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

May 1, 2021

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Executive Summary

Electric utilities in NC 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 NC.

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 NC 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 NC. 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: <u>Preliminary geospatial flood risk assessment for Eastern NC grid</u> – using publically 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: <u>Dynamic flood depth analysis during historical Hurricanes and grid impacts</u> – 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: <u>Operational modeling of the NC grid under recreated historical flooding conditions</u> – 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 publically 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 (Campbell, 2012; U.S. President's Council of Economic Advisers, 2013). 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 (Murawski, 2018), and Hurricane Florence caused outages for more than 500,000 (Rice, 2018). 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 (Wells, 2020). 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 NC, 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 (SEIA, 2020); 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:

1) *What critical NC grid assets are presently in the path of flooding from inland flooding resulting from hurricanes and other extreme precipitation events?*
2) *Can flooding maps and depth information from recent storms be used to recreate the chronology of flood impacts experienced by the NC grid?*
3) *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?*

In the following sections, we discuss the methods used in our research, major findings, and conclude with a set of recommendations and suggested implementation actions.

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:

Task 1: Preliminary geospatial flood risk assessment for Eastern NC grid – We collected publically 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.

<u>Task 2: Dynamic flood depth analysis during historical Hurricanes and grid impacts</u> **–** 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.

<u>Task 3: Operational modeling of the NC grid under recreated historical flooding conditions</u> **–** 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.

Findings

Task 1 - Preliminary geospatial flood risk assessment for Eastern NC grid

In Task 1, we collected publically 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 (see Figure 1 and Figure 2). The location of power plants was obtained through the U.S. Environmental Protection Agency's eGRID database (EPA, 2019), while the location of transmission assets (including substations) was obtained through the U.S. Department of Homeland Security's Homeland Infrastructure Foundation-Level Data (HIFLD) program (DHS, 2021).

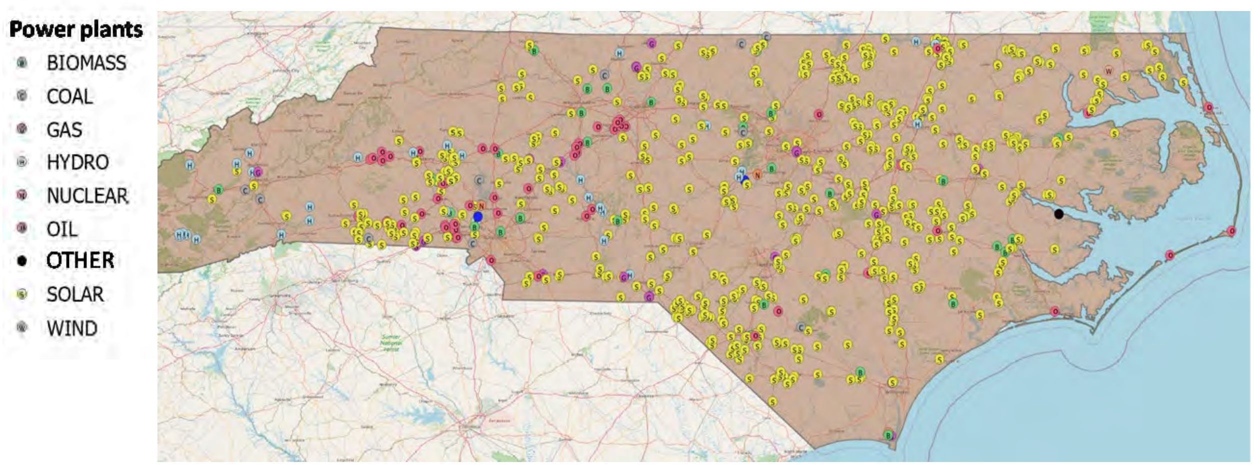

Figure 1. Location of electric power generators in North Carolina as of 2018. Source. U.S. Environmental Protection Agency.

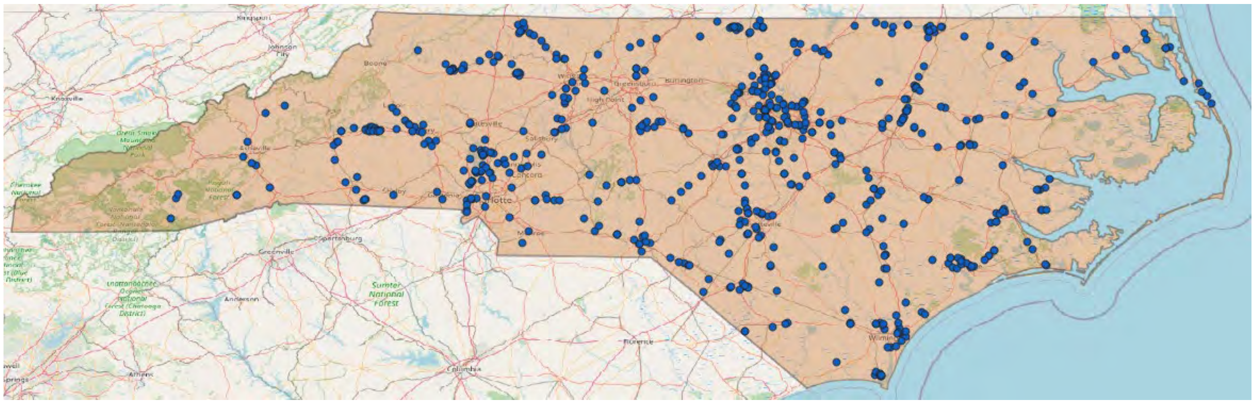

Figure 2. Location of selected major electrical substations North Carolina. Note: substations shown here are not a complete list of substations in North Carolina. These selected stations are those that form the basis of the grid operations model described in Task 3.

We also acquired flooding data from North Carolina Department of Emergency Management, consisting of maps showing maximum areal extent of flooding for two recent hurricanes (Matthew and Florence), as well as “probabilistic” flood extent data (both areal extent and depth) for several return periods (1-in-10-, 25-, 50-, 100-, and 500-years). We refer to these scenarios as T10, T25, T50, T100, and T500 in the remainder of this report. We then superimposed the areal extent of flooding for these historical storms and different flood severity levels on a map of NC grid assets. Where flood maps indicated any amount of flooding (water depth > 0) occurring at the location of an electric power generator or substation, this information was recorded as a conservative, upper bound estimate on flooding impacts. Figure 3 shows an example of this type of analysis for Hurricane Florence, performed for a smaller number of substations (blue dots) that form the basis of the grid operations model described in Task 3. The red colored areas represent the maximum flooding extent for this storm, and many substations (blue dots) lie within this colored area.

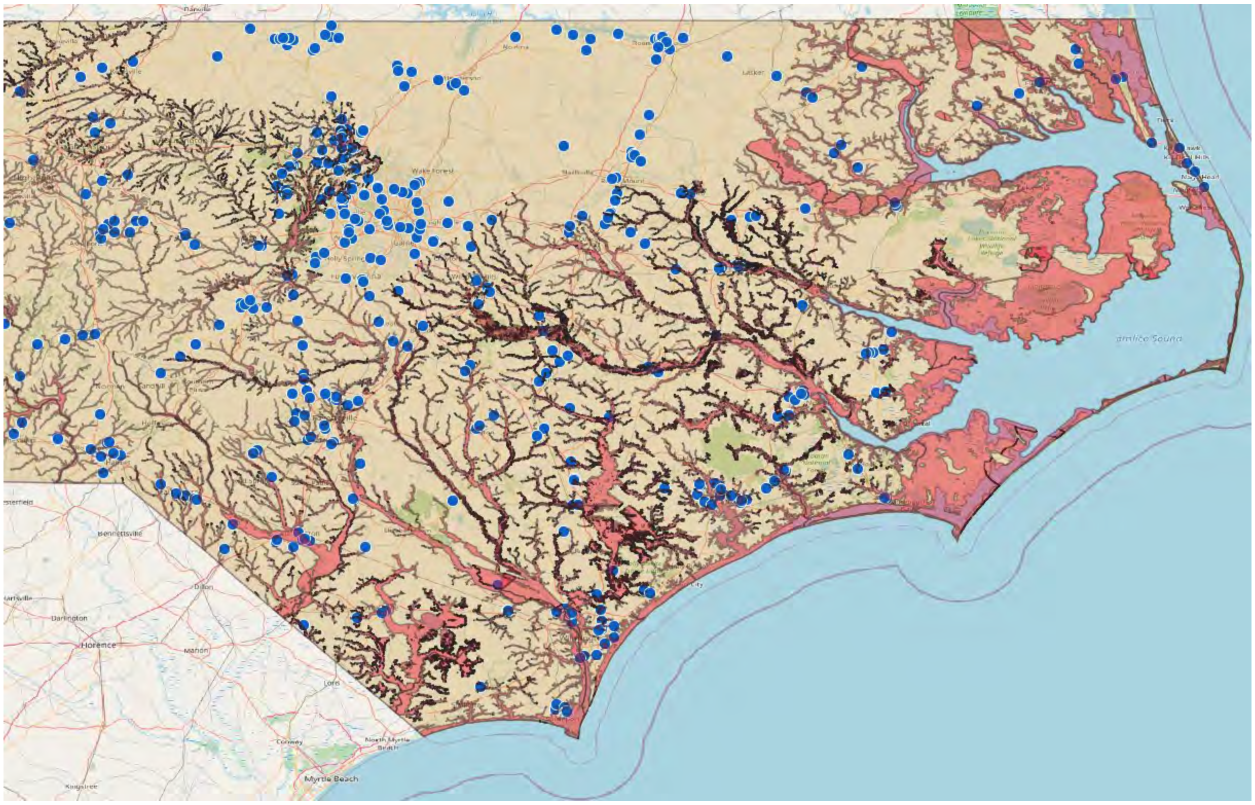

Figure 3. Maximum flooding extent from Hurricane Florence (red) shown alongside the locations of selected major electrical substations (blue dots) in Eastern North Carolina. Note: substations shown here are not a complete list of substations in North Carolina. These selected stations are those that form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

Figures 4-5 describe how much generation capacity in North Carolina is located where flooding occurs. Results are shown for each flood severity level (T10 through T500) as well as for two historical hurricane events (Florence and Matthew). Note again that these data do not necessarily mean that grid assets listed actually experience damage from flooding (that would depend on the locational depth of inundation and the height of sensitive equipment). Instead, this should be viewed as a very conservative estimate for the amount of generating capacity that could be potentially impacted by flooding. For example, Figures 4-5 indicate that a significant amount of hydropower is in the areal path of flooding; this is because many of the physical powerhouses connected to North Carolina's hydroelectric dams are located extremely close to rivers (the same is true for coal and some natural gas power plants that make use of surface water for cooling purposes). However, due to the proximity of these power plants to rivers, their sensitive electrical equipment is typically located at sufficient heights to avoid damage from flooding.

Note that in terms of the greatest number of individual power plants impacted (Figure 4), solar photovoltaic farms represent the most significant type of generation at risk of flooding.

However, the typical size of a solar farm in North Carolina is around 5 MW, so the share of total installed capacity at risk made up by solar farms is relatively small (Figure 5). Still, solar power, which has been increasing substantially in NC in recent years, especially in Eastern North Carolina, appears to be disproportionately at risk, considering that it only makes up 5% of the installed generation mix.

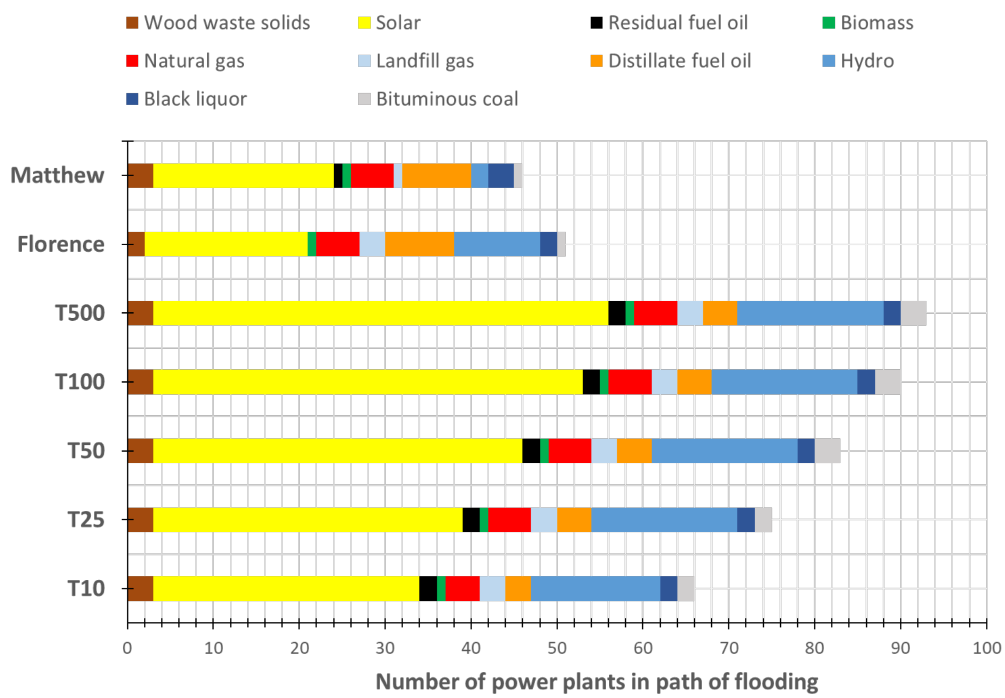

Figure 4. Number of power plants in areal path of flooding for historical storms Matthew and Florence, as well as for the probabilistic flooding scenarios developed by the Department of Emergency Management.

We find that the cumulative generation capacity within the areal path of flooding increases with more severe storms (ranging from T10 to T500) (Figure 5). Hurricane Florence shows particularly high levels of capacity in the path of flooding, due in large part to more than 2000 MW of coal-fired generating capacity (concentrated a few plants) being potentially affected.

Figure 6 shows similar information for substations in North Carolina, based on the complete list of substations in the U.S. DHS HIFLD database. In general, we find that the number of substations in the areal path of flooding increases as a function of storm intensity (going from T10 to T500) and that Hurricane Florence shows the greatest potential for impacts to substations among the historical storms.

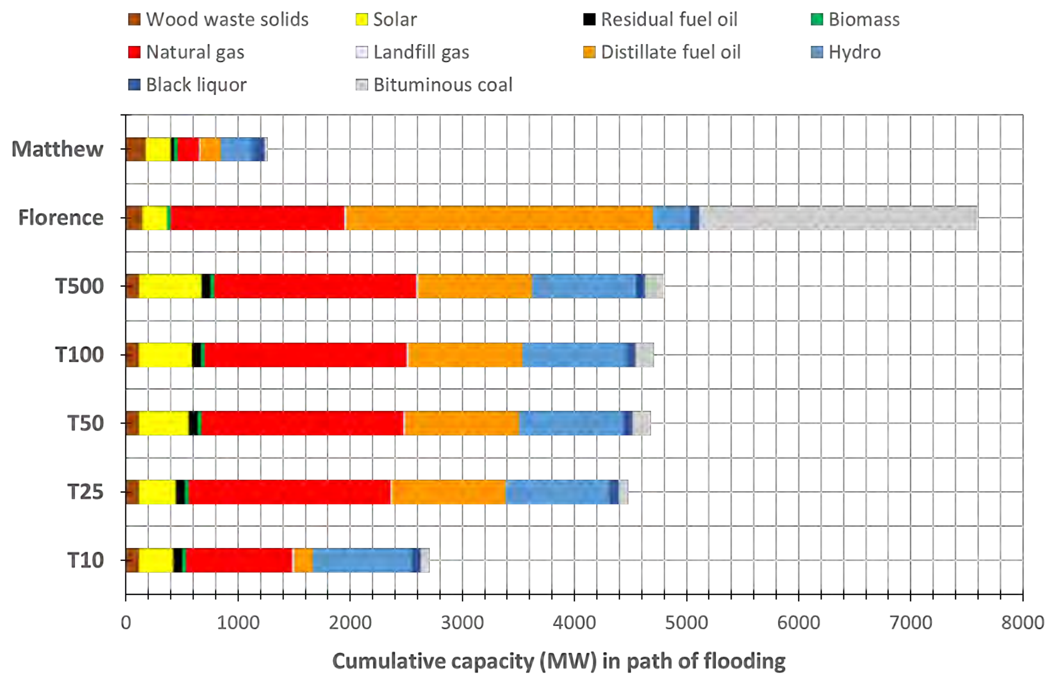

Figure 5. Cumulative installed capacity (in megawatts) in areal path of flooding for historical storms Matthew and Florence, as well as for the probabilistic flooding scenarios developed by the Department of Emergency Management.

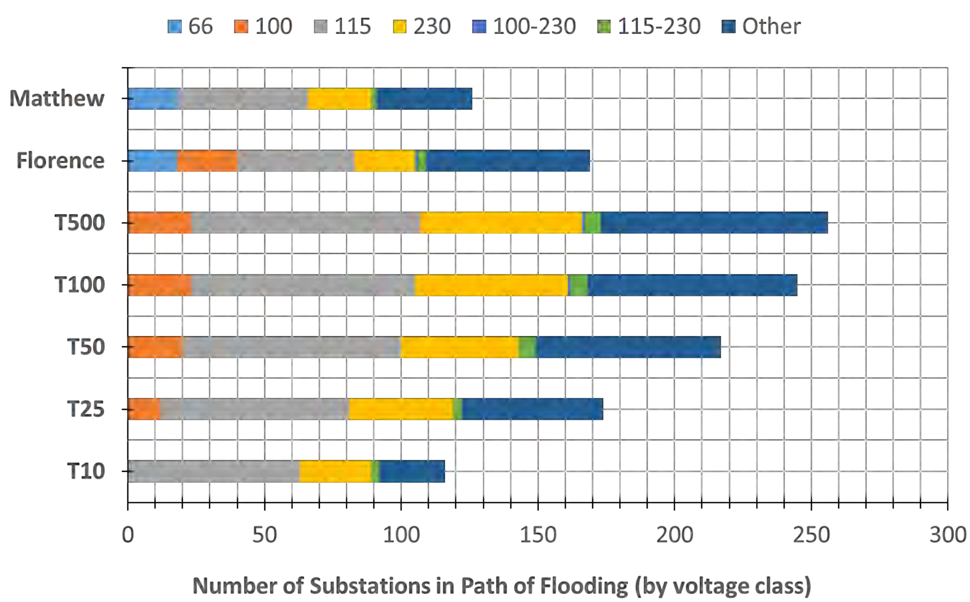

Figure 6. Number of electrical substations in North Carolina in the areal path of flooding for historical storms Matthew and Florence, as well as for the probabilistic flooding scenarios developed by the

Department of Emergency Management. Information shown is for the complete list of substations in the U.S. DHS HIFLD database

Task 2: Dynamic flood depth analysis during historical Hurricanes and grid impacts

In Task 2, we made use of "high water mark" (maximum flooding depth) information collected for recent storms as well as dynamic streamflow data collected from US Geological Survey (USGS) gages to recreate spatial and temporal projections of flooding depth across parts of Eastern North Carolina impacted by recent historical storms. The goal of this task was to expand on the conservative, preliminary assessment of potential flooding impacts on grid assets produced in Task 1, which relied only on information related to the maximum areal extent of flooding.

First, high water mark flooding data was collected for a discrete set of points across Eastern North Carolina from the USGS, for three recent hurricanes (Matthew, Florence and Dorian). This information conveys the maximum flooding depth experienced at a specific location during each storm, but it does not describe when this flooding occurred, nor does it characterize how persistent through time this flood was. In order to estimate the timing of flooding impacts, the research team matched each high water mark with a nearby USGS streamflow gauge within the same river basin. Then, each USGS gauge and high water mark pairing was 'bias corrected', i.e. the difference between the high water mark flooding depth and the maximum stream gauge height at the USGS station was calculated, and then this difference was subtracted from the stream gauge time series.

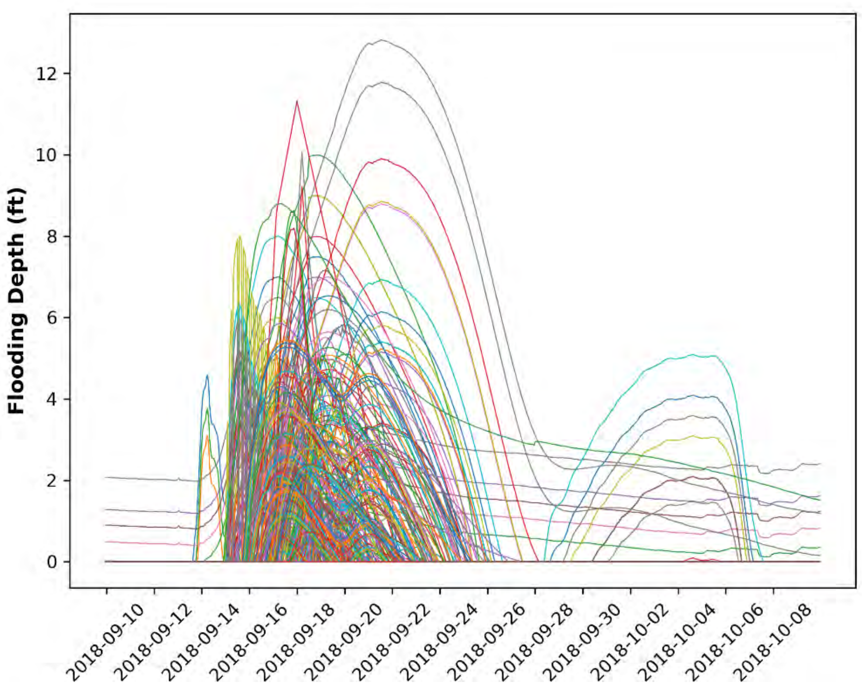

Figure 7. Estimated chronologies of flooding depth at high water marks locations in Eastern North Carolina during Hurricane Florence.

This correction was performed for every USGS gauge and high water mark pairing, yielding estimated chronologies of flooding depth at each high water mark. Figure 7 shows estimated chronologies of flooding depth at each high water mark station during Hurricane Florence. Each line in Figure 7 represents a different high water mark. Note that across all the high water mark sites, the timing and severity of maximum flooding depth varies considerably.

In addition to estimating the timing of flooding impacts, the research team also sought to use estimated time series of high water mark information to interpolate the depth of flooding at nearby areas where grid sensitive grid assets are located, and then develop chronologies of potential impacts. The estimated time series of flooding depth at each high water mark site were used as inputs into a spatial "kriging" analysis in Esri ArcGIS that interpolates gradients of flooding depth across the entire areal extent of flooding on an hourly time step, focusing first on Hurricane Florence.

For each hour from midnight on September 10, 2018, through 11pm on October 10, 2018, the estimated flooding depth at each high water mark location was identified. Within each river basin (Lumber, Cape Fear, Neuse, and Tar), a separate spatial kriging analysis was conducted, and then region-wide flooding depth maps were created. This allowed the research team to directly connect stream gauge heights at different USGS stations to spatial estimates of flooding and potential grid impacts. For example, Figure 8 shows a "bias corrected" hydrograph for one USGS stream gauge that was paired with a high water mark near the town of Kinston, NC on the Neuse River. Four time periods are highlighted, which generally track the chronology of flooding experienced near Kinston, NC during Hurricane Florence. The y-axis shows flooding depth (negative values indicate flooding of zero, with any value above zero indicating flooding).

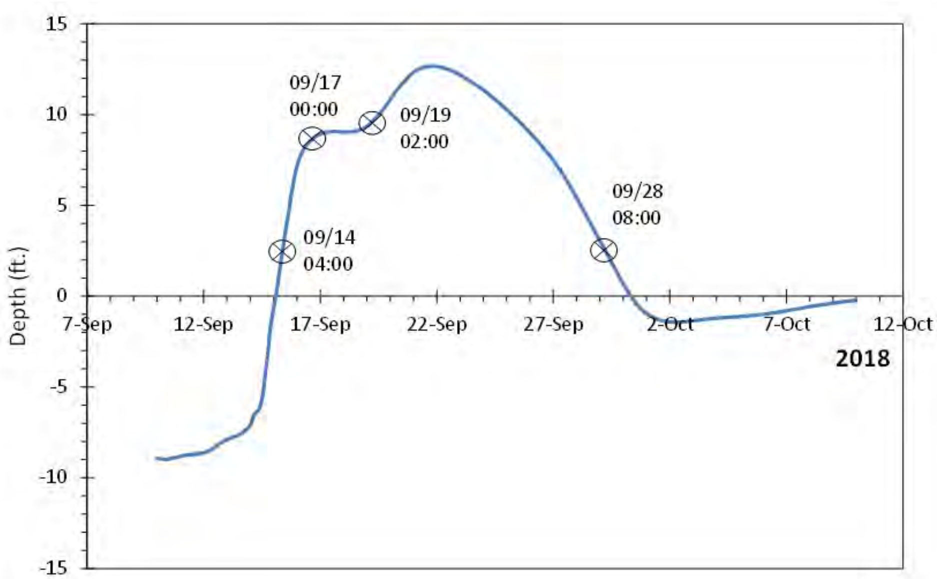

Figure 8. Estimated flooding depth at a high water mark site located close to Kinston, NC on the Neuse River.

For each of the times highlighted in Figure 8, Figures 9-12 shows spatially interpolated flooding estimates in each of the four basins considered. Each dot shown the location of a high water mark. Blue shading measures the estimated depth of flooding, both at the high water mark locations, and across the larger spatial extent. This interpolated flooding depth information is then “clipped” by the observed flooding extent for Hurricane Florence (Figure 3).

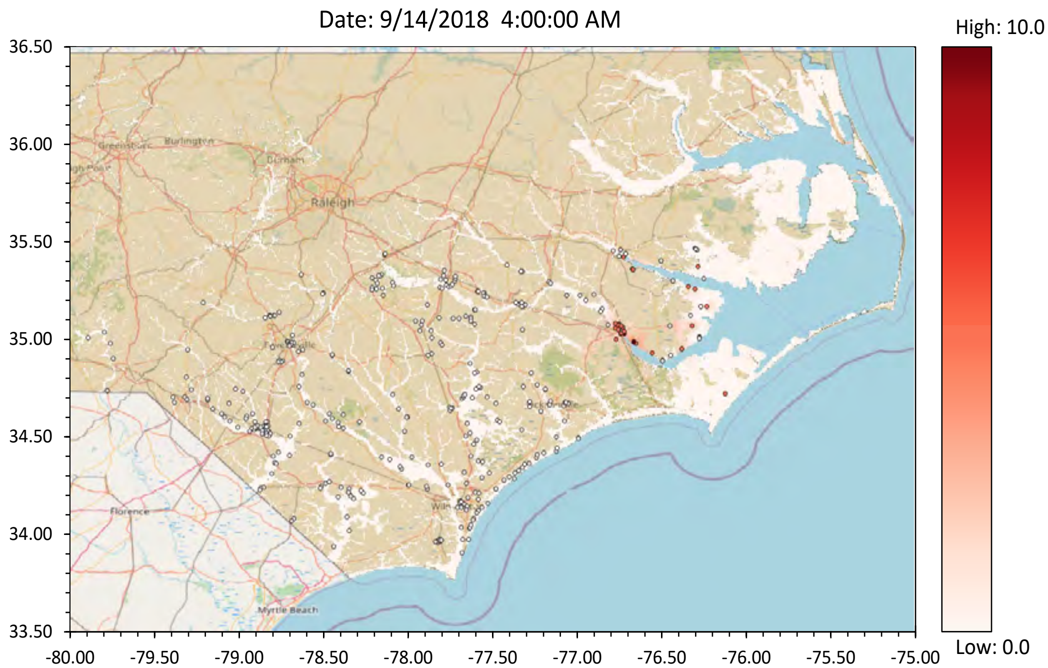

Figure 9. Results of spatial kriging of flooding depth during Hurricane Florence on 9/14. Dots represent the location of “high water mark” information that was used to bias correct local USGS streamflow data. All flooding depth shown (red) is in feet. This information is then “clipped” by the observed flooding extent for Hurricane Florence.

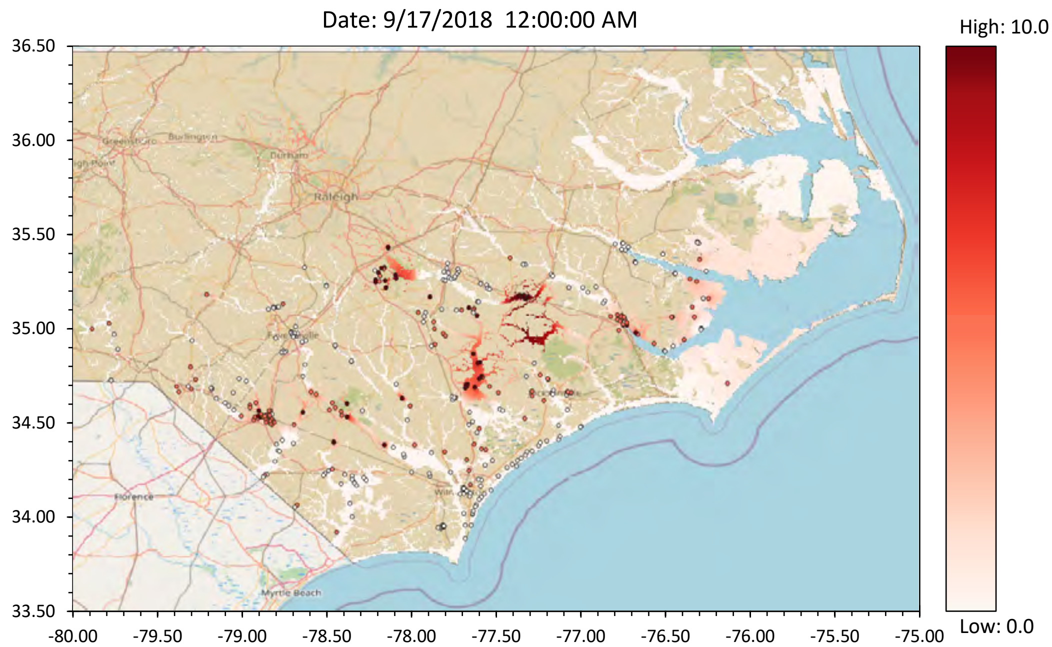

Figure 10. Similar results for Hurricane Florence on 9/17, 2018.

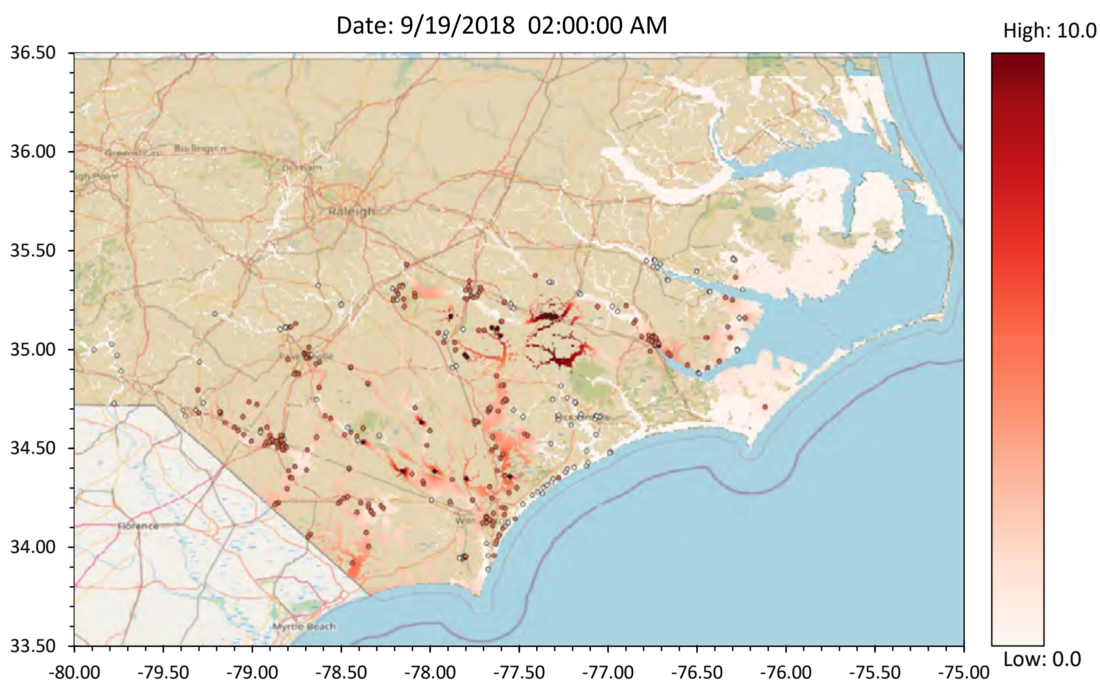

Figure 11. Similar results for Hurricane Florence on 9/19, 2018.

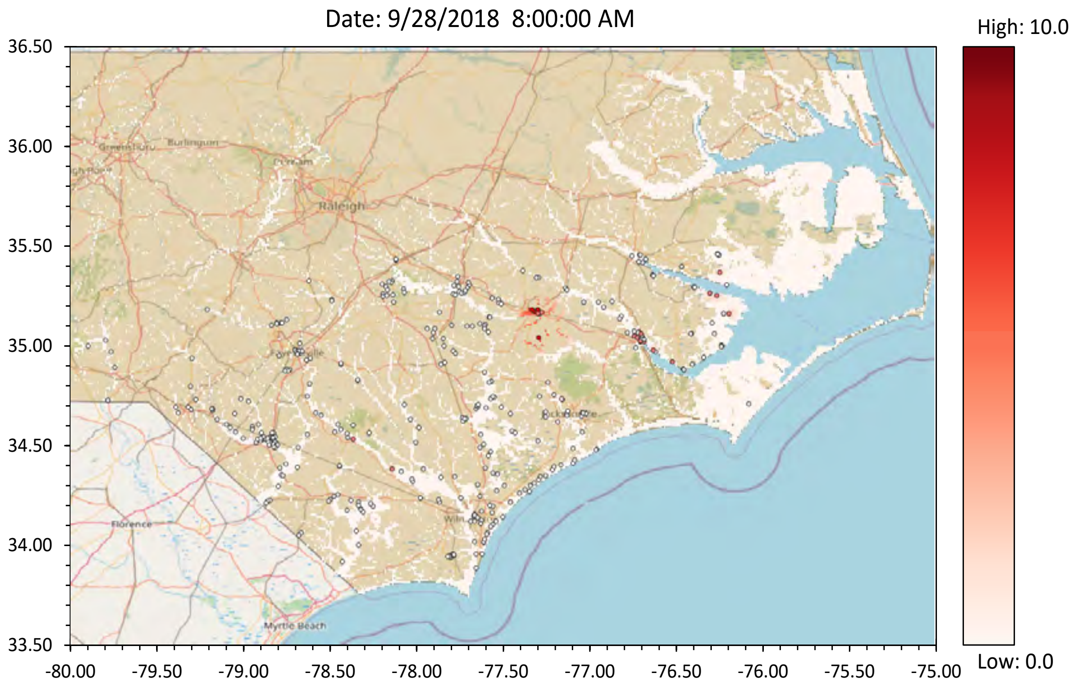

Figure 12. Similar results for Hurricane Florence on 9/28, 2018.

In Figure 13, we show spatially interpolated flooding depths across the four basins at the exact hour corresponding to maximum flooding depth at the high water mark near Kinston, which (based on streamflow conditions alone) we estimate occurred in the evening of September 21, 2018.

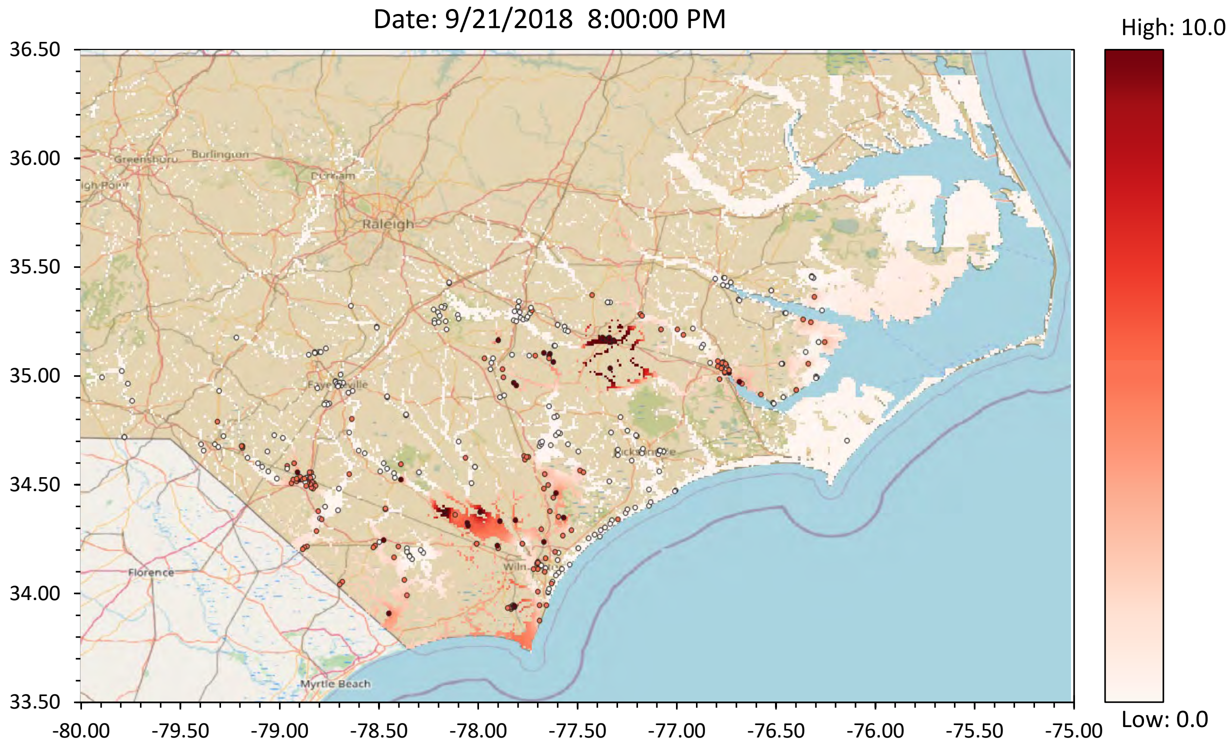

Figure 13. Estimated flooding depth across Eastern North Carolina at the time of the highest flood stage in Kinston near the Neuse River on September 21, 2018.

Hourly maps of estimated flooding depth across the historically observed areal flood extent for Hurricane Florence 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 Hurricane Florence. 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 quantified assuming sensitive equipment is located at several different heights (0ft, 2ft, 3ft, and 5ft); these essentially represent a basic test of a widely suggested intervention aimed at reducing the impacts of flooding, i.e. raising the elevation of sensitive electrical equipment at substations and solar farms.

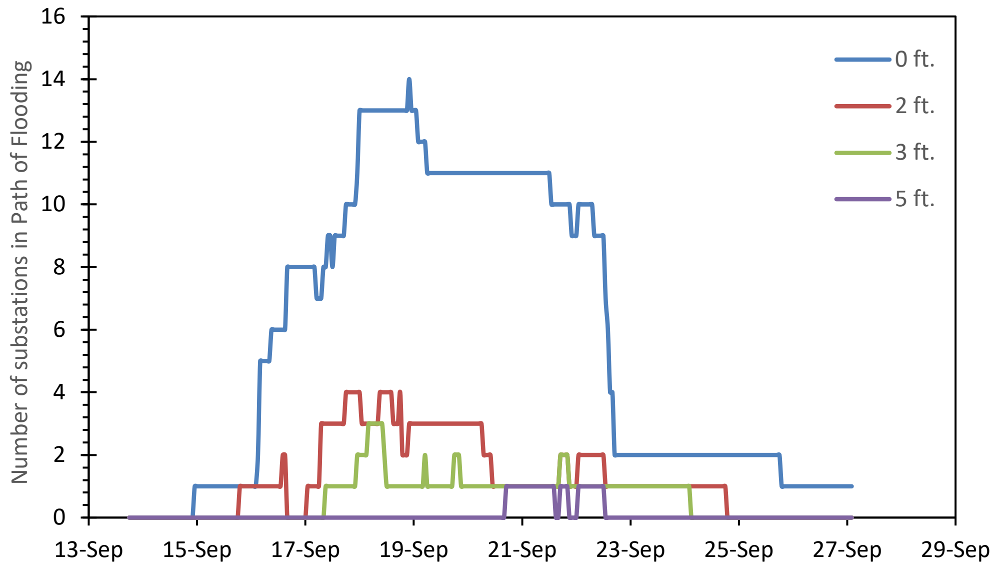

Figure 14. Estimated number of substation in the path of flooding for the Florence Event.

Figure 14 shows the estimated chronology of impacts during Hurricane Florence to the reduced set of substations shown in Figure 2, assuming several different heights of sensitive equipment. In general, the timing of impacts correspond to estimated chronologies of flooding depths shown in Figure 7. Note as well that raising the height of sensitive equipment appears to dramatically reduce the number of assets impacted, as well as the duration over which at least some bulk electric power system equipment is impacted. This suggests that raising the height of equipment may be an effective approach for dealing with the risks of flooding the potential for wider impacts on the grid.

However, two major unknowns persist that make flood risk quantification for the North Carolina grid difficult. First, little (publically available) information is available about the exact height of sensitive equipment at substations and solar farms spread across Eastern North Carolina. Without this information, it is difficult to know the exact timing and extent of impacts that occurred during the historical storms, or make projections for the future.

Second, without directly simulating the impacts of damage at solar farms and substations within an electric power system simulation model, it may remain unclear what the potential is for more localized impacts from flooding to have wider system impacts (including in non-flooded areas) as a result of altered network functionality. In an attempt to help address this second question, the research team made significant advances in developing a detailed, open source simulation model of the North Carolina grid, which will be used in the future to answer related questions.

Task 3 – Open source simulation model of NC power grid

At the beginning of this project the research team identified that there was not a detailed grid operations model capable of answering questions related to flooding resilience in North Carolina. So a third task for the research team was to develop such a model and make it publically available as a resource for policymakers and researchers in the state. Although the research team has not (yet) explored the impacts of flooding on the NC grid using this new software, we have finished its construction, tested its functionality, and made a stable version publically available (https://github.com/romulus97/NCGridMod).

The model is called the Mountains to Sea model (M2S), named after the long-distance trail for hiking that traverses North Carolina from the Great Smoky Mountains to the Outer Banks. It was developed entirely at North Carolina State University, with the assistance of researchers at Pacific Northwest National Laboratory.

Power grids are networks consisting of power plants, electricity substations, power lines, and distribution transformers, which collectively maintain reliability by providing many paths for electricity to flow from generators to multiple load centers. The power system in North Carolina consists of hundreds of power plants, thousands of miles of high-voltage power lines, and thousands of low-voltage power lines and distribution transformers, which connect the state's electricity customers. The operation of the grid is managed by a combination of entities, most notably Duke Energy, the North Carolina Electric Membership Corporation, and Dominion Energy. It is the responsibility of these entities to ensure that demand and supply are balanced at all times.

Grid simulation models that represent the detailed operational decision making required to balance demand and supply through the control of generation at individual power plants and power flows on transmission lines are referred to as Unit Commitment and Economic dispatch (UC/ED) models. UC/ED models mimic real world grid operations by "committing" generating units to operate and then "dispatching" the generating units to operate to meet demand. These models simulate the production and delivery of electricity to load centers via transmission lines, while adhering to a range of physical constraints and reliability specifications (e.g., maintaining operating reserves) required by the energy regulatory agencies. Additional objectives may include minimizing production costs, maximizing revenues for utilities, and/or integrating specific technologies, such as renewables. UC/ED models often take into account the grid's network structure, where generation assets and points of demand are spatially distributed but connected on a nodal basis. Individual generator operations are represented with technology-specific capabilities, costs and constraints, and electricity demand is represented as dynamic time series. In addition to their ability to simulate real-time operations (with varying levels of resolution and fidelity), UC/ED models are often used in conjunction with long-term capacity expansion planning processes to further evaluate the economics, sustainability, and resilience of future electricity infrastructure.

The M2S model is a customizable UC/ED model that represents the North Carolina grid as a network of 600+ nodes and 400+ high voltage transmission lines (Figure 12). The operations of over 300 individual generators are represented. M2S simulates the behavior of the North

Carolina grid on an hourly basis by minimizing the cost of meeting constantly fluctuating electricity demand, which is allocated across the 600+ nodes in the system according to population. Outputs of the model include reliability metrics (e.g. losses of load), power flows along transmission lines, unit specific generator behavior, overall system cost and emissions, and locational marginal prices. Our intent is to leverage this new model to complete our intended scope of work regarding flooding resiliency, and then develop the model further to help answer critical economic and policy questions in service of the state.

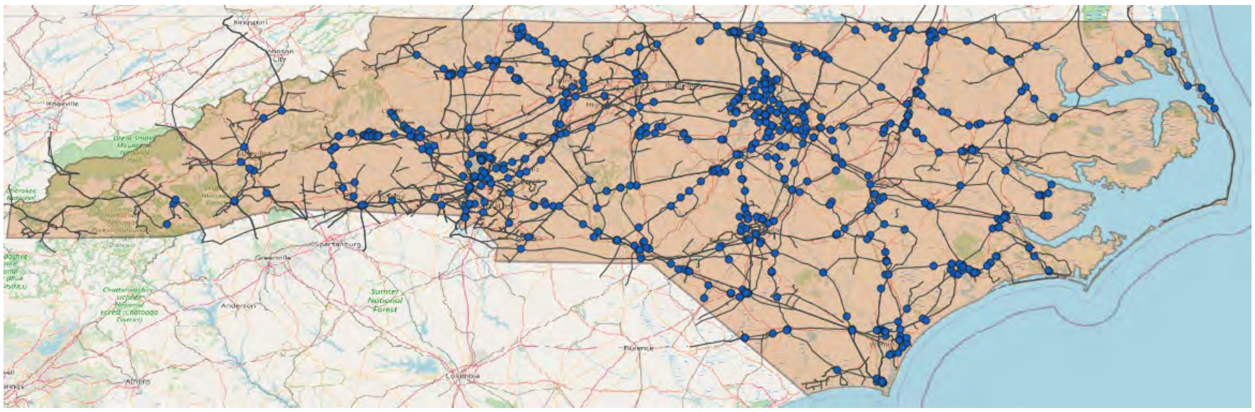

Figure 15. Nodal topology of the Mountains-to-Sea (M2S) grid operations model, which was developed at NC State University and is publically available at https://github.com/romulus97/NCGridMod.

Recommendations/Management Implications

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.

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 publically 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 NC 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 NC 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, when parts of the Eastern NC 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 NC 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.

Implementation Actions

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

   a) identify the communities and sections of the grid in Eastern NC most at risk of prolonged electric outages due to flooding
   b) prioritize the need for protective intervention based on likelihood of occurrence and potential for negative consequences
   c) gain knowledge about grid operators' contingency plans before, during and severe, localized flooding events

   (Priority: high, Time frame: short term (1-2 years to make significant impact)

2. 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: short term (1-2 years to make significant impact)

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