Lumber & Little Pee Dee Watersheds for SC Flood IMPACT

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Modeling and Programming performed by AECOM (SCDNR consultant). Modeling and results subject to change with improvement from detailed surveys, studies, and improved technology.

16. Abstract

SC Flood Inundation and Mapping for Action (IMPACT) reduces the stress from uncertainty of flood events by instantly and visually communicating forecasted flooding to state agencies and the public. SC Flood IMPACT analyzes multiple data sources to provide flooding forecasts including peak flow, water surface elevations, time, inundation extents, and other useful information.

This report is specific to the Lumber & Little Pee Dee Hydrologic Unit Code (HUC) 8 Watersheds; however, SC Flood IMPACT is intended to cover the entire state if provided additional funding. SC Flood IMPACT is in the initial phase, with the hope that more features will be provided on the website in future phases.

17. Key Word	18. Distribution Statement
Flood forecast, library mapping, cloud computing, 2D modeling, and flood alert system	For SCDOT and the Steering Committee only.

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Disclaimer

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views of the South Carolina Department of Transportation or Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

The State of South Carolina and the United States Government do not endorse products or manufacturers. Trade or manufacturer's names appear herein solely because they are considered essential to the object of this report.

Acknowledgments

South Carolina Department of Natural Resources (SCDNR) would like to thank South Carolina Department of Transportation (SCDOT) for the opportunity to develop the Lumber & Little Pee Dee Watersheds for SC Flood Inundation and Mapping for Action (IMPACT). This area has historically been prone to flooding during natural disasters. SCDNR would also like to thank the members of our team that worked tirelessly on this project. The innovation of this project has resulted in the development of new tools and modern technological advances. The knowledge and experience gained from Little Pee Dee and Lumber watersheds have pushed the envelope of flood mapping for South Carolina. While Little Pee Dee and Lumber watersheds are only the second riverine areas completed for SC Flood IMPACT, we are hopeful that additional areas will be funded in the future. We look forward to future phases of development for this project and to enhance our relationship with SCDOT.

Executive Summary

The State of South Carolina has recently experienced numerous severe storm events resulting in devastating floods. Specifically, the flooding that resulted from Hurricane Matthew in 2016 highlighted the need to produce inundation maps to be used by multiple government agencies and partners for emergency response. As part of SCDNR's inundation mapping efforts for Hurricane Florence, the 2D hydraulic modeling approach was identified as an efficient and effective method for delivering inundation mapping for large magnitude events. This approach was again used to provide inundation mapping for Hurricane Dorian in 2019 for emergency response.

The previous extreme weather events have emphasized several critical needs for the State, including:

- Increase public awareness of flood hazards by identifying areas that may experience flooding,
- Provide a publicly available flood alert system, and
- The need for more resilient mitigation planning and emergency management.

To address these needs, SCDNR began pursuing funding to build a system that prebuilds and displays forecasted inundation maps for utilization during storm events.

The funding provided under this Research Grant developed and quality-controlled flood inundation libraries that contain 10 flood frequency scenarios for both the Little Pee Dee and the Lumber Hydrologic Unit Code (HUC 8) Watersheds. The library information was produced in the form of depth rasters. The depth rasters were loaded into the SC Flood IMPACT website library repository. The repository is programed to display the appropriate depth raster that corresponds to the forecasted event. The website will automatically update as the forecast is refined and once the rainfall event has ended, the site updates based on precipitation data and USGS/NWS gauge information.

Access to the inundation information will be limited for general users to just the extent of inundation boundary. Employees of SCDOT will be able to request elevated access that will provide the ability to view the depth raster. SCDOT will be provided a list of its employees that are requesting access to verify if this level of access is needed. Also, SCDOT will notify SCDNR to remove access to any employees that have left the agency or no longer need elevated access. SCDNR will provide on an agreed upon timeframe a list of SCDOT employees with access to audit.

The information produced augments the SC Flood IMPACT website and assists in providing state and local officials, as well as the public, with a reliable and accessible resource to communicate flood hazards and identify areas at risk of flooding.

Completion of the first phase of the SC Flood IMPACT website, flood inundation libraries for the Little Pee Dee and Lumber HUC 8 Watersheds has set a precedent for the state of South Carolina. It is hopeful that with future funding, SC Flood IMPACT website will continue to propel the State as one of the leading states in the country for flood awareness and preparedness. We recommend additional funding for enhancements that could increase functionality of the website. Examples of future enhancements are as follows:

- Toggle of Storm Events
- More enhanced calibration and verification of storm events
- Hydrographs at structure locations
- Produce specialized reports
- Finish out Coastal inundation
- Finish out Riverine (HUC 8) Modeling

One of the benefits resulting from this project is 2D modeling which identifies all areas that are at risk of flooding, as opposed to 1D modeling which focuses on a single stream. As a result, SC Flood IMPACT differentiates itself in this regard compared to similar websites that only display flooding within a mile upstream or downstream of a stream that has a U.S. Geological Survey (USGS) gauge. Likewise, Federal Emergency Management Agency's (FEMA) National Flood Insurance Program (NFIP) tends to only cover streams with a drainage area of at least 1 square mile, ignoring smaller streams, pluvial, and urban flooding. SC Flood IMPACT provides all flooding whether that be a rural farmer's crop, a small stream in the backyard of a home, or the Great Pee Dee River. The statewide coverage will reach more end users and provide a unique product in comparison to the alternatives.

Providing this information days in advance of the arrival of a large magnitude storm aids state agency and their partners in emergency response and preparations. As a result of the inundation library, flood inundation maps will no longer need to be created as an event-by-event basis. The SC Flood IMPACT website will provide instantaneous forecast inundation maps automatically on the website up to 84 hours in advance of forecasted storm events. The forecast is updated every three hours.

The Steering Committee for this project was:

Tom Knight, SCDOT, Chairman
Stan Roof, SCDOT
Roberto Ruiz, SCDOT
Elizabeth Thebo, SCDOT
Blake Gerken, FHWA

We would like to recognize former Steering Committee members:

Randall Mungo, SCDOT, Former Chairman
Levi McLeod, SCDOT

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List of Acronyms

1D	One-Dimensional
2D	Two-Dimensional
AEP	Annual Exceedance Probability
CN	Curve Number
CTP	Cooperating Technical Partner
DEM	Digital Elevation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
FEMA	Federal Emergency Management Agency
FIMAN	Flood Inundation Mapping Network
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Studies
HEC-HMS	Hydrologic Engineering Center - Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center - River Analysis System
HMGP	Hazard Mitigation Assistance Grant
HUC	Hydrologic Unit Code
IDS	Intermediate Data Submissions
IMPACT	Inundation and Mapping for Action
LiDAR	Light Detection and Ranging
NFIP	National Flood Insurance Program
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmosphere Administration
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
QC	Quality Control
QA	Quality Assurance
QPF	Quantitative Precipitation Forecasts
SCDOT	South Carolina Department of Transportation
SERFC	Southeast River Forecast Center
SOMA	Summary of Map Action
SSURGO	Soil Survey Geographic
USGS	U.S. Geological Survey
WHAFIS	Wave Height Analysis for Flood Insurance Studies

1. Introduction

The State of South Carolina has experienced multiple severe storms and floods in the recent years resulting in the need for more precise information prior to a flood event (see **Error! Reference source not found.**). SCDNR's extensive knowledge and experience from producing the FEMA Flood Insurance Studies provided the framework to produce inundation mapping. After producing inundation mapping for Hurricane Matthew, SCDNR began applying for funding to build the SC Flood IMPACT website. The initial funding for the website was provided by the Hazard Mitigation Grant Program (HMGP). That funding covered the development of the website and the functionality that is available at this time (see Appendix B). The initial funding only provided modeling and inundation library repositories for the Black River Watershed and the Charleston County Coast. The ultimate goal is for the entire state to have inundation models and library repositories. SCDOT, through this project, provided funding to produce modeling and inundation library repositories for the Little Pee Dee and the Lumber River Watersheds.

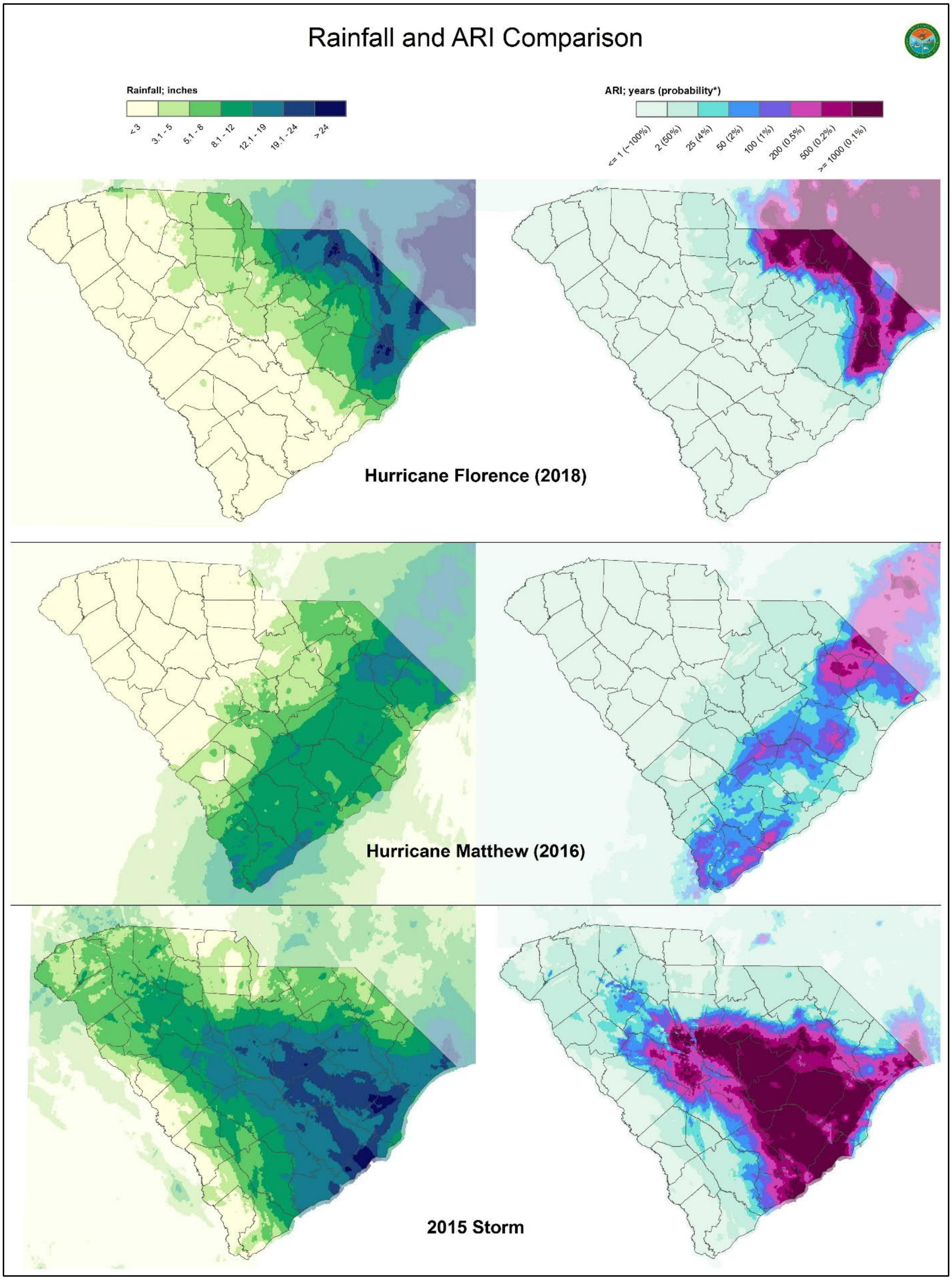

Figure 1. Recent Major Storms (SC State Climatology Office)

The flooding that resulted from Hurricane Matthew in 2016 highlighted the need to produce inundation maps to be used by multiple government agencies and partners for emergency response. As part of SCDNRs inundation mapping efforts for Hurricane Florence in 2018, the 2D hydraulic modeling approach was identified as an efficient and effective method for delivering inundation mapping for large magnitude events. This approach was again used to provide inundation mapping for Hurricane Dorian in 2019 for emergency response.

These extreme weather events have emphasized several critical needs for the State, including:

- Increase public awareness of flood hazards by identifying areas that may experience flooding,
- Provide a publicly available flood alert system, and
- The need for more resilient mitigation planning and emergency management.

SC Flood IMPACT is the proposed solution to address these critical needs as the State will benefit greatly from instantaneous forecasts, accessible flood information, and an alert system. SC Flood IMPACT is a library of pre-run HEC-RAS 2D models and associated databases. Access to the library is granted based on user level as there are several users (such as federal and local governmental agencies, the public, etc.) and their use range from mitigation planning to emergency management.

Within SC Flood IMPACT are several goals discussed below including statewide coverage, multiple scenarios, holistic approach, data-driven reasoning, and comprehension.

Goals of SC Flood IMPACT:

- Statewide coverage
- Multiple scenarios available
- Holistic approach to flooding
- Data-driven reasoning and analysis
- Ability to provide information quickly and effectively to all users

For SCDOT, the significance of SC Flood IMPACT includes but is not limited to:

- Inundation scenarios that will identify areas that are at risk for flooding,
- Ability to create and export exhibits (maps) of areas forecasted to flood, and
- Determine where measures need to be taken to keep the roads open (e.g. HESCO barriers).

2. Literature Review

The flood inundation libraries that were produced for the Little Pee Dee and Lumber Watersheds directly augment SC Flood IMPACT. SC Flood IMPACT is a unique project in that it was not restricted by any standard protocol, which paved the way for innovative methodologies. As a result, many specialized procedures were developed and utilized. These alternative procedures were explored and investigated to ensure that the most-informed path was taken. Ultimately, the decision on which methodology to use was based on:

- Fulfilling the purpose of the project and its many uses,
- Most effective and reasonably performed within constraints such as budget, data management, technology, and resources,
- Expandability and scalability to other regions of South Carolina,
- Tailored to the geography of the southeast as opposed to national implementation, and
- Interface between components such as how well it functions with other aspects of the system.

A review of existing similar applications was conducted and based on this current system, no other system presently performs in this manner. The closest comparison would be Flood Inundation Mapping Network (FIMAN) which utilizes 1D modeling for the state of North Carolina. This system appears to be the most accurate at the gage and decreases in accuracy as you move further away from the gage.

2.1 The System

2.1.1 One-Dimensional (1D) vs Two-Dimensional (2D) Hydraulic Modeling

All 2D models were created using Hydrologic Engineering Center - River Analysis System (HEC-RAS). HEC-RAS is a software program that models the hydraulics of water flow through natural rivers and other channels. It is designed to perform one-dimensional and two-dimensional hydraulic calculations for a full network of natural or constructed channels, overbank, and floodplain areas. The software allows simulating flow in natural or artificial channels to calculate the water level for performing flood studies and determining the areas that are likely to flood.

Historically, 1D modeling has been used to identify flood risk areas; however, SC Flood IMPACT uses 2D models due to the justifications found in **Error! Reference source not found.** below:

Table 1. 1D vs 2D Hydraulic Modeling Comparison (AECOM)

Item	1D	2D
Study Area	Limited to flooding in main streams (only between cross sections)	Captures all areas that can flood as 2D is not limited to a single stream or tributary
Accuracy	Most applicable in well-defined channels (such as a stream in mountainous terrain) since only one direction of flow is analyzed	Enhanced capability for identifying backwater and swampy regions as flow can travel in multiple directions.
Standards	Well-Defined and Researched	Continually evolving ("early adopter" phase of technology cycle)
Expandability	Limited capabilities in the long term	Programmed to endure future complexities and capabilities. Modeling software is consistently being revised and enhanced.
Computation	Very quick computation time (typically less than 1 minute) and minimal storage required	Computation time could take hours up to weeks. For numerous simulations, Cloud Computing and Data infrastructure is recommended. Storage size can be high (>10 GB)
Labor	Heavy on human assumptions and definitions to perform tasks with low amount of computer processing	Heavy on model calibration, but allows the computer to process most of the computations
Results	Limited to information at several hundred cross sections	Information available at millions of locations.

HEC-RAS versions 5.07, 6.0 and 6.1 were used for Little Pee Dee and Lumber watersheds. HEC-RAS version 6.1 became available as the project was ongoing.

2.1.2 Library vs Live Run

Ideally, SC Flood IMPACT would run storm scenarios on an event-by-event basis; but practically, the storm events must be stored in a library. This comes down to three time-related and one cost-related factor for consideration for determining the choice of library vs. live run.

First, determining when the forecast is within acceptable accuracy to commence running the model as the forecast typically improves closer to the arrival of the storm. It is assumed that three days out is a reasonably accurate timeframe to begin flood predictions and refining the forecast as the weather event gets closer.

Second, determining how much lead time is required before the storm occurs. This time period is assumed to be at least one day as this would be the minimum amount of time the public would need to evacuate.

Third, establishing how much time and cost is required for the models to run. For hurricane events, all models would need to run in half a day or less. Models could take hours to weeks to run depending on their size and complexity. Regarding cost, running a model for each weather event would be excessively expensive versus using an existing library repository. A storm event from the library may be used for multiple storms with similar input predictions; whereas, on the impromptu modeling is constrained to a specific storm.

2.1.3 Forecasting Sources

Forecasting sources that were considered for this project were provided by the following institutions:

- National Weather Service (NWS),
- NWS National Water Center,
- NWS Weather Prediction Center,
- European Centre for Medium-Range Weather Forecasts (ECMWF),
- National Oceanic and Atmosphere Administration (NOAA), and
- Southeast River Forecast Center (SERFC).

2.2 Hydrologic and Hydraulic Modeling

This section discusses the input data used for the hydrology and hydraulic modeling performed as part of this project.

2.2.1 Digital Elevation Model (DEM)

A DEM is a representation of the bare earth topographic surface of the Earth excluding trees, buildings, and any other surface objects. All DEMs were based on Light Detection and Ranging (LiDAR) and were provided by SCDNR.

2.2.2 Land Use, Land Cover, and Curve Numbers

National Land Cover Database (NLCD) 2016 coverage and Natural Resources Conservation Service (NRCS) soils data were used to determine the Curve Number (CN). The CN is an input parameter accounting for losses in the system such as vegetation, erosion, ground saturation, aerial reduction factor, etc. Regarding the geography of South Carolina, the CN values are adjusted based on prior modeling experience and calibration to historic events.

2.2.3 Manning's n Values

Manning's n values are another input parameter that measures roughness and directs the speed of flow. National coverage was developed for the 2D computational mesh using roughness values for given NLCD land classifications shown in Table 2. Similarly, to the CN, the Manning's n variables were calibrated to the land characteristics of South Carolina and are model specific.

Table 2. Roughness Coefficients (NLCD)

NLCD Classification	Grid Code	Minimum Values	Maximum Values
Open Water	11	0.025	0.033
Developed, Open Space	21	0.01	0.05
Developed, Low Intensity	22	0.038	0.063
Developed, Medium Intensity	23	0.056	0.094
Developed, High Intensity	24	0.075	0.125
Barren Land	31	0.025	0.035
Deciduous Forest	41	0.1	0.16
Evergreen Forest	42	0.1	0.16
Mixed Forest	43	0.1	0.16
Scrub/Shrub	52	0.035	0.07
Grassland/Herbaceous	71	0.025	0.035
Pasture/Hay	81	0.03	0.05
Cultivated Crops	82	0.025	0.06
Woody Wetlands	90	0.1	0.17
Emergent Herbaceous Wetland	95	0.075	0.17

2.2.4 Precipitation

While rainfall is complex, hydraulic modeling simplifies rainfall to three factors:

1. Quantity (depth in inches) of rain,
2. Spatial distribution (where it falls), and
3. Temporal distribution (intensity over time).

Precipitation distributions were compared to historical rainfall and the NOAA Atlas Third Quartile was found most similar; therefore, this rainfall distribution was applied in the models.

2.2.4.1 Spatial Distribution

Precipitation rarely falls at the same depth and intensity for an entire region. For example, **Error! Reference source not found.** below represents the non-uniform precipitation during the October 2015 storm event.

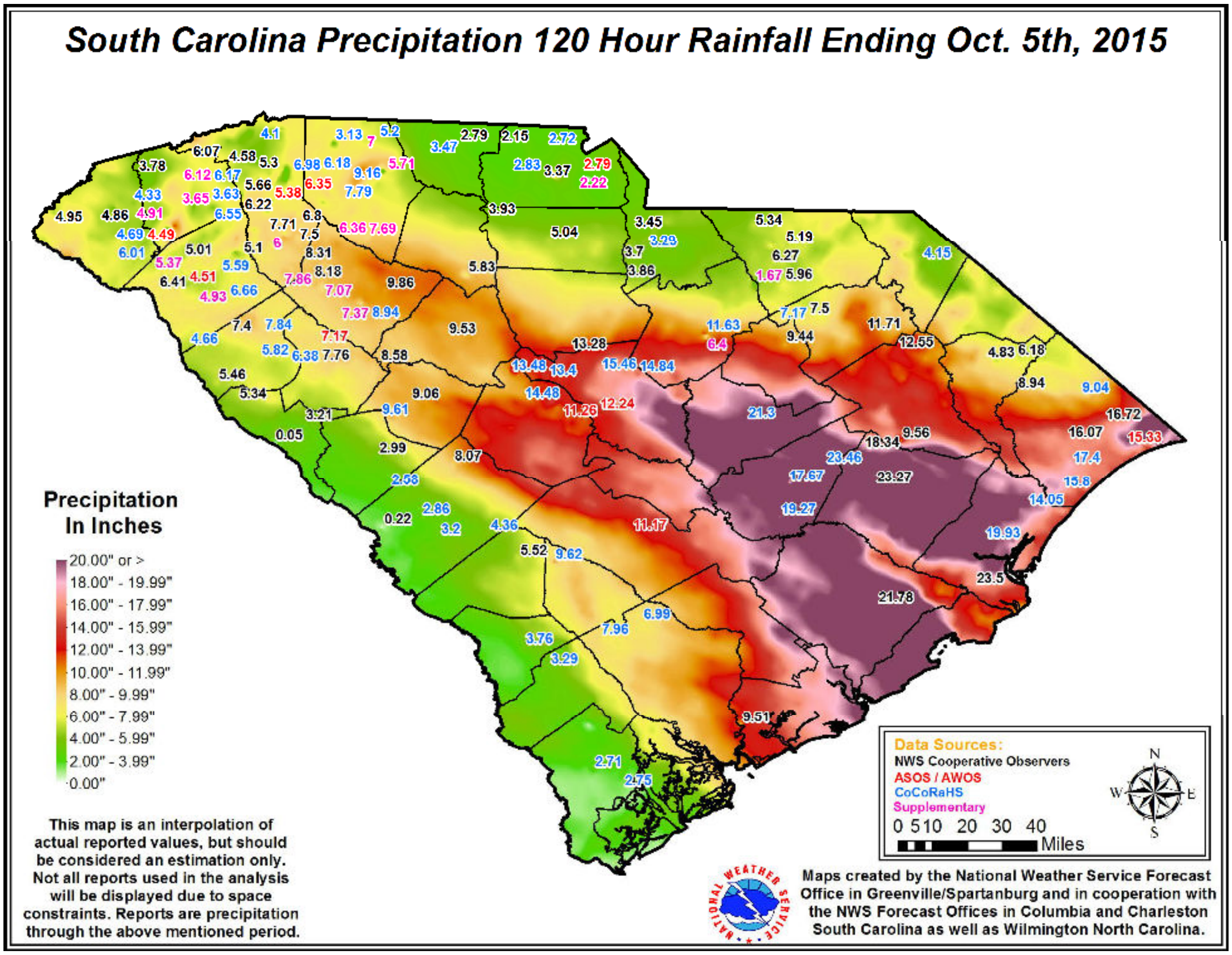

Figure 2. Precipitation Distribution (NWS Greenville-Spartanburg)

Theoretically, to account for spatial rainfall variation, the 2D model size may be limited to a small area no larger than 50 square miles. The area of interest would then be broken into many models and eventually brought back together. However, this process is unreasonable for such large watersheds; therefore, spatial variation is accounted only between large, modeled areas and not within the model itself. The approach described above is the most conservative as it represents rain falling uniformly throughout the entire watershed.

If desired, spatial variation can be addressed at a later phase as additional events can always be generated and added to the library.

2.2.4.2 Depths

Precipitation depths are taken from NOAA Atlas 14 at multiple precipitation points. These point depths are averaged over the model and a best fit formula is created to interpolate to any storm event.

The maximum rainfall on a record for a 24-hour period for South Carolina is 14.8 inches (approximately 0.1% Annual Exceedance Probability as determined by NOAA, see Figure 3). However, the NWS National Prediction Center has recorded the maximum total rainfall from a tropical cyclone was 23.6 inches (Figure 4). Storms that last two to four days commonly reach depths greater than the 1,000-year rainfall event.

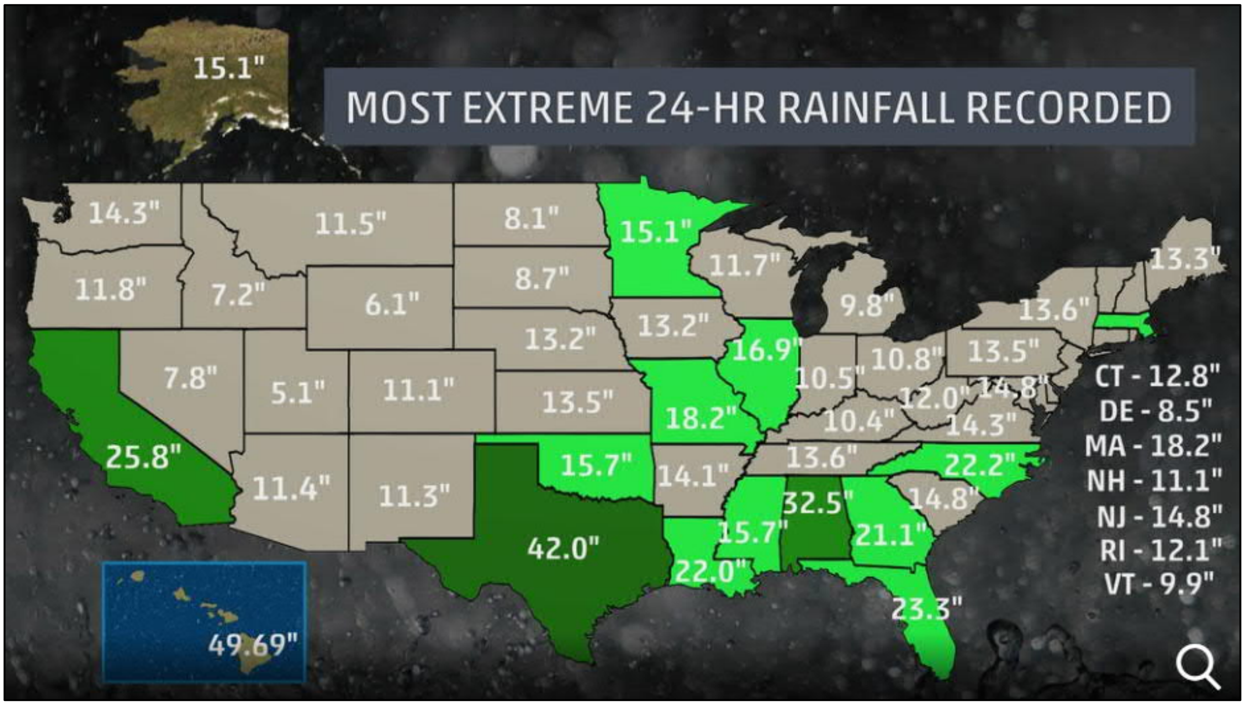

Figure 3. Maximum 24-HR Rainfall on Record (NOAA)

Furthermore, upon comparing South Carolina to other neighboring southeastern states, the rainfall in SC is observed to be among the lowest. For example, North Carolina's record is 150% higher, Florida 190%, and Texas 270%. Even if South Carolina is an outlier, rain from North Carolina will flow into South Carolina through watersheds that span both states. This leaves South Carolina in a vulnerable position and increases the likelihood of flooding.

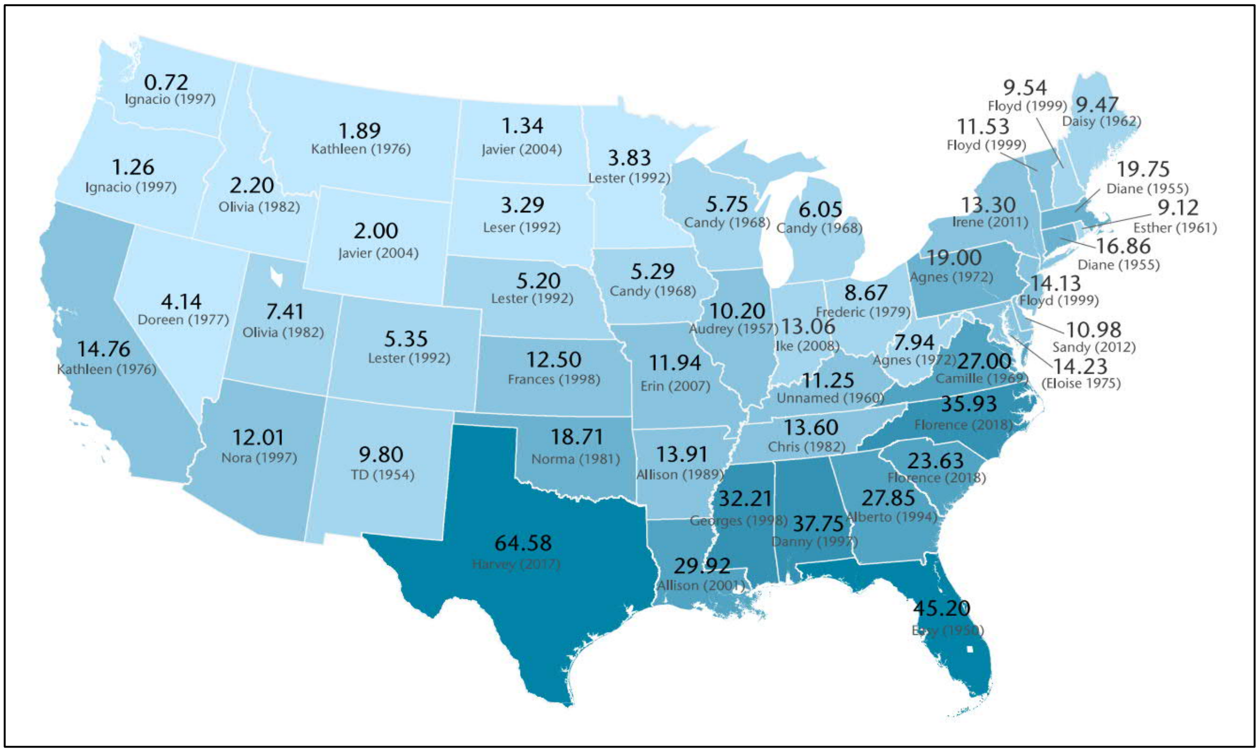

Figure 4. Maximum Tropical Cyclone Rainfall Records per State (NWS Weather Prediction Center)

Lastly, SC Flood IMPACT understands that it is critical to be more precise during a 1,000-year flood event (although those occurrences are less frequent) than for a 2-year storm event (although that is more common) because it is the larger events that have the greatest risk to life and property.

2.2.5 Dams and Levees

Potential flooding and increased discharges from dam or levee breaches were not considered at this time as the variations in flooding would be extensive and require numerous additional model runs. If desired, these scenarios could be created for future phases.

2.2.6 Breaklines

Breaklines are a set of polylines used to change the way the mesh (model area) is created and therefore the ability for water to convey. They are used to force cell faces to follow a terrain ridge or high point and are applied at all major transportation lines that can be determined within the DEM. Breaklines can also be added to other features within the DEM such as levees and around ponds.

2.2.7 Structures

As-built survey data (such as culvert dimensions and bridges) were not inserted into the model. However, where deemed appropriate, adjustments were applied to more realistically convey the effect that structures have on flow.

2.2.8 Inundation Mapping

Inundation boundary extents and rasters were developed for multiple storm events. The flood maps were refined from the initial output of HEC-RAS due to the rain-on-grid mechanism, which maps any depth of 0.001 feet or greater. A flooding depth of 0.001 feet is too shallow to pose a danger to the public and identifying it on the website is unnecessary. Therefore, in order to focus on flooding depths that pose a danger to life and property, the flooding is only displayed at 1.0 feet or higher. The figure below compares HEC-RAS raw boundary extents (yellow, depth of 0.001 ft) to refined results (blue, greater than 1 foot). Notice that many neighborhoods would be displayed as flooded (yellow) boundaries, but after refined results (blue) the flooding is mostly contained within the streets as opposed to the channels.

Figure 5. Flood Inundation Boundary (SC Flood IMPACT)

3. Methodology

3.1 Library of Events

SC Flood IMPACT is a library of pre-run HEC-RAS 2D models and associated databases. Access to the library is granted based on user level as there are several users (such as federal and local governmental agencies, the public, etc.) and their use range from mitigation planning to emergency management.

3.2 Algorithms

SC Flood IMPACT considers major factors that contribute to flooding such as precipitation, streamflow, tidal influence, initial model conditions, and dam releases (see Figure 6 below). From each of these factors, data is continuously analyzed using algorithms multiple times each day. The end goal is for the algorithm to choose an event from the library to display. By default, the website will not display a flooding scenario from the library until an event is triggered by the algorithm.

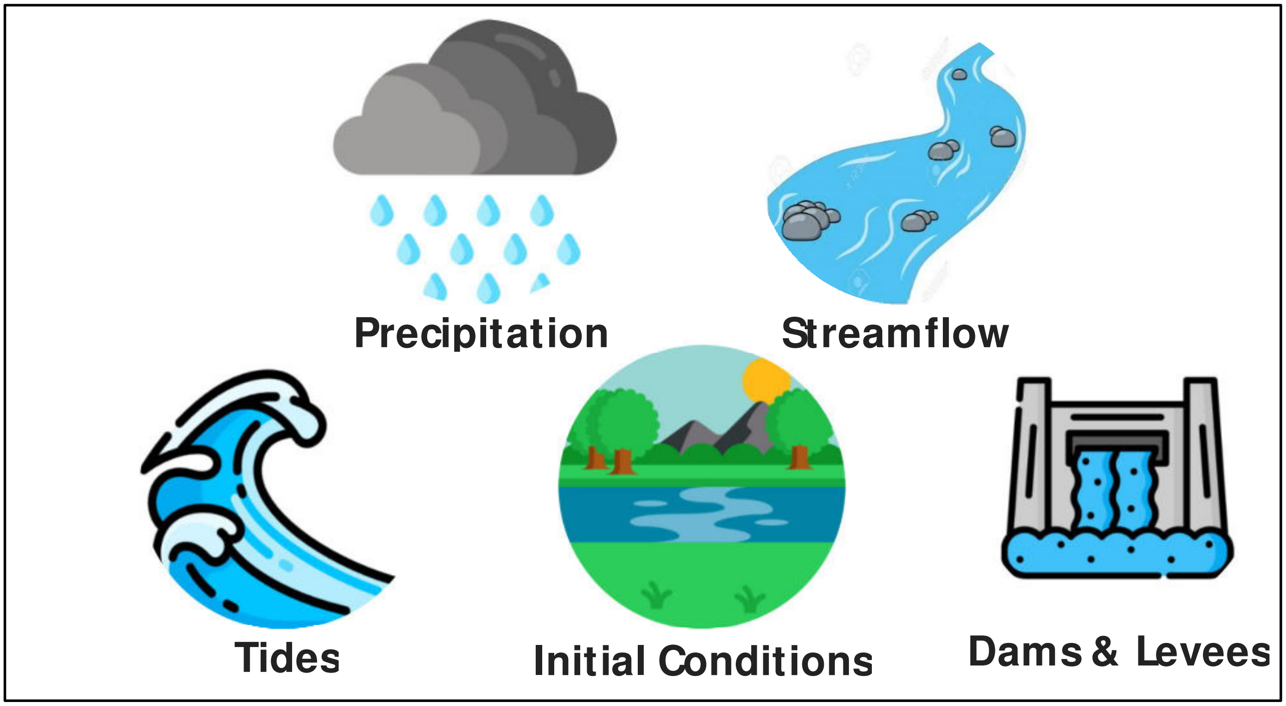

Figure 6. Input Parameters (SC Flood IMPACT)

3.3 Verification

SC Flood IMPACT records information into a database that may be used to:

- Improve forecasts by understanding which factors to utilize, ignore, or adjust,
- Find gaps within the system and prioritize areas of improvement,
- Improve the accuracy of flooding events with enhanced algorithms,
- Enhance the quality of assumptions in future areas or additional events in an existing area, and
- More efficiently communicate flooding events and historical results.

3.4 Quality Assurance and Quality Control

Quality Assurance (QA) and Quality Control (QC) were performed on all major aspects of this project including hydrology, hydraulic modeling, calibration, mapping, verification, and website creation. These categories consisted of numerous tasks to ensure each component of SC Flood IMPACT was functioning properly.

Passing was determined if the appropriate data sets, methodologies, and acceptable tolerances were applied. For example, the most up-to-date LiDAR datasets from SCDNR were utilized, as well as the most recent SC Regression equations.

The quality control checklist is shown in Table 3 and is discussed in further detail below:

Table 3. QA & QC Checklist (AECOM and SCDNR)

Hydrology QA & QC:	PASS	FAIL
Watershed Delineation	X	
Soil Type, Land Use, Manning's n values	X	
Precipitation Depth, Duration and Temporal Distributions	X	
Riverine Flows: Magnitude, Timing, and Relations	X	
Interpolated and Extrapolated Hydrologic Values	X	
Coastal Conditions	X	
Hydraulic QA & QC:	PASS	FAIL
Hydrology applied appropriately to the model	X	
Digital Elevation Model	X	
Breaklines	X	
Model Stability and Error Reduction	X	
Calibration QA & QC:	PASS	FAIL
Regression Equations	X	
Rating Curves	X	
Historical Events and High Water Marks	X	
FEMA National Flood Hazard Layer	X	

Mapping QA & QC:	PASS	FAIL
Non-threatening flooding removed	X	
Flooding gaps removed	X	
Backwater	X	
Website QA & QC:	PASS	FAIL
Load & Speed Testing	X	
Bug Testing	X	
Website Fires automatically	X	
Verification QA & QC:	PASS	FAIL
External and Internal Source Accountability	X	
Non-conventional means	X	
Database checks	X	

Hydrology quality assurance and control process starts with the delineation of the models to ensure that runoff from rainfall, backwater riverine effects, and coastal storm surge were properly being accounted for within the model. Several initial 2D models were run to test these variables and adjustments were made as necessary. Other datasets such as Manning's n values, land use, and soil type were adjusted per watershed area.

Hydraulic quality assurance and control consisted of evaluating the model's stability and volume percent error. The goal was to be under a 5% volumetric error. The majority of the models had a fraction of a percent of error.

Calibration quality assurance and control was the most extensive step as it ensured the 2D model was reasonable and included multiple examinations. One assessment was to compare the DEM to historical gage records to determine the appropriate starting water surface elevations and incorporate DEM modifications as needed. Initial models were run, and adjustments made to the 2D mesh and DEM, until flow conveyance was reasonable. Riverine flows and stages were compared to regression equations, FEMA Effective FIS, High Water Marks, and photographs. Furthermore, historical gage data was analyzed to ensure timing, magnitude, and volume of the riverine flows were reasonable. While each historic storm as different, an ensemble and range of appropriate controls were created to ensure the theoretical event was reflective of the area.

SCDNR and AECOM performed internal reviews of each modeling result and mesh cell data. Examples include ensuring that if mesh cells peak to an unreasonable extreme, those cells were adjusted to a normal level based on neighboring cells.

The website underwent an internal QC and QA from AECOM and SCDNR. Both organizations reviewed the website's features, functionality, and performed tests for any bugs. AECOM also performed load and speed testing capabilities of the website.

4. Findings

Flood Frequency Libraries were developed for the Little Pee Dee and the Lumber HUC 8 Watersheds. The libraries contain 10 flood frequency return intervals. The libraries will display on the SCDNR SC Flood IMPACT website during forecasted flood events. The SC Flood IMPACT website uses publicly available Quantitative Precipitation Forecasts (QPF) data from the NWS Weather Prediction Center, and Quality Controlled precipitation from the National Centers for Environmental Information, and gauge data from U.S. Geological Survey (USGS) and NWS stream gauges. This information is then used to have the website to pull the appropriate corresponding flood frequency layer from the library.

Table 4 provides a list of the flood frequency recurrence intervals and annual exceedance probabilities (AEP) contained in each HUC 8 library.

Table 4. Library Flood Frequencies (SC Flood IMPACT)

Recurrence Interval (years)	Annual Exceedance Probability (%)
10	10
25	4
50	2
100	1
150	0.67
250	0.4
500	0.2
1,000	0.1
1,500	0.067
2,000	0.05

Each library provides a range of flood frequency events from small magnitude (10% AEP) to larger than historically recorded events (up to 0.05% AEP). An example of the depth rasters for the Little Pee Dee and Lumber watersheds is shown in Figure 7 below.

It is important to note that the first HUC 8 area modeled and uploaded to SC Flood IMPACT was Black Watershed. This information is relevant as the methodologies utilized to build the Little Pee Dee and Lumber libraries were enhanced based on knowledge gained from developing the Black Watershed. In addition, a storm occurred in February 2021 that caused the website to respond by displaying inundation layers from the library. Please refer to Section 8.1 – Appendix A for more information.

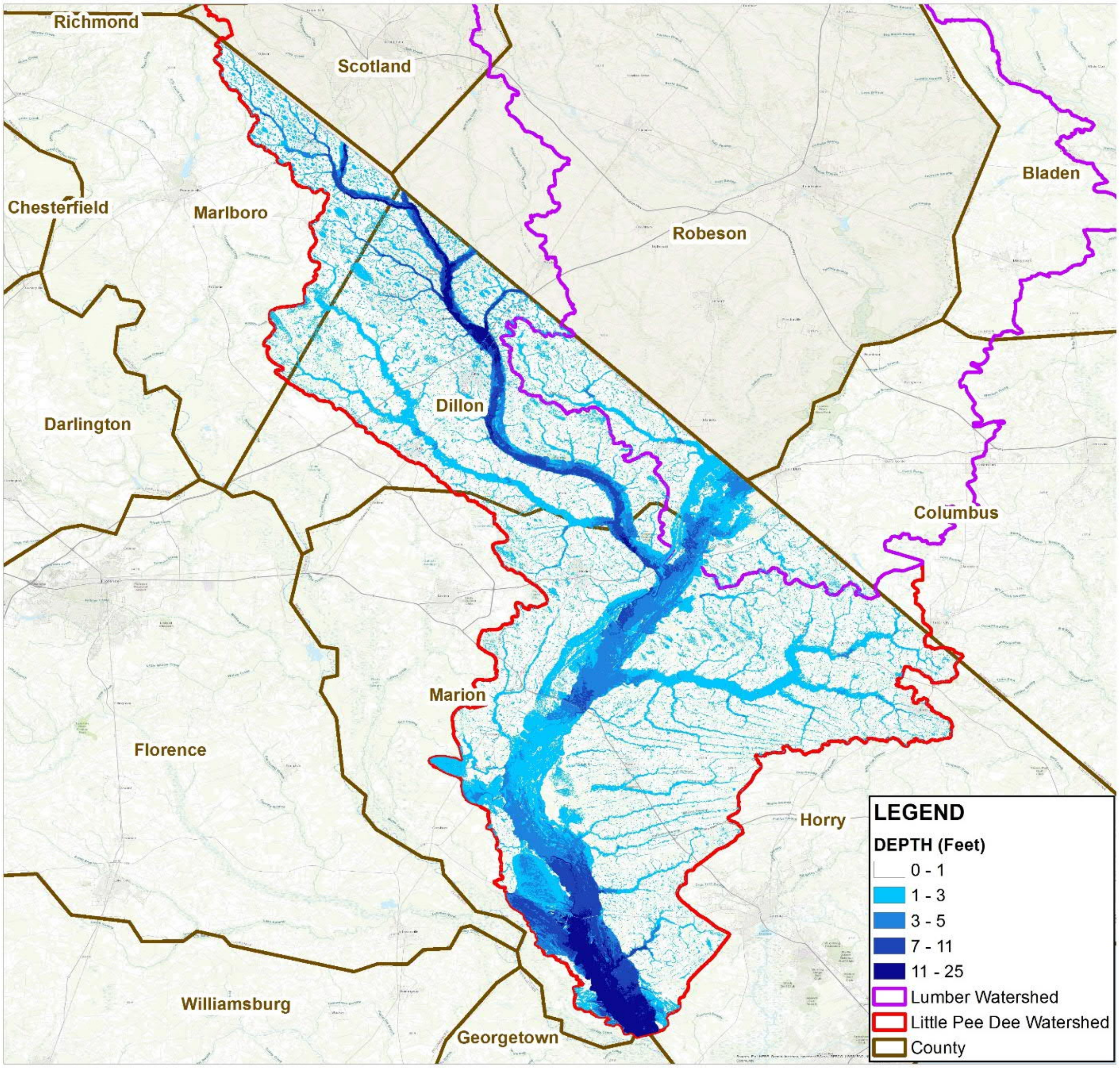

Figure 7. 0.1% AEP Inundation Depth Raster for Little Pee Dee and Lumber Watersheds (SC Flood IMPACT)

In addition to displaying forecasted flood maps, the SC Flood IMPACT website also provides a system for non-transportation related incidents (such as boat ramps), displays USGS gauge information, identifies potentially flooded buildings, transmits flood alerts, displays an interactive map viewer of Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) information, and provides the ability to download effective county information such as engineering models and coastal data. Please refer to Section 8.2 – Appendix B for a summary of all the website features.

5. Discussion

The proposed project of utilizing 2D hydraulic modeling to produce quality-controlled flood inundation libraries for Little Pee Dee and Lumber watersheds has been achieved for this project.

There were various factors that initially affected the mapping results:

- Transition from HEC-RAS versions 5.0.7 to 6.1. Version 6.1 contained significant improvements and new features to 2D modeling, methodologies, and techniques. This transition contained a few relevant bugs such as:
  - Output results from HEC-RAS did not account for modifications to the terrain, and
  - Various slope dimensions were auto adjusted by the model between 6.0 and 6.1 versions resulting in excessively deep, artificial detention areas.

While some of the challenges above were unanticipated, all were addressed and rectified as part of the quality control task.

Additional factors that affected the results:

- It is important to note that the depth is typically measured starting at either the normal water surface elevation or at ground level. Large water bodies may be deeper than indicated.
- For the general public, the flood maps will be presented as a solid boundary layer containing flood depths of 1 foot or greater. For users with elevated access (such as SCDOT), the flood maps will display depths of flooding in increments of one to two feet.

One of the main benefits of using rain-on-grid 2D modeling is that it identifies all areas that are at risk of flooding, as opposed to 1D modeling which focuses on a single stream. As a result, SC Flood IMPACT differentiates itself in this regard compared to similar websites that only display flooding within a mile upstream or downstream of a stream that has a USGS gauge. Likewise, FEMA's National Flood Insurance Program (NFIP) tends to only cover streams with a drainage area of at least one square mile, ignoring smaller streams, pluvial, and urban flooding. SC Flood IMPACT displays flooding whether that be a rural farmer's crop, a small stream in the backyard of a home, or the Great Pee Dee River as it is created using rain-on-grid in a 2D model. The statewide coverage will reach more end users and provide a unique product in comparison to the alternatives.

SC Flood IMPACT website was then augmented to include these inundation boundary extents and water depth rasters. Advantages for SCDOT include identifying areas that are at risk for flooding prior to the storm arriving. SCDOT could then determine which measures need to be taken to keep specific roads open, create and distribute maps of areas forecasted to flood, and utilize potential flood impacts to determine where to stage resources.

5.1 Project Deliverables

The scope of services outlined for this project include the following:

- Task 1: Develop a mapping library of at least 10 recurrence storm events using 2D modeling for Little Pee Dee Watershed,
- Task 2: Develop a mapping library of at least 10 recurrence storm events using 2D modeling for Lumber Watershed,
- Task 3: QA/QC of 2D mapping products,
- Task 4: Associated programming required to upload mapping libraries to SC Flood IMPACT website,
- Task 5: Provide SCDOT with elevated access to SC Flood IMPACT website,
- Task 6: Draft Final Report,
- Task 7: Final Report, and
- Task 8: Attend in person/virtual coordination meetings as needed.

All project deliverables were achieved and, in many cases, exceeded. For the mapping libraries, at least 10 recurrence storm events (scenarios) were created for each watershed. Flood maps were generated in the form of riverine flooding boundary polygons and flood depth rasters.

6. Conclusion, Recommendations, and Implementation

6.1 Conclusions

The Little Pee Dee and Lumber inundation raster libraries were created to be displayed on the SC Flood IMPACT website. This website provides state and local officials, as well as the public, with a reliable and accessible resource to communicate flood hazards and identify areas at risk of flooding.

Providing this information days in advance of the arrival of a large magnitude storm will aid government agencies and their partners with emergency response. As a result of the inundation library, flood inundation maps will no longer need to be created on an event-by-event basis. For the Little Pee Dee and Lumber watersheds, instantaneous forecast inundation maps will automatically display on the website up to 84 hours in advance of forecasted storm events. The forecast of 84 hours is based on precipitation data produced by the ECMWF. The forecast is updated every three hours.

Completion of the first phase of this project has set a precedent for the state of South Carolina. It is hopeful that with future funding, SC Flood IMPACT will continue to propel the State as one of the leading states in the country for flood awareness and preparedness.

6.2 Recommendations

While Phase 1 of SC Flood IMPACT is complete, it is only the beginning of providing South Carolina with an innovative flood alert system. Moving into Phase 2, the following considerations are recommended to further enhance the features provided by SC Flood IMPACT:

- Mitigation Planning Tool – allows the user to display and compare various storm scenarios, including up to 10 annual chance storm events as well as hindcast historic events (such as 2018 Hurricane Florence).

- Funding for calibration and verification of collected storm events. The more storm events that occur, the more stored data to compare the forecasted prediction to the actual occurrence. This will further refine SC Flood IMPACT's precision in forecasting the actual rainfall event. Shared verification information from SCDOT would also be very useful. For example, when SCDOT sends personnel to check if a road is flooded, information (such as USGS high water marks) could be utilized to improve SC Flood IMPACT.

- Inclusion of additional information for SCDOT regarding structures. SCDOT could provide survey information in the form of a spreadsheet listing the freeboard and low chords for specific structures. This information could indicate which bridges and roads would be inundated during a storm event and warrant closure to ensure public safety.

- Hydrographs could be created at USGS active Gauges, Rapid Deployment Gauges, select road crossings, and other areas of interest.

- The following information from SCDOT could be used to assist with verification/calibration and improve the modeling results used in SC Flood IMPACT:
  - Photographs of flooded structures that could be used on the website. This includes old photos that can be related to a date to match to an event in the library.
- Produce specialized reports containing information such as the water surface elevations at bridges, how many roads are impacted by flooding, how many buildings are predicted to flood, etc.

Further funding for additional riverine and coastal modeling areas and/or website features not listed above are needed to grow SC Flood IMPACT. Further discussion on how SCDOT would like to modify and improve SC Flood IMPACT is encouraged.

6.3 Implementation Plan

The flood frequency raster libraries for the Little Pee Dee and Lumber watersheds were generated and uploaded to the SC Flood IMPACT website which met the requirements of the deliverables.

SC Flood IMPACT is operational and the next steps towards implementation are for SCDOT to sign up for user access and become familiarized with the website features via training.

7. References

Elements of SC Flood IMPACT:

1. Hydrology
    a. Watershed HUC Delineation –
        i. https://www.usgs.gov/core-science-systems/ngp/national-hydrography/watershed-boundary-dataset?qt-science_support_page_related_con=4#qt-science_support_page_related_con
    b. Land use and land cover - U.S. Department of Agriculture, Chapter 5 of the NRCS National Engineering Handbook Part 630. Amended May 2012.
        i. https://www.mrlc.gov/
        ii. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for [North & South Carolina]. Available online. Accessed [2019].
    c. CN
        i. U.S. Department of Agriculture, Natural Resources Conservation Service, Urban Hydrology for Small Watersheds TR-55, June 1986.
    d. Manning's N values
        i. Chow, V. T., 1959, Open-channel hydraulics: New York, McGraw-Hill Book Company, 680 p.
        ii. Calenda, G.C., C.P. Mancini, and E. Volpi. (2005). "Distribution of Extreme Peak Floods of the Tiber River from the XV Century." Advances in Water Resources. 28(6):615-625.
    e. DEM / LiDAR
        i. South Carolina - South Carolina Department of Natural Resources, LiDAR data by County, June 2019, online at http://www.dnr.sc.gov/GIS/lidarstatus.html
        ii. https://www.dnr.sc.gov/GIS/lidarstatus.html
        iii. North Carolina - https://sdd.nc.gov/sdd/DataDownload.aspx
    f. Precipitation
        i. National Oceanic and Atmospheric Administration. NOAA Atlas 14, Volume 2, Version 3 Precipitation-Frequency Atlas of the United States. Silver Spring, Maryland, 2017.
            a. http://hdsc.nws.noaa.gov/hdsc/pfds/
        ii. Software
            1. U.S. Army Corps of Engineers. Hydrologic Engineering Center – Hydrologic Modeling System. (HEC-HMS) Version 4.2.

g. Major Storm Events
    i. SCDNR Climatology Office
        1. https://www.dnr.sc.gov/water/climate/sco/
        2. https://scdnr.maps.arcgis.com/apps/MapJournal/index.html?appid=2ac87a4a698c4e26902c1babbdba871b

2. Hydraulics
    a. Riverine Modeling
        i. Software
            1. U.S. Army Corps of Engineers. Hydrologic Engineering Center – River Analysis System (HEC-RAS) Version 5.0.7.
            2. U.S. Army Corps of Engineers. Hydrologic Engineering Center – River Analysis System (HEC-RAS) Version 6.0.
            3. U.S. Army Corps of Engineers. Hydrologic Engineering Center – River Analysis System (HEC-RAS) Version 6.1.
3. Website Features
    a. Data
        i. Effective FEMA NFIP
            1. https://msc.fema.gov/portal/advanceSearch
        ii. Building Footprints
            1. Provided by Microsoft Maps, dated 2012-2020 online at https://github.com/microsoft/USBuildingFootprints

8. Appendices

8.1 Appendix A – Black Watershed and Charleston Coastal Inundation Libraries

8.1.1 Black Watershed Flood Maps

Black Watershed was the first HUC 8 area chosen for SC Flood IMPACT and was funded by a HMGP awarded to SCDNR.

On SC Flood IMPACT, Black watershed will automatically display if a storm event is forecasted to occur within 84 hours. The forecasted flooding map presented on the website is updated every three hours.

For the general public, the flood maps will be presented as a solid boundary layer containing flood depths of one foot or greater. For users with elevated access (such as SCDOT and SCDNR), the flood maps will display depths of flooding in increments of one to two feet, up to a depth of 19 feet, see Figure 8.

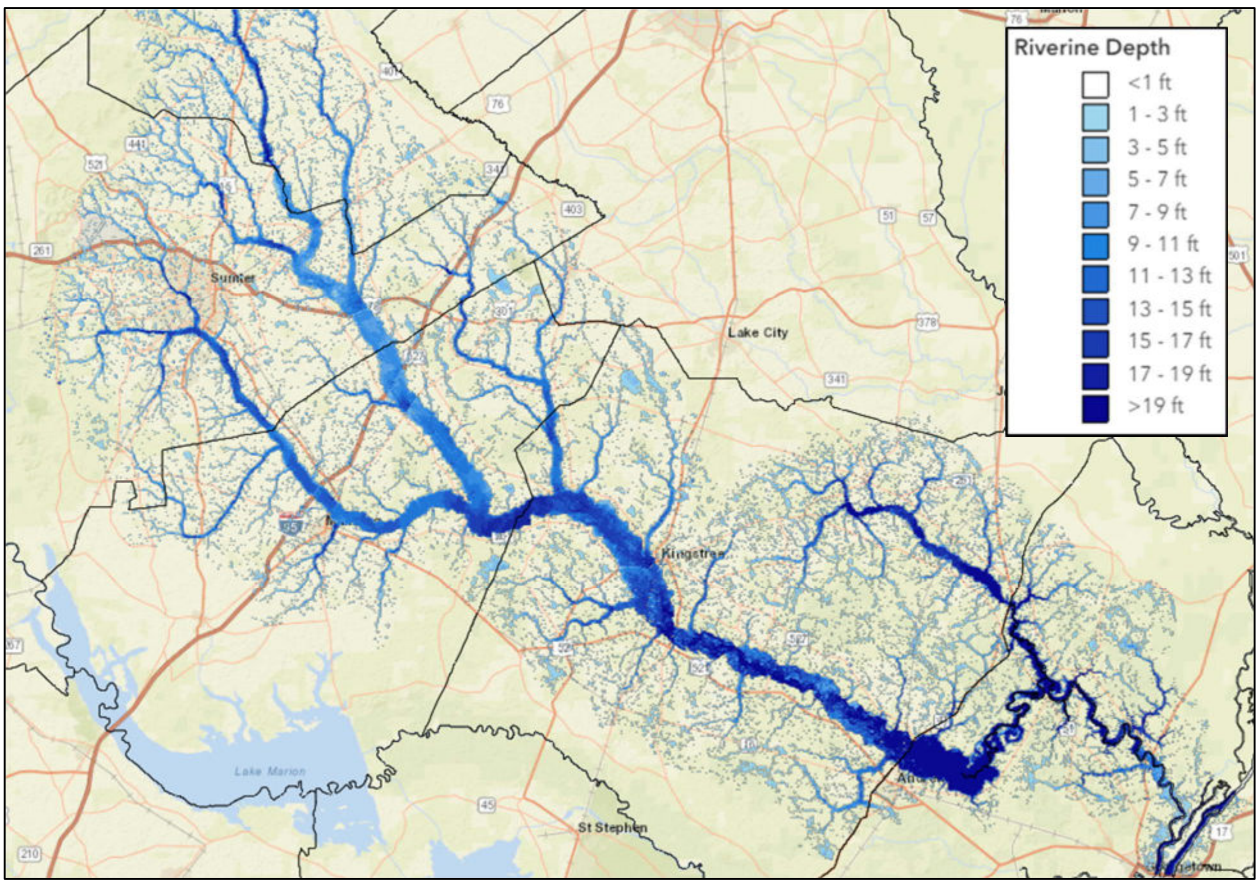

Figure 8. Black Watershed Flooding Extent (SC Flood IMPACT website)

8.1.2 Charleston Coastal / Tidal Flood Maps

The HMGP grant also provided funding for coastal flooding maps for the coast of Charleston County. NOAA's coastal information was utilized to produce a tidal flooding boundary layer (shown in Figure 9 for the coast of Charleston County. The forecasted flooding extents are updated every six hours. The boundary layer shows only the flooding extents.

Figure 9. Charleston Coastal Flooding Extent (SC Flood IMPACT website)

8.1.3 Website Storm Event Exercise

Regarding forecasting, the website was online starting February 2021, and contained the pilot areas Black Watershed and the Charleston county coastline. For Black watershed, the first applicable storm occurred around February 26, 2021 entailing about three inches of rainfall within 24 hours (1-year storm event). Upon performing verification of the forecasted rainfall and USGS gauge discharges, the findings were mixed as the forecasted rainfall was less than one inch and the forecasted riverine flows were significantly higher than actual. If the forecast predicted the actual three inches of rain instead of one inch, then the forecasted water surface elevations of SC Flood IMPACT would have been within a couple of tenths of a foot of the actual results at USGS gauges. This first test proved the need for the verification of forecasts and the dependence the system places upon them. While the first storm was not perfectly mapped, the main goal of the pilot was to develop the infrastructure that will improve precision over time. As the shortfalls of this first storm were addressed, the next storm could bring additional adjustments to consider.

8.2 Appendix B - Summary of Website Features

SC Flood IMPACT website contains several elements including:

- forecasted flooding for riverine and coastal areas,
- displaying gauge flood status,
- identifying potentially flooded buildings,
- ability to print forecasted flood maps and flood alerts, and
- providing effective and preliminary riverine and coastal data for downloading (since Map Modernization).

SC Flood IMPACT home page (see Figure 10) allows the user to navigate to two main pages:

1.) Floodplain Map Viewer, and
2.) Flood Inundation / Alerts Viewer.

Each of these options contains additional features that are discussed in the sections below.

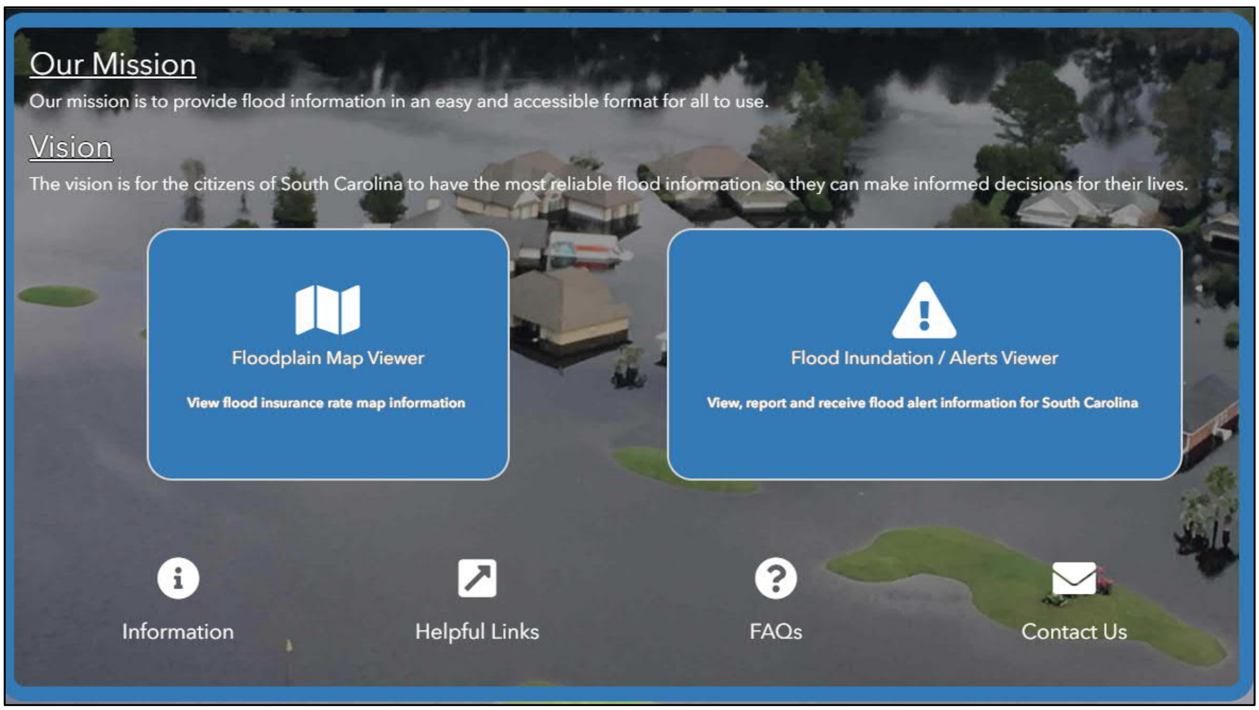

Figure 10. SC Flood IMPACT Main Page (SC Flood IMPACT website: www.scfloodimpact.com)

8.2.1 Floodplain Map Viewer Features

The purpose of the floodplain map viewer is to display FEMA FIRM information and provide users with effective data from FEMA's NFIP.

8.2.1.1 FEMA FIRM Information

Effective, Preliminary and map changes since last FIRM information for the entire state of South Carolina is available for the user to pan around and navigate (see Figure 11 below). If desired, the user can type in a specific address or click directly on the map to view the following:

- Flood zones (e.g. Zone A, AE, VE, and X),
- Cross sections,
- Coastal Transects,
- Effective floodplain boundaries,
- Preliminary floodplain boundaries,
- Map changes since last FIRM, and
- Effective FIRM panel numbers (such as 45067C0137E shown in the figure below).

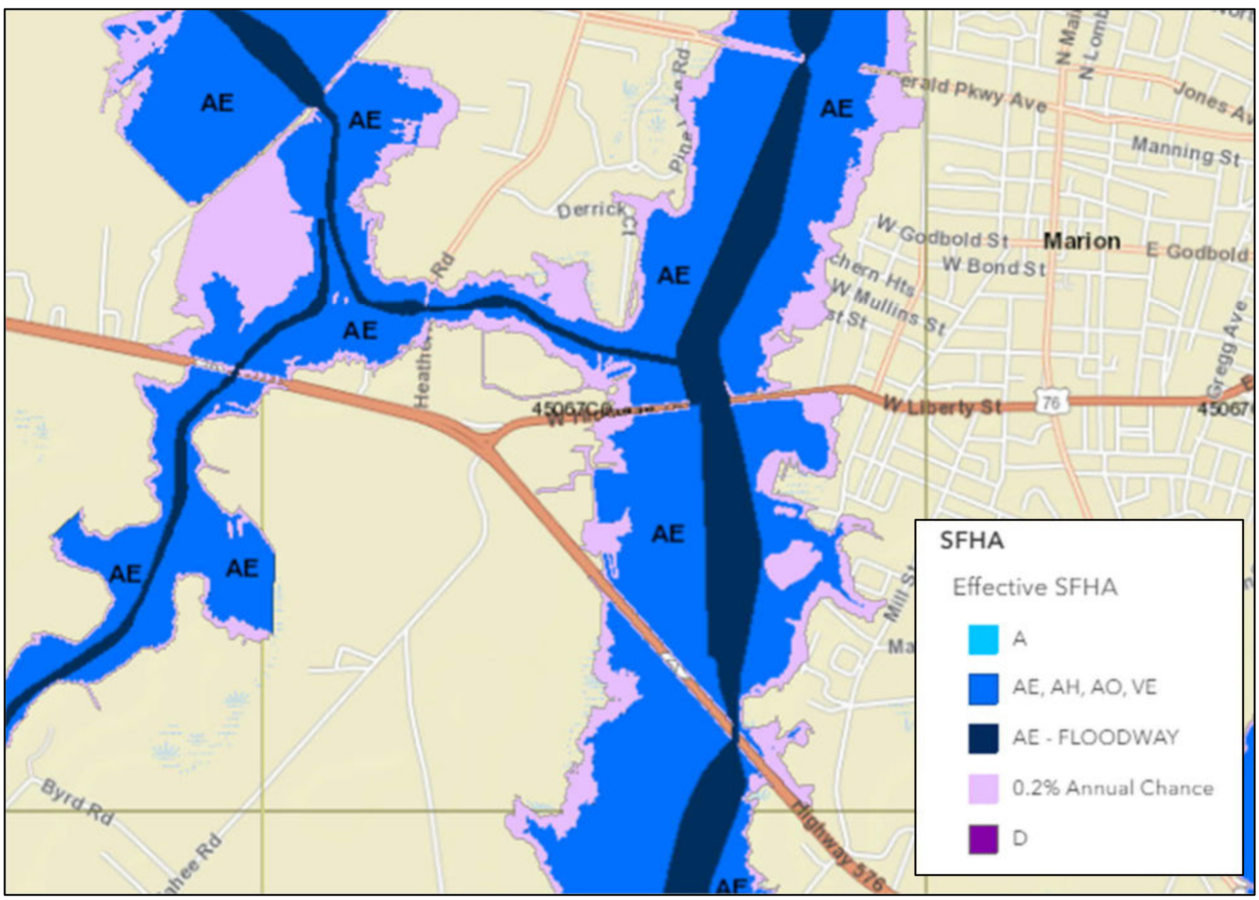

Figure 11. Effective Floodplain Boundaries in Marion County (SC Flood IMPACT website)

8.2.1.2 National Flood Insurance Program Data

All recent and future FEMA NFIP studies will be uploaded and stored on SC Flood IMPACT for public and/or governmental use. Please note that SC Flood IMPACT only contains engineering models for riverine studies that utilized more recent hydraulic modeling programs such as HEC-RAS. Requests for any model produced prior to the state entering the Cooperating Technical Partners (CTP) Agreement should contact FEMA directly.

The information available for download includes:

- Effective hydraulic engineering models,
- Summary of Map Actions (SOMA's),
- Flood Insurance Studies (FIS), and
- Effective coastal data such as Wave Height Analysis for Flood Insurance Studies (WHAFIS), transects, Intermediate Data Submissions (IDS) 4 and 5 reports, and runup and overtopping.

8.2.2 Flood Inundation / Alerts Viewer Features

The purpose of the Flood Inundation / Alerts Viewer is to allow users to view, report, and receive flood alert information. There are numerous features that will be available to both the public and state government officials in regards to emergency planning and evacuation. These features are discussed in the sections below.

8.2.2.1 Riverine Flood Maps

Riverine flooding for Little Pee Dee and Lumber watersheds will automatically display if a storm event is forecasted to occur within 84 hours. The forecasted flooding map presented on the website is updated every three hours.

For the general public, the flood maps will be presented as a solid boundary layer containing flood depths of one foot or greater. For users with elevated access (such as SCDOT and SCDNR), the flood maps will display depths of flooding in increments of one to two feet, up to a depth of 19 feet.

8.2.2.2 Reporting Incidents

There are numerous types of incidents that the public can report. Users can click a specific location in South Carolina and fill out the report form (Figure 12) including adding an attachment such as a photo of an impassible road due to flooding or a downed powerline.

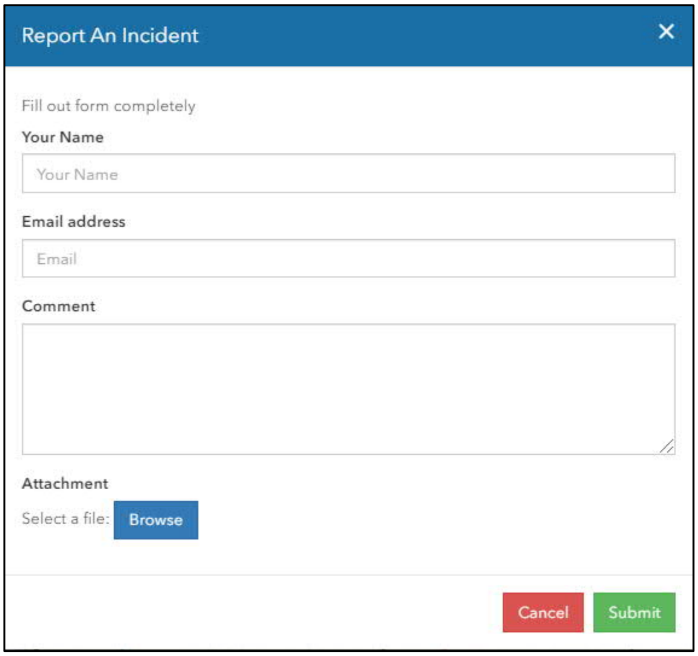

Figure 12. Incident Report Form (SC Flood IMPACT website)

Incidents will be reviewed by an administrator before being uploaded to the website. This feature is not intended to replace existing reporting state agency tools. It is more tailored for informational purposes only. Figure 13 illustrates how incidents will appear on the website.

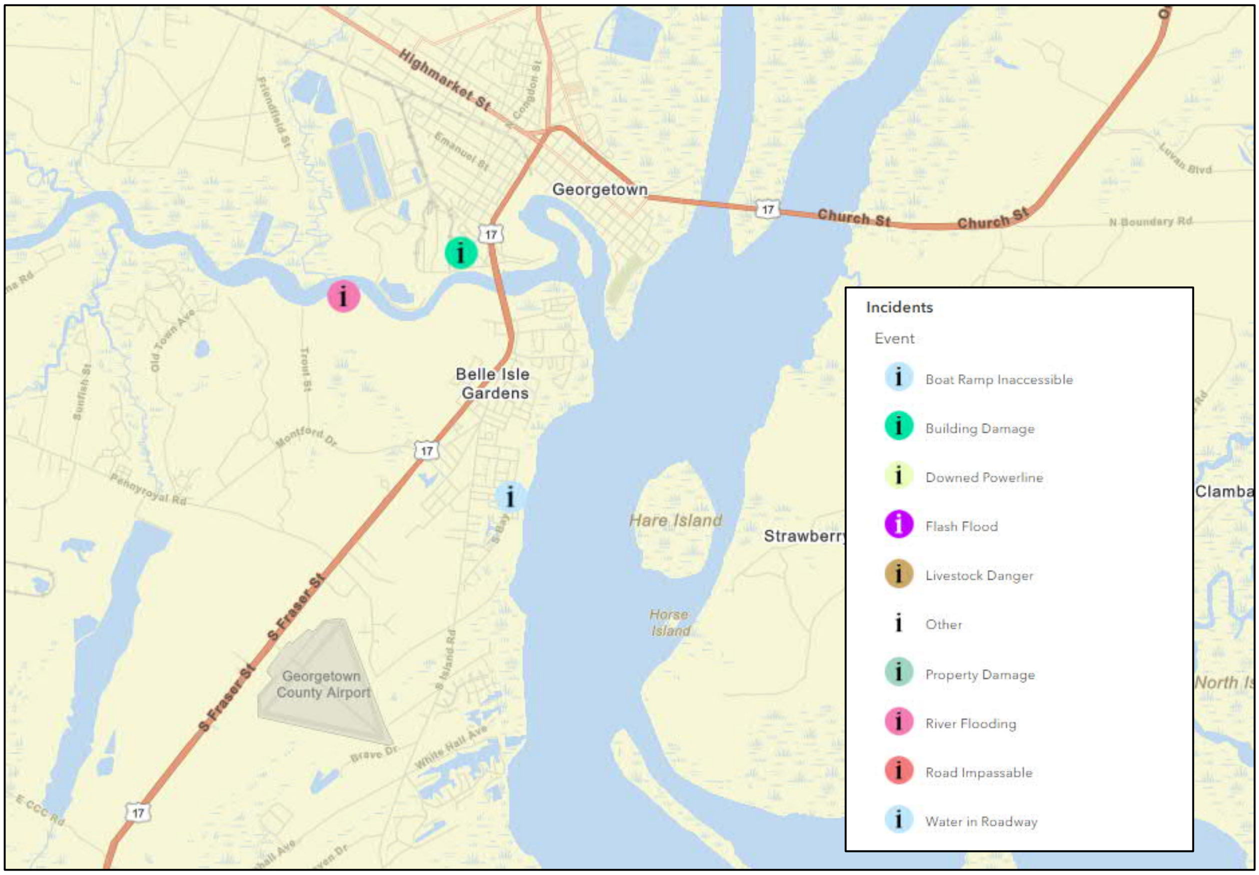

Figure 13. Reportable Incidents surrounding City of Georgetown (SC Flood IMPACT website)

8.2.2.3 Gauges

SC Flood IMPACT displays the current flooding status of all SERFC gauges in South Carolina represented by shape and color, see Figure 14.

- Shape
  - triangle - represents an increase or rising of flood levels
  - inverted triangle - represents a decrease or falling of flood levels
  - square - represents a constant level of flooding
- Color
  - Purple – Major Flood Stage
  - Red – Moderate Flood Stage
  - Orange – Minor Flood Stage
  - Yellow – Action Flood Stage
  - White – No information or no action flood stage

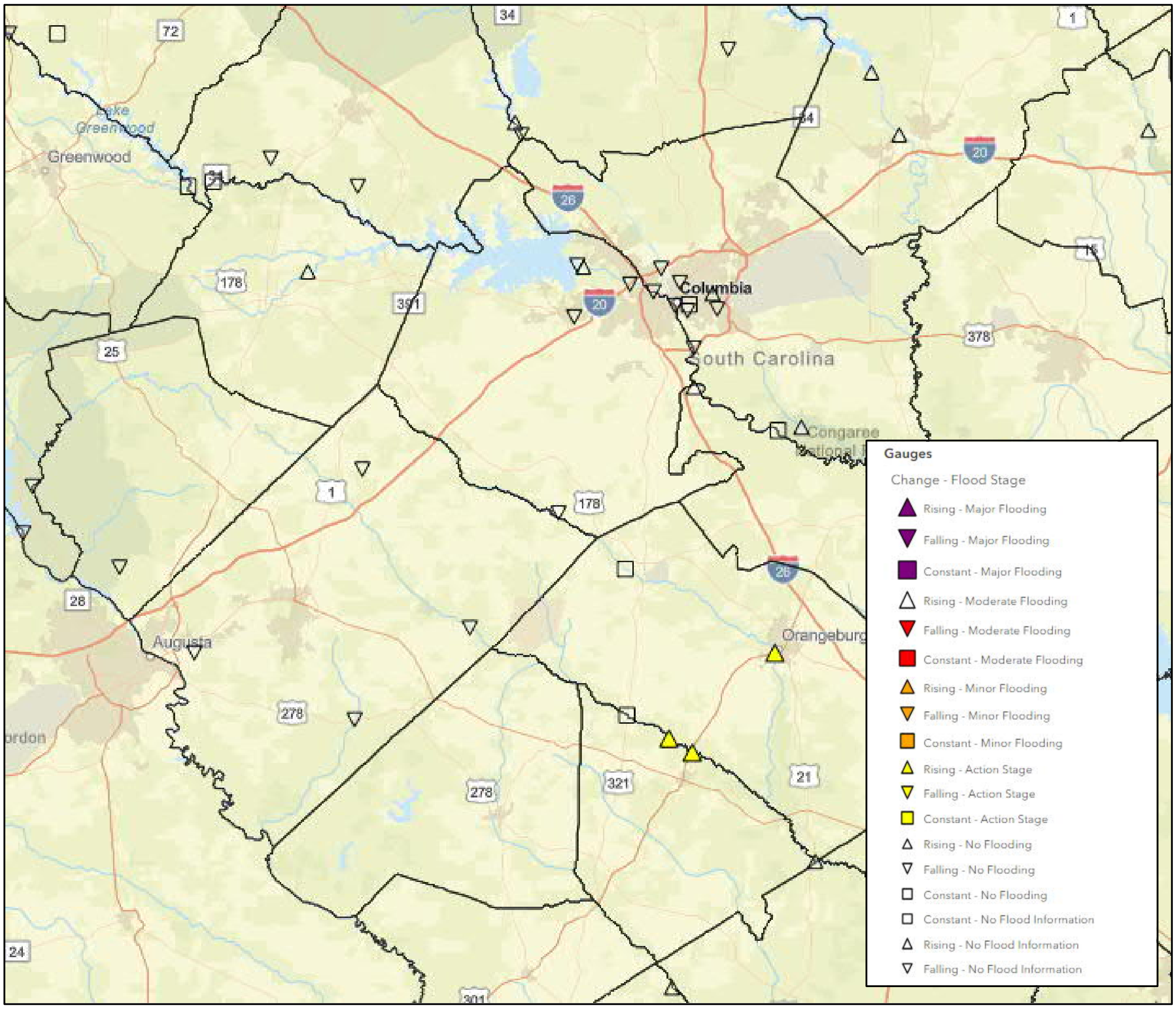

Figure 14. Flood Status Levels at Gauges (SC Flood IMPACT website)

By clicking on forecasted gauges, additional information will display such as the current and forecasted stages, and a chart with flood elevations associated with each flood status (action, minor, moderate, and major status) as shown in Figure 15 below.

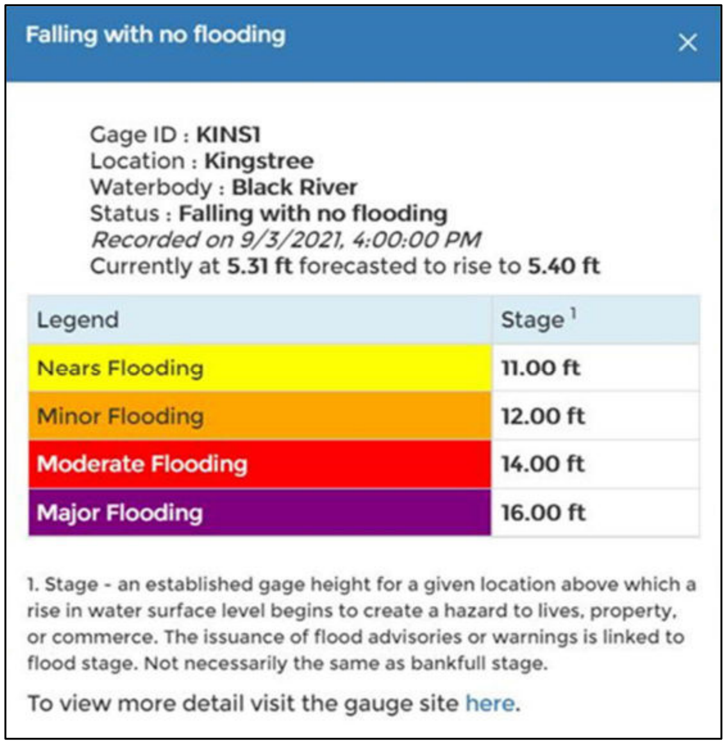

Figure 15. Flood Information at Forecasted Gauge ID ORBS1 (SC Flood IMPACT website)

8.2.2.4 Flooded Buildings

Building footprints are another feature available on SC Flood IMPACT (see Figure 16). During flooding events, buildings will be illustrated in red to indicate their potential risk of flooding. This feature was included to assist in search and rescue. Building footprints were provided by Microsoft (data acquired from 2012 to 2020).

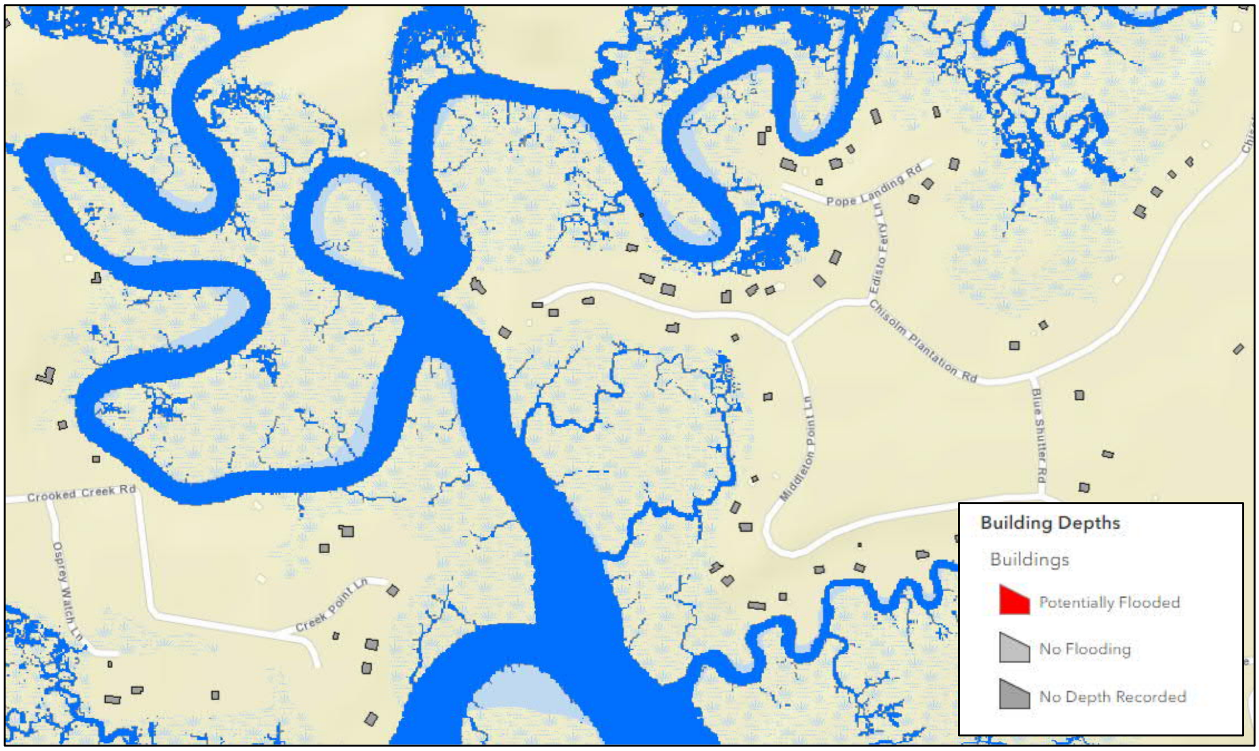

Figure 16. Building Flooding Depths (SC Flood IMPACT website)

8.2.2.5 Radar

Rainfall radar information is a useful feature that can be toggled on and off. Radar data was provided by the National Weather Service. Figure 17 below illustrates the radar on the website.

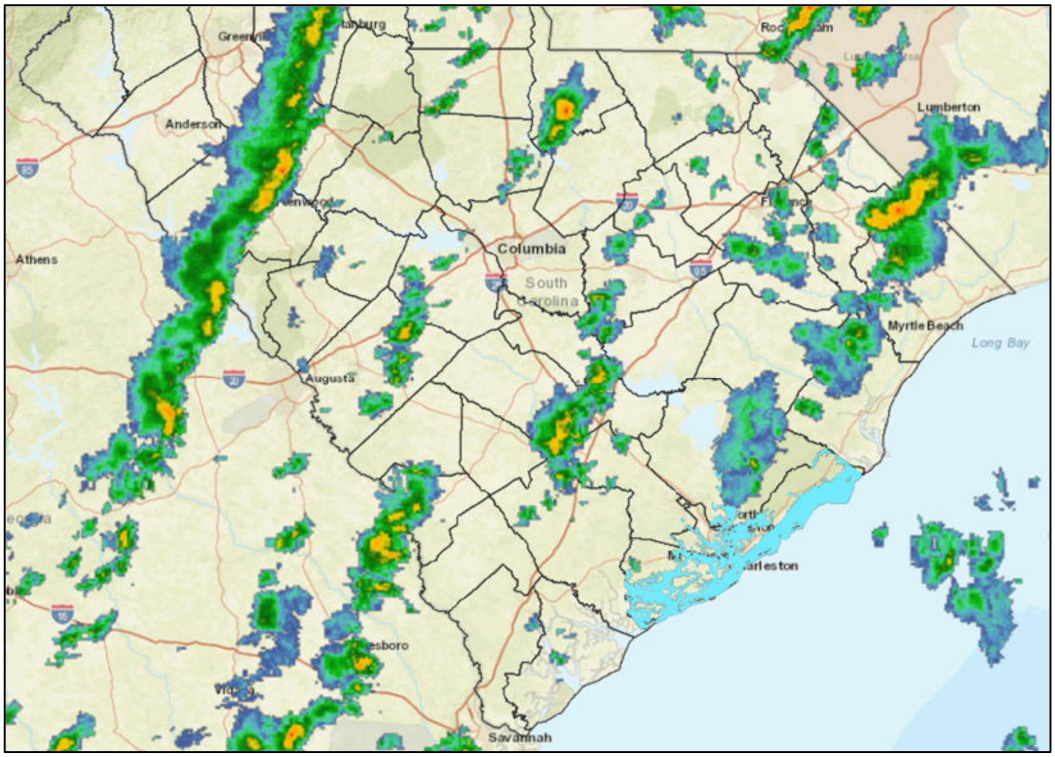

Figure 17. SC Flood IMPACT Radar (SC Flood IMPACT website)

8.2.2.6 Boat Ramps

Freshwater and saltwater boat ramp database and locations were provided by SCDNR (see Figure 18). Users can interactively click on a specific boat ramp to gather additional information such as the owner, surrounding water body, and current status of the ramp (open or closed).

Figure 18. Boat Ramps surrounding Georgetown County (SC Flood IMPACT website)

8.2.2.7 Evacuation Routes

Evacuation Routes are also provided for citizens who reside in the lower half of the state (see Figure 19). This layer was provided by SCDNR.

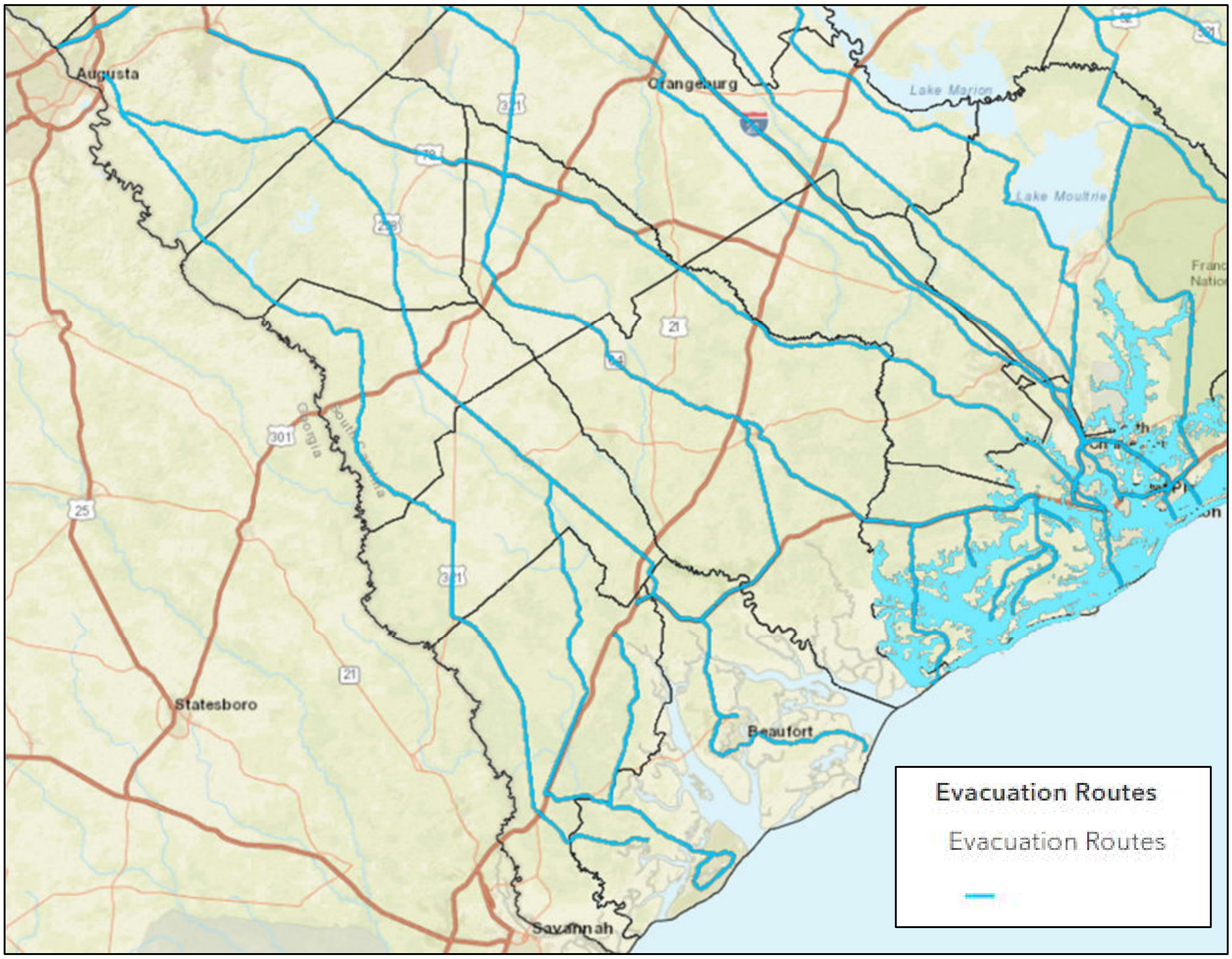

Figure 19. South Carolina Evacuation Routes (SC Flood IMPACT website)

8.2.3 Creating and Exporting Exhibits

In both the 'Floodplain Map Viewer' and 'Flood Inundation / Alerts Viewer' navigation panes, the user can create and export exhibits for individual use. Figure 20 below is an example of an exhibit of the effective floodplain boundaries for Marion County.

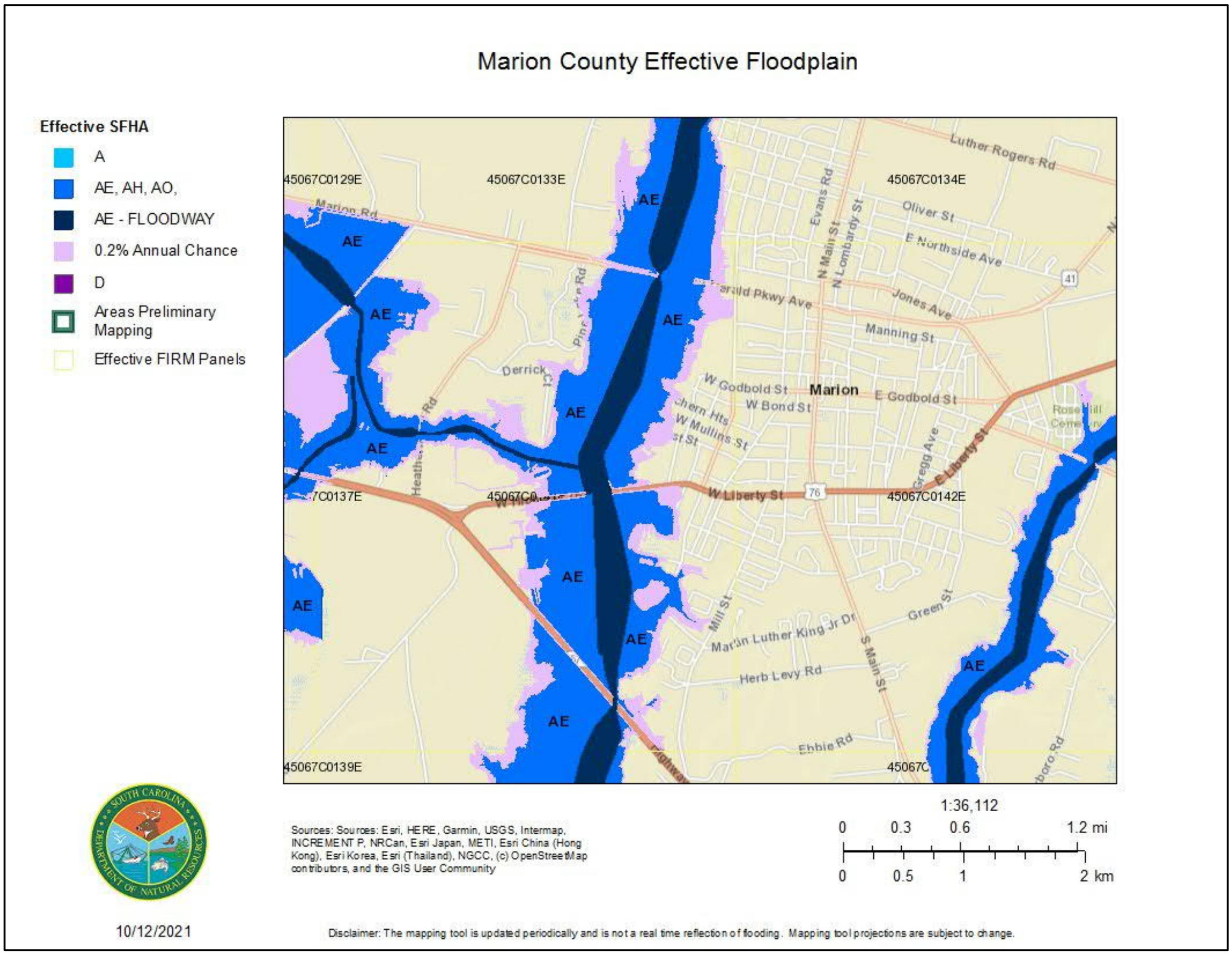

Figure 20. Marion County Effective Floodplain Boundaries Exhibit (SC Flood IMPACT website)

Figure 21 is an example of an exhibit created in the Flood Inundation / Alerts Viewer navigation pane. This figure also depicts gauges, boat ramps, and a flooding incident.

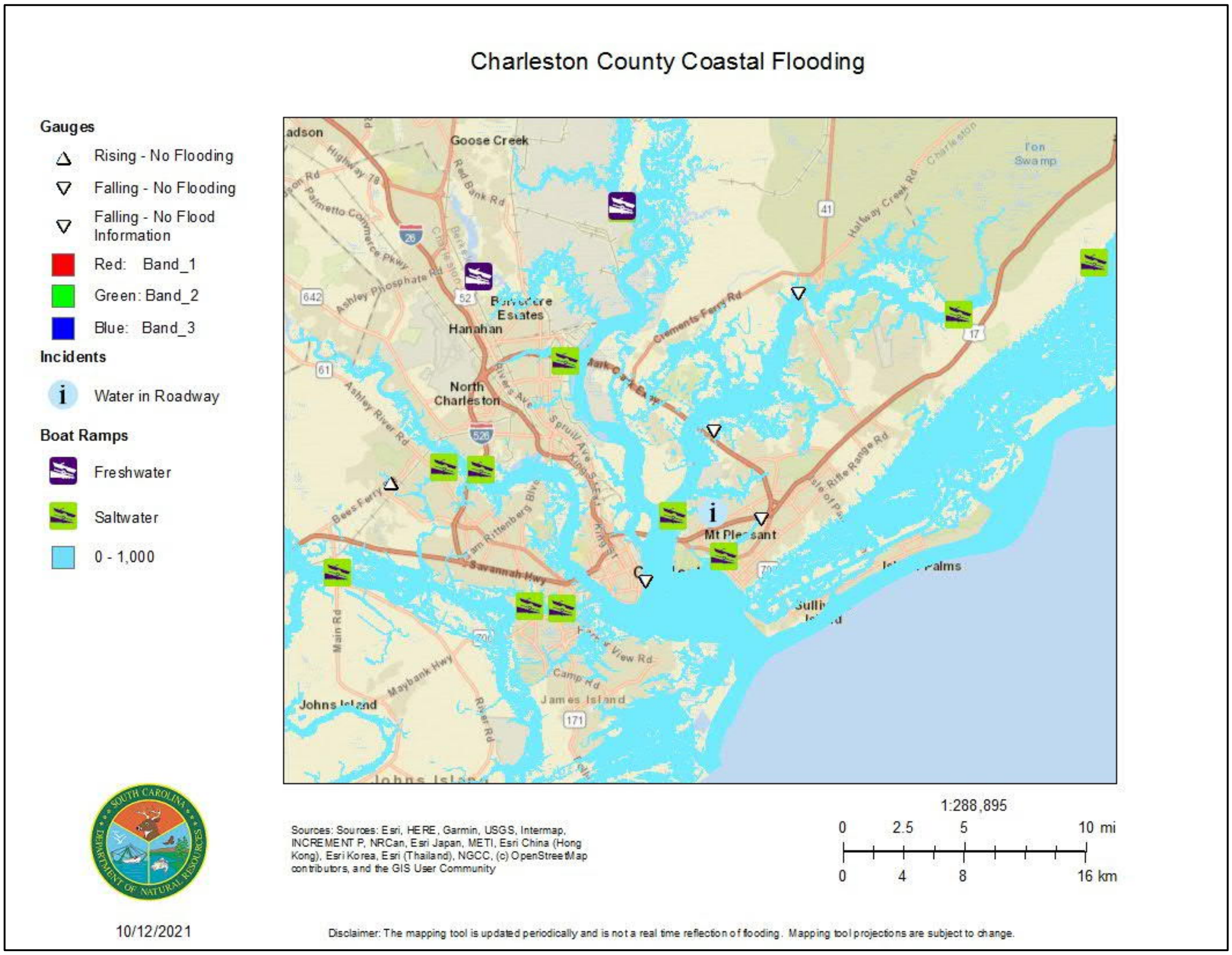

Figure 21. Charleston County Flooding Exhibit (SC Flood IMPACT website)