Final Report to the North Carolina Policy Collaboratory
NC Flood Resilience Study

The University of North Carolina at Chapel Hill

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Executive Summary

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.

**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:

A. Utilize the ADCIRC coastal hazards model to assess storm surge flooding throughout coastal North Carolina caused by Hurricane Florence; and
B. 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.

A. 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. 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 (Stewart & Berg, 2019). 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 (Kossin, 2018). 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.

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

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

Hurricane Florence formed just off the coast of Africa as a tropical depression and became the sixth named Atlantic storm of the 2018 hurricane season on September 1. Florence made its way across the Atlantic over the next two weeks, going through multiple strengthening and weakening phases along the way Figure 1. It reached a peak intensity with a minimum central pressure of 937 mb and estimated sustained winds of 130 knots on September 11 while 725 nautical miles east-southeast of Cape Fear, North Carolina (Stewart & Berg, 2019). As Florence approached the southeast coast of North Carolina, the forward speed slowed down, making landfall at Wrightsville Beach on September 14th as a category 1 hurricane. Florence gradually weakened after landfall as it moved slowly southwest into South Carolina, bringing constant rainbands onto the Coastal Plain of North Carolina. By the 16th Florence had moved further west and downgraded to a tropical depression and then accelerated north, becoming extratropical over West Virginia on September 17th (Stewart & Berg, 2019).

Figure 1. Track and intensity of Hurricane Florence, 2018
A.1. Evaluate the performance of the ADCIRC model for capturing coastal storm tide (surge plus tide) and flooding during Hurricane Florence 2018

Over the past two decades ADCIRC (co-developed and maintained by co-PI R. Luetich, http://adcirc.org) has become one of the most widely used community modeling platforms for storm surge / coastal flooding predictions across academia, governmental agencies and the private sector. This is due to its inclusion of critical physics (e.g., high resolution bathymetry and topography; features such as levees and floodwalls; spatially varying land cover and its influence on both surface wind conditions and bottom stress; coupled waves, surge, tides and runoff; multiple meteorological model forcings); accurate numerics; optimization for high performance computing; and the existence of an active research community that continues to advance the model’s capabilities (http://adcirc.org). ADCIRC is widely used for storm surge / inundation research, including: retrospective hurricane storm surge studies; storm surge hazard investigations under past, present and future climate scenarios; and morphology change associated with surge/wave events. It is also widely used for hazard assessment, design and other applied coastal water level / storm surge assessments, including: FEMA National Flood Insurance Program (NFIP) coastal hazard maps; damage estimates under the 2012 COASTAL Act; USACE regional coastal hazard studies; USACE IPET forensic study of levee/floodwall failure following Hurricane Katrina; USACE re-design of the levee/floodwall system around New Orleans and design of levee/floodwall system alternatives in greater Houston / Galveston, TX; NOAA’s VDATUM program; and Louisiana’s Comprehensive Master Plan for a Sustainable Coast (2012, 2017, 2023).

ADCIRC has been previously configured for eastern North Carolina by R. Luetich and B. Blanton at UNC for North Carolina’s most recent FEMA National Flood Insurance Program study. This configuration is used as a starting point for the current study.

High quality reanalysis of the wind and pressure fields for Hurricane Florence were obtained from the Ocean Weather company to represent the storm in ADCIRC. In addition ADCIRC has its own internal tropical cyclone model (Generalized Asymmetric Holland Model - GAHM) that creates spatial wind and pressure fields using data that is available in Best Track files released by the National Hurricane Center. These are first assessed using a large suite of meteorological observations that were collected throughout the region during the storm to establish the accuracy of these representations of the storm itself. This is followed by an assessment of the storm tide response from ADCIRC versus waterlevel observations collected during the storm.

Data for this study was collected from several sources. A primary source for water level data collection was from the USGS Flood Event Viewer, which provides water level gauge data recorded at permanent stream gages, rapidly deployed gages, and storm tide sensors. In addition to these sites, water level data was collected from the NOAA tidal stations in the affected areas and from the State of NC FIMAN network of stations. Wind data was acquired from a variety of sources that have been aggregated and made available by WeatherFlow Datascope (https://ds.weatherflow.com). Sources include stations owned by WeatherFlow, the National Weather Service, Weather Underground Personal Weather Station Network, and the NOAA National Ocean Service (NOS) and National Data Buoy Center (NDBC). In addition, wind data was supplied by the Florida Coastal Monitoring Program at two rapidly deployed stations. In total, data was collected for 137 water level sites and 79 wind stations.
Observed wind velocity data varied in sampling height and frequency at different wind station locations. For comparison with the reanalysis / model winds which were specified at a 10-meter height above ground and a 10-minute time interval, observations were adjusted to a 10-meter height based on the logarithmic wind profile. Reanalysis / model winds collected at time intervals shorter than 10 minutes were interpolated to ADCIRC’s 10-minute output times. In cases when the observations were collected at time intervals longer than 10 min, the ADCIRC model winds were interpolated to the timing of the observations. To analyze and compare wind velocity between the model and observations, the top 20 percent of the observed wind speed values over a 60-hour window of time from September 13th 00:00 UTC to September 15th 12:00 UTC were selected. This window was large enough to capture the storm's primary effect along the entire North Carolina coast. Thus comparisons and error statistics were computed for wind speed and direction during the strongest 12 hours of observed winds, using model values at the corresponding times. It was determined through a quality check that 65 locations were appropriate to use with the statistical analysis. Statistics were computed in two geographic regions falling north and south of latitude 34.8 deg (Figure 2).

![Wind Stations Divided into 2 Regions](image)

**Figure 2.** Wind Stations are divided into North and South regions for model statistical evaluation

Observed water level data were available at a higher frequency at all stations and were therefore interpolated to ADCIRC’s 10-minute output times. Results are presented using peak water levels which typically represent the worst conditions during the storm. Maximum observed water levels were identified and compared with the maximum model value, whether or not this occurred at exactly the same time. Consequently, this ignored timing errors in the peak value and focused on the peak water levels themselves; generally, the timing error was small. A quality check of the observed data limited the analysis to 78 water level stations that had an identifiable surge peak. Statistics were computed in three geographical regions: north of latitude 34.8, Onslow Bay and Cape Fear/South, Figure 3.
Figure 3. Water Level Stations are divided into North, Onslow Bay, and Cape Fear/South regions for model statistical evaluation.

Error statistics used to evaluate model performance are root mean square error (RMSE), mean error (ME), and normalized mean error (NME):

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (M_i - O_i)^2}{n}}
\]

\[
ME = \frac{1}{n} \sum_{i=1}^{n} (M_i - O_i)
\]

\[
NME = \frac{\sum_{i=1}^{n} (M_i - O_i)}{\sum_{i=1}^{n} (O_i)}
\]

where \(M\) represents the model data and \(O\) the observed data.

A.2. Identify geographical areas in eastern NC that experienced the combined effects of coastal surge and rainfall-runoff leading to compound flooding during Hurricane Florence

Having established the accuracy of ADCIRC for capturing Florence water levels in section A.1, model results are compared with observed water level time series data to infer areas that most likely experienced compound flooding.

B. Hindcast of Hurricane Florence in LISFLOOD

In this project, we used the New River watershed as a pilot case to test the ability of existing models to represent the combined impacts of marine and precipitation-based processes on coastal flooding in the watershed. The New River Watershed (U.S. Geological Survey (USGS) Hydrologic Unit Code (HUC) 10-digit 0302030201) is located in Onslow County and encompasses the majority of the Cities of Richland and Half Moon, as well as parts of the City of Jacksonville, NC (Figure 4). Developed areas are less than 8.5% of the land cover in the 417 square kilometer watershed. The dominant land covers are cultivated crops, woody wetlands, and forests (Table 1). Land surface elevations across the watershed range from 2-5 m above the
North American Vertical Datum 1988 (NAVD88) at the downstream boundary to ~50 m above NAVD88 in the northwestern portion of the watershed.

Figure 4. The New River Watershed is located in the Coastal Plains of eastern North Carolina and drains into the estuary below the City of Jacksonville before entering the Atlantic.

The New River serves as the primary drainage channel for the watershed; it flows 46 km southeast from Richlands, NC to Jacksonville, NC where it enters the larger New River estuary near Highway 17. The New River is characterized by low-gradient coastal streams with woody-wetland floodplains. Dredging occurs from the New River Inlet located at the Atlantic coast up to Jacksonville for boaters and commercial fishermen (https://www.jdnews.com/article/20160312/NEWS/160319672). Several tributaries drain the watershed including Mill Swamp, Mill Creek, Half Moon Creek, Cowhorn Swamp, Blue Creek, Sandy Run Branch, Bachelor’s Delight Swamp, and Jenkin’s Swamp. The main channel and several of its tributaries are tidally influenced. As a result, storm tide has the potential to propagate far inland; for example, near Gum Branch, tidal influences are still noticeable at the USGS gage located nearly 20 km upstream of Old Jacksonville Bridge (see Figure 5).
Storm surge from Hurricane Florence resulted in approximately 1.5 meters water level at Jacksonville and there was over 524 mm (20.6 in) of rainfall that fell over the watershed. As the storm surge began to recede on 9/15, streamflow began to increase due to significant rainfall-runoff across the landscape causing a rise of water levels at Jacksonville (Figure 6).
B.1. Building an Inland Hydrodynamic Model Using LISFLOOD-FP

To represent overland surface processes within the New River Watershed, we employ a raster-based flood inundation model called LISFLOOD-FP (Bates et. al, 2010). This model is advantageous because it is computationally efficient and accurate for generating large-scale flood maps. We selected a two-dimensional model because of its ability to capture multidirectional flow.

LISFLOOD-FP explicitly solves a two-dimensional, simplified version of the shallow water equations using a finite difference method. Convective acceleration is not included in the equations because it makes a negligible difference for floodplain flow. The information needed to solve these equations is retrieved from gridded inputs (i.e., ASCII files) of elevations and overland roughness (e.g., Manning’s $n$). The model uses rectangular channels to simulate one-dimensional channel flow in the subgrid (Neal et. al, 2012). Water is exchanged between the channel and floodplain (e.g., grid and subgrid) but momentum is not conserved across the boundary. Spatially uniform rainfall, infiltration, and evaporation can be applied to the grid. The model can be forced using time series water level data at locations identified within the model domain or at domain boundaries.

To create a continuous elevation raster for the model, a 5-meter LiDAR-derived, Digital Elevation Model (DEM) was obtained from the NC Spatial Data Download (SDD) Repository (https://sdd.nc.gov/) and a 90-meter U.S. Coastal Relief Model (CRM) from NOAA (https://www.ngdc.noaa.gov/mgg/coastal/crm.html). Bathymetry data for the lower New River near Jacksonville were digitized from NOAA nautical charts (https://charts.noaa.gov/PDFs/11542.pdf) and incorporated into the topobathymetric dataset used in the models. The final elevation dataset was masked using the USGS watershed HUC10 boundary with the downstream edge located at the start of the estuary below Old Jacksonville Bridge. To reduce model run times, the final DEM used in the LISFLOOD-FP model was resampled to a 30-meter resolution. The resulting baseline hydrodynamic model is made up of 462,899 grid cells (Figure 7).
To represent channels less than the native resolution of the model, we extracted surveyed channel data from existing Hydraulic Engineering Center-Hydraulic River Analysis (HEC-RAS) models that were developed for mapping the FEMA Special Flood Hazard Areas (SFHA). These models and associated data are archived by the NC Department of Emergency Management and are publicly available via the NC Flood Risk Information System (FRIS) (https://fris.nc.gov/). The survey data is incorporated in the models as river cross-sections. We used the cross-sectional data to determine the bed elevation, bank elevation and channel width for the New River and select tributaries. Using the ground truthed stream centerline from the HEC-RAS models, we generated a 30-m raster and assigned channel information to each cell based on the nearest HEC-RAS cross-section. We tested the impact of using a locally weighted smoothing (LOESS) function to interpolate the channel shape between the HEC-RAS cross-sections and found that the model results were not sensitive to this extra pre-processing step. Where channel widths were equal to or greater than 30-meters (the native model resolution), the bed elevation was burned into the DEM; where channel widths were less than 30-meters, the data was stored as a 30-m grid representing channel bathymetry (Figure 7). A large amount of time was spent collecting, georeferencing, and cleaning this data before it could be incorporated into the models. This is discussed in more detail in the findings and is important for our recommendations.

We used 30-meter resolution land use and land cover (LULC) data from the 2016 Multi-Resolution Land Characteristics (MLRC) Consortium’s National Land Cover Database (NLCD) for the Continental United States (CONUS) to parameterize the surface roughness. There are 15 LULC classes in the New River Watershed that are assigned a Manning’s roughness coefficient used by the model to simulate overland flow. We conducted a sensitivity test to understand how changing the Manning’s roughness coefficient within the expected range would impact the model results for Hurricane Florence. Based on this test, we selected the standard values of roughness parameters for the land classifications in the New River Watershed as shown in Table
1. (https://grasswiki.osgeo.org/wiki/NLCD_Land_Cover). The channels (e.g., subgrid) were assigned a Manning’s roughness coefficient of 0.1 which could be specified in the model setup file.

**Table 1.** The description and area of the NLCD Land Cover types in the New River Watershed and the Manning’s roughness coefficient (Manning’s n) used in the model.

<table>
<thead>
<tr>
<th>Description</th>
<th>Manning’s n</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Water</td>
<td>0.025</td>
<td>5.7</td>
</tr>
<tr>
<td>Developed, Open Space</td>
<td>0.04</td>
<td>33.4</td>
</tr>
<tr>
<td>Developed, Low Intensity</td>
<td>0.1</td>
<td>22.8</td>
</tr>
<tr>
<td>Developed, Medium Intensity</td>
<td>0.08</td>
<td>9.7</td>
</tr>
<tr>
<td>Developed, High Intensity</td>
<td>0.15</td>
<td>2.7</td>
</tr>
<tr>
<td>Barren Land (Rock/Sand/Clay)</td>
<td>0.0275</td>
<td>0.7</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>0.16</td>
<td>1.7</td>
</tr>
<tr>
<td>Evergreen Forest</td>
<td>0.18</td>
<td>83.3</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>0.17</td>
<td>19.8</td>
</tr>
<tr>
<td>Shrub/scrub</td>
<td>0.1</td>
<td>16.2</td>
</tr>
<tr>
<td>Grassland/Herbaceous</td>
<td>0.035</td>
<td>9.6</td>
</tr>
<tr>
<td>Pasture/Hay</td>
<td>0.0325</td>
<td>1.7</td>
</tr>
<tr>
<td>Cultivated Crops</td>
<td>0.0375</td>
<td>90.1</td>
</tr>
<tr>
<td>Woody Wetlands</td>
<td>0.12</td>
<td>114.4</td>
</tr>
<tr>
<td>Emergent Herbaceous Wetlands</td>
<td>0.07</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Because there is limited rain gage data in the watershed for Hurricane Florence, we use Multi-Radar Multi-Sensor (MRMS) quantitative precipitation estimate (QPE) which is available at a 1km spatial resolution and a 15-minute temporal resolution from the Iowa State MRMS repository. MRMS is rain gage corrected. We used the gridded MRMS radar-rainfall to compute basin-averaged rainfall at each timestep (see Figure 6). The final LISFLOOD-FP model had the basin-averaged MRMS time series applied uniformly across the domain. The state provided hourly rainfall data for two rain gages (Figure 8). The NHOF gage is located at the Pumpkin Center and is part of the Fixed Remote Automated Weather Station (RAWS) network (https://raws.nifc.gov/). The NBAC gage is located in Holly Ridge and is part of NOAA’s Automated Weather Observing System (AWOS) (https://www.ncei.noaa.gov/access/search/data-search/global-hourly). Rain gage measurements recorded during a tropical cyclone are highly uncertain given the wind. The total volume of rainfall from the basin-averaged MRMS was 523 mm (20.6 in) between 9/14 and 9/18. The total rainfall measured at the NBAC gage was 489 mm (19.3 in) and the temporal patterns are most similar to the basin-averaged MRMS. The gage at NHOF measured a total of 753 mm (29.6 in) and the majority of this rainfall occurred before
storm surge on 9/15. We assumed the basin-averaged MRMS was a suitable representation of the total rainfall and temporal pattern of rainfall across the watershed.

Figure 8. (left) Rain gage locations NBAC and NHOF relative to the New River Watershed. (right) Hurricane Florence rainfall time series at the rain gages compared to the basin-averaged MRMS radar-rainfall.

A time series of ADCIRC-modeled storm tide was applied as a water level time series at the downstream end of the LISFLOOD-FP model domain (upstream end of the estuary) (Figure 9). We use a constant infiltration rate of 7.92 mm/hr across the model domain which is typical for sandy clay soils common to the Coastal Plains. The model run starts with 1 m (above NAVD88) of water in the channels and we use a spin-up period of 7 days to allow the model to reach a steady-state.
To validate the performance of the model, observed water level data was collected from two USGS gages managed by the South Atlantic WSC Raleigh Field Office. The New River Gum Branch gage (USGS 02142914) located near Thrift, NC has water level and discharge records starting in 1987. A rapid deployment gage was installed temporarily on the New River at Old Bridge Street at Jacksonville, NC (USGS 0209303201) for Hurricanes Matthew and Florence. Water level and water quality data was collected at a gage below HWY 17 Bridge in Jacksonville from 2007 to 2012 (USGS 0209303205) as part of the Defense Coastal/Estuarine Research Program (DCERP). Additionally, USGS high water marks (HWM) were collected at several locations throughout the watershed for Hurricane Florence and were used to validate the model (https://stn.wim.usgs.gov/FEV). The locations of the gages and HWMs are shown in Figure 9.
Findings

A.1 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 10).

![Figure 10. Maximum wind speeds modeled using two forcing methods, OWI (left) and GAHM (right)](image)

An example of the comparison during the period from Sept 12 - Sept 15 at four North Carolina coastal locations is shown in Figure 11. Summaries of the mean average difference between the OWI and GAHM wind fields and observations are presented in Figure 12; statistical differences are presented in Table 2.
Figure 11. Example comparisons between modeled and observed Hurricane Florence wind speed and direction time series at four North Carolina Coastal locations, New Bern, Beaufort, Wrightsville Beach and Federal Point.
Figure 12. Summary mean wind speed and directional errors during the 12 hours of highest winds during hurricane Florence. Warm (cold) colors indicate the OWI or GAHM wind speed was higher (lower) than observations or wind direction was counter clockwise (clockwise) of the observations.
Table 2. Mean wind speed and direction error statistics. The dividing line between the North and South Regions is 34.8 deg N latitude.

<table>
<thead>
<tr>
<th>Wind Speed</th>
<th>OWI</th>
<th>GAHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Region</td>
<td>ME (ms⁻¹)</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>NME</td>
<td>4.7%</td>
</tr>
<tr>
<td></td>
<td>RMSE (ms⁻¹)</td>
<td>2.4</td>
</tr>
<tr>
<td>South Region</td>
<td>ME (ms⁻¹)</td>
<td>-1.6</td>
</tr>
<tr>
<td></td>
<td>NME</td>
<td>-7.5%</td>
</tr>
<tr>
<td></td>
<td>RMSE (ms⁻¹)</td>
<td>3.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>OWI</th>
<th>GAHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Region</td>
<td>ME (degrees)</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>RMSE (degrees)</td>
<td>10.4</td>
</tr>
<tr>
<td>South Region</td>
<td>ME (degrees)</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>RMSE (degrees)</td>
<td>23.6</td>
</tr>
</tbody>
</table>

These analyses suggest that both OWI and GAHM provide reasonable representations of the hurricane. ME and RMSE are very similar in the North Region, which includes the Outer Banks and Pamlico Sound. GAHM wind speeds are slightly higher at a few Outer Banks locations and at the southern end of Pamlico Sound. These results are reflected in the statistics for the North region showing an NME for GAHM of 6.3 percent and 4.7 percent for OWI. OWI has a slightly lower RMSE in the North at 2.4 ms⁻¹ compared to 2.7 ms⁻¹ for GAHM. In the South region GAHM has a lower ME (approximately zero) and comparable RMSE to OWI. OWI wind speed is biased low in this region, which is closest to the storm eye.

OWI and GAHM have lower directional ME and RMSE errors in the North, where the wind direction is more slowly varying, than near the core of the storm in the South where the wind direction varies rapidly in space and time. RMSE are nearly identical in the North at about 10.5 degrees, but GAHM wind directions are biased slightly clockwise (ME of -3.7 degrees). In the South, RMSE are again nearly the same at about 23.5 degrees. OWI mean wind directions are
biased in the counterclockwise direction while GAHM directions are biased clockwise from the observed mean wind directions.

Figure 13. Maximum storm surge modeled using two forcing methods, OWI (left) and GAHM (right)

Figure 13. displays maximum storm surge that occurred throughout the duration of Hurricane Florence as modeled using the two forcing methods, OWI and GAHM without astronomical tides. The largest surge occurs in the Neuse and Trent River Estuaries that connect to the western portion of Pamlico Sound where geographic funneling and the extended fetch cause surge of greater than 3 meters, exceeding surge values along the western shore of Pamlico Sound by more than 1 meter. Despite being closer to the eye of the storm and subject to substantially stronger winds, surge in Onslow Bay is generally less than 2 meters.

Figure 14. Summary maximum water levels during hurricane Florence. Warm (cold) colors indicate the model water levels were higher (lower) than observations

Overall, ADCIRC simulations including astronomical tides reasonably capture the maximum observed water levels, although each meteorological forcing generates better performance in different coastal regions. OWI is more accurate in the Pamlico Sound region, further from the center of the storm. As noted above these areas were the recipients of the maximum storm surge which was well captured using the OWI forcing. GAHM’s generally stronger winds tended to
overpredict peak water levels, particularly in the Trent River Estuary. Both forcing methods reproduce peak water levels well in the Neuse River Estuary.

Water levels generated using GAHM meteorology have less ME and a slightly lower RMSE than those using OWI along Onslow Bay. In general OWI driven water levels are low in this region which is consistent with the low bias of OWI winds in Onslow Bay.

**Table 3.** Maximum water level error statistics. The dividing line between the North and Onslow Bay regions is 34.8 deg N latitude. The dividing line between Onslow Bay and Cape Fear/South regions is the east side of the Cape Fear River.

<table>
<thead>
<tr>
<th>Water Levels</th>
<th>OWI</th>
<th>GAHM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ME (m)</td>
<td></td>
</tr>
<tr>
<td>North Region</td>
<td>-0.08</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>NME</td>
<td>-4.5%</td>
</tr>
<tr>
<td></td>
<td>RMSE (m)</td>
<td>0.15</td>
</tr>
<tr>
<td>Onslow Bay Region</td>
<td>ME (m)</td>
<td>-0.25</td>
</tr>
<tr>
<td></td>
<td>NME</td>
<td>-12.3%</td>
</tr>
<tr>
<td></td>
<td>RMSE (m)</td>
<td>0.31</td>
</tr>
<tr>
<td>Cape Fear/South Region</td>
<td>ME (m)</td>
<td>-0.10</td>
</tr>
<tr>
<td></td>
<td>NME</td>
<td>-6.0%</td>
</tr>
<tr>
<td></td>
<td>RMSE (m)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**A.2 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 15, 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, Figures 16, 17.
Figure 15. Precipitation accumulation during Hurricane Florence, September 13-18

Figure 16. Examples of North region water levels with primarily a storm surge signal that more quickly recedes to normal levels.
Figure 17. Examples of Onslow Bay and Cape Fear/South region water levels showing a surge followed by heightened water levels due to river runoff.

At New Bern and other locations in the North region a strong surge signal occurred that quickly receded, with the hydrograph returning close to a normal level by September 15th. The ADCIRC simulations match the observations closely, although they fall slightly below the observed water levels as the surge receded, which is probably due to the increased flow in the Neuse and Trent Rivers, Figure 16.
At Jacksonville and at other Onslow Bay locations there is clear evidence of compound flooding, Figure 17. Water level observations at Jacksonville are particularly clear with a surge peak occurring after mid-day on September 14 that is well captured by the ADCIRC simulations, followed by a higher water level peak beginning near the end of the day on the 14th and extending for several more days due to hydrological flow. A surge and hydrologic signature can be seen at many of the estuarine locations connected to Onslow Bay and further to the south with the magnitudes and timings depending on the local geography and watershed sizes. Again, in most areas ADCIRC appears to accurately capture the surge signal reasonably well, although without including the hydrological component it cannot capture the compound effects.

One area where ADCIRC seems to significantly underpredict the storm surge occurs at the western end of Bogue Sound, near the mouth of the White Oak River. This area experienced extreme precipitation accumulation (Figure 15) that may have quickly lifted water levels and would not be reflected in ADCIRC results.

**B. LISFLOOD-FP Hurricane Florence Hindcast Results**

A key aim of this project was to investigate whether a compound flood modeling approach is accessible to the State of North Carolina using available data and tools. Here we summarize the performance of the coupled-modeling approach that was taken to simulated Hurricane Florence total water levels in the New River Watershed. Insights related to modeling challenges and data limitations are discussed as they are integral to advancing coastal flood hazard assessments.

**B.1. Model Results**

First, we highlight the importance of using a modeling approach that is able to account for the multiple mechanisms of flooding (e.g., surge and rainfall) that yielded high water levels during Hurricane Florence.

![Figure 18](image.png)

**Figure 18.** An example of how the LISFLOOD-FP model is unable to reproduce the hydrograph at Old Jacksonville Bridge for Hurricane Florence when only surge or rainfall (with a constant water level of 0m above NAVD88 at the coast) is applied.

We compared the LISFLOOD-FP model performance against water level time series records at two USGS gage locations (Gum Branch and Jacksonville Bridge) and 7 USGS high water marks
for Hurricane Florence. We focused on the model's ability to capture the magnitude and timing of the peak water level. We compare two model constructions: one with channels and one without channels integrated into the model domain. At the Gum Branch gage, located halfway up the river, the model shows skill in its ability to capture the rising and falling limb of the hydrograph both with and without channels included (Figure 19). Though tides are measured at the Gum Branch gage (Figure 5), the impact of storm surge on the water level is not evident for Hurricane Florence which will be discussed later.

![Image: LISFLOOD-FP modeled water level (meters above NAVD88) for Hurricane Florence compared to USGS records at the Gum Branch gage. The model results without channels (e.g., 30-m DEM) are shown in blue while the model results with channels (e.g., 30-m DEM w/ Channels) are shown in red.](image)

**Figure 19.** LISFLOOD-FP modeled water level (meters above NAVD88) for Hurricane Florence compared to USGS records at the Gum Branch gage. The model results without channels (e.g., 30-m DEM) are shown in blue while the model results with channels (e.g., 30-m DEM w/ Channels) are shown in red.

At the Old Jacksonville Bridge gage, the tide signal is dampened and lagging but the model is able to capture the timing and magnitude of the initial peak storm surge with and without channels (Figure 20). As the surge is receding, the hydrograph begins to climb as streamflow increases due to 20.6 inches of rainfall over the watershed. The influence of channels on the modeled water level is most evident when both rainfall and surge coincide at the lower portion of the watershed. While the model captures the falling limb of the hydrograph at the Old Jacksonville Bridge, it predicts the second peak earlier than what was measured and overestimates the magnitude of the peak by approximately 1m. This is likely due to the spatial heterogeneity of the rainfall across the watershed that cannot be represented by LISFLOOD-FP. Additionally, variations in the capacity of the watershed to hold water, whether in the soil or depressions, are not well captured by the low-resolution model.
Figure 20. LISFLOOD-FP modeled water level (meters above NAVD88) for Hurricane Florence compared to USGS records at the Old Jacksonville Bridge gage. The model results without channels (e.g., 30-m DEM) is shown in blue while the model results with channels (e.g., 30-m DEM w/ Channels) is shown in red.

To evaluate the model performance we computed the Root Mean Square Error (RMSE), the Peak Error (PE) and the Time of Peak Error (TPE) at each gage (Table 4). For the Old Jacksonville Bridge (OJB) gage, we calculated statistics for each peak. The model over-predicts the peak water level later than what was observed at Gum Branch. At OJB, the model predicts the magnitude of the storm surge later than what was observed (Peak 1) and overpredicts the water level from Peak 2 earlier than what was observed. The RMSE at Gum Branch and at OJB for Peak 2 were approximately 0.6 m. This is likely due to the sensitivity of the rising and falling limb of the hydrograph to pulses of rainfall at Gum Branch and compound flooding hydrodynamics at OJB. The RMSE at OJB for Peak 1 was lower at 0.4 m indicating a better fit to the observed data. Irregularities here are related to the drawdown prior to the storm surge and the falling limb of the storm surge prior to peak streamflow.

Table 4. Model statistics including Peak Error (PE), Time of Peak Error (TPE), and the Root Mean Square Error (RMSE) computed between the USGS observations at Gum Branch and Old Jacksonville Bridge (OJB) and the LISFLOOD-FP modeled water level.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>PE (m)</th>
<th>TPE (hr)</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gum Branch</td>
<td>0.13</td>
<td>-2.5</td>
<td>0.57</td>
</tr>
<tr>
<td>OJB Peak 1</td>
<td>0.00</td>
<td>-5.5</td>
<td>0.37</td>
</tr>
<tr>
<td>OJB Peak 2</td>
<td>0.94</td>
<td>4</td>
<td>0.55</td>
</tr>
</tbody>
</table>

We also compared the modeled water levels to the measured elevations at 7 HWM locations (Figure 21). The model underestimated the water levels by ~2m behind Gum Branch Road on Half Moon Creek. The roadway elevation was edited in the model terrain to restrict flow to the channel only (e.g., limited floodplain flow unless roadway overtopping) but this did not significantly improve the model performance. Additional investigation is required into the grid and subgrid data at this location. Some of the uncertainty in the total water level might also arise from error in the rainfall input which will be discussed later.
Figure 21. (top) LISFLOOD-FP modeled max water depth for Hurricane Florence and HWM locations. (bottom) HWM comparison to modeled water depth.
B.2. Discussion of Model Limitations

We used validated ADCIRC model output for Hurricane Florence as the downstream boundary condition in the LISFLOOD-FP model to simulate compound flooding. With limited USGS observational gage data for other recent storm events, we focused on validating the model for a single event: Hurricane Florence. While the model shows skill in reproducing the total water levels, there is some error in the results that is likely caused by inherent uncertainty in the input data and limitations of the computational model structure.

First, the spatiotemporal variability of hydrologic parameters such as precipitation and infiltration is known to influence the response of the watershed and therefore the timing and magnitude of flood wave. However, the open access version of LISFLOOD-FP that we used in this study does not allow for spatially or temporally varying infiltration limiting our ability to represent heterogeneities in the storage capacity of the landscape (e.g., varying soil types, impervious surfaces) that may influence the rainfall-runoff process. In addition, the open access version of LISFLOOD-FP does not allow for spatially-varied precipitation to be input as a model parameter. While the total volume of the basin-averaged radar-rainfall matches the total rainfalls measured at the closest rain gages, there may still be some error in the model results caused by the spatially uniform rainfall applied across the model domain. Compound flood models for the state of NC would benefit from a denser rain gage network with high-resolution (temporal and spatial) rainfall measurements that can be applied directly to models.

Second, the Manning’s roughness coefficients (Table 1) remain constant throughout the simulation and do not vary with increased water depth. Prior to the inundation of the floodplain, we would expect waves to be slowed by resistance caused by wetland vegetation. However, as the floodplain is inundated (e.g., land type starts as vegetation and becomes open water), we expect the propagation of water (e.g., streamflow or surge) to change with reduced resistance from vegetation. Neither LISFLOOD-FP nor ADCIRC are able to model vertically and horizontally varying roughness across a model element. This problem is common to most hydrologic and hydrodynamic models and remains a challenge for improving the representation of complex flows in low-gradient watersheds where water depths are shallow and the influence of vegetation may be significant. One solution is to use multiple Manning’s roughness grid inputs, however this would require stopping and restarting the simulation during the middle of the event to swap out the base grid information.

Third, LISFLOOD-FP ignores convective acceleration and does not simulate wind-wave interactions. Our results indicate that momentum is lost across the ADCIRC-LISFLOOD model connection which influences both the propagation of water upstream (e.g., tides and storm surge) and downstream (e.g., streamflow) in the models. A first indication is that the modeled tides are dampened and lagging which is likely caused by a loss of momentum at the coastal boundary. Within the model, storm surge propagation is influenced by the loss of momentum across the model boundary as well as the interaction between surge and streamflow in the channel and floodplain dampening the magnitude and timing of the peak (Table 4) compared to ADCIRC which had a slight positive bias at OJB for Hurricane Florence (see Figure 17).

Fourth, our results indicate that the inclusion of channels in the model significantly improved the model performance in the lower portion of the watershed. As such, we recommend that future efforts to model compound flooding in Eastern NC leverage existing surveyed cross-sectional
data that has been archived by the NC Department of Emergency Management within the States’ HEC-RAS models. However, it should be noted that extracting bathymetric survey data from model geometry files is resource intensive, in part because many of the existing HEC-RAS models are older and the channel reach and associated cross-section data is not georeferenced. To integrate the bathymetry data within our models, it was necessary to join the non-georeferenced model data to a georeferenced shapefile of model cross-sections (available on NC FRIS) prior to extracting the data necessary to build our models. Exact matches were not always the case, requiring us to alter the code for these exceptions. This process was labor and time intensive. Using the insights gained from this study, we are working to improve and expand upon our methodology of extracting channel data so that it can be applied for over 39,900 HEC-RAS models archived on NC FRIS - amounting to hundreds of thousands of surveyed cross-sections (Figure 22). The result would be a consistent, contiguous dataset of NC streams which is needed for accurate compound flood modeling across the state.

As a final note, the representation of the terrain in the grid and subgrid (e.g., floodplain-channel connectivity) can be improved using LiDAR and geospatial smoothing or interpolation techniques along the stream. Similarly, large-scale topographic features (e.g., roadways, berms, levees, dams) should be incorporated into future terrain models to improve the simulation of storage throughout the watershed.

Figure 22. There are over 39,000 mapped streams across North Carolina, each with a separate HEC-RAS model constructed using bathymetric survey data.
**Recommendations**

Compound flooding – driven by the interaction of heavy rainfall, riverine, and coastal flooding during tropical cyclone events – 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. Coastal flood hazard estimates should consider the interactions between storm surge and rainfall-runoff.

There are no fully coupled inland and coastal models that can capture both inland and coastal flood processes, and questions remain as to how to efficiently and accurately represent compound flood events using existing models. More research is needed to investigate the influence of the model boundary location and connection on the propagation of surge and streamflow. Additionally, we recommend using gauge data and basin and river network characteristics to determine the watershed response (e.g., time-lag between rainfall and peak streamflow) to understand the frequency at which the models should pass information to each other.

Continued effort should be pursued to utilize coastal flood models (ADCIRC) and hydrological models (LISFLOOD-FP) to model compound flood hazards throughout eastern North Carolina. Significant hurdles to be overcome to achieve this capability include incomplete geospatial datasets to fully configure these models as well as incomplete knowledge about how best to couple the models to accurately capture the compound flood zone.

There is no integrated database that contains information on channel properties and surrounding floodplain topography that can be used to configure coastal and hydrological flood hazard models, particularly for smaller tributaries and channel reaches in the North Carolina coastal plain. Future work should leverage existing state-wide datasets of surveyed channel data and high resolution LiDAR to create a single, integrated geospatial database that can be used to incorporate channels and their associated floodplains into flood hazard models. Gaps in the existing datasets, particularly where cross-sectional surveys may be outdated or lack resolution, should be identified, and filled.

Coastal hazards are evolving due to changing storm patterns, sea level rise, and coastal erosion. We recommend that the state identify coastal communities where compound flooding is likely to result in hazards that are different from those currently shown on FEMA floodplain maps. Utilize improved coastal hazard estimates to support cost-benefit analyses of both structural and non-structural flood mitigation alternatives at household and community scales over the short- and long-term.
Implementation Actions

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)*

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)*