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RESEARCH & DEVELOPMENT

Predicting Roadway Washout Locations During Extreme Rainfall Events

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16. Abstract

NCDOT provided data for 1410 locations where hydraulic structures (culverts & bridges) washed out during Hurricanes Matthew and Florence and during extreme flooding that occurred in 2020. Washouts were confirmed for 1313 locations. Drainage area, watershed characteristics and structure capacity and physical parameters were calculated and compiled for all washouts. The same data was also compiled for 3,610 structures that did not washout in a six-county area of the Coastal Plain that were located within a 1 km buffer radius of a washout. Statistical analysis revealed that rainfall intensities did not explain the differences between washout and non-washout locations. Washouts were found to be most common in small watersheds (<0.5 mi^2), along secondary roads, on corrugated metal and reinforced concrete pipes with diameters < 72 in. In addition, lack of a headwall, shorter pipe lengths, high headwall over pipe diameter ratios and lower pipe area to watershed area ratios were common factors for many washout locations. A SAS Viya platform was developed in collaboration with the SAS Institute to allow for viewing, comparing, and exporting the data by proximity to a point, watershed or county boundary.

Hydrologic and hydraulic modeling was conducted to identify and evaluate potential resilient routes for 3 study watersheds. HEC-HMS models were developed for two watersheds, Hunting and Drowning Creeks and a HEC-RAS rain-on-grid model was developed for Nahunta Swamp. The HEC-HMS models were used along with HEC-RAS to evaluate overtopping discharges at major crossings. I77 and US421 in Drowning Creek were identified as potential resilient routes and several river crossings in the Hunting Creek watershed were shown to have moderate to high resilience. However, the HEC-HMS and HEC-RAS approach to evaluate potential resilient routes was found to be limited because only ~15% of the washouts statewide occurred on FEMA mapped streams. For Nahunta Swamp, nine theoretical resilient routes were identified and evaluated using the HEC-RAS rain-on-grid model outputs. Modeled water levels for the 25, 50, 100 and 500-year storm were compared to the roadway elevation at all hydraulic structures and at every 50-foot segment of roadway along the nine resilient routes to determine depths of overtopping. Costing procedures for upgrading all structures and roadways above the flood level were developed. NCSU guided the SAS Institute in developing the Transportation Resilience Identification and Prioritization (TRIP) tool using the road, hydraulic and overtopping data as well as the costing procedures. The TRIP tool allows the user to 1) view and compile impacts of past storms and design storms, 2) prepare asset management summaries for existing roads and hydraulic structures, 3) evaluate the resilience of key transportation routes, and 3) estimate costs for increasing the resilience of existing routes to each design storm. In addition, NCSU developed a computer application to import radar rainfall data into HEC-RAS rain-on-grid models.

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Executive Summary

Since the mid-1990s, North Carolina has experienced more frequent extreme events that have negatively affected our transportation infrastructure. Road flooding, damage, washout, short and long-term closures have resulted in loss of life, traffic delays, expensive repairs and negative impacts to citizens and communities. In response, North Carlina Department of Transportation (NCDOT) contracted NC Sea Grant and the NC State University Biological and Agricultural Engineering Department (NCSU) to evaluate factors that contribute to road washouts and to develop procedures for identifying potential roadways that could serve as critical resilient routes during and immediately following extreme rainfall and flooding events.

NCDOT provided data for all washout locations where the Hydraulics Unit had prepared designs for replacement structures. The data was focused on locations where pipes were severely damaged or completely washed away by Hurricanes Matthew and Florence or during extreme flooding that occurred in 2020. This data was carefully screened and reviewed to validate the location of the washout and the structure size and features at this location. Washouts were confirmed for 1313 of 1410 locations provided. For each location, a drainage area was delineated, and specific watershed characteristics were determined (e.g. slope, runoff curve number, etc.). The structure size, length, material, road functional class, and presence of headwall were compiled. The structure equivalent flow area was calculated. Elevations of the roadway and streambed downstream were also estimated from LiDAR data. In addition, using a 1 km buffer radius around all washout locations in a six-county area of the Coastal Plain, the same data was compiled for 3,610 adjacent structures that did not washout. Statistical analysis including machine learning and use of the SAS Institutes' Viya data analytics platform were used to evaluate washouts. Rainfall intensities did not explain the differences between washout and non-washout locations. Washouts were found to be most common in small watersheds (<0.5 mi^2), along secondary roads, on corrugated metal and reinforced concrete pipes with diameters < 72 in. In addition, lack of a headwall, shorter pipe lengths, high headwall over pipe diameter ratios and lower pipe area to watershed area ratios were common factors for many washout locations. The SAS Viya platform provided insightful ways of quickly viewing, comparing, and exporting the data by proximity to a point, watershed or county boundary.

The second phase of the project was focused on identifying and evaluating potential resilient routes for three study watersheds. HEC-HMS models were developed for two watersheds: Hunting and Drowning Creeks. The HEC-HMS models were used along with HEC-RAS to evaluate overtopping discharges at major crossings. However, the coarse nature of HMS models limited their use for evaluating smaller crossings along potential resilient routes. A HEC-RAS rain-on-grid model was developed for a third watershed, Nahunta Swamp. Nine theoretical resilient routes were identified and evaluated using the HEC-RAS rain-on-grid model outputs. Modeled water levels for the 25,50, 100 and 500-year storm were compared to the roadway elevation at all hydraulic structures and at every 50-foot segment of roadway along the nine resilient routes to determine depths of overtopping. Costing procedures for upgrading all structures and roadways above the flood level were developed. All road, hydraulic and overtopping data as well as the costing procedures were provided to the SAS Institute for creating a prototype geospatial data visualization tool using SAS Viya. The Transportation Resilience Identification and Prioritization (TRIP) tool was developed to 1) view and compile impacts of past storms and design storms, 2) prepare asset management summaries for existing roads and hydraulic structures, 3) evaluate the resilience of key transportation routes, and 3)

estimate costs for increasing the resilience of existing routes to each design storm. In addition, to facilitate acquisition and import of radar rainfall data into the HEC-RAS rain-on-grid model for this analysis, a coded computer application was developed. The tool is available for NCDOT and NCEM to download gridded historical and predicted rainfall, transform the data into HEC-DSS format, extract model output and calculate roadway inundation shapefiles.

1 Introduction

Recent hurricane and tropical storm-induced extreme rainfall events caused hundreds of culvert and bridge washouts and less severe damage to hundreds more. These types of failures present serious vulnerabilities in the transportation network and pose a safety risk. With future climate projections indicating that storms are likely to occur more frequently, become stronger, travel at a slower pace, and produce more rainfall, the potential for additional washouts in the future is a growing concern. In addition, NCDOT is currently unable to predict where washouts are likely to occur, and thus can only react to failures as they are reported. In response to these concerns NCDOT issued a research call to evaluate past washouts and develop methods for predicting where washouts are likely to occur.

NC Sea Grant and NC State University Biological and Agricultural Engineering Department were selected to complete a study to address washouts vulnerabilities. The study effort included geospatial analysis, statistical modeling, hydraulic modeling, application development and the creation of visual analytics dashboards. The primary goals of this project were to (1) characterize past washout data in terms of location, drainage area and culvert and landscape attributes, and (2) determine if these factors could be used to predict washout locations. (3) develop hydrologic and hydraulic models to help predict potential road washouts, (4) develop an application to help run the models and visualize the results, and (5) develop a network of resilient routes for the modeled watersheds. The methods, results and conclusions from these efforts are presented in this report.

2 Methods

2.1 Characterize Culvert and Bridge Washouts

NCDOT provided NCSU with their database of washout locations for which the Hydraulics Unit developed design recommendations for structure replacements. This dataset may not contain all the washout locations. Overall, the washout location data were in poor condition (particularly for Hurricane Matthew) with respect to the completeness and accuracy. A substantial amount of time was dedicated to moving data points to the correct locations and formatting the data into a usable form. Some of the remaining questionable locations were sent to NCDOT for review. After evaluation and review, NCSU was able to confirm, with some confidence, the locations of 700/728 washouts for Matthew, 485/489 washouts for Florence and 190/193 washouts for the 2020 storms. However, some of the attribute data such as pipe size, material type, and cover were missing and could not be located by NCDOT (Figure 2-1; Table 2-1).

Table 2-1. Total washout locations data completeness.

Storm	DOT Data	Location Confirmed	Size Available
Matthew	728	700	667
Florence	489	485	464
2020 Storms	193	190	182

After finalizing the locations of the washouts, the watersheds for all the washout that occurred during Matthew, Florence, and the 2020 storm events were delineated using StreamStats for the larger watersheds on the main drainage network and ArcHydro or manual methods in ArcGIS for the smaller watersheds.

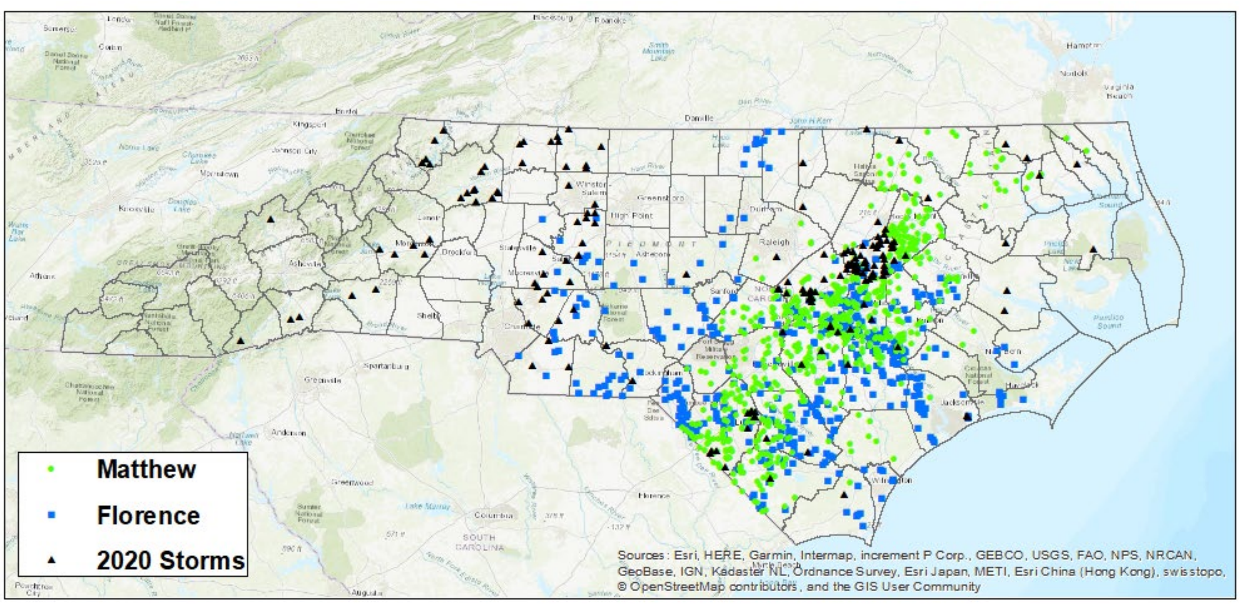


Figure 2-1. Washout locations for Hurricanes Matthew and Florence and 2020 storms.

2.2 Washouts Versus Non-Washouts

2.2.1 Coastal Plain Study Area

The washout locations were mapped and a six-county area in the coastal plain was identified where approximately half (603/1186) of the washouts during Matthew and Florence occurred (Figure 2-2). This area included Robeson, Sampson, Duplin, Wayne, Johnston, and Bladen Counties. Overall, these counties had 2,317 Non-National Bridge Inspection Standards (NBIS) structures, 1,411 NBIS structures, and 29,091 Maintenance pipes. Delineating the watersheds for all the non-washout locations (>30,000) for comparison was not feasible. Instead, the Maintenance Pipes within a one-kilometer radius (Figure 2-3) and the Non-NBIS and NBIS Structures within a two-kilometer radius of each Florence and Matthew washout were selected for analysis. In addition, Maintenance Pipes with a diameter less than 24" were removed, as very few pipes (<5%) smaller than 24" washed out during Florence and Matthew. This reduced the number of non-washouts for comparison to 944 Non-NBIS, 102 NBIS Structures, and 1,223 Maintenance Pipes.

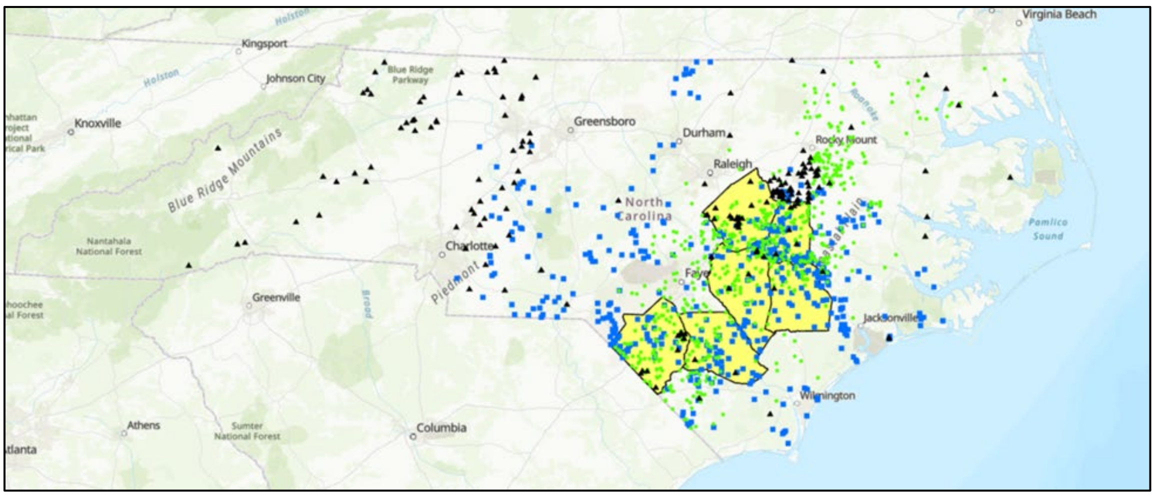


Figure 2-2. Six County Study Area.

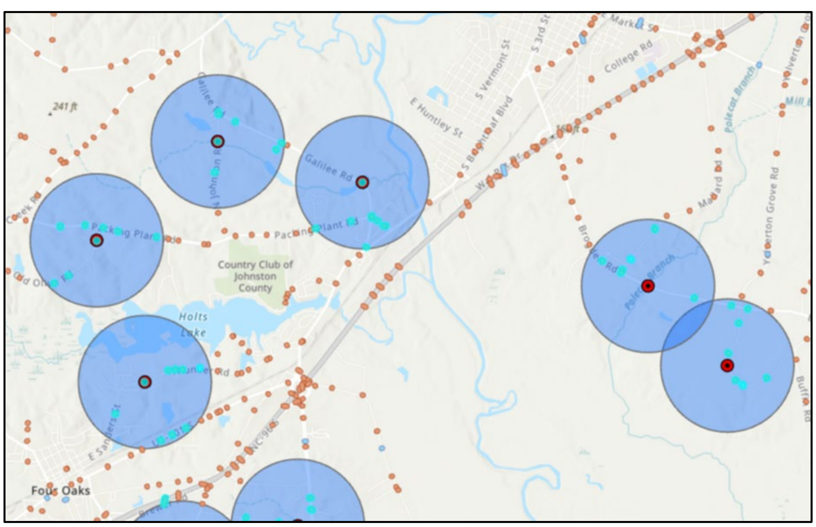


Figure 2-3. Washout locations buffered to select nearby non-washouts.

2.2.2 Nearest Structure Analysis

For each of 2020, Florence and Matthew washout locations, the nearest non-washout location on the same stream or of similar watershed size were identified (see examples in Figure 2-4). Many locations did not have nearby comparable non-washouts, so they were excluded.

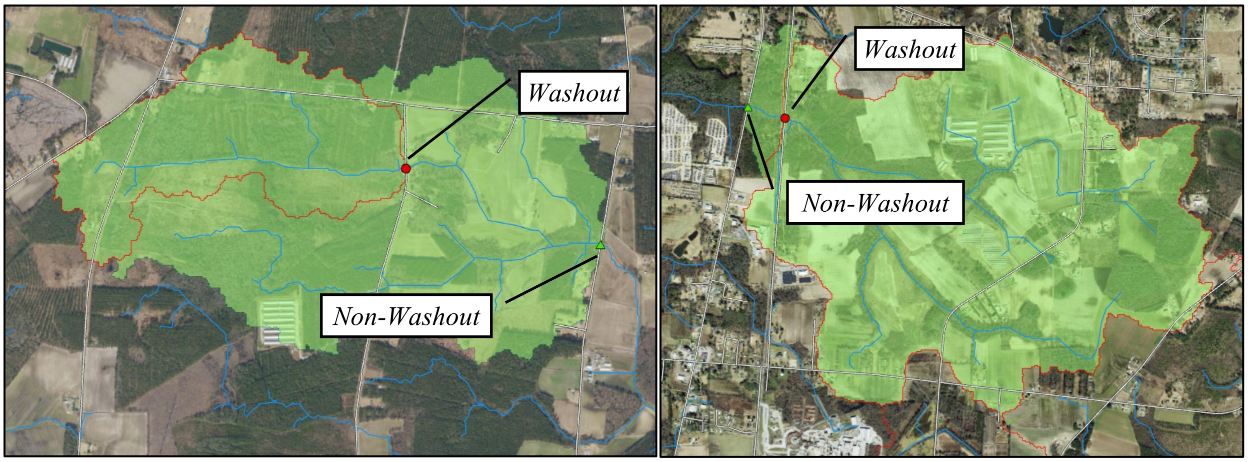


Figure 2-4. Example of non-washout structure in closest proximity to washed out structure.

2.2.2.1 Washout Attributes

Parameters that may relate to road washout were calculated/summarized for each location. These parameters included watershed attributes, structure dimensions, rainfall, and parameters calculated from DEM data (Table 2-2).

Table 2-2. Parameters calculated for washout locations.

Parameter	Source
Drainage Area	StreamStats and manual delineations
Drainage area characteristics: Slope, CN	Calculated in ArcGIS using SSURGO soils, NLCD landcover and NCDOT 20-ft elevations data
Pipe size, material, presence of headwall, length	From NCDOT database on pipe washouts.
Rainfall total and intensity	NC State Climate office radar rainfall
Ratio of pipe area to drainage area	Calculated as a normalized estimate of relative pipe capacity
Elevation Measures • Elevation difference between culvert and min and max road surface along 1000-ft road segment at culvert. • Elevation difference between channel invert and road surface	Calculated from NCEM 3-ft LiDAR and statewide Road Ribbon LiDAR – see Figure 2-5

Rainfall: Hourly gridded rainfall data for storm events were obtained from the North Carolina State Climate Office. The data were provided in a custom Polar Stereographic coordinate system that could not be projected in ArcGIS. The software R was used with the GDAL package to transform the data and project it into a WGS84 coordinate system. The hourly rainfall rasters for each storm were then combined into multidimensional rasters (NetCDF). The centroid of each watershed was calculated in ArcGIS and R was used to extract the hourly time series of rainfall for each location NetCDF file. Statistics such as the total rainfall, the maximum hourly intensity, and the maximum 2-, 3- and 6-hour rainfall accumulations were calculated. Examples of the radar rainfall data for Hurricanes Matthew and Florence are provided in Figure 2-6 and Figure 2-7.

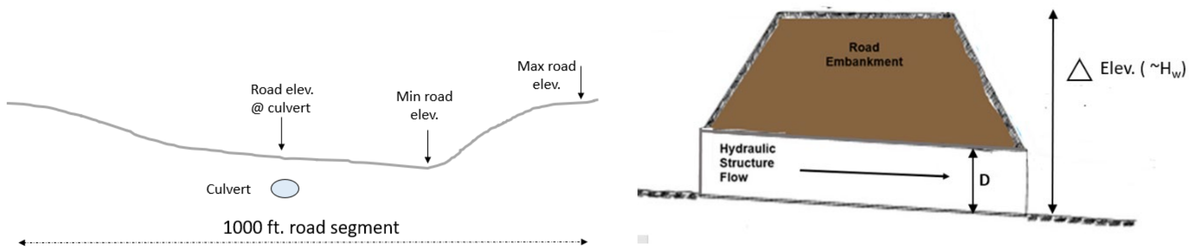


Figure 2-5. Example of elevation data-based parameters

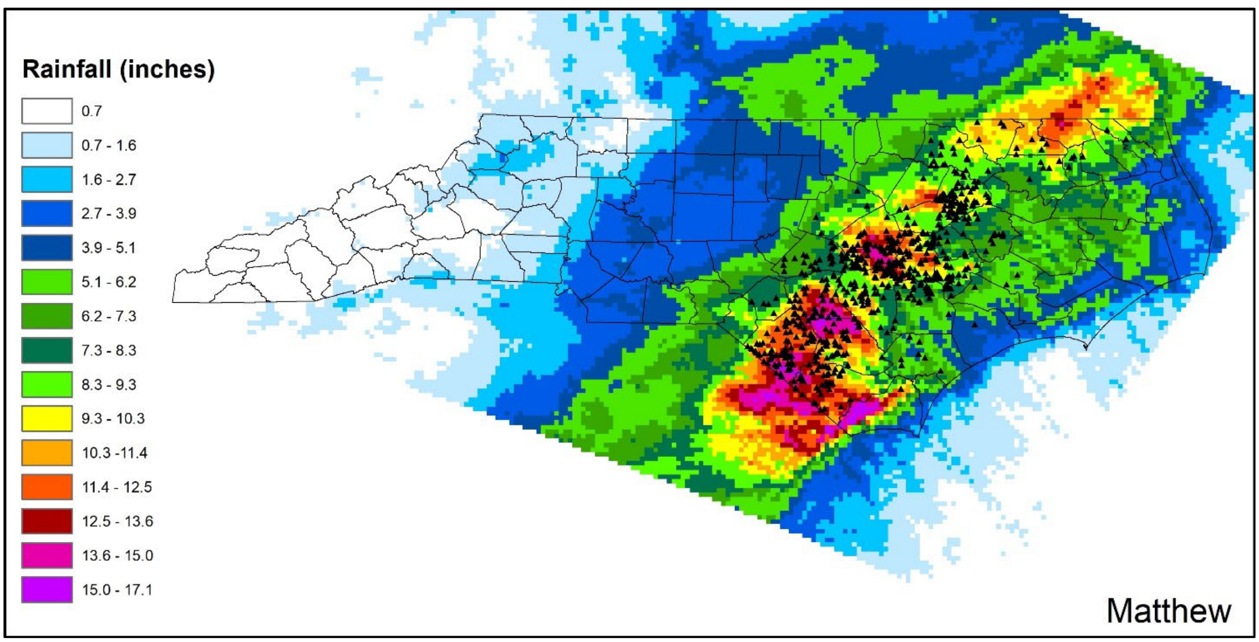


Figure 2-6. Hurricane Matthew rainfall totals.

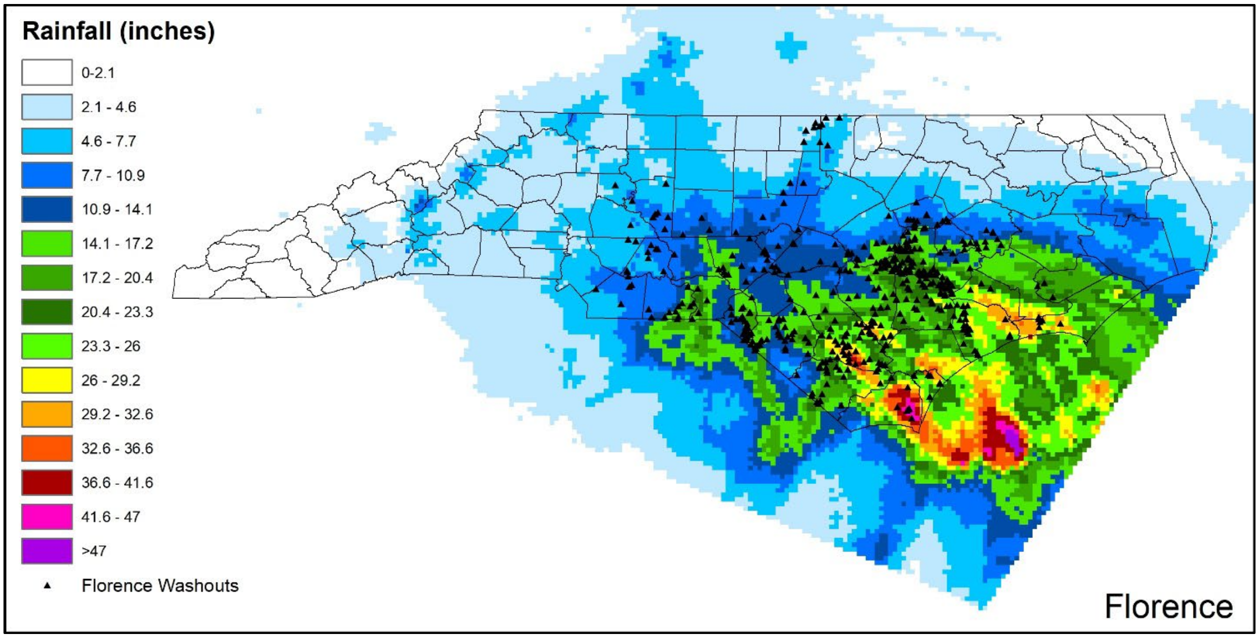


Figure 2-7. Hurricanes Florence rainfall totals.

2.3 Predicting Washouts Locations

Regression and machine learning methods were tested to determine if washout locations could be predicted from pipe, watershed and landscape attributes. Random forest, a classification algorithm that aggregates the outcomes of many decision trees, and logistic regression, which is used to model dichotomous outcomes (washout; no washout) were both applied.

2.4 SAS VIYA Washout Dashboard

All the data on washouts and non-washout structures for a six-county area in the Coastal Plain that includes Bladen, Duplin, Johnston, Robeson, Sampson, Wayne counties were provided to SAS to input into their Visual Analytics (Viya) platform. The Viya tool allows for rapid statistical comparisons based on data queries, and geospatial criteria. The data included 603 washouts and 3,610 nearby non-washout pipes. This data set represents approximately half the total washouts that occurred due to Hurricanes Florence and Matthew. The SAS dashboard was constructed to enable map displays of washout locations combined with statistical graphs and tabular summaries of washout locations. The dashboard also allows for data selection combined with updates to all graphs and tabular summaries by county, watershed boundary and by applying a radius of choice to any selected location.

2.5 Hydrologic and Hydraulic Modeling

Three subbasins (one in each physiographic region - Figure 2-8) were selected for modeling based on drainage area (~HUC 10) and the presence of a USGS gaging station for model calibration including Hunting Creek (155 mi^2), Drowning Creek (183 mi^2) and Nahunta Basin (77 mi^2).

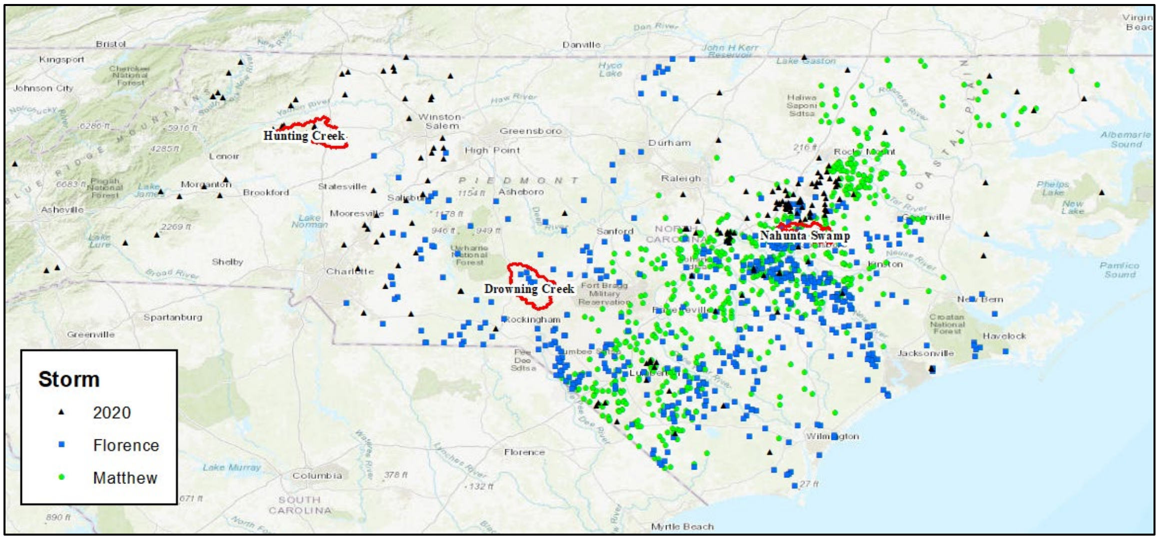


Figure 2-8. Study Subbasin Locations

2.5.1 HEC-RAS Model Coverage

To examine if the existing effective HEC-RAS models could be used in our analysis, the State HEC-RAS model coverage was overlaid with the washout data. Only about 15% of the mapped road washouts from Hurricanes Matthew and Florence and the 2020 storms were included in the existing HEC-RAS models (Table 2-3). None of the washouts in the study watersheds were located on FEMA mapped streams and only a small percentage of the road crossings were covered by the HEC-RAS models (Table 2-4).

Table 2-3. HEC-RAS effective model coverage of road washouts.

Storm Washout	Included in HEC-RAS Models	Within Mapped Floodplain	Drowning	Hunting	Nahunta
Matthew	90/705 (13%)	125/705 (16%)	-	-	-
Florence	75/486 (15%)	93/486 (19%)	-	-	-
2020 Storms	28/191 (15%)	31/191 (16%)	-	-	-

Table 2-4. HEC-RAS Model coverage in study watersheds

WS	Non-NBIS (in HEC-RAS)*	Maintenance Total: >24" (in HEC-RAS)**	Structures (in HEC-RAS)*
Drowning Creek (Piedmont)	37 (6)	**595**: *177* (8)	29 (23)
Hunting Creek (Mountains)	123 (15)	**1891:** *459* (15)	83 (48)
Nahunta Swamp (Coastal Plain)	40 (3)	**603**: *267* (1)	19 (18)

*Indicates total number of structures and the portion of these structures that are included in the HEC-RAS effective models (in parentheses).
**Indicates total number of maintenance pipes (bold), the portion of these pipes that are > 24 inches in diameter (italicized) and the number of pipes that are included in the HEC-RAS effective models (in parenthesis).

2.5.2 Hunting and Downing Creek HEC-HMS Modeling

HEC-HMS models were developed for Drowning Creek and Hunting Creek.

2.5.2.1 Setting

The Drowning Creek watershed (183 mi^2) for the USGS gage at US 1 (#02133500) encompasses parts of Moore, Montgomery, and Richmond counties of central NC (Figure 2-9). The watershed is located in the transition area between the Piedmont and Sandhills physiographic regions. The topography of the watershed is gently sloping to flat. Soils are of the Lakeland-Gilead-Blaney association. Many of these soils are composed predominantly of sand making them excessively drained with rapid to moderate permeability. Land use/cover in the watershed is mostly forest and wetland with agricultural areas mixed in. Small urban (residential) areas occur mostly along the eastern boundary of the watershed.

The Hunting Creek watershed (155 mi^2) to the USGS gage at Houstonville Road encompasses parts of Wilkes, Yadkin, and Iredell counties, which are in the Mountains physiographic region of NC (Figure 2-9). The topography is moderate to steeply sloping with forest on the steep slopes and some residential development and agricultural land in the mostly narrow stream valleys. Soils in the watershed are of the Ashe-Evard association in the mountainous western portion and of the Cecil-Appling-Pacolet association in the rest of the watershed.

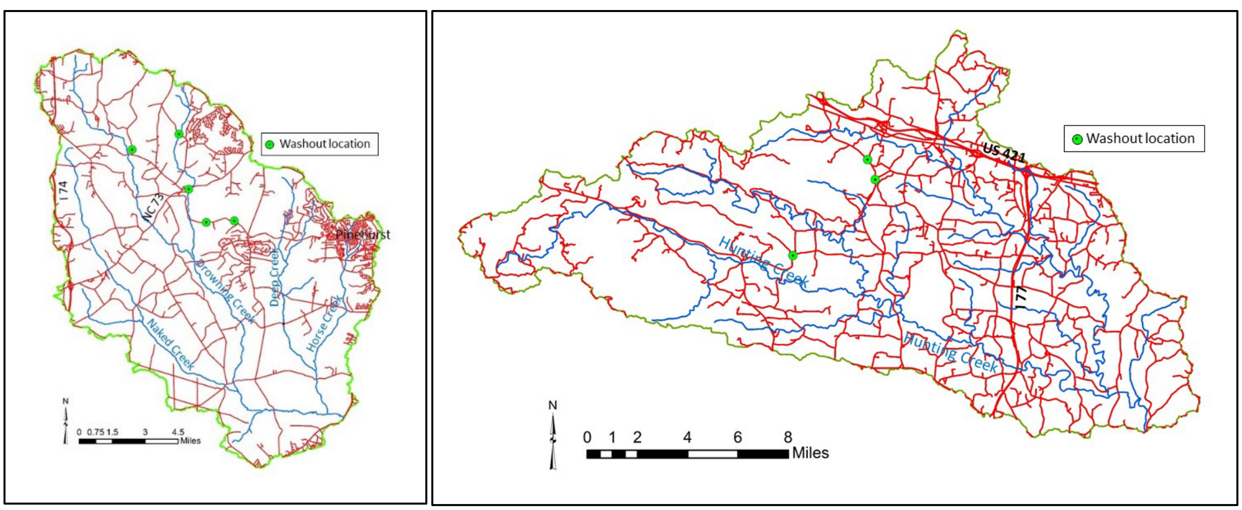


Figure 2-9. Drowning Creek (left) and Hunting Creek Watersheds (right).

2.5.2.2 HEC-HMS Modeling Procedure

U.S. Army Corps of Engineers Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (USACE, 2017) and River Analysis System (HEC-RAS) (USACE, 2016) models were applied. The HEC-HMS model (version 4.8) was used to estimate peak flows/discharges within the study watersheds. The curve number (CN) method was chosen to compute runoff, the SCS unit hydrograph method to simulate discharge hydrographs, and the Muskingum-Cunge method to route discharge through stream channels. Procedures for determining inputs for each method are outlined below.

The digital elevation models (DEMs) for the Drowning and Hunting Creek watersheds were obtained from the North Carolina Emergency Management's (NCEM) LiDAR database (NCEM, 2018) and entered into the HEC-HMS model for each watershed. The physical description of the watershed was then built using the various routines of the HEC-HMS model. From this, subbasins were delineated. The size of the subbasins were defined as relatively small so they were similar in size to the drainage areas for the washouts; however, limitations on computing power, data, and time prevented the subbasins from being small enough for each washout (3 washouts corresponded to the location of subbasin outlets). Subbasin shape files were exported to ArcGIS to determine area-weighted composite CNs for each subbasin from landcover and soils data obtained from the 2016 National Land Cover Database (NLCD) (MRLC, 2022) and the NRCS SSURGO (NRCS, 2018) soils database from October 2018. For Hydrologic Soil Groups (HSG) with a dual classification (e.g. A/D or B/D), the given area was assumed to consist of an equal proportion of each HSG. All soils classified as 'urban soils' were assigned to HSG D. Initial abstractions for all subbasins were set to 0.2.

From the DEMs the HEC-HMS model determined a stream network for each watershed including reach length and slope for each stream channel. Representative cross-sections for major stream channels in each watershed were obtained from the NCEM's Floodplain Mapping HEC-RAS input dataset. Cross-sections for small tributary stream reaches were estimated as trapezoidal with the dimensions based on drainage area and/or experience. Manning's roughness coefficients for the reaches were estimated based on literature values, values in the HEC-RAS dataset, and experience. These values were often adjusted during calibration.

Rainfall inputs for the model were obtained from the NC State Climate Office and from TR55. The Drowning Creek model was calibrated from September 9, 2018 to October 4, 2018 and Hunting Creek was calibrated from November 10, 2020 to November 15, 2020. Details about rainfall inputs and calibrations are provided in the Appendices.

2.5.3 Nahunta Swamp Rain-on-Grid Model

Because of the very limited number of crossings that intersected the HEC-RAS models, the coarse resolution of the HMS models, and the wider availability of hydrodynamic modeling, rain-on-grid modeling was applied to Nahunta Swamp. In addition, the coarse nature of the HMS models made it very difficult to identify potential resilient routes and would require intensive customization for each subbasin. Another advantage of rain-on-grid models is the physical-based nature of the modeling that routes flow across a grid, while HMS applies a unit hydrograph transformation.

2.5.3.1 Setting

The Nahunta Swamp is located in Wayne County within the Neuse River Basin. The headwaters of the swamp/stream start in eastern Johnston County and flow about 27 miles east until it merges with Contentnea Creek. The modeling for this project was limited to the drainage area upstream of the USGS gage at Bullhead Road. This portion of the watershed is gently sloping to flat and encompasses several swamp-like areas where there is often little discernable flow/discharge. The gradient of Nahunta Swamp is relatively uniform and gently sloping throughout its length. Soils are typically acidic and leached with uplands containing well to moderately well-drained soils of the Norfolk-Goldsboro-Aycock association, while lowlands typically contain poorly-drained soils of the Johnston-Chewacla-Kinston association. Both soil associations have a sandy to clay loam subsoil underlain by unconsolidated layers of sand, silt and clay. Land use in the 77 mi^2 watershed is predominantly agricultural (55%) with some moderate-sized residential areas along the southern boundary of the eastern third of the watershed. Wetlands (20%) and forests (15%) also make up a substantial portion of the watershed.

2.5.3.2 HEC-RAS Model Setup

A HEC-RAS 2D (USACE, 2022) rain-on-grid model was developed for the Nahunta Swamp study area. The model grid spacing was set at 150-feet (Figure 2-10). Breaklines were added along roads and streams and spacing set at 50 or 150-feet. The floodplain and upland model topography were based on 5-ft resolution NCEM LiDAR DEMs (NCEM, 2018) and the channel bathymetry was based on interpolated cross sections from the 1D effective HEC-RAS models. Spatial Manning's roughness values were set based on 2016 National Landcover Database (NLCD) data (MRLC, 2022). A summary of the model inputs is provided in Table 2-5.

The model terrain was hydro-corrected by 'burning' in the culverts and bridges at roadway embankments using the 'Terrain Modification' tool in RAS Mapper. The width of the terrain modification was based on the width of the culverts.

The Green-Ampt method was used for spatial infiltration. The soils data for the spatial variation in Green-Ampt inputs was based on SSURGO soils data (NRCS, 2020) and parameter ranges were set based on values provided in the HEC-RAS 2D user's manual. Initial soil moisture condition (percent saturation) was based on a watershed averaged Soil Moisture Active Passive (SMAP) L4 Global 3-hourly 9km EASE-Grid Surface Soil Moisture (Das et al., 2019) prior to the start of rainfall for a given storm event.

Hourly gridded rainfall data (National Weather Service MPE data) for the observed storms were obtained from the North Carolina State Climate office. Streamflow for model calibration was obtained from the US Geological Survey.

At each road crossing, '2D Area Connections' were added to enable output of flow and water surface elevation in DSS format at the crossing location. The overflow computation method was set to 'Normal 2D Equation Domain.'

Table 2-5. Rain-on-Grid model inputs.

Input	Description	Source
Elevation	5-ft DEM	(NCEM, 2018)
Channel bathymetry	NC Floodplain Mapping Program 1D HEC-RAS models	(NCEM, 2019)
Soils	SSURGO soils	(NRCS, 2020)
Land Cover	NLCD 2016	(MRLC, 2022)
Rainfall	MPE hourly data	NC State Climate Office
Stream Flow	Continuous streamflow	USGS

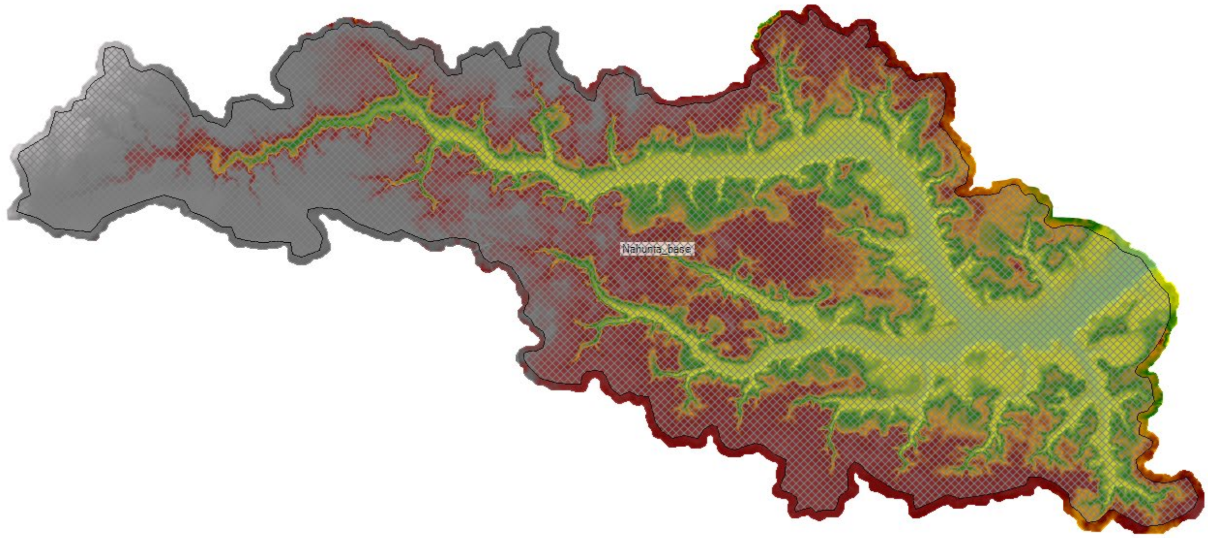


Figure 2-10. Nahunta Swamp model domain and topography.

2.5.3.3 Model Simulations

The model was run using an adaptive time step based on the Courant number. The Courant number is typically constrained to 0.45 to 1 (HEC-RAS manual). However, the HEC-RAS manual also indicates that for systems where the flood wave is not changing rapidly the Courant number can be substantially higher (up to 5 in low gradient systems). Because these conditions were met the Courant number was allowed to vary from 0.45 to 2. There was no substantial difference between the simulation runs using a maximum Courant number of 1 versus 2 (less than 0.02 ft difference in WSE). The models were run using the full momentum equation 2D solver in HEC-RAS (SWE-ELM).

2.5.3.4 Model Calibration

The model was calibrated by adjusting Manning's roughness values and Green-Ampt parameters in a systematic way until the discharge and elevations closely matched the observed values at the catchment outlet.

2.5.4 Application to Download and Transform Rainfall Data

A Python based application was developed to download gridded historical and predicted rainfall (Table 2-6), transform the data into HEC-DSS format, extract model output and calculate roadway inundation shapefiles. The program used a variety of open-source Python packages and the USACE's Hydrologic Engineering Center's Vortex and HEC-RAS Controller programs to accomplish these tasks. See more details in the Appendix.

Table 2-6. Rainfall Data Sources available for download from Application

Rainfall	Period	Source
Historical Rainfall	2015-present	Multi-RADAR Multi-Sensor System (MRMS) Estimates from Iowa State University's Mesonet database. GRIB2 files – 4 km resolution
Predicted Rainfall	60-hour forecast produced every 6 hrs.	National Centers for Environmental Prediction North American Mesoscale Forecast System (NAM). – GRIB2 files

2.6 Transportation Resilience Identification and Prioritization (TRIP) Tool

The second phase of the project was focused on developing methods of identifying and evaluating potential resilient routes. Resilient or "safe" routes are roadways that are not overtopped or flooded during extreme events. Developing a tool to identify these routes would improve emergency response and movement of critical resources during and after extreme events. And, if no "safe" route is identified, it is important for NCDOT to identify the most cost-effective routes for upgrading to a resilient route. The resilient route analysis focused on the Nahunta Swamp rain-on-grid model since this model allowed for evaluating structures that did not overlap with the effective HEC-RAS hydraulic models. The use of this model was reinforced by NCEM's current efforts to develop statewide rain-on-grid models. To develop a tool for visualizing and compiling summaries for the resilient route analysis, NCSU provided data and collaborated with the SAS Institute to develop a prototype geospatial data visualization (GDV) tool for the Nahunta Swamp watershed using SAS Viya. A Viya dashboard was developed to combine rain-on-grid hydraulic model outputs with road, culvert, and bridge data in order to:

- View and compile impacts of past storms and design storms.
- Prepare asset management summaries for existing roads and hydraulic structures.
- Evaluate the resilience of key transportation routes.
- Estimate costs for increasing the resilience of existing routes to each design storm (25-, 50-, 100-, 500-Year).

2.6.1 TRIP Development Methods

2.6.1.1 Identify potential resilient routes.

For the prototype of Nahunta Swamp, nine potential routes were selected for evaluation. These routes consisted of north-south and east-west roads for this demonstration. For potential future expansion, these routes would be selected based on connecting important locations (i.e., communities, emergency facilities, military bases, schools, evacuation routes).

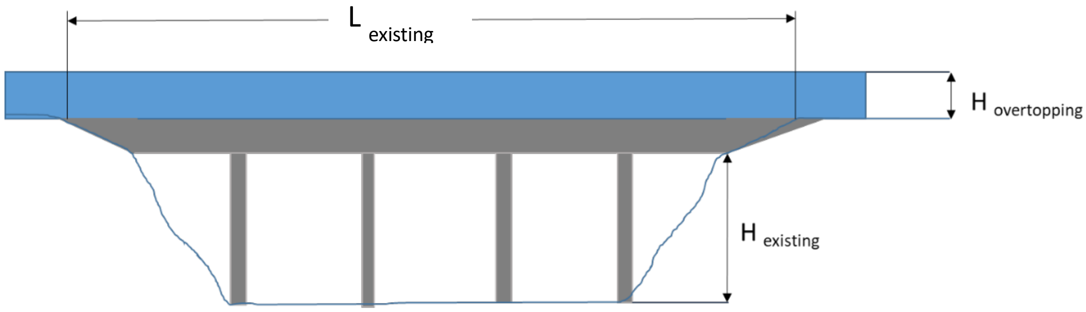
2.6.1.2 Compare rain-on-grid water surface elevations to road elevations, and bridge and culvert data to predict overtopping.

The water surface raster corresponding to various rainfall return periods were compared to the road surface LiDAR elevation raster to calculate depth of overtopping at each structure and for each 50-foot segment of roadway for all nine resilient routes.

2.6.1.3 Develop planning level cost relationships for upsizing culverts, bridges and raising and armoring roads.

- **Bridge Upgrade Costs**
  For all storms where the bridge capacity is exceeded, costs were determined by estimating a new Bridge Deck area. This area was calculated by multiplying the existing total road width (both lanes + shoulder) by the new span length of the bridge opening. The procedures followed are outlined below.

$$Upgrade\ cost = Area_{deck} \times \frac{\$}{ft^2}$$



First, calculate additional capacity needed, A_{new}

$$A_{new} = H_{overtopping} \times L_{existing}$$

Second, determine the new bridge length to accommodate this additional capacity, L_{new}

$$L_{new} = \frac{A_{new}}{H_{existing}} + L_{existing}$$

Finally, calculate the new bridge deck area, $Area_{deck}$

$$Area_{deck} = W_{road} \times L_{new}$$

Where:

A_{new} = additional capacity needed to convey the storm causing overtopping
$H_{overtopping}$ = depth the water overtopping the road at the location of the bridge for the given storm (See crossing overtopping analysis above)
$L_{existing}$ = existing length of the bridge span over the waterway (Structure Length in BridgeWatch data)
L_{new} = new existing span length to accommodate the storm and prevent overtopping
$H_{existing}$ = existing height of the bridge above the bottom of the stream (difference between the "Stream Elevation" obtained from DEM data and "Road Top Elevation" from BridgeWatch data minus 3 feet; NCSU will provide this value for all Structures in the Nahunta Basin)
W_{road} = existing width of the road. This is the sum of all travel lanes, shoulder and median widths (obtained from the Road Characteristics Arcs data layer)

- **Non-NBIS and Maintenance Pipe**

  For all storms where the structure capacity is exceeded, costs were determined based on the length of the pipe ("LengthFeet" in both the Non-NBIS and the Maintenance Pipe data). This length was multiplied by the unit costs for "Culvert" upgrade.

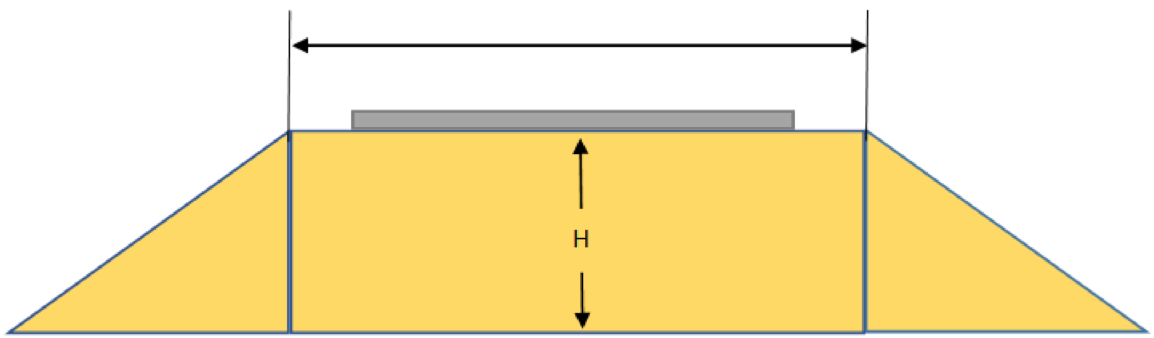
- **Calculate Costs for Road Upgrade**

Road upgrade costs were based on the depth of overtopping and the length of overtopping. Costs include Fill, Marking, Curb and Gutter and Traffic Control. The cost of each element is shown below (Table 2-7).

a. Fill

Fill volume is calculated based on the depth of overtopping and the total length of road segment overtopped by each incremental depth.

$$Fill\,Volume = \frac{(W \times H + 2H^2) \times L_{total}}{27\,(\frac{yd^3}{ft^3})} \times \$\,yd^3$$



Where:

W = Total width of road including both travel lanes, and both shoulders width (“SrfcWidth”– for null or 0 assume 24), left and right shoulders (“RtShldrWid” and “LftShldrWid”- if null or 0 assume 5)
H = Max Overtopping Depth (feet) for each overtopping category
L_{total} = Total length of road included in each overtopping depth category

b. Marking
Sum the length of road in miles overtopped for each storm event. Stratify the road over-topping length by the width of the road, “SrfcWidth”. Roads less than 3 lanes are considered 36 feet or less. Road widths greater than 36, categorize as 4 lane or greater. Sum the overtopping length for each of these two categories for each storm level. Multiply each summed total length by the matching marking cost per mile.

c. Curb and Gutter
Identify and sum the length of any road sections with “RtShldrType” or “LftShldrType” with the classification of “Curb-Concrete”. Identify the areas within this class that are overtopped by each storm event. Sum the length of road that is overtopped. Multiply this total length by the unit costs for curb and gutter.

d. Traffic Control

Sum the total length of road that is overtopped for each storm event, multiply this length in miles by the unit costs for traffic control.

Note: attribute field names for this section are from "Road Characteristics Arcs" layer.

e. Armoring

Armoring cost will be applied to the 100 and 500-year scenario only. All structures and adjacent roadway that are overtopped by ≤ 1 foot of water and where velocity of flow exceeds 2 ft/s, then armoring will be selected instead of raising the elevation of the road as a cost savings measure. All locations where the overtopping is ≤ 1 foot and the velocity is less than 2 ft/s, then no modifications will be required. The velocity and depth parameters should have an option for modification by NCDOT, so they should be NCDOT input parameters along with costs. The estimate shall be as follows:

$$Armorning\ Cost = \frac{Length_{Road} \times [\sqrt{\Delta\,Elev^2 + (2 \times \Delta\,Elev)^2} + 2]}{9\ ft^2/yd^2} \times \$/yd^2$$

Where:

Length $_{Road}$ = Sum of the 50-foot road segments with overtopping by 0.1 to 1 foot

ΔE*lev* = "Armor _ h" attribute from updated Road Segments Layer

Table 2-7. Estimated unit costs for TRIP tool

Item	Unit	Unit Costs
Culvert	Linear Foot (LF)	$1800
Bridge	Square Foot (SF)	$150
New Roadway	Square Yard (SY)	$100
Marking (2-3 Lane)	Foot (FT)	$10
Marking (≥4 Lane)	Foot (FT)	$14
Curb & Gutter	Foot (FT)	$25
Fill Soil	Cubic Yard (CY)	$25
Traffic Control (2-3 Lane)	Mile (MI)	$150,000
Traffic Control (≥4 Lane)	Mile (MI)	$300,000
Riprap Armoring	Square Yard (SY)	$85

Data layers used for this analysis:

1. Road Characteristics Arcs - https://connect.ncdot.gov/resources/gis/pages/gis-data-layers.aspx
2. Bridge Dimensions – Data layer coming from BridgeWatch Program/ESP
3. NC Emergency Management rasters of water levels for all return interval storms (i.e. 25-year, 50-year, 100-year, 500-year) as obtained from their HEC rain-on-gGrid model.
4. Road Ribbon Layer – Includes elevations of the roads from the DEM

5. Updated Non-NBIS and Maintenance Pipe data – Kurt will send this.
6. Structures layer - https://connect.ncdot.gov/resources/gis/pages/gis-data-layers.aspx - "Structure Locations Statewide." Filter for "Bridge Type" = 'Bridge' or 'Pipe' or 'Culvert'. And "FTR_INTRSC" should be a river or creek, not a road or railroad (i.e., not an overpass).
7. Existing Height of bridges from bed of the stream up to the top of road elevation based on DEM data and BridgeWatch road elevation.
8. Road Segments layer: 50-foot segments that includes depth of overtopping for 25, 50, 100, 500-year events, velocity for the 100 and 500-yr segments, and armoring depth.

2.6.1.4 Provide all data and cost analysis procedures to SAS Institute

NCSU provided all road and structure inundation data to the SAS Institute for building the Data Analytics Dashboard (Viya). The data were used in the dashboard to summarize the number of structures and length of road overtopped and the associated upgrade cost for each of the potential resilient routes.

2.7 Hunting and Drowning Creek Resilient Route Analysis

2.7.1 Culvert Capacity Evaluation

The physical characteristics for hydraulic structures at each washed out location (e.g., location, culvert diameter, length) were obtained from the NCDOT database. For some crossings, missing data were estimated to compute the discharge capacity. For example, culvert slope was estimated from the average slope of the stream channel upstream and downstream of the crossing (obtained from HEC-HMS or GIS when available). When there was no stream channel present, the slope was set based on typical valley slopes for the local region. These data were entered into the FHWA's HY8 culvert hydraulic analysis program to compute a peak discharge capacity of the crossing.

The discharge capacity for each washed-out culvert was computed using HY8. For many small drainages, the road crossing location did not match with a subbasin outlet or reach in the HEC-HMS model. To estimate the peak discharge at these locations, the subbasin drainage area was changed to the drainage area for the crossing and all other inputs for the subbasin were unchanged. The HEC-HMS estimated peak discharges at each road crossing for both historic and design storms were then compared to the culvert capacity to assess washout potential.

Data for other road crossings near the washed-out crossings were obtained from the NCDOT database. Drainage areas were delineated and NRCS curve numbers were calculated for each location. The pipe full cross-sectional area and the ratio of cross-sectional area to drainage area were computed and compared to the ratios for the wash-out locations.

2.7.2 Resilient Route Evaluation

HEC-RAS was used to determine the discharge that would overtop (at least 0.1 ft of water over the road surface) at major road crossings for several roads in the Drowning and Hunting creek watersheds. The major crossings were only those included in the HEC-RAS models for selected streams, which were obtained from the NC Flood Risk Information System. Cross sections at each crossing were identified in the models and the bridge/road deck elevations recorded. When available, rating tables for water surface elevation (WSE) versus discharge were used to determine the discharge at which road overtopping would occur. The overtopping discharge was divided by the 100-yr discharge for the nearest cross section in order to compare the relative capacity of all structures. Peak discharges from the HEC-HMS model were also compared to the overtopping discharge for each crossing.

A more thorough assessment of a resilient route requires evaluating every crossing along the route; however, this can be very labor intensive. As an example, crossings with culverts of at least 24 inches in diameter were evaluated along an 8-mile stretch of NC 73 which runs east-west across the Drowning Creek watershed. A cursory evaluation of 5 maintenance pipes that were 24 inches in diameter comparing the pipe area to drainage area was conducted. A more detailed evaluation was conducted for five maintenance pipes ≥ 30 inches in diameter and two non-NBIS. The capacity of each pipe was determined using the diameter, length, and overburden found in the NCDOT database. The slope for each culvert was set at 0.01. The capacity of five maintenance pipes ≥ 30 inches in diameter and 2 non-NBIS pipes were calculated using HY8. For two of the pipes (MP-063-00672 and MP-077-00021) the drainage areas could not be determined from digital data; therefore, the peak discharge during hurricane Florence was not estimated. Peak discharges for hurricane Florence and several design storms were also evaluated for these locations using the HEC-HMS model.

3 Results

3.1 Washout Characteristics

About 55% of the washouts locations drained areas of less than 0.5 square mile (Figure 3-1). Drilling down further, about one quarter of the wash outs had drainage areas of less than 0.1 square miles (Figure 3-2). Given the small drainage areas, it follows that about 50% of the washed out structure had equivalent diameter of 48 inches or less. Around 70% were 72 inches in diameter or smaller (Figure 3-3). A majority (~60%) were characterized as "Maintenance" pipes (<54" in diameter). Only 2-4% of the washouts occurred at structures covered by the National Bridge Inspection Standards (NBIS) program (Figure 3-4).

The washouts were also primarily concentrated on secondary roads (~90%) (Figure 3-5), which is not surprising given structures on secondary roads make up an overwhelming majority of the pipes in NCDOT's inventory (~85% of "Maintenance" pipes and ~70% of Non-NBIS pipes). In addition, structures on primary roads are typically sized to accommodate larger flows compared to secondary roads. The data also indicated most washouts occur at structures that lack a headwall: however, these data were not always complete and it was not always possible to determine if there had been a headwall prior to a washout (Figure 3-6).

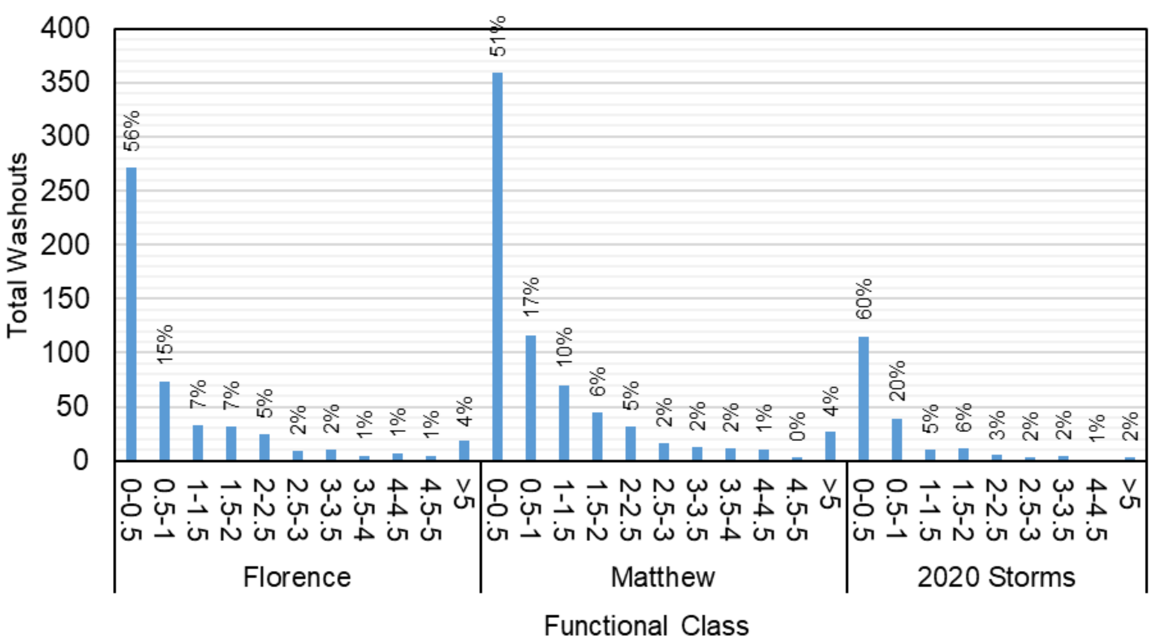


Figure 3-1. Structure washouts by drainage area.

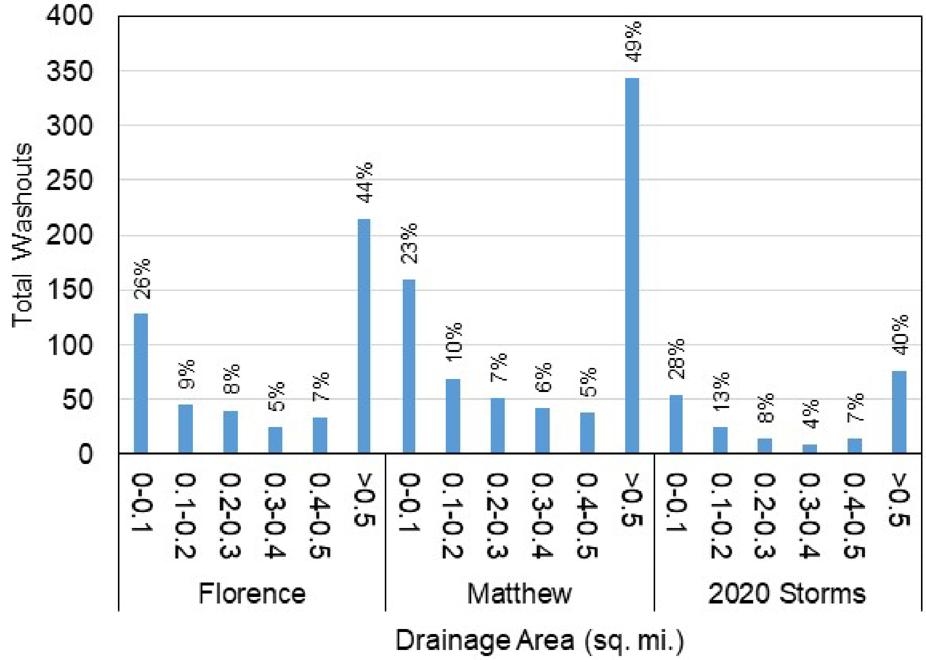


Figure 3-2. Structure washouts by drainage area (less than 0.5 square miles).

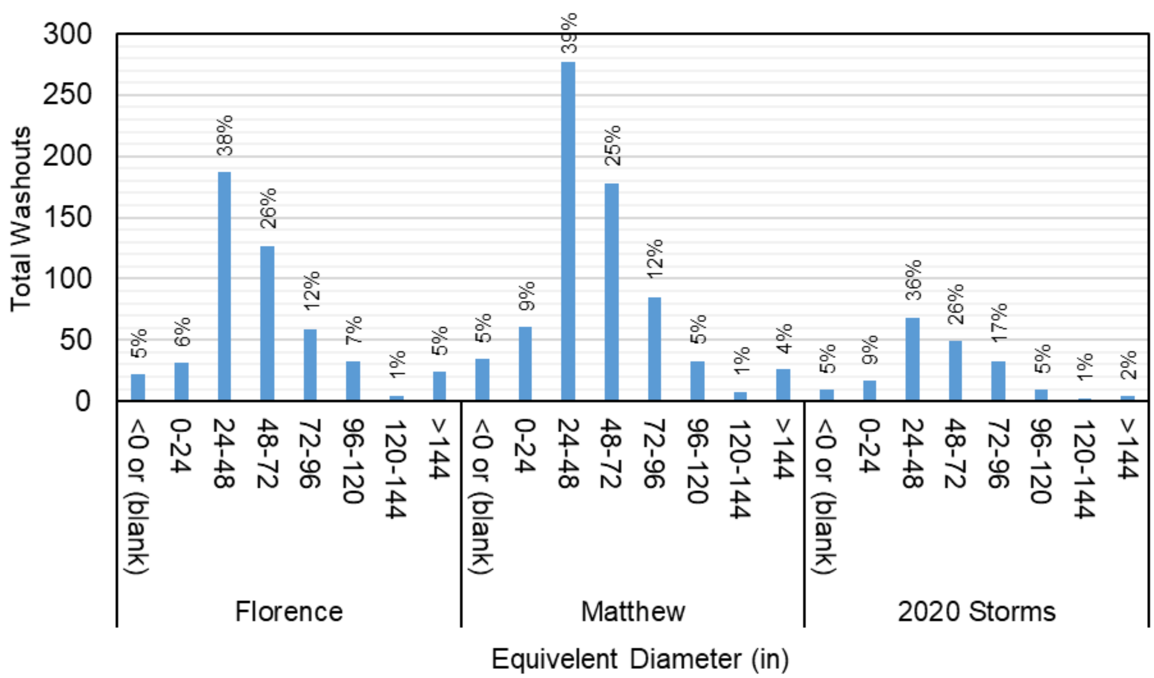


Figure 3-3. Washouts by equivalent pipe diameter.

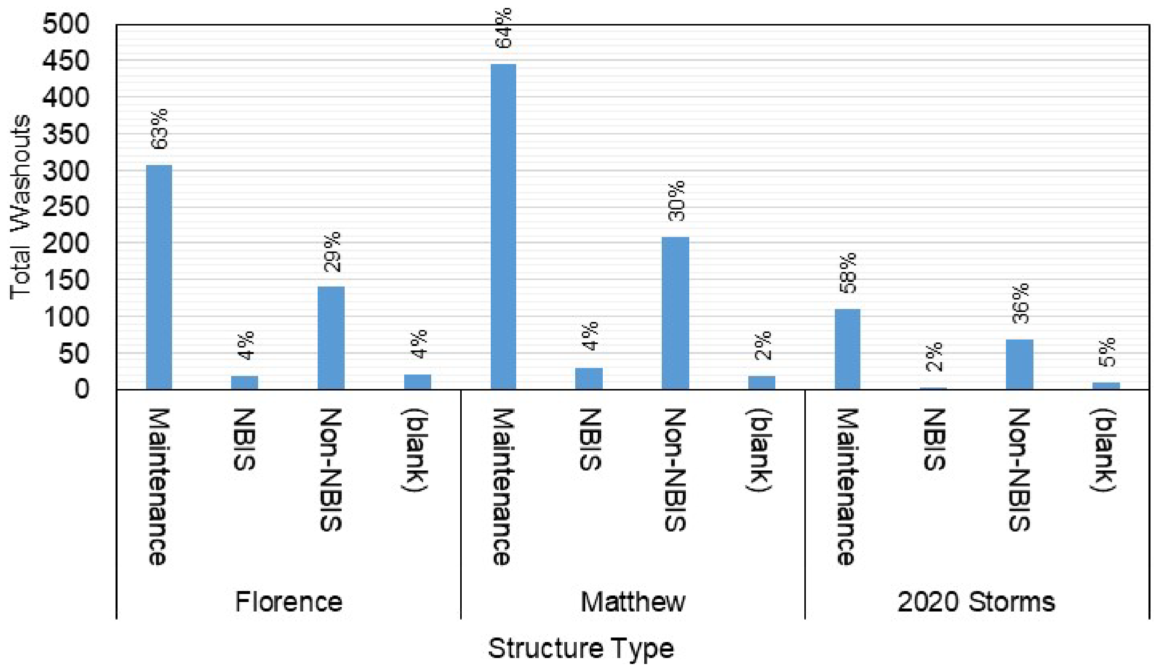


Figure 3-4. Structure washouts by type

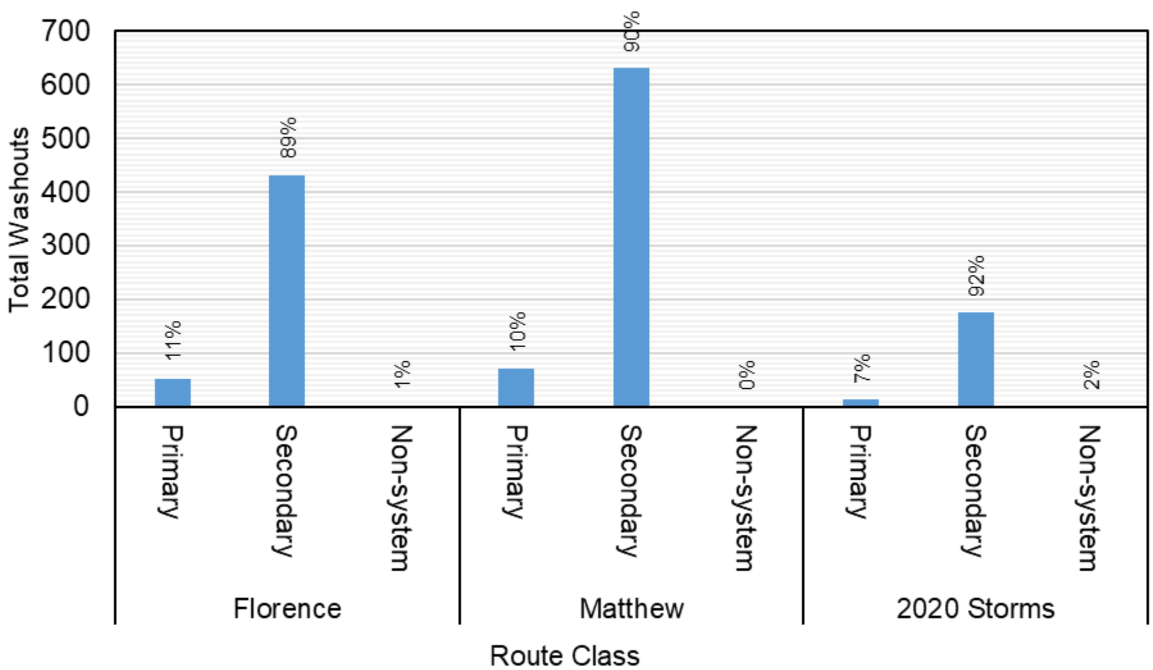


Figure 3-5. Structure washouts by road classification.

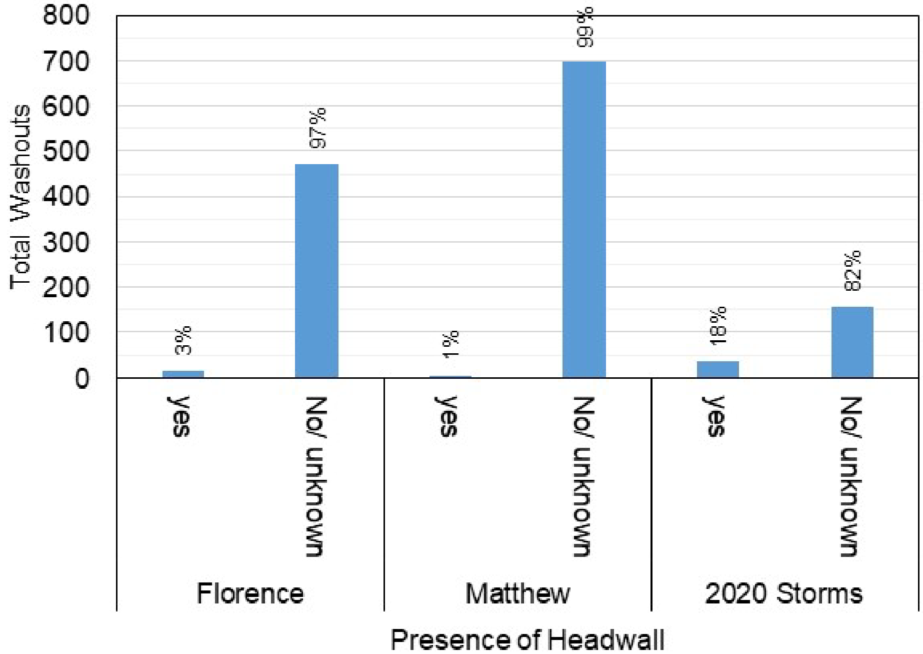


Figure 3-6. Structure washouts by headwall presence.

3.2 Washouts versus Non-Washouts

3.2.1 Six County Study Area

The comparison of washout and non-washout locations did not identify any parameters that clearly indicated a structure would be washout out. This may indicate some washouts are related to very site-specific conditions such as the condition of the pipe and embankment or specific flow conditions that impact failure, backwater vs. free flow over the downstream embankment.

However, there were some parameters that may indicate a greater susceptibility to washout. First, and most obvious, was that pipes that were sized smaller relative to their catchment were generally more apt to failure. This was observed for both the Florence and Matthew washouts (Figure 3-7 and Figure 3-8). However, there was not an identifiable threshold that could be used to identify which structures were likely to wash out. The impact of structure sizing was most apparent for structures with equivalent diameters from 25 to 84 inches for Matthew and all size classes greater than 24 inches for Hurricane Florence.

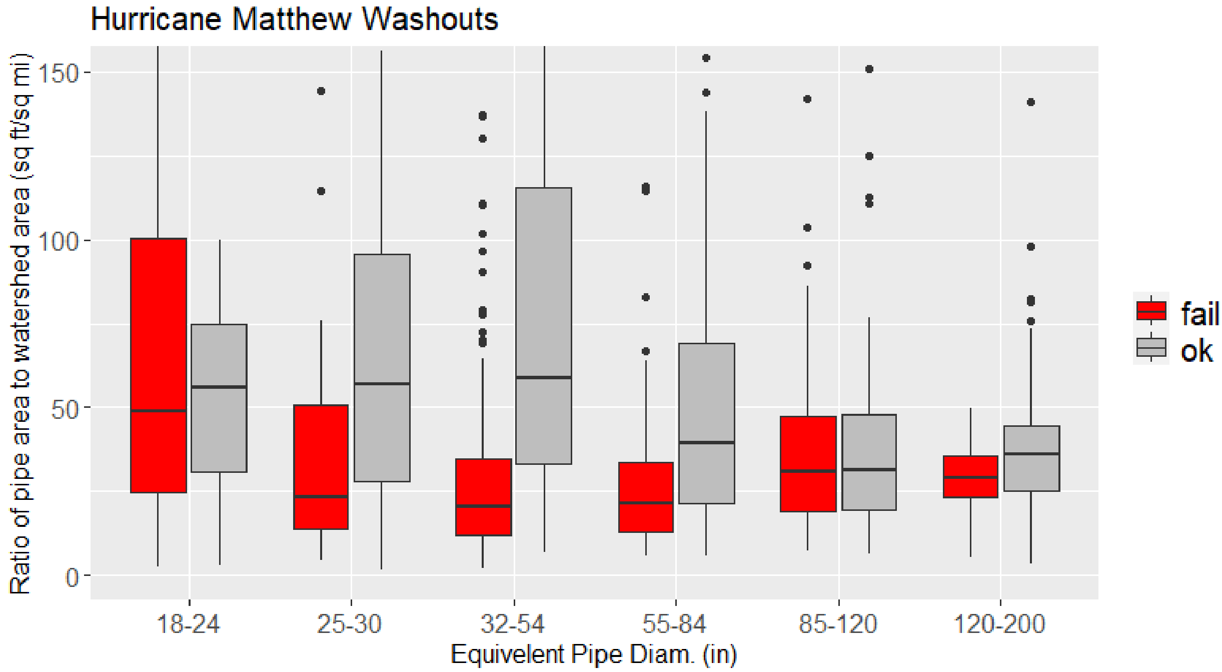


Figure 3-7. Ratio of pipe area to watershed area for Hurricane Matthew washouts versus non-washouts.

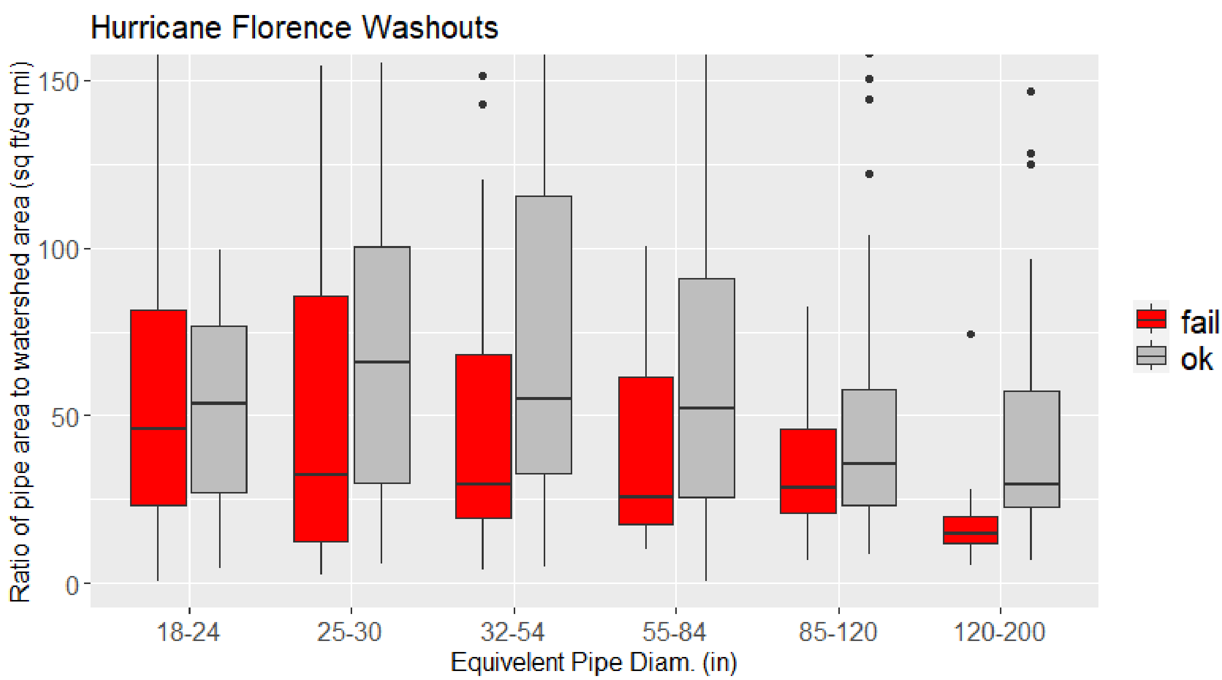


Figure 3-8. Ratio of pipe area to watershed area for Hurricane Florence washouts versus non-washouts.

Another variable that appeared to be important in contributing to washout likelihood was the ratio of the headwater to structure diameter, with higher values more likely to washout (Figure 3-9 and Figure 3-10). However, this relationship was less clear than the pipe size to watershed area ratio.

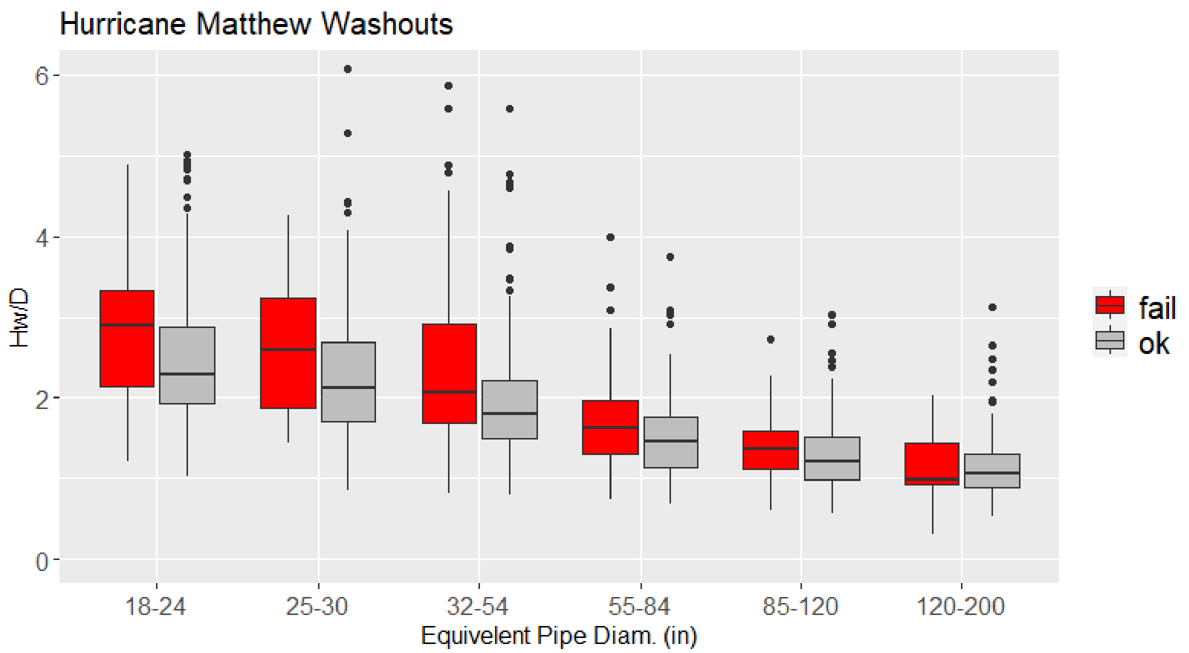


Figure 3-9. Ratio of headwater to structure diameter (Hw/D) for Hurricane Matthew washouts versus non-washouts.

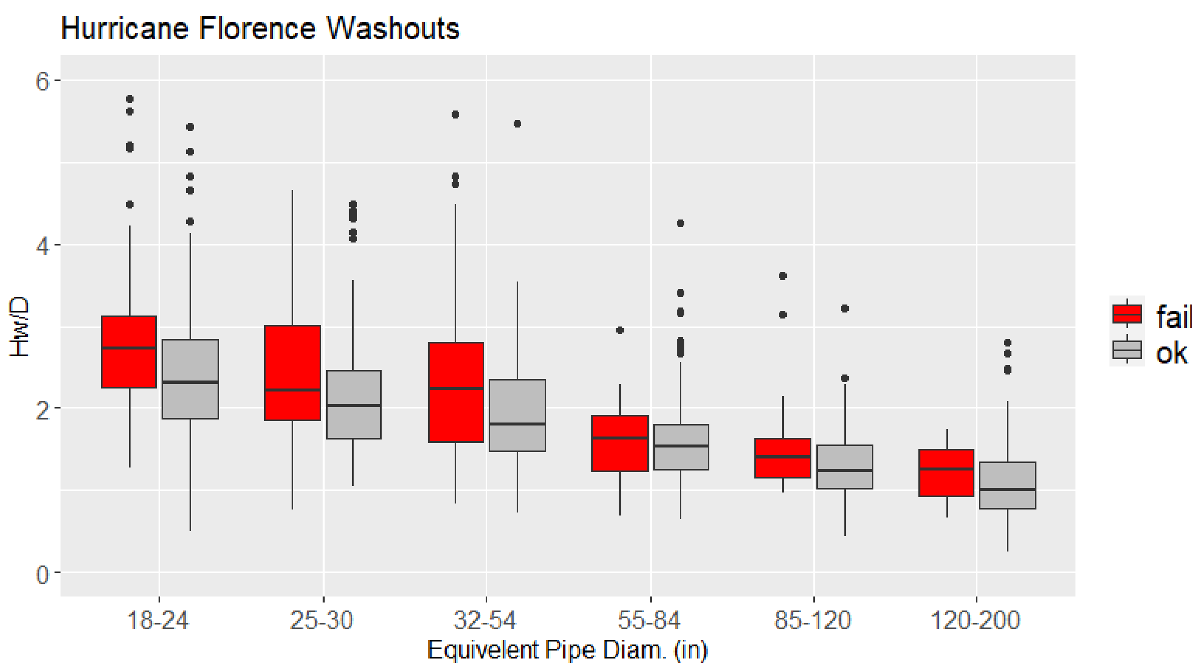


Figure 3-10. Ratio of headwater to structure diameter (Hw/D) for Hurricane Florence washouts versus non-washouts.

3.2.2 Nearest Structure Analysis

The structure nearest to the washed-out structure (either on the same stream or of similar drainage area) was compared to the washed-out structure. Again, of structure pairs (washout and non-washout), about 65% of washouts had a smaller hydraulic capacity relative to their drainage area than the non-washouts (Figure 3-11). However, 35% had a very similar or higher capacity than the nearby non-washouts so capacity is not the whole story. Washouts likely also relate to localized conditions such as slope, and potentially the condition/age of the existing structure and any debris blockage that occurs during a storm event.

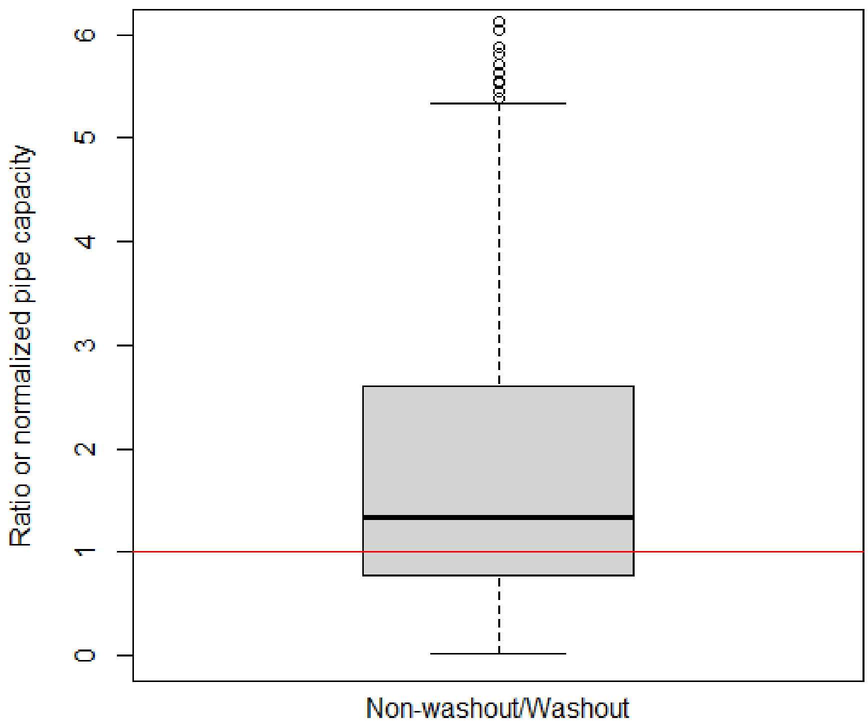


Figure 3-11. Ratio of normalized pipe capacity (pipe flow area/watershed area) between non-washout and adjacent washout locations. Red line indicates equal normalized size for washout and nearest non-washout.

3.2.3 Repeat Washouts

Overlaying the Hydraulics Unit's pipe replacement recommendations layers from Hurricanes Matthew and Florence indicated only thirteen repeat washout locations. The ratio of hydraulic capacity (pre-Matthew /post-Matthew) for the washout locations is shown in Figure 3-12. The washouts that failed a second time during Hurricane Florence were either not increased in size or only minimally increased when compared to the other structures that were replaced following Hurricane Matthew. So, inadequate sizing was likely a factor for washout at these locations. However, some sites that were not upsized did not wash out, so localized flow conditions and culvert condition/age are also likely factors that could not be quantified as part of this analysis.

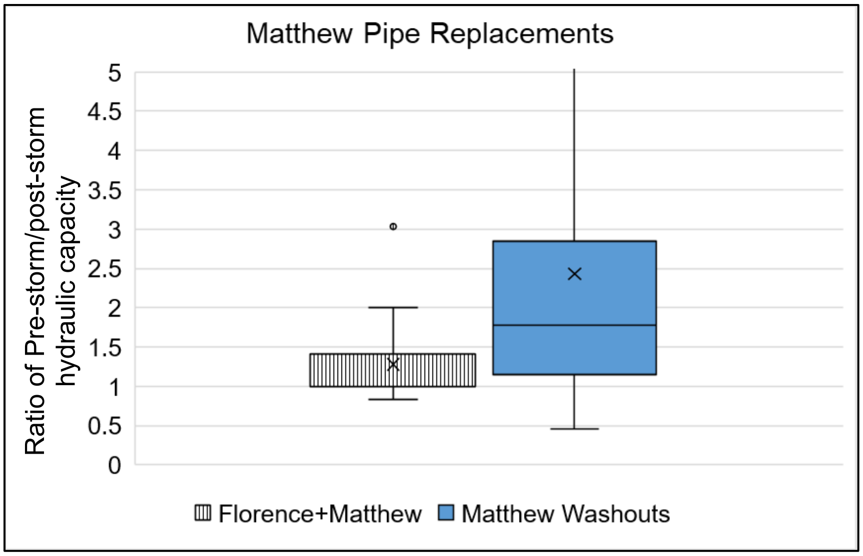


Figure 3-12. Ratio of pre- to post-Matthew hydraulic capacity of washout locations. The blue box represents locations that washed out during Matthew but not Florence. The hatched box represents locations that washed out during both storms.

3.2.4 Rainfall

The ratio of rainfall intensities (Florence rainfall/ Matthew rainfall) for locations that washed out during Florence, Matthew, or both are shown in Figure 3-13. For ratios <1, rainfall intensities were greater during Hurricane Matthew than for Hurricane Florence at the given location. Most of the locations (75-80%) that washed out during Hurricane Matthew had higher rainfall intensities during Matthew than Florence. However, a majority of the locations (~60%) that washed out during Hurricane Florence also had higher rainfall intensities during Hurricane Matthew. This indicated that some washouts might simply be a function of rainfall intensity and discharge, while other factors contributed to washouts at other locations. This may indicate different failure mechanisms as well. For example, the rainfall during Hurricane Matthew occurred over a 24-hour period, almost following a SCS-Type II distribution, which likely produced a single, high peak flow. Whereas the rainfall during Florence occurred over 3 days and likely produced longer periods of sustained higher flows and potentially multiple peaks, leading to more saturated road embankment conditions.

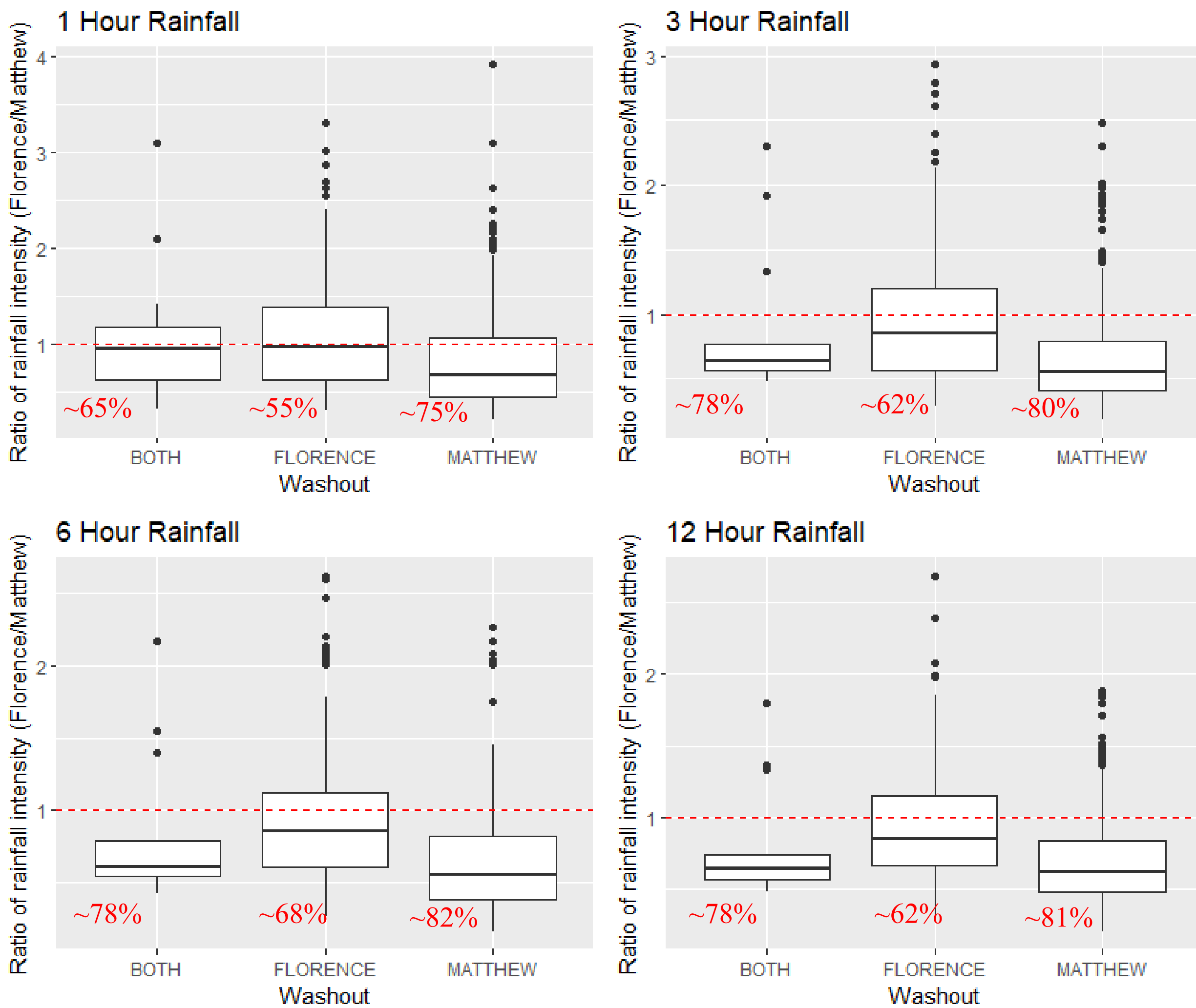


Figure 3-13. Ratio of rainfall intensities (Florence Rainfall: Matthew Rainfall) for locations that washed out during Hurricanes Matthew, Florence, or both.

3.2.5 Predicting Washout Locations

Overall, the ability of statistical machine learning models to predict washout locations was very limited. The final models tested, and the results are included in Table 3-1. The initial random forest model (Model 1) produced an error rate of 59% for washout locations for hurricane Matthew. By adding the 'headwall presence variable' to the random forest model (Model 2) the class errors were reduced to 38% for washouts and 9% for non-washouts. However, this error rate may have artificially been reduced because the headwall variable was often missing in the Matthew dataset. Testing this model (Model 2) using the input data from Hurricane Florence resulted in a high error rate for the identification of the washout locations (57%). Again, because of the extreme differences in the rainfall characteristics, washout mechanisms may differ between these two storms.

Logistic regression produced similar results to random forest with an error rate for washout locations of ~60% and less than 10% for the non-washout locations. Adding the headwall variable to the model reduced the error for the Matthew dataset (~40% error for washout location); however, testing the model with the Florence dataset again produced error of ~60% for the washout locations and increased the error rate to over 20% for non-washout locations.

It is likely that all the variables that explain washout probability are not present in our data set, or simply cannot be explained by this type of approach. Other important variables that should be added include pipe condition at the time of the storm, percent pipe obstruction, time of failure, the localized hydraulics at the time of failure, presence of armoring, local slope, pipe inverts.

Table 3-1. Classification models for prediction of washout locations.

Model	Variables	Confusion Matrices	
Model 1 Random Forest	Normalized hydraulic capacity, headwater/diameter, diff between road elev at pipe and high road elev, diff between road elev at pipe and low road elev, diff between road elev and ditch elev, watershed avg slope, watershed curve number, 3hr rainfall intensity	 fail ok	fail ok class.error 93 135 0.59 62 449 0.12 kappa = 0.31
Model 2 – Random Forest – Train with Matthew data	Normalized hydraulic capacity, headwater/diameter, diff between road elev at pipe and high road elev, diff between road elev at pipe and low road elev, diff between road elev and ditch elev, watershed avg slope, watershed curve number, 3hr rainfall intensity, headwall presence	 fail ok	fail ok class.error 141 87 0.38 49 462 0.09 kappa = 0.55
Model 3 – Random Forest - Test with Florence data	“ “	 fail ok	fail ok class.error 67 89 0.57 26 292 0.08 kappa = 0.39
Model 5 – Logit Regression	Normalized hydraulic capacity, headwater/diameter, diff between road elev at pipe and high road elev, diff between road elev at pipe and low road elev, diff between road elve and ditch elev, watershed avg slope, watershed curve number, 3hr rainfall intensity	 fail ok	fail ok class.error 82 146 0.60 38 473 0.07
Model 6 – Logit Regression – Train with Matthew data	Normalized hydraulic capacity, headwater/diameter, diff between road elev at pipe and high road elev, diff between road elev at pipe and low road elev, diff between road elve and ditch elev, watershed avg slope, watershed curve number, 3hr rainfall intensity, headwall presence	 fail ok	fail ok class.error 135 93 0.40 51 460 0.10
Model 6 – Logit Regression-Test with Florence data	“ ”	 fail ok	fail ok class.error 68 88 0.56 74 244 0.23

3.3 SAS VIYA Washout Dashboard

The washout dashboard includes six tabs including: EDA, Matthew Explanation, Florence Explanation, Rainfall Compare and Data Dictionary.

The EDA tab includes the analysis comparing the 603 washout locations to the 3610 non-washout locations for the six-county area in the Coastal Plain (Bladen, Duplin, Johnston, Robeson, Sampson, Wayne). The non-washout locations that were used for comparison do not include all undamaged pipes and structures; only non-washouts greater than or equal to 24" in diameter and within a buffered distance of the washed-out location (1 km for maintenance pipes and 2km for Non-NBIS pipes) were included. The EDA tab allows the user to filter between results for Hurricane Matthew and Hurricane Florence. Figure 3-14 shows the locations for all washouts (ok) and non-washouts (fail) combined with a pie chart to indicate the total count for each for Hurricane Matthew. Several additional graphical displays comparing single and multiple parameters were also created. For example, Figure 3-15 compares the pipe area to watershed area ratios for washouts to non-washouts sorted by watershed area. This display enables the user to see that washout structures were undersized compared to the non-washouts, however under sizing does not appear to be a factor for the very largest watersheds larger than >10 square miles.

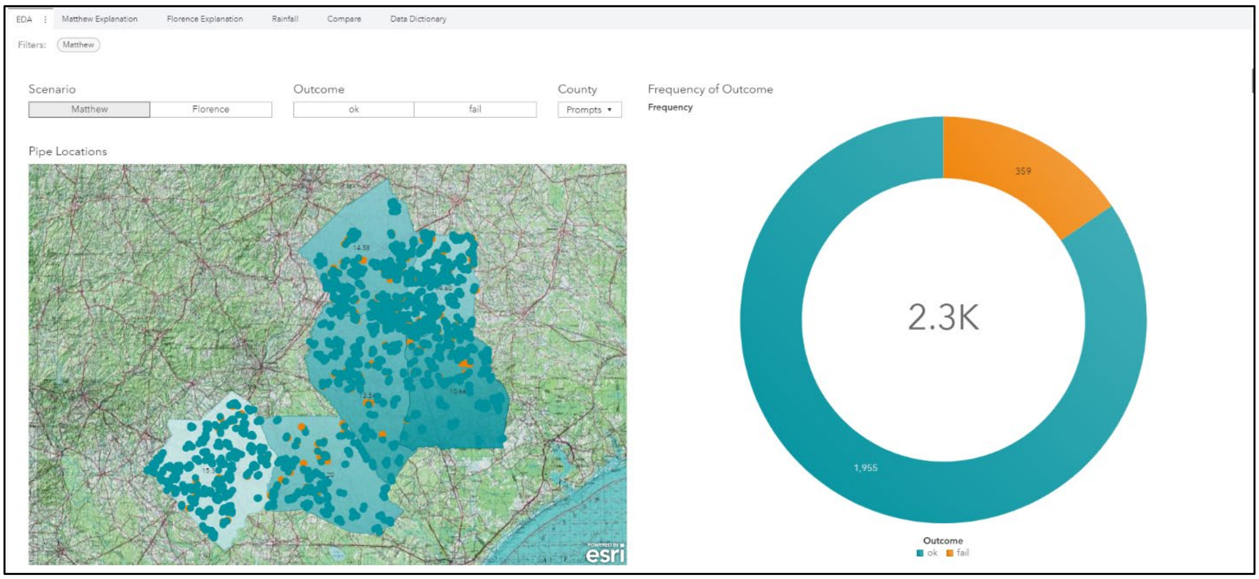


Figure 3-14. EDA tab showing results for all washout and non-washout structures in the five-county study area.

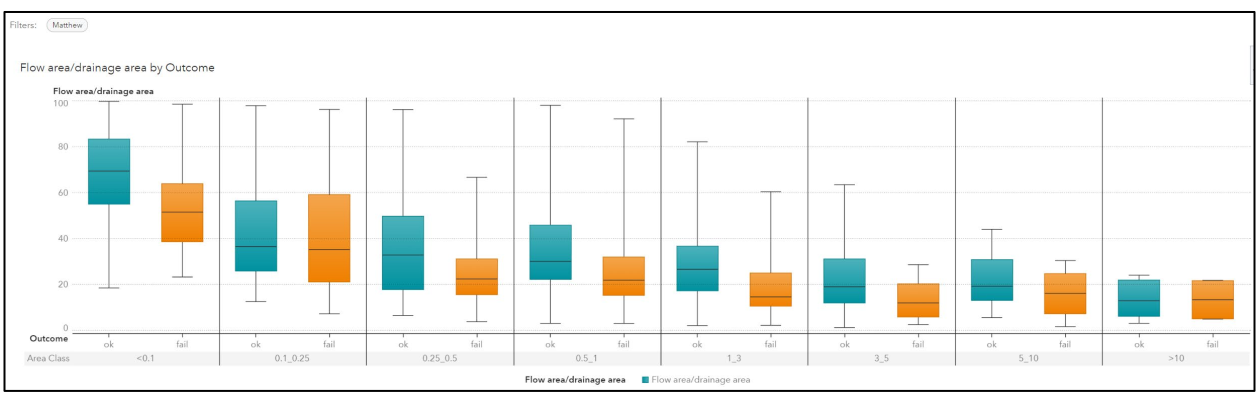


Figure 3-15. Comparison of flow area to drainage area for washout and non-washout structures sorted by watershed area for Hurricane Matthew

Numerous other comparisons are provided in the EDA tab that include drainage area, rainfall data, county, pipe flow area, equivalent pipe diameter, pipe material, road class, headwall presence, pipe shape, and HW/D. For each chart, the user can generate a report or modify the chart type used to display the data. In addition, tabular summaries of the data can be easily viewed, printed, and exported. A sample printed summary is shown in Figure 3-16.

Drainage Table

Stream ID ▲	Area Class ▲	U_ID ▼	Pipe Material ▲	Drainage Area	CN	S	Ia	Rainfall Total	Q	V	Pipe Flow Area
30010	<0.1	WS_M_1015	RC	0.04	76.50	3.07	0.61	15.33	12.17	0.05	7.07
		WS_M_1004	RC	0.04	66.87	4.95	0.99	14.19	9.59	0.03	3.14
	0.5_1	MAT_ws_137	CM	0.91	63.40	5.77	1.15	15.33	10.07	0.77	74.62
	1_3	MAT_ws_144	CM	1.76	64.83	5.43	1.09	15.33	10.31	1.51	19.63
30014	<0.1	WS_M_985	RC	0.05	74.06	3.50	0.70	13.83	10.37	0.04	4.91
	0.1_0.25	MAT_ws_127	RC	0.13	70.26	4.23	0.85	13.83	9.79	0.11	3.14
	3_5	WS_N_712	CM	3.40	62.91	5.90	1.18	14.17	8.93	2.53	38.47
		WS_N_711	CM	4.47	64.21	5.57	1.11	14.17	9.14	3.41	76.93
		WS_N_710	CM	3.75	63.70	5.70	1.14	14.17	9.06	2.83	39.25
30015	<0.1	WS_M_438	RC	0.10	71.33	4.02	0.80	14.46	10.55	0.09	3.14
	0.5_1	WS_M_439	CM	0.59	68.68	4.56	0.91	14.17	9.86	0.48	7.07
		MAT_ws_122	RC	0.63	68.50	4.60	0.92	14.17	9.83	0.52	9.81
30021	0.1_0.25	WS_M_981	RC	0.14	56.87	7.58	1.52	14.46	8.16	0.10	4.91
	1_3	MAT_ws_146	CM	2.54	62.02	6.12	1.22	14.46	9.05	1.92	19.63

Figure 3-16: Export of pipe data for Hurricane Matthew. Rows shaded yellow indicate washout locations.

The dashboard also allows for data selection combined with updates to all graphs and tabular summaries by county, watershed boundary and by applying a radius of choice to any selected location. Figure 3-17 below shows an example summary for subbasin 913 located in Wayne County. The display shows the washout (8) and non-washout (55) locations. Using the tab filters, the user can isolate the dashboard view to a specific county, washout or non-washout pipes only and secondary or primary roads. Figure 3-18 shows the map location for all failed pipes in Wayne County that occurred during Hurricane Matthew on secondary roads. All summary graphs and tabular data are updated with this specific filter group, enabling the user to quickly produce maps and data for a particular scenario or location of interest.

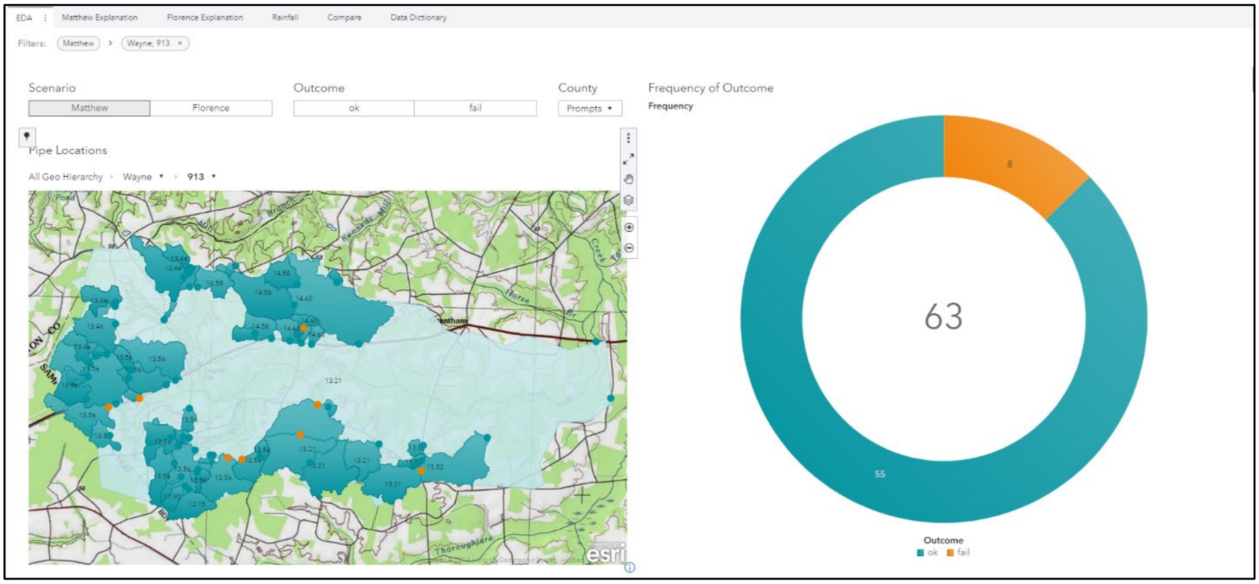


Figure 3-17. Washout and non-washout locations compared for Subbasin 913 in Wayne County.

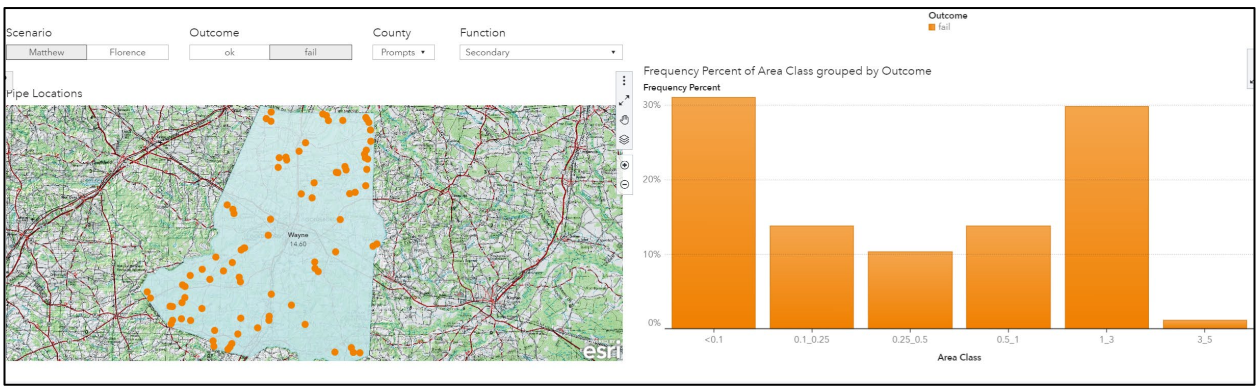


Figure 3-18. All washout locations in Wayne County that occurred on secondary roads during Hurricane Matthew.

The Matthew and Florence explanation tabs provide the variables that have the most influence on washouts and reports the washout likelihood statistics for each individual variable. The user can select a variable by clicking on the corresponding bar from the chart on the left and this will display the statistical summary and an accompanying graphical display specific to this variable. The summary for equivalent diameter for Hurricane Florence is provided below in Figure 3-19. From this summary the user can see that if the pipe does not have a headwall or this data was not included in the pipe database, then there is a 95.83% chance that the pipe failed.

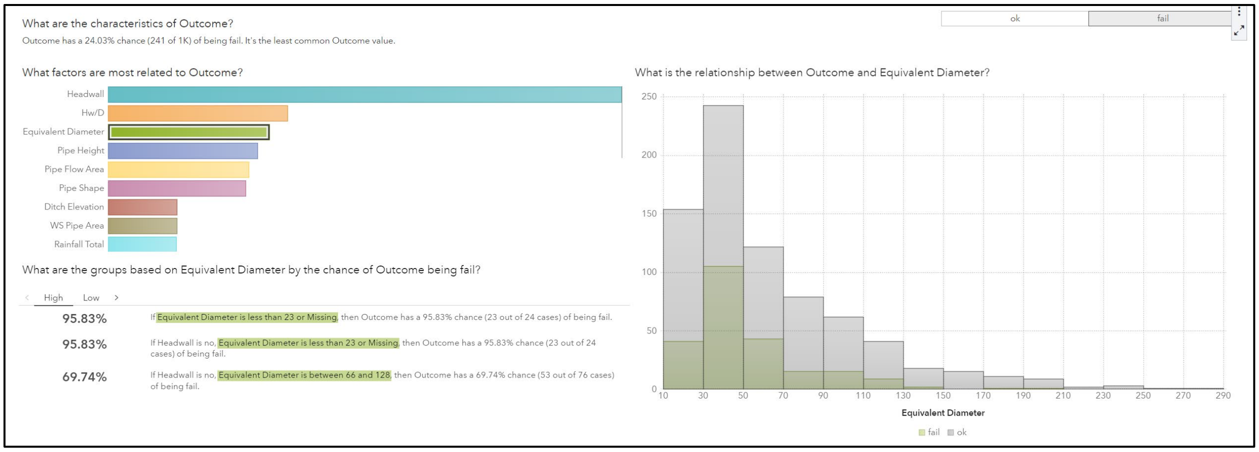


Figure 3-19. Florence explanation tab display for equivalent diameter.

The rainfall tab provides the summary of incremental and cumulative rainfall and discharge for Hurricane Matthew and Florence. The user can also select to view the rainfall and flow totals for washout (fail) or non-washouts (ok). Figure 3-20 shows the rainfall and flow totals for Hurricane Matthew that fell in the drainage basins that flow to all failed pipes in the six-county study area.

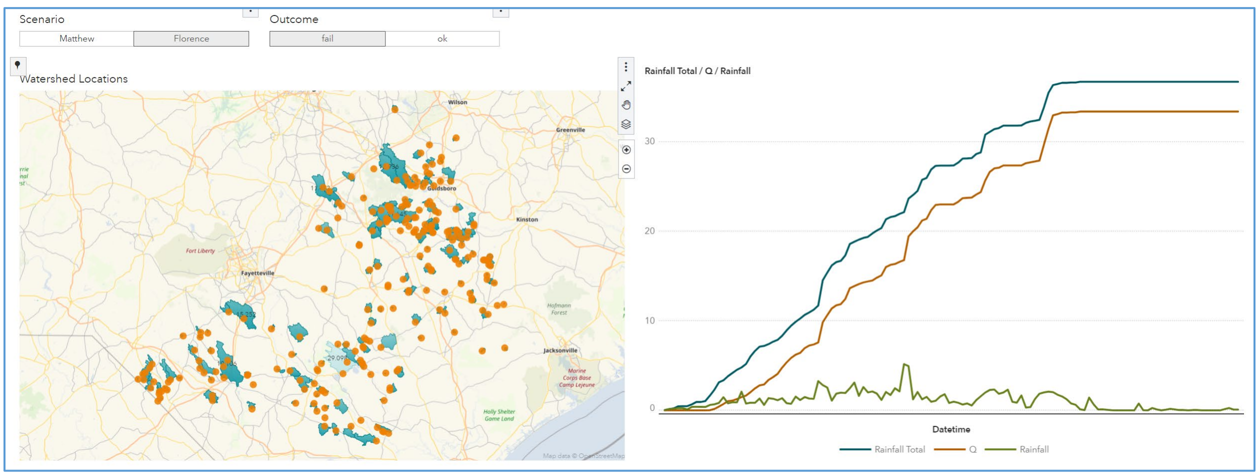


Figure 3-20. Incremental rainfall and cumulative total rainfall and discharge for all washout locations during Hurricane Florence.

The compare tab provides a tabular summary of all data specific to Matthew and Florence. And the data dictionary tab provides the name and definition for all variables included in the dashboard.

3.4 Hydrologic and Hydraulic Modeling

3.4.1 HEC-RAS Rain-on-Grid Model

The rain-on-grid model (Figure 3-21) could be readily calibrated to a range of storm events at the watershed outlet by changing infiltration parameters and Manning's roughness values (Table 3-2). Three infiltration methods were tested (Curve Number, Green-Ampt, and Constant Loss) and all produced reasonable results. However, the Green-Ampt was selected for use because it is a more physically based method in which initial moisture conditions can be easily reset.

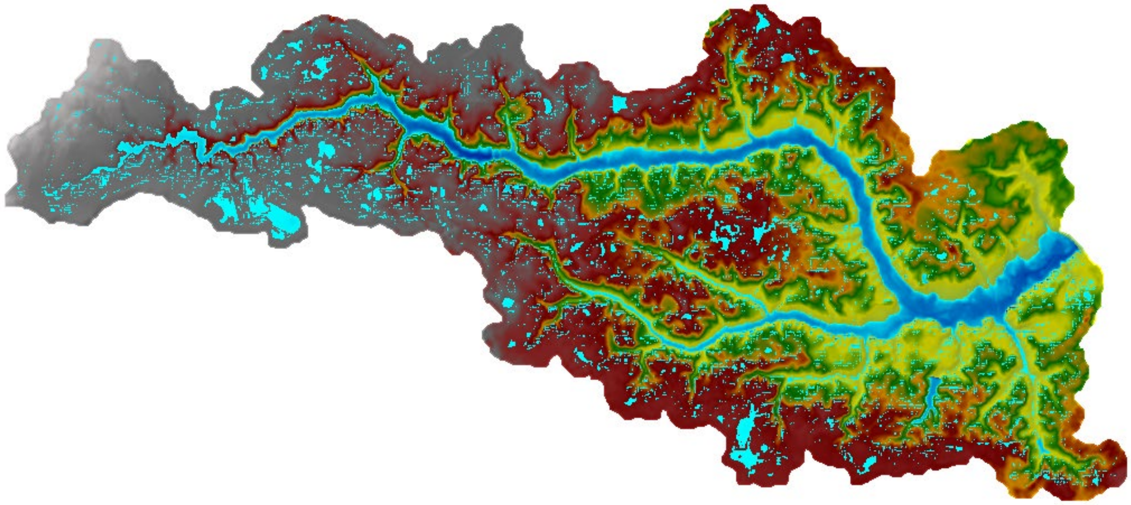


Figure 3-21. Rain-on-grid model results showing WSE over topography.

When the model was calibrated to Hurricane Matthew and then run for other storms with only the initial soil saturation modified based on satellite soil moisture readings, the goodness of fit to the observed data was not as strong (Table 3-2 and Figure 3-22). This is potentially related to rainfall intensity as the model was calibrated to higher rainfall intensity (Hurricane Matthew). Given these results as well as the uncertainty surrounding predictions of rainfall timing, intensity and spatial extent, the use of the rain-on-grid models for predictive modeling is somewhat limited at this time. The use of the rain-on-grid model results should be focused at the planning level to identify and quantify potential risk rather than real-time precise predictions of flooding. As more data is collected, the capabilities of HEC-RAS advance, and Satellite rainfall data becomes available closer to real time, this assessment may change.

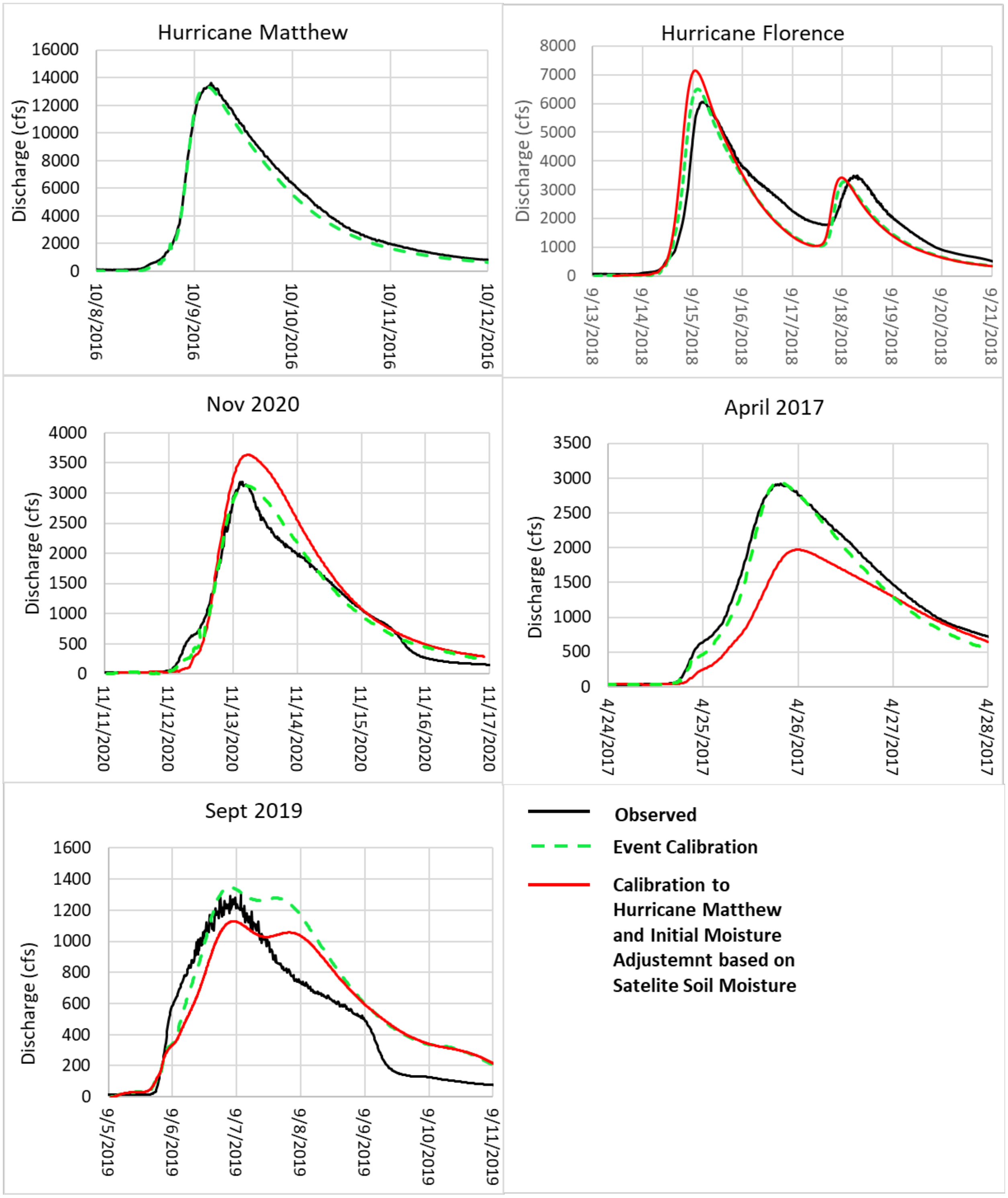


Figure 3-22. Calibration/validation results for HEC-RAS rain-on-grid model for Nahunta Swamp watershed.

Table 3-2. Calibration/validation results for HEC-RAS rain-on-grid model for Nahunta Swamp watershed using satellite soil moisture for initial condition.

Storm	Total Rainfall (in)	Max 1 hour rainfall intensity	Initial Soil Moisture Content (%)	Observed		Simulated		Difference	
				Qp (cfs)	WSEp (ft)	Qp (cfs)	WSEp (ft)	Qp (cfs)	WSEp (ft)
Matthew	9.0-12	1.1-2.6	90	13600	68	13350	67.7	-250	-0.3
Florence	13-15	1.0-1.4	50	6060	64.2	7080	64.8	+1020	+0.6
Apr 2017	5.0-6.5	0.4-0.55	63	2920	62.1	1940	62.0	-980	-0.1
Sept 2019	5.0-6.0	0.6-0.8	40	1300	59.1	1130	60.7	-170	+1.6
Nov 2020	5.0-7.0	1.0-1.4	73	3190	62.3	3600	63.1	+410	+0.8

Qp = Peak discharge
WSEp = Peak water surface elevation

3.5 Application to Download and Transform Rainfall Data

RRT-HydroMap (Radar Rainfall Transform, Hydraulic Model Output, and Mapping) is an application developed by NC State University Biological and Agricultural Engineering and NC Sea Grant for the NC Department of Transportation Hydraulics Unit. The application is meant for downloading radar rainfall data and transforming the data into DSS format for input in HEC-RAS rain-on-grid models. The application also has the capability to directly input data into your model, output results and to summarize statistics for each rainfall event such as rainfall depth and intensity for different durations.

3.5.1 Download Historical Rainfall Tab

The Historical rainfall tab (Figure 3-23) facilitates the download of **MRMS QPE** gridded precipitation data from **Iowa State University's Iowa Environmental Mesonet (https://mtarchive.geol.iastate.edu/)**. The "GaugeCorr_QPE" data is available from 2015 to 2020 across the conterminous U.S. From 2020 to present the "Multisensor_QPE" data is used. The user can select the download timeframe (Note that long time periods may require a long time to download).

- The user must input coordinate bounds (decimal degrees) for the download data.
- The MRMS data is in the UTC time zone. The user can select a different time zone and the application will shift the gridded data in time.
- The user must select a location to save the created DSS file. The DSS file is created in SHG Grid System. The cell size can be specified in the "Setting" Tab (default 2000 m).
- The user can upload a shapefile of their study area to view along with the download coordinates.
- The "View coordinates in map" can be selected to view the input coordinate zone on a HTML map (Figure 3-24).
- This tab also generates GeoTiff files and an HTML map (Figure 3-25) that displays the rainfall return period from NOAA Atlas 14 values (about 2-3 minutes).

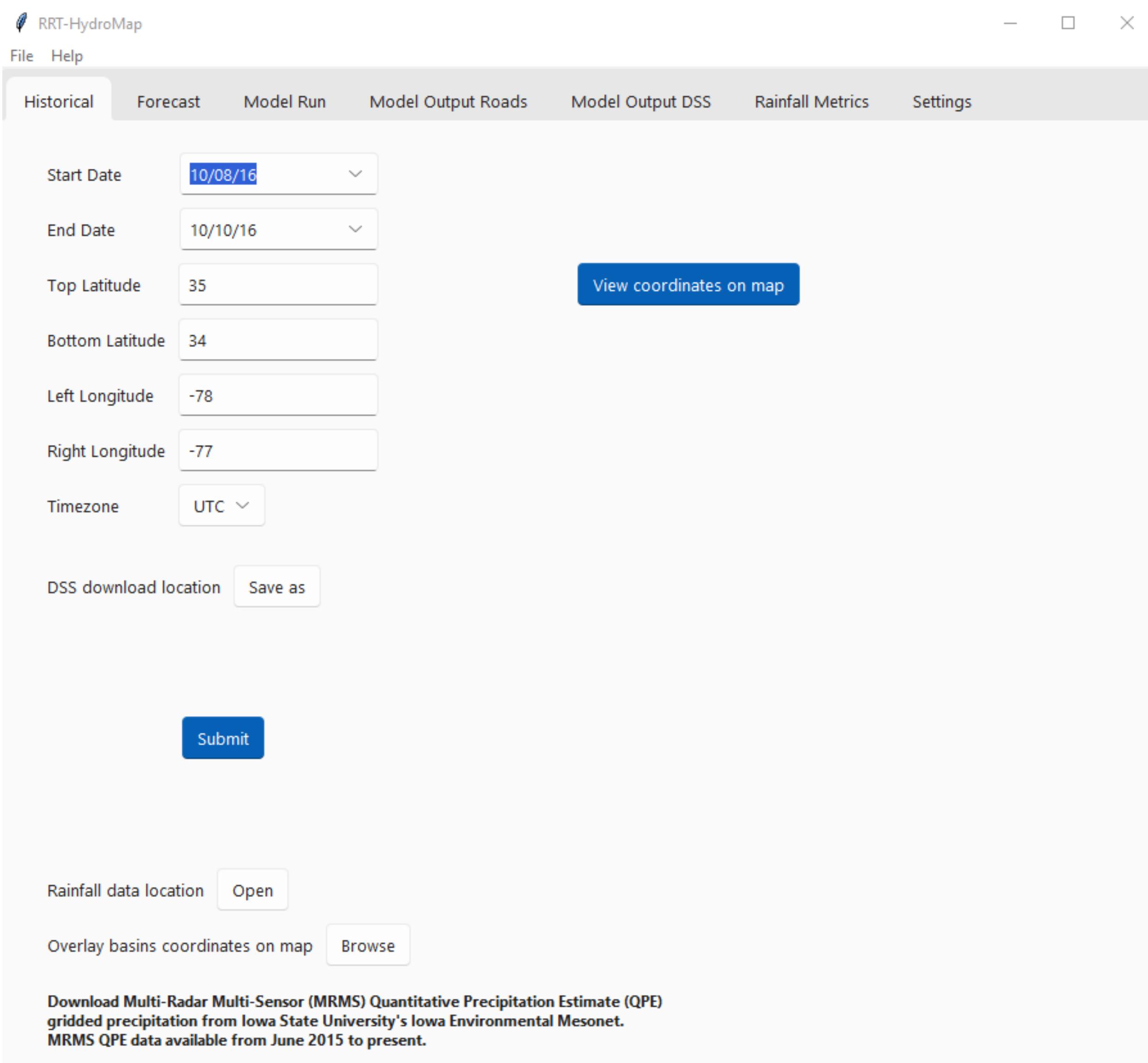


Figure 3-23. Historical rainfall data download tab screenshot.

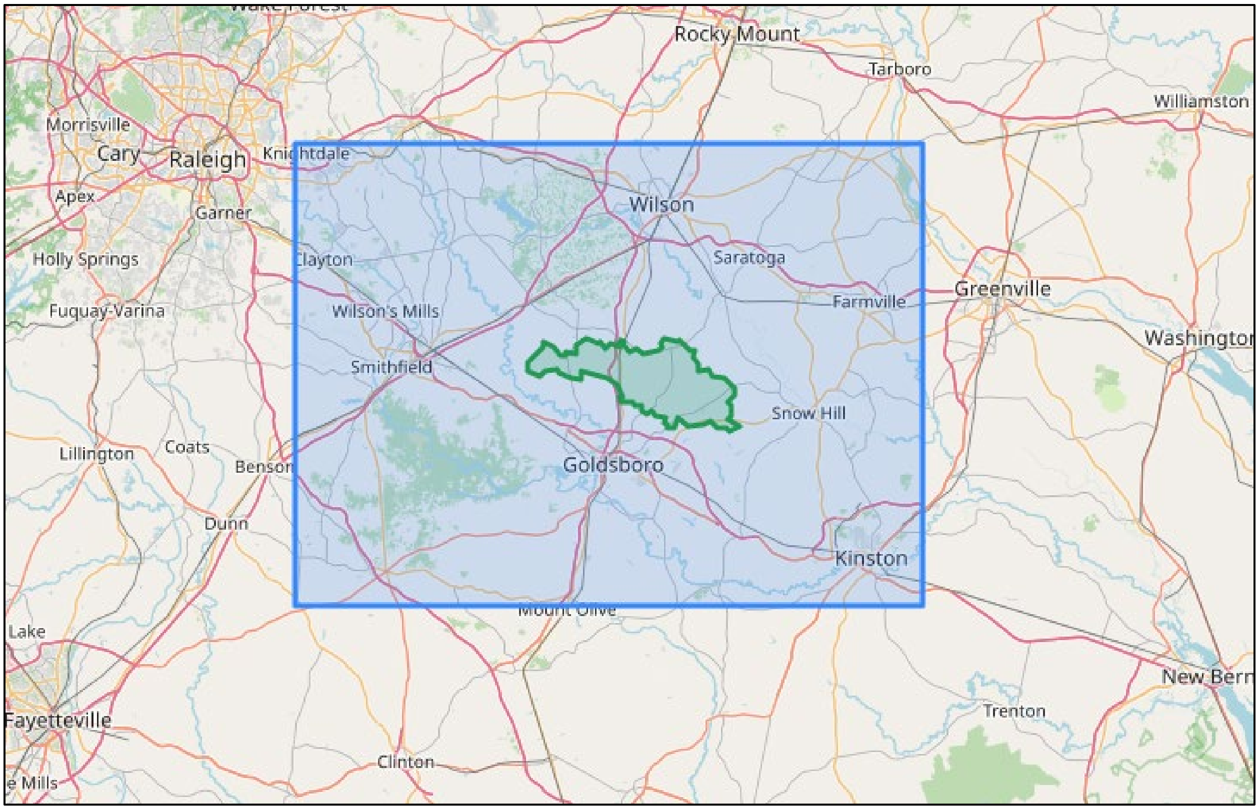


Figure 3-24. Model bounds overlain by rainfall data download area HTML map.

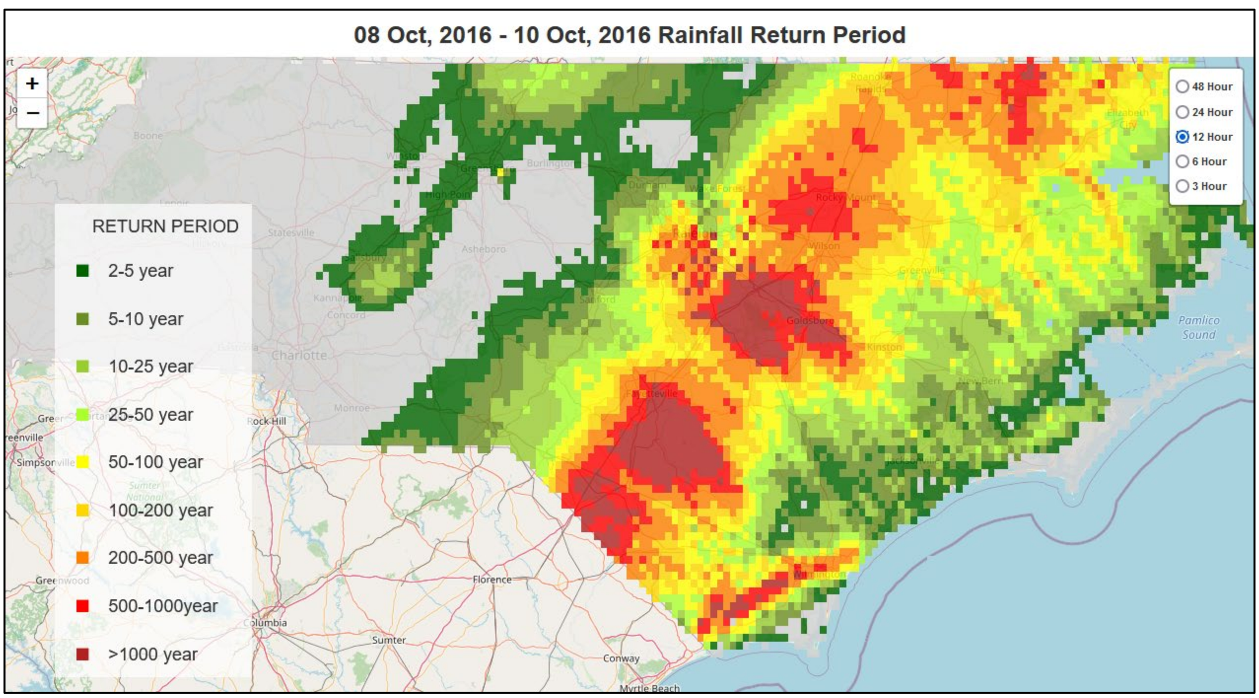


Figure 3-25. Rainfall return period HTML map.

3.5.2 Forecast Rainfall Tab

This Forecast rainfall tab (Figure 3-26) facilitates the download of the National Centers for Environmental Prediction 60-hr forecast based on the American Mesoscale Forecast System Model- (https://nomads.ncep.noaa.gov/cgi-bin/filter_nam_conusnest.pl). Inputs and functionality are similar to the Historical tab.

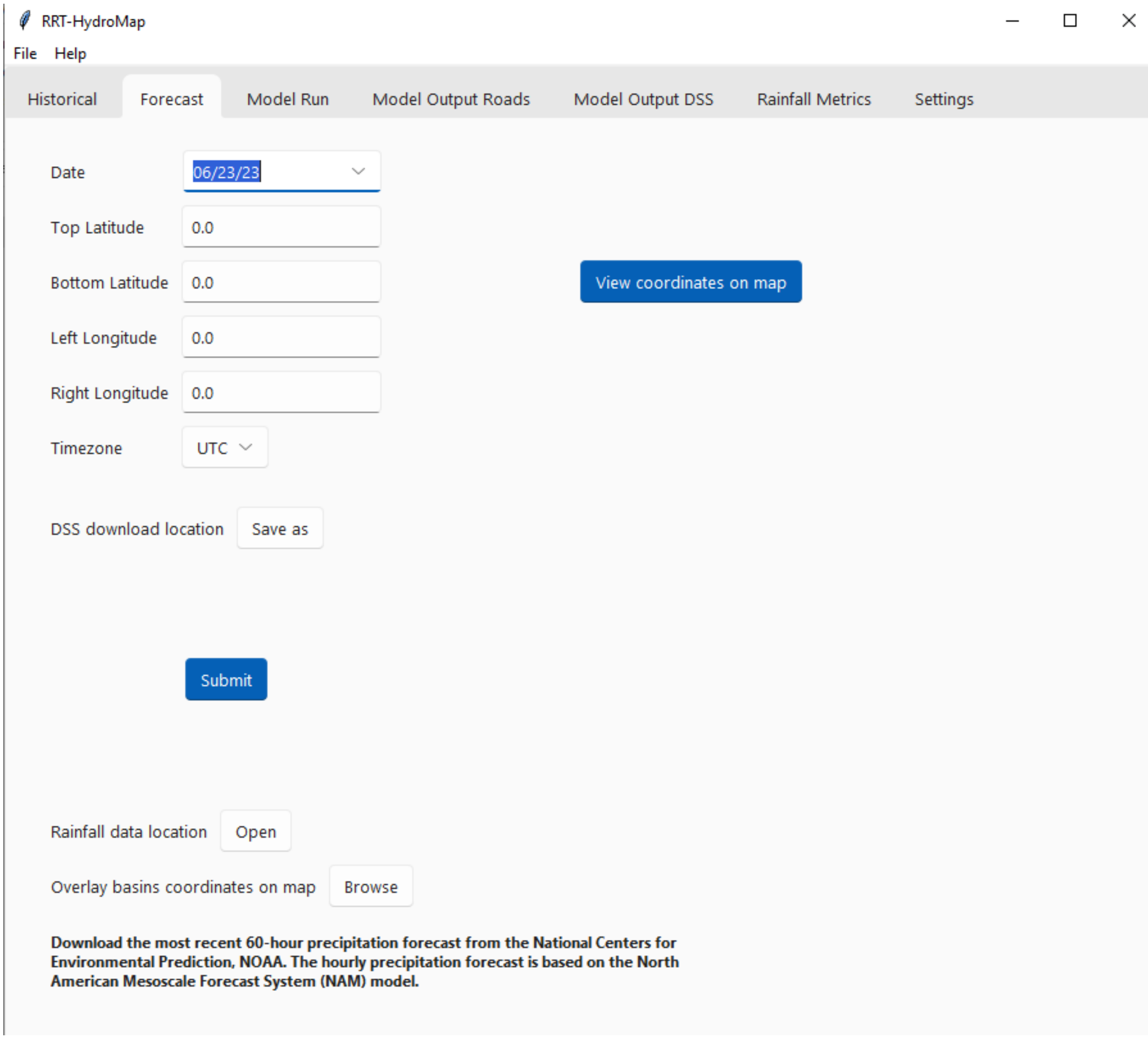


Figure 3-26. Forecast rainfall data download tab screenshot.

3.5.3 Model Run Tab

This Model Run tab (Figure 3-27) allows the model to be run without opening HEC-RAS. If the Green-Ampt infiltration method is used, then the user can change the initial moisture condition. For the best functionality, a project should be set up with only one plan file in a dedicated location, as this tab runs the current plan. HEC-RAS must first be installed.

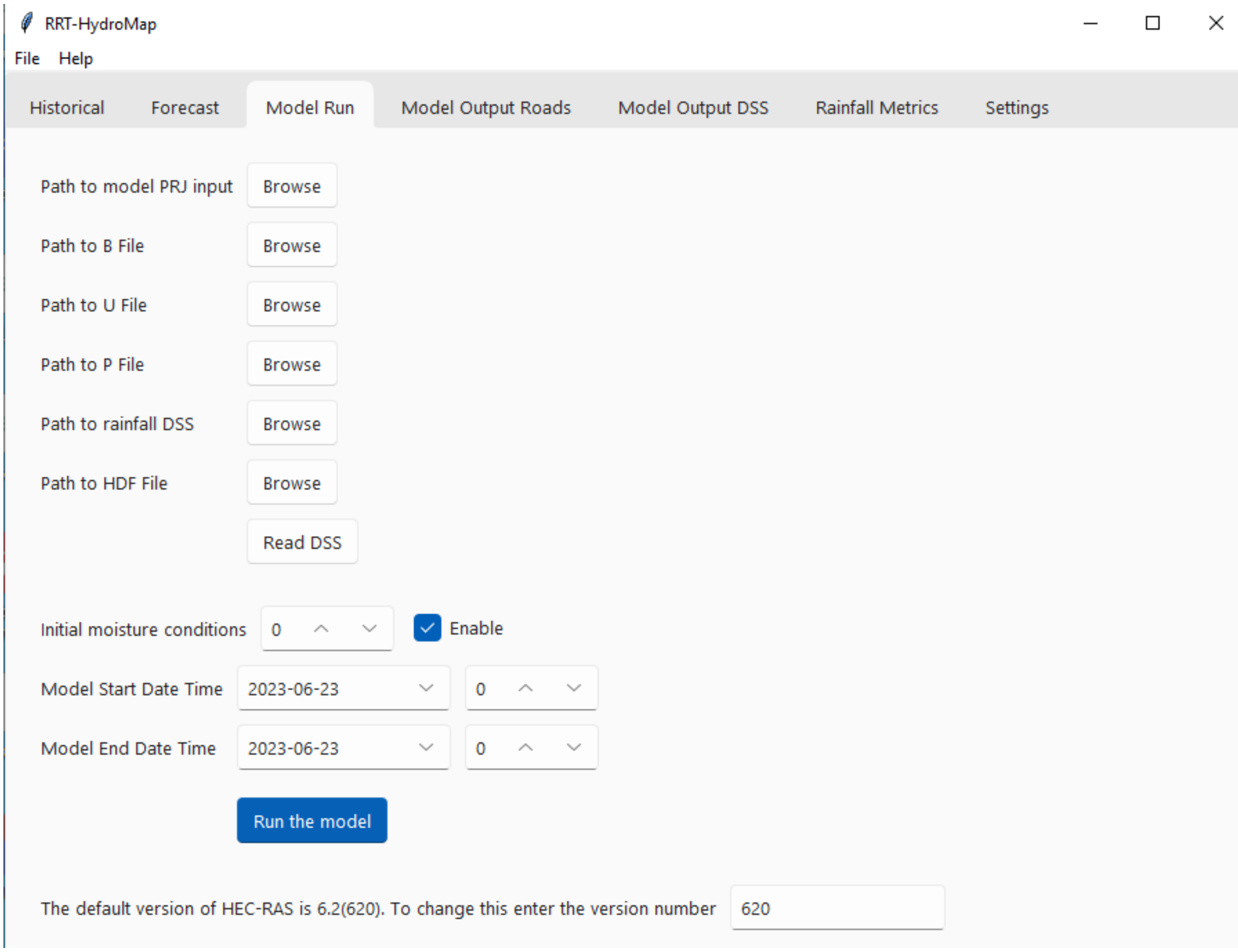


Figure 3-27. Model run tab screenshot.

3.5.4 Model Output Roads Tab

This Model Output Roads tab (Figure 3-28) compares a HEC-RAS 2D WSE .tif file to the Road Ribbon LiDAR elevation data and generates a shapefile of inundation depths for road segments and structures. An HTML map of the road inundation is also generated. The resulting HTML map showing the road and structure overtopping depths are shown in Figure 3-29 and Figure 3-30, respectively.

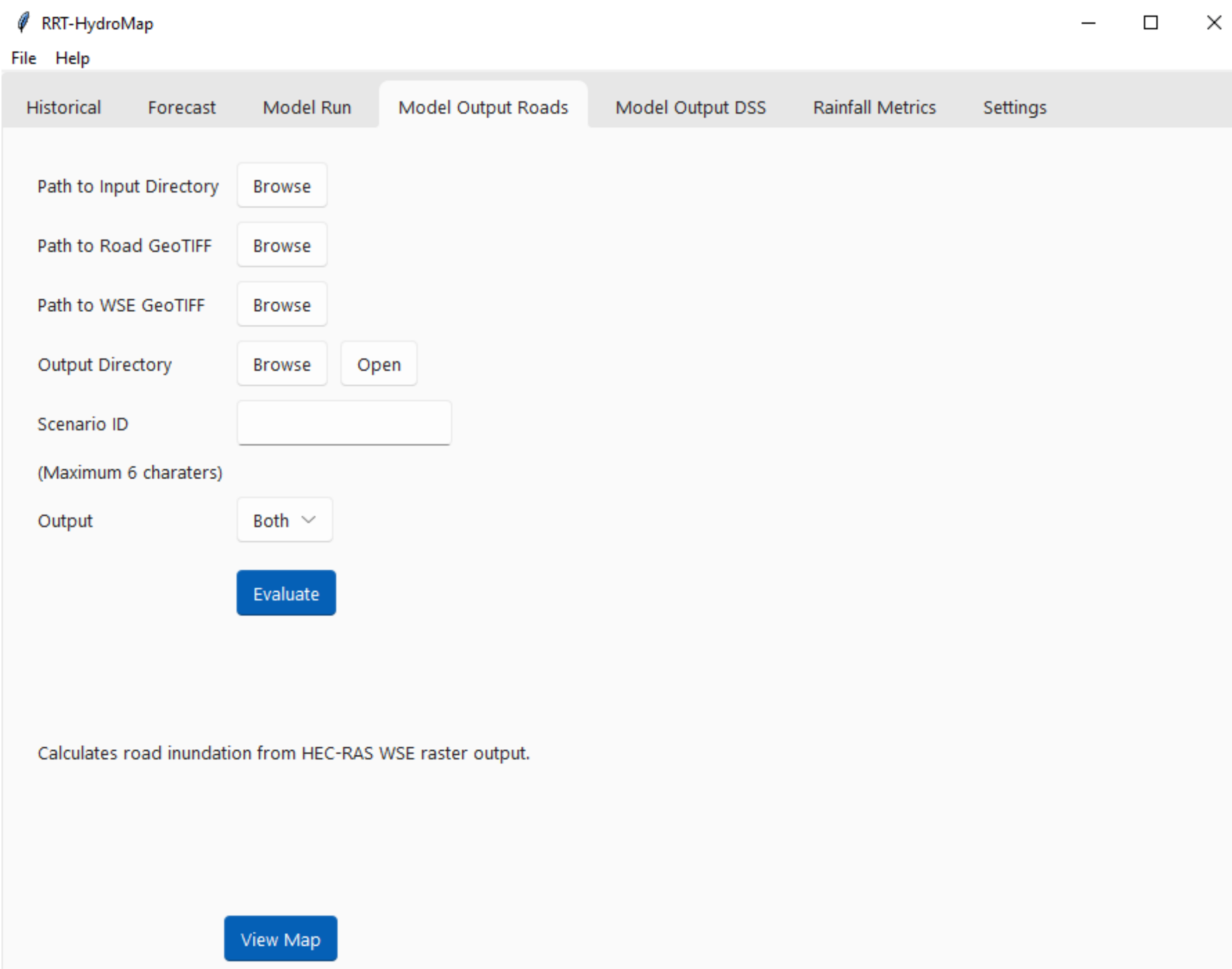


Figure 3-28. Model output roads tab screenshot.

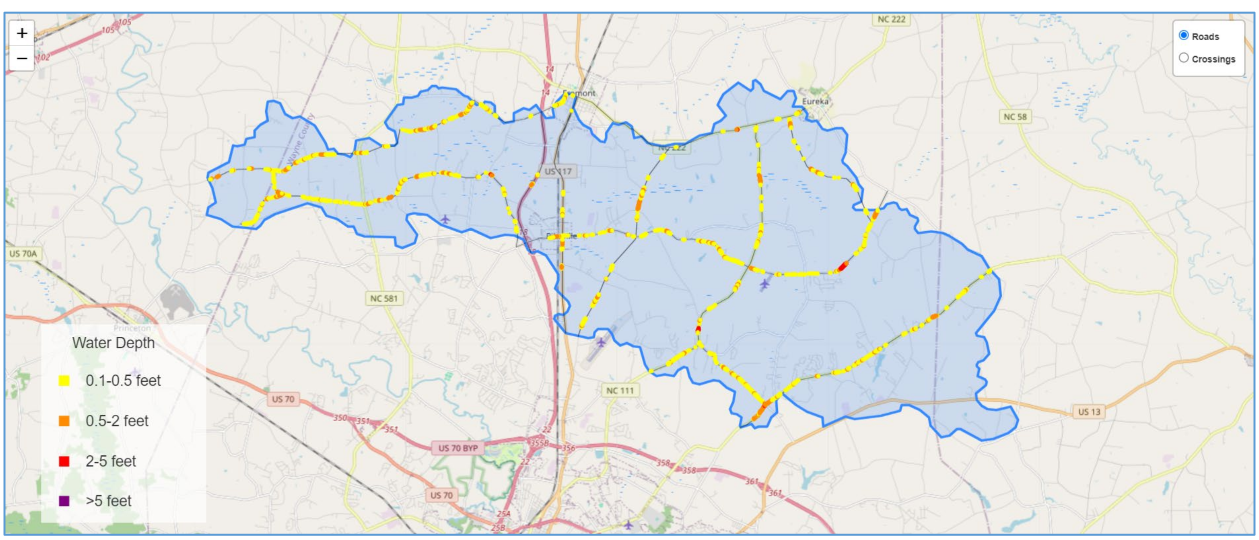


Figure 3-29. HTML view of road inundation for the 100-year storm.

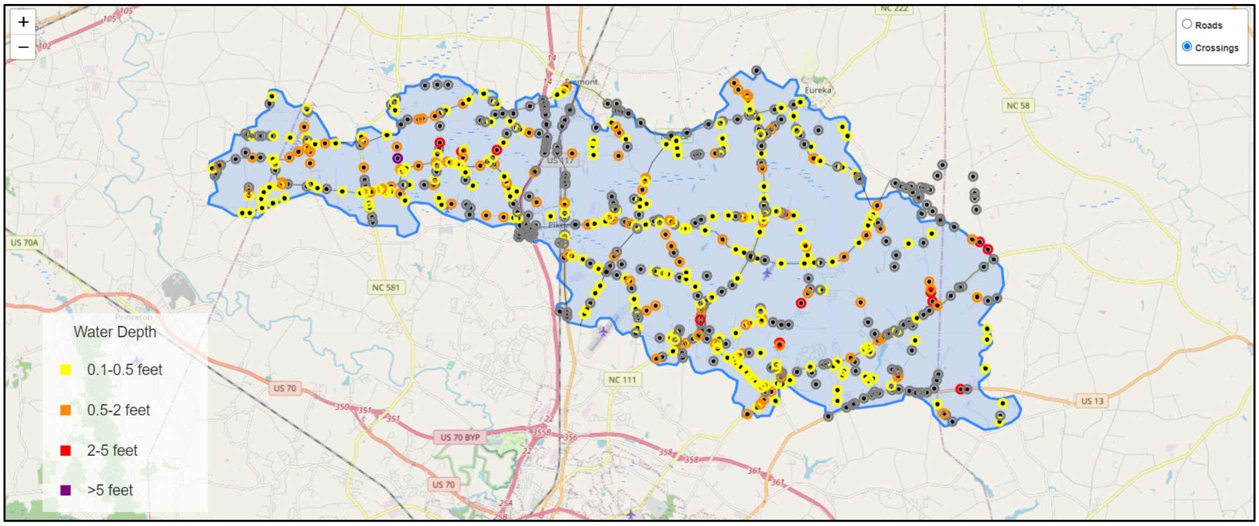


Figure 3-30. HTML view of structure inundation for the 100-year storm.

3.5.5 Model Output DSS Tab

This Model Output DSS tab (Figure 3-31) allows for the output and graphing of "2D Area Connections" from the output DSS file. A .csv file named "pipes.csv" is required.

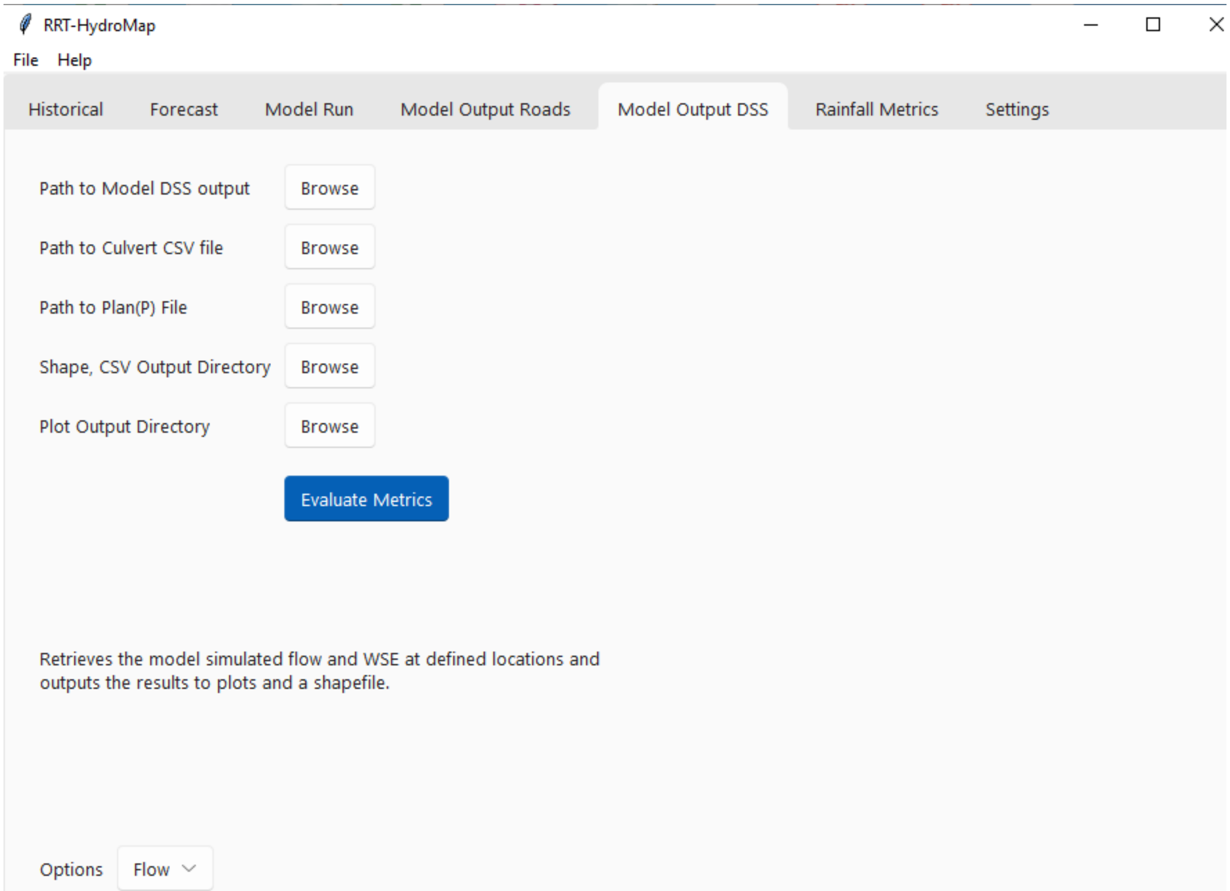


Figure 3-31. Model DSS output tab screenshot.

Rainfall Metrics Tab

The Rainfall Metrics tab (Figure 3-32) summarizes the hourly rainfall by zones in a shapefile.

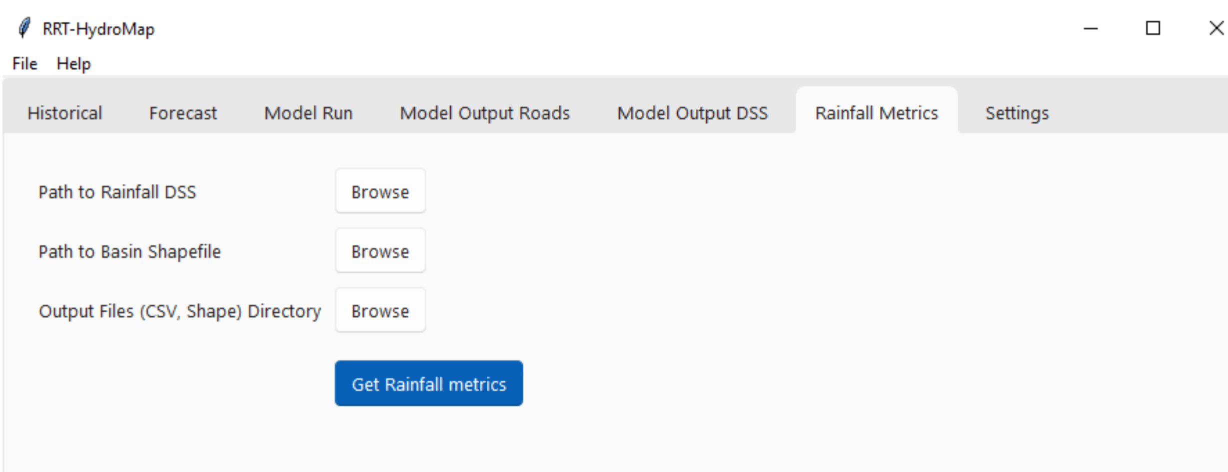


Figure 3-32. Rainfall metrics tab screenshot.

3.6 Transportation Resilience Identification and Prioritization (TRIP) Tool

The SAS Viya dashboard, TRIP Tool, has two tabs including Asset Management and Storm Viewer. The Asset Management tab displays asset summary for resilient routes and structures, including asset report details for Nahunta Swamp. The asset tab also shows the location and depth of overtopping along roadways and at structures. The tab also reports the upgrade costs necessary for upgrading all overtopped features to each modeled return interval storm period. The Storm Viewer tab displays the depth of overtopping along roadways and at structures in Nahunta swamp for a selected storm.

3.6.1 Asset Management

The Asset Management tab displays asset summaries for the nine resilient routes identified in the Nahunta Swamp watershed. The tab also allows for viewing the resilience of all structures in the watershed to each storm level modeled using the rain-on-grid modeling results, including the 25, 50, 100 and 500-year storms. The tab displays and summarizes the 1) number of structures by type (i.e. maintenance pipes, non-NBIS and NBIS structures), 2) total length of road and number of structures, 3) the number of structures and length of road that are overtopped, and 4) the costs estimated for making each resilient route, including upgrading all roads and structures, to each design storm level. The cost estimates are shown as stacked bars for each design storm with structure and road upgrade costs indicated separately. In addition, to the total costs for raising all roads that are overtopped, the cost savings for not raising roads that are overtopped by less than a foot and implementing armoring in locations where velocities exceed 2 ft/s is also indicated. In addition to the map display of the watershed and structures, tabular summarizes of structure overtopping, structure costing, road overtopping and road costing are provided at the bottom of the page. The asset management tab on full view shows all structures in the watershed and the overtopping summaries of the 68.9 miles of resilient route, 611 structures, road and structure overtopping, costs for making resilient to each design storm are shown below in Figure 3-33.

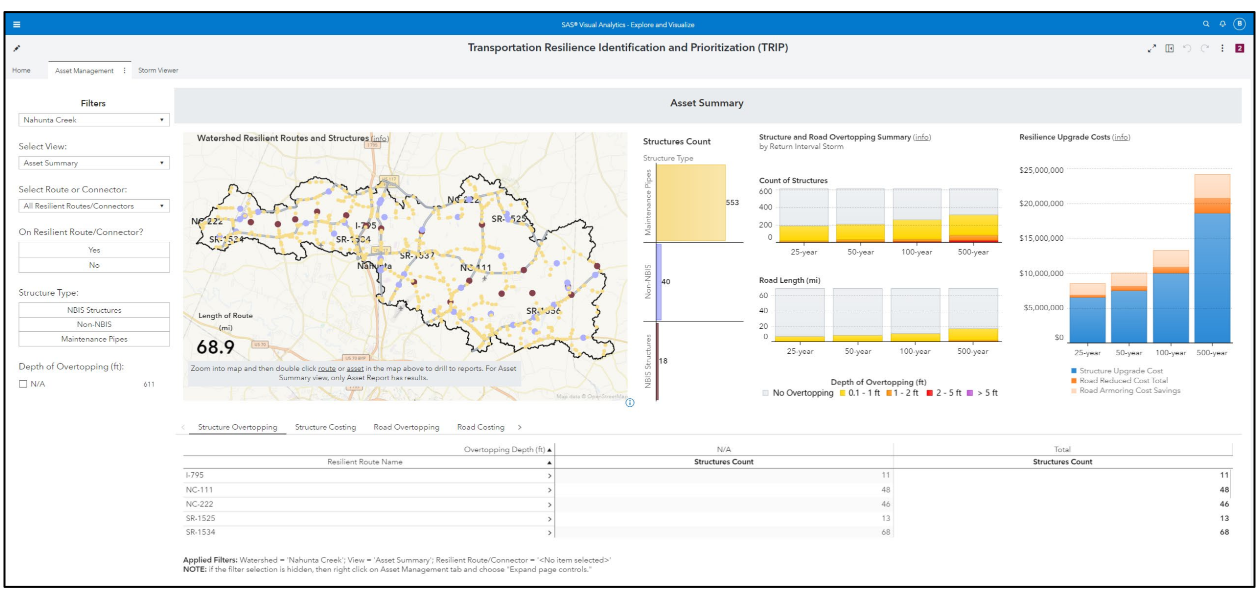


Figure 3-33. Asset Management Tab showing the full asset summary for the Nahunta Swamp watershed.

Using the filters on the left sidebar of the tool allows the user to isolate views and summaries to specific storms and to only structures that are located along the 9 resilient routes as well as to summaries for each specific structure type (i.e. maintenance, non-NBIS and NBIS) below). The filters allow the user to better visualize impacts to specific structure types for each storm level. Using these filters for example, can show that 8 NBIS structures are overtopped by the 500-year storm – 3 at less than 1 foot, 2 at 1-2 foot and 3 at 3-5 foot. The user can also see the locations and depths where structures are vulnerable to overtopping at each storm return interval (see Figure 3-34). In contrast, there are 208 maintenance pipes that are overtopped during the 500-year storm event. (see Figure 3-35)

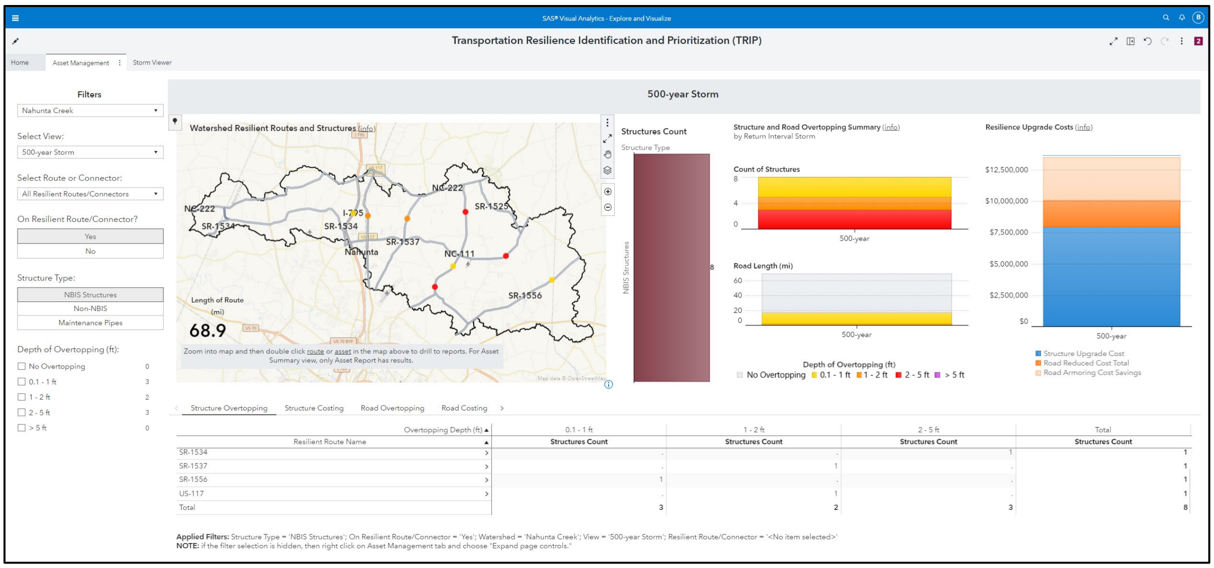


Figure 3-34. Overtopping summary for all NBIS structures along 68.9 miles of resilient routes for the 500-year storm.

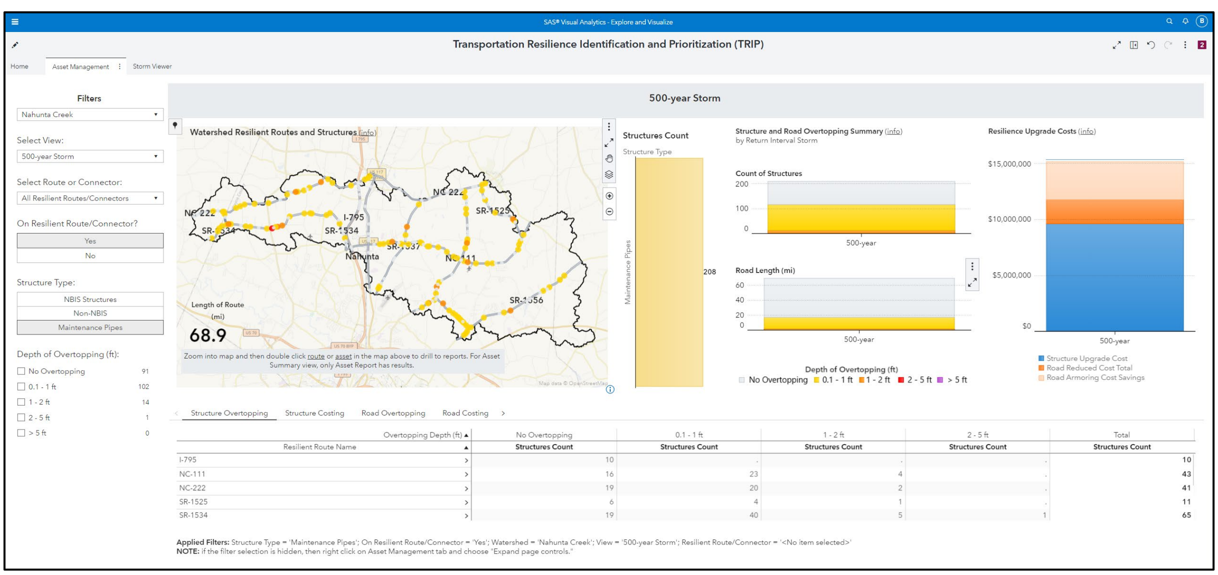


Figure 3-35. Overtopping summary for all maintenance pipes along 68.9 miles of resilient routes for the 500-year storm.

Using the filter located at the bottom of the left panel, users can select specific overtopping depths to isolate map views and summaries. This option can be used to identify locations where more extreme overtopping depths of structures are of concern. For example, Figure 3-36 indicates there are 42 structures in the Nahunta Basin that are overtopped by greater than 1 foot. In addition, using the summary tabs at the bottom, viewing the graphs on the right, and viewing road overtopping maps and reports for each resilient route (Figure 3-37 and Figure 3-38), we can locate 0.8 miles of roadway that are overtopped by greater than 1 foot using the dashboard. Because greater overtopping depths increases the risk of drivers and pedestrians being swept off roads, these locations could be targeted for inspection, modeling and potential upgrade.

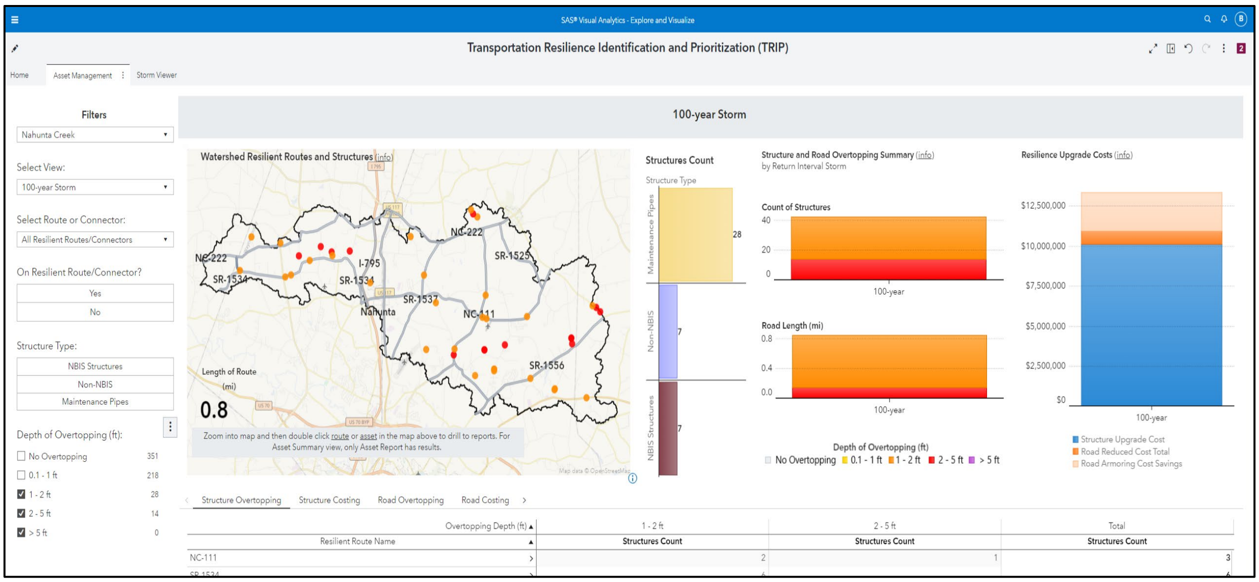


Figure 3-36. All structures overtopped by >1 ft for the entire Nahunta Basin (n=42) and summary for road overtopping along nine resilient routes (n=0.8 miles).

The user can zoom in on the watershed map and double click a single resilient route to generate a summary specific to this route. These summaries can also be accessed by selecting a specific resilient route on the "select route or connector tab" in the tool filters. For example, SR 1537 has 15 structures and 0.5 miles of roadway that are overtopped along this 5-mile route during the 100-year storm and the cost to make the route resilient to this storm is $585,319 (See Figure 3-35). When the cursor hovers over the road route on the map or any of the graphics on the right side, pop-up windows appear that generate summaries of overtopping and costing.

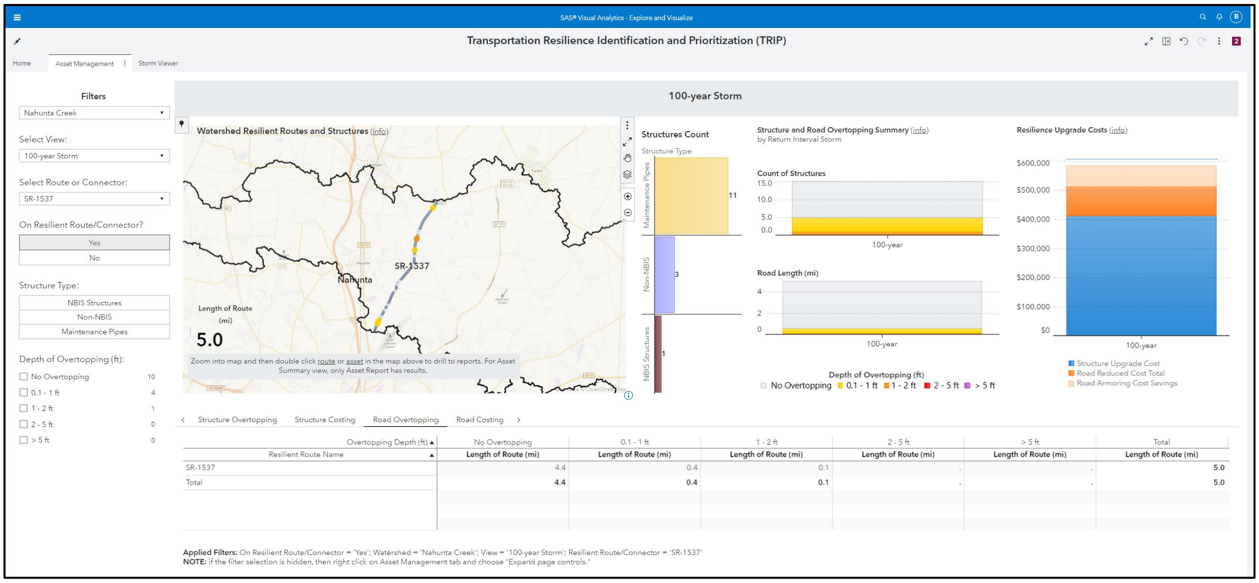


Figure 3-37. Overtopping summary for SR 1537 for the 100-year storm with views isolated to structures along the selected resilient route only.

By double-clicking on any selected route, the user will see a pop-up window that allows them to select one of three reports including the asset summary, storm upgrade costs, and resilient route overtopping. The summaries provide details for road overtopping and each specific structure including its overtopping depth and the cost estimated to upgrade that structure to each specific return internal storm. For example, Figure 3-36 provides the costs summary to upgrade SR 1556 to a 50-year storm level. Overtopping depths and upgrade costs for each specific structure are provided in the summary report. Using the printer icon in the top right corner allows the user to print copies of all reports.

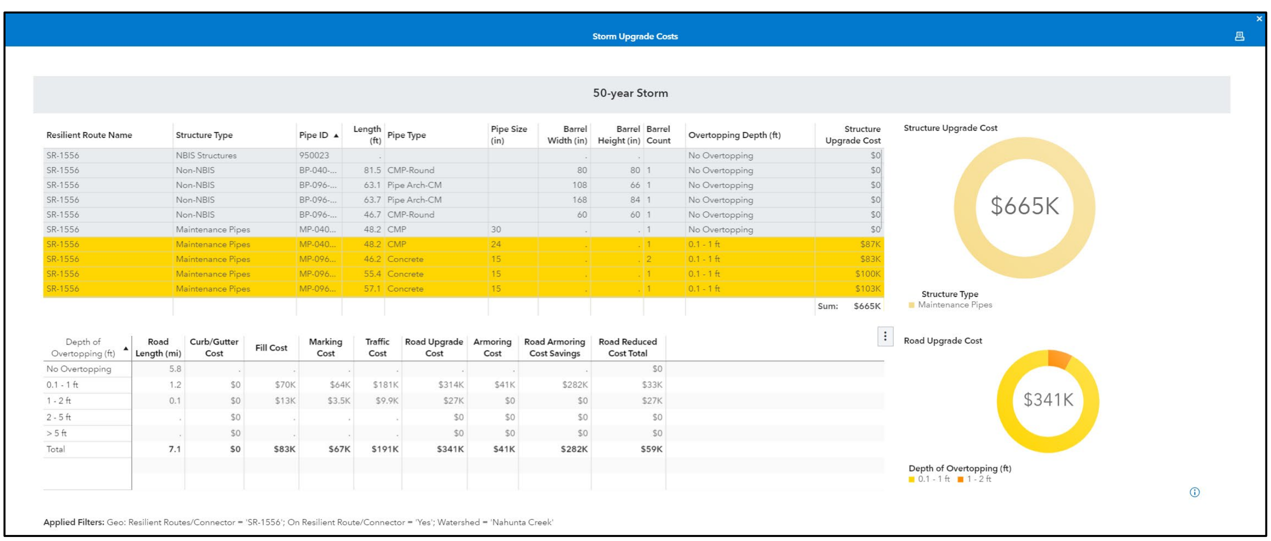


Figure 3-38. Upgrade cost summary for SR 1556 for the 50-year storm.

From the detailed road overtopping report, the user can zoom to the route and view the overtopping depth for each 50-foot road segment (Figure 3-39). In addition, using the “show where armoring is an option?” filter, the user can specifically identify locations where overtopping is less than one foot and velocities were greater than 2 ft/s, thus armoring is recommended to provide resilience as a cost savings alternative to raising segments of road that are overtopped by less than 1 foot (Figure 3-40).

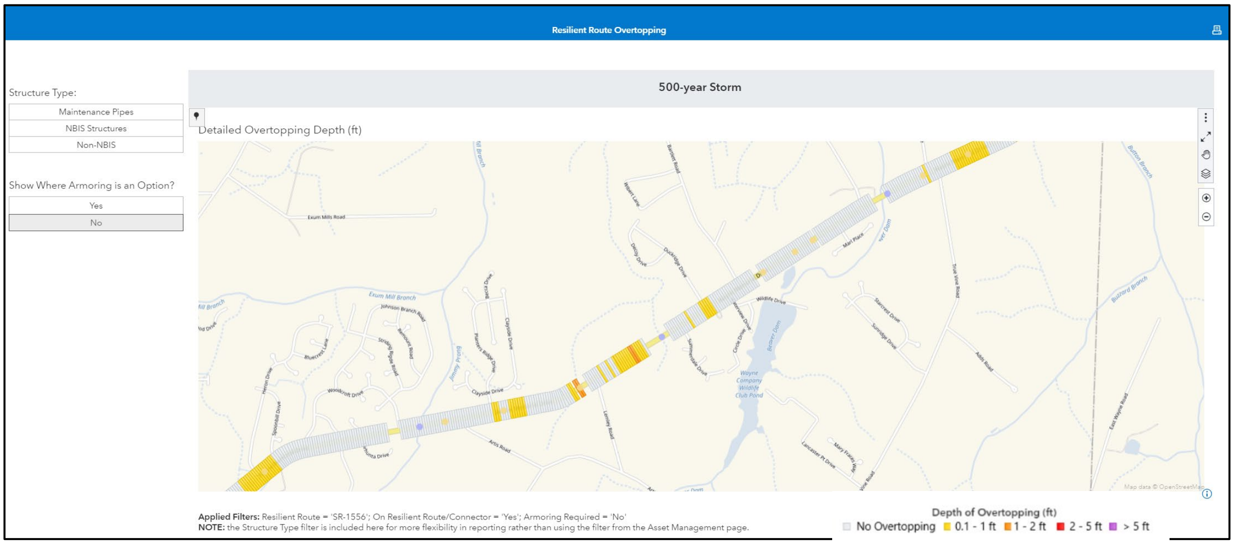


Figure 3-39. Resilient route overtopping summary report for SR 1556 to the 500-year storm.

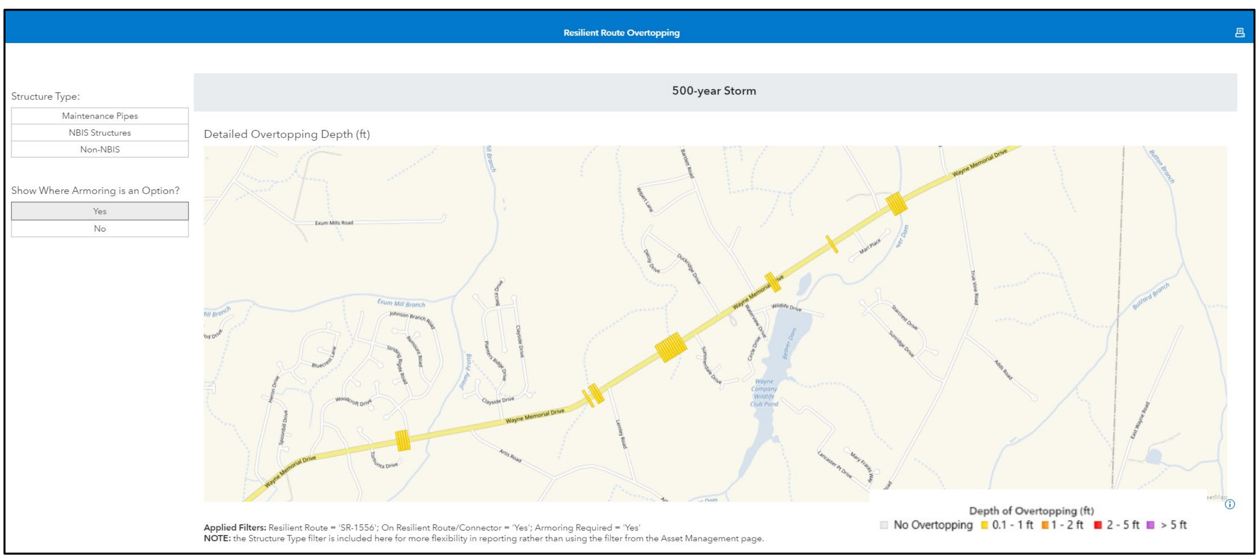


Figure 3-40. Locations where armoring can be used on road segments that are overtopped by less than 1 foot on SR 1556 to reduce the cost of improving resilience to the 500-year storm.

3.6.2 Storm Viewer

The Storm Viewer tab provides graphical summaries for two past extreme events, hurricanes Matthew and Florence. The rainfall equivalent by return period can be displayed for five separate storm durations (i.e. 3,6,12, 24 and 48 hours). In addition, the viewer indicates the overtopping of all structures for the entire Nahunta Swamp watershed and all roadway segments along the 68.9 miles of roadway for nine resilient routes (see Figure 3-41).

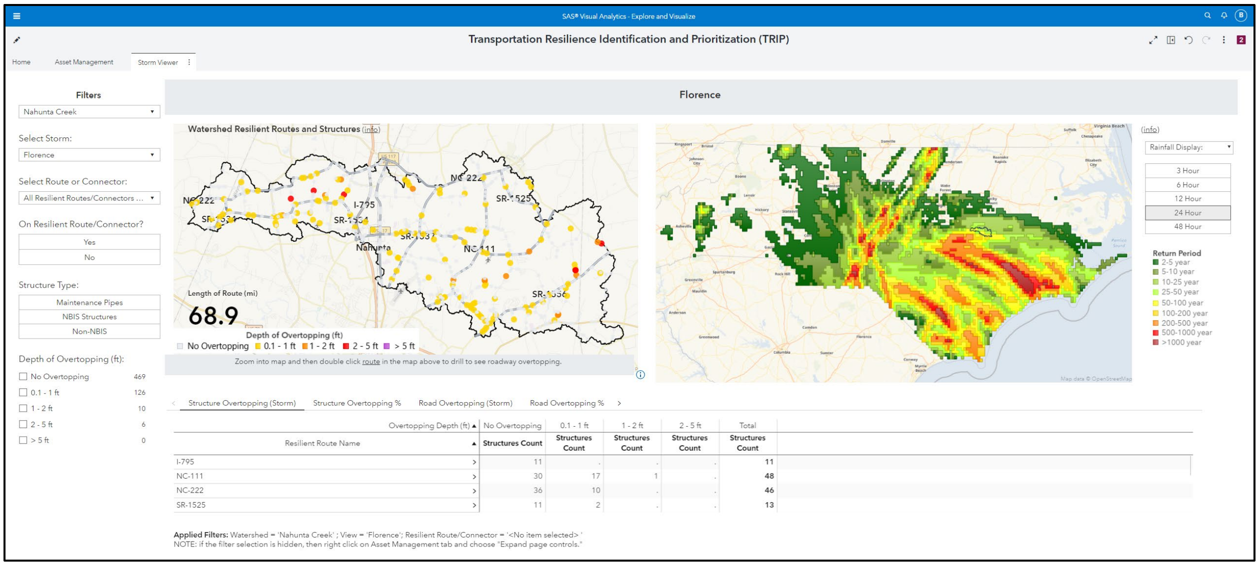


Figure 3-41. Storm Viewer tab for Hurricane Florence indicating the 24-hour design storm equivalent rainfall (right) and structure and road overtopping summary for all structures in Nahunta Swamp basin and road segments along 68.9 miles of resilient routes.

Using the filters on the left side panel of the dashboard, the user can isolate views and summaries to specific storms, routes, and structure types or to all structures in the watershed that are not along the nine resilient routes. Filters can also be used to isolate map views to show structures with no overtopping or other specific depths of overtopping. For example, this filter was used to show that no structures along the nine resilient routes were at risk of greater than 2 feet of overtopping and only two structures along NC 111 were at risk of overtopping by more than 1 foot (Figure 3-42). Therefore, the storm viewer could be used to quickly identify areas where more severe road and structure overtopping were of concern during storm events if predicted radar rainfall is input into the HEC-RAS model and outputs are transferred to the SAS dashboard for processing and display.

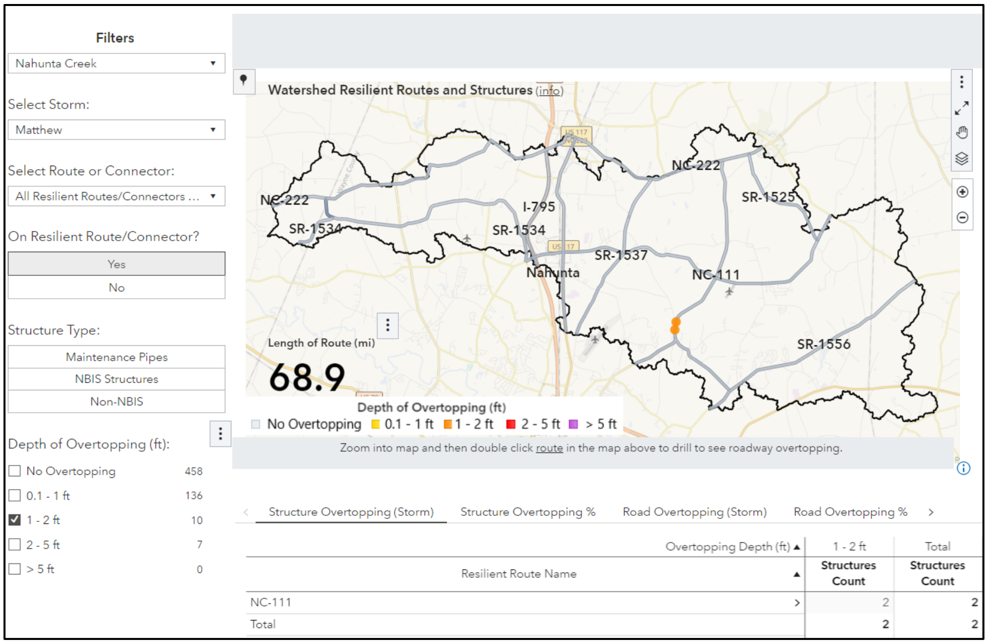


Figure 3-42. Structures at risk of 1-2 feet of overtopping during Hurricane Matthew along nine resilient routes.

Using the report tabs along the bottom, the user can view summaries by count of structures or length of road or by the percentage of structures over road length overtopped separated by each resilient route (see Figure 3-43). From Figure 3-43, we can see that the Nahunta Swamp watershed experienced rainfalls in the 100 to >1000-year rainfall when viewing the 12-hour storm duration.

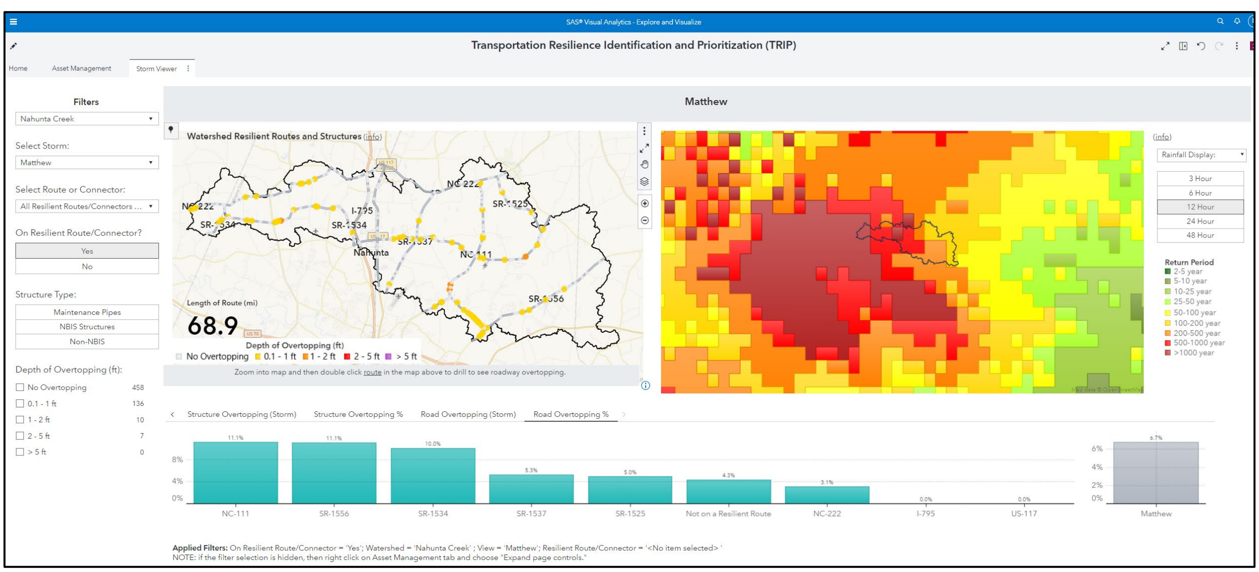


Figure 3-43. Hurricane Matthew, 12 Hour equivalent rainfall showing % of roadways vulnerable to overtopping during this storm. Radar rainfall map zoomed to Nahunta Swamp.

Like the Asset Management tab, double-clicking a resilient route on the map enables the user to generate views showing specific locations of structure and road overtopping by depth for each past storm and summaries for structure overtopping by specific water level (Figure 3-44).

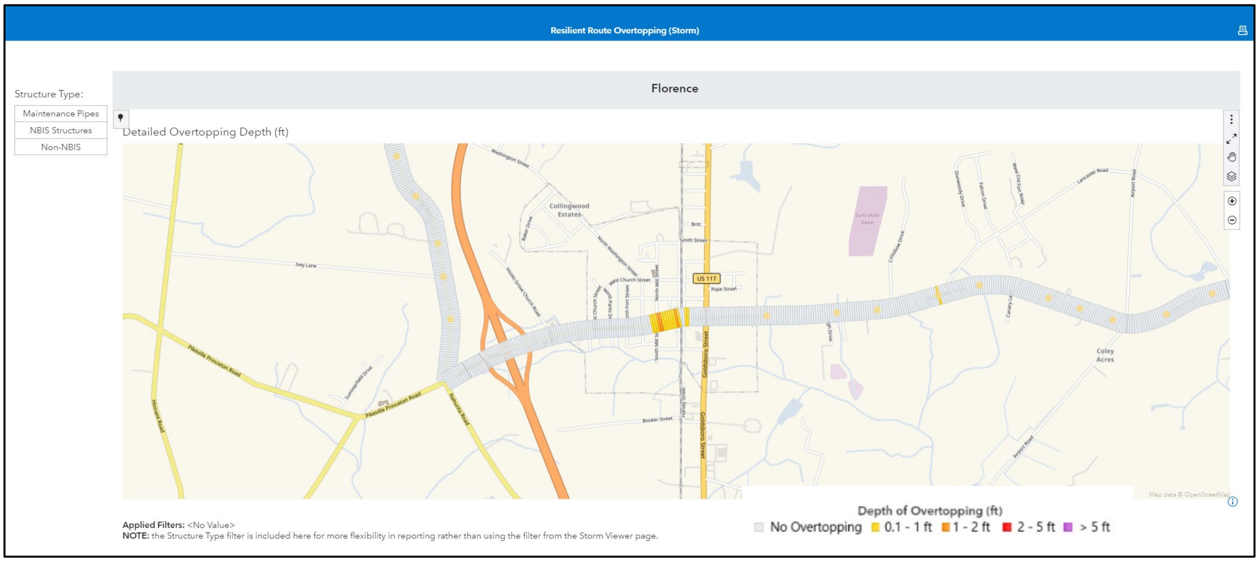


Figure 3-44. Visual summary of structures and road vulnerable to overtopping during Hurricane Florence along SR 1534 near Pikeville.

3.7 Hunting and Drowning Creek Overtopping and Resilient Route Analysis

3.7.1 Washed Out Road Crossings

Five crossings that washed out during hurricane Florence in the Drowning Creek watershed are shown in Figure 3-44 and three crossings that washed out during a storm in November 2020 in the Hunting Creek watershed are shown in Figure 3-45. Key characteristics for these washouts are listed in Table 3-3. The washout culverts for Drowning Creek ranged from 30 to 48 inches in diameter (maintenance pipes), while those for Hunting Creek were 60-72 inches (non-NBIS). The estimated peak discharge during Florence exceeded the capacity for 4 of the 5 crossings/culverts in the Drowning Creek watershed (Table 3-3 in bold). The peak discharge exceeded the capacity by at least 90 cfs for three culverts located along SR1129 and SR1122. The ratio of the pipe full culvert area (ft^2) to the drainage area (DA) in square miles was less than 10, indicating that the culvert was probably undersized. For the washouts on NC73 and SR1140, the pipe to drainage area ratio was much greater. The reason(s) for the washouts is unknown, but could be due to several factors including culvert condition (e.g. broken back or break causing piping) or obstruction.

The DA to culvert/pipe area ratio was calculated for 30 crossings with diameters ranging from 24 to 48 inches and located near the 5 that washed out in the Drowning Creek watershed (Table 3-3). The DA to culvert cross section area ratios for 26 of the 30 culverts were at least 20 (Figure 3-45). The 4 culverts with a lower ratio, had drainage areas with NRCS curve numbers of less than 54, which indicates relatively low runoff potential. These results indicate that the DA to culvert area ratio may be a good indicator of potential washout risk for culverts in the Piedmont and that combining it with curve number may improve predictions.

For the Hunting Creek crossings, the capacity calculated for each washed out culvert far exceeded the simulated peak discharge for the November 2020 storm, so the reason for washout is unknown. Two of the pipe area to drainage area ratios (55 and 118) were much greater than those of the culverts in Drowning Creek (Table 3-3). This may be due to the steeper topography and less permeable soils resulting in greater peak discharges.

For the 20 nearby crossings that did not washout, the pipe cross sectional area to drainage area ratios ranged from 22 to 168 with all but 4 being greater than 55 (Figure 3-45). These results indicate that pipe area to drainage area ratio could serve as an indicator of potential washouts for the mountains as well, even though the ratio may not be as strong of an indicator of washouts as it was for the Piedmont watershed.

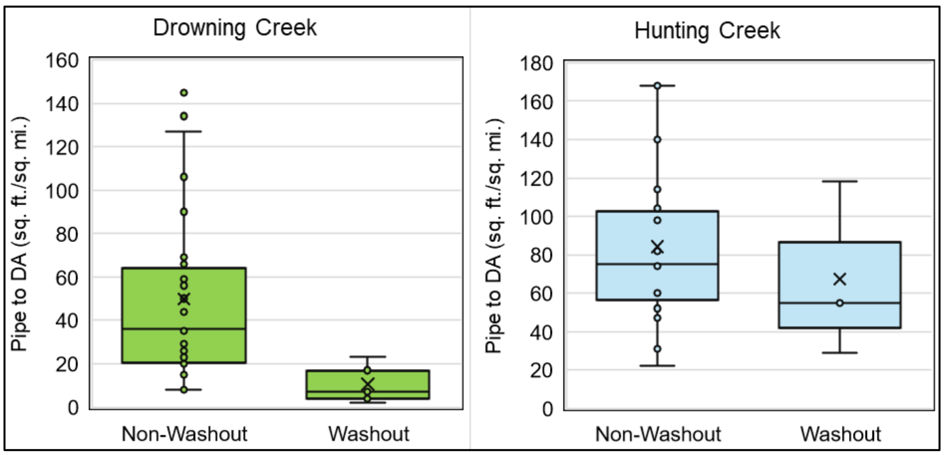


Figure 3-45. Pipe area to drainage area ratio for washout and non-washouts in Drowning and Hunting Creeks.

Table 3-3. Culvert Data and Peak Discharge Capacity for Washed Out Road Crossings.

Road	**Diameter**	**Length**	**Over[a]**	**Material**	**Slope[b]**	**Capacity[c]**	**Storm Q[d]**	**Pipe to DA[f]**
	in	ft	ft			cfs	cfs	ft^2/mi^2
				Drowning Creek				
SR1129	48	42	11.0	CMP	0.010	204	**294**	4
SR1122a	36	42	6.0	CMP	0.010	62	**331**	2
SR1122b	42	42	na	na	0.010	81	**231[e]**	7
NC73	30	70	10.1	CMP	0.010	21	**25[e]**	23
SR1140	48	na	11.0	CMP	0.005	151	40	17
				Hunting Creek				
SR2400	60	45	9	CMP	0.020	179	64[e]	55
SR2400	72	48	8	CMP	0.020	222	94	118
SR2412	72	58	15	CMP	0.010	385	214	29

[a] Difference in elevation of road crest and culvert invert.
[b] Estimated based on slope of channel reach and maximum slope expected.
[c] Computed using HY8 with known data plus assumptions.
[d] Estimated from HEC-HMS model for Florence (Drowning) and November 2020 (Hunting).
[e] Estimated from HEC-HMS with subbasin area reduced to drainage area of culvert.
[f] Cross sectional area of culvert (ft^2) divided by the drainage area to the culvert (mi^2).

3.7.2 Road Crossings Overtopping Assessment

The crossings located along named streams/creeks in the Drowning Creek watershed indicating their pipe capacity ratio relative to the 100-year discharge are shown in Figure 3-46.The peak discharges for the 100-yr rainfall event did not exceed the overtopping discharge at any crossing and only two crossings (SR1102 and SR1126) were exceeded by hurricane Florence (see Appendix for additional information). Six of the crossings had overtopping discharges of more than three times the 100-yr discharge, indicating they are highly flood resilient. However, higher capacity crossings are dispersed across different roads and streams/creeks preventing the identification of a single resilient route.

The crossings and their pipe capacity ratio relative to the 100-year discharge for Hunting Creek watershed are shown in Figure 3-47 and Figure 3-48. The overtopping discharge at 6 crossings was exceeded by the peak discharge for the 100-yr rainfall with the greatest exceedance (195%) occurring at the Lewis Church Road crossing over Hunting Creek. Only one crossing (Lewis Church Road) was exceeded by the peak discharges for the November 2020 storm. Seven of the crossings (including I77) had overtopping discharges of more than three times the 100-yr discharge indicating they are highly flood resilient.

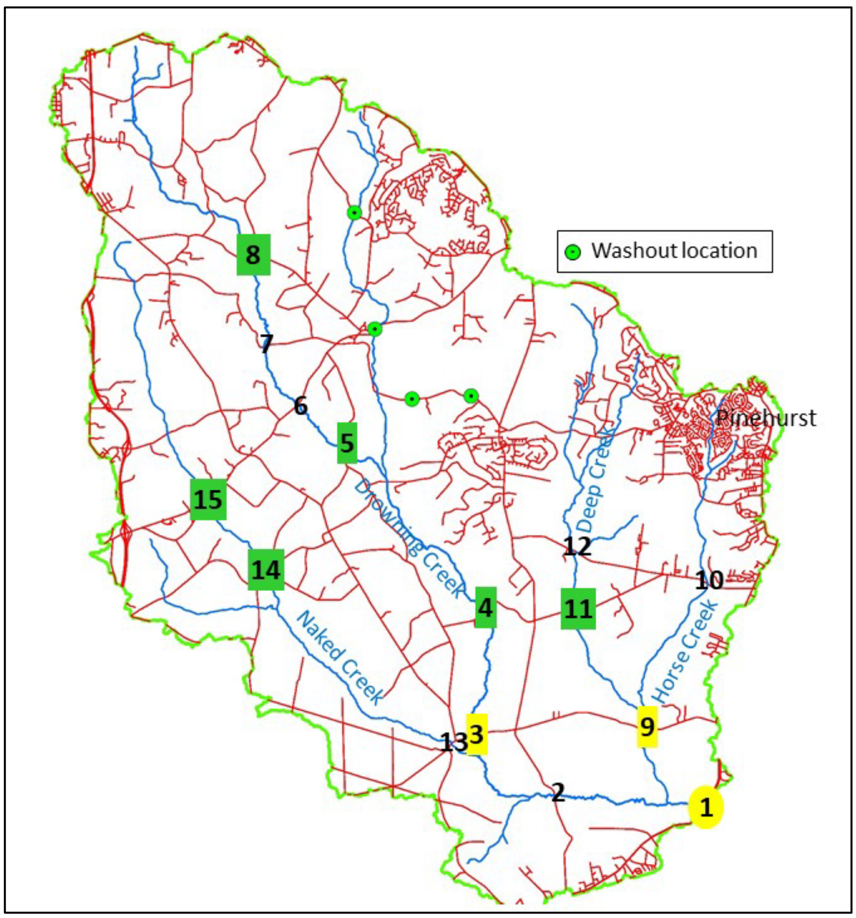
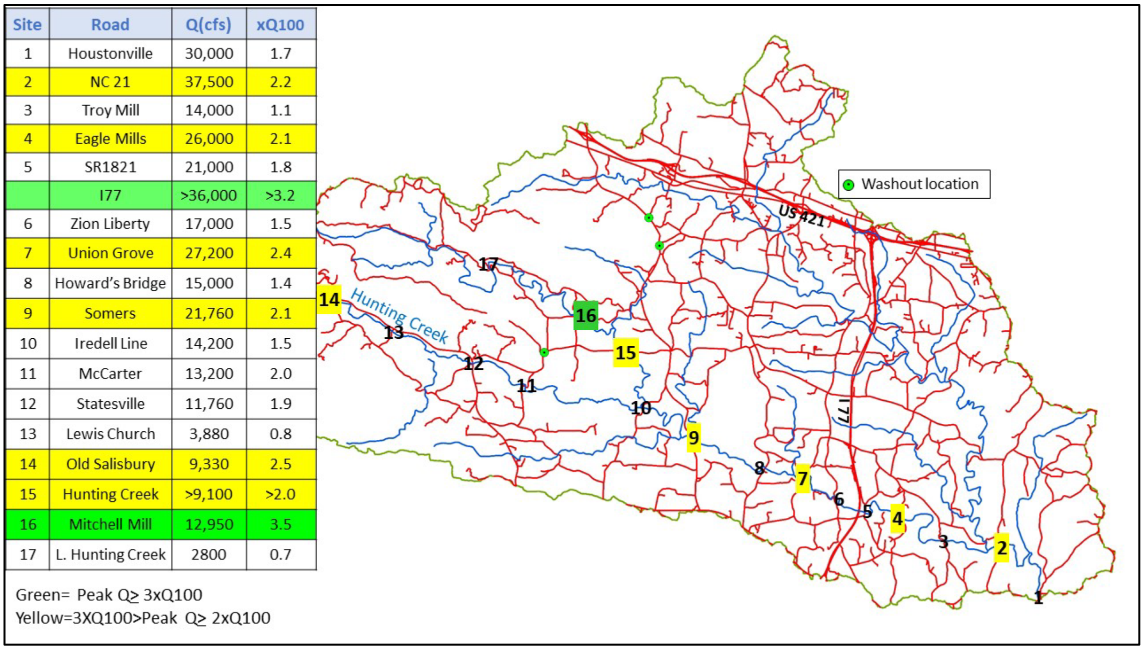
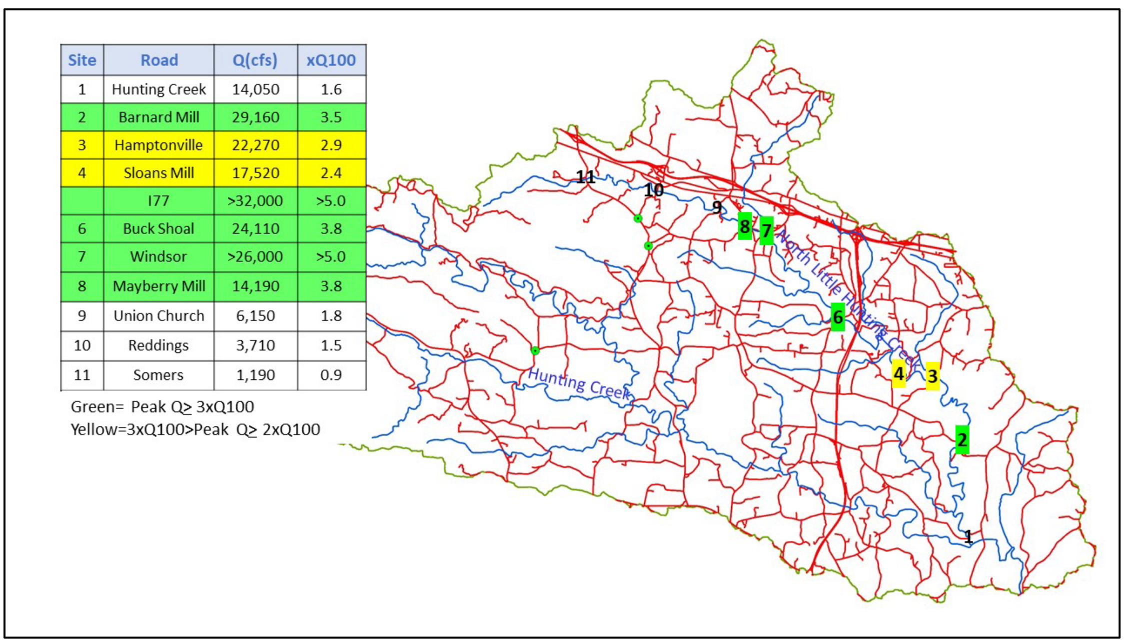


Figure 3-46. Overtopping discharges for major stream crossings in Drowning Creek (green highlight is >=3 times 100-yr Q; yellow highlight is 2-3 times the 100-yr Q; no highlight is <2 times 100-yr Q).



Site	Road	Q(cfs)	xQ100
1	Houstonville	30,000	1.7
2	NC 21	37,500	2.2
3	Troy Mill	14,000	1.1
4	Eagle Mills	26,000	2.1
5	SR1821	21,000	1.8
	I77	>36,000	>3.2
6	Zion Liberty	17,000	1.5
7	Union Grove	27,200	2.4
8	Howard's Bridge	15,000	1.4
9	Somers	21,760	2.1
10	Iredell Line	14,200	1.5
11	McCarter	13,200	2.0
12	Statesville	11,760	1.9
13	Lewis Church	3,880	0.8
14	Old Salisbury	9,330	2.5
15	Hunting Creek	>9,100	>2.0
16	Mitchell Mill	12,950	3.5
17	L. Hunting Creek	2800	0.7

Figure 3-47. Overtopping discharges for Hunting Creek (green highlight is >=3 times 100-yr Q; yellow highlight is 2-3 times the 100-yr Q; no highlight is <2 times 100-yr Q).



Site	Road	Q(cfs)	xQ100
1	Hunting Creek	14,050	1.6
2	Barnard Mill	29,160	3.5
3	Hamptonville	22,270	2.9
4	Sloans Mill	17,520	2.4
	I77	>32,000	>5.0
6	Buck Shoal	24,110	3.8
7	Windsor	>26,000	>5.0
8	Mayberry Mill	14,190	3.8
9	Union Church	6,150	1.8
10	Reddings	3,710	1.5
11	Somers	1,190	0.9

Figure 3-48. Overtopping discharges for North Little Hunting Creek (green highlight is >=3 times 100-yr Q; yellow highlight is 2-3 times the 100-yr Q; no highlight is <2 times 100-yr Q).

3.7.3 Resilient Route Assessment

When a route is identified as necessary to remain open during extreme events, the capacity of each stream/waterway crossing should be evaluated. Based on our analysis of major crossings, some possible resilient routes in Drowning Creek are I77, US421 and Barnard Mill Road to Hunting Creek Church Road to Windsor Road, but additional analysis to evaluate all crossings is necessary to confirm this. In the Hunting Creek watershed there was one highly resilient and 6 moderately resilient crossings over Hunting and Little Hunting Creek and 4 highly resilient crossings over North Little Hunting Creek.

Ten crossings with culverts of at least 24 inches in diameter were evaluated for resilience along an 8-mile stretch of NC 73 including. Results are show in Table 3-4. Estimated peak discharges for Hurricane Florence were much less than the computed culvert capacity, except for MP-063-00671. For this culvert, the peak storm discharge was 74% of the pipe capacity. The drainage area to pipe area ratio for this culvert was 23, which was the lowest for all the crossings. This data indicates that NC 73 should have had no washouts during Florence and, in fact, none of these crossings washed out. Estimated peak discharges for the 500-yr storm were less than the corresponding peak discharge for Florence. Based on this analysis, NC 73 should be highly resilient to future extreme events.

Table 3-4. Culvert Data for NC 73 Road Crossings with Pipes ≥ 24 inches in Diameter.

Pipe	Diameter	Length	Over[a]	Pipe to DA[b]	Capacity[c]	Florence[d] Q	500yr Q
	in	ft	ft	ft^2/mi^2	cfs	cfs	cfs
MP-063-00672	24	54.7	7	na	42	na	na
MP-063-00680	24	52.6	6	39	13	6.3	1.4
MP-063-00681	24	51.4	4	-	26	-	-
MP-077-00015	24	35.9	6	63	30	2.9	1.5
MP-077-00022	24	78.3	8	39	29	4.7	2.5
MP-063-00671	30	45.8	>10	23	34	25	8.7
MP-063-00674	30	61.1	9	23	63	63	22.0
MP-063-00675	36	48.7	5	-	55	-	-
MP-077-00021	30	144.9	10	na	67	na	na
MP-077-00009	36	107.0	8	124	97	3.3	1.7

[a] Difference in elevation of road crest and culvert invert.
[b] Pipe/culvert cross sectional area (ft^2) to drainage area (mi^2) area ratio.
[c] Computed using HY8.
[d] Estimated from HEC-HMS model for Florence and adjusted by drainage area ratios.
[e] Estimated using HEC-HMS with 500-yr SCS type II storm (10.1 inches).

This process of using HEC-HMS and HEC-RAS to evaluate potential resilient routes is limited because of the coarse nature of HMS modeling and the limited coverage of HEC-RAS models (only ~15% of the washouts statewide were on FEMA mapped streams). The future widespread availability of rain-on-grid modeling across the state makes this type of approach more appropriate for planning level resilient route analysis.

4 Conclusions and Recommendations

Analysis of the washout data revealed that most of the washouts in the hydraulics unit database for Hurricanes Matthew and Florence and the 2020 storms occurred at road crossings of waterways with smaller catchments (~60% less than 0.5 sq. mi. and ~25% < 0.1 sq mi.). About 65% of the washouts occurred at structures with equivalent diameter of 24-72 inches and ~90% occurred on the secondary road network (similar to the overall distribution structures across the network). While the data was incomplete, most of the washed-out structures (~82-99%) did not appear to have headwalls.

Comparison of washout to nearby non-washouts did not reveal any direct predictors, but washouts appeared more likely to occur at pipes with smaller hydraulic capacity and higher embankments. Washouts also tend to occur where there are short lengths of round pipe. Analysis of washouts along the same stream reach or similar nearby drainage area indicated that about 65% of the structures that washed out had less hydraulic capacity than the nearby non-washout. However, 35% of the washouts had higher normalized hydraulic capacity.

Machine learning classification models did not perform well for predicting which locations were most at risk of washing out with error rates for washouts locations ~60%. The SAS Viya platform provided interesting ways of quickly comparing the data by proximity to a point, watershed, county, etc., but did not reveal any additional predictive factors. Strong predictors of washouts were likely not identified due to missing variables, as well as inherent uncertainty with localized conditions during a storm event and the mechanisms that propagate a washout.

After conducting hydrologic modeling using HEC-HMS and analyzing the HEC-RAS model network availability relative to where washouts occurred and where structures are located, the very sparse overlap between the two, as well as NCEM's efforts at statewide rain-on-grid model development shifted the focus of this project to HEC-RAS rain-on-grid modeling. A HEC-RAS rain-on-grid model was developed and calibrated for Nahunta Swamp watershed to facilitate the development of procedures and tools for identifying and prioritizing resilient transportation routes.

An application (RRT-HydroMap) was also developed to download historical or forecast gridded rainfall data and transform it to HEC-DSS format for input into the HEC-RAS rain-on-grid models. The application also has the capability to calculate and map the rainfall return period, run the model, and compare the HEC-RAS simulated WSE to roadway elevations and output maps.

Finally, NCSU directed SAS Institute on the creation of the Transportation Resilience Identification and Prioritization (TRIP) tool. The TRIP tool is an online dashboard for the evaluation of resilient routes. The dashboard uses water levels from the HEC-RAS results to determine the road and structure overtopping in order to estimate the cost of upsizing structures or raising roads to prevent flooding. Routes can then be compared to determine which is the least costly to make a resilient route.

Recommendations

- Ensure that pipe databases are accurate and up-to-date and contain the information needed to evaluate their capacity. For example, when a structure is replaced in the field, there should be a SOP for updating this information in the central database.

- Continue collecting information and details on road washouts to build a high-quality database. Over time, as this dataset expands, analysis may reveal additional causal factors of road crossing washout.
- Build out the proposed Transportation Resilience Identification and Prioritization (TRIP) tool to the areas covered by NCEM's HEC-RAS rain-on-grid models. This effort should include additional work to first identify important nodes in the transportation network and connector routes that can be evaluated as potential resilient routes.

5 References

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6 Appendices

6.1 HEC-HMS Modeling

6.1.1 HEC-HMS Rainfall Input

Rainfall data for input into the HEC-HMS model were obtained from two sources. For model calibration, hourly rainfall data were obtained for at least two locations/points in the watershed from the NC State Climate Office (NC SCO) using radar precipitation estimates calibrated to nearby raingages (Table 6-1). The estimates were then used for all of the HEC-HMS subbasins located in the part of the watershed in which the point was located.

For the 25-, 50-, and 100-yr design storms, total rainfall accumulation data were obtained from the TR55 manual (Table 6-1). The same total was used for every HEC-HMS subbasin in the watershed, thereby assuming a uniform spatial distribution. Rainfall accumulation for the 500-yr design storm was obtained from the Atlas14 website using the midpoint of the watershed for the location of the point estimate. The SCS type II storm was used for the rainfall distribution for each watershed and each storm to maintain consistency and because most of the Neuse River Basin is in the type II region. As shown in Table 6-1 a considerable range of rainfall accumulations were used to evaluate the impacts of the NI implementation on peak discharge.

Table 6-1. Rainfall for storm events simulated in HEC-HMS.

Rainfall Event	Storm Rainfall Depth (in)	
	Drowning Creek	Hunting Creek
Florence/Matthew	16.7-18.4[1]	na
Nov, 2020	Na	5.1-5.3[1]
SCS II 25yr 24 hr[2]	6.4	5.7
SCS II 50yr 24hr	7.0	6.3
SCS II 100yr 24 hr	8.0	7.0
NOAA 500yr 24 hr	10.1	10.1

[1] Range of two points as estimated by NC State Climate Office.
[2] From TR55 manual.

6.1.2 Calibrate HEC-HMS model for Drowning Creek

Discharge measurements for Drowning Creek were obtained from the USGS gage at US1 (#02133500) for September 9, 2018 to October 4, 2018. Hourly rainfall data for the same period was obtained from the NC State Climate Office (SCO) for a selected point in the northern (lat 35.233; lon -79.663) and southern (lat 35.133; lon -79.592) halves of the watershed. These point rainfall estimates were then input for HEC-HMS subbasins in the corresponding northern and southern halves of the watershed.

The HEC-HMS model was run and calibration was accomplished by 'adjusting' input parameters such as curve number (CN), lag time (LT), the peak rate factor (PRF), and channel roughness (n) in a systematic way so that peak and total discharge for Hurricane Florence closely matched monitored/observed discharge as shown in Figure 6-1. The initial peak discharge and runoff volume were much higher than observed; therefore, input parameters were adjusted to reduce runoff. The three greatest adjustments from the initial HEC-HMS input file were that the

Manning's roughness coefficients for all Drowning Creek channel reaches and tributaries were increased considerably from 0.035, the lag times for each subbasin were increased, and the CNs were decreased by ~40-50%. As much as possible, similar adjustments were made for all subbasins and stream reaches equally to try to maintain spatial symmetry within the watershed. After many simulation runs, the final HEC-HMS discharge hydrograph had excellent agreement with the observed discharge hydrograph as evidenced by a Nash-Sutcliffe model efficiency coefficient of 0.99. Further, the simulated peak discharge was within 0.2% of the observed and the total volume of runoff was within 1.7% of the observed.

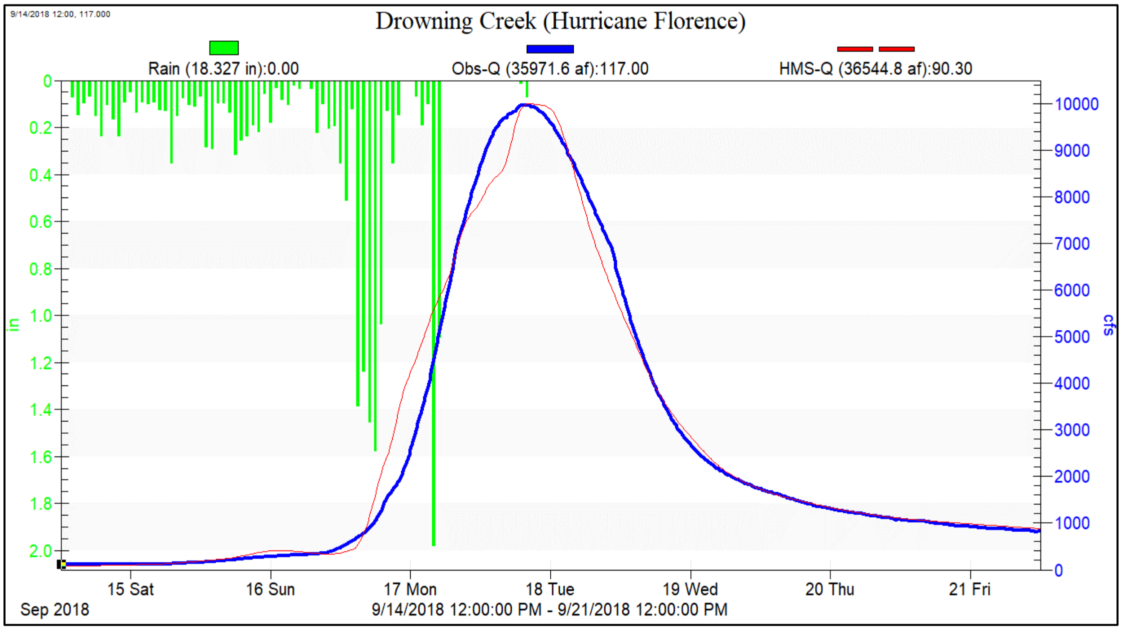

Figure 6-1. Observed and HMS-simulated discharge hydrograph at the outlet of Drowning Creek.

6.1.3 Calibrate HEC-HMS model for Hunting Creek

Discharge measurements for Hunting Creek were obtained from the USGS gage at Houstonville Road (#02118500) for November 10, 2020 to November 15, 2020. Rainfall data for the same period was obtained from the NC State Climate Office (SCO) for a selected point in the western (lat 36.083; lon -80.948) and eastern (lat 36.070; lon -83.832) halves of the watershed. Point estimates of rainfall were entered for the appropriate HEC-HMS subbasins according to their proximity to the selected points. The HEC-HMS model was run and calibration was accomplished by 'adjusting' input parameters such as curve number (CN), lag time (LT), peak rate factor (PRF), and channel roughness (n) in a systematic way so that peak and total discharge for the November 11-12 storm closely matched monitored/observed discharge as shown in Figure 6-2. The initial peak discharge and runoff volume using inputs generated from literature and typical values were much less than observed; therefore, input parameters were adjusted. The greatest adjustments were that the Manning's roughness for all Hunting Creek channel reaches and tributaries were increased from 0.035 to 0.05-0.08 and that the PRFs for HEC-HMS subbasins were increased from 454 to 600. Other adjustments included decreasing the lag times and increasing the CNs for subbasins. As much as possible, similar adjustments were made for all subbasins and stream reaches equally to try to maintain spatial symmetry within the watershed. After many simulation runs, the final HEC-HMS discharge hydrograph had good agreement with the observed discharge hydrograph as evidenced by a Nash-Sutcliffe model efficiency coefficient of 0.92. Further, the simulated peak discharge was within 3% of the observed and the total volume of runoff was within 3.5% of the observed.

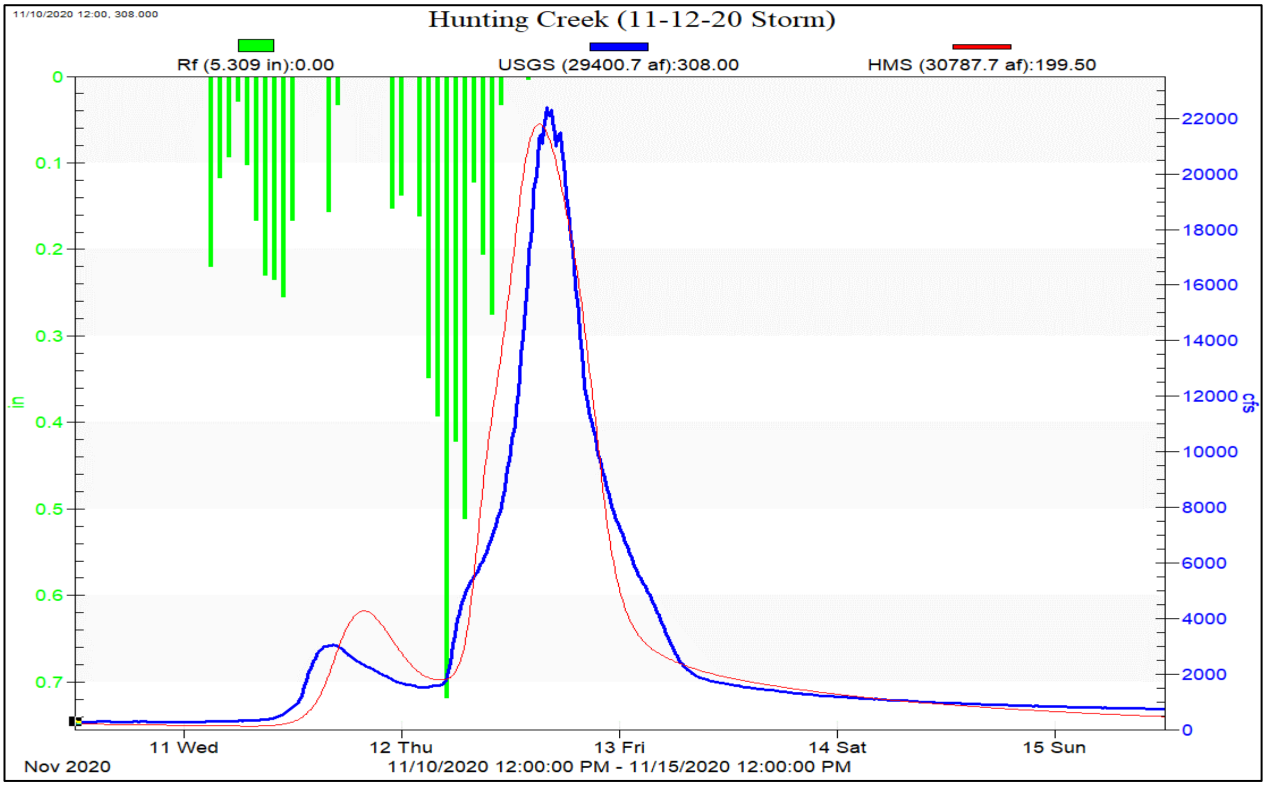

Figure 6-2. Observed and HMS-simulated discharge hydrograph at the outlet of Hunting Creek.

6.1.4 Additional Road Crossings Overtopping Analysis Results

The tables provide 1) the peak discharges for the 100-yr and a historic storm 2) the discharge at which water overtops the road surface (Overtop Q) and 3) the ratio of the pipe capacity to the 100-yr discharge (xQ100).

Table 6-2. Peak Discharges for Major Road Crossings in the Drowning Creek Watershed.

No.	Road	Florence[1] cfs	Overtop Q[2] cfs	xQ100[2]
Drowning Creek				
1	US1 North	10,009	16,400	2.0
	US1 South	10,009	18,800	2.3
2	SR1102	**7,553**	3,400	0.8
3	SR1113	4,825	11,000	2.6
4	SR1123	4,390	19,200	5.1
5	SR1124	1,887	9,300	3.7
6	NC73	1,908	4,130	1.7
7	SR1122	1,929	2,400	1.0
8	SR1126	**1,392**	1,150	3.3
Horse Creek				
9	SR1102	2,765	6700	2.4
10	SR1112	792	1030	1.1
Deep Creek				
11	SR1113	1,191	5600	3.7
12	SR1112	1,191	1990	1.4
Naked Creek				
13	SR1003	1,777	2,960	1.1
14	SR1424	1,519	5,180	3.0
15	NC73	1,256	4,260	3.0

[1] The peak discharge for the 100-yr rainfall storm was estimated using the HEC-HMS model.
[2] Overtopping discharge divided by the 100-yr discharge (Q100) both from HEC-RAS model.

Table 6-3. Peak Discharges for Roads in the Hunting Creek Watershed.

	Road	100yr Rain[1] cfs	Nov2020[1] cfs	Overtop Q[2] cfs	xQ100[2]
Hunting Creek					
1	SR2115	31,388	22,400	30,000	1.7
2	US 21	30,669	21,072	37,500	2.2
3	SR1813	18,650	12,520	14,000	1.1
4	SR1832	18,216	12,130	26,000	2.1
5	SR1821	18,058	12,000	21,000	1.8
	I77	17,859	11,850	>40,000	>3.2
6	Zion Liberty	17,584	11,620	17,700	1.5
7	SR1832	17,643	11,640	27,200	2.4
8	SR1852	16,939	11,090	15,000	1.4
9	SR1807, Somers	16,292	10,440	21,760	2.1
10	SR2414	15,322	9,510	14,200	1.5
11	SR2423 McCarter	10,089	5,920	13,200	2.0
12	NC 115	10,191	5,740	11,760	1.9
13	Lewis Church	7,595	**4,080**	3,880	0.8
14	Old Salisbury	na	na	9,330	2.5
Little Hunting Creek					
15	Hunting Creek	6,137	3,455	>9,074	>2
16	Mitchell Mill	4,296	2,336	12,952	3.5
17	L. Hunting Creek	3,656	1,933	2,313	0.7
N. Little Hunting Creek					
1	SR1829	13,749	8,630	15,050	1.6
2	SR1828	13,677	8,380	29,160	3.5
3	SR1102	13,389	7,920	22,270	2.9
4	SR1119	12,010	7,020	17,520	2.4
5	I 77	11,063	6,240	>32,000	>5.0
6	SR1103	10,680	6,020	24,110	3.8
7	Windsor Rd	8,471	4,560	>26,000	>5.0
8	Mayberry Mill Rd	4,722	2,600	14,190	3.8
9	Union Church Rd	3,972	2,160	6,150	1.8
10	Reddings Rd	2,266	1,250	3,710	1.5
11	Somers Rd	1,144	580	1,190	0.9

[1] Estimated using HEC-HMS model.
[2] Overtopping discharge divided by the 100-yr discharge (Q100) both from HEC-RAS model.

6.2 RRT-HydroMap help file

RRT-HydroMap Help File

For questions or to report errors contact Jack Kurki-Fox – jjkurkif@ncsu.edu

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DISCLAIMER

Computer Requirements

Application and supporting file size: 2.25 GB

This application was tested using a computer with:
Processor: 12th Gen Intel(R) Core(TM) i7-12700H 2.30 GHz
Installed Ram: 32.0 GB

NOTE: Devices with a slower processor will likely experience increased runtimes.

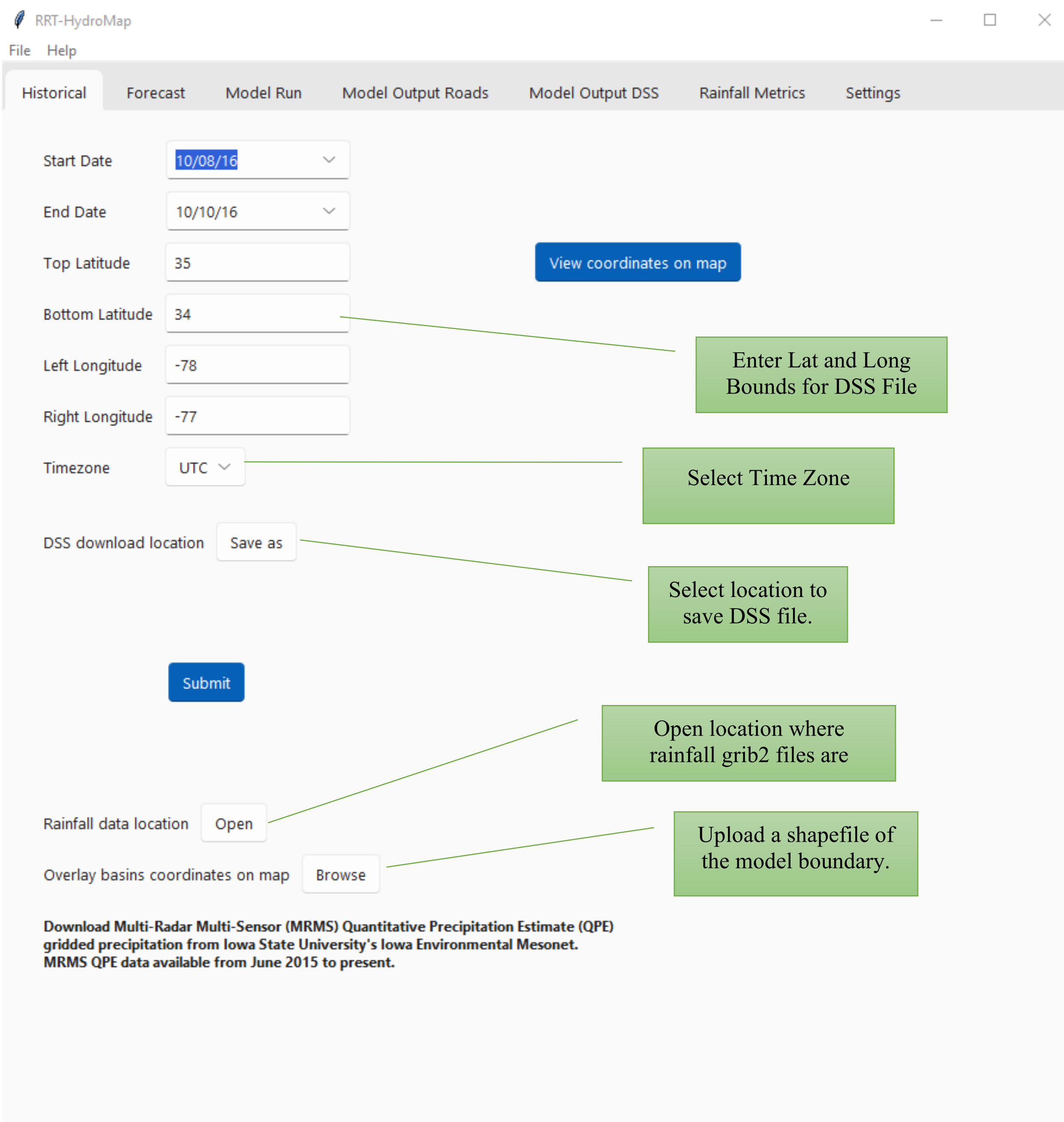
RRT-HydroMap (Radar Rainfall Transform, Hydraulic Model Output, and Mapping) is an application developed by NC State University Biological and Agricultural Engineering and NC Sea Grant for the NC Department of Transportation Hydraulics Unit. The application is meant for downloading radar rainfall data and transforming the data into DSS format for input in HEC-RAS rain-on-grid models.

6.2.1 Historical Tab

This tab facilitates the download of **MRMS QPE** gridded precipitation data from **Iowa State University's Iowa Environmental Mesonet (https://mtarchive.geol.iastate.edu/)**. The "GaugeCorr_QPE" data is available from 2015 to 2020 across the conterminous U.S. From 2020 to present the "Multisensor_QPE" data is used. The user can select the download timeframe (Note that long time periods may require a long time to download).

- The user must input coordinate bounds (decimal degrees) for the download data.
- The MRMS data is in the UTC time zone. The user can select a different time zone and the application will shift the gridded data in time.
- The user must select a location to save the created DSS file. The DSS file is created in SHG Grid System. The cell size can be specified in the "Setting" Tab (default 2000 m).
- The user can upload a shapefile of their study area to view along with the download coordinates.
- The "View coordinates in map" can be selected to view the input coordinate zone on a HTML map.

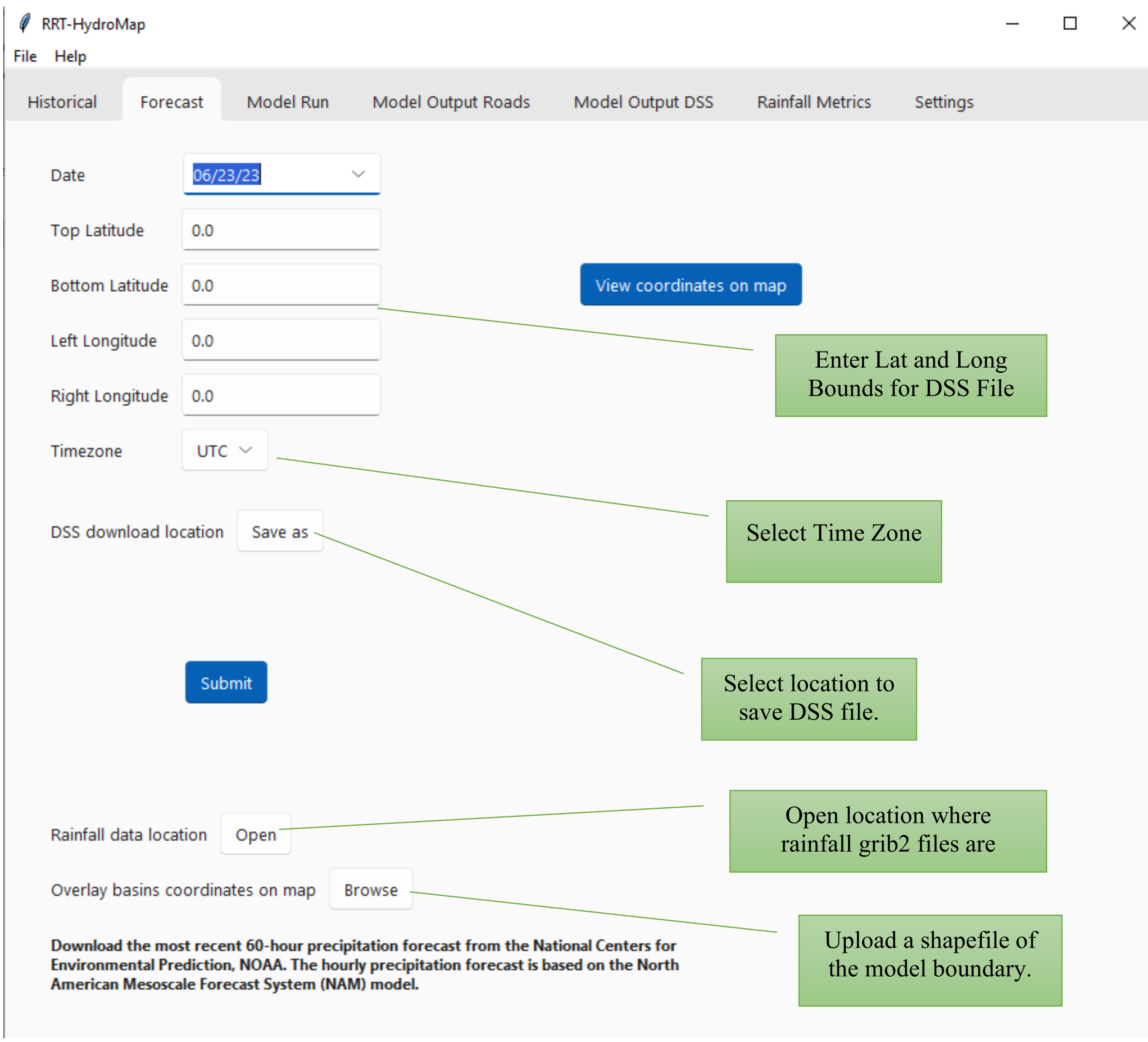
- This tab also generates GeoTiff files and an HTML map that displays the rainfall return period from NOAA Atlas 14 values (about 2-3 minjutes).



6.2.2 Forecast Tab

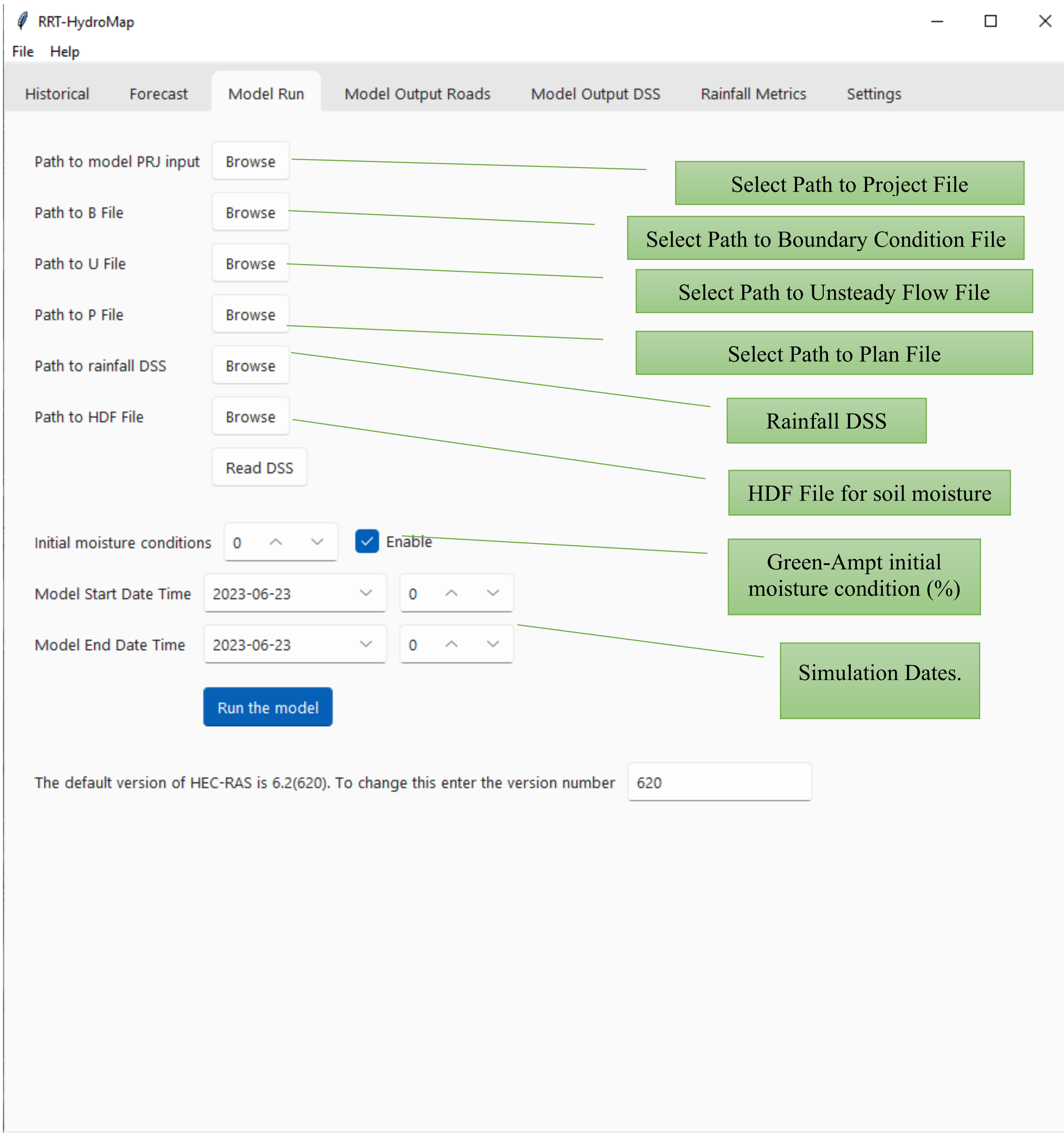
This tab facilitates the download of the National Centers for Environmental Prediction 60-hr forecast based on the American Mesoscale Forecast System Model- (https://nomads.ncep.noaa.gov/cgi-bin/filter_nam_conusnest.pl). Inputs and functionality are similar to Historical Tab

Caution: The functionality of this has been tested due to the lack of a substantial, widespread predicted rainfall event during the testing period.



6.2.3 Model Run Tab

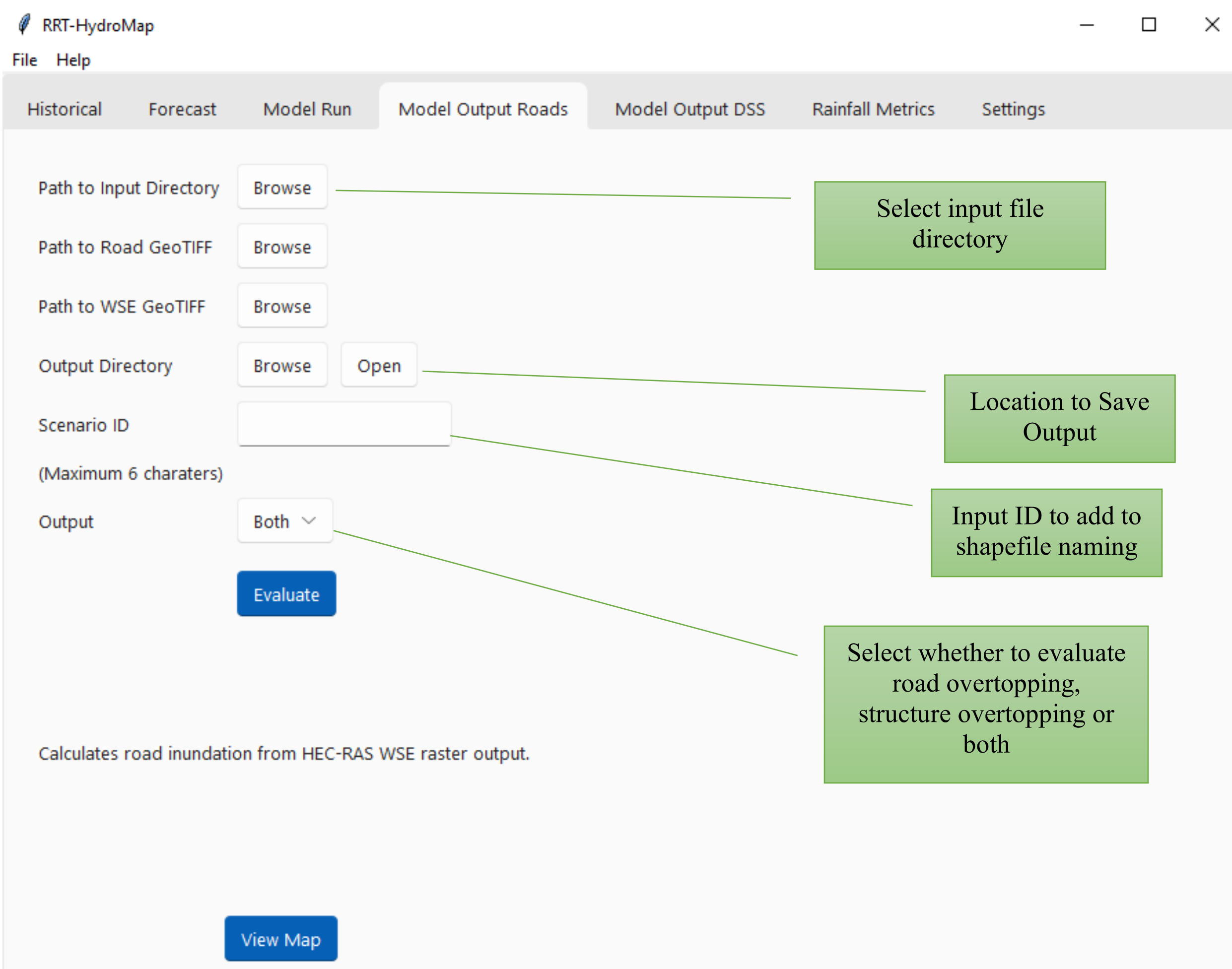
This tab allows the model to be run without opening HEC-RAS. If the Green-Ampt infiltration method is used, then the user can change the initial moisture condition. For the best functionality, a project should be set up with only one plan file in a dedicated location, as this tab runs the current plan. HEC-RAS must be installed.



6.2.4 Model Output Roads Tab

This tab compares a HEC-RAS 2D WSE .tif file to the Road Ribbon LiDAR elevation data and generates a shapefile of inundation depths for road segments and structures. An HTML map of the road inundation is also generated.

- Path to input directory: Contains shapefiles for the road network, road buffer, and structures. All the files should be in “NAD 1983 StatePlane North Carolina FIPS 3200 Feet” projection. The file names and field must match exactly as described below.
    - “road_segments.shp” contains segments along road (e.g., 50 feet) to measure overtopping. This file must contain a unique field named “ID” that is an integer and a field “RouteName”, which contains the NCDOT road number.
    - “road_buffer.shp” - This is the “road_segements.shp” buffered to cover the road surface. This allows for the use of zonal statistics to calculate overtopping depth for each segment.
    - “crossings.shp” contains all the maintenance pipes, non-NBIS pipes and NBIS structures. Must contain a field “PipeID” which contains the unique NCDOT ID used for each structure.
    - “crossings_buffer.shp” – This is the “crossings.shp” buffered to the area where the structure overtopping should be evaluated using zonal statistics.
    - “model_bounds.shp” polygon file of the 2D model domain.
    - “roads.shp” – line file of roads for display purposes only.

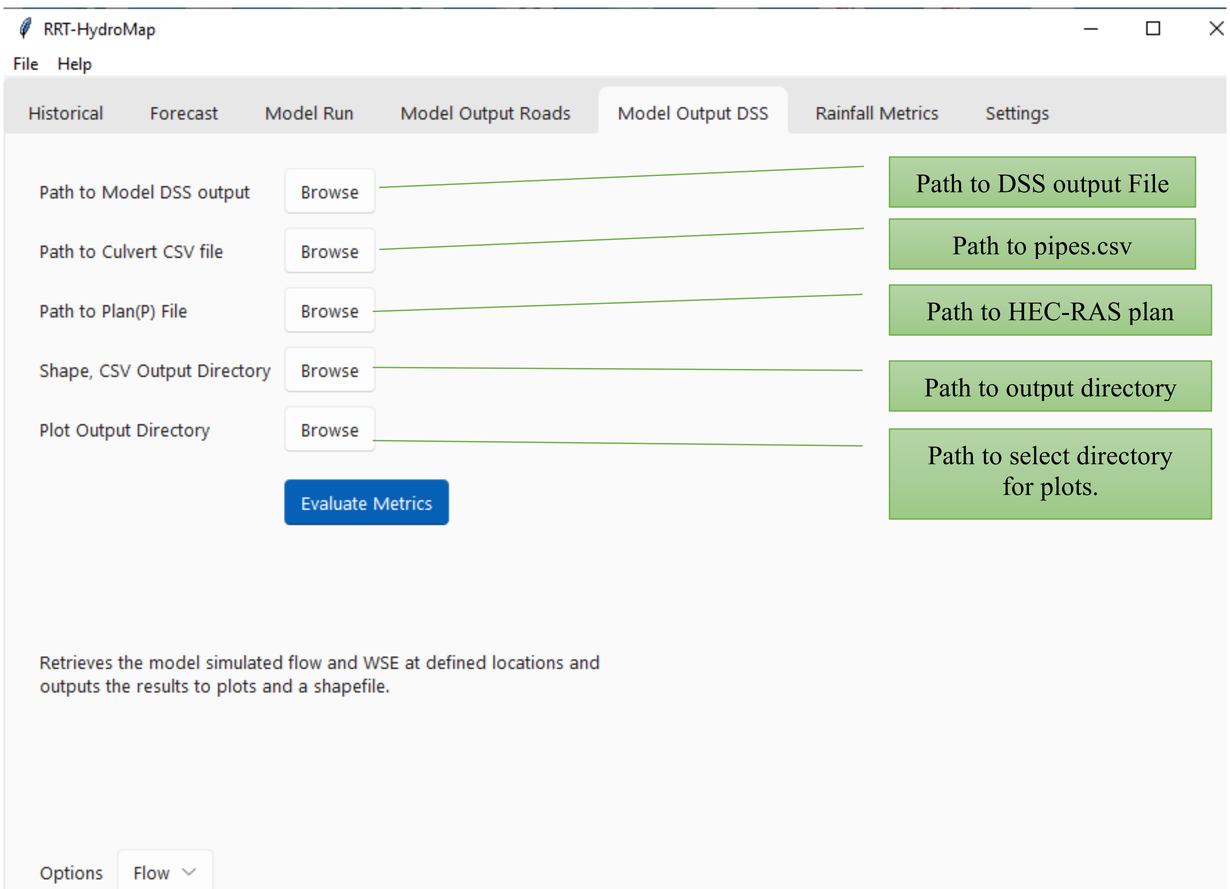

RRT-HydroMap
File Help
Historical
Forecast
Model Run
Model Output Roads
Model Output DSS
Rainfall Metrics
Settings
Path to Input Directory
Browse
Path to Road GeoTIFF
Browse
Path to WSE GeoTIFF
Browse
Output Directory
Browse
Open
Scenario ID
(Maximum 6 charaters)
Output
Both
Evaluate
Calculates road inundation from HEC-RAS WSE raster output.
View Map
Select input file directory
Location to Save Output
Input ID to add to shapefile naming
Select whether to evaluate road overtopping, structure overtopping or both

6.2.5 Model Output DSS Tab

This tab allows for the output and graphing of "2D Area Connections" from the output DSS file. A .csv file named "pipes.csv" is required. The file must be formatted exactly as shown below.

- "PipeID" is the name of the 2D area connection in the HEC-RAS model.
- "Q_over" is the structure's flow (cfs) capacity at overtopping.
- "road_elev" is the elevation of the roadway at the crossing.

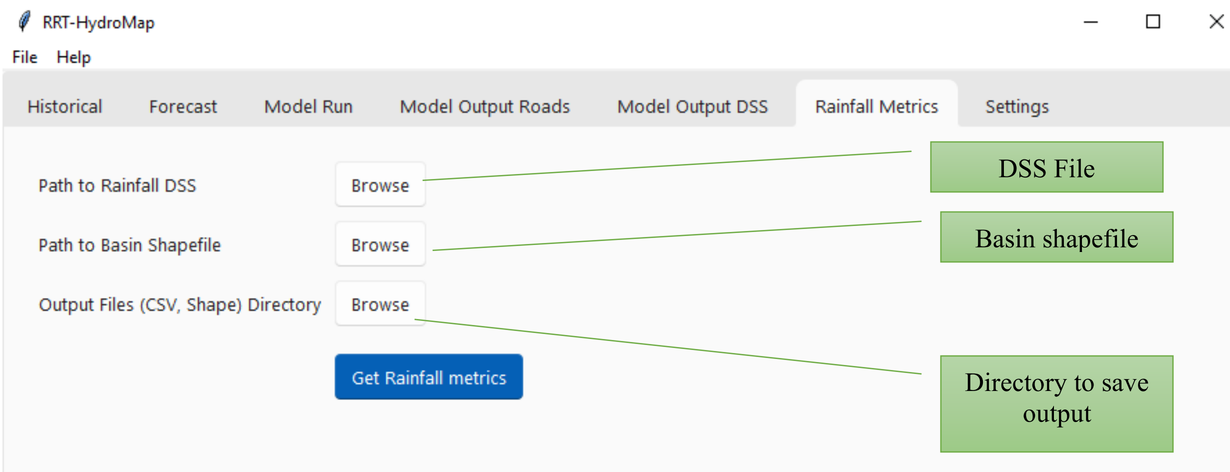
PipeID	Lat	Long	Q_over	road_elev	road	desc
BP-096-2037	35.49392	-77.9817	870	130.8	US-117	72" x 96" RCBC
BP-096-2120	35.52471	-78.0814	208	139.1	SR-1337	80" x 60" CMP Arch
BP-096-2123	35.51175	-78.0991	246	142.5	SR-1336	60" CMP (2)
BP-096-2137	35.4765	-77.9669	277	125.2	SR-1537	66" RCP



6.2.6 Rainfall Metrics Tab

This tab summarizes the hourly rainfall by zones in a shapefile.

The basin shapefile requires a field "Name" of type "string." The "Name" field should be a unique ID for each of zones to characterize the rainfall.



<u>Settings</u>

This tab includes setting for the DSS rainfall grid spacing in meters.

<u>Appendix</u>

This program is written in Python 3.9

Python packages used:

- Fiona 1.8.22
- Folium 0.14.0
- Gdal 3.5.2
- Geocube 0.4.0
- Geopandas 0.10.2
- Geotiff 1.7.1
- Hdf5 1.12.2
- shapely=1.8.5
- rtree=1.0.1
- pyproj=3.4.0
- eccodes
- h5py
- pywebview 3.7

- Matplotlib 3.7.1
- Numpy 1.23.5
- Pydsstools 2.2
- Pywin32 306
- Rasterio 1.3.3
- Rasterstats 0.18.0
- Requests 2.28.1
- Rioarray 0.14.1
- Rascontrol
- Pandas 1.4.4
- gribapi

Other programs used:

- Vortex 0.10.25
- Jython 2.7.2