ABSTRACT

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Emergency managers rely on fast and accurate storm surge predictions from numerical models to make decisions and estimate damages during storm events. One of the challenges for such models is providing a high level of resolution along the coast without significantly increasing the computational time. Models with large domains, such as the Advanced CIRCulation (ADCIRC) model used in this study, are accurate in predicting water levels and their variation in complex coastal regions, however their spatial resolution may limit their predictions of flooding at the scale of buildings, roadways, and critical infrastructure. A new tool has been developed that uses Geographic Information System (GIS) scripts to enhance the resolution of maximum water level predictions at the boundary of predicted flooding using a high-resolution Digital Elevation Model (DEM). The water levels predicted by the lower resolution model are extrapolated outward to where the water would intersect with the higher resolution elevation dataset. The result is a highly-refined flooding boundary that represents inundation on scales smaller than the typical ADCIRC mesh resolution. This tool can process a 15-m DEM for all 32 coastal counties of the state of North Carolina in less than 15 minutes during a storm event. Comparison of results using spatial building datasets showed that for a simulation of Hurricane Matthew, 2,353 buildings were predicted to be flooded in Carteret County, NC prior to enhancing resolution and 3,298 post-enhancement, an increase of 40 percent. In Dare County, the increase was 22 percent. This dramatic increase in flooded buildings shows the importance of achieving high accuracy in floodplains, as a relatively small change in predicted flooding extent can have a substantial impact on the predicted number of flooded buildings. The validity of these results was tested via comparisons to results of an ADCIRC model with the same 15-m resolution as the DEM in Dare County. Dare County is a coastal region with widely-varying topography and land cover, and preliminary comparisons have shown that the GIS method is accurate in coastal regions with steeper slopes and less accurate in flatter, low-lying areas.

Improving Accuracy of Real-Time Storm Surge Inundation Predictions

by Nelson Tull

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APPROVED BY:

Helena Mitasova

Alejandra C. Ortiz

Joel C. Dietrich Chair of Advisory Committee

DEDICATION

To my two grandmothers, Susan Tull and Edythe Holmgren For without their endless love and selflessness I would not be where I am today.

BIOGRAPHY

Nelson Tull was born in Providence, RI in 1994 to Jim Tull and Dana Holmgren. He grew up there, where he attended Classical High School. He attended the University of Massachusetts – Amherst, where he obtained a B.S. in Civil and Environmental Engineering in 2016. He then continued his education in civil engineering at North Carolina State University, where by chance, and with the help of his advisor Casey Dietrich, he was able to explore the amazing field of coastal engineering. Beyond the academic world, Nelson is passionate about sports, the Lord of the Rings, and rivers.

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CHAPTER

INTRODUCTION

Hurricanes can have devastating impacts on coastal communities, in the form of wind damage and flooding. Riverine flooding from heavy rainfall can be significant in inland areas, while communities on the coast are impacted by both riverine flooding and wind-driven flooding. Storm surges can be particularly devastating for low-lying coastal areas, depending on several factors such as storm strength and size, storm forward speed, and length and slope of the continental shelf [Irish et al., 2008]. Hurricane Katrina (2005) generated more than 10 m of combined surge and wave action along parts of the Mississippi coast [Fritz et al., 2007], while also causing record-breaking damage and casualties in the New Orleans area and leading to major overhauls in hurricane protection planning and storm surge forecasting capabilities. The U.S. Atlantic coast has also seen its share of devastation from hurricanes. Certain locations along the North Carolina coast experienced water levels 3 m above normal during Hurricanes Fran (1996), Floyd (1999), Isabel (2003), and Irene (2011), all of which resulted in damages of several billion dollars [Barnes, 2013]

During the Atlantic hurricane season (June-November), emergency managers along the U.S. Gulf of Mexico and Atlantic coasts rely on fast and accurate predictions of storm surge to make decisions before, during, and after a storm. Numerical storm surge models can provide emergency managers with such predictions. For a numerical model to be of use for emergency managers, it must be accurate in its predictions of maximum water levels, duration of flooding, and wave heights generated by a storm. The model must be both efficient and accurate, specifically at locations with significant population and infrastructure. It is the accuracy of these hydrodynamic predictions at critical points overland that defines the needs of emergency managers during a storm [Cheung et al., 2003]. It is less relevant how well offshore circulation and wave climate can be modeled, but rather how these processes will affect hydrodynamics at critical infrastructure for which timely decisions are required. Predictions of coastal flooding are then used by emergency managers to determine the neighborhoods and infrastructure that may be at risk of damage from an approaching storm.

For numerical models in general, simulation accuracy is increased as the number of computational points in the model is increased, but this can also lead to an increase in simulation time. For hindcast simulations and floodplain mapping studies, accuracy is of paramount concern, and a greater number of computational points may be used throughout the domain. For forecasting applications, however, simulation speed is very important, and finding an appropriate balance between model resolution and computational time is critical.

However, although land elevation can be more accurately represented with higher model resolution, the details are often averaged and smoothed for small-scale topographic features such as small channels and roadways. Thus, when used in forecasting, numerical storm surge models can be accurate in predicting water levels along the coast, in estuaries, and over land, but may not describe accurately the extent of flooding on smaller, buildingto-building scales. This is the scale of concern to emergency managers, who need to determine specific neighborhoods and buildings that are at risk of flooding and make informed decisions regarding evacuations and resource deployment. The ability to extend flooding predictions to smaller, local scales is crucial.

The problem of predicting flooding across various spatial scales is common for all numerical storm surge models. Most models are dynamic (physics-based) and can represent processes at both small and large scales, and can also be practical for applications where the local region of interest is relatively small and simulation speed is not a critical factor. For other applications, such as in flood forecasting or when small-scale flood prediction is desired for a large domain, these methods may be too computationally-intensive. Simpler, faster techniques exist, particularly GIS-based techniques that model flooding in a way that does not incorporate any physics. Such techniques are commonly referred to as static approaches where, combined with a Digital Elevation Model (DEM), flood predictions are mapped using a planar surface that intersects the DEM based on relative elevations of the water and land. Such a simple rule-based method may not compare in accuracy to a more complex, physics-based model. However, it may be much faster and, therefore, appropriate for use in forecasting applications, especially when used in conjunction with a dynamic numerical model.

In this study, we describe and evaluate a method for enhancing (downscaling) the resolution of real-time storm surge predictions for the state of North Carolina (NC) using a simple, fast mapping technique and a high-resolution DEM to provide a better estimate of local-scale coastal flooding. Any effort to downscale such predictions for real-time forecasting applications across a large domain must consider simplicity as much as possible. It may not be appropriate to model complex inundation processes, nor would it be reasonable to account for topographic variations on the scale of a few meters. A practical method for downscaling storm surge forecasts, then, should use a model resolution no finer than the length scale of the physical features of interest. In the present study, we are concerned with flooding on the scale of features such as buildings and roadways, for which an appropriate resolution is about 15 m. A DEM at this resolution resolves much more topographic complexity than a large-scale numerical model can. The downscaling method presented in this paper uses an automated, open-source mapping technique that can be applied in real-time on a statewide domain and can post-process model output in less than 15 minutes.

Chapter 2 provides background on the ADvanced CIRCulation (ADCIRC) model used in this study and its application in forecasting, as well as a review of the literature pertaining to small-scale flood mapping techniques. Chapter 3 explains the methodology for how the flood mapping technique was developed, automated, and implemented in real-time, and how it was evaluated as part of this study. In Chapter 4, examples of this method are shown for all of coastal NC for Hurricane Matthew (2016) storm surge predictions and for others during the 2017 hurricane season. In addition, these results are compared with results from a high-resolution ADCIRC mesh as an assessment of accuracy. Finally, the concluding Chapter 5 summarizes the key findings and overall importance of this study, including any potential limitations of the proposed method, and identifies areas for future work.

CHAPTER

2

BACKGROUND

2.1 Real-Time Storm Surge Forecasting

2.1.1 Physics-Based Numerical Models

Modeling storm surge is a complicated task. Storm surge is a result of strong winds blowing over a large water body and pushing the water up onto the land. To model accurately this process, there needs to be model resolution at several scales. Tides are an important factor, both in determining the total storm tide (storm surge plus tide) and in their interaction with storm surge. Modeling long-wave processes like tides typically requires a large geographic domain, and therefore physics-based storm surge models should represent processes on oceanic scales. Also important in computing storm surge, though, is the nearshore bathymetry. The amount of storm surge is strongly related to the depth, slope, and smoothness of the continental shelf, and therefore models must use sufficient resolution to effectively represent the bathymetry. Modeling the overland flow resulting from storm surges requires an even greater level of model complexity to represent the local topography and land type.

Ocean circulation, tides, and surge are often computed via some form of the depthaveraged shallow water equations. These equations are derived from the Navier-Stokes equations of fluid motion by averaging out turbulence and vertical variations in the water column. Examples of such models are the ADvanced CIRCulation (ADCIRC) [Westerink, Muccino, et al., 1992], Semi-implicit Eulerian-Lagrangian Finite-Element [Zhang & Baptista, 2008], and Sea, Lake, and Overland Surges from Hurricanes (SLOSH) [Jelesnianski et al., 2008] models. The primary concern of such models are tides and wind-driven water surface setup, both of which are long-wave processes with wavelengths much longer than the depth of the water column. For these processes, variations in the water column are minor compared to variations in the horizontal direction, the pressure in the water column can be considered hydrostatic, and the water column can be assumed to be well-mixed. The dominant forcings become the surface and bottom stresses. The shallow water equations contain the appropriate amount of complexity for modeling large-scale ocean circulation and storm surge, and thus are widely used for such applications.

For these governing, continuous, differential equations to be solved on a computer, they must be discretized and solved at a finite set of computational points. The numerical method can vary for the discretization, with common choices being finite difference, finite volume, and finite element approaches. For each of these approaches, the computational domain must be represented by a mesh, or a connected surface of polygons (elements) and vertices that represents the physical surface of the domain, where each mesh vertex represents a location in three-dimensional space. In storm surge modeling, the mesh represents the bathymetry and topography of the ocean and land, respectively. As the vertex spacing is decreased, corresponding to decreasing element sizes, the higher the resolution becomes in the mesh, and its representation becomes more accurate. However, there is a correlation between mesh resolution and computational expense. With large geographic domains, it may not be feasible computationally to use meshes with very high resolution across the entire domain.

Models used for forecasting applications need to be optimized for providing accurate predictions at speed. Use of the shallow water equations provides part of this optimization by setting aside the physics that are not important for storm surge and coastal flooding. Models can also become more efficient by utilizing meshes that are coarsened in areas that are not of interest and that are efficiently designed with higher resolution in regions that are of interest [Hagen et al., 2001]. Forecast models should also have a mechanism for quickly developing the wind forcing from atmospheric forecasts, which usually consist of a limited set of parameters such as storm size and location through time. An important aspect of forecasting models then is to be able to develop a wind and pressure field from this limited information and interpolate it to the mesh [Holland, 1980; Peng et al., 2006; Gao et al., 2017].

As an example, the SLOSH model is run operationally by the National Hurricane Center (NHC) to provide fast forecasts of surge during hurricanes [Glahn et al., 2009]. SLOSH performs its computations on curvilinear, structured meshes that represent regional scales, referred to as "basins." A SLOSH basin mesh has its highest resolution at a specified area overland (of particular interest) and decreases in resolution concentrically away from the coast. It does not resolve processes on oceanic scales, but it has been modified recently to incorporate tides [Forbes, Rhome, et al., 2014], and current work is moving toward coupling SLOSH to a wave model. Although the resolution of a typical SLOSH mesh is higher at the coast, it is still relatively coarse compared to other larger-domain, higher-resolution models, and thus it sacrifices accuracy. For example, inter-model comparisons of Hurricane Ike (2008) simulations showed that SLOSH was unable to predict the forerunner surge at Galveston [Kerr et al., 2013], whereas more highly-resolved models were successful in doing so. However, because of the smaller domain and coarser resolution, a SLOSH simulation will generally take less than a minute to run on a desktop computer. The NHC is then able to run many ensemble simulations by varying the predicted storm track and other parameters, and, using historical storm information, develop a maximum surge envelope as guidance for decision-makers.

In contrast, the ADCIRC model [Westerink, Muccino, et al., 1992; Westerink, Luettich Jr, et al., 2008] is designed for unstructured, finite-element meshes that resolve entire ocean basins but also contain a majority of elements in coastal and overland areas with relatively higher resolution. ADCIRC provides a more accurate representation of nearshore bathymetry and topography, and as a result its water level predictions are also more accurate [Kerr et al., 2013] compared to those of SLOSH. The trade-off is that a typical ADCIRC forecast simulation will take between 60 to 90 minutes, depending on the computational resources. Both models vary significantly in their forecasting speed and accuracy, but both can provide useful guidance for emergency managers during a storm. Models may have different levels of resolution, however it is important to note that no numerical storm surge

model is capable of predicting flooding at building-scale resolution over a large domain.

This study uses ADCIRC, which is tightly-coupled with the Simulating WAves Nearshore (SWAN) model [Booij et al., 1999; Zijlema, 2010; Dietrich, Zijlema, et al., 2011] for storm surge applications and has been successfully validated and used extensively in hindcasting and design studies [Dietrich, Tanaka, et al., 2012; Hope et al., 2013; Bhaskaran et al., 2013; Sebastian et al., 2014]. In hindcasting studies that use highly-accurate, data-assimilated wind fields, ADCIRC+SWAN can typically achieve accuracy with a mean absolute error less than 25 cm [Dietrich, Westerink, et al., 2011]. ADCIRC is also used extensively in forecasting, via the ADCIRC Surge Guidance System (ASGS), which is a scripting system designed to automatically run ADCIRC simulations and deliver real-time predictions of storm surge [Mattocks, Forbes & Ran, 2006; Fleming et al., 2008; Mattocks & Forbes, 2008; Forbes, Luettich, et al., 2010; Dresback et al., 2013; Dietrich, C. N. Dawson, et al., 2013]. During a tropical storm event, the NHC issues an advisory every 6 hr consisting of a 5-day forecast of parameters for the storm size, intensity, and location through time. After each advisory is issued, the ASGS retrieves automatically these storm parameters and uses them to build a vortex model [Holland, 1980] to compute the pressures and wind velocities that force ADCIRC. The accuracy of ADCIRC forecasts is reliant on accurate atmospheric forcing. For forecasts during early advisories when the storm is still relatively far from the region of interest, there is significant uncertainty regarding these storm parameters. However, this method of parametric wind modeling during a storm has been shown to be accurate under the constraints of forecasting applications [Dietrich, Muhammad, et al., 2018]. After interpolating the wind and pressure time series information to the mesh, ADCIRC is run on several hundreds or even thousands of computational cores. The ASGS has been applied and is currently functioning in several geographic locations along the U.S. coast, including in NC, where it is referred to as the North Carolina Forecast System (NCFS) [Blanton, McGee, et al., 2012].

2.1.2 Communication of Flood Forecasts

It is important that the model output (i.e., maximum water levels) be shared in a format that is convenient for end-users and easily understood and applied, especially for forecasting applications. Results can be visualized in discrete polygon format, where file size is greatly reduced and predicted water levels can be easily visualized and used in common GIS applications (Figure 2.1). Polygon shapefiles are created from ADCIRC output via the Kalpana Python script [Cyriac et al., 2018]. In this format, emergency managers are able to compare predicted flooding extents with building datasets to determine at-risk buildings as a storm approaches the coast. Emergency managers may also use the Coastal Emergency Risks Assessment (CERA, cera.coastalrisk.live), a web-mapping application that displays ADCIRC forecasts in real-time. SLOSH forecast output is communicated similarly, with maximum water level predictions and surge animations delivered to emergency managers via a file transfer protocol (ftp) site [Glahn et al., 2009].

Any of these visualization techniques will be limited, at least initially, by the spatial resolution used to represent the coastal region in the storm surge model. For example, the latest mesh typically used for storm surge forecasting in NC is the NC v9.98 (NC9) mesh [Blanton & Luettich, 2008]. This mesh has been validated [Blanton & Luettich, 2010] and applied in studies of forecasting accuracy [Cyriac et al., 2018]. It consists of 622,946 vertices and 1,230,430 triangular elements that cover the entire Western North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea, although most of the elements are concentrated in North Carolina (Figure 2.2). Element sizes range from about 10 to 100 km on a side in the deep Atlantic Ocean to as small as about 15 to 25 m near the Oregon Inlet and Cape Fear River, but elsewhere the smallest elements are generally on the order of 100 to 200 m along barrier islands and other inlets. Resolution is relaxed some in the Pamlico and Albemarle Sounds, with element sizes larger than 1500 m in water away from land. The mesh resolves inland areas only for NC, while other coastlines in the domain are modeled as no-flow boundaries with a tangential slip boundary condition. More than 56 percent of the total mesh resolution is located over dry land in NC. Apart from barrier islands and certain inland channels with smaller elements, most inland regions in the mesh are resolved by elements closer to 500 m on a side. As more than 90 percent of elements in the NC9 mesh are located in coastal NC regions, it is the ideal mesh in terms of efficiency to use for forecasting in NC. The bathymetry of the NC9 mesh was developed from several DEMs, as described in Blanton, Madry, et al. [2008], which were combined into a single dataset with 10-m resolution throughout the NC coastal regions. The elevations in this dataset are all relative to the North American Vertical Datum of 1988 (NAVD88).

The resolution of the NC9 mesh is sufficient for conveying flow along the coast, into estuaries and onto floodplains [Westerink, Luettich Jr, et al., 2008; Dresback et al., 2013], but there is a level of complexity of coastal features that it cannot represent. If the motivation is to describe the extent of storm surge inundation on smaller, building-to-building scales



Figure 2.1 Example output from an ADCIRC prediction for Hurricane Matthew Advisory 27 showing maximum water levels in NC represented by discrete polygons. Advisory 27 was issued by the NHC less than four days prior to actual landfall in South Carolina, when the storm track and wind speed forecasts posed a serious threat to NC coastal regions.

(about 15 m), this complexity becomes more important. Figure 2.3 shows a zoomed view of a Hurricane Matthew ADCIRC forecast in NC, visualized on the CERA website. At this scale, it is evident that even though the forecast is predicting water levels of more than



Figure 2.2 Average mesh resolution in the NC9 mesh. Highest resolution is limited to complex coastal features such as barrier islands and inlets.

2 m above mean sea level in this coastal river, in many locations the flooding extent is not even reaching the mean shoreline, which is delineated by the black line in the figure. This is unrealistic, and it is a result of the relatively coarse mesh resolution (about 500 m in this example) that does not capture the smaller-scale details of the coastline, channels, or roadways. This is a common trade-off for large-domain numerical storm surge models, which cannot represent these details in a way that is computationally feasible for forecasting. However, solving this problem is critical for emergency managers; therefore, it is important to downscale and enhance these coastal flood forecasts using a technique that runs quickly and independently of the mesh.

2.2 Review of High-Resolution Flood Mapping

Due to the high level of concern for flooding, both riverine and coastal, a variety of studies have sought to provide effective methods for modeling flood risk at local and regional



Figure 2.3 ADCIRC flooding forecast for Advisory 27 of Hurricane Matthew in the lower Neuse River in Carteret County, NC, as displayed by the CERA website (cera.coastalrisk.live). The mean shoreline is delineated by the black line, and the water levels predicted in this coastal river should be high enough to cause flooding up to and beyond the mean shoreline. The extent of flooding does not match up well with the coastline, as demonstrated by the amount of light blue (open water) visible between the mean shoreline and the contoured ADCIRC water levels, and many smaller-scale channels are not well-represented by this resolution.

scales. The topic has garnered even more attention due to the widespread availability of high-resolution elevation data from LiDAR surveys, leading to high-accuracy DEMs. Blumberg et al. [2015] used a nested grid approach to simulate high-resolution urban flooding in the New York metropolitan area, while Wang et al. [2014] coupled an ocean-scale model to a high-resolution urban inundation model to hindcast the devastating flooding of Hurricane Sandy (2012) in Manhattan. Yin et al. [2016] also used a coupled approach to study Hurricane Sandy using the sub-grid model FloodMap [Yu & Lane, 2006], with an emphasis on computational efficiency for an end goal of using the coupled model to simulate many synthetic surge events in a probabilistic way.

Bates & de Roo [2000] developed the raster-based LISFLOOD-FP model for riverine flooding. The model incorporates basic physical processes that are relevant for predicting flood inundation extent, but ignores other aspects of the physics that are deemed not as important to the particular application of inundation prediction. They found that their model, in comparison with aerial observations, generally outperforms a "planar," or static,

bathtub model that does not incorporate any physics, while also outperforming a more physically-complex, finite element model. However, for river reaches where the stage was modeled accurately, the static model compared favorably to the observed flooding extent for the particular river and storm event studied. The model was used in an application of coastal flooding in Bates, R. J. Dawson, et al. [2005], where it was also found that the simple but physics-based model significantly outperformed the static model in several test cases in the United Kingdom. LISFLOOD-FP was then used in a study by Purvis et al. [2008] in the Bristol Channel with an applied dynamic tidal boundary condition. Distinguishing between small-scale modeling of inland (riverine) and coastal flooding is significant, as coastal water levels, especially storm surges, can vary dramatically along the coast or in an estuary. Because there is no single reference water level in these cases, simple bathtub models are difficult to apply accurately and a spatially-varying approach is necessary.

Although it does not account for physics, the static approach to flood modeling is used often, especially for studies involving flood mapping and risk analysis under different sealevel rise scenarios [Brown, 2006; Heberger et al., 2009; Knowles, 2010; Lichter & Felsenstein, 2012; Poulter & Halpin, 2008]. Using a DEM, the static approach floods all DEM cells where the input water level (say, from a model output) is greater than the elevation of the DEM. Hydraulic connectivity may or may not be taken into account. As explained by Gallien et al. [2011], this approach can lead to instantaneous (and erroneous) flooding of entire neighborhoods if, for example, water levels at a point on the boundary become higher than a neighborhood flood protection structure. Therefore, in cases where hydraulic structures are important, they must be modeled physically so as to avoid this problem. Ramirez et al. [2016] found that static models in general do not compare well to dynamic (physics-based) models for coastal flooding applications and should be avoided as long as computational speed is not of primary concern. Even in cases where speed is important, the authors recommend a reduced-complexity model that incorporates some physics but remains simple enough to conserve computational effort. The difference in computational effort between these methods is not quantified, however, and to the authors' knowledge, similar methods of flood model downscaling have not been applied for forecasting purposes nor for large, statewide domains. A simple, static method may yet be the most suitable method for such an application where there are significant time constraints.

The static approach may be most appropriate for studies involving coastal flooding due to sea-level rise, where there is much less temporal variability in the water levels compared

to those caused by a storm event (although morphodynamics may become important on long-term scales). However, the static approach may also be sufficient for storm surge applications depending on the spatial scale of the problem. Aerts et al. [2013] used the ADCIRC model to simulate water levels along the coast of New York City for several synthetic storm events using a mesh that did not include any land areas; water levels were simply extrapolated from the coast into the city using a static method. If the large-scale model (ADCIRC) output has adequate resolution in the nearshore area, and if the distance over which water levels are being extrapolated is relatively short, then the static method may be practical. This method may be even more practical for use with a mesh that actually does resolve land areas, such as those used in storm surge forecasting. A static extrapolation of water levels for this case should theoretically be over a lesser distance, as the model may have already pushed water over land, and water levels at the wet-dry interface of the model may have been reduced due to frictional dissipation. An extrapolation of these water elevations to where they intersect with the equivalent elevation contour in the highresolution DEM may then be a simple yet effective way to better represent local inundation while accounting for the constraints of forecasting and statewide application.

2.3 Objectives

The goal of this study is to improve accuracy of real-time storm surge forecasts by using high-resolution topographic data, as outlined in Figure 2.4. The complete objectives and tasks for this study are:

- 1. Develop a method to enhance the resolution of ADCIRC maximum water level forecasts at speed via a static extrapolation applied across the state of NC, which involves:
 - (a) interpolating model results from mesh to high-resolution raster.
 - (b) extrapolating this raster to lower areas in the DEM that are hydraulically connected.
 - (c) converting new, enhanced guidance from raster to vector polygon format.
- 2. Quantify how much model accuracy is improved through this method by:
 - (a) constructing an ADCIRC mesh with overland resolution identical to DEM.

(b) running simulations of Hurricane Matthew on this refined mesh to compare with the enhanced output.

The first objective uses the simple, static method to maximize computational efficiency. The second objective evaluates the accuracy of this method via comparisons with a high-resolution, "true" prediction of flooding for Dare County, NC. The results produced by the refined mesh, for the same storm and model conditions, should theoretically provide a base comparison upon which we can evaluate the assumptions posed by the static method. Although there is no expectation of a perfect match between these two methods, we hypothesize that the results will be comparable enough to where the static method will be a marked improvement over nominal ADCIRC forecasts.



Figure 2.4 Flow chart describing general process proposed in this study.

CHAPTER

3

METHODOLOGY

3.1 Enhancing Resolution

A DEM for North Carolina (NC) was obtained from NC Emergency Management (NCEM). The resolution of the DEM is 50 ft (or about 15 m; SI units will be used throughout this study), derived from the Quality Level 2 (QL2) LiDAR survey of NC in 2014. Although coverage exists for the entire state, this study used only the 32 NC coastal county DEMs overlapping with at least part of the NC9 ADCIRC mesh. The resulting raster for the 32-county DEM consists of more than 430 million cells (Figure 3.1). The process of enhancing the resolution of an ADCIRC forecast using this DEM consists of (1) interpolating (downscaling) ADCIRC points (water levels) to a raster at the same resolution as the DEM (15 m), (2) extrapolating this water-level raster to polygon format for convenience of distribution.



Figure 3.1 DEM for 32 coastal NC counties at 15 m resolution.

3.1.1 Downscaling to High-Resolution Raster

The first step is to downscale the results of the ADCIRC simulation to a raster equivalent in resolution to the DEM (15 m) using an Inverse Distance Weight (IDW) interpolation method. The results of interest from the simulation are the maximum water levels, which are obtained in ADCIRC by saving the highest water level at each vertex for all time steps. (The surface representing maximum water levels then does not represent a surface of water levels that occurred at any one time.) The output file with maximum water levels is used to create a high-resolution raster by linear interpolation. For the entire coast of NC, this involves interpolating about 600,000 mesh vertices to a raster with over 430 million cells. For any given storm simulation, many of the overland vertices will be dry, and therefore they will not have a data value. However, it is not possible to predict which vertices will be

dry for a particular storm or simulation, and so the method for interpolation must consider all vertices in the NC region.

Because the computational region for NC is so large, interpolating to a high-resolution raster is computationally-intensive. To speed up the process, it was necessary to precompute the IDWs. For each raster cell, there are six associated values: vertex numbers for each of the three closest vertices, and distances from the cell to each of those three vertices. This pre-computation of IDWs was performed by loading the NC9 mesh file into ArcGIS and converting the mesh to a raster, where each cell in the raster is assigned a number corresponding to the mesh element in which it resides. Distances between the center of each cell and each of the three vertices are then calculated using a Python script, and the results are stored in a text file containing one line per raster cell. This file allows for a faster interpolation process where no searching is required; a simple algebraic expression is all that must be solved for each cell.

3.1.2 Extrapolation of Water Levels

The interpolated ADCIRC raster, now downscaled to the same resolution as the DEM, can be processed with the DEM to develop a new raster of water levels that better represents the complexities of the high-resolution topography. Because of some of the limitations presented in the previous section, the water levels at the edges of the downscaled ADCIRC raster may be higher than the underlying topography in the DEM. Therefore, the raster needs to be extended outward to where those water levels would intersect with the DEM, as illustrated in Figure 3.2. This is performed using a set of GIS raster processing methods described below.

The mapping software used to enhance the resolution of ADCIRC is GRASS GIS, or simply GRASS (Geographic Resources Analysis Support System), an open-source GIS with great capability for processing large raster datasets efficiently [GRASS Development Team, 2017]. By being open-source, fast, and easily automated using Python scripts, GRASS is the ideal tool for working with large raster-based datasets. GRASS is organized via a set of "locations" and "mapsets" that comprise the directory structure of the program. A GRASS location contains a set of mapsets that all use the exact same geographic coordinate system and projection, while the individual mapsets contain the raster and vector maps specific to a particular project. By default, GRASS creates a mapset called "PERMANENT" that is used to store read-only maps like a DEM, which may be accessed from another working



Figure 3.2 Illustration of the problem being addressed with this methodology, in profile view. (a) shows an example ADCIRC water level prediction where the model resolution is much less than that of the high-resolution representation of topography and (b) shows the end goal of the method described in this section.

mapset. For working mapsets, a geographic region must be specified before performing any operations to set the boundaries and resolution, using the "g.region" module. GRASS contains many such modules written mostly in C and Python that are used to process maps as well as perform other general geospatial operations. As an open-source program, variations of modules can be created by editing the source code of the existing module and implementing them back into the GRASS library.

The main module in GRASS used in this study is the "r.grow" module, where the "r" indicates raster operation. The module takes an input raster and expands it outward into neighboring, "null" regions by a specified number of cells (referred to as the radius), effectively appending new rows and columns to the original raster. The new, grown cells are given the value of the closest cell in the original raster (Figure 3.3a, 3.3b). For this module to extrapolate water levels, it must consider the ground surface elevation in the DEM. The r.grow code was modified to accept both an input map (ADCIRC water levels) along with a base map (DEM), and an additional criterion was added such that the new, grown cells are retained in the output raster only if the water level value is greater than the value of the DEM at the same location (Figure 3.3c). This is a one-to-one comparison, as the resolution of the two rasters is identical following the previous interpolation step.

The grow radius can be specified by the user, and it will vary by application due to the ADCIRC mesh resolution and local topography. Our initial radius was 500 cells, or about 7,500 m. This radius, while somewhat arbitrary (and large), was chosen because this is the length necessary to push water into finer-scale estuaries and rivers. ADCIRC cannot convey



Figure 3.3 Conceptual illustration of the r. grow module using a radius of two raster cells, and how it was modified to incorporate an elevation check. (a) Raster of water levels (color) at the same resolution as the underlying DEM (grayscale). The black line in the following figures indicates the boundary of this original raster. (b) Raster expanded using the original r. grow module in GRASS. (c) Result of using the modified r. grow to incorporate an elevation check with the DEM. (d) Final result, where new, "grown" cells are retained only if their value is greater than that of the corresponding DEM cell and if it is connected to the original raster.

surge into rivers that are narrower than the length of a few mesh elements, but when surge is extended into the river or estuary via r.grow, it may continue to move up the channel for a long way based simply on the elevation check. For these cases, the large radius was appropriate, however in other locations there can be a significant over-prediction when using a radius of this size. Because the value of the radius is location-dependent, the effects of using different radii are examined in the next chapter. For example, it may also be appropriate to use a radius of 30 cells (450 m), a value representative of typical NC9 element sizes along the wet-dry front, to sufficiently represent flooding on scales smaller than the elements in the mesh.

The new raster created by this process will contain wet cells that are not hydraulicallyconnected to the original ADCIRC raster (Figure 3.3c), an undesirable result, which can be due to low areas in the DEM isolated from the flooding by areas with higher elevation (such as a low-lying neighborhood behind a dune). To fix this problem, a combination of other GRASS modules are utilized to identify groups of new, isolated raster cells and then remove them if they are not connected to any part of the original ADCIRC raster. The resulting flooded surface has effectively been extended farther overland to where the water elevations intersect with the land elevation. In some locations, this extrapolated distance is as much as 7,500 m (such as in a small-scale coastal river), while in others, it is not changed at all (Figure 3.3d).

Figure 3.4 illustrates this process for a stretch of barrier island in Carteret County, NC, where the ADCIRC raster is superimposed on the DEM and then extrapolated over the lowerlying DEM cells. The dune crest is evident in the DEM, shown by the lighter shades of gray in Figure 3.4b. To the southwest (bottom-left), there is a noticeable lack of elevation where the dune is much lower, or perhaps even nonexistent, while the back-barrier on the northwest (top-left) side is characterized by flatter sloping topography. In Figure 3.4c, the ADCIRC raster is superimposed onto the DEM after being interpolated. The difference in scale between the ADCIRC mesh and DEM resolution is evident here, as the distance between the mesh vertices (black points) is much greater than the distance between raster cells. In this example, strong winds are blowing from the northwest, causing a significant surge on the sound side of the island of more than 2 m, while on the ocean side the maximum water levels are around 1 m relative to NAVD88. Overtopping is predicted to occur to the southwest, coinciding with those lower areas that lack a significant dune. However, on the ocean side, the predicted flooding extent is not reaching the mean shoreline, as illustrated by the visible white area. The result of extrapolating the water levels onto the barrier island from both sides is shown in Figure 3.4d, which is the equivalent of what is shown in Figure 3.3d. None of the new, "grown" raster cells have values of water elevation greater than the elevation of the underlying DEM cell. In most places, the dune is still not being overtopped,

except for in one location at the top of the figure. The script that performs this process runs in a few seconds on a desktop computer for such a small region of only 40,000 raster cells. More important is how this process scales to a domain as large as the state of NC, which is discussed in the following section.

To reduce the size of the dataset and for convenience of use by emergency managers, the enhanced raster is binned using intervals of 0.5 ft (0.15 m) and converted to a shapefile after the process is completed. The shapefile is easier to send to end-users via e-mail because of its reduced size, and it can be used to intersect with spatial datasets to quickly determine buildings and infrastructure at risk of flooding during a storm.

3.1.3 Implementation in Forecasting

The script used to run the enhanced resolution process takes, on average, about 45 min to run on a desktop computer. This is too long for forecasting purposes, as it is more than half the time needed to run an ADCIRC+SWAN simulation during a storm. The interpolation process and the final conversion from raster to polygons make up the majority of the run time. It was necessary to parallelize the code and run it on a High-Performance Computing (HPC) cluster. GRASS first needed to be installed on the cluster, which was a simple task, as GRASS is easily executed from the command line both on a desktop as well as in an HPC environment. To do this, a location with at least one mapset must be created, and then the same geospatial operations can be performed from the command line. The script itself was modified to allow for domain decomposition of the NC coastal region. The DEM can be decomposed into as many as 16 subregions, divided by straight lines in the eastwest direction, forming rectangular subregions. Subregions must be overlapped by some amount to avoid errors at the boundaries, and this overlap amount was chosen to be the same as the radius (Figure 3.5).

To run the job in parallel and use this domain decomposition scheme, a GRASS mapset is created for each of the cores being used. Because the DEM is located in the PERMANENT mapset and is accessible from all other mapsets, it does not need to be copied. The subregions are defined in the interpolation stage of the process, where an ADCIRC raster is created for each subregion based on the scheme defined in Figure 3.5. Each raster is then imported to its respective mapset, and the region is specified based on the boundaries of the raster. Then the r.grow process occurs within the local region only. Although it was not possible to parallelize the process of converting from raster to polygon, the ability to



Figure 3.4 First test case on small section of barrier island in Carteret County, NC. (a) DEM for Carteret County, test area shown by red box. (b) DEM section of barrier island, 200×200 cells or 3×3 km. The dune crest is evident by the lighter shades. (c) ADCIRC water level raster superimposed on DEM. The points represent mesh vertices. Visible white area represents water not reaching the mean shoreline on the ocean side. (d) ADCIRC raster after running the modified **r**.grow process, where flooding is extended farther over land to where it intersects the DEM.

run the script on 16 cores reduced the run time to less than 15 minutes on average, a much more practical run time for real-time prediction.



Figure 3.5 DEM decomposition scheme for parallel processing. For clarity, this example shows four subregions, but the code and DEM can be parallelized into as many as 16 subregions. Although not visible at this scale, the three intermediate lines shown are actually two parallel lines offset by a distance of 30 raster cells (450 m), a value that would be used with a radius of 30 cells, to account for inconsistencies at the boundaries.

The process also needed to be automated, such that it would run every time a new ADCIRC result is posted during each NHC advisory. Similar to the scripts used in the NCFS that detect new NHC advisories, a continuously-running script was written to check every 20 seconds for a new ADCIRC forecast posted in the online NCFS repository. When a new forecast is found, the file containing the maximum water levels is downloaded to the HPC cluster, and the job is submitted in parallel on 16 cores. A Fortran code was written to automatically copy the new mapsets and name them according to the active core ID number, and each core then executes the same set of commands for each region. When the parallel job is finished, the new, enhanced rasters for each subregion are combined into one

mapset where they are patched together, binned at specified intervals, and converted to shapefile format. The final shapefile is sent in an email along with job-specific information and text to emergency managers.

3.2 Evaluation with a High-Resolution ADCIRC model

The method of enhancing the resolution of ADCIRC flooding predictions described above does not consider any physical processes, but instead uses a static approach to extrapolate water levels. Therefore, it is of interest to evaluate how this method might compare to a method that does account for physics. A good comparison for this can be an ADCIRC model with overland mesh resolution equal to the resolution of the DEM. Such a model will of course account for factors such as conservation of mass and momentum, bottom friction, and local wind direction and surface stresses, and thus the result should be the most accurate model of flooding extent. A refined ADCIRC mesh was developed to represent flooding at the same scales as the DEM for comparing with the enhanced guidance.

3.2.1 Mesh Development

A mesh with 15 m resolution across the entire state of NC would be too detailed and would exceed the limits of available computing resources. Instead, the high resolution was applied for analysis of Dare County, NC. Dare is the easternmost county in NC, consisting mostly of barrier islands but also including Roanoke Island, which contains the county seat in Manteo, and the eastern end of the Albemarle-Pamlico Peninsula, which is herein referred to as inland Dare and is mostly low-lying, flat marsh land with only a few small towns (Figure 3.6). Dare County was selected as a study area in part because of this diverse topography and geometry and also because of its location and vulnerability to severe storm damage. Furthermore, because the majority of the county consists of barrier island, a high-resolution mesh for the entire county is more manageable computationally for ADCIRC+SWAN simulations than other counties with more land area.

The new mesh was created by modifying NC9 in Dare County and surrounding areas. In overland regions, the mesh was constructed from a scatter point representation of the Dare County DEM, where each new vertex co-location with each DEM point, and the vertex elevations take on the values of the corresponding DEM points. As a result of this one-toone conversion, the new mesh appears as a structured grid with each square cell bisected



Figure 3.6 Dare County study area highlighted in red.

diagonally to create a large set of identical, isosceles triangular elements, each with two 15-m edges. This is the case only for the dry-land elements in Dare. In nearby regions, the mesh is flexible as it transitions to larger elements that match those in the original NC9. The average mesh spacing is shown in Figure 3.7 and a close-up view of a small stretch of Dare County barrier island is shown in Figure 3.8, where the regular grid in the center of the image represents areas in the DEM, and the normal, unstructured mesh configuration represents areas of open water not in the DEM. The final mesh contains 5,668,366 vertices and 11,321,270 elements – more than nine times larger than the NC9 – with 90 percent of this resolution located in Dare County and its surrounding waters.

Although the mesh elevation for overland areas in Dare is taken directly from the DEM, surrounding vertices in the transition region and those that do not have real values in the DEM (and should be bathymetric) are assigned depths from the original NC9 mesh via



Figure 3.7 Resolution of refined Dare County mesh. The mesh is equivalent to NC9 in all regions outside of Dare and its near vicinity. In overland regions in Dare, element spacing is constant and exactly equivalent to the spacing of cells in the DEM (15 m).

linear interpolation. Due to incongruities resulting from differences in the alignment of the DEM and NC9 topography, some regions in the mesh along the interface between these two datasets needed to be smoothed. For example, in some locations the dune crests were not in the same location in the two datasets, and applying the NC9 elevation to the new mesh resulted in an additional, phantom dune crest. To fix this issue, vertices with elevations that were both obtained from the NC9 mesh and were shallower than 2 m were iteratively averaged with their neighbors to form a smooth transition region between the DEM topography and NC9 bathymetry. As a result, the transition between this topography and the 2 m depth contour is much smoother. The topography from the DEM was not affected, and therefore the mesh topography remains an exact representation of the DEM in Dare.

Spatially-varying parameters defined for the NC9 mesh (e.g., horizontal eddy viscosity, Manning's *n*, surface canopy coefficient, etc.) were applied to the new refined Dare County



Figure 3.8 Close-up plot of the refined mesh for a typical stretch of barrier island in Dare County. The triangular mesh is structured over land, but transitions to a flexible unstructured mesh in open water.

mesh via a nearest-neighbor approach. Regarding the horizontal eddy viscosity, the NC9 mesh applies values of 10 m^2 /s at all open-water vertices and 2 m^2 /s at all overland vertices. However, early test simulations on the refined mesh with these values revealed numerical instabilities evident in the water levels on parts of Roanoke Island that were most likely due to the high-resolution, complex representation of topography, making it necessary to adjust the eddy viscosity parameter for the regions in Dare County. After testing several combinations of values, the eddy viscosity was changed to 20 m^2 /s for the high-resolution regions, while the remaining vertices retained the same values as in the NC9. The higher eddy viscosity in overland regions of Dare County was sufficient to prevent similar instabilities from occurring.

3.2.2 Modification of the NC9 Base Mesh

To ensure the comparison between meshes is as equivalent as possible, NC9 was modified to reflect these changes in both the bathymetry and eddy viscosity. The smoothing interpo-

lation procedure used for the shallow coastal regions was applied to the refined mesh as well as to NC9. The NC9 retained its original elevation values in areas far enough away from the interpolated regions, but for those dry-land and shallow-water vertices in Dare County, the new bathymetry was applied to each NC9 vertex via an inverse-distance-squared weighted average. This method ensures that NC9 is representing the same elevation surface as the Dare County mesh, albeit at a much coarser resolution. As for the eddy viscosity, although there is no reason in general to increase its value in Dare, NC9 vertices falling within the Dare dry-land region were also given a value of 20 m²/s for the sake of consistency.

3.2.3 Hurricane Matthew Simulations

A best-track, Generalized Asymmetric Holland Model (GAHM) [Holland, 1980] wind field for Hurricane Matthew was used to force ADCIRC on the refined Dare County mesh. Due to CFL stability concerns with small elements in relatively deep water, the model time step was reduced to 0.5 s. The smaller time step together with such a large mesh required a powerful computing cluster, so access to the Texas Advanced Computing Center (TACC) was acquired for the purpose of running tidal spin-up and hurricane simulations. Simulations for both the refined mesh and the NC9 base mesh consisted of a 15-day, tides-only spin-up starting 17 September 2016 and a 9-day simulation of Hurricane Matthew starting 02 October 2016. The hurricane simulation was run with waves using a SWAN coupling interval of 20 min and a maximum number of iterations per time step of five, typical of NCFS forecasts. Running on 3,072 cores on Stampede2, the tides-only simulation took about 9.75 hr, and the hurricane simulation took about 16.5 hr. The NC9 base simulation was run using similar settings on the NC State University cluster.

The maximum water levels file produced by the refined mesh simulation was uploaded to GRASS as a raster. Because the points are already at the same resolution as the DEM in overland areas, there is no need for interpolation; each point can be converted directly to a corresponding raster cell. In the following chapter, Section 4.2 will present a comparison of three flooding extents: the NC9 base run, the NC9 base run with enhanced resolution, and the Dare County refined mesh. Each of these three cases are represented by rasters at 15-m resolution.

CHAPTER

4

RESULTS AND DISCUSSION

This chapter presents the results of the enhanced resolution method, including its application to the entire NC coast in real-time, as well as an evaluation of accuracy using a highly-refined ADCIRC mesh for Dare County. The former is discussed in Section 4.1, while the latter results are discussed in Section 4.2.

4.1 NC9 Results at DEM Resolution

The enhanced resolution technique was first developed and analyzed using wind fields from Hurricane Matthew (2016) forecast simulations. After developing a robust, automated process for enhancing resolution of ADCIRC forecasts, the process was operated in NC during the 2017 hurricane season. Results and discussion for both the Matthew simulations and the 2017 hurricane season operations are presented and discussed in this section.

4.1.1 Hurricane Matthew (2016)

Matthew was a powerful storm that caused severe damage in the Caribbean Sea and along the U.S. Atlantic coast during 2016. It had a peak intensity as a category 5 hurricane on the Saffir-Simpson scale, before weakening to category 1 before it made landfall in South Carolina. The storm then moved offshore. Matthew caused significant damage in NC due mostly to heavy rainfall, however the storm did push surge along the coast and in the sounds, where total water levels reached 1.5 m near Wrightsville Beach and close to 2 m on the sound side of Hatteras Island [Thomas et al., 2018].

Wind fields used in ADCIRC forecasts are generated from a parametric vortex model, which uses a few storm parameters (such as size, intensity, forward speed, etc.) to develop fields for surface pressures and wind speeds that are temporally- and spatially-variable [Dietrich, Muhammad, et al., 2018]. These wind fields can be regenerated by using archives retrieved from the Renaissance Computing Institute (RENCI) OPeNDAP server, where NCFS input and output files are archived. This archive includes wind fields for each advisory of major storms, as well as for the best-track analysis by the NHC in the months following a storm event [Stewart, 2017]. The NHC issued a total of 47 advisories for Hurricane Matthew, beginning on 28 September and lasting through 9 October. With Matthew Advisory 27, which was issued on 1700 EDT 4 October and about 3 days and 18 hr before the storm's actual landfall in South Carolina, the NHC forecasted the storm to track eastward and make landfall in southern NC. If this forecast had been correct, then the storm surges would have been much larger in the state than actually occurred (Figure 2.1), with maximum water levels greater than 3.5 m along the coastline of Onslow County down through New Hanover County. Matthew's true effects on the surge and flooding in NC are represented well by the ADCIRC simulation using the NHC best-track information [Thomas et al., 2018], which predicted a maximum water level of about 2.8 m in overland parts of Carteret County but was much less along the barrier islands. While the Advisory 27 simulation caused great concern for emergency managers in NC and may represent a worst-case scenario for coastal flooding, the best-track simulation is a good representation of the true flooding that occurred during Matthew.

ADICRC forecasts alone can provide crucial information for emergency managers preparing for a storm. However, enhanced-resolution forecasts may provide emergency managers with a better prediction of flooded buildings and neighborhoods. Figure 4.1 shows the enhanced resolution Matthew best-track forecast side-by-side with the original forecast. Differences are difficult to discern when viewing on the scale of the entire coast, but the zoomed views at Morehead City (Figure 4.2) and in the lower Neuse River (Figure 4.3) show the increased complexity of the predicted flooding boundary after downscaling to match the 15-m DEM. Flooding has been extended into many finer-scale channels and floodplains across the entire domain. As mentioned previously, the initial radius used for enhancing resolution was 7,500 m, however in many places the flooding extent is only a short distance from the equivalent elevation contour and is not extended by much, even with such a large radius. In other places, flooding that was not previously conveyed into smaller river channels by ADCIRC is now extended through these channels, sometimes as much as 7,500 m upriver.



Figure 4.1 Water level raster (a) before and (b) after enhancing resolution for entire NC coast. Results are not shown in regions like the Atlantic Ocean and the Pamlico and Albemarle Sounds, due to the mask applied to save computational effort in regions that are not included in the DEM (i.e., open-water).

The original ADCIRC prediction shown in Figure 4.2a has locations where water is not reaching the mean shoreline, as indicated by the white space between the predicted flooding extent and the topography in the DEM. There are many channels in the DEM that are too narrow to have been represented in the ADCIRC mesh, and therefore the flooding



Figure 4.2 Example of enhanced resolution on small-scale flooding, from Figure 4.1, both (a) before and (b) after enhancing resolution. Location is near Morehead City in Carteret County.

extent also does not include these areas. However, the enhanced resolution extends the predicted flooding (Figure 4.2b), where now many of these smaller-scale channels are being flooded, and several other highly-complex regions are being represented. Toward the bottom of the image, there are several narrow channels with very complex geometry that are represented in the DEM. The interesting feature visible in the DEM to the bottom-right of the image is actually a densely-populated neighborhood in Atlantic Beach, just across the Bogue Sound from Morehead City, built on a system of canals containing 300-500 houses. The topographic details of this neighborhood are too fine to be resolved by the mesh, but, with the enhanced resolution, the flooding is moving into these small channels. The water levels here are less than a meter above NAVD88, so there is not much overland flooding. In other areas in the Bogue Sound, flooding is pushed to the mean shoreline or farther, depending on the water surface elevation relative to the DEM.

The same Matthew prediction shows higher water levels in the lower Neuse River on the opposite side of Carteret County than those near Morehead City, as shown in Figure 4.3. The enhanced-resolution flooding goes the mean shoreline in areas where it was not doing so previously, and, in many cases, the flooding extent is significantly farther inland. The



Figure 4.3 Example from Figure 4.1 in the lower Neuse River near its mouth in the Pamlico Sound, just north of Carteret County, both (a) before and (b) after enhancing resolution. Areas shown as white after the enhancement are fully open-water and not included in the DEM.

final boundary is much more complex, with most of the lower-lying (darker) areas in the DEM being flooded.

The increased complexity of the flooding boundary is evident with the enhanced resolution, but it may seem like the total flooded area does not increase significantly. However, when aggregated over the entire coast of NC, the newly flooded areas are significant. The flooding extent at some locations is increased by up to 7,500 m as flooding is allowed to move into smaller-scale rivers and estuaries, which is obviously a dramatic increase in predicted flooding. Although much of this new flooding is over the open-water of rivers, the enhanced resolution can still make a big difference in the total flooding.

To better understand the enhanced flooding added to ADCIRC predictions, we analyze both the total land area and the number of buildings flooded by the predictions, before and after enhancing resolution. The building dataset used for this analysis was obtained from NC Emergency Management, and it contains the footprints for all buildings in the state. Thus, the number of flooded buildings can be determined by a simple spatial intersection, in which buildings are considered flooded if they fall within the flooding boundary specified by the ADCIRC original or enhanced-resolution prediction. The total flooded area is computed by counting the active raster cells that are in overland regions.

This comparison is performed for Carteret County, Dare County, and the entire NC coast, and the results are summarized in Table 4.1 for the best-track simulation and Table 4.2 for the Advisory 27 simulation. Even for a smaller radius of 30 cells, the number of flooded buildings is increased significantly with the enhanced resolution. This signifies that there are many buildings located in the floodplains that may or may not be predicted to be flooded depending on the resolution of the flood forecast model. Another interesting observation is that, for both storms and both r.grow radii, the total land area flooded buildings is increased more in Carteret. This mismatch is likely due to the fact that the majority of the Dare County land area is inland Dare, which is sparsely-populated and consists of very low-lying (1 m above NAVD88), flat topography with very few buildings. Because of this, water levels are extrapolated a great distance over land (in most areas up to the extent of the r.grow radius), which results in a large increase in flooding but smaller increase in number of flooded buildings.

This may also explain why the percent increase in flooded area is larger for Dare than for Carteret, as the limiting factor for flat topography is more likely to be the radius, whereas the radius probably has less of an influence for steeper topography due to the shorter distance from shoreline to higher elevation contours. The DEM for Carteret shows that much of its coastline can be characterized by steeper topography that is harder to represent with mesh resolution of about 200 to 500 m. Many buildings near the complex Carteret coastline are not in the flood zone of the original ADCIRC simulation, but may become flooded when water levels are extrapolated even a short distance. However, there are just over 40,000 buildings in Dare and just over 50,000 buildings were predicted to be flooded in Dare than in Carteret in both the original ADCIRC simulation and the enhanced versions. As can be expected, the different patterns observed between the two counties are averaged out to some degree when aggregated for the entire state.

This is not the case for Advisory 27, as the water levels were predicted to be much higher near Carteret County, and more buildings are flooded in Carteret than in Dare. The percent increases of these metrics in Table 4.2 for Advisory 27 are generally less than those in Table 4.1. A possible explanation is that with higher water levels predicted along the

		r.grow radius (cells)		
Region	Statistic	None	30 (% change)	500 (% change)
Carteret County	Bldgs.	2,353	3,298 (40.2)	3,344 (42.1)
	Area (km ²)	489	547 (11.8)	568 (16.1)
Dare County	Bldgs.	4,711	5,754 (22.1)	6,028 (28.0)
_	Area (km ²)	249	284 (13.9)	332 (33.3)
North Carolina	Bldgs.	28,018	37,146 (32.6)	39,534 (41.1)
	Area (km ²)	2,791	3,333 (19.4)	3,849 (37.9)

Table 4.1 Differences in flooded area and number of flooded buildings for Hurricane Matthew

 best-track simulation.

majority of the coast, there is already appreciable flooding predicted in overland areas and less of chance, for example, of water levels not reaching the mean shoreline as discussed previously. Thus, although there will always be some increase in predicted flooding with the enhanced resolution, its impact may be slightly less for higher surge events.

4.1.2 Real-Time Implementation (2017)

The 2017 Atlantic hurricane season was active with three major hurricanes (Harvey, Irma, and Maria) causing extensive damage in the Caribbean and along the U.S. Gulf coast. Although NC was not hit directly by any of these hurricanes, the enhanced resolution ADCIRC post-processing was operational from June through November 2017. As ADCIRC was running forecast simulations for each advisory of these hurricanes (as well as Jose, Nate, and Philippe), an automated process was running on the NC State University HPC cluster that downloaded the maximum water levels file, submitted the parallel post-processing job, and sent the enhanced guidance to emergency managers as an email attachment.

The NCFS generally gives first priority to the Hurricane Surge On-Demand Forecasting System (HSOFS) mesh, which resolves the shoreline along the entire Atlantic and Gulf coasts with an average resolution of 500 m and down to 150 m at some locations. When a storm is still in the Caribbean and the storm track is highly uncertain, it is reasonable to

		r.grow radius (cells)		
Region	Statistic	None	30 (% change)	500 (% change)
Carteret County	Bldgs.	9,198	12,494 (35.8)	12,635 (37.4)
	Area (km ²)	610	674 (10.5)	688 (12.7)
Dare County	Bldgs.	8,320	10,394 (24.9)	10,491 (26.1)
	Area (km ²)	427	490 (14.6)	563 (31.9)
North Carolina	Bldgs.	71,742	87,992 (22.7)	92,706 (29.2)
	Area (km ²)	4,091	4,694 (14.7)	5,274 (28.9)

Table 4.2 Differences in flooded area and number of flooded buildings for Hurricane Matthew Advisory 27 simulation.

use a mesh with wide coverage over a range of coastlines. However, simulations are started on the NC9 mesh for storms moving up the U.S. Atlantic coast. In 2017, the first major hurricane to strike the U.S. was Harvey, which dealt incredible damage to the Houston area due to its heavy and long-lasting rainfall. Harvey was never predicted to move up the U.S. Atlantic coast, and thus ADCIRC predictions were limited to the HSOFS mesh. Although NC did not experience any hurricane conditions, the enhanced resolution system was still actively post-processing these predictions for NC. The goal was to ensure that the system was working properly and the output was in the expected format.

For Hurricane Irma, the storm could have moved to the east, to the west, or through the center of Florida. When the NHC issued Advisory 35 on 1700 EDT 7 September, the consensus track predicted the storm to move northward over Florida, which was very close to the actual track. If the storm had veered to the right, it could have posed a serious threat to the U.S. Atlantic coast. The NCFS began running simulations on the NC9 mesh during Advisory 31, exactly 24 hr previously, in anticipation of this possible eastward track. In addition to running simulations for the consensus forecast, the NCFS ran one ensemble member for each mesh that featured a perturbation of one of the storm parameters. At this point in the storm, that was the "veer right" ensemble member, which corresponds to the scenario where the hurricane track is shifted closer to the right edge of the cone of uncertainty. The veer right ensemble for Advisory 35 predicted water levels that were higher than usual in NC, although not comparing to the serious storm surge predicted in the South Atlantic Bight along the coasts of Georgia and South Carolina. These predicted water levels are shown in Figure 4.4. The highest water levels are in South Carolina, but the southernmost part of the NC coast was still predicted to experience water levels of 2 m above NAVD88 and up to 1 m in Carteret County. This is one example of a real-time ADCIRC prediction that was automatically post-processed to enhance resolution. An example of the difference in predicted flooding extent before and after the enhanced resolution is shown in Figure 4.5. As before, there are some locations where the extent has not changed at all, and some locations where the new surface is much farther inland or conveyed into small-scale channels.

For the 2017 hurricane season, an additional option was created to allow for subtraction of raster cells in the original ADCIRC raster that are over-predicted, that is, where the water level is lower than the ground surface in the corresponding cell in the DEM. The extent of flooding is still the same, but the enhanced raster then has less total flooded cells because many cells are removed prior to the extrapolation step. This method is more desirable, as it renders dry those locations in local high regions where the elevation is not captured in the ADCIRC mesh but is in the DEM. This step increases the complexity of the raster, though, and the final step of converting the raster to polygons can take much longer. In general, processing a result on the NC9 took 13 to 15 min, while for HSOFS results the time was usually between 16 to 19 min. Without any major storms hitting NC in 2017, invoking the option to remove over-predicted water levels added only 1 to 2 min to the processing. The added processing time generally increases for greater surge events when there is more overland flooding, to the point where enhancing resolution can take 30 to 40 min with subtraction of over-predicted water levels for a storm like Hurricane Matthew. Although this was not the case for the 2017 storms in NC, the subtraction option was given less priority than the normal method due to the extra computational effort involved with a more serious potential storm.

4.2 High-Resolution Dare County Mesh Comparison

To evaluate the accuracy of the enhanced-resolution, static extrapolation method, the flooding extent should be validated with a "true" flooding extent for a given storm. The



Figure 4.4 ADCIRC maximum water level prediction in the Carolinas for Irma Advisory 35 "veer right" ensemble member. Water levels are higher than normal in Carteret County and increase moving south toward South Carolina.

ideal method for model validation is to use observational data. ADCIRC validation studies make use of coastal gauges and ocean buoys to compare modeled and observed water levels and wave heights, respectively. Validating a predicted flooding extent, though, is much more complicated, as there are typically not enough overland gauges with which to compare it, and aerial imagery during the peak of a storm is difficult to obtain. And, even if there were a number of overland gauges and sufficient aerial imagery available, it would still be difficult to validate our spatial plots of maximum water levels, which are not equivalent to a predicted flooding surface at a particular time during the storm. The maximum water



Figure 4.5 Predicted flooding extents for the Irma Advisory 35 "veer right" prediction, before (dark blue) and after (light blue) enhancing resolution, at the west end of Oak Island, NC., indicated by the label in Figure 4.4. The radius of extrapolation was 7.5 km, as for all 2017 simulations.

levels represent the maximum value occurring at each mesh vertex across all time-steps in the simulation, and thus values at different vertices may or may not coincide with a the same time during the storm. Furthermore, simulations of storm surge do not include flooding from rainfall, which may be a significant contributor to both inland flooding and coastal flooding. It would not be possible to differentiate between the two types of flooding using aerial imagery.

For these reasons, an ADCIRC simulation with refined resolution in Dare County is used to represent the most thorough comparison of flooding. Our assumption is the ADCIRC solution will converge to a true flooding representation as its mesh resolution is increased, and thus the ADCIRC simulation should be a good target for comparison in Dare County. The enhanced-resolution, static extrapolation method is compared to this more accurate flooding extent.

Before beginning the comparison, it is important to note the limitations of our assumption. First, even the high-resolution simulation is limited by its representation of the ground surface. The mesh elevation will always be smoothed to some extent based on the resolution, the dataset from which it is derived may be several years old, and landscapes (particularly dunes) can change quite a bit over the course of years. Second, another factor with a strong influence on flooding extent is the wet-dry algorithm of ADCIRC, which consists of an element checking scheme that is commonly-used in numerical models. Elements in ADCIRC are wetted if the local water level gradient (as represented by a friction velocity, typically larger than 0.01 m/s) favors motion toward the neighboring dry vertex. Elements are dried if the total water depth is smaller than a minimum value (typically 0.1 m). This is an *ad hoc* method designed mainly for computational robustness. It does not conserve mass and, in overland areas where there are high-resolution elements, the wave propagation can be dampened artificially if the time-step is not sufficiently small [Medeiros & Hagen, 2013]. It is important to understand some of these limitations that are related to the assumption being made in the following analysis that simulations run on the high-resolution ADCIRC mesh will be the most accurate representation of flooding with which we can compare the enhanced resolution results.

For clarity of presentation, the three flooding surfaces will be abbreviated as:

- *Base* The maximum water levels from the ADCIRC best-track Matthew simulation using the NC9 mesh.
- *Enhanced*(30) The maximum water levels from the *Base* case, with the flooding downscaled and extrapolated by using the enhanced-resolution technique with a radius of 30 cells (450 m).
- *Subtracted*(30) The enhanced-resolution results from the *Enhanced*(30) case, but with a removal of predicted flooding in locations where the DEM ground surface is higher than the ADCIRC wet points.
- *Refined* The maximum water levels from an ADCIRC simulation similar to the *Base* case, but with a refinement in overland regions of Dare County so the mesh resolution

is the same as the DEM (15 m).

4.2.1 Results in Dare County

The four rasters of storm tide water levels (*Base, Enhanced*(30), *Subtracted*(30), *Refined*) were compared in Dare County using two metrics: total overland area flooded, and number of buildings flooded. In addition to these quantitative metrics, visual inspection of the flooding surfaces was used to explain some of the noticeable patterns.

Although the r.grow radius used during the 2017 hurricane season was 500 cells (7.5 km), this radius was later determined to be too large and unrealistic. There appeared cases in Dare County where, if the barrier island was narrow enough, new but erroneous flooding was produced by the extrapolation because hydraulic connections were incorrectly established. With a radius of 30 cells (450 m), it may not be possible to push water as far up some of the finer channels as was shown in Section 4.1, but the distance is similar to the average overland mesh resolution in NC9. As was shown by the results in Tables 4.1 and 4.2, in most cases the increase in the radius from 450 m to 7.5 km does not result in a proportionate increase in flooded buildings or even flooded area. The majority of the increase is most likely from the induced surge in rivers and flooding over very flat topography, because in other areas along the coastline the water levels are only extrapolated to where they intersect with the land, and that distance is generally less than 450 m.

Refined results, produced by the ADCIRC+SWAN Matthew best-track simulation, are shown in Figure 4.6. For most of the coast, the water levels and spatial extent of flooding are identical to *Base*, as the two meshes are the same in regions outside of Dare. The highest water levels in Dare are close to 1.3 m just west of inland Dare in the Alligator River and on the sound side of Hatteras Island near the towns of Buxton and Frisco. Significantly higher surge is evident outside of Dare on the sound side of Carteret County.

A comparison of three water level rasters is given in Figure 4.7. At this region scale, the most noticeable differences are the flooding extents in inland Dare. Also noticeable in Figure 4.7a is the white space along the east end of inland Dare and around Roanoke Island (the peninsula protruding into the Albemarle Sound in the top-left is not part of Dare County), which as before corresponds to water failing to reach the mean shoreline. This is corrected in both Figures 4.7b and 4.7c.

The total inundation area and number of buildings predicted to be flooded are compared for the different simulations in Table 4.3. Included are numbers for the *Subtracted(30)*



Figure 4.6 Output maximum water levels for *Refined*. In regions outside Dare, water levels and overland flooding are virtually the same as *Base*.

surface with initially over-predicted water levels removed from the raster. From these results, *Base* over-predicts flooding by a significant margin, with 18.6% of land area flooded compared to only 13.4% in *Refined. Enhanced*(*30*) increases the flooded area to 29.2%, which represents an even greater over-prediction. Referring back to Figure 4.7c, the flooding predicted by *Refined* does not move nearly as far over land when compared to the *base* flooding in Figure 4.7a. The same is true for flooded buildings. *Base* is already predicting more flooded buildings than *Refined*, and *Enhanced*(*30*) then dramatically increases the number of buildings. This is the case despite the fact we are using an r. grow radius of only 450 m. Subtracting the over-predicted raster cells has a nontrivial impact on both



Figure 4.7 Water level rasters superimposed onto DEM of Dare County: (a) *Base*, (b) *Enhanced*(30), and (c) *Refined*.

quantities, but the numbers for *Subtracted*(30) are still much closer to *Enhanced*(30) than to the results of *Base*.

4.2.2 Comparisons Based on Land Type

To understand better the potential benefits of the enhanced-resolution method, it was necessary to evaluate the results on a more case-by-case basis, with emphasis on results at local scales and on varying land types. The topography of Dare County varies widely, and aggregating results over the entire county may not be representative of the strengths and weaknesses of the method. Inland Dare makes up about 74% of the total land area

	Statistic (% of total in Dare)		
Simulation	Bldgs.	Area (km ²)	
Base	1,940 (4.8)	185 (18.6)	
Enhanced(30)	3,742 (9.3)	291 (29.2)	
Subtracted(30)	3,407 (8.4)	279 (28.0)	
Refined	1,674 (4.1)	133 (13.4)	

Table 4.3 Differences in flooded area and number of flooded buildings in Dare County.

of Dare (although it contains only 3.5% of the buildings), and consists mostly of flat, lowlying land. Because it is so large, it tends to be the first place where results are inspected visually, as in Figure 4.7. There are several examples used in this paper to describe the limitations of large-domain storm surge models, but surge moving over topography such as that of inland Dare is not necessarily one of them. It is evident that at the resolution of the NC9 mesh (400 to 500 m over inland Dare), ADCIRC can effectively push water across flat marsh land. For this land type, the relatively coarse mesh resolution is not averaging out much topographic variation and, therefore, can convey flow as more of a balance between momentum and frictional dissipation. For inland Dare, one additional row of elements wetted in NC9 is the equivalent of close to 500 m of flooding inland, which as shown in Table 4.3 can be significant across such a large area.

A visual comparison of flooding extent in inland Dare by itself is shown in Figure 4.8. Much of the discussion above can be explained by the differences in these images. Because the land is so flat, *Enhanced(30)* shown in Figure 4.8b extends the flooding of *Base* (Figure 4.8a) by the full radius of 450 m in most directions. If the water levels at the edge of the flooding extent of *Base* are higher than the ground elevation, and if the ground elevation does not change much for a long distance, then the water levels will be extrapolated as far as is allowed by the radius, even after the initial results from the model are reduced somewhat by frictional dissipation. The flooding statistics presented in Table 4.4 for inland Dare show similar discrepancies as those for the entire county. The small number of buildings simply show how sparsely-populated this region is, while the total flooded area shows how *Base* is

predicting more than 50% more flooding than Refined.



Figure 4.8 Comparison of water level rasters in inland Dare for (a) *Base*, (b) *Enhanced*(*30*), and (C) *Refined*.

The regions in Dare with steeper topography are mostly limited to the outer edge of the barrier islands where there are sizable dunes. Some locations in Dare (e.g., Kitty Hawk) have sloped topography but are also relatively high in elevation and less prone to flooding. The Dare County barrier islands are not a large percentage of the total land area. However, they contain the majority of the buildings, and flooding on these islands is very important for emergency managers in NC. Figure 4.9 shows a comparison of predicted flooding extents along a stretch of barrier island in Dare, near the town of Avon. The flooding produced by *Enhanced(30)* and *Refined* are a closer match both in extent and in complexity. *Base* produces the flooding boundary in Figure 4.9a, where water is not reaching the mean shoreline in several locations, but both the *Enhanced(30)* (Figure 4.9b) and *Refined* (Figure 4.9c) rasters match the topography. On the sound side to the west of the island (left in the image), the flooding extent of *Enhanced(30)* is farther inland than that of *Refined* in most

	Statistic (% of total)		
Simulation	Bldgs.	Area (km ²)	
Base	156 (11.0)	160 (21.9)	
Enhanced(30)	191 (13.5)	228 (31.1)	
Subtracted(30)	172 (12.2)	219 (29.9)	
Refined	42 (3.0)	104 (14.1)	

Table 4.4 Differences in flooded area and number of flooded buildings in inland Dare, shown inFigure 4.8.

locations, but the difference is very small. Only by close examination is it possible to see small-scale flooding filling in the lowest-lying topography where it is not in *Refined*. On the ocean side (right), the flooding extents are nearly identical. Water reaches the mean shoreline and is stopped just before the dunes at the same locations in both rasters.

To quantify the comparison for areas with steeper topography, a polygon was digitized in GRASS to create a mask that isolates all areas between the back side of the dune and the ocean. The mask runs the entire length of the barrier islands in Dare, but does not include the lower-gradient back-barrier regions of the islands. For example, the mask includes the flooding present on the ocean (right) side of the island in Figure 4.9, but does not include the back-barrier flooding on the west side of the island. This is a rough estimate of steep topography, as the dunes are not consistent in height and slope along the barrier islands, but it provides a proxy for a land type that can be contrasted with that of inland Dare. For the entire length of the barrier islands, the total land area included is 26.1 km² and the number of buildings is 3,611.

The number of flooded buildings and land area for these simulations are presented in Table 4.5. For both metrics, *Enhanced*(*30*) over-predicts when compared to the *Refined* flooding. However, it may be trivial to look at the number of flooded buildings for this stretch of island because there are not many in total, and such a small amount of them are actually flooded. The area metric is more significant, as the flooding predicted by *Refined* is much closer to *Enhanced*(*30*) than it is to *Base*. This result is consistent with the observation in Figure 4.9 that the flooding on the ocean side is nearly identical. Of course,



Figure 4.9 Comparison of water level rasters along the barrier island at Avon, NC, for (a) *Base*, (b) *Enhanced*(30), and (C) *Refined*.

it is not identical along the entire Dare coastline, but it is clear that along the dune, the static method for enhancing resolution is a clear upgrade over the normal NC9 ADCIRC predictions.

Enhanced-resolution ADCIRC predictions clearly give a more-complex representation of coastal inundation that accounts for finer-scale topographic details. This method may not be suitable for regions of very low-lying, flat topography where ADCIRC does not generally under-predict flooding, but it can be an improvement in regions of steeper topography. For those regions, a typical ADCIRC mesh may be too coarse to represent topography that changes rapidly in the cross-shore direction, and therefore enhancing resolution of these predictions can be beneficial.

	Statistic (% of total)		
Simulation	Bldgs.	Area (km ²)	
Base	4 (0.1)	0.6 (2.2)	
Enhanced(30)	19 (0.5)	3.8 (14.4)	
Subtracted(30)	18 (0.5)	3.7 (14.3)	
Refined	10 (0.3)	3.0 (11.5)	

Table 4.5 Differences in flooded area and number of flooded buildings in areas near the dunes of the Dare County barrier islands.

CHAPTER

5

CONCLUSIONS AND FUTURE WORK

The ability to represent processes on multiple spatial scales is critical in numerical storm surge modeling. When these models are used in forecasting where simulation speed is critical, it is often not possible to resolve the smaller spatial scales necessary for accurate prediction of neighborhood- and building-scale inundation. As a result, there may be regions along the coast where the flooding extent is under-predicted. This study presented a GIS-based technique to downscale and enhance the resolution of ADCIRC+SWAN storm surge predictions in real-time for the state of North Carolina using a high-resolution DEM. The technique was run operationally during the 2017 hurricane season and enhanced guidance was provided to NC emergency managers immediately following completion of an ADCIRC prediction. It provides emergency managers with an ability to predict flooding at local scales across a large geographic domain in a short period of time. This technique is intended for use in real-time forecasting, and thus it is a simpler, rule-based process that does not include physics. The accuracy of this technique was evaluated using a refined ADCIRC mesh for Dare County. The major conclusions of this evaluation are summarized below:

- 1. The GIS method is less accurate in flat, low-lying regions and more accurate in regions with steeper topography. In relatively flat regions, normal ADCIRC flooding predictions are more likely to over-predict flooding because there is generally lower mesh resolution in these areas and the extent of flooding may be more sensitive to the wet-dry algorithm. There is a better chance for under-prediction in steeper coastal regions, as the mesh resolution may not capture the variation in topography over shorter distances. The radius of extrapolation used by this method was varied from 450 m to 7.5 km, where the smaller radius works better for barrier islands and the larger radius is more effective in estuaries with many small-scale coastal rivers and steeper topography. Comparisons of total flooded area and number of flooded buildings in Carteret and Dare Counties led to similar conclusions about the importance of coastal geometry and land type. In Dare, enhancing resolution generally resulted in a greater increase in inundated area than in Carteret, because the latter consists of many areas with high topography in close proximity to open water, whereas the majority of Dare is low-lying and flat. Refining an ADCIRC mesh for Carteret and performing a similar analysis to the one performed for Dare could provide additional insight on this matter, as the unique combination of barrier islands, estuaries, and floodplains in Carteret would most likely yield results that differ from those in Dare.
- 2. Enhancing resolution of more extreme storm surge predictions may result in a lesser increase in flooding extent than for lower surge predictions. This is suggested by the comparison of the Hurricane Matthew best-track simulation and Matthew Advisory 27 simulation, the latter of which predicted much higher surge throughout NC. Greater surge predictions will usually predict flooding to travel farther over land, and thus in some locations the extrapolated water levels at this wet-dry boundary may already be closer to higher elevation contours in the DEM. This is most likely dependent on coastal geometry, and a more in-depth study of how this process works with different combinations of predicted surge and geometry is needed to verify this theory.

This study focused on the state of North Carolina, but it can be applied in other coastal regions of similar size as well as long as there is a statewide DEM available. Application to a new region would require changing the scheme of parallelization, as the domain decomposition scheme using latitudinal strips was devised specifically for NC. The parallelization of the DEM and code was necessary due to the lengthy interpolation step. The interpolation step as described in this paper may not be necessary though, as it is possible to convert

ADCIRC points directly to polygon format, and convert the polygons directly to a raster in under a minute for the entire state. The resulting raster would no longer be a continuous surface because of the binning required to create a polygon shapefile, but defining a very small binning interval can negate most of this difference. Choosing to use this technique would make application to other coasts easier, without a need for precomputing IDWs and perhaps even the need for parallelization.

Further research may involve incorporating some level of physics to the code, or perhaps some additional set of rules to represent processes such as frictional dissipation of overland flooding. This may increase accuracy in places like inland Dare, where overland flooding is tapered off due to the frictional resistance of vegetation. Other potential rules, such as a radius of extrapolation related to the difference between water level and DEM at the predicted flooding boundary can be considered. In smaller estuaries, it may be more important to consider mass-conservation principles.

Researchers will continue to improve the accuracy of coastal flooding predictions, because they are critical for decision-making before, during, and after storms. The methods presented in this study will add an important element to the suite of coastal flood modeling capabilities, providing decision-makers with enhanced guidance during storm events. For the majority of coastal North Carolina, this process can be a significant upgrade to current methods of neighborhood-scale, real-time inundation prediction. It is an evolving process, and with continued development toward improving accuracy and speed, it can become a standard technique in coastal flooding prediction.

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