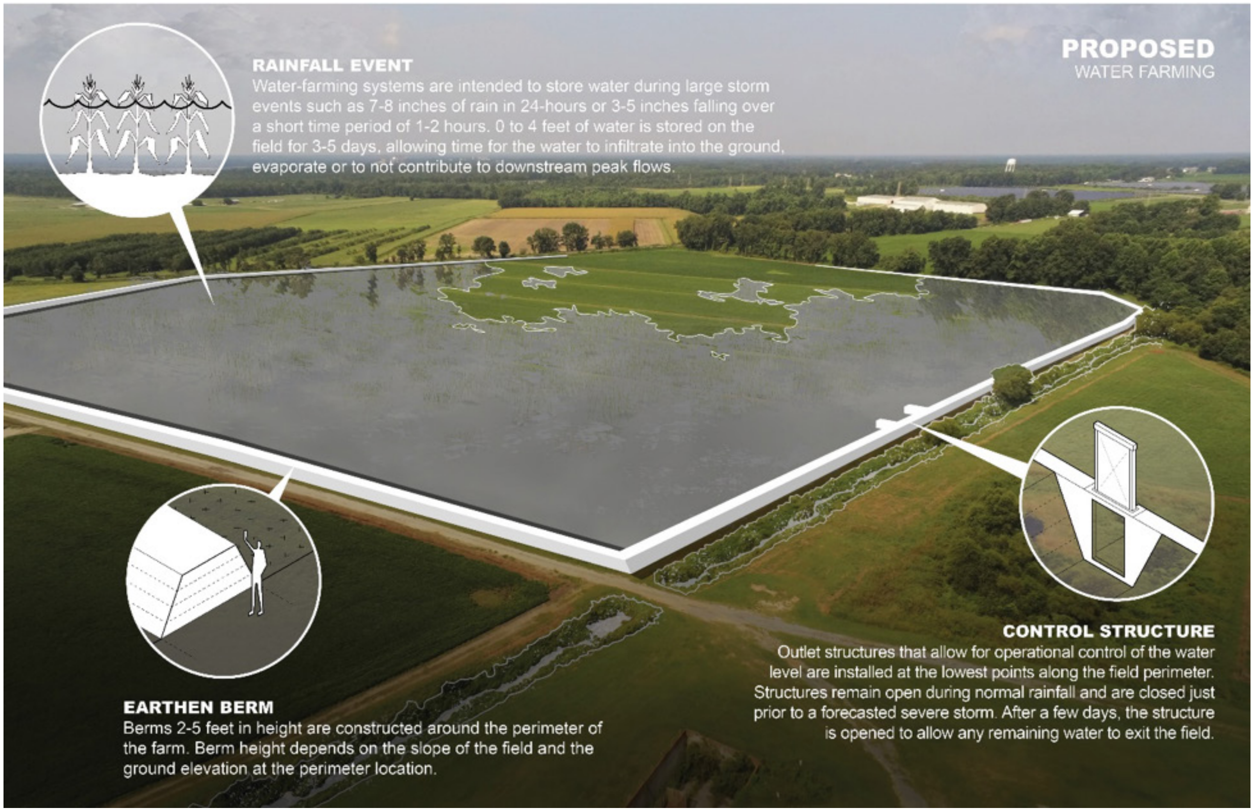

Figure: Concept Rendering of Water Farming

Flood Control Wetlands

Locations where existing drainage ditch systems that captured at least 35 acres of watershed area were strategically identified for the creation of flood control wetlands. Unlike wetland restoration efforts typically employed for mitigation banks, flood control wetlands require extensive excavation in order to expand the capacity of the existing ditch to store a greater volume of water during a flooding event. Earthen embankments, berms and drainage control structures can be added to restored or created wetlands to maximize their flood storage capacity. The wetlands are designed to temporarily store floodwater then slowly release the water after the event. When it rains, the embankment blocks the flow of water and causes water to back up into the wetland area.

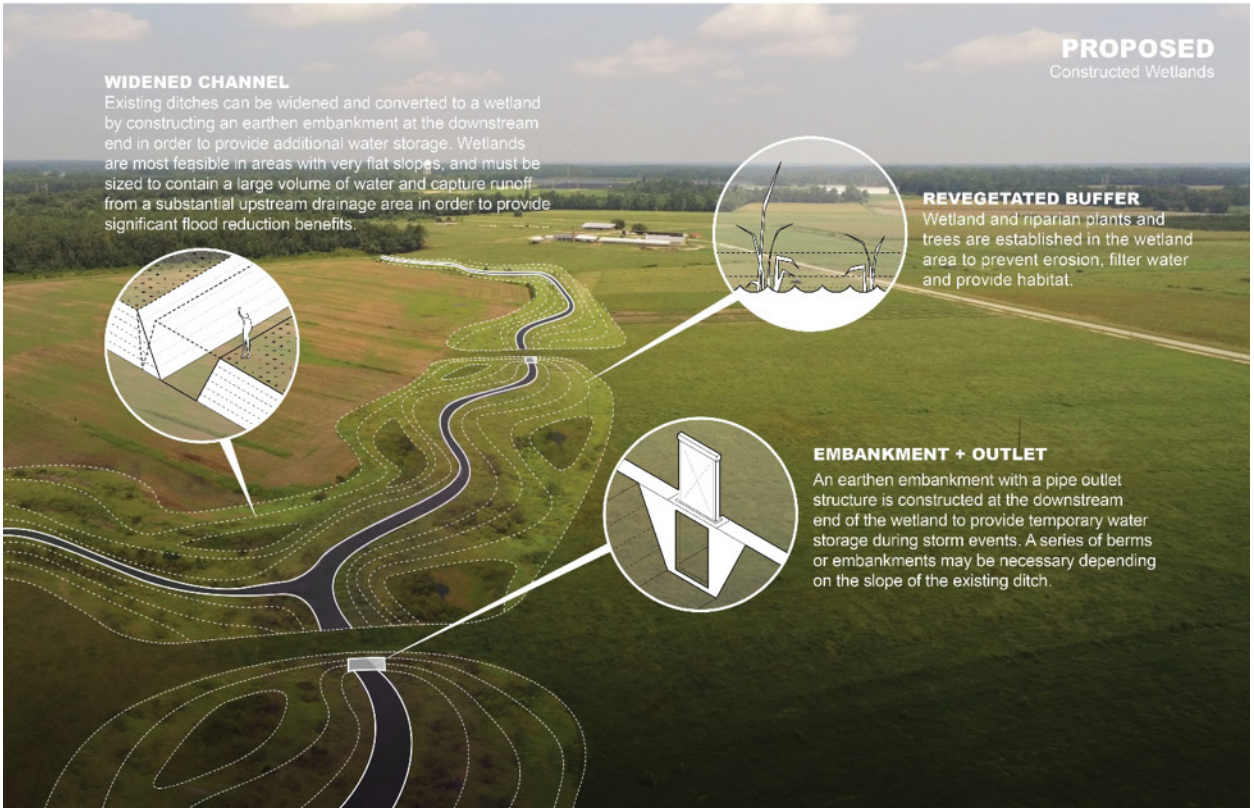

Figure: Concept Rendering of Flood Control Wetland

Reforestation

Both conservation reforestation and agroforestry opportunities were considered through our analyses. Agroforestry is the practice of integrating farming practices with silviculture by growing trees and crops on the same unit of land, or trees and pasture animals on the same unit of land. The National Commodity Crop Productivity Index (NCCPI) was used to identify lower crop productivity areas. Lowland areas were evaluated for bottomland hardwood forested wetlands and upland areas for loblolly pine plantations.

Other Practices

Most cropland in eastern North Carolina has the potential to employ the remaining agricultural NI measures (cover crop and hardpan breakup), however, these measures have a lesser ability to reduce flooding during moderate to extreme rainfall events. Mapping, ground truthing and modeling of these measures was therefore not conducted. Limited opportunities for stream restoration and floodplain expansion were identified during visits to the subwatersheds, so these measures were also not considered for modeling or further evaluation.

NI potential and peak flow reductions from the three study watersheds were extrapolated to the full middle Neuse Basin using regression relationships developed from the subwatershed results. Existing NC Division of Emergency Management (EM) floodplain mapping models were used to estimate water level reductions along the Neuse River and several tributaries. The peak discharge and river water level changes were used to estimate the number of structures that would experience less flooding along the Neuse River with a focus on the communities of Kinston and Goldsboro.

The total costs of establishing the NI measures in the middle Neuse River Basin were estimated to quantify the potential direct and indirect economic benefits of investing in NI. Project elements and the resulting spending pathways (labor, materials, fuel, etc.) were based on past restoration projects and input from stream and wetland contractors and practitioners. To evaluate the feasibility and cost associated with various leasing and purchase agreements the team held workshops and conducted a detailed survey of more than 50 landowners. The web-based survey was circulated to farmers across six counties within the Basin to estimate the costs of leasing and buying land for NI practices. The estimated total costs were then input into the IMPLAN economic impact assessment software system to estimate the potential secondary economic benefits of investing in NI. In addition, detailed economic engineering and finance analyses were conducted for multiple scenarios of the seven NI measures identified to determine average costs for the selected measures and the payments that might be required for landowners to adopt them.

A committee of working lands experts was formed to explore the innovative NI measures identified and consider the process that would be necessary to implement a NI-based conservation program focused on flood mitigation. Science, economics, community collaboration, and governance structures relevant to conservation and environmental programs both within and outside of North Carolina were reviewed. Results were used to prepare program development and communications recommendations.

Summary of Key Findings

Total Natural Infrastructure Opportunity

Approximately 10.5% of the Middle Neuse Basin (112,737 acres) that drains to Kinston was identified as suitable for three key measures identified for floodwater retention and flood mitigation including reforestation, water farming and wetlands. NI opportunity is greatest in the lower portion of the basin where the land is flatter and less developed (see Figure below). The total acreage considered suitable for each measure is provided below in the Table.

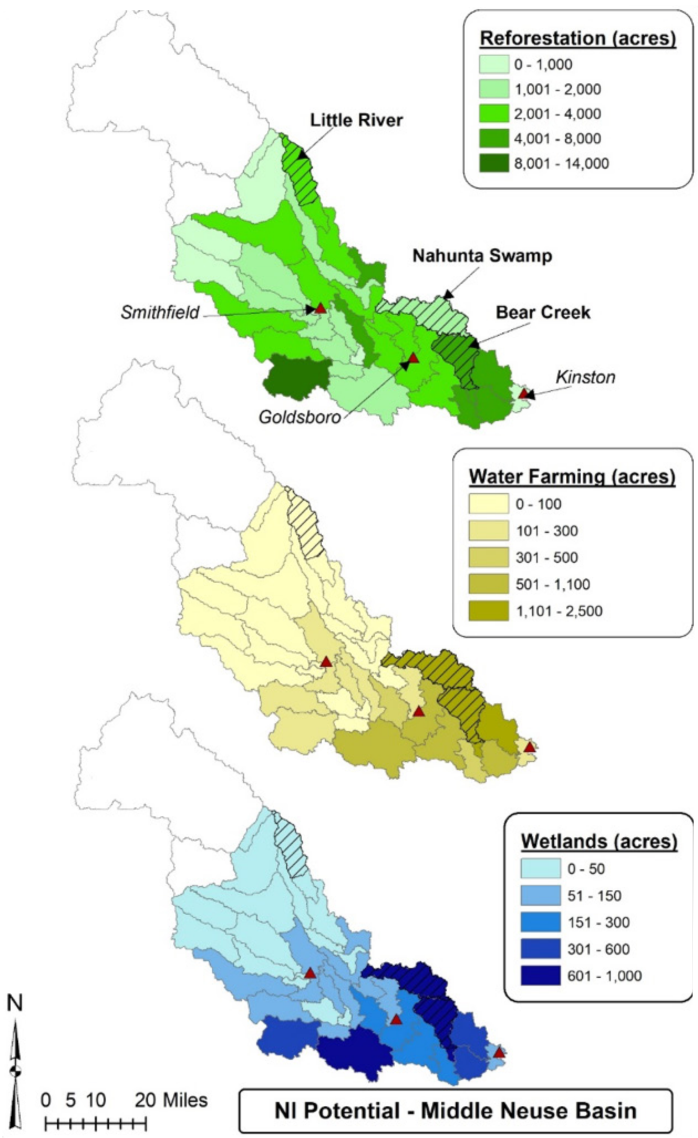

Figure: Opportunity for Reforestation, Water Farming and Wetlands within the Study Area of the Middle Neuse Basin.

Peak Flow Reduction

Implementation of NI has the potential to reduce peak flow and resulting flooding. The degree of flood reduction is a function of the density and location of NI implementation in a watershed. Flood reductions are more substantial along smaller tributaries than the mainstem of the river.

For two of the selected subwatersheds (Nahunta Swamp and Bear Creek) peak flow reduction at the watershed outlets ranged from 13 -24% for the 100-year event for the full implementation of NI (i.e., reforestation, water farming and wetlands). These reductions would decrease water levels by less than 0.5 feet near the outlet because of the flat wide floodplains and low stream slope. Within the subwatershed, downstream of the most intensive NI implementation, the local peak flow reduction approached 50% for the 100-year event (1% chance of occurring during any given year), resulting in a decrease in water level of more than 1 foot in some areas. This illustrates the potential for NI to be used to mitigate localized flooding issues in smaller watersheds.

Peak flow reduction in Little River was minimal (<1%) for the 100-year event due to limited opportunity for NI using the three selected measures on the relatively steeper lands. However, opportunities exist to retain water using more traditional methods such as dry detention and/or reforestation, but peak flow reductions were limited. Implementation of eight dry detention structures along tributaries reduced peak discharge at Zebulon by less than 5.0% for large storm events (e.g., 100-yr, Hurricane Matthew).

If all the NI opportunity (wetland, water farming and reforestation) identified in the Middle Neuse Basin were implemented, peak flow and associated river level reductions for Smithfield would be negligible (< 0.1 feet). Peak flow reductions for Goldsboro and Kinston during a Hurricane Matthew-scale event would be 4.4 and 5.3%, which would result in approximately 0.3 feet in water level reduction for Goldsboro and 0.4 feet for Kinston. Reductions in water surface for the Neuse River were approximately 0.3 feet for all storms evaluated at Goldsboro and between 0.4 and 0.5 feet for storms evaluated at Kinston. The principal three NI measures also could reduce flooding from small tributaries, streams, and low-lying lands that flood farm fields and structures. Use of more of the 18 measures identified in the initial screening across a broader area of the watershed would decrease flooding somewhat, but their additional contributions would be less.

Water Quality

Water quality modeling in both Bear Creek and Nahunta Swamp indicated that the percent reductions in nutrients for reforestation was roughly equivalent to the percent of the watershed reforested. Whereas, for Little River conversion of about 6% of the land to forest reduced total nitrogen (TN) by 12% and total phosphorus (TP) by 17%. Wetlands in Bear Creek resulted in 6 to 10% total nitrogen reduction and 5 to 7% in Nahunta Swamp, while total phosphorus reduction ranged from 2.5 to 6.0%. Combining wetlands and reforestation could result in more than a 15% reduction in annual TP and TN in Bear Creek and up to 8% in Nahunta Swamp. The wetlands could also capture a substantial portion of the influent sediment load because of the large wetland to watershed ratio. Using the reductions and the NC DEQ DMS nutrient credit rates for the Neuse River Basin, the nitrogen credits from wetland restoration projects were estimated to cover ~23% of the construction costs. Monetary credits are not currently offered for sediment or phosphorus reductions; however, there is significant ecological and environmental value in reducing these pollutants.

Total Establishment Costs

The costs for implementing all natural infrastructure measures totaled approximately $726 million (Table below). Wetlands have the highest water storage potential relative to area and also capture runoff from larger contributing areas. The cost for wetlands is much higher than the other measures due to the extensive grading necessary to create enough storage volume to reduce peak flows during very large storms (100- and 500-year). Traditional wetland restoration in the Coastal Plain, which involves filling ditches to restore pre-disturbance hydrology, would not provide substantial flood control benefits during very large storm events. Costs were estimated for 7 of the other 18 NI infrastructure measures as well, and while they were less, their hydrological effects were not modeled due to their smaller opportunity to store floodwaters from major storms. The three principal measures and others might reduce on farm flooding and damages, but these benefits were not examined in this research.

		Reforestation	Water Farming	Wetland Restoration	NI Total
	Total Area of Opportunity Identified (Acres)	97,050	10,530	5,157	112,737
NI Practices	% of Middle Neuse Study Area that Drains to Kinston	9.1%	1.0%	0.5%	10.5%
	Costs (Millions)	$15.5	$34.1	$677	$726
	Costs Per Acre	$68 - $396	$3,242	$131,208	
	Water Storage Potential (acre-ft/acre)	0.1-0.33	1	3	
	Cost Per Unit Water Stored ($/acre-ft/acre)	$206-$3,960	$3,242	$43,736	
Construction	Jobs directly created	87	69	1,509	1665
	Total employment impacts	454	371	8,146	8971
	Employment multiplier	5.23	5.39	5.40	
	Direct economic impacts	$40,944,836	$34,100,509	$716,176,056	$791,221,401
	Total economic impacts	$86,071,833	$80,518,681	$1,745,969,156	$1,912,559,670
	Total economic multiplier	2.10	2.36	2.44	
Monitoring + Maintenance	Jobs directly created	8	19	19	46
	Total employment impacts	14	36	35	85
	Employment multiplier	1.86	1.86	1.86	
	Direct economic impacts	$1,024,704	$2,632,500	$2,578,500	$6,235,704
	Total economic impacts	$2,013,749	$5,173,390	$5,067,269	$12,254,408
	Total economic multiplier	1.97	1.97	1.97	

Table: Total acres of opportunity identified, implementation costs, water storage potential, unit costs, and economic and employment impacts (direct and total – including direct, indirect, and induced) for construction and monitoring and maintenance phases for water storage for reforestation, water farming measures and wetland restoration NI practices in the Middle Neuse River Basin (above Kinston, NC) Monitoring and maintenance figures assume middle scenario (B) for water farming and wetland restoration per-acre costs.

Damage Reductions to Structures

Lowering the water surface resulted in damage reductions to structures ranging from 7% to 21% for Goldsboro and 10% to 18% for Kinston, depending on the storm event (Figure below). The largest damage reduction percentages were for the 50-year storm in both locations. Considering two theoretical 30-year future scenarios, damage reductions to structures resulting from NI implementation were estimated to range from $23 to $35 million, which represented approximate 14% and 13% of total existing structure damage costs for the two scenarios considered. The number and scale of events was matched closely to the past 30-years for the first scenario and included one 25-year, one 50-year and one 100-year storm for both Goldsboro and Kinston. In addition, two storms smaller than the 25-year storm were added for Goldsboro. For the second scenario, the 100-year storm was replaced with a 500-year storm. It should be noted that flow monitoring on the Neuse River at Kinston over the past 90 years has not recorded a flood reaching the magnitude of the 500-year event to date, but projections for climate changes make this or more frequent floods an increasing probability. Total benefits of reduced flooding due to NI would also include reduced indirect cost, reduction in damages to crops and other infrastructure such as roads and utilities, as well as many additional valuable ecosystem services associated with NI. Quantifying these additional storm impacts and flood mitigation measures and benefits was beyond the scope of this study, but certainly warrants further research.

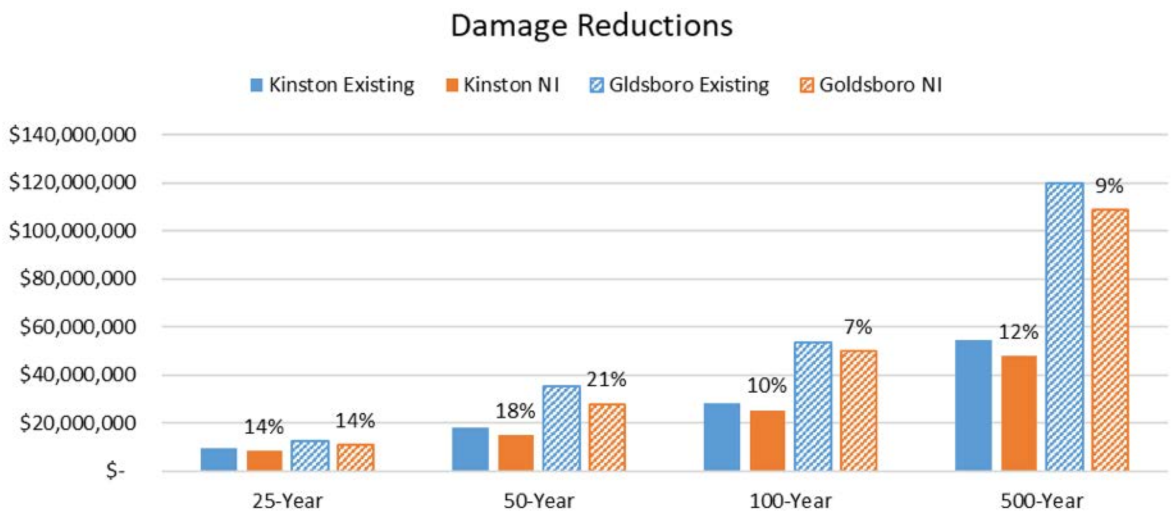

Figure: Estimated Damage Reductions to Structures for each Return Interval Storm for Kinston and Goldsboro.

Regional Economic Benefits

Overall, we found that NI construction phases have consistent employment multipliers around 5.0, meaning 4 jobs are created for each direct NI job created, and economic multipliers around 2, meaning $2 in gross regional product created for each $1 invested, across all NI practices. Implementation of these projects has similar economic impacts for each dollar invested, although wetland restoration generates the highest number of jobs (approximately 8,000 jobs) and total economic impact (approximately $1.7 billion) by a significant amount.

If all modeled NI projects were completed, we estimate that the State would generate approximately 1600 jobs directly in NI, and just under 9000 jobs overall, with a total of $1.9 billion in total economic impacts during the construction period. During long-lived monitoring and management efforts after construction, both the employment and economic output multipliers for all practices hover just under two. In this phase, water farming and wetland restoration have similar overall effects – each generate just under 20 jobs directly in NI and approximately 35 jobs overall. Reforestation results in about half as many jobs. In terms of economic impacts, both water farming and wetland restoration are estimated to yield about $2.5-$2.6 million in direct economic impacts and approximately $5 million in total economic impacts. Although the monitoring and maintenance impacts are smaller, these activities and associated impacts will occur every year, while construction impacts are only incurred once, when the NI project is built.

Conservation Program Costs and Payments

The costs to establish all the practices outlined in the Table above were estimated using discounted cash flow and capital budgeting analyses to calculate the potential annual government payments needed for landowners to achieve a break-even point of a 6% internal rate of return. It was assumed all establishment costs would be paid for, and annual payments for 10 years would be required to cover maintenance costs for each practice, and no added land lease or purchase costs would be needed. Modification of traditional agriculture measures—no-till, hardpan breakup, forestry, and agroforestry—were the cheapest measures examined, with payments of $8 to $36 per acre required for 10 years. However, these measures have lower potential to store water in large storm events. Wetland construction ($78/ac/10 yr) and water farming ($106/ac/10 yr) were the most expensive, but have more potential to store larger amounts of water for a longer period. Tiling with drainage controls designed to store water was quite affordable, ($2/ac/10 yr) and stream restoration was expensive ($70/ft/10 yr), and apt to have intermediate water storage prospects. Excel spreadsheet templates for each scenario are available to landowners, technical specialists, policy makers, or other researchers.

The complete Natural Systems: Improving Resilience to Coastal Riverine Flooding report with citations, figures and recommendations can be found at: https://collaboratory.unc.edu/current-projects/flood-resilience/

Natural Systems: Enhancing the Role of Wetlands in Flood Mitigation Through Policy

Jonas Monast, UNC-Chapel Hill School of Law

Overview

This research summarizes the current state of wetlands protections in North Carolina and recommends statutory and regulatory steps to expand the role of wetlands in the state's flood mitigation strategy.

North Carolina and the federal government each have jurisdiction over the state's wetlands and streams. The scope of federal Clean Water Act jurisdiction has expanded and contracted over time, particularly regarding coverage of wetlands. North Carolina law protects "Waters of the State," which includes a more expansive definition of jurisdictional waters than the Clean Water Act. Other state laws include specific protections for coastal and estuarine waters and marshlands.

The EPA and the Army Corps of Engineers implemented a new definition of "waters of the United States" in 2020, removing some wetlands and streams from federal jurisdiction. State law governing wetlands, streams, and other water bodies remain in place, but the change in federal jurisdiction created a permitting gap for development impacting certain wetlands and streams in North Carolina. The NC Department of Environmental Quality proposed temporary rules in March 2021 to reestablish a permitting mechanism for projects impacting waters subject to state wetlands protections but no longer covered by federal Clean Water Act jurisdiction.

The fluctuations in federal wetlands jurisdiction, and uncertainty regarding state wetlands permitting authority, risk undermining protections for wetlands at a time when North Carolina policymakers are seeking strategies to prepare the state for future storms. The white paper follows the discussion about state and federal jurisdiction with four recommendations to maintain and enhance the role of wetlands in North Carolina's flood resilience strategy:

- Ensure regulatory certainty by maintaining current protections and mitigation requirements.
- Fund flood control projects authorized in the 2020 Water/Wastewater Public Enterprise Reform Act (HB 1087)
- Expand opportunities for landowners and local governments to protect natural systems that contribute to flood mitigation.
- Provide local governments with capacity building and coordination support.

Research Questions

The impact of the 2020 Navigable Waters Protection Rule on NC wetlands protections and mitigation requirements.

- The current state of federal and state jurisdiction over navigable waters and wetlands in North Carolina;
- The history of the Clean Water Act rules defining "waters of the United States" jurisdiction and related court decisions;
- Options to clarify North Carolina wetlands jurisdiction following the promulgation of the 2020 Navigable Waters Protection Rule.
- Identify models for expanding the flood mitigation role of wetlands in North Carolina.

Findings

The 2020 federal Navigable Waters Protection Rule removed some waters from federal jurisdiction, but it did not affect the existing scope of the NC Waters of the State protections. Following the change, state-issued Clean Water Act permits (§401 permits) continue to cover wetlands adjacent to federal jurisdictional waters but no longer apply to "significant nexus" wetlands—wetlands that remain subject to 15A NCAC 02B .0231. This created a permitting gap in North Carolina.

The lack of permitting authority has caused some projects that would impact wetlands to stall, because they were unable to receive a permit that would authorize replacement of the wetland through mitigation. DEQ proposed temporary rules in March 2021 to reestablish a permitting mechanism for projects impacting waters subject to state wetlands protections but no longer covered by the federal WOTUS definition.

There are a number of existing programs in North Carolina that could serve as models for expanding the flood mitigation role of wetlands and other natural systems. The white paper highlights three such programs: the Conservation Reserve Enhancement Program (CREP), a US Department of Agriculture cost share program, NC Land and Water Fund and Agriculture Development and Farmland Preservation Trust Fund, and the Clean Water State Revolving Fund.

A student takes notes about the water levels of the Battle Park creek. Photo courtesy of the University of North Carolina at Chapel Hill.

Recommendations

Maintain Existing Wetland Protections and Mitigation Requirements

Maintaining existing protections for wetlands and streams is a critical first step to enhancing natural systems for flood mitigation, particularly as North Carolina lawmakers seek cost-effective strategies to improve the state's resilience to major storms. DEQ's proposed temporary permitting rule would achieve that goal in the near-term.

Implementing permanent rules that ensure ongoing wetlands protections and clarify permitting requirements would result in multiple benefits for the state. First, many existing wetlands contribute to flood mitigation and deliver additional ecosystem and economic advantages. Reducing regulatory requirements could undermine state flood resilience goals. Doing so could also increase the cost of achieving similar levels of flood mitigation potential. The current wetland and stream mitigation requirements allocate the cost of wetland impacts to the actors directly causing the impacts. Reducing wetland and stream protections would, therefore, place the costs on taxpayers in order to replace wetland acreage rather than the project developers.

Second, maintaining existing protections would provide certainty for the regulated community, stakeholders and government officials overseeing permitting requirements. As noted in Section II, federal Clean Water Act jurisdiction has expanded and contracted over time, and judicial interpretations of the Clean Water Act's WOTUS requirements have created confusion and different rules for different parts of the country. Because North Carolina's Waters of the State rules remain in place even as federal requirements shift, state rules can maintain constancy and certainty. The General Assembly could provide a greater degree of regulatory certainty by enacting legislation to codify the existing wetland and stream protections. It is important to note that legislative changes limiting CEQ's NC Waters of the State authority could have the opposite effect, increasing the state's vulnerability to changes in federal regulations.

Third, maintaining existing protections would provide stability for wetland mitigation protect developers and the Division of Mitigation Service's in-lieu fee program. DMS contracts with private companies to develop large mitigation projects and purchases mitigation credits if necessary to facilitate timely options to the regulated community. These projects may take years to develop. If near-term jurisdictional changes reduce demand for private mitigation and DMS in-lieu fee mitigation. In turn, this could shrink the pipeline of available projects, thus delaying or preventing development if wetland rules become more stringent in the future.

Provide Funding for Flood Storage Capacity Projects Authorized in the 2020 Water/Wastewater Public Enterprise Reform Act (HB 1087)

The 2020 Water/Wastewater Public Enterprise Reform Act (HB 1087) established an innovative new program to increase flood storage capacity. The law builds upon the in-lieu fee mitigation program and expands the types of projects the DMS may invest in to include flood storage projects that "create[] or restore[] a quantify of flood storage capacity expressed in acre-feet." These projects may include "the creation or restoration of wetlands, streams, and riparian areas, temporary flooding of fields, pastures, or forests, and other nature-based projects that can demonstrably increase flood storage capacity."

The flood capacity programs authorized in HB 1087 are distinct from the Clean Water Act and Waters of the State protections for wetlands and streams, allowing DMS to fund projects based on flood water retention capacity rather than ecological function. While HB 1087 focuses on water retention rather than ecological function, wetlands conservation and construction should qualify if they meet the retention requirements. HB 1087 authorizes the new program but does not appropriate funding for projects. DMS is funded by fees collected through the in-lieu mitigation program, which is driven by the regulatory requirement to mitigate stream and wetland impacts. The flood storage program is voluntary, so the success of the flood storage projects will depend either upon state appropriations or federal funding. Initial funding could focus on demonstration projects in different watersheds to evaluate project design and identify long-term funding needs, or prioritize early projects in the highest priority areas.

Expand Opportunities for Landowners and Local Governments to Protect Natural Systems that Contribute to Flood Mitigation

The preceding recommendations focus on regulatory requirements or project implementation by DMS and private sector wetland mitigation providers. Expanding incentives for private landowners and local governments to participate in wetland restoration and creation could complement the first two recommendations and significantly expand protected areas that contribute to flood mitigation.

There are existing incentive programs and funding mechanisms that the General Assembly could expand to increase flood mitigation projects. For example, the Conservation Reserve Enhancement Program (CREP), a US Department of Agriculture cost share program, funds conservation measures to "improve water quality, reduce soil erosion, reduce the amount of sediment, phosphorous and other pollutants entering waterbodies, improve wildlife habitat and restore wetlands." In North Carolina, CREP enrollment covers 76 counties in NC, including the following river basins: Yadkin-Pee Dee, Roanoke, Cape Fear, Neuse, Lumber, White Oak, Tar-Pamlico, Chowan, and Pasquotank. Landowners voluntarily enter into a conservation easement with the state and receive annual payments and reimbursement for conservation expenses. Easements may last for 10, 15, or 30 years, or be permanent.

In order to qualify for CREP, "land must be located in the project area and be either cropland or marginal pastureland. Cropland must meet cropping history criteria and be physically and legally capable of being planted in a normal manner to an agricultural commodity. Marginal pastureland along streams may also be eligible for enrollment." The N.C. CREP has a goal of enrolling 85,000 acres of riparian and 15,000 acres of non-riparian wetlands. As of Sept. 30, 2019, total CREP enrollment included 30,977 acres. Cumulative enrollment (including acreage no longer enrolled) included 26,794 acres of riparian buffer and 2,171 acres of wetland restoration. Increasing resources for outreach to landowners could help achieve the CREP enrollment goals. CREP could also be a model for a state-funded flood mitigation-focused program that covers lands that do not qualify for CREP. This type of voluntary program could complement the HB 1087 flood control projects funded by DMS and enable more private landowners to participate in flood mitigation efforts.

The General Assembly could also expand existing state programs that fund conservation and working land protections. For example, the NC Land and Water Fund (NCLWF) (formerly the Clean Water Management Trust Fund) provides grants for purchasing property or conservation easements. The NCLWF funding covers numerous ecological and cultural goals. Flood mitigation is not an explicit goal, but the priorities include protecting and improving water quality and creating riparian buffers. Similarly, the NC Agriculture Development and Farmland Preservation Trust Fund helps preserve working lands in the state. Like the NCLWF, this program does not focus on flood mitigation, but the working lands protected by the program could still assist with water absorption and retention. Both grant programs provide funding for conservation easements, and the NCLWF also provides funding for purchasing property. Unlike CREP, however, these programs do not include the annual payments for lands enrolled in temporary or permanent easements. The General Assembly could expand funding the programs and potentially increase the mission of either program to include flood mitigation.

Generally, local governments and non-profit organizations must acquire and monitor conservation easements. These governments or organizations must have the staff resources to do so, and the conservation easements must meet their organizational goals. If the state expands resources for flood control-focused conservation easements, it may also need to assess the ability of these governments or organizations to acquire additional easements. Organization support, or potentially allowing state agencies to hold the easements (similar to CREP), may be necessary. Furthermore, conservation easements have financial benefits for landowners (via payments for the easement and/or tax benefits), but may reduce local property tax revenue depending on the amount of land in easements and whether or not the land was in present use valuation programs prior to establishing the easement. This could create a disincentive for local governments to pursue additional conservation easements. Including this option as part of the state's flood mitigation strategy may require local government support to replace lost tax revenue.

The Clean Water State Revolving Fund (CWSRF) is another potential source of support for local government investments in natural system flood mitigation projects. Each state has a CWSRF that combines federal and state funds that revolve to provide a continuous and replenishing source of funds. Initially focused on providing funding for water treatment facilities, states now use the CWSRF to support a variety of projects to protect water quality. In 2016, the EPA announced a Green Infrastructure Policy for the Revolving Fund, recognizing the benefits of protecting natural areas, including flood protection. North Carolina could look to other states innovating in the use of their CWSRF to explore opportunities to support both water quality and flood mitigation goals in watersheds. Numerous other funding opportunities and conservation-focused programs could serve as models for North Carolina to expand protections for wetlands and other flood mitigation strategies

Provide Local Governments with Capacity Building and Coordination Support

Local governments are responsible for many of the decisions that shape landscapes. Through land use planning, mitigation planning, and municipal infrastructure investments, these governments are on the front line of storm response and mitigation measures. State funding can help local governments develop the staff expertise to identify, evaluate, and implement priority projects for natural system flood mitigation. Local governments may also need additional capacity to develop proposals for federal funding, such as FEMA's Building Resilient Infrastructure and Communities (BRIC) program. Coordination support for local governments could further help optimize the role of natural systems at a watershed level.

Numerous existing North Carolina institutions provide training and support for landowners and local governments. For example, the NC Cooperative Extension Service offers education and technical assistance on a variety of conservation and land management objectives. The regional councils of government assist with planning and coordination. The UNC School of Government regularly provides training, research, and education to assist local governments across the state, including capacity building for environmental service providers offered by the School of Government's Environmental Finance Center. Additional resources could help position these institutions, as well as additional university programs and government agencies, assist local communities as they expand natural flood mitigation options.

The complete Natural Systems: Enhancing the Role of Wetlands in Flood Mitigation Through Policy white paper with a list of citations, figures and recommendations can be found at: https://collaboratory.unc.edu/current-projects/flood-resilience/

Natural Systems: Compound Flooding

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Rick Luettich, UNC Institute of Marine Sciences

Overview

Compound flooding – driven by the interaction of heavy rainfall, riverine, and coastal flooding during tropical cyclone events – is likely a significant driver of total water levels during coastal flood events experienced in North Carolina. Yet, current hydrodynamic models cannot fully represent the influences of both inland and coastal processes on total water levels. Accurately delineating the depth and extent of coastal flooding due to severe weather events impacting the U.S. East Coast is paramount to addressing community resilience in North Carolina over the long term.

Project Goals

The goals of this project were to (1) assess eastern North Carolina's current modeling systems for compound flooding (the combined effects of precipitation and coastal storm surge flooding); (2) locate areas in eastern North Carolina that are susceptible to compound flooding; and (3) improve the representation of small coastal streams in coastal flood hazard models using the New River watershed as a pilot case.

Research Methods

We relied on several hydrodynamic models, including the ADCIRC Model, LISFLOOD-FP, and HEC-RAS to predict coastal flooding. We validated the models' performance against observed water level data collected during Hurricane Florence (2018) and other recent storm events. Much of our time was spent collecting and evaluating existing state and federal topography and bathymetry data necessary to accurately delineate the spatial characteristics of coastal streams in hydrodynamic models.

Summary of Findings

- Compound flooding was observed during Hurricane Florence and is expected to be a significant driver of total water levels during other North Carolina coastal flood events, particularly in small coastal streams and watersheds because of the short travel times of the inland flood wave in these systems.

- ADCIRC modeling of the coastal storm surge from Hurricane Florence suggested the area south of Cape Lookout was most susceptible to compound flooding. Accurate surge modeling is important for separating the surge and non-surge contributions to total water level and therefore for identifying periods of compound flooding in measured water levels records.

- Existing large-scale coastal flood hazard models (ADCIRC) and hydrologic models (LISFLOOD-FP) lack detailed information about channel properties for smaller tributaries and channel reaches on the North Carolina coast. Model results suggest that the representation of channel bathymetry is critical to accurately representing the timing and magnitude of the flood wave, as well as total water levels during coastal flood events.

- National channel property databases can be highly inaccurate in flat coastal areas such as eastern North Carolina. While North Carolina has detailed lidar topography data and river/stream cross section data, integrating these data to enable modeling of compound flooding is not easily done.

Research Questions

This project sought answers to the following questions:

1. To what extent is compound flooding likely to be a significant determinant of water levels and flooding during coastal storms in eastern North Carolina?
2. How well do currently available coastal (e.g., ADCIRC) and inland (e.g., LISFLOOD-FP) flood hazard models represent compound flooding from coastal storms?

To address these questions, we developed two interrelated projects, described below:

- Utilize the ADCIRC coastal hazards model to assess storm surge flooding throughout coastal North Carolina caused by Hurricane Florence; and
- Utilize the LISFLOOD-FP inland hazards model to represent precipitation-based flooding in the New River watershed caused by Hurricane Florence. Include ADCIRC storm surge results to yield an initial estimate of compound flooding in this watershed.

Utilize the ADCIRC coastal hazards model to assess storm surge flooding throughout coastal North Carolina caused by Hurricane Florence

The landfall of Hurricane Florence along the southern coast of North Carolina in September of 2018 presented new opportunities for modeling storm surge with the ADCIRC coastal hazards modeling system developed at UNC-Chapel Hill. While the typical track for a hurricane impacting North Carolina generally follows the US Southeast coast, approaching North Carolina on a northward trajectory, Hurricane Florence took a unique westward track making landfall in the Wrightsville Beach area of Onslow Bay. In addition to the unique track, Florence slowed to 5 knots just as it made landfall. As a result of its slow forward speed Florence produced a record-breaking rainfall event in addition to producing upwards of 3.5 meters of storm tide. These characteristics strongly suggest that at least a portion of the flooding that occurred along the North Carolina coast and coastal plain was due to compound flooding, making Florence an excellent case study of this phenomenon.

Predictions of compound flooding events are rare at the present time, making the study of Hurricane Florence particularly timely. In addition, Florence may represent what can be expected from future hurricanes as a consequence of climate change and sea surface temperature warming on landfalling tropical storm impacts. Recent studies have shown that forward speeds of Atlantic hurricanes could be slowing down, particularly once they have made landfall. This lengthens the opportunity to precipitate over coastal regions.

In this project we focus on modeling the storm tide, (the combined tide plus storm surge) caused by Hurricane Florence as a starting point for identifying the occurrence of compound flooding. By comparing the storm tide results with observational data, we identify the part of observed water levels that were due to the storm tide and infer the part of the observed water level record that was most likely due to hydrological processes.

<u>Project A Goals:</u>

- Evaluate the performance of the ADCIRC model for capturing coastal storm tide (surge plus tide) and flooding during Hurricane Florence 2018.
- Identify geographical areas in eastern NC that experienced the combined effects of coastal surge and rainfall-runoff leading to compound flooding during Hurricane Florence

Utilize the LISFLOOD-FP with ADCIRC as a downstream boundary condition to provide a first estimate of compound flooding in the New River watershed caused by Hurricane Florence

River and floodplain routing is an important aspect of coastal flood hazard modeling and requires a realistic representation of the channel shape and capacity. Recent advances in computing have made it feasible to deploy physics-based, numerical models at a high-resolution (e.g., 30-m) to simulate multi-mechanistic flooding (e.g., compound flooding) at regional, continental and global scales. Large rivers are typically represented in these models as a channel with a rectangular shape because of its efficiency and relative accuracy in capturing channel capacity. In contrast, small coastal streams and channels are often ignored in these large-scale models due to the paucity of easily accessible data on their characteristics. We expect that the delineation of small channels is important for accurately capturing compound flooding (e.g., the timing and magnitude) as they control the conveyance of runoff from the landscape into the drainage network.

In this project, we use the New River watershed as a pilot case to test our hypothesis. We chose the New River Watershed because it is a relatively small coastal plain watershed with limited urbanization and a clear compound signal (Project A). There are several small, tidally influenced tributaries that feed into the main stem of the New River allowing us to investigate their role in routing flood waters during Hurricane Florence. We collect coastal topography and bathymetry data from a variety of existing state and federal databases and build a hydrodynamic model using the hydrodynamic model LISFLOOD-FP to capture the impact of rainfall-runoff and storm surge on flooding inland. We test the performance of the model against USGS observed gage data and high-water marks (HWMs) using output from the validated ADCIRC model for Hurricane Florence (Project A) as a downstream boundary condition.

Project B Goals:

- Evaluate the current models and data availability in eastern North Carolina used by the NC Division of Floodplain Management for flood prediction; and
- Improve modeling of the timing of the flood wave and total water levels driven by coastal surge and precipitation-based flooding in eastern NC using the New River Watershed as a pilot study.

Findings

ADCIRC Hurricane Florence Hindcast Results

ADCIRC simulations were performed using either the OWI and GAHM meteorological forcing for the 11-day period 0000 UTC 07 September to 0000 UTC 18 September which fully covered Florence's coastal impact. A preliminary comparison with observed data indicated that the OWI winds had a directional error that increased close to the eye of the storm and that the GAHM were generally too strong using the default settings in ADCIRC. Both were adjusted to reduce these systematic errors and the adjusted winds were used in the analyses reported below. ADCIRC simulations were performed with and without astronomical tides; simulations that included astronomical tides were initiated using a 15-day tides-only spin-up, to establish ambient tidal conditions, prior to imposing the meteorological forcing. Simulation results without tides are used to indicate the magnitude of the surge itself, whereas all comparisons with observational data were done using model results that included astronomical tides to capture the full water level response.

Maximum wind speeds from both the OWI and GAHM data indicate the storm impacted land with winds that bordered between tropical storm and category 1 strength. Speeds are quite consistent between the two datasets with the GAHM winds being slightly stronger than OWI (Figure below).

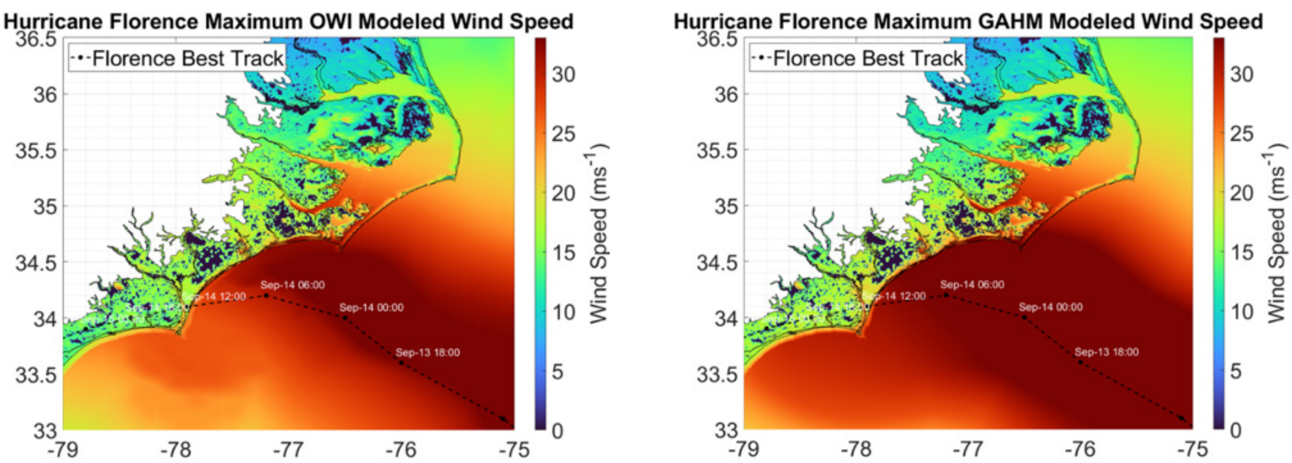
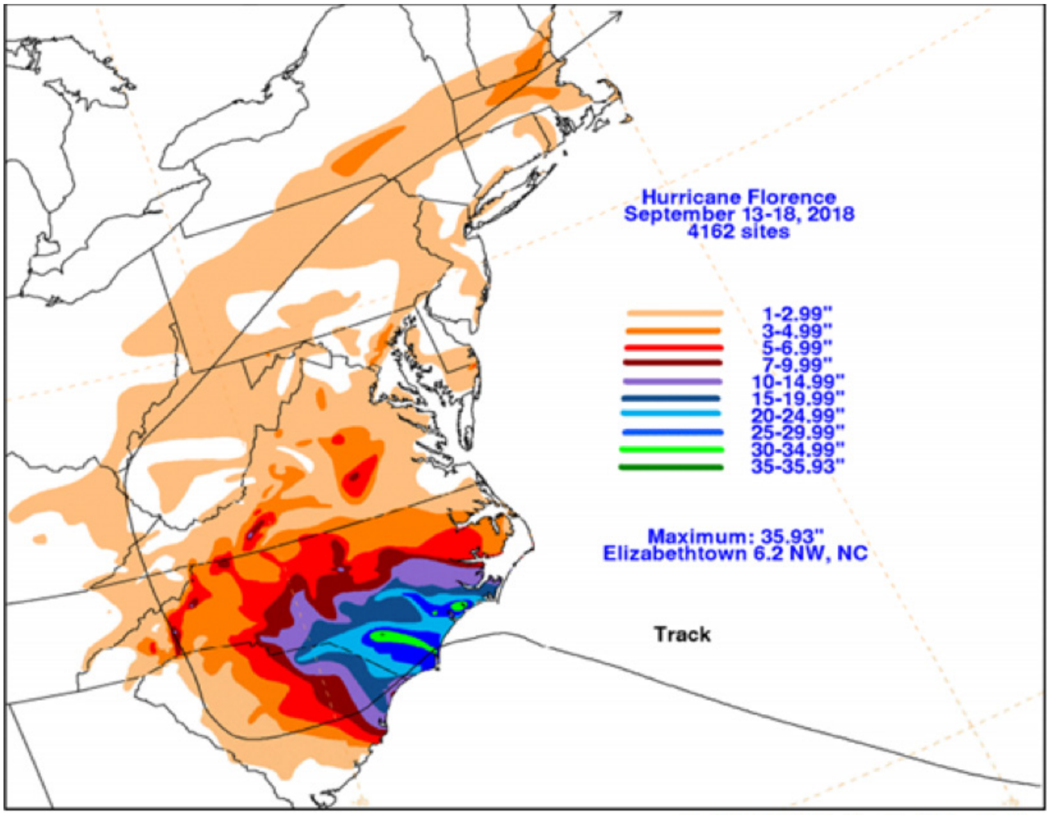


Figure: Maximum wind speeds modeled using two forcing methods, OWI (left) and GAHM (right)

Evidence for Compound Flooding During Hurricane Florence

Due to the slow forward motion of the storm and the heavy rainfall it deposited on eastern North Carolina (Figure below) we anticipate that coastal water levels were influenced both by storm surge and by hydrologic inputs as reflected in compound flooding. Time series plots of water level were evaluated for indications of the presence of both the surge and the hydrologic components, and clearly show the presence and timing of both during the storm.



Credit: NOAA Weather Prediction Center

Figure: Precipitation accumulation during Hurricane Florence, September 13-18, 2018.

The complete Natural Systems: Compound Flooding report with citations, figures and recommendations can be found at: **https://collaboratory.unc.edu/current-projects/flood-resilience/**

Infrastructure: Inundation of Stormwater Infrastructure

Mike Piehler, UNC Institute for the Environment

Overview

Stormwater infrastructure mitigates precipitation-driven flooding in urban areas, but only if the infrastructure can drain. Coastal areas increasingly experience flooding due to elevated receiving water levels from extreme storms or tides, but the inundation of coastal stormwater infrastructure by elevated water levels has not been broadly assessed.

We conservatively estimated stormwater infrastructure inundation in coastal North Carolina (NC) incorporated municipalities by identifying areas of high tide flooding (HTF) on roads. We also modeled stormwater infrastructure inundation across a range of water levels in four NC municipalities (i.e., Beaufort, New Bern, Nags Head, and Wilmington) and measured infrastructure inundation in one (Beaufort).

Findings

- 65 NC municipalities had estimated road area impacted by HTF, and over 1/3rd had >1% road area impacted.
- Smaller municipalities were more likely to have higher relative amounts of HTF on roads.
- Modeling results and water level measurements suggested that extensive inundation of underground stormwater infrastructure frequently occurs during typical water levels.
- Of the four modeled municipalities, the two with the most extensive stormwater infrastructure inundation (i.e., Beaufort and Nags Head) had approximately 1% of their total road area impacted by HTF.
- Model results show that stormwater infrastructure can sometimes act as a conduit for elevated receiving waters to flood low-lying inland areas that would otherwise be disconnected.

Management Implications

- Stormwater infrastructure inundation is common and likely increases the occurrence of urban flooding in coastal NC by reducing the capacity of drainage networks.
- Stormwater infrastructure inundation is often underground under current conditions, making it difficult to observe.
- Issues with stormwater network survey data quality and availability make it difficult to directly characterize and model the extent of the issue.
- The issue of stormwater infrastructure inundation will rapidly increase with sea level rise.
- Many low-lying coastal areas will need to adapt quickly to mitigate stormwater network inundation and excessive stormwater runoff due to the effects of climate change.

Introduction

Stormwater infrastructure can mitigate precipitation-driven flooding when there are no obstructions to draining. Coastal areas increasingly experience recurrent flooding due to elevated water levels from storms or tides, but the inundation of coastal stormwater infrastructure by elevated water levels has not been broadly assessed. We conservatively estimated stormwater infrastructure inundation in municipalities along the Atlantic United States coast by using areas of high tide flooding (HTF) on roads as a proxy. We also modeled stormwater infrastructure inundation in four North Carolina municipalities and measured infrastructure inundation in one.

Over 600 east coast municipalities had road area impacted by HTF, and over 1/3rd had >1% road area impacted. Modeling results and water level measurements indicated that extensive inundation of underground stormwater infrastructure frequently occurs during typical water levels. These results suggest that stormwater infrastructure inundation is common and increases the occurrence of urban flooding along the east coast of the US.

Adam Gold, a doctoral student in the Environment, Ecology and Energy Program within the UNC College of Arts & Sciences, poses for a portrait on January 27, 2020, near a pond in a housing subdivision in Beaufort, North Carolina. Gold's research aims to determine how urban land use affects coastal water quality and how stormwater ponds, that are often used to collect stormwater runoff, process pollutants. "Results from my research will have a positive impact on the health of coastal waters by helping urban areas in the coastal plain mitigate the negative ecological effects of stormwater runoff," said Gold, "I chose to study water because it is essential to life, but there are also a lot of water-related problems. I have always wanted my work to have a positive impact on the environment and people's lives, and I think that solving water-related problems will do that.".

Photo courtesy of the University of North Carolina at Chapel Hill.

Coastal flooding is a longstanding issue which has been exacerbated by climate change. Flooding due to extreme storm events such as hurricanes is increasing, and these extreme storms can cause massive amounts of damage to coastal communities. While sea level rise is predicted to increase the impact of extreme storm events on coastal areas, it is also increasing the incidence of recurrent nuisance flooding known as "high tide flooding" (HTF). Many cities in the United States (US) already experience multiple days of HTF a year, with the number of flood days rapidly increasing. During dry weather, this recurrent nuisance flooding can be disruptive to local infrastructure and economies. Combined with typical storm conditions, high tide flooding can impede stormwater drainage and result in more significant compound flooding.

Stormwater drainage networks aim to prevent flooding from stormwater runoff, but sea level rise threatens to reduce the efficacy of coastal stormwater networks. The goal of reducing precipitation-driven flooding has conventionally been achieved using an underground pipe network that quickly conveys stormwater runoff to a receiving waterbody using gravity. Older stormwater networks were designed to accommodate conditions at the time of their construction under the assumption that future conditions and variability will be similar to those in the past, but climate change has invalidated this assumption.

Relative sea level rise in some coastal areas of the US has increased mean sea level by up to a foot since the 1960s, so many coastal stormwater networks are increasingly inundated by typical high tide water levels or rising groundwater levels. Stormwater network inundation reduces how well the system drains during storm events, but recurrent stormwater network inundation by saltwater also corrodes stormwater infrastructure, promotes saltwater intrusion to groundwater, and can mobilize fecal bacteria from co-located sanitary sewer lines.

Inundation of underground stormwater networks has been reported in multiple cities in the US, but a broad characterization of stormwater network inundation has not been conducted. Recent studies of compound flooding show how both stormwater network inundation and precipitation influence coastal flooding, but most of these studies focus on small areas or specific extreme storm events to recreate real-world flooding conditions using hydrodynamic models. These flooding estimates are extremely useful for the modeled study areas, but the limited spatial or temporal resolution of flooding estimates may limit their utility to identify vulnerable infrastructure hotspots at larger spatial scales or during dry-weather conditions. Regional- or national-scale estimates of stormwater network inundation do not exist, but these estimates, or even proxies, of stormwater network inundation would be helpful in characterizing the extent and scale of the issue. For broad estimates of stormwater network inundation to identify vulnerable infrastructure during dry- or wet-weather conditions, static inundation ("bathtub") models that use a digital elevation model (DEM) to estimate inundation at discrete water levels may serve as useful tools for managers. Static inundation models have limitations, such as over-estimating flooding extent relative to hydrodynamic models, but their simplicity makes them well-suited for use as a diagnostic tool at large spatial scales.

In this study, we used simple proxies, static inundation models, and water level measurements to estimate stormwater network inundation at varying spatial scales. Through modeling, we also tested how stormwater networks influence flooding when receiving waters are elevated and how stormwater network inundation relates to current NOAA coastal flood thresholds. To identify locations along the eastern US coast where stormwater network inundation may occur, we used buffered road data from the OpenStreetMap and NOAA high tide flooding estimates to find roads within incorporated municipalities that experience HTF, and thus likely also have subterranean inundation of the stormwater network draining the road.

To characterize inundation of the stormwater network in the coastal town of Beaufort, NC, we measured water levels in stormwater infrastructure over a period of 8 months and compared them to water levels from a nearby NOAA tide gauge. We then used a static inundation model both with and without a coupled pipe network model to estimate stormwater network inundation and overland flooding across a range of water levels in Beaufort and three other cities in NC (Wilmington, Nags Head, and New Bern).

Research Methods

High Tide Flooding on Roads along the US East Coast

We used publicly available national-scale road and high tide flooding datasets to find areas where the two datasets overlapped in incorporated municipalities along the east coast of the US. We suggest that areas where roads are inundated during high tide flooding can act as a conservative proxy for areas where stormwater network inundation occurs during high tide events. This estimate can be considered conservative because without stormwater network infrastructure data, we cannot estimate the extent of inundation in pipes that are underground. Therefore, the only way to estimate the incidence of underground stormwater network inundation at a national or regional scale is to detect the end results of stormwater network inundation, which is overland flooding caused by surcharge from the stormwater network or overland flooding that is actively entering the stormwater network. This assumption would likely not apply in lower-density or rural areas if there is no stormwater network present, but we believe that this assumption is reasonable within the boundaries of incorporated municipalities.

The east coast of the US is comprised of fifteen states, ranging from the Atlantic coast of Florida to Maine, and these fifteen states were selected as the extent for the stormwater network inundation estimate. Census bureau incorporated municipality boundaries were downloaded for each state in order to constrain the estimate to urban areas, where the underlying assumption of the coincidence of roads and stormwater networks is likely strongest. High tide flooding estimates from NOAA were downloaded for each state, and these estimates consist of approximately 3-meter resolution raster data sets that indicate areas where "minor flooding" occurs based on a common impact threshold derived from the local tidal range (Minor flood threshold (m) = 1.04 * (Mean Higher High Water – Mean Lower Low Water) + 0.5). Road data for each state were downloaded from the open-source OpenStreetMap (https://www.openstreetmap.org). The OpenStreetMap road dataset was selected rather than the Census Bureau's TIGER dataset because the OpenStreetMap dataset explicitly identifies bridges and tunnels. Bridges and tunnels were removed from the roads dataset because including bridges and tunnels could create false positives for the inundation estimates, where the bridge or tunnel appears to overlap high tide flooding extent when it is actually over (bridges) or under (tunnels) the inundated area; most bridges are removed from the DEMs used to calculate high tide flooding estimates.

Site Description

We measured various stormwater network water levels and modeled inundation in Beaufort, a small town located in coastal North Carolina on a peninsula between the mouths of the Newport and North Rivers. The downtown area of Beaufort is located directly adjacent to Taylor's Creek, a channel that receives either brackish flow from the Newport/North rivers or saline water from the Atlantic Ocean via Beaufort Inlet. Taylor's Creek has a mean semi-diurnal tidal range of 3.11 ft (NOAA gage 8656483). The downtown area has moderate urban land use and uses conventional subsurface piping to convey stormwater from impervious surfaces directly to Taylor's Creek. The town has no stormwater backflow measures, and often documents "sunny day" high-tide flooding and compound flooding during storm events. A recent survey of the stormwater network by a civil engineering firm produced measurements for most of the downtown area.

Stormwater network inundation was also modeled in Wilmington, New Bern, and Nags Head, North Carolina. Each dataset had sporadic missing values for pipe or structure elevations, but New Bern had a large section of upland new development that was excluded due to missing survey elevations. All three cities (and Beaufort) have some distinctly different characteristics, but they all have all have flooding issues and large areas of development that rely on subsurface stormwater conveyance directly to a receiving waterbody. Wilmington is both the largest city and the city with highest elevation and relief.

Water Level

Two stormwater outfalls in Beaufort were selected for water level monitoring, and water level within the pipes was measured every 30 minutes from June 2017 to February 2018 (8 months) using a Teledyne Isco low-velocity flow sensor (pressure transducer for level). In late November (for 3 months), we began measuring water level in a storm drain upstream from the MP site.

A NOAA water level gauge located in Beaufort on Taylor's Creek, and data were downloaded from this station to compare to our measured water levels. Using NOAA water level data and the surveyed invert elevations of our monitored sites (NAVD88), the water level in each monitored site was estimated every 30 minutes, coincident with the measured water levels within the pipes. Pipe diameter measurements for the two monitored outfalls and one storm drain were used to calculate the percent cross-sectional area inundated at the pipe ends for each time step of measured water level.

Inundation Modeling

Stormwater network GIS data were obtained from each individual municipality by request. In total, we contacted 14 municipalities in coastal North Carolina and received data from 8 municipalities. After data QC, we determined that only 5 municipalities had adequate data for the purpose of inundation modeling, and the main selection criteria were data coverage of the majority of the city and elevation or depth data for stormwater inverts. We chose four municipalities with good quality data: Beaufort, Wilmington, Nags Head, and New Bern.

Findings

High Tide Flooding on Roads Along the US East Coast

High tide flooding on roads was estimated to occur to some extent in 656 incorporated municipalities along the US east coast, indicating that inundation of stormwater infrastructure may occur in many of these municipalities during high tide unless backflow measures exist (Figure below). The metro areas of Miami, FL, New York City, NY, and Boston, MA had the largest estimated extent of high tide flooding on roads, partially because of the overall large amount of roads (Figure a,b). The majority of estimated impacted roads are classified as service (e.g., parking lots, alleys, etc.) or residential roads, but larger and higher-traffic roads (tertiary – trunk) were also estimated to be impacted in larger metro areas (Figure b,c).

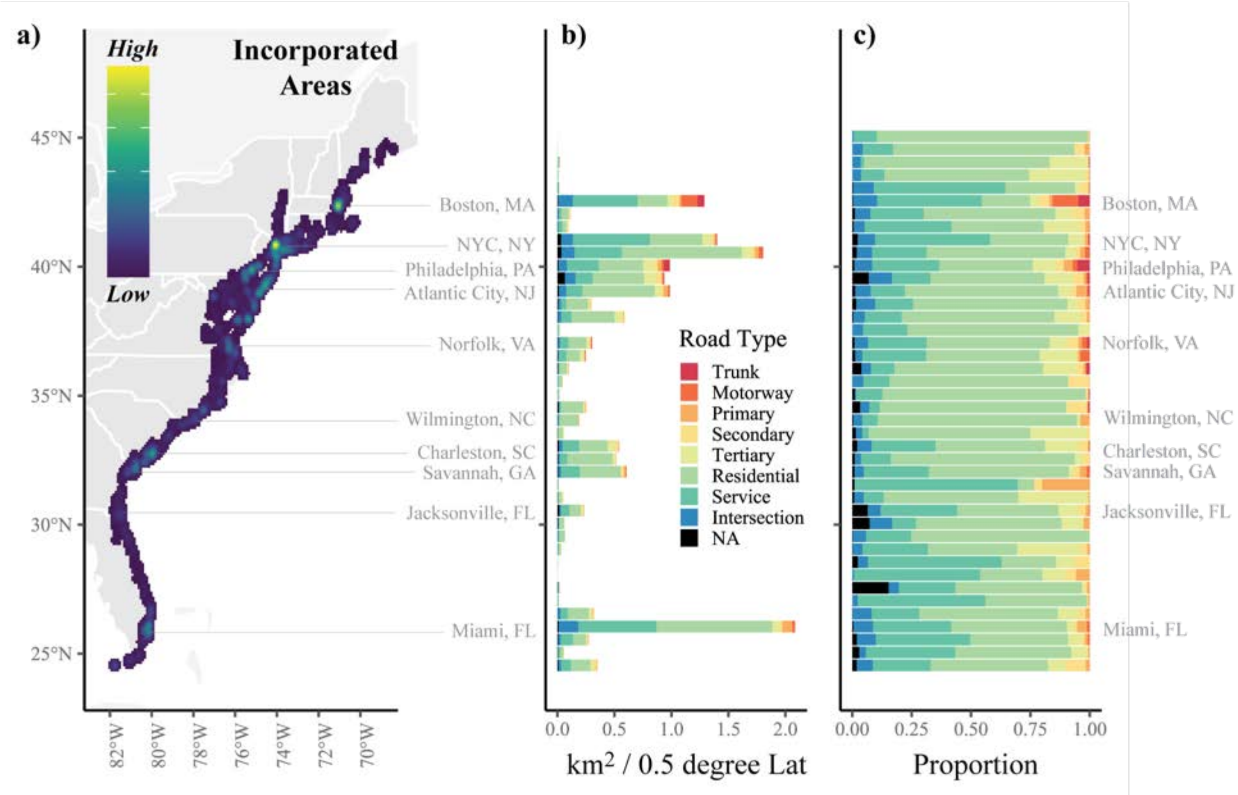


Figure: Area of high tide flooding on city roads. a) Density map of areas where high tide flooding overlaps roads in incorporated areas, b) road area overlapping estimated high tide flooding extent binned by 0.5 degrees of latitude, and c) proportion of impacted road area separated by road type.

Using estimates of total road area for each incorporated municipality, we found that the median percent of total road area impacted by HTF decreased as total road area increased (ρ = -0.25, $p < 0.001$, Figure 2), and the relative impact of HTF on roads varied greatly between municipalities, ranging from just over 0 to 94.5% of total road area impacted by HTF. While a majority of municipalities along the US east coast that currently experience HTF on roads had relatively small amounts of total road area impacted by HTF (median = 0.28%, Figure below), approximately 1/3rd of the municipalities had greater than 1% of total road area impacted by HTF and approximately 13% of the municipalities had greater than 5% of total road area impacted HTF (Figure below). Of the four municipalities measured or modeled in this study, Beaufort had the highest percent of total road area impacted by HTF (1.17%), followed by Nags Head (1.04%), Wilmington (0.23%), and New Bern (0.19%).

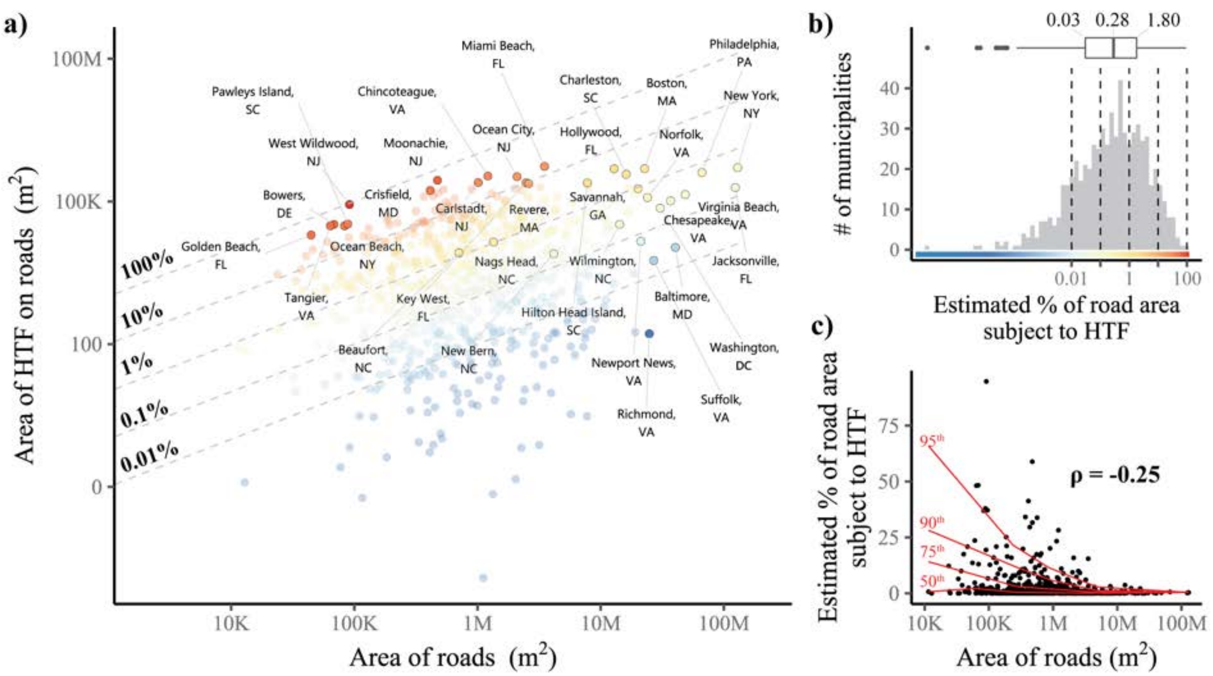


Figure: High tide flooding on city roads compared to total road area. a) Road area affected by high tide flooding (HTF) versus total road area for municipalities along the US east coast that experience some degree of HTF. Dotted lines and color indicate the estimated percent of road area subject to HTF in each municipality. Selected municipalities labeled, including the four study municipalities. b) Histogram of percent of total road area impacted by HTF. c) Percent of total road area impacted versus total road area with smooth quantiles (red).

Measured Water Levels

In Beaufort, NC, the two monitored stormwater outfalls experienced some degree of tidal inundation every tidal cycle throughout the 8-month monitoring period. (data shown for December 2017 in Figure below). The upstream monitored storm drain (MP-upstream) was located more than 200 meters up-network from the corresponding outfall (MP-outfall), but MP-upstream also experienced significant tidal inundation during more extreme high-tide events (Figure below). Water level in each monitored outfall was predicted based on NOAA water level from a nearby gauge and the invert elevation of the infrastructure. Predicted water level measurements corresponded well with observed water levels (r2 = 0.72 – 0.95), as did cumulative distribution functions of predicted and observed pipe inundation percent. The predicted water levels for the MP-upstream site were slightly higher than the measured water levels, and the predicted cumulative distribution of inundation percent over-predicted the occurrence of small amounts of inundation in the storm drain.

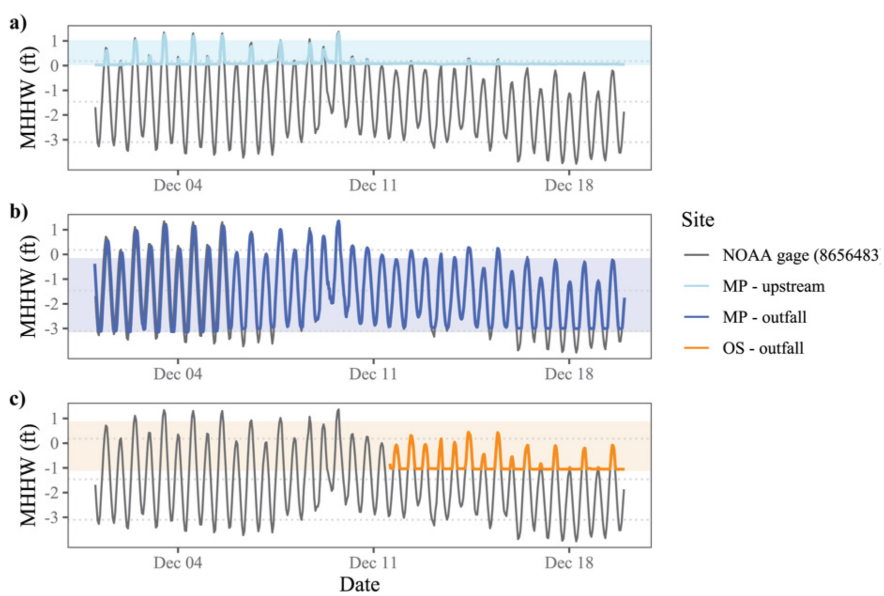


Figure: Snapshot of measured water levels in pipes. Example of water level measured in selected pipes (color lines) and a NOAA tide gage in Beaufort, NC (grey line) in December 2017. Shaded areas represent the dimensions of the pipe, showing that the monitored pipes were frequently filled with water from the receiving water body. Water level from OS – outfall (panel a) is missing on the graph prior to Dec. 11 due to equipment malfunction.

Impacts of Network Inundation

Inundation of stormwater infrastructure can have a large local impact on the frequency and magnitude of urban flooding, but this phenomenon remains difficult to characterize. Using national high tide flooding and road data, this study demonstrated that tidal inundation on coastal roads, and thus stormwater infrastructure, occurs in municipalities along the east coast of the US. Measuring stormwater infrastructure inundation at a local scale in Beaufort, NC, gauged stormwater outfalls were inundated by the tide daily while the monitored upstream storm drain was inundated during extreme high tides. Predictions of pipe water level based on local NOAA water level data and pipe elevations showed that predicted outfall water levels corresponded well with measured water levels, but predicted water levels for the upstream storm drain were slightly higher than measured water levels, highlighting an acknowledged weakness of static inundation models. Using a 2D static inundation model coupled with a 1D stormwater network model (see Methods), we found that all four study municipalities likely experience frequent inundation of underground stormwater infrastructure that impairs their ability to convey stormwater. Inundation of the underground stormwater network occurred at water levels far below local NOAA "minor flooding" thresholds (~ 1.75 ft above MHHW), suggesting that current and future estimates of high tide flooding extent and frequency may drastically underestimate urban flood risk due to reduced stormwater capacity. While stormwater networks aim to drain stormwater runoff, model results from Beaufort and Nags Head showed that the stormwater network can act as a conduit for elevated downstream waters to flood low-lying inland areas that would otherwise be disconnected from receiving waters. Overall, this study shows that stormwater network inundation in coastal US municipalities is common and can increase the risk of overland flooding.

The measured and estimated stormwater network inundation in this study demonstrate the frequency of stormwater network inundation and the associated decrease in network drainage during wet weather along the east coast of the US. It is well-known that elevated water levels are a major driver of coastal urban flooding during extreme storm events such as hurricanes, but this study further shows that stormwater networks may often have reduced capacity to convey runoff during typical weather conditions and water levels far below local NOAA "minor flooding" thresholds frequently used to characterize high tide flooding.

Storm surge is not required to impair stormwater network drainage; typical high tides can affect network drainage during wet weather even absent overland flooding due to tides. Although Beaufort had the largest estimated impact at typical water levels (< 1 ft MHHW), it is important to note that it was the smallest of the four study municipalities with most of the surveyed infrastructure in the downtown portion of the municipality along a developed waterfront. A low percent of impacted stormwater inlets in another municipality could still mean a large impact in specific lower-lying spots within the municipality, especially if the municipality also encompasses inland area with higher elevations (e.g., Wilmington).

Inundation estimates of infrastructure in the study cities, especially Beaufort and Nags Head, also suggest that the stormwater network may act as conduit for receiving waters to flood low-lying areas at high water levels. Both of these municipalities had approximately 1% of their total road area impacted by HTF, suggesting that this specific issue may be widespread given that 1/3rd of the incorporated municipalities along the US east coast that experience HTF on roads had similar or greater levels of HTF impact on total road area. This overland flooding that is counterintuitively exacerbated by stormwater networks could have negative impacts during both dry and wet weather. During dry weather, this overland "nuisance" flooding could have negative economic impacts for local businesses by limiting access.

During wet weather, this overland flooding would effectively reduce the ability of the surrounding area to drain, depending on the amount of precipitation. An example of this high-tide flooding via the stormwater network is evident in Beaufort, where a section of road adjacent to Taylor's Creek (Front St.) is predicted to flood at 1-2 ft MHHW. These model results align with high tide flood reports at this location and NOAA estimates of high tide flooding during dry weather.

Issues Characterizing Network Inundation

While inundation of stormwater networks appears widespread and common in our study area, directly characterizing the scale of the issue of stormwater network inundation remains a challenge due to issues of data quality and availability.

Good quality stormwater network data is key to assessing the impacts of inundation on the stormwater network, but inadequate funding likely hinders the collection of stormwater infrastructure survey measurements. For example, in North Carolina, many municipalities raise the majority of funding for stormwater management directly through local stormwater fees. While stormwater fees are a common means of raising funding for stormwater projects, they often do not generate enough funding for necessary stormwater infrastructure projects. Approximately 18% of stormwater fees tracked over the past decade in North Carolina have not been increased during that time period, and 36% of the fees that have been increased did not keep pace with inflation despite rising budget needs. Also, municipality size and property values likely both contribute to higher stormwater fees, thus allowing more populous cities or areas with higher property values to collect more money for stormwater projects than smaller towns with lower property values, despite the fact that smaller towns are more likely to have a higher degree of road impacts from HTF.

Addressing Network Inundation in the Short- and Long-term

The threat of coastal flooding is increasing due to rising seas and the effects of climate change on precipitation patterns, and many low-lying coastal areas will need to adapt quickly to both increased stormwater network inundation and excessive stormwater runoff.

For stormwater network inundation in the short term, the most direct engineering solution is to install tide gates that prevent flow up-network when receiving water levels are elevated. These tide gates reduce tidal inundation, and there are even efforts to make these tide gates responsive to current and predicted inundation to increase their efficacy. Though this retrofit to the current stormwater network may be effective in the short- to medium-term, predicted increases in sea level and groundwater will inevitably lead to continuously inundated outfalls in vulnerable locations and decreased surface storage of stormwater further inland.

Addressing the long-term issue of coastal urban flooding, which includes both stormwater network inundation and excess stormwater runoff volumes, will require substantial investment in planning and upgrading drainage systems discussion of this broader adaptation and planning effort is outside the scope of the current study, but these strategies broadly include updating infrastructure to address network inundation (e.g., backflow prevention, pumping), decentralized or low impact development to manage stormwater (e.g., stormwater harvesting), landscape-scale planning to incorporate surface storage of flood waters, and possibly managed retreat or buyouts of vulnerable areas.

Future investigation is needed to further characterize the extent of coastal stormwater network inundation to inform planning efforts, and the simple modeling framework presented here can be used as an initial step for both municipalities and researchers.

The complete Infrastructure: Inundation of Stormwater Infrastructure report with citations, figures and recommendations can be found at: https://collaboratory.unc.edu/current-projects/flood-resilience/

Infrastructure: Enhancing Stormwater Control Measures

Bill Hunt, Department of Biological and Agricultural Engineering, NC State University

Overview

Stormwater control measures (SCMs) are a community's first line of defense against flooding associated with large storm events; yet, often that line of defense fails. Interviews were conducted with a wide range of professionals in the stormwater management field with practical experience in SCM design, construction, and/or maintenance. The purpose of these interviews was to gather insight into how SCMs can be made more resilient, so that their integrity was less likely to fail during large storm events. NC State personnel synthesized that information and produced these recommendations.

The interviews yielded the following conclusion: SCMs that are (1) appropriately situated, (2) well designed, (3) constructed per design, and (4) reliably maintained are more resilient than SCMs that are not. Hereafter, these four elements are referred to as "SCM Resiliency Fundamentals." Per the interviewees, many SCMs fail at least one of the above fundamentals.

Of the four resiliency fundamentals, reliable maintenance stands out as most problematic. It appears that upkeep needs that help ensure long term performance of SCMs are not being reliably conveyed to the property owner. Perhaps the most important action we can take to improve SCM resiliency is to improve maintenance reliability of SCMs, so that they can operate with minimal damage during large events. In short: the maintenance and operation of the SCM must be first understood by the property owner/ manager and then enforced by the governing jurisdiction.

While the report provides many recommendations regarding the four SCM Resiliency Fundamentals, notable highlights among them are: (1) designing and constructing emergency spillways that work, (2) avoiding internal erosion within forebays, and (3) ensuring healthy vegetation stands as appropriate in SCMs. Lastly, designers and maintenance personnel strongly requested more latitude in maintaining SCMs in advance of imminent large events. In particular, they would like the flexibility to pump water from SCMs into waterways before large storms hit. In some jurisdictions, this might require a change in code enforcement.

Lastly, there was general consensus among the interviewees that (1) well-vegetated SCMs are likely more resilient and (2) that visible SCMs are more likely to be maintained. Remembering that well-maintained SCMs are more resilient SCMs, perhaps stormwater practices should be incorporated into the landscape as amenities?

The summary guidelines presented in this report address each of the four SCM resiliency fundamentals. NC DEQ's response to earlier NC legislative action (the development of Minimum Design Criteria for SCMs) provides a strong foundation for SCM resilience. In other words, we are not "starting from scratch.

Stormwater Control Measures

Coastal stormwater control measures (SCMs) can substantially reduce peak flows, increase basin lag time, and improve water quality via runoff storage and pollutant removal. However, changing boundary conditions (e.g., seasonal high-water table (SHWT) and pluvial event characteristics) can impair SCM storage and conveyance capacity, consequently reducing treatment efficiencies. Storm event variability with respect to intensity, duration and frequency can change the hydroperiod and storage volume needed to treat the water quality event. Currently, SCMs within the coastal plain of North Carolina are designed to capture and treat the entire volume of runoff generated from the contributing watershed during the 1.5-inch storm event or, if discharging to shellfish areas, the volume difference between post- and pre-development conditions during the 1-year, 24-hour storm. This requires a volume of runoff to be captured, known as the water quality volume; the depth of which is selected so that at 80-90% of all rain that falls is treated during normal antecedent moisture conditions.

Along the Outer Banks, some localities require volumes associated with the 4.3-inch storm event from a commercial development to be captured and treated. Currently, stored water is required to be released from detention-based practices in two to five days. With more frequent precipitation events, water may not vacate an SCM in time to make room for the next event. In many coastal communities, groundwater is rising, especially in watersheds with shallow unconfined aquifers. Because of shallower-than-normal water tables, not only will SCM treatment efficiencies decline, but storage and conveyance capacity can become greatly impaired. Extended periods of inundation, especially that by brackish and saltwater from storm surge, can devastate freshwater flora further reducing treatment efficiency, while concomitantly increasing the risk of erosion and resuspension of sediment-borne pollutants. Therefore, updated SCM design and maintenance guidance is needed to address the issues of the changing boundary conditions. The purpose of this report is to suggest such guidance. Presented is a synthesis of the opinions from a diverse field of stormwater engineers, designers, managers, and maintenance specialists working with green stormwater infrastructure in coastal and near-coast communities.

Research Methods

Professionals representing a variety of backgrounds and geographic locations were interviewed. The interview process consisted of organized questioning and discussion regarding flood resilient designs and types of stormwater control measures.

Findings

The Fundamentals

While it might be considered elementary, the interviews yielded the following conclusion: SCMs that are (1) appropriately situated, (2) well designed, (3) constructed per design, and (4) reliably maintained are more resilient than SCMs that are not. Hereafter, these 4 elements are referred to as “SCM Resiliency Fundamentals.” Per the interviewees, many SCMs fail at least one of the above fundamentals.
The summary guidelines presented in the next section address each of the 4 SCM resiliency fundamentals. NC DEQ’s response to earlier NC Legislative action (the development of Minimum Design Criteria for SCMs) provides a strong foundation for SCM resilience. In other words, we are not “starting from scratch.”

Of the four resiliency fundamentals, reliable maintenance stands out as most problematic. That is likely because professionals who understand SCM purpose (designers) are responsible for the first three resiliency fundamentals. They then hand off the practice to an entity (developer, homeowner association, etc.) that may not understand SCM purpose. Hence, upkeep needs that help ensure long-term performance of SCMs are not reliably conveyed to the property owner. Perhaps the most important action we can take to improve SCM resiliency is to improve maintenance reliability of SCMs, so that they can operate with minimal damage during large events. In short: the maintenance and operation of the SCM must be first understood by the property owner/ manager and then enforced by the governing jurisdiction.

What Designers Can Do to Enhance Resiliency

<u>Siting SCMs for Resiliency</u>

Along with current design guidance (NCDEQ 2017), designers should ensure that the SCM design and operation account for the four resiliency fundamentals. Appropriately situating an SCM can extend the design life, reduce restorative maintenance, and avoid costly retrofits. Picking the best location for an SCM requires a knowledge of the proposed site’s (1) soil types, (2) seasonal high-water table (SHWT), (3) land use and condition within the watershed, and (4) proximity to nearby surface waters.

Soil texture and drainage class determines the applicability of an SCM. Infiltration-based practices (infiltration basins, permeable pavement, and infiltration swales) should be situated on well to moderately-well drained sand for desired exfiltration and aerobic filtration. Retention-based SCMs (constructed stormwater wetlands, wet retention ponds, and wet swales) should be situated on somewhat poorly to very poorly drained sands, clays, or marine organics since these practices continue to function properly when saturated. A group of practices can be located in a wide range of soil types, with a modification of design elements needed per in-situ soil. These SCMs include sand filters, bioretention cells, dry detention basins, underground detention basins, and detention-based permeable pavement.

Existing soil surveys should first be reviewed to determine soil texture and drainage class and then be confirmed on site. Soil core sampling is highly recommended. While on site, the SHWT needs to be determined by a licensed professional. The location of the SHWT has a dramatic impact on the functionality of most SCMs. High water tables, for example, tend to prohibit the use of bioretention.

Along with the soils and hydrologic analysis of the contributing drainage area, the designer requires an understanding of (1) the upstream land use and (2) how adjacent surface waters impact the SCM. When the watershed draining to the SCM is unstable and therefore is likely to contribute a high sediment load (e.g., from a large row crop operation or active construction site), an SCM's storage and conveyance capacity will likely be severely affected. SCMs located downstream of unstable watersheds are not likely to be resilient.

Nearby surface waters (e.g., sounds, estuaries, and large rivers) can cause two problems for SCMs: inundation and reverse flow-caused erosion. Designers are often not accounting for reverse flow from downstream, and because they do not plan for excess shear stress from the downstream direction, berm blowouts are likely. Long-term SCM damage could result from extended periods of inundation by brackish or saltwater killing many of the non-salt tolerant plants. Once protection provided by vegetation (i.e., stabilization of internal features by vegetation) is lost, subsequent (usually smaller) storms then erode exposed soils. This may lead to the resuspension and release of many years' worth of captured sediments and their associated pollutants. Siting an SCM with sufficient gravitational drainage (whenever possible) will limit the period of inundation, thus helping vegetation rebound. Healthy vegetation directly relates to SCM resiliency.

Designing SCMs for Resiliency

Along with Minimum Design Criteria (MDC), additional attention should be given to other design features that are critical to SCM resilience. Properly designing a SCM requires consideration of (1) side slopes, (2) inlet structures, (3) forebays, (4) outlet structures and trash racks, and (5) emergency spillways.

Parts of the coastal plain are predominantly sand, and thus the side slopes of an SCM constructed in mainly sandy soils should not exceed 3:1 (H:V) to prevent soil slippage, or sloughing. Some sands, even at slighter slopes, may be unstable unless amended with compactable fill. During floods, side slopes become saturated. This increases soil pore pressure which reduces the effective stress of the soil such that when the surface water drains away the side slopes slough.

Design of the inlet structures should consider both energy dissipation of the rising limb and peak discharge conveyance (even when inundated). Erosive failure can be mitigated by directing or angling inflows away from the back berm of the forebay (Figure below). Another option is to add distance between the inlet and the berms.


Figure: Design Fundamental: Inlet structure angled away from forebay berm, and well armored berms. Left: Flared end section with energy dissipators to reduce scour. Forebay with protected internal flow path – berm side slope – armor. Right: Well armored forebay with concrete walls protecting the internal flow path.

The forebay's first role is to dissipate energy of the incoming flow. As water slows, coarse sediments and gross solids fall out, leading to the forebay's second function (storage of pollutants). Current MDC standards generally require a forebay to be approximately 10 to 15% of the SCM's surface area. Anecdotal evidence suggests that proportionally larger forebays improve SCM resilience. To prevent erosion of internal features (e.g., earthen berms, concrete or wooden weirs) the designer must protect internal flow paths (Figure). Forebays are protected by a lining (or armament), which typically consists of riprap (Figure below), gabion baskets, concrete walls (Figure below) forced turf matting. Proper installation of forebay armament is essential. For example, when using riprap, the rock must be underlain by non-woven geotextile, to prevent the cobbles from sinking into the in-situ soil. If a geotextile is used, it must be keyed-in (i.e., tucked into and buried under the soil on the edges) so that it does not ravel or wash away.

Figure: Design Fundamental: Well-armored forebay berm. Right: Well-armored primary flow path – side slope of berm – with nonwoven geotextile. Left: Coir geotextile keyed-in under rip rap and soil along secondary flow path – top of berm. Well armored internal flow path – upper berm.

Wet pond MDC's require the outlet to be sufficiently far from the inlet to avoid short-circuiting. Similarly, the outlet of any SCM should be sufficiently far away from the berm or basin side slope to avoid erosive back eddies unless well armored (Figure below). Designers must also provide access to the outlet to facilitate maintenance (Figure below). This can be done via an earth and rock peninsula or elevated walkway.

Figure: Design Fundamental: Accessible outlet structure on well-armored berm. Left: Well armored access berm for outlet structure. Right: Well-armored access berm for outlet structure.

Trash racks can become clogged, accumulating substantial debris jams that reduce the conveyance capacity of piping infrastructure (Figure below). Flow blockage will prematurely flood the basin and activate the emergency spillway. Trash racks and outlet structures should be designed with a redundancy of flow paths to reduce the likelihood of complete blockage by accumulated debris (Figure below). For example, the wet pond is holding an extra foot of water due to excess straining of accumulated debris on the trash rack. This can be prevented by designing the trash rack to be sufficiently above, below, and offset from the orifice. Anti-seep collars must be used along with proper pipe bedding. This prevents piping (i.e., erosion of soil through cracks in pipes) inside a berm or dam that cause sinkholes.

Figure: Design Fundamental: Redundancy of flow paths for trash racks and outlet structures. Left:. Four flow paths are present: a draw down skimmer orifice, an intermediate flow weir, an overflow weir, and an emergency spillway. Right: Clogged low and intermediate flow orifice lacking redundancy and offset trash rack.

Overflow (or emergency) spillways are the designated location for overflow from an SCM, and, as such, their design is critical for SCM resiliency. To avoid dam/berm overtopping, the overflow spillway must be located sufficiently below the lowest point of the dam/ berm (Figure below). This ensures that only the well-armored portion of berm (the overflow spillway) experiences erosive flow. Emergency spillway armament is typically concrete, riprap or reinforced turf matting. The armor should vertically extend well into the normal pool (for retention SCMs) or the basin bottom (of detention or infiltration SCMs) to prevent erosion during high flow discharge. Moreover, the "back" (or downstream side) of the SCM needs to be protected from storm surge inundation. This necessitates the emergency spillway design, notably the lining/armament, to extend to at least the outside toe of the berm/ dam. Hydraulic modeling of the spillway should inform the extent, sizing, and placement of this protection. Finally, the spillway overflow must be directed away from at risk properties to further reduce flooding.

Figure: Design Fundamental: Overflow (emergency) spillway well armored and below top of berm. A. Spillway is sufficiently below the top of berm and rip rap extends below the normal pool. B. Spillway armament extends to toe of berm slope.

For some SCMs, adaptive designs should be employed. For example, dry detention basins may need to be designed with flexible planting schemes if the practice remains unintentionally wet post-construction. This is also a maintenance concern and will be further addressed in that section. Due to low gradients found within coastal watersheds, conveyance SCMs like swales will experience extended durations of inundation. Wetland vegetation that can tolerate these conditions should be considered within an adaptive planting plan. If flow conveyance SCMs are apt to grow wetland vegetation, then their cross-section will likely need to be enlarged to account for increased resistance to flow caused by larger wetland vegetation.

Engineers design with factors of safety to account for uncertainty. For stormwater engineers, that factor of safety should account for the observed – and sometimes shocking – depths of precipitation and severity of clogging. A factor of safety for precipitation would require (1) SCMs to capture larger water quality volumes and (2) swales and channels to safely convey flows resulting from higher precipitation intensities. It is noted that enlarging the footprint of SCMs likely makes them less attractive to developers. Factors of safety for clogging severity of outlet structures could include redundancy of flow paths. For example, utilizing two three-inch drawdown orifices in lieu of one four-inch orifice would discharge similar flow rates, but likely be redundant in the event of clogging. MDC's require most basin SCMs to retain runoff for two to five days. The designed drawdown should be on the short end of this range (i.e., two to three days), because this allows for some amount of clogging to occur and provides time for captured runoff to still vacate within five days.

The complete Infrastructure: Enhancing Stormwater Control Measures report with citations, figures and recommendations can be found at: https://collaboratory.unc.edu/current-projects/flood-resilience/

Infrastructure: Assessing Operational Flooding Risks for Substations and the Wider North Carolina Power Grid

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Overview

Electric utilities in North Carolina are increasingly cognizant of the impacts that weather extremes (droughts, floods, heat waves, etc.) have on the cost and reliability of bulk power systems, as well as the ramifications for dependent retail customers. North Carolina's utilities, including Duke Energy and the many rural electric cooperatives and municipal power agencies in the state, are no exception. With major hurricanes (Matthew, Florence and Dorian) hitting the state in three of the past four years, there is new urgency to study the vulnerability of the state's power grid to flooding, especially in eastern North Carolina.

During hurricanes, wind and tree damage to local distribution lines are generally responsible for a higher number of total customer outages. But an additional risk for electricity service can be flooding of substations. Repairing substations can take much longer due to the need to allow floodwaters to recede, potentially leading to longer outages for affected communities. In addition, widespread, catastrophic flooding of substations in eastern North Carolina may pose unforeseen risks for the larger state system. One example is the state's increasing reliance on solar power. As of 2016, roughly 75% of the renewable energy Duke Energy generates was located in eastern North Carolina. As this dependency increases, an open question is whether some portion the state's solar power assets are at risk of stranding by flooding during hurricanes, and what effects this may have on the rest of the NC grid. This study attempts to address some of these questions through research activities divided to three separate tasks:

Task 1: Preliminary Geospatial Flood Risk Assessment for Eastern North Carolina Grid

Using publicly available GIS data detailing the location of electric power generation assets and flooding data from NC Emergency Management, we identified the number and type of grid assets within the inundation zone of recent historical Hurricanes and probabilistic storms. For this initial analysis, no consideration was given to the timing, depth of inundation, and/or the height of sensitive equipment at electric substations and generating units, which strongly impact actual damages, but results identified < 100 electric generators (1000s of installed MW of capacity) and hundreds of electrical substations in the areal footprint of severe flooding.

Task 2: Dynamic Flood Depth Analysis During Historical Hurricanes and Grid Impacts

We used maximum flooding depth information collected for recent storms as well as USGS streamflow data to estimate chronologies of flooding depth across the areal flooding footprint of Hurricane Florence on an hourly basis. Hourly maps of estimated flooding depth across eastern North Carolina were then used to identify the number and type of grid assets impacted by flooding through time over the 2-3 week period before, during, and after the event. Findings suggest that raising the height of sensitive equipment could be an effective way minimize the number of grid assets impacted.

Task 3: Operational Modeling of the North Carolina Grid Under Recreated Historical Flooding Conditions

We developed an open source, grid operations model designed specifically to simulate the behavior of the NC power grid during extreme weather events, including flooding impacts. The model is complete and publicly available online.

Motivation and Research Questions Addressed

A significant share of damages from extreme weather in the U.S. (between $25 and $70 billion annually) is related to electricity service outages. Electric power systems are particularly vulnerable to extreme weather, especially extreme temperatures, droughts, wildfires, violent storms, and flooding. The U.S. grid, and each is essentially operated as a single, massive, synchronous machine. System operators meet constantly fluctuating electricity demand through coordinated operations of power plants, transmission lines, and other critical infrastructure. Even with physical redundancy built-in and emergency protocols in place, extreme weather events regularly overwhelm these measures and disrupt the tenuous balance between electricity supply and demand.

Electric utilities across the U.S. are increasingly cognizant of the impacts that weather extremes have on the cost and reliability of bulk power systems, as well as the ramifications for dependent retail customers. North Carolina's utilities, including Duke Energy and the many rural electric cooperatives and municipal power agencies in the state, are no exception. With major hurricanes (Matthew, Florence and Dorian) hitting the state in three of the past four years, there is new urgency to study the vulnerability of the state's power grid to flooding, especially in Eastern NC. Hurricane Matthew knocked out power to 1.2 million customers in the state, and Hurricane Florence caused outages for more than 500,000. In advance of Hurricane Dorian's approach, Duke Energy anticipated 700,000 people losing electric service. These outages were caused by a combination of wind damage and saturated soil conditions, which caused downed wires and utility poles, and to a lesser degree the flooding of substations.

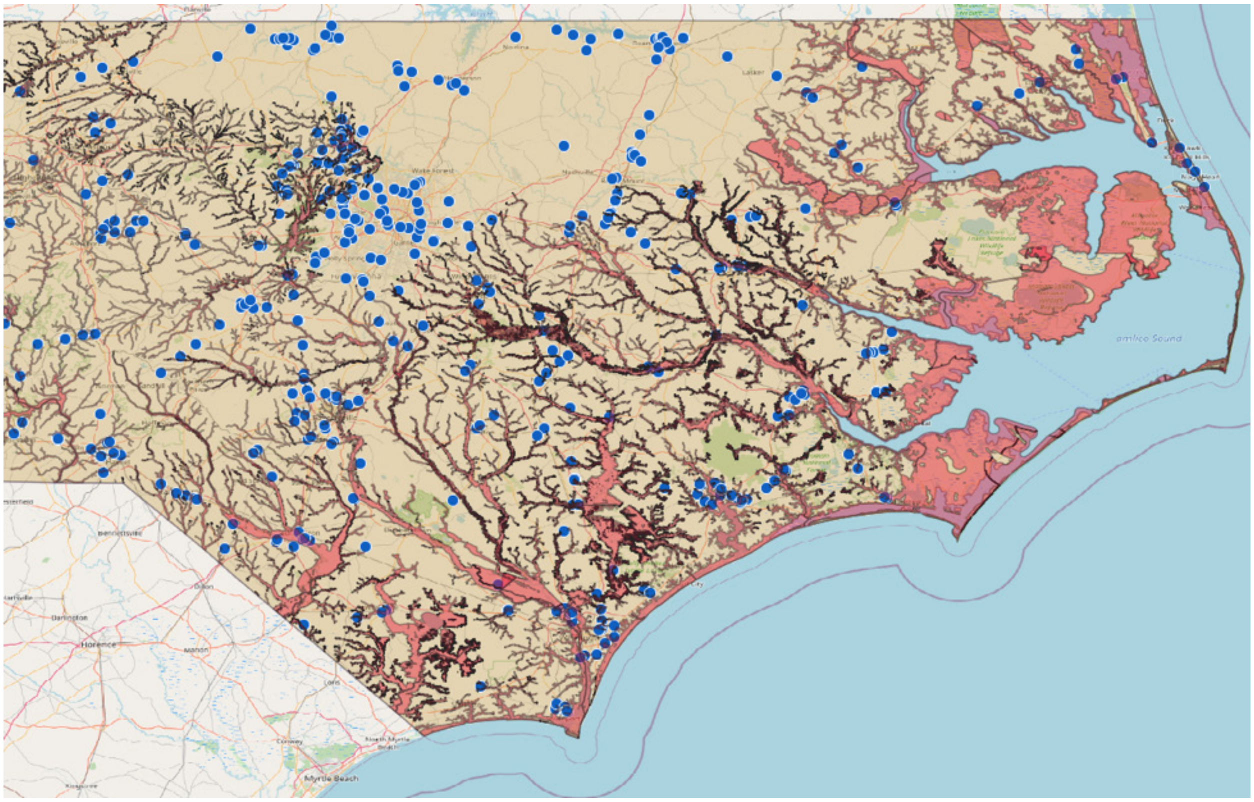
Substations play a critical role in the grid: they increase the voltage of electricity flows produced by power plants for export onto the wider state grid; and they decrease the voltage of electricity flows from transmission lines down to safe levels for distribution to homes and businesses. Although wind and tree damage to local distribution lines are likely responsible for a higher number of total customer outages, when substations are damaged from flooding, repairing them can take much longer due to the need to allow floodwaters to recede.

Learning from the impacts of earlier storms, during Hurricane Dorian utilities in NC were proactive in trying to protect substations prone to flooding using temporary barriers, and in some cases permanent flood barriers are being installed. However, the nature of hurricane-based flooding is difficult to predict. While a positive first step, basing risk mitigation practices on experiences during a few previous storms may leave significant portions of the NC grid exposed to future flooding. In addition, widespread, catastrophic flooding of substations in Eastern NC may pose unforeseen risks for the larger state system.

One example is the state's increasing reliance on solar power. Most solar capacity in the state is located in eastern North Carolina, due in part to an abundance of suitable land. As of 2020, North Carolina is the #3 state in the U.S. in terms of installed solar power capacity; as this dependency increases, a pressing question is whether some portion the state's solar power assets are at risk of stranding by flooding during hurricanes, and what effects this may have on the rest of the NC grid.

In this report, we present results of research activities focused on answering three major questions facing the NC grid with respect to flooding:

- What critical NC grid assets are presently in the path of flooding from inland flooding resulting from hurricanes and other extreme precipitation events?
- Can flooding maps and depth information from recent storms be used to recreate the chronology of flood impacts experienced by the NC grid?
- Can simulation models be used to recreate how grid operations respond dynamically to flooding impacts, including altered power flows on transmission lines and generation schedules?



Maximum flooding extent from Hurricane Florence (red) shown alongside the locations of selected major electrical substations (blue dots) in eastern North Carolina. Note: substations shown here are not a complete list of substations in North Carolina. These selected stations are those that form the basis of the grid operations model described in Task 3.

Research Methods

Our research approach was developed based upon research team communications with the following grid stakeholders in North Carolina, which including representatives from the North Carolina Electric Membership Corporation (NC EMC) and Duke Energy.

- Nelle Hotchkiss (Chief Operating Officer, EMC)
- Michael Youth (Government and Regulatory Affairs Council, EMC)
- Lee Ragsdale (Senior Vice President, Energy Delivery, EMC)
- Bob Beadle (Director, Grid Infrastructure, EMC)
- Jim Umdenstock (Principal Engineer, Duke Energy)
- Rhett Trease (Engineer, Duke Energy)

The research team found these communications instructive and extremely valuable. However, it should be noted that the contents of this report have not been reviewed by the stakeholders listed above, and should not be viewed as representative of their personal opinions or the official positions of their organizations. The research team would like to thank the individuals listed above for their unofficial participation in our research activities, which helped inform the questions addressed and improved the methods employed.

Based on our communications with the above stakeholders and an internal assessment of available data, the research team developed a methodological plan consisting of three major tasks:

<u>Task 1: Preliminary Geospatial Flood Risk Assessment for Eastern North Carolina Grid</u>

We collected publicly available GIS data detailing the location of electric power generation assets (nuclear, coal, natural gas, and oil, biomass and utility scale solar power) and substations. We acquired flooding data from NC Emergency Management. We then superimposed the area extent of flooding for several different flood severity levels (corresponding to estimated return frequencies of 10, 25, 50, 100 and 500 years), as well as maximum flooding extent from Hurricanes Florence and Matthew on a map of NC grid assets. Using GIS software to perform simple intersection analysis, we determined the number and type of grid assets within the inundation zone at each risk level. For this initial analysis, no consideration was given to the timing, depth of inundation, and/or the height of sensitive equipment at electric substations and generating units, which strongly impact actual damages. Thus, this preliminary geospatial analysis should be viewed as a very conservative estimate of assets-at-risk; essentially, if the GIS data indicated that any amount of flooding occurs on the ground at the location of an asset, we assumed that asset could be affected.

Task 2: Dynamic Flood Depth Analysis During Historical Hurricanes and Grid Impacts

Here, we made use of "high water mark" (maximum flooding depth) (USGS, 2021) information collected for recent storms as well as dynamic streamflow data collected from USGS gages to recreate time series of flooding depth at a discrete set of points across eastern North Carolina. Time series of flooding depth at each point were then used as inputs into a spatial "kriging" analysis, in which we interpolated gradients of flooding depth across the areal flooding footprint of Hurricane Florence on an hourly basis. Hourly maps of estimated flooding depth across eastern North Carolina were then used to identify the number and type of grid assets impacted by flooding through time over the 2-3 week period before, during, and after the event. In addition, we performed a sensitivity analysis on the height of sensitive equipment at each location. The number of grid assets impacted by flooding was assessed at several heights (0ft, 2ft, 3ft and 5ft.), which flooding depths greater than these heights assumed to caused damage and impact the functionality of equipment.

Task 3: Operational Modeling of the North Carolina Grid Under Recreated Historical Flooding Conditions

The goal of this effort was to simulate the hourly operations of the NC bulk electric power system during a historical flooding event. Modeling results should help the research team understand how power flows throughout the NC grid change in response to losses of load (from damaged distribution lines and substations), impacted solar farms, and de-energization of coastal power plants in anticipation of flooding and wind damage. This final task involved the development of a new, open-source model designed specifically to simulate the behavior of the NC power grid during extreme weather events. Compared to Tasks #1 and #2, Task #3 is a far more ambitious research target, involving software development from scratch and the use of computer resources to simulate the events of interest. The research team made considerable progress towards this final goal, and the model (which is freely available to the public) has been completed; however, the research team has not (yet) completed a full investigation of the response of the NC grid to flooding events using the model. We anticipate completing this work within 3-6 months; this remaining work will be financially supported by another source.

Recommendations

Due to the widespread and critical nature of electric power infrastructure in North Carolina, and the need to serve communities who live in flood prone areas, substantial portions of the North Carolina grid are in the areal path of flooding from hurricanes and other extreme precipitation events. This is a pressing concern, given the severity of recent storms that have impacted the state, and the connected nature of the power grid, which could (in theory) result in impacts from flooding "cascading" across parts of the grid that are not directly flooded.

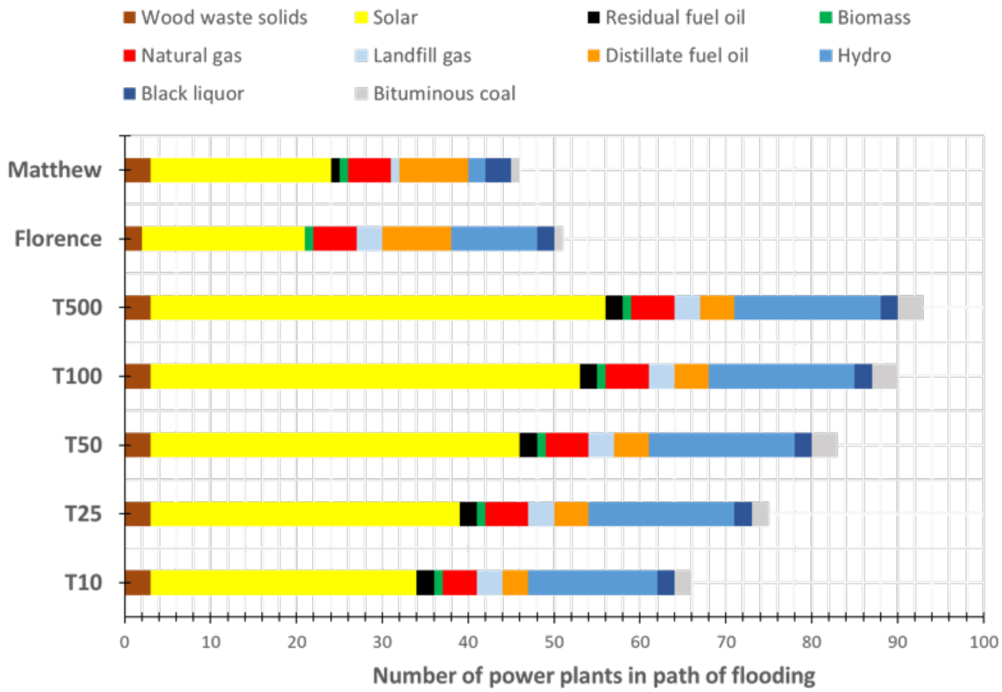


Figure: Number of power plants in areal path of flooding for historical storms Matthew and Florence, as well as for the probabilistic flooding scenarios developed by the Division of Emergency Management.

The findings of the research team suggest that many different types of grid assets may be somewhat exposed to flooding risks, ranging from fossil fuel power plants to solar farms and electrical substations. In terms of the likelihood to impact health and safety, the impacts of flooding on power systems above the distribution level remain difficult to assess. Historically, most power outages due to extreme storms including hurricanes have been caused by outages on the distribution level, though these have typically been more quickly repaired. The potential for widespread, prolonged flooding of substations raises the possibility in some parts of the North Carolina grid that communities in smaller towns, which may have more limited redundancy in grid infrastructure (i.e., fewer substations capable of serving electrical load), could experience power losses for many days and/or weeks.

Failures of this kind may be difficult to predict, given the varied nature of how storms cause flooding in North Carolina. Furthermore, the research team found little publicly available information regarding the height of sensitive equipment (often related to electrical relays) at substations. Our results do show that raising the height of sensitive electrical equipment could substantially reduce risks for substations in eastern North Carolina. The research team is aware of activities currently underway by Duke Energy and the NCEMC to safeguard assets including substations from flooding risks. But the research team does not have detailed knowledge of how these respective systems are being evaluated to determine which substations are high priority for protection. Nor was the research team able to gain detailed knowledge of how power system operators would respond to an event in which certain electrical substations are damaged from prolonged flooding, causing entire communities to lose power for days or weeks. The research team also, at present, lacks an understanding of what types of additional critical infrastructure (e.g., water treatment and distribution systems), in which communities, could go offline as a consequence of prolonged power outages.

Our primary recommendation, as an output of this study, would be to convene a small working group or task force made up of grid participants, an independent coordinators and/or researchers. Working on behalf of the state, the goal of the group would be to: 1) identify the communities and sections of the grid in eastern North Carolina most at risk of prolonged electric outages due to flooding; 2) prioritize the need for protective intervention based on likelihood of occurrence and potential for negative consequences (e.g., health and safety impacts); and 3) gain knowledge about the contingency plans in place for grid operators before, during and severe, localized flooding events.

In parallel to these efforts, additional modeling work may be useful in further identifying scenario specific vulnerabilities and running preparedness exercises. For example, better understanding is needed of the potential for extreme flooding events in eastern North Carolina to negatively impact the functionality of solar farms in this region (which may or may be exporting power to other parts of the state). Likewise,

UNC Institute of Marine Sciences. Morehead City, NC. Photo courtesy of the University of North Carolina at Chapel Hill.

when parts of the eastern North Carolina grid go down due to direct impacts from flooding, it is possible that other sections of the grid that are not flooded could also lose functionality (or become at higher risk of reliability impacts), either inadvertently or due to deliberate de-energization of certain parts of the grid for safety reasons. On this note, in our discussions with grid stakeholders at Duke Energy and NCEMC as part of this study, it became that flooding events like hurricanes, which can be forecasted, involve advanced safety precautions (e.g., shutting down coastal power plants, reduced electricity demand from evacuation) that can alter the supply and demand balance as well. These atypical conditions (in combination with flood impacts) should be considered when modeling impacts of flooding on the eastern North Carolina grid and wider state system.

Models like M2S could be useful in exploring many of these questions; it is the intention of the research team to pursue these further over the next 4-6 months, with the support from a federal grant. M2S will be the primary research tool used, and this preliminary use case should provide a useful example to the state of its capabilities for answering flooding specific questions policy and economic questions, as well as a wider set of questions related to the future sustainability, reliability, and resilience of the NC grid.

The complete Infrastructure: Assessing Operational Flooding Risks for Substations and the Wider North Carolina Power Grid report with citations, figures and recommendations can be found at:
https://collaboratory.unc.edu/current-projects/flood-resilience/

Flood Resiliency and Water and Wastewater Utilities in North Carolina

Erin Riggs, Environmental Finance Center, UNC-Chapel Hill
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Overview

The Environmental Finance Center was charged with investigating water and wastewater utility flood resilience, and the research utilized a mixed methods approach, including mapping vulnerable infrastructure, assessing financial conditions via benchmarks, investigating recovery spending, a focus group style group discussion at a School of Government workshop, and conducting, qualitative interviews and cases studies at four utilities across three river basins.

Between 2016 and 2019, three major hurricanes struck the North Carolina coast: Matthew (2016), Florence (2018) and Dorian (2019). Hurricanes Matthew and Florence deposited an unprecedented amount of rain on the coast of North Carolina. In general, Matthew's rainfall was greater than Florence, but Florence hit when river levels were already high. In areas closer to the piedmont, the flood waters receded relatively quickly, but in the low-lying eastern portion of the state, the rivers rose and, in some cases, took weeks to recede below flood stage. For many of these communities, flooding is not a foreign concept, but rarely leaves the amount of damage associated with these two storms.

A report on Hurricane Matthew produced by NOAA, states that the storm produced in excess of 10 inches of rain across a large region– including northern SC, NC, and southern Virginia. The heaviest rainfall was reported in Columbus County, NC, where the storm was met with other meteorological patterns and produced over 18 inches of rain over two days. In North Carolina, 25 deaths resulted from the storm, nearly all associated with flooding and vehicular travel. The town of Fair Bluff, NC had nearly 85% of the town inundated with water at some point after the storm, and the town of Lumberton, NC had nearly 1500 residents displaced after an apparent levy break. In total, it is estimated that Hurricane Matthew caused $1.5 billion in property damage to nearly 100,000 buildings in NC.

According to NOAA and data from USGS storm gauges, rainfall from Hurricane Florence ranged from anywhere between 10 inches to 35 inches along the border of NC and SC, with the highest rainfall (35.93 inches) in Elizabethtown, NC. The slow movement of the storm both before and after landfall allowed rainbands to continue to move inland from the warm Atlantic, causing significant freshwater flooding. According to USGS data, 22 stream gauges in NC measured record peak stages as a result of Hurricane Florence. Florence resulted in 15 direct fatalities, 14 of which were due to freshwater flooding. Significant flooding caused major agricultural losses, both field crop and animal (chickens, hogs). In NC, Florence caused $22 Billion in damages.

The state estimated approximately $88 million in water/wastewater/stormwater need as a direct result of Hurricane Florence, and an additional $25 million in resiliency needs across water, wastewater, stormwater and electrical/gas utilities.

These two storms, while the most damaging of all within the scope of this research, are merely precursors to future storms without action. As development across the coastal plain continues, stream flooding will continue to worsen, creating additional hazards to property, human life, and infrastructure.

As part of this study, the vulnerability of critical infrastructure, including water and wastewater infrastructure, was assessed. This vulnerability assessment was three fold, including mapping critical infrastructure, assessing utility finances, and conducting semi-structured interviews to determine past damages and future resilience measure.

The impetus on resilience water and wastewater infrastructure is not unique to North Carolina. Indeed, the Environmental Finance Advisory Board advised US EPA on flood resilience in 2019. US EPA has launched an all day flood resilience training for water and wastewater utilities, and several states (California, Massachusetts, Rhode Island, etc.) have launched state specific guidance and funding for flood resilience.

Impact on Infrastructure and Importance of Resilience Within Utilities

In low-lying eastern portions of the state of North Carolina, the height above sea level can vary on the order of a few feet. By nature, sewer infrastructure tends to be placed in the lowest lying areas of town. Additionally, both water and sewer rely on an intake and outfall, often from and into larger water bodies. Combined with floods, this puts numerous aspects of critical infrastructure within an area that is susceptible to rising waters.

This is not unlike other regions of the United States. Take New Orleans for example. After Hurricane Katrina hit in late August, 2005, both of New Orleans' wastewater treatment plants were damaged. The smaller plant was back online in September, but the larger plant was not functioning until November 2005, and was suffering from regular problems nearly a year later. The damage to wastewater treatment facilities in New Orleans alone was estimated at approximately $1.2 billion.

As infrastructure is assessed and vulnerabilities are determined, utilities often aim to raise pump stations, armor or "harden" assets, make critical infrastructure submersible, and ensure adequate redundancies in the system. All of these actions can protect a water or sewer utility from rising flood waters, but all of them come at a cost. Often, these costs are competing with basic water and sewer infrastructure needs, absent the additional challenge of large storms and rising floodwaters.

Financially, utilities can also be vulnerable to large flood events. In cases where homes or businesses are damaged, floods can equate to large losses in service population for months. Additionally, when infrastructure is damaged, FEMA funds are often months, if not years away from being awarded. In these cases, utilities are often required to use cash on hand, or the "fund balance" to repair and replace what is required to restore service.

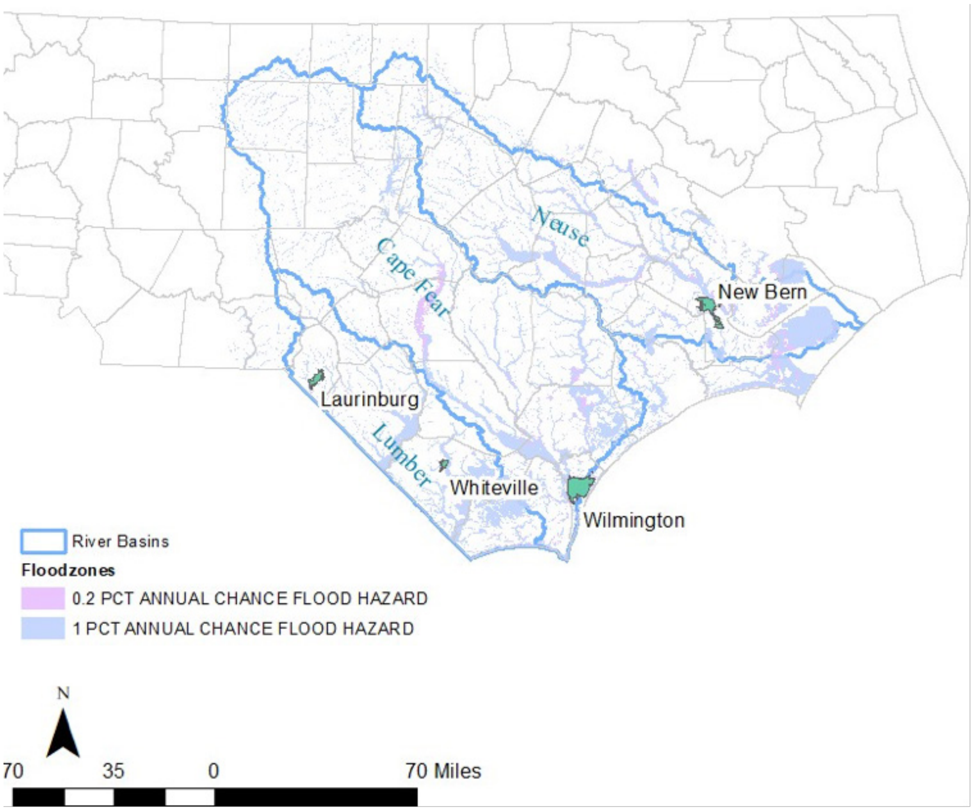
In New Orleans, preliminary reports cited the challenges with flight from the area post-Katrina, and what that may mean for utility revenues and long-term financial sustainability. Indeed, according to the US Census Bureau, the population of New Orleans (not the service population) dropped from 454,000 in 2005 to 208,000 in 2006. As of 2018, the population has rebounded to 391,000, but has leveled off and may be decreasing. This example fails as it connects to eastern North Carolina. New Orleans is a large city, already experiencing economies of scale as it pertains to water and wastewater service. Much of eastern North Carolina is small, and many utilities are already suffering with small service populations and tight budgets.

With this in mind, the research aims to assess water and/or wastewater resilience in eastern North Carolina. First, infrastructure and floodplains were mapped to determine vulnerable infrastructure. Then, four case studies were conducted with utilities of various sizes and with ranging impacts from Hurricanes Matthew and Florence to better understand the damage done, the recovery process, and steps towards future resilience.

Research Methods

Flood Plain Mapping

To assess vulnerability of utilities in the Lumber, Cape Fear, and Neuse river basins, key infrastructure (water and wastewater treatment plants, water and wastewater distribution pumps, and wastewater pipes) was compared to flood plain maps for those areas. The flood maps display a 1 percent chance of flooding (100 year flood plain A designation on flood map) and a 0.2 % chance of flooding (500 year flood plain: B,C designation). The infrastructure was clipped to the basins, and the intersection of infrastructure points and flood maps features were found.



Locations of basins studied.

We found that nearly one third of sewer treatment plants and 23% of sewer pumps are in the 100-year flood plain. Although sewer treatment plants and sewer pumps tend to be in low-lying areas because pipes run to the lowest point to gather wastewater, the fact that one of every three sewer treatment plants is at risk of flooding relatively frequently highlights the widespread vulnerability of these types of infrastructure in the Cape Fear, Lumber and Neuse River basins.

It's important to note that this analysis does not take into account any modifications a system has made to elevate pumps or treatment facilities–it is just the elevation of the land at which the piece of infrastructure is located.

Case Studies

To supplement the quantitative data produced through GIS, four case studies were conducted of local government utilities that suffered damages from Hurricanes Matthew and Florence. These case studies included questions related to the damages incurred and any loss of service, details on the new infrastructure, challenges with funding/financing after a natural disaster, and any changes the utility has made to be more resilient.

Nine utilities were identified: three within each river basin of interest. These utilities were identified as ranging in service population, with a small, medium, and large utilities identified in each basin. The nine utilities included Whiteville, Laurinburg, Fayetteville, Cape Fear Public Utilities Authority (CFPUA), New Bern, Kinston, Lumberton, Concord, and Raleigh. Of these, seven were contacted. Given the distance from the coastal plain, Raleigh and Concord were not contacted. Four utilities responded.

Interviews were conducted with CFPUA, Whiteville, Laurinburg, and New Bern, resulting in four complete case studies. Given the range of service population, and financial, technical, and managerial capacity, as well as the proportion of the utility in the floodway, the interviews provided very different perspectives on utility damages and future resilience.

Finally, to further build the body of qualitative research, a series of open-ended questions were asked during a presentation at the UNC-Chapel Hill School of Government's Annual Water and Wastewater Finance workshop in February 2020. These questions were intended to gauge what utilities are planning for (i.e., 100-year flood, 500- year flood) and why that threshold was chosen.

Financial Analyses

Perhaps the most overwhelming takeaway from the qualitative feedback was the lack of financial support following large storms. Two of the four respondents mentioned waiting years for FEMA money to come in, effectively relying on the utilities fund balance to buffer the costs of emergency replacements in the wake of the storm.

Given these takeaways, an in-depth financial analysis was completed for all nine utilities, looking at their water/wastewater rates and finances, as available from the NC Water and Wastewater Rates Dashboard, over the last five years. The results for the four completed case studies were added to the case study results. Finally, during the tenure of this research, the EFC also created a Financial Resiliency Dashboard to assess impacts of COVID-19. Given the impacts of major floods on fund balances, the tool is also relevant to utilities affected by natural disasters.

Funding/Financing Research

The final component of the research included an in-depth analysis of funding/financing sources available to utilities within the state, a broad review of resilience funding programs in other states/regions, and research regarding innovative funding/financing mechanisms for resilience. These three, distinct, portions of research represent the resources already available, those that exist in other areas of the US and may have applicability to NC, and the mechanisms that are emerging within financial markets to support utility resilience, but may not have immediate applicability to North Carolina Utilities.

Wastewater Infrastructure Tends to be Most Vulnerable

Of the communities interviewed, most cited wastewater impacts as a result of Matthew and/or Florence. And it makes sense, as stated previously, wastewater infrastructure tends to be built at the lowest point in town, making it ripe for flooding impacts. The infrastructure is often built in the floodplain to utilize gravity and reduce pumping, and given the cost of a new Wastewater Treatment Plant, moving is not a quick or easy solution. The most common wastewater treatment failure cited was an overflow at the treatment plant and the disposal of untreated waste into waterways. While the public health impacts are slightly further removed than the loss of drinking water service, the environmental and downstream impacts still necessitate a better understanding of how to resolve these challenges going forward.

Recommendations

Policy Recommendation

The State should consider water holistically, thinking about the connectedness of water resources when making legislative changes related to flood resilience.

Vulnerabilities are Real, but the Impacts can be Buffered by Reliable Staff

All communities explained at least one serious issue as a result of Florence and/or Matthew. In some cases, the issue was isolated and in others it was system-wide. Regardless of the scope of the issue, all respondents cited the hard work of their staff as a reason the issue was not worse or was resolved quickly. In some cases, staff braved hurricane conditions to curb the issue and in other cases staff worked around the clock. Water and wastewater infrastructure is largely hidden from the greater community and workforce development is a growing challenge in the field. Going forward, utilities should continue to invest in their staff and showcase the staff's hard work to the public–perhaps without showcasing the system vulnerabilities.

Policy Recommendation

The State should work to improve workforce development within the water and wastewater sector, especially as the current workforce ages and the new workforce dwindles in size.

Recovery Funding is not Reliable

Despite heavy reliance on FEMA funding, most respondents cited great challenges with attaining that funding. Respondents cited heavy turnover within FEMA, lack of communication, and years long waiting times for funding as reasons for concern. Indeed, one utility noted that their auditor stated they could no longer put FEMA money on their accounts receivable, as it had been too long. This will have a negative impact on their financial indicators and likely raise red flags at the Local Government Commission. While utilities cited that they do believe the money will come, FEMA is no longer a quick lifeline. Grant funders like the Golden Leaf Foundation were considered much more efficient partners, likely signaling a need for change in the FEMA system.

Policy Recommendation

The State should consider launching a bridge funding/financing program that allows utilities to borrow money to repair/replace critical infrastructure while waiting for FEMA money.

Fund Balances Connect the Dots

Fund balances in North Carolina have been growing. Since the NC Division of Water Infrastructure began to require a larger fund balance to attain their funding or financing, utilities have been putting aside more cash for a rainy day. This has proved fruitful in the wake of large storms. Many utilities cited paying for repairs with the fund balance, in hopes of being reimbursed by FEMA. Given the uncertainty around timing of FEMA money, fund balances have been a lifeline for utilities, even if it means deferring other capital improvements to make ends meet in the short- term. Going forward, fund balances will continue to be a vital part of financial resilience and should continue to be utilized. Indeed, reserves will continue to be important as utilities approach hurricane season, as damages may be costly and revenue shocks could be significant.

Policy Recommendation

The LGC and NC DWI should continue putting an emphasis on building fund balances.

Resilience Planning is not Clearly Defined

North Carolina lacks clear guidance on how to be resilient. Other groups, like US EPA and the State of California, have provided lengthy documents on utility resilience, but some parts are fuzzy. The US EPA flood resilience guidance is a workshop style, including asset criticality exercises and videos of a small utility in Maine that invested in resilience. But the workshop lacks the follow-up or technical assistance required to see the implementation of resilience through. Indeed, attendees at the School of Government workshop nearly all cited different definitions of resilience and resilience planning, most due in part to a.) attaining FEMA funding, or b.) prior experience during storms. Going forward, North Carolina should consider providing water and wastewater utility specific guidance on resilience; both physical and financial.

Policy Recommendation

The State should work to operationalize “resilience” planning for water and wastewater utilities, providing a clear definition and actionable steps for utilities to become more resilient.

The complete Flood Resiliency and Water and Wastewater Utilities in North Carolina report with citations, figures and recommendations can be found at: https://collaboratory.unc.edu/current-projects/flood-resilience/

Public Health Impacts and Storm Events

Rachel Noble, UNC Institute of Marine Sciences
Jill Stewart, Environmental Sciences and Engineering, UNC-Chapel Hill

Overview

Flooding and storm surges associated with extreme events are associated with an increased risk of infection for the public. In the State of North Carolina, this risk can be compounded by compromised stormwater and sewage conveyance systems, as well as compromises in poultry and hog fecal waste lagoons. The major risk factors for outbreaks associated with flooding are 1) contamination of drinking-water systems, including both municipal and private drinking water wells 2) exposure to floodwater and consumption of foods contaminated by floodwaters, and 3) legacy contamination of food, shellfish and recreational waters. There is an increased risk of infection of water-borne diseases contracted through direct contact with polluted waters, such as wound infections.

In order to advance our ability to mitigate the risks associated with floodwaters, it is vital to prioritize such risks through the use of quantitative analysis tools. Fortunately, a few laboratories across the State of North Carolina, including the laboratories of Drs. Stewart and Noble, have devoted efforts to developing the capacity for direct pathogen measurements in wastewater, stormwater, hog lagoon wastewaters, recreational waters, drinking water and shellfish.

This project was originally designed to conduct storm-associated sampling to begin to characterize the sources of fecal material and pathogens present in floodwaters. The project demonstrated the capacity for quantification of pathogens associated with flooding versus background levels of microbial contaminants in water systems, and began the process of understanding the distribution and duration of impacts associated with flooding events.

Summary of Research Findings

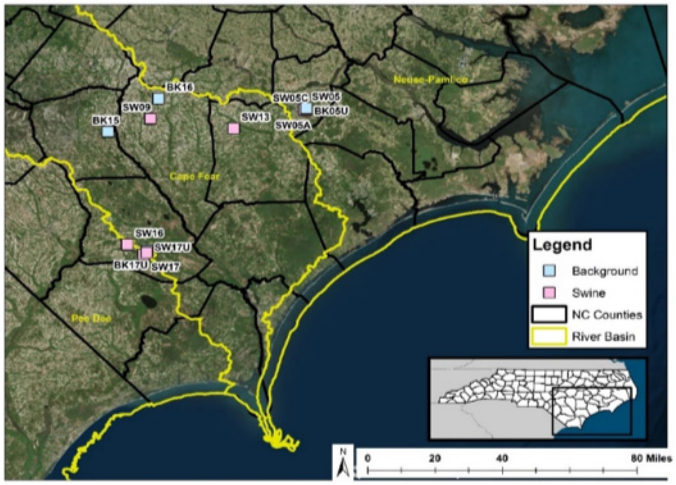
- Precipitation-related effects on concentrations of E. coli and other fecal indicator bacteria are not limited to large hurricane events but can occur across a range of precipitation events, particularly when groundwater levels are high and antecedent rainfall creates saturated soils.
- There is merit in conducing direct measures of bacterial and viral pathogens as well as antimicrobial resistance to supplement fecal indicator bacteria analysis to identify locations with pathogen hazards and to better characterize risks to human health.
- In order to develop mitigation strategies for microbial contaminants from flooding, it will be vital to quantify sources of fecal contamination. At this juncture, both human and hog waste are implicated in floodwaters from different sampling events.
- Flooding can be associated with increased levels of pathogens and antimicrobial resistance in surface waters, with effects lasting for days to weeks.
- Risks from microbial hazards including pathogens and antimicrobial resistance are higher in locations proximal to human and animal wastewaters. This is a concern in North Carolina in areas with food animal production that use waste lagoon systems and in municipalities with aging and decaying wastewater infrastructure.
- Septic, package treatment plant, and low resource sewage infrastructure deserve further review for their potential impacts on human health from the perspectives of drinking water and shellfish consumption.
- Of particular interest to the research being conducted as part of this program is that both laboratories have now invested in molecular analysis equipment that permits real-time, fully quantitative analysis for a range of viral pathogens important to public health concerns, including SARS-CoV-2 and related variants. The application of this technology moving forward will permit NC to lead an advanced set of studies on the impacts of flooding and extreme events.

Dr. Rachel Noble of the UNC-Chapel Hill Institute of Marine Sciences, examines water samples in her lab taken from a beach near Morehead City. Photo courtesy of the University of North Carolina at Chapel Hill.

Research Methods

We conducted sample collection during and in response to Hurricane Florence. Samples included for this work were collected from selected locations in the Lumber, Cape Fear, and Neuse river basins (Figure below). These basins include almost 4 million NC residents, over 2,000 confined swine operations, over 1,600 confined poultry operations, and almost 25,000 miles of NC rivers and streams, with an estimated 1.4 million residents who likely depend on on-site septic systems for wastewater management. These locations were highlighted for sample collection due to the precipitation patterns from Hurricane Matthew, the complex contributions of wastes from multiple (human and hog) sources, and concerns about contamination of private drinking water wells.

Over 250 samples were collected and analyzed in response to extreme events for microbial contaminants. The project team is building a database for selection of pathogen response variables that will allow the development of a new monitoring system, as well as future predictive models. Our research currently includes regulatory targets such as total coliforms, fecal coliforms, and E. coli, as well as other targets of public health concern including antibiotic resistant bacteria, HF183 human fecal marker, Vibrio sp., somatic and male-specific coliphages, Campylobacter sp., Salmonella sp. and respiratory and gastrointestinal viral pathogens.



Sampling locations for post-Florence sampling events.

All samples were analyzed for fecal indicator bacteria E. coli using standard membrane filter techniques, or standard IDEXX enzymatic substrate techniques or both. Male-specific (F+) coliphage and somatic coliphage were quantified using vetted, published single-agar overlay approaches. Salmonella sp. concentrations were determined using vetted, published culture-based approaches. Salmonella sp., HF183, and Pig-2-Bac quantification for species and pathogenicity islands were completed following molecular approaches.

E. coli (CFU/100mL)
E. coli IDEXX (MPN/100mL)
Total Coliforms IDEXX (MPN/100mL)
F+ coliphage (PFU/100mL)
Somatic coliphage (PFU/100 mL)
Salmonella (MPN/100mL)
Salmonella ttr (copies/100mL)
Salmonella invA (copies/100mL)
Campylobacter (copies/100mL)
HF183 (copies/100mL)
Pig-2-bac (copies /100mL)

Measurement	9/24/2018		11/14/2018		4/24/2019		9/18/2019	
	Mean	CI	Mean	CI	Mean	CI	Mean	CI
Prior Precipitation: 48 h (inches)	0	0	1.5	1.0 - 2.1	0	0	0.004	0 – 0.014
Prior Precipitation: 7 days (inches)	0.04	0.02 - 0.06	2.3	1.9 - 2.7	1.3	1.0 - 1.6	0.2	0.06 - 0.2
E. coli (CFU/100mL)	650	0 - 1482	816	233 – 1,399	112	59 - 164	NA	NA
E. coli IDEXX (MPN/100mL)	779	0 - 2010	734	274 – 1,194	105	58 - 152	469	27 - 911
Total Coliforms IDEXX (MPN/100mL)	>24,196[1]	NA	15,753	9,885 – 21,621	11,423	6,852 – 15,994	19,896	15,606 – 24,186
F+ coliphage (PFU/100mL)	17	0 - 43	13	1 - 25	3.4	2 - 5	0.17	0 – 0.5
Somatic coliphage (PFU/100 mL)	145	0 - 408	169	20 - 319	26	0 – 68	58	0 – 135
Salmonella (MPN/100mL)	5.8	2.9 - 8.7	1.8	1.8 - 1.8	3.2	1.8 - 4.5	28	0 – 63
Salmonella ttr (copies/100mL)	BD	BD	BD	BD	BD	BD	BD	BD
Salmonella invA (copies/100mL)	BD	BD	BD	BD	BD	BD	BD	BD
Campylobacter (copies/100mL)	2,063	0 – 4,225	788	249 – 1,327	TBD	TBD	TBD	TBD
HF183 (copies/100mL)	1,130	0 – 3,287	301	174 - 428	TBD	TBD	TBD	TBD
pig-2-bac (copies /100mL)	17,652	0 – 54,555	21	5 – 37	TBD	TBD	TBD	TBD

[1] All samples above detectable limit

Table: Mean and 95% confidence interval (CI) for outcomes measured and observed precipitation for four sampling dates post-Hurricane Florence. BD= below detectable limit; NA=not applicable; TBD=to be determined, outcomes not yet assessed in laboratory.

Measurement	n Sample Dates	n Samples	Sprayfield-impacted Sites		Background Sites		p-value
			Mean	95% Confidence Interval	Mean	95% Confidence Interval	
E. coli (CFU/100mL)	3	36	401	119 – 682	776	33 – 1144	0.36
E. coli IDEXX (MPN/100mL)	4	48	658	208 – 1108	249	81 – 826	0.17
Total Coliforms IDEXX (MPN/100mL)	4	48	18,880	16,219 – 21,542	15,690	11,394 – 23,177	0.20
F+ coliphage (PFU/100mL)	4	48	9.1	0.3 – 18	7.8	0 – 17.5	0.39
Somatic coliphage (PFU/100 mL)	4	48	135	33 – 237	30	0 – 165	0.0095*
Salmonella (MPN/100mL)	4	48	7.7	1 – 14	13.5	0 – 28.5	0.48
Campylobacter (copies/100mL)	2	24	1,826	365 – 3,288	623	106 – 2,343	0.12
Salmonella ttr (copies/100mL)	4	48	BD[1]		BD		
Salmonella invA (copies/100mL)	4	48	BD		BD		
HF183 (copies/100mL, ddPCR)	2	24	226	139 – 313	1,693	0 – 3,088	0.54
pig-2-bac (copies /100mL, qPCR)	2	24	13,251	0 – 37,925	8	5 – 13,253	0.007*

[1]BD= below detectable limit; *significant difference between swine and background sites p<0.05 for Mann-Whitney non-parametric test for difference in mean rank

Table: Mean and 95% confidence interval for measured outcomes among sprayfield-impacted and background sites among post-Florence sampling events.

	Background sites # isolates	Sites close to lagoons # isolates	Relative risk (95% CI)
Number of *E. coli* isolated	356	556	
Resistant to at least one class of antibiotics	20 (6%)	81 (15%)	2.59 (1.62 – 4.15)
Resistant to at least two classes of antibiotics	0 (0%)	11 (2%)	n/a
Resistant to at least three classes of antibiotics (multi-drug resistance)	1 (0.3%)	14* (2.5%)	8.96 (1.18 – 67.9)

*Eleven isolates were also positive for beta-lactamase production that confers resistance to a wide variety of penicillin and cephalosporin drugs. These bacteria are classified as extended-spectrum beta-lactamase (ESBL) *E. coli* and are listed as a serious threat by the US CDC.[41] We do not know the pathogenicity of these particular isolates.

Table: Number, percent, and relative risk of E. coli isolates with observed resistance to tested antibiotics.

Figure: 48-hour prior precipitation on E. coli concentration at sites sprayfield-impacted (SW) and background (BK) sites: SW17, SW17U, BK17U (top) and sites SW05, SW05A, SW05C, BK05U (bottom) at sampling events and after Hurricane Florence.

Findings

- Although this is a pilot project with relatively few sampling events characterized, there is a trend toward higher concentrations of molecular markers and microbial contaminants in floodwaters immediately following Hurricane Florence, than during a non-storm impacted period.
- Our findings indicate that both human fecal and hog fecal contamination was prevalent in the floodwaters following Hurricane Florence. This is cause for serious concern, because these sources of fecal contamination would be expected to pose a serious risk to the public.

Recommendations

(1) Surveillance and response

- Now that we have developed advanced techniques for high throughput characterization and quantification of microbial contaminants in light of the COVID-19 pandemic, we recommend a stratified random sampling approach to characterize floodwaters and non-flood impacted waters with priority devoted to assessing the relative impact of sewage and hog fecal material on relevant systems.
- Improved system characterization of pathogens will benefit from a simultaneous assessment of the reports of GI pathogen, wound infection and floodwater related exposures and risks by analysis of the NC DETECT emergency room data.

(2) Accurately quantifying pathogens and genes is a first step towards understanding whether water sources pose risks to human health. Especially during extreme events, it is important to efficiently determine health risks.

- Vibrio: This is a pathogen with outcomes in the NC Surveillance System (e.g., NC DETECT). We are working on improving methods for quantifying the known virulence sub-strains of Vibrio that can cause infection which may be more useful than past approaches to quantify Vibrio at the species level.
- Antimicrobial resistance genes: We are hoping to use more advanced molecular diagnostic approaches for quantification of combinations of antimicrobial resistance genes that may be more indicative of risk to humans.

(3) Stakeholder engagement: It is certain that engagement with relevant stakeholders, including municipal wastewater utilities, hog and livestock farming operations, and county health departments will permit a further assessment of the risks posed by floodwaters. Thankfully, we have already accomplished much of this stakeholder relationship building with WWTP utilities through the COVID-19 pandemic, so working with them to address flooding and flood/stormwater resilience strategies will be a valuable next phase of effort.

The complete Public Health Impacts and Storm Events report with citations, figures and recommendations can be found at: https://collaboratory.unc.edu/current-projects/flood-resilience/

ONGOING RESEARCH

Ongoing Research

Overview

It is important to note that the work conducted as part of the Flood Resiliency Study is just one collaboration of the many ongoing projects in North Carolina focused on reducing and responding to flooding and strengthening resilience. Multiple state agencies, local governments, non-profits and industry organizations are all working to identify solutions that will improve the planning, response, and recovery efforts before and after the next storm event.

While this specific study has been completed, a number of the research team members and other university faculty across the state continue to be involved in significant research projects related to resiliency. A few examples of this work are briefly noted below.

Dynamics of Extreme Events, People and Places

A team of researchers at UNC-Chapel Hill are exploring how exposure to extreme weather events affects both people and the environment they live in over time. The research team is made up of various expertise, including engineering, environmental sciences, population sciences, and policy and planning. The project is designed to develop the infrastructure for drawing representative samples of people and places throughout eastern North Carolina that are at varying risks to extreme events. Working together over the next decade, they plan to build an integrated data platform to measure the ways that natural systems and humans respond to extreme weather events. The project will also assess how intensifying storms of the future will affect habitats and populations of coastal regions of North Carolina and elsewhere.

Environmental Justice Issues

One research topic that is receiving increased interest relates to environmental justice issues that arise from storm events and the response by governmental agencies to those communities impacted by flooding. In particular, these concerns arise during the floodplain buyout process. One of the largest barriers to receiving floodplain buyouts is related to long wait times. A report from 2019 found that it takes upwards of five years for a buyout funded by FEMA to be completed once a flood takes place. This long wait is incredibly damaging to those with limited access to resources as they are left for years without assistance. Additionally, previous research found that residents who are at risk of flooding and are most likely to wait for buyouts as a form of relief are lower-income. The flood plain buyout program may also negatively affect the local tax base and social cohesiveness in low-wealth communities and homeowners as they are being incentivized to move.

NC Sea Grant

A new North Carolina Sea Grant informational web page offers strategies and resources for improving flood mitigation and transportation resilience in eastern North Carolina communities. Concise sections cover major floods in North Carolina, their transportation impacts, and future flooding risks. Another section describes methods to improve resilience, such as updating design standards for new roads and creating more rigorous floodplain ordinances. A final section offers online tools that communities can use for forecasting and planning.

Recent Major Flood Events in Eastern North Carolina

STORM	**YEAR**	**RAINFALL** (inches)	**DAMAGE** (billions)	**FEMA DISASTER COUNTIES**	**FATALITIES**
Florence	2018	25-35	$17.0	28	40
Matthew	2016	18-20	$4.8	45	28
Floyd	1999	17-20	$9.4	66	51

UNC Institute for the Environment

The Center for Resilient Communities and Environment was established by the UNC Institute for the Environment. The center engages communities in a process of understanding their vulnerability to acute and chronic natural stressors, and works to quantify the risk from those stressors and develop strategies to strengthen community and natural system resilience. The Center brings together faculty and students from across the University to collect new data, synthesize existing information, and extend our understanding of how community social, ecological and physical systems work. The center's mission is to produce transformative research that offers solutions for more resilient and sustainable communities, translate this research to meet community needs, and create impactful learning experiences for students and the communities in which we work.

Resilience Reframed

One of the leading national scholars on legal issues related to resiliency is Professor Donald Hornstein at UNC School of Law. His recent research examines the potential for investments in implementing resiliency and some of the challenges facing wide scale adoption of resiliency policies and projects. Prior research on this topic repeatedly highlighted large payback ratios, underscoring the idea that an ounce of prevention is worth a pound of cure. Professor Hornstein continues to be active on this topic recently receiving funding from the national Sea Grant organization to train attorneys in North Carolina on representing low-wealth communities and communities of color in eastern North Carolina on future floodplain buyouts.

Since 2016, with funding from the North Carolina General Assembly, the NC Policy Collaboratory has supported multiple research and community-based projects to address the significant impacts following large storm events. Most notably, following Hurricane Matthew a team of researchers funded by the Collaboratory worked with six eastern North Carolina communities to help develop their recovery plans.

Although the Flood Resiliency Study is completed, the Collaboratory plans to continue to support ongoing research on this topic.

Institute of Marine Sciences. Photo courtesy of the University of North Carolina at Chapel Hill.

APPENDICES

Appendix I

I

Legislative Text of Session Law 2019-224, Section 2.1 (8)

$10,160,000 to The University of North Carolina Board of Governors to be used as follows:

a) $160,000 to the North Carolina Policy Collaboratory (Collaboratory) for the ModMon program.

b) $2,000,000 to the Collaboratory to study flooding and resiliency against future storms in Eastern North Carolina and to develop an implementation plan with recommendations. The Collaboratory shall report the flooding and resiliency implementation plan to the Joint Legislative Emergency Management Oversight Committee no later than December 1, 2020. Notwithstanding Section 3.1(c) of S.L. 2018-134, funds allocated to the Collaboratory as provided in this sub-subdivision shall revert on December 30, 2020. The University of North Carolina shall not charge indirect facilities and administrative costs against the funding provided for the Collaboratory from the Hurricane Florence Disaster Recovery Fund.

c) $8,000,000 to the University of North Carolina Wilmington (UNC-W) for repairs and renovations to the Dobo Hall science building, which was damaged by Hurricane Florence.

Legislative Text of Session Law 2020-74, Section (8)(b)

Section 2.1 of S.L. 2019-224, reads as rewritten:

The Collaboratory shall report the flooding and resiliency implementation plan to the Joint Legislative Emergency Management Oversight Committee no later than ~~December 1, 2020~~ June 1, 2021. Notwithstanding Section 3.1(c) of S.L. 2018-134, funds allocated to the Collaboratory as provided in this sub-subdivision shall revert on ~~December 30, 2020~~ June 30, 2021.

Appendix II: Study Team Roster

II

Floodplain Buyouts

Project Team:	
Todd BenDor	Odom Institute; UNC Dept. of City and Regional Planning
David Salvesen	UNC Institute for the Environment
Miyuki Hino	UNC Deptartment of City and Regional Planning
Nikhil Kaza	UNC Deptartment of City and Regional Planning
Antonia Sebastian	UNC Deptartment of Geological Sciences
Jonas Monast	UNC School of Law
Rebecca Kihslinger	Environmental Law Institute (ELI)
PhD Students:	
Jordan Branham	UNC Deptartment of City and Regional Planning
Nora Schwaller	UNC Deptartment of City and Regional Planning
Tibor Vegh	UNC Deptartment of City and Regional Planning and Duke Nicholas Institute
Master's Students	
Shane Sweeney	UNC Deptartment of City and Regional Planning
Hallee Haygood	UNC Deptartment of City and Regional Planning
William Curran-Groome	UNC Deptartment of City and Regional Planning
Hunter Quintal	UNC Department of Geolgoical Sciences
Undergraduates:	
Emily Apadula	UNC Institute for the Environment
Kels Peterson	UNC Institute for the Environment

Financial Risk of Flood Events in Eastern NC

Project Team:	
Greg Characklis	Center on Financial Risk in Environmental Systems; UNC Dept. of Environmental Sciences and Engineering
Antonia Sebastian	UNC Department of Geological Sciences
Simona Denaro	UNC Deptartment of Environmental Sciences and Engineering
Harrison B. (H.B.) Zeff	UNC Deptartment of Environmental Sciences and Engineering
Graduate Students:	
Benjamin Foster	UNC Deptartment of Environmental Sciences and Engineering
Joy Hill	UNC Deptartment of Environmental Sciences and Engineering
Rachel Kleiman	UNC Deptartment of Environmental Sciences and Engineering
Hope Thomson	UNC Deptartment of Environmental Sciences and Engineering

Natural Systems: Improving North Carolina's Resilience to Coastal Riverine Flooding

Project Team:

Barbara Doll	NC Sea Grant, NC State University
Jane Harrison	NC Sea Grant
Dan Line	NCSU Deptartment of Biological and Agricultural Engineering (BAE)
Jack Kurki-Fox	NCSU Deptartment of Biological and Agricultural Engineering (BAE)
Fred Cubbage	NCSU College of Natural Resources (CNR)
Ted Shear	NCSU College of Natural Resources (CNR)
Andy Fox	NCSU College of Design (CoD)
Travis Klondike	NCSU College of Design (CoD)
Madalyn Baldwin	NCSU College of Design (CoD)
Todd BenDor	Odum Institute; UNC Dept. of City and Regional Planning
David Salvesen	UNC Institute for the Environment
Michelle Lovejoy	NC Soil & Water Conservation Foundation (NCSWCF)

Student Researchers:

Delandra Clark	NC State University
Chris Hollinger	NC State University
Meredith Hovis	NC State University
Jana Hunter	NC State University
Sophie Kelmenson	UNC-Chapel Hill
Tibor Vegh	UNC-Chapel Hill

Project Advisors:

Will McDow	Environmental Defense Fund (EDF)
Krissy Hopkins	United States Geological Survey (USGS)
Keith Larick	NC Farm Bureau
Tom Potter	NC Soil & Water Conservation Foundation (NCSWCF)
Bryan Evans	NC Association of Soil and Water Conservation Districts
Bill Lester	UNC Department of City and Regional Planning

Natural Systems: Enhancing the Role of Wetlands in Flood Mitigation Through Policy

Project Team:

Jonas Monast	UNC School of Law

Research Assistants:

Sarah Baker	UNC School of Law
Vanessa Dane	UNC School of Law
Caroline Lim	UNC School of Law
Mireya McAlpine-Braxton	UNC School of Law
Amy Mull	UNC School of Law

Natural Systems: Compound Flood Modeling

Project Team:

Antonia Sebastian	UNC Deptartment of Geological Sciences
Rick Luettich	UNC Institute of Marine Sciences
Brian Blanton	Renaissance Computing Institute (RENCI)

Postdoctoral Researchers:

Youcan Feng	UNC Institute of Marine Sciences

Graduate Students:

John Ratcliff	UNC Deptartment of Marine Sciences
Lauren Grimley	UNC Deptartment of Geological Sciences

Research Technician:

Crystal Fulcher	UNC Institute of Marine Sciences

Infrastructure

Inundation of Stormwater Infrastructure

Mike Piehler	UNC Institute for the Environment, UNC Institute of Marine Sciences
Adam Gold	UNC Institute for the Environment
Chelsea Brown	UNC Institute of Marine Sciences
Suzanne Thompson	UNC Institute of Marine Sciences

Enhancing Stormwater Control Measures

Bill Hunt	NCSU Biological and Agricultural Engineering
Caleb Mithchell	NCSU Biological and Agricultural Engineering

Assessing Operational Flooding Risks for Substations and the Wider North Carolina Power Grid

Jordan Kern	NCSU Deptartment of Forestry and Environmental Resources
Luis Prieto Miranda	NCSU Deptartment of Civil, Construction and Environmental Engineering

Flood Resiliency and Water and Wastewater Utilities in NC

Erin Riggs	UNC Environmental Finance Center
Austin Thompson	UNC Environmental Finance Center
Elsemarie Mullins	UNC Environmental Finance Center

Flood Resilience Data Collection

Leila Hashemi Beni	NCA&T University Department of Built Environment

Public Health and Storm Events

Jill Stewart	UNC Deptartment of Environmental Sciences and Engineering
Rachel Noble	UNC Institute of Marine Sciences

Public Engagement

Kathleen Gray	UNC Institute for the Environment
Jonas Monast	UNC School of Law
Neasha Graves	UNC Institute for the Environment
Victoria Triana	UNC Institute for the Environment

Appendix III: Acknowledgments

III

The ongoing work of the Collaboratory's Flood Resiliency Study has involved dozens of faculty, staff and students at UNC-Chapel Hill, NC State University, and North Carolina A&T University. The Collaboratory staff and board recognize the valuable contributions made by many to catalyze and undertake the research projects described in this final report.

Collaboratory Staff

Jeff Warren, Executive Director

Laurie Farrar, Budget and Finance

Steve Wall, Outreach Director

Hope Thomson, Graduate Research Assistant

Rebecca Rice, Graduate Research Intern

Collaboratory Environmental Policy Interns (UNC undergraduate students) Claire Bradley, Taylor Fitzgerald, Lucy Gray, Elizabeth Kendrick, Dylan Morgan and Mandy Pitz conducted background research in support of this study and also contributed to the drafting of the report.

Layout, graphics and design for this report was conducted by Kyle McKay with UNC-Chapel Hill.
Curation of the Flood Resiliency Study webpage is managed by Gary Wilhelm with UNC-Chapel Hill.

Collaboratory Advisory Board

Cover photo courtesy of the University of North Carolina at Chapel Hill.

COLLABORATORY
FLOOD RESILIENCY STUDY

Final Report to the North Carolina General Assembly, *JUNE 2021*

NC Policy Collaboratory

THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL