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Tar–Pamlico River Basin Flood Risk Management Feasibility Study: Hydraulics and Hydrology Report

Technical Report and Documentation for the Basin-Wide Hydrologic Assessment

Existing Conditions - Future Without Project Conditions & Alternative Analysis

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1. Introduction

1.1 Objective of Study

The Tar-Pamlico Basin has a history of flooding during severe storm and hurricane events. The basin was severely impacted by Hurricanes Fran (1996), Floyd (1999), Matthew (2016), and Florence (2018) causing widespread flooding and damage to residential and commercial buildings. The communities of the Tar-Pamlico Basin have been very active in pursuing flood damage reduction measures to reduce future flooding. Due to recurring damages sustained during hurricane events, most recently Hurricane Florence, the State of North Carolina has requested USACE to pursue a feasibility study to reduce future flood damages in the basin. The project was included in the 2019 Additional Supplemental Appropriations for Disaster Relief. The FCSA was signed 8 April 2020. The major study risk is identification of implementable alternatives across multiple focal areas, as well as basin-wide alternatives that reduce localized flooding or reduce overall flood risk in the basin.

1.2 Watershed Description

The Tar-Pamlico River basin is the fourth largest river basin in North Carolina and is one of only four river basins whose boundaries are located entirely within the state. The Tar River originates in north central North Carolina in Person, Granville and Vance counties and flows southeasterly until it reaches tidal waters near Washington and becomes the Pamlico River. The river empties into the Pamlico Sound. The Pamlico River is a tidal estuary that flows into the Pamlico Sound. Major tributaries of the Tar River include Fishing Creek, Swift Creek, Little Fishing Creek, Conetoe Creek, Chicod Creek, the entrance to Pamlico Sound. Based on the 2011 National Land Cover Data, the Tar-Pamlico River Basin's estimated developed area is ~7%, agriculture ~29%, wetlands ~23% grassland/scrub ~12% and forest ~27%. Development and population growth centers around Greenville, Rocky Mount, Washington, Tarboro and in rural areas within commuting distance to Raleigh, NC.

1.3 Study Area

The study area is comprised of river reaches along the mainstem of Tar River and its major tributaries, beginning just downstream of Greenville, NC. The study originally included the region of the Tar River near Washington, as well as portions of the Pamlico River primarily affected by coastal flooding. However, regions affected by coastal flooding were removed from consideration (see Section 1.3 of the integrated feasibility report and environmental assessment).

3. Flood Frequency Analysis

3.1 Stream Gage Data

The Tar-Pamlico Basin has 13 stream gage sites, of which 8 are located along the Tar River mainstem. The two critical pieces of data needed from these locations are the gage height and discharge observations and/or discharge estimates based on river rating curve approximations. Water-year summary reports for each USGS gage were acquired to identify large magnitude floods that are outside of the systematic record used to estimate flow frequency curves. Research was completed by reviewing USGS historical flood reports and basin wide summaries to find any missing events from the USGS gage data to ensure the highest level of accuracy possible when performing the Bulletin 17C Analysis. Listed below in Table 1 are the USGS gages that are within the Tar-Pamlico Basin.

Table 1: Summary of Available USGS gages located in the Tar Pamlico Basin

Location	USGS NO.	USGS Drainage Area	Annual Maximum Flow Data: From/To		Record Total
<text>	<#>	<sq. miles>	YYYY-MM-DD	YYYY-MM-DD	<count>
TAR RIVER NEAR TAR RIVER, NC	2081500	167.0	1940-05-25	2020-02-07	81
TAR R AT US 401 AT LOUISBURG, NC	2081747	427.0	1934-12	2020-06-18	60
TAR RIVER AT NC-581 NEAR SPRING HOPE, NC	2081942	670.7	2012-09-20	2020-06-20	9
TAR RIVER NEAR NASHVILLE, NC	2082000	701.0	1929	1971	43
TAR R BL TAR R RESERVOIR NR ROCKY MOUNT, NC	2082506	777.0	1973-02-06	2010-10-01	39
TAR RIVER AT NC 97 AT ROCKY MOUNT, NC	2082585	925.0	1977-03-09	2020-06-18	44
SWIFT CREEK AT HILLIARDSTON, NC	2082770	166.0	1924	2020-06-18	58
LITTLE FISHING CREEK NEAR WHITE OAK, NC	2082950	177.0	1960-07-31	2020-02-08	61
FISHING CREEK NEAR ENFIELD, NC	2083000	526.0	1910	2020-06-20	107
TAR RIVER AT TARBORO, NC	2083500	2,183.0	1897-03-19	2020-06-22	119
CONETOE CREEK NEAR BETHEL, NC	2083800	78.1	1955	2001-06-19	46
TAR RIVER AT GREENVILLE, NC	2084000	2,660.0	1887-11-07	2016-02-09	91
CHICOD CR AT SR1760 NEAR SIMPSON, NC	2084160	45.0	1976-01-28	2020-02-07	41
PAMLICO RIVER AT WASHINGTON, NC	2084472	3,200.0	1999-10-21	2019-09-06	17

TAR RIVER BELOW DAM NEAR LANGLEY CROSSROADS, NC	208250410	775.0	2012-04-10	2020-06-18	9

Footnote 1* The Tar River Below Dam Gage was not used due to its limited record length and unsatisfactory uncertainty tolerance

3. Climate Assessment

3.1 Climate Assessment Report

This Tier 1 ECB 2018-14 assessment of climate change impacts is required by U.S. Army Corps of Engineers (USACE, "the Corps") Engineering and Construction Bulletin (ECB) 2018-14, "Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects." This assessment documents the qualitative effects of climate change on the hydrology in the region as well as its impacts to the Tentatively Selected Plan (TSP). The ECB 2018-14 analysis is targeted at identifying potential impacts and risks to the Tar-Pamlico Basin Feasibility Analysis Study due to climate change. Appendix A contains the Comprehensive Climate Impact Analysis.

USACE projects, programs, missions, and operations have generally proven to be robust enough to accommodate the range of climatic change over their operating life cycle duration. However, recent scientific evidence shows that in some places and for some impacts relevant to USACE operations, climate change is shifting the baseline naturally occurring and therefore our predictions for impact to the Project Tentatively Selected Plan (TSP). This is relevant to USACE because the assumptions of stationary climate conditions and a fixed range of natural variability, as captured in the historic hydrologic record may no longer apply.

3.1.1 Observed Trends in Current Climate and Climate Change

3.1.1.1 Literature Review Summary

The consensus in the recent literature points toward mild increases in annual temperature in the South Atlantic-Gulf Region over the past century, particularly over the past 40 years. While much of the area is located within the so-called "warming hole" identified by various researchers (including Carter et al., 2014), recent studies have demonstrated significant warming for other parts of the area (particularly northern portions) since the 1970s. Annual precipitation totals have become more variable in recent years compared to earlier in the 20th century. Evidence has also been presented, but with limited consensus, of mildly increasing trends in the magnitude of annual and seasonal precipitation for parts of the study area. These results are seemingly contradicted by several studies that have shown decreasing trends in streamflow throughout the area, particularly

since the 1970s. This paradox is discussed by Small et al. (2006), who attribute it largely to seasonal differences in the timing of the changes in precipitation vs. streamflow. The study authors evaluated watersheds that experienced minimal water withdrawals and/or transfers. Results presented here also suggest that increasing temperatures may also play a role in decreasing streamflows, despite the lack of corresponding precipitation decline.

3.1.1.2 Climate Hydrology Assessment Tool

The Climate Hydrology Assessment Tool (CHAT) developed by USACE and was utilized to examine trends in observed annual peak streamflow for the various gage locations. The CHAT tool is used to fit a linear regression to the peak streamflow data in addition to providing a p-value indicating the statistical significance of a given trend.

A summary of the regression trends and their statistical significance is shown in the results tab below. Individual graphical output for all gages and period of record data analyzed is shown in the Climate Assessment Report Appendix. Every gage that was analyzed via CHAT did not have a statistically significant linear trend. A few of the gages were not within the CHAT and the Tar River at Greenville, NC gage did not have the 30-year period of record needed to perform the analysis, so it was not analyzed either. There were no statistically significant trends detected in either gage that would indicate significant changes in observed streamflow due to climate change, long-term natural climate trends, or land use/land cover changes. A summary of the resulting trends are shown in Table 2.

3.1.1.3 Climate Hydrology Assessment Tool Results

Table 2: Summary of Observed Streamflow Trends in Annual Peak Streamflow using CHAT

Gage Number	Gage Name and Location	POR for CHAT	POR for NSD	POR Note	Regression Slope	P-Value	Trend Direction	Significance
02081500	Tar River near Tar River, NC	1940-2014	1940-2014	Complete	8.477	0.645	Upward	Insignificant
02081747	Tar R at US 401 at Louisburg, NC	1964-2014	1964-2014	Complete	42.442	0.314	Upward	Insignificant
02082000	Tar River near Nashville, NC	N/A	N/A	Not in CHAT or NSD	N/A	N/A	N/A	N/A
02082506	Tar River below Tar R Reservoir near Rocky Mount, NC	N/A	N/A	Not in CHAT or NSD	N/A	N/A	N/A	N/A
02082585	Tar River at NC 97 at Rocky Mount, NC	1977-2014	1977-2014	Complete	-5.974	0.939	Downward	Insignificant
02082770	Swift Creek at Hilliardston, NC	1964-2014	1964-2014	Complete	25.847	0.409	Upward	Insignificant
02082950	Little Fishing Creek near White Oak, NC	1960-2014	1960-2014	Complete	9.582	0.807	Upward	Insignificant
02083000	Fishing Creek near Enfield, NC	1915-2014	1915-2014	Complete	-8.263	0.556	Downward	Insignificant
02083500	Tar River at Tarboro, NC	1895-2014	1906-2014	Complete	-15.017	0.564	Downward	Insignificant
02083800	Conetoe Creek near Bethel, NC	N/A	N/A	Not in CHAT or NSD	N/A	N/A	N/A	N/A
02084000	Tar River at Greenville, NC	1997-2014	1997-2014	Length not sufficient	N/A	N/A	N/A	N/A
02084160	Chicod Creek at SR1760 near Simpson, NC	1976-2014	1976-2014	Complete, minus gap (1988-91)	39.246	0.07	Upward	Insignificant
02084472	Pamlico River at Washington, NC	N/A	N/A	Not in CHAT or NSD	N/A	N/A	N/A	N/A

3.1.1.4 Nonstationarity Detection Tool

The USACE Nonstationarity Detection (NSD) Tool was used to assess whether the assumption of stationarity, which is the assumption that the statistical characteristics of a time-series dataset are constant over the period of record, is valid for a given hydrologic time-series dataset. Nonstationarity are detected using 12 different statistical tests which examine how the statistical characteristics of the dataset change with time (Engineering Technical Letter (ETL) 1100-2-3, *Guidance for Detection of Nonstationarities in Annual Maximum Discharges*; *Nonstationarity Detection Tool User Manual*, version 1.2).

A Nonstationarity can be considered “strong” when it exhibits consensus among multiple Nonstationarity detection methods, robustness in detection of changes in statistical properties, and a relatively large change in the magnitude of a dataset’s statistical properties. Many of the statistical tests used to detect Nonstationarities rely on statistical change points, these are points within the time series data where there is a break in the statistical properties of the data, such that data before and after the change point cannot be described by the same statistical characteristics. Similar to Nonstationarities, change points must also exhibit consensus, robustness, and significant magnitude of change.

Only one stream gage produced a Nonstationarity and it is the 020817747 Tar R at US 401 at Louisburg, NC gage. The NSD calculated that a consensus of distribution occurred in 1971 by the CVM and KS methods, but the calculations presented no robustness. All other gages either did not have enough data to perform an analysis or the data that was found on USGS was not recent enough to be feasible for the analysis. The results table can be found in section 2.1.1.5 below and the individual results for each gage can be found in the Climate Assessment Report Appendix.

3.1.1.5 Nonstationarity Detection Tool Results

Table 3: Summary of Observed Streamflow Trends in Annual Peak Streamflow using NSD

Gage Number	Gage Name and Location	POR for CHAT	POR for NSD	POR Note	Consensus	Robustness	Conclusion
02081500	Tar River near Tar River, NC	1940-2014	1940-2014	Complete	No	No	None
02081747	Tar R at US 401 at Louisburg, NC	1964-2014	1964-2014	Complete	Yes	No	CVM & KS in 1971
02082000	Tar River near Nashville, NC	N/A	N/A	Not in CHAT or NSD (ended in 1970)	N/A	N/A	N/A
02082506	Tar River below Tar R Reservoir near Rocky Mount, NC	N/A	N/A	Not in CHAT or NSD (ended in 2010)	N/A	N/A	N/A
02082585	Tar River at NC 97 at Rocky Mount, NC	1977-2014	1977-2014	Complete	No	No	None
02082770	Swift Creek at Hilliardston, NC	1964-2014	1964-2014	Complete	No	No	None
02082950	Little Fishing Creek near White Oak, NC	1960-2014	1960-2014	Complete	No	No	None
02083000	Fishing Creek near Enfield, NC	1915-2014	1915-2014	Complete	No	No	None
02083500	Tar River at Tarboro, NC	1895-2014	1906-2014	Complete	No	No	None
02083800	Conetoe Creek near Bethel, NC	N/A	N/A	Not in CHAT or NSD (ended in 2001)	N/A	N/A	N/A
02084000	Tar River at Greenville, NC	1997-2014	1997-2014	Length not sufficient	N/A	N/A	N/A
02084160	Chicod Creek at SR1760 near Simpson, NC	1976-2014	1976-2014	Complete, minus gap (1988-91)	No	No	None
02084472	Pamlico River at Washington, NC	N/A	N/A	Not in CHAT or NSD (length not sufficient)	N/A	N/A	N/A

3.1.2 Projected Trends in Current Climate and Climate Change

3.1.2.1 Literature Review Summary

There is strong consensus in the literature that air temperatures will increase in the study area, and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of approximately 2 to 4 ºC by the latter half of the 21st century for the South Atlantic-Gulf Region. The largest increases are projected for the summer months. Reasonable consensus is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long-term future compared to the recent past. Projections of precipitation in the study area are less certain than those associated with air temperature. Results of the studies reviewed here are roughly evenly split with respect to projected increases vs. decreases in future annual precipitation. This is not unexpected as, according to the recently released NCA (Carter et al., 2014); the southeast region of the country (inclusive of the South Atlantic-Gulf Region) appears to be located in a "transition zone" between the projected wetter conditions to the north and dryer conditions to the west. There is, however, moderate consensus among the reviewed studies that future storm events in the region will be more intense and more frequent compared to the recent past. Similarly, clear consensus is lacking in the hydrologic projection literature. Projections generated by coupling GCMs with macro-scale hydrologic models in some cases indicate a reduction in future streamflows but in other cases indicate a potential increase in streamflows in the study region. Of the limited number of studies reviewed here, results are approximately evenly split between the two.

3.1.2.2 Climate Hydrology Assessment Tool

The USACE Climate Hydrology Assessment Tool (CHAT) was used to assess projected, future trends within the Neuse-Pamlico watershed, HUC-0302. The tool displays the range of projected annual maximum monthly streamflows from 1950 - 2099, with the projections from 1950 – 1999 representing hindcast projections and 2000 – 2099 representing forecasted projections.

Upon examination of the range of model results, there is a clear increasing trend in the higher projections, whereas the lower projections appear to be relatively stable and unchanging through time. The spread of the model results also increases with time, which is to be expected as uncertainty in future projection increases as time moves away from the model initiation point. Sources of variation and the significant uncertainty associated with these models include the boundary conditions applied to the GCMs, as well as variation between GCMs and selection of RCPs applied. Each GCM and RCP independently incorporate significant assumptions regarding future conditions, thus introducing

more uncertainty into the climate changed projected hydrology. Climate model downscaling and a limited temporal resolution further contribute to the uncertainty associated with CHAT results. There is also uncertainty associated with the hydrologic models. The large spread of results highlights current climatic and hydrologic modeling limitations and associated uncertainty. The results for this tool are shown in Appendix A.

3.1.2.3 Vulnerability Assessment

The USACE Watershed Climate Vulnerability Assessment Tool (VA Tool) facilitates a screening level, comparative assessment of how vulnerable a given HUC-4 watershed is to the impacts of climate change relative to the other 202 HUC-4 watersheds within the continental United States (CONUS). The tool can be used to assess the vulnerability of a specific USACE business line such as “Flood Risk Reduction” or “Navigation” to projected climate change impacts. Assessments using this tool help to identify and characterize specific climate threats and particular sensitivities or vulnerabilities, at least in a relative sense, across regions and business lines. The tool uses the Weighted Ordered Weighted Average (WOWA) method to represent a composite index of how vulnerable a given HUC-4 watershed (Vulnerability Score) is to climate change specific to a given business line. The HUC-4 watersheds with the top 20% of WOWA scores are flagged as being vulnerable.

Flood risk reduction is the most relevant business line for the Tar Pamlico River Basin Feasibility Study and is the primary business line analyzed with the USACE Climate Vulnerability Assessment Tool. Other business lines included in the VA Tool are ecosystem restoration, emergency management, hydropower, navigation, recreation, regulatory, and water supply. While the flood risk reduction is the main business line discussed in detail, all other business lines were analyzed as well.

For the Flood Risk Management business line, the HUC 0302 Neuse-Pamlico Basin is not within the top 20% of vulnerable watersheds within the CONUS for any of the four scenarios, which is not to say that vulnerability to future climate change does not exist within the basin. Table 4 displays the overall vulnerability scores for the business line relevant to this study under both wet and dry scenarios and under both time epochs. The rest of the result figures and data can be found in Appendix A.

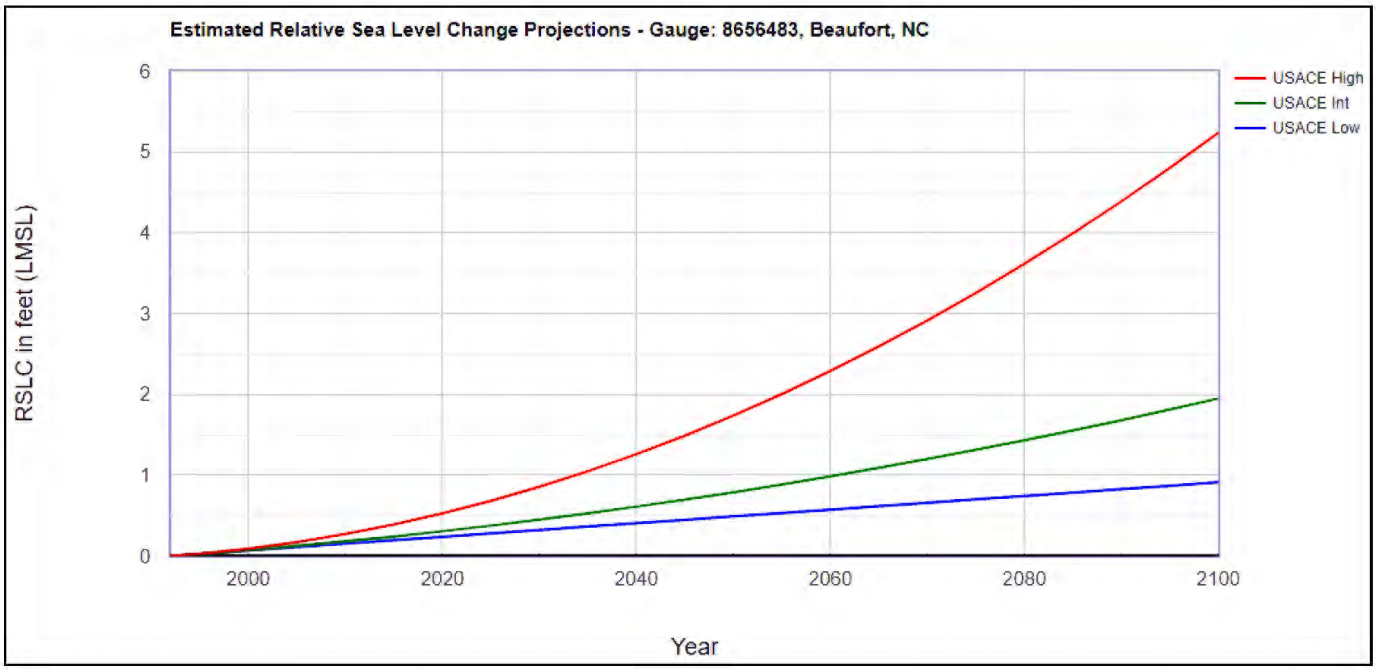
Table 4: Overall Vulnerability Score for Epochs and Selected Scenarios

Business Line	**Flood Risk Reduction**	
Epoch	**2050**	**2085**
Dry	45.13	47.59
Wet	48.16	51.99

3.1.2.4 Sea Level Change Assessment

Using the USACE Sea-Level Change Curve Calculator (Version 2019.21) historical rates and future rates are calculated for the Beaufort, NC Gage 8656483. According to ER 1100-2-8162 these rates are then used by the calculator to produce three curves which are the *USACE Low Curve*, *USACE Intermediate Curve*, and the *USACE High Curve*. The *USACE Low Curve* is calculated using the historic rate of sea-level change for each given location. The *USACE Intermediate Curve* is computed from the modified National Research Council (NRC) Curve I considering both the most recent Intergovernmental Panel on Climate Change (IPCC) projections and modified NRC projections with the local rate of vertical movement added. The *USACE High Curve* is computed from the modified NRC Curve III considering both the most recent IPCC projections and modified NRC projections with the local rate of vertical land movement added. The results for Beaufort, NC gage can be found in Figure 1. The results of the calculator for the year 2024 (start year) & 2100 (end year) are as follows: Low Curve is 0.91ft, Intermediate Curve is 1.95ft, and High Curve is 5.24ft with base level year established at 2024. A table of the curves can be found in Appendix A. The PDT removed areas from analysis below Greenville that were primarily impacted by tidal process. The PDT included Greenville because the risk is riverine. The RSLR estimates were applied to the downstream boundary condition to reflect relative sea level change impacts. A new section is being added to the H&H appendix to summarize the coincident frequency analysis (riverine + coastal storm surge) that supported this decision to remove areas that were inundated by coastal flooding. The decision to exclude coastal-influenced areas from the study was informed by the study authority, which only authorized the examination of riverine flooding, and coordinated with the vertical team. See the

Figure 1: Estimated Relative Sea Level Change Projection Curves Beaufort, NC Gage 8656483



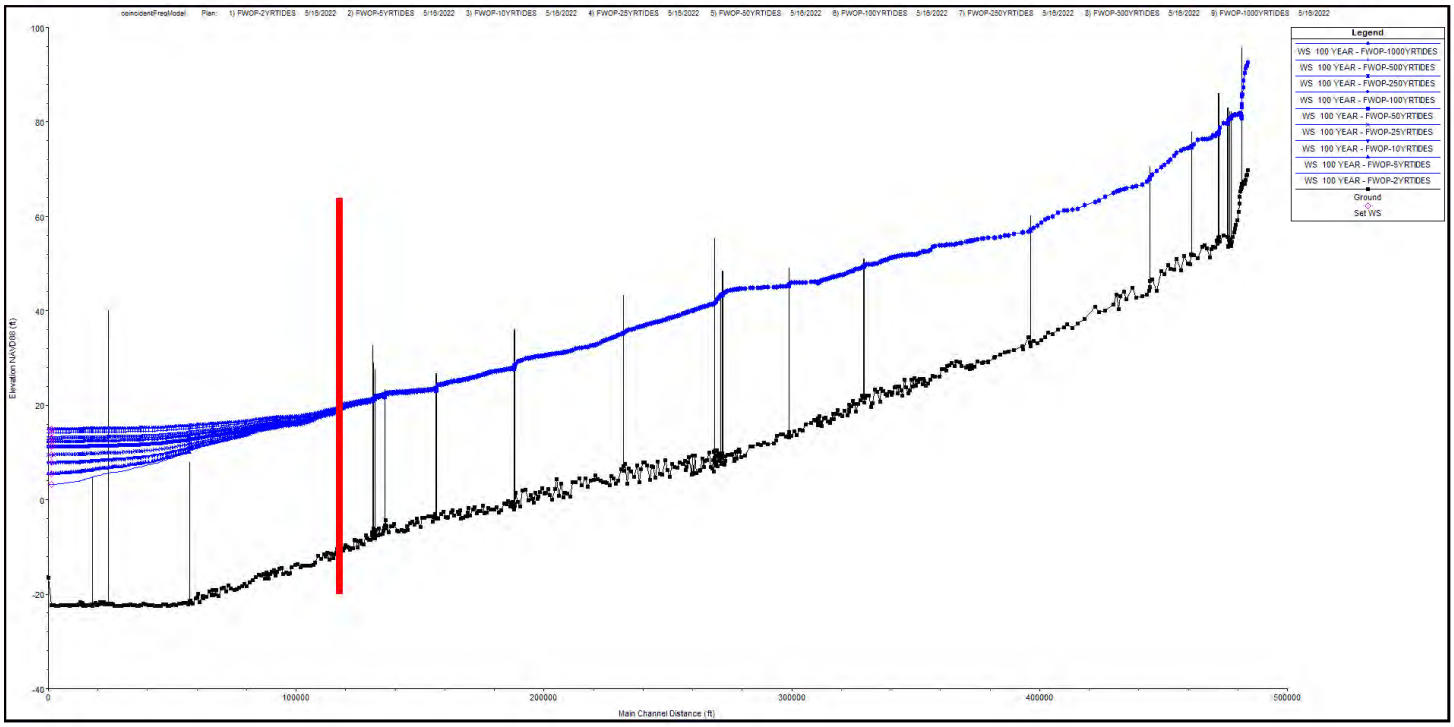


Figure 2: Water surface elevations analyzed for sensitivity due to relative sea level change impact Alt 264 Bypass Bridge (on red line in profile); sensitivity results.

3.1.3 Current Climate and Climate Change Conclusion

Based on the results of this analysis there is no significant trends that have been observed over time for the Tentatively Selected Plan (TSP), a summary of all risks as related to Sea Level Rise and Climate Change have been quantified in Table 5: Climatic Residual Risks Related to the Project. There will be a slight increase in temperature in the future with some uncertainty regarding precipitation and hydrology. The Climate Hydrology Assessment Tool for projected trends indicates

that the trend is considered statistically significant, however the Tentatively Selected Plan (TSP) will not be impacted by increased temperature due to the measures having non-structural elements only. The Vulnerability Assessment Tool was analyzed for the project area and the results stated that the project was not vulnerable compared to all other HUCs nationally. This does not mean that there are zero vulnerabilities regarding climate change. The tool recognizes that the change in flood runoff, combined with the acres of urban area within the 500-year floodplain, are the driving flood risk reduction vulnerability. Based on the USACE Sea-Level Change Curve Calculator for the Beaufort, NC Gage the Tar-Pamlico River Basin will be affected by sea-level rise over the next century. The results of the calculator for the year 2100 are as follows: Low Curve is 0.91ft, Intermediate Curve is 1.95ft, and High Curve is 5.24ft. These results can be found in Appendix A. The results and findings the climate impact change analysis should be used to inform the downstream hydraulic model boundary conditions as well as gain an understanding behind the degree of climatic changes that could influence the effectiveness of measures and flood risk in future years. Due to the conclusions and trends observed no additional consideration has been provided to future increases in precipitation depths, precipitation intensities, and stream gage flow observations.

Table 5: Climatic Residual Risks Related to the Project

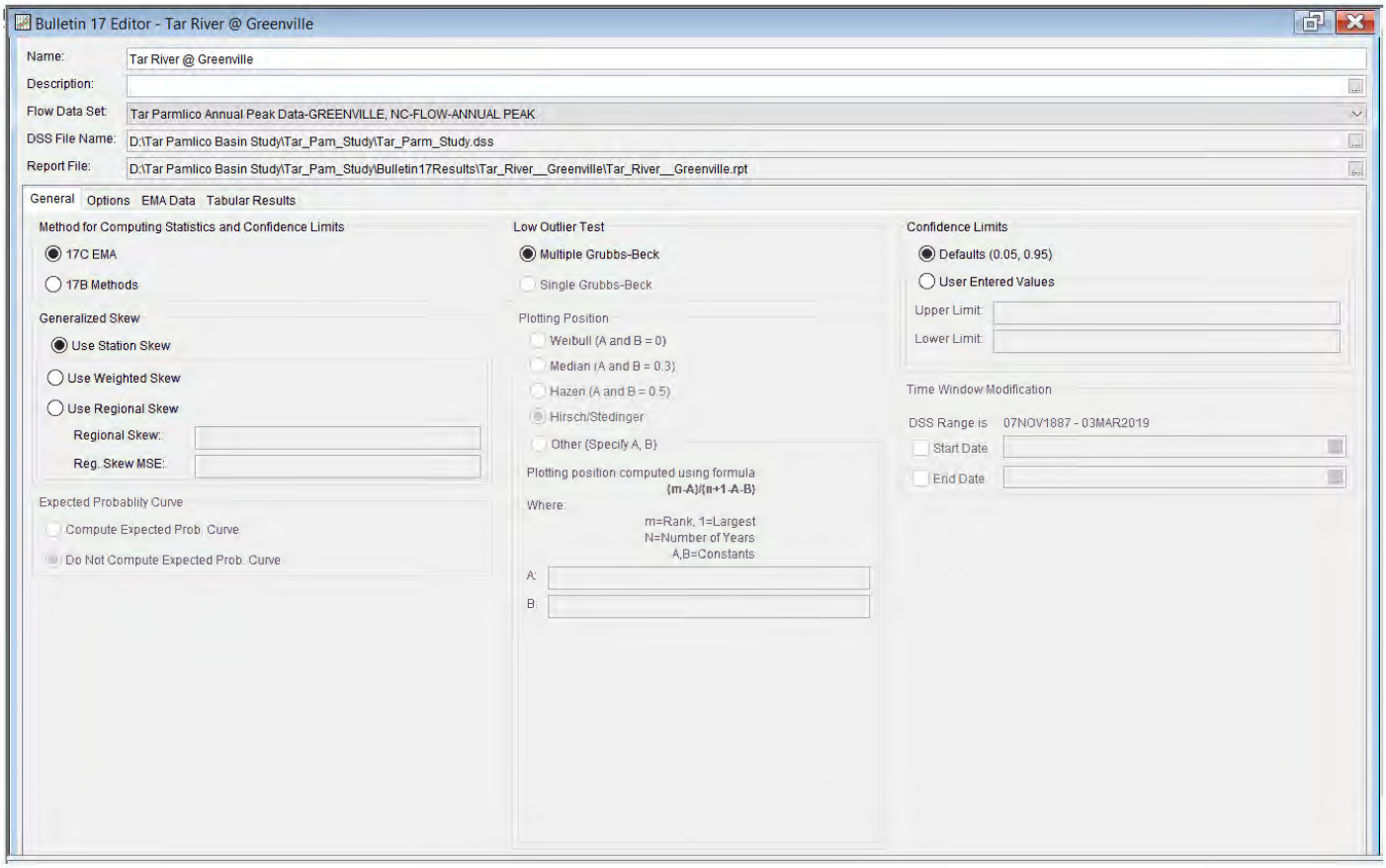
Residual Risks					
Project Feature	*Trigger*	*Hazard*	*Harm*	*Qualitative Likelihood Rating*	*Justification for Rating*
Alternative 3A: Maximum Net Economic Benefits/NED Plan	Storm event magnitude that initiates flood damages	Future knowledge of large floods could increase the frequency of flow	Future flood risk may be characterized by floods that have not occurred yet, floods will continue to occur however protected from damages	Unlikely	The industry best practices in statistical hydrology were used to compute confidence bounds and uncertainty was provided to the Flood Damage Analysis through standard deviation of error
Alternative 3B: Comprehensive Benefits Plan	Storm event magnitude that initiates flood damages	Future knowledge of large floods could change the flow frequencies experienced	Future flood risk may be characterized by floods that have not occurred yet, floods will continue to occur however protected from damages	Unlikely	Trends noted during the climate impact analysis does not conclude that increasing precipitation or stream flow records indicate a rise in flood magnitudes, nor is larger floods i.e. Hurricane Matthew expected to be more frequent
Dry Flood Proofing	Relative sea level rise increases to the extent that impact the riverine water surface profiles	Higher downstream stages in Pamlico Sound would increase the impact of backwater up the Tar River Mainstem	Dry flood proofing would not be sufficent to deliver flood damage reduction	Unlikely	The recommended plan includes dry floodproofing to the 1% AEP plus 2 feet, or a max height of 4 feet whichever was greater. Results of a sensitivity analysis indicate that relative sea level change, the high RSLC curve expects 2.2 feet and 1.3 feet which corresponds to 2100 and 2075 respectively. The additional 2 feet provides resiliency for the future project under both loading conditions. However, the 4-foot maximum height would result in higher residual risk at higher rates of RSLC, if water surface elevations exceed 4 feet. This uncertainty impacts only two reaches in the recommended plan. Under the intermediate RSLC scenario, no reaches within the study area upstream from US264 bypass bridge are effected by sea level rise for 50 year planning horizon.
Install dwelling vents	Relative sea level rise increases to the extent that impact the riverine water surface profiles	Higher downstream stages in Pamlico Sound would increase the impact of backwater up the Tar River Mainstem	Dry flood proofing would not be sufficent to deliver flood damage reduction	Unlikely	The recommended plan includes elevating to the 1% AEP plus 2 feet. Results of a sensitivity analysis indicate that relative sea level change, the high RSLC curve expects 2.2 feet and 1.3 feet which corresponds to 2100 and 2075 respectively. The additional 2 feet provides resiliency for the future project under both loading conditions. This uncertainty impacts only two reaches in the recommended plan. Under the intermediate RSLC scenario, no reaches within the study area upstream from US264 bypass bridge are effected by sea level rise for 50 year planning horizon.

3.2 Bulletin 17C Analysis

The Bulletin 17C Analysis was performed using the Hydrologic Engineering Center's Statistical Software Package (HEC-SSP) Version 2.1.1. This analysis is used to develop the flood frequency curves for each gage within the basin as well as defining confidence bounds based on expected moments. The first step in this analysis is to import the annual maxima series data as well as collect historical information regarding the magnitude or evidence of historic storms and evaluate the appropriateness of applying Bulletin 17C Frequency Analysis. Nearly all gages in the basin satisfy the 15-year minimum record length to complete this analysis other gages are available within the watershed boundary, however they either collect coastally influenced stage conditions, collect water quality chemistry, or have less than 15 years of annual maxima data. The Tar River below dam near Langley Crossroads, NC was not used due to its unsatisfactory record length, however this record would not provide reliable estimates at remote frequencies due to the nature of extrapolating flow frequency from a limited Period of Record < 15 years. Stream records located downstream from the Tar River Reservoir are impacted by regulation, however due to the minimal regulated versus unregulated flow comparison. The Tar River Reservoir operates reservoir based on INFLOW=OUTFLOW and flood control purposes are not authorized project benefits.

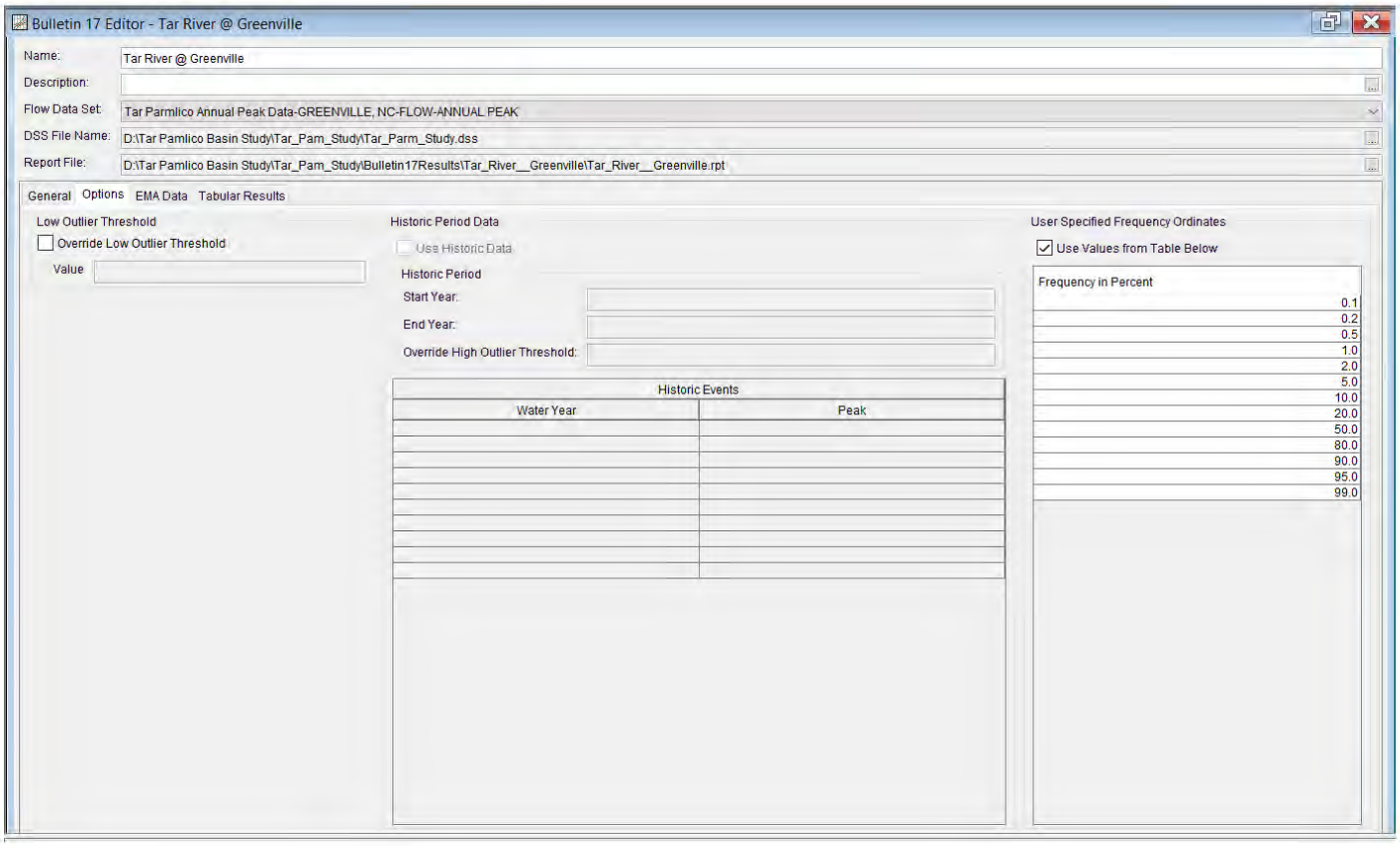
Along with the gage data there were error codes imported for each gage to inform confidence by things like debris, regulation, or gage inaccuracy. Before beginning the analysis on each gage historical events, regional events, and any other events outside of the period of record were researched to ensure the highest level of accuracy. When setting up the analysis the general inputs were as shown in Figure 3. All general inputs and options inputs were the same for every gage, including but not limited to user defined frequency ordinates and confidence bounds for the 5%, 25%, 50%, and 95% estimates.

Figure 3: Bulletin 17C Analysis General Input Settings



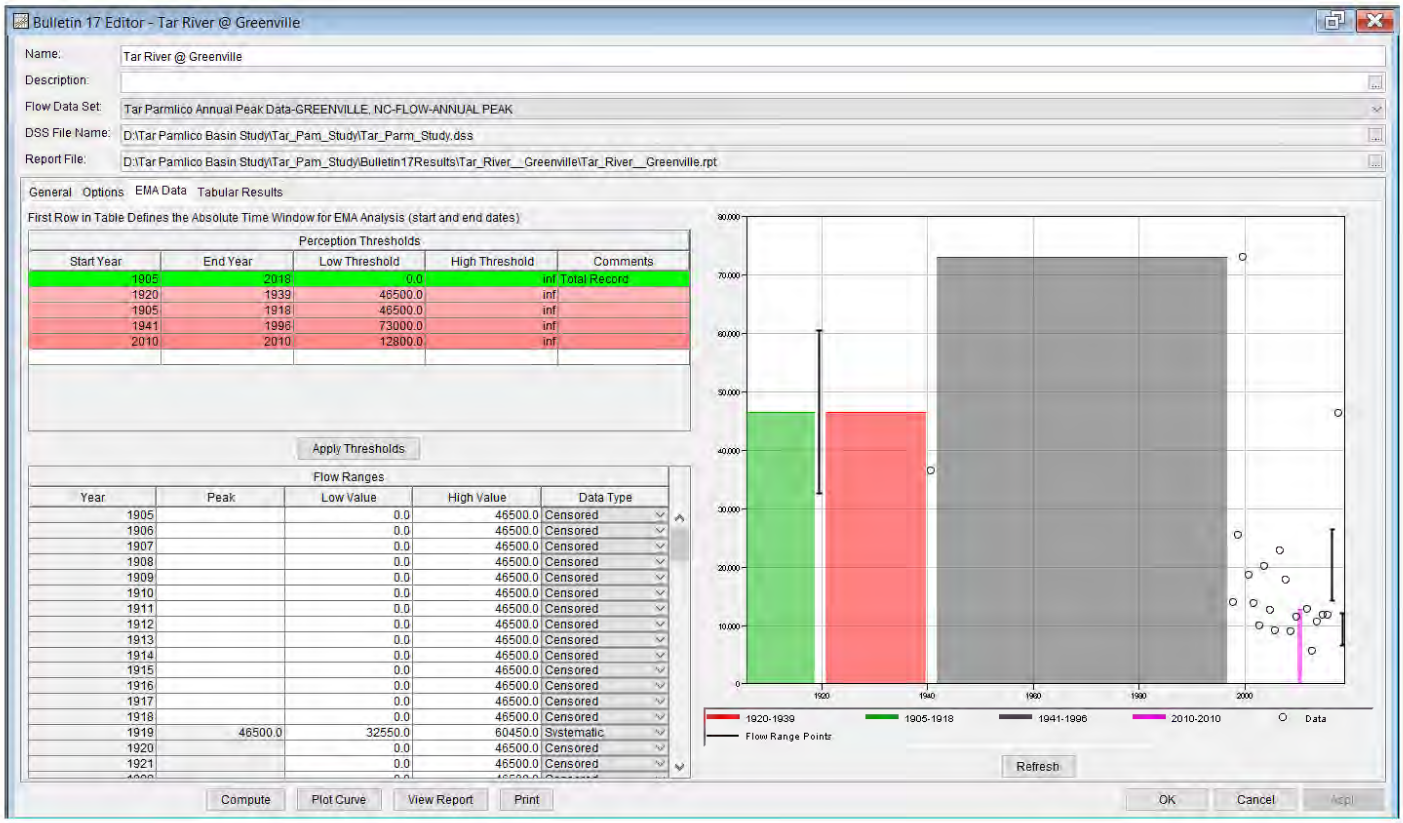
The options chosen are shown in Figure 4 as well as user defined annual exceedance probabilities required for feasibility study.

Figure 4: Bulletin 17C Analysis Options Inputs



The next step in the analysis uses a combination of systematic, historic, and perception thresholds to inform the Expected Moments Algorithm (EMA). This data is then completed using perception thresholds with incomplete or missing records as well as for the accuracy of each value as estimated using data collection accuracy and measurement error estimation. An example of the final EMA data tab before computing is shown below in Figure 5 for the Greenville, NC gage. The EMA data tab for each gage is attached in Appendix A.

Figure 5: Bulletin 17C Analysis EMA Data



Gages that had missing or incomplete data were provided perception thresholds estimated using the evidence of historic floods. As shown in Figure 5 above, the green, red, and grey blocks in the right schematic plot are instances of filling the gaps through the perception that the shaded regions were the largest flood possible or would have been discovered through documentation research. Perception thresholds were used to add these blocks represented in the graph by defining a start year, end year and discharge magnitude.

Once the perception thresholds were complete the USGS code peak flow errors were used to determine the accuracy of each historic flood peak. The points that were assigned a code for a lower level of accuracy were given a +/- 30% range above and below the point to assume it was potentially skewed by things like debris. This was input into the chart by assigning that given point a new low value and high value in the flow ranges list. The low value was 70% of the given value and the high value was 130% of the given value. The original given value was then moved to the peak location in the flow ranges list. The result of this action is what created the vertical black lines in the chart in Figure 6.

The output plot for each gage was generated and with an example flow frequency plot and the tabular results are shown in Figure 6 and Table 6 for the Greenville, NC gage.

Figure 6: Bulletin 17C Analysis Resultant Flow Frequency Plot

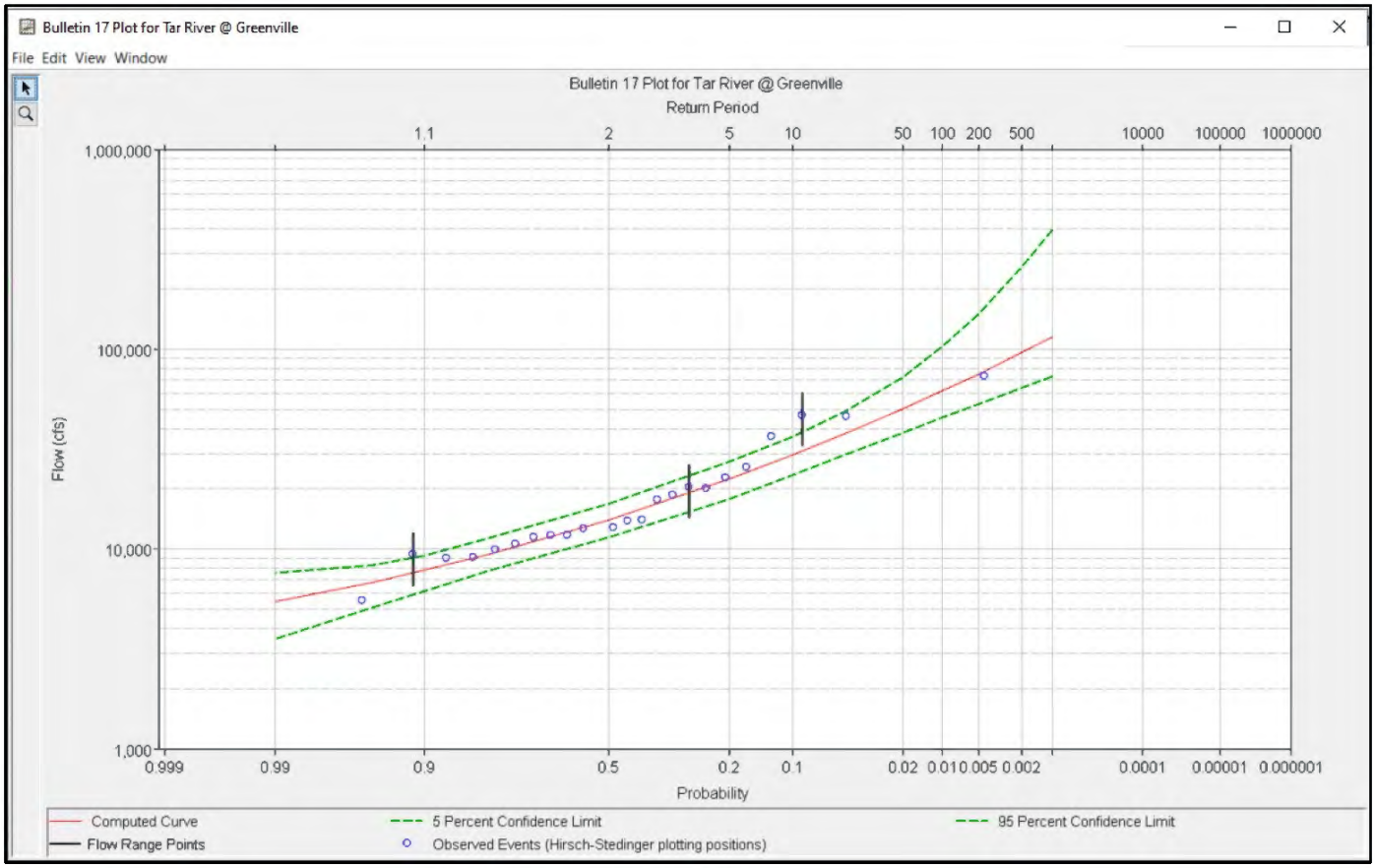
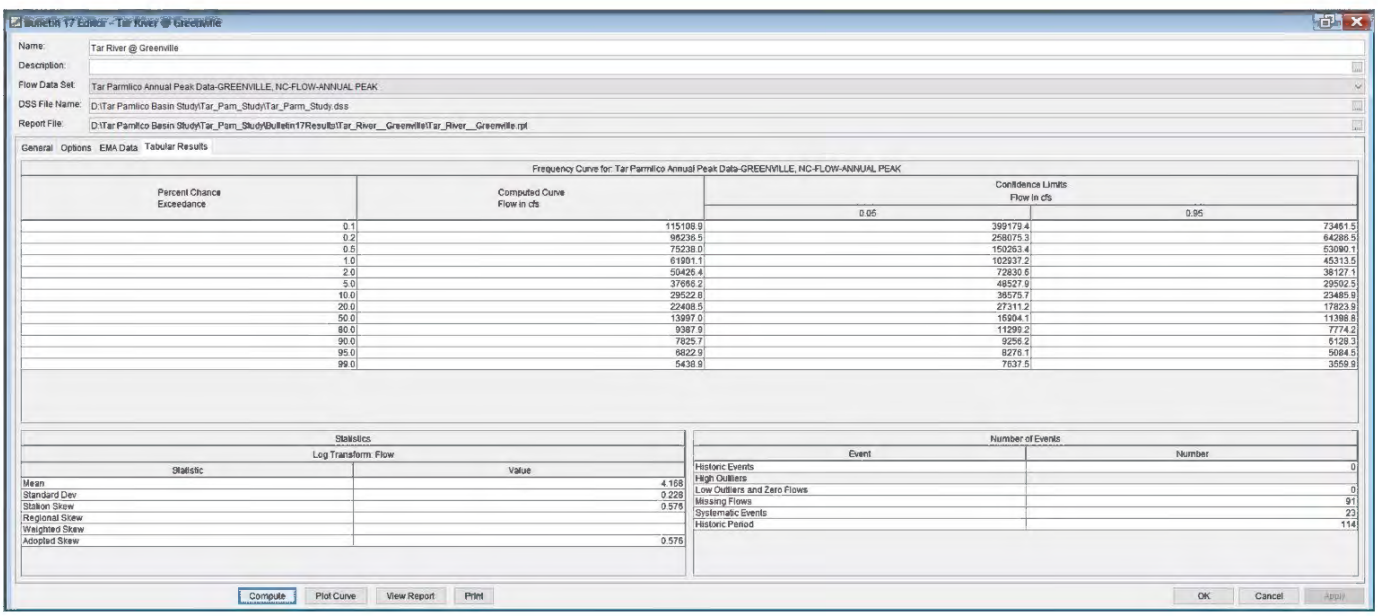


Table 6: Bulletin 17C Analysis Flow Frequency Tabular Results



Bulletin 17 Editor - Tar River @ Greenville

Name: Tar River @ Greenville

Description:

Flow Data Set: Tar Pamlico Annual Peak Data-GREENVILLE, NC-FLOW-ANNUAL PEAK

DSS File Name: D:\Tar Pamlico Basin Study\Tar_Pam_Study\Tar_Pam_Study.dss

Report File: D:\Tar Pamlico Basin Study\Tar_Pam_Study\Bulletin17Results\Tar_River__Greenville\Tar_River__Greenville.rpt

General | Options | EMA Data | Tabular Results

Frequency Curve for: Tar Pamlico Annual Peak Data-GREENVILLE, NC-FLOW-ANNUAL PEAK

Percent Chance Exceedance	Computed Curve Flow in cfs	Confidence Limits Flow in cfs	
		0.05	0.95
0.1	115108.9	399179.4	73461.5
0.2	96236.5	258075.3	64286.5
0.5	75238.0	150263.4	53090.1
1.0	61901.1	102937.2	45313.5
2.0	50425.4	72830.6	38127.1
5.0	37666.2	48527.9	29502.5
10.0	29522.8	36575.7	23485.9
20.0	22408.5	27311.2	17823.9
50.0	13997.0	16904.1	11398.8
80.0	9387.9	11299.2	7774.2
90.0	7825.7	9256.2	6129.3
95.0	6822.9	8276.1	5084.5
99.0	5438.9	7637.5	3559.9

Statistics

Log Transform: Flow

Statistic	Value
Mean	4.168
Standard Dev	0.229
Station Skew	0.575
Regional Skew	
Weighted Skew	
Adopted Skew	0.575

Number of Events

Event	Number
Historic Events	0
High Outliers	
Low Outliers and Zero Flows	0
Missing Flows	91
Systematic Events	23
Historic Period	114

Compute | Plot Curve | View Report | Print | OK | Cancel | Apply

This procedure was completed for every gage in the basin with sufficient record length. All EMA data charts, flow frequency tabular results are presented in Tables 6 through 17.

Table 7: Tar River at Greenville, NC USGS NO. 02084000

Greenville			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	115109	399179	159031	92246	73462
500	0.2	96237	258075	126436	79188	64287
250	0.4	79976	170751	100207	67474	55719
200	0.5	75238	150263	92913	63967	53090
100	1.0	61901	102937	73305	53826	45314
50	2.0	50426	72831	57631	44732	38127
20	5.0	37666	48528	41655	34109	29503
10	10.0	29523	36576	32237	26974	23486
5	20.0	22409	27311	24343	20525	17824
2	50.0	13997	16904	15137	12908	11399
1.25	80.0	9388	11299	10092	8729	7774
1.111111111	90.0	7826	9256	8417	7193	6128
1.052631579	95	6823	8276	7440	6159	5085
1.01010101	99	5439	7638	6286	4643	3560

Statistic Summary	
Statistic	Value
Mean	*4.168*
Standard Deviation	*0.228*
Station Skew	*0.576*
Regional Skew	
Weighted Skew	
Adopted Skew	*0.576*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*91*
Systematic Events	*23*
Historic Period	*114*

Footnote 2: All discharges shown in this table are in cubic feet per second

Table 8: Tar River near Tar River, NC USGS NO. 02081500

Tar River			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	25183	42344	30063	21809	18479
500	0.2	22984	36252	26857	20246	17482
250	0.4	20800	30841	23804	18628	16386
200	0.5	20099	29230	22852	18095	16010
100	1.0	17931	24591	19988	16397	14759
50	2.0	15770	20449	17257	14628	13367
20	5.0	12914	15632	13830	12164	11273
10	10.0	10733	12447	11353	10189	9492
5	20.0	8499	9616	8928	8099	7561
2	50.0	5279	5943	5540	5029	4684
1.25	80.0	3151	3584	3329	2967	2685
1.111111111	90.0	2367	2746	2531	2184	1874
1.052631579	95	1853	2214	2014	1666	1332
1.01010101	99	1146	1501	1306	959	638

Statistic Summary	
Statistic	Value
Mean	*3.71*
Standard Deviation	*0.257*
Station Skew	*-0.286*
Regional Skew	
Weighted Skew	
Adopted Skew	*-0.286*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*2*
Missing Flows	*0*
Systematic Events	*80*
Historic Period	*80*

Footnote 3: All discharges shown in this table are in cubic feet per second

Table 9: Tar River at US 401 at Louisburg, NC USGS NO. 02081747

Louisburg			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	36234	81036	46322	30199	24878
500	0.2	31921	64536	39640	27149	22817
250	0.4	27912	51133	33691	24212	20745
200	0.5	26682	47379	31919	23289	20075
100	1.0	23040	37212	26823	20491	17982
50	2.0	19652	28978	22292	17787	15867
20	5.0	15518	20483	17062	14337	13022
10	10.0	12611	15522	13596	11799	10826
5	20.0	9840	11536	10461	9289	8580
2	50.0	6179	7044	6516	5860	5423
1.25	80.0	3928	4484	4150	3707	3387
1.111111111	90.0	3114	3594	3313	2907	2582
1.052631579	95	2577	3029	2770	2367	2018
1.01010101	99	1818	2285	2022	1592	1220

Statistic Summary	
Statistic	Value
Mean	*3.795*
Standard Deviation	*0.237*
Station Skew	*0.094*
Regional Skew	
Weighted Skew	
Adopted Skew	*0.094*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*0*
Systematic Events	*56*
Historic Period	*56*

Footnote 4 All discharges shown in this table are in cubic feet per second

Table 10: Tar River below Tar River Reservoir near Rocky Mount, NC USGS NO. 02082585

Rocky Mount BL RES			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	31354	66697	39769	26173	21515
500	0.2	28410	55308	35066	24197	20312
250	0.4	25555	45647	30715	22196	19014
200	0.5	24654	42857	29384	21545	18574
100	1.0	21907	35058	25456	19502	17130
50	2.0	19233	28403	21814	17417	15551
20	5.0	15787	21056	17390	14574	13223
10	10.0	13216	16448	14292	12335	11270
5	20.0	10627	12598	11345	9989	9158
2	50.0	6942	8047	7369	6539	5985
1.25	80.0	4482	5227	4782	4181	3730
1.111111111	90.0	3550	4205	3823	3258	2783
1.052631579	95	2921	3540	3188	2622	2104
1.01010101	99	2014	2628	2288	1695	1136

Statistic Summary	
Statistic	Value
Mean	*3.838*
Standard Deviation	*0.223*
Station Skew	*-0.096*
Regional Skew	
Weighted Skew	
Adopted Skew	*-0.096*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*0*
Systematic Events	*39*
Historic Period	*39*

Footnote 5 All discharges shown in this table are in cubic feet per second

Table 11: Tar River at NC 97 at Rocky Mount, NC USGS NO. 02082585

Rocky Mount			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	38900	91117	49985	32449	26863
500	0.2	34745	73135	43349	29566	24949
250	0.4	30821	58459	37363	26741	22984
200	0.5	29604	54335	35564	25842	22340
100	1.0	25963	43115	30341	23084	20298
50	2.0	22513	33962	25628	20364	18184
20	5.0	18210	24427	20083	16806	15258
10	10.0	15107	18806	16331	14114	12929
5	20.0	12075	14264	12867	11379	10484
2	50.0	7918	9075	8367	7494	6911
1.25	80.0	5236	6010	5546	4928	4474
1.111111111	90.0	4233	4911	4514	3936	3458
1.052631579	95	3557	4199	3833	3250	2726
1.01010101	99	2577	3248	2874	2239	1664

Statistic Summary	
Statistic	Value
Mean	*3.901*
Standard Deviation	*0.216*
Station Skew	*0.073*
Regional Skew	
Weighted Skew	
Adopted Skew	*0.073*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*0*
Systematic Events	*43*
Historic Period	*43*

Footnote 6 All discharges shown in this table are in cubic feet per second

Table 12: Swift Creek at Hilliardston, NC USGS NO. 02082770

Hilliardston			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	37639	351697	67247	25956	18225
500	0.2	28486	200789	46998	20549	14983
250	0.4	21406	112190	32693	16136	12207
200	0.5	19491	90967	29055	14898	11401
100	1.0	14475	48056	20059	11538	9146
50	2.0	10625	25997	13750	8815	7224
20	5.0	6889	12090	8230	5997	5117
10	10.0	4832	7065	5500	4335	3794
5	20.0	3263	4239	3592	2989	2654
2	50.0	1715	2051	1844	1595	1429
1.25	80.0	1030	1197	1092	972	894
1.111111111	90.0	828	950	878	778	700
1.052631579	95	708	844	762	655	578
1.01010101	99	556	774	634	488	404

Statistic Summary	
Statistic	Value
Mean	*3.275*
Standard Deviation	*0.306*
Station Skew	*0.803*
Regional Skew	
Weighted Skew	
Adopted Skew	*0.803*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*0*
Systematic Events	*56*
Historic Period	*56*

Footnote 7 All discharges shown in this table are in cubic feet per second

Table 13: Little Fishing Creek near White Oak, NC USGS NO. 02082850

White Oak			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	69960	773161	137917	43390	26654
500	0.2	49846	376477	89106	32958	21515
250	0.4	35354	185659	57495	24875	17230
200	0.5	31617	148349	49917	22686	16009
100	1.0	22254	74814	32149	16939	12649
50	2.0	15546	38617	20676	12510	9857
20	5.0	9522	16930	11515	8182	6873
10	10.0	6457	9531	7387	5769	5031
5	20.0	4272	5579	4713	3906	3461
2	50.0	2285	2733	2454	2130	1920
1.25	80.0	1485	1670	1554	1421	1333
1.111111111	90.0	1268	1437	1334	1204	1112
1.052631579	95	1146	1383	1235	1064	954
1.01010101	99	1006	1379	1146	878	711

Statistic Summary	
Statistic	Value
Mean	*3.418*
Standard Deviation	*0.293*
Station Skew	*1.244*
Regional Skew	
Weighted Skew	
Adopted Skew	*1.244*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*0*
Systematic Events	*60*
Historic Period	*60*

Footnote 8 All discharges shown in this table are in cubic feet per second

Table 14: Fishing Creek near Enfield, NC USGS NO. 02083000

Enfield			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	40682	95706	52606	33684	27594
500	0.2	33942	70887	42479	28731	24043
250	0.4	28124	52332	34092	24325	20782
200	0.5	26427	47424	31714	23014	19790
100	1.0	21646	34830	25197	19244	16878
50	2.0	17530	25463	19824	15894	14202
20	5.0	12953	16693	14149	12025	10988
10	10.0	10036	12036	10728	9458	8766
5	20.0	7493	8558	7888	7140	6686
2	50.0	4506	4987	4696	4323	4069
1.25	80.0	2887	3172	3000	2777	2624
1.111111111	90.0	2343	2578	2440	2244	2095
1.052631579	95	1996	2225	2092	1895	1737
1.01010101	99	1520	1818	1641	1400	1229

Statistic Summary	
Statistic	Value
Mean	*3.673*
Standard Deviation	*0.249*
Station Skew	*0.47*
Regional Skew	
Weighted Skew	
Adopted Skew	*0.47*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*0*
Systematic Events	*105*
Historic Period	*105*

Footnote 9 All discharges shown in this table are in cubic feet per second

Table 15: Tar River at Tarboro, NC USGS NO. 02083500

Tarboro			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	75697	128109	89833	66224	57067
500	0.2	66211	104582	76935	58825	51506
250	0.4	57553	84998	65511	51909	46161
200	0.5	54929	79424	62120	49780	44484
100	1.0	47252	64086	52395	43444	39399
50	2.0	40233	51359	43785	37500	34485
20	5.0	31838	37822	33880	30164	28199
10	10.0	26046	29603	27330	24932	23547
5	20.0	20605	22713	21407	19870	18902
2	50.0	13516	14621	13957	13089	12491
1.25	80.0	9173	9905	9469	8880	8460
1.111111111	90.0	7590	8234	7857	7313	6891
1.052631579	95	6534	7169	6804	6245	5788
1.01010101	99	5013	5779	5337	4672	4151

Statistic Summary	
Statistic	Value
Mean	*4.141*
Standard Deviation	*0.21*
Station Skew	*0.299*
Regional Skew	
Weighted Skew	
Adopted Skew	*0.299*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*5*
Systematic Events	*118*
Historic Period	*123*

Footnote 10 All discharges shown in this table are in cubic feet per second

Table 16: Conetoe Creek near Bethel, NC USGS NO. 0203800

Bethel			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	31912	407186	69313	17952	9729
500	0.2	21303	182036	41255	12993	7643
250	0.4	14198	82781	24622	9363	5964
200	0.5	12454	64516	20868	8417	5497
100	1.0	8278	30247	12519	6020	4240
50	2.0	5487	14640	7553	4273	3230
20	5.0	3168	6000	3924	2667	2188
10	10.0	2077	3258	2426	1826	1565
5	20.0	1350	1862	1518	1216	1059
2	50.0	743	918	805	689	622
1.25	80.0	527	594	552	504	472
1.111111111	90.0	477	550	505	449	411
1.052631579	95	452	544	489	415	362
1.01010101	99	430	544	482	373	278

Statistic Summary	
Statistic	Value
Mean	*2.947*
Standard Deviation	*0.28*
Station Skew	*1.736*
Regional Skew	
Weighted Skew	
Adopted Skew	*1.736*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*0*
Systematic Events	*44*
Historic Period	*44*

Footnote 11 All discharges shown in this table are in cubic feet per second

Table 17: Chicod Creek at SR1760 near Simpson, NC USGS NO. 02084160

Simpson			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	20069	131186	32429	14638	10774
500	0.2	16203	82832	24643	12243	9288
250	0.4	12961	50596	18584	10138	7919
200	0.5	12035	43193	16938	9517	7502
100	1.0	9481	26474	12614	7748	6278
50	2.0	7357	16291	9281	6203	5156
20	5.0	5097	8659	6035	4461	3820
10	10.0	3729	5426	4244	3341	2913
5	20.0	2597	3404	2872	2367	2087
2	50.0	1366	1671	1482	1258	1114
1.25	80.0	765	929	829	705	620
1.111111111	90.0	579	706	631	527	445
1.052631579	95	466	580	514	415	333
1.01010101	99	319	444	371	267	192

Statistic Summary	
Statistic	Value
Mean	*3.155*
Standard Deviation	*0.317*
Station Skew	*0.368*
Regional Skew	
Weighted Skew	
Adopted Skew	*0.368*

Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*4*
Systematic Events	*40*
Historic Period	*44*

Footnote 12 All discharges shown in this table are in cubic feet per second

Table 18: Tar River near Nashville, NC USGS NO. 02082000

Nashville			Confidence Limits			
Return Period	Percent Chance Exceedance	Computed	5%	25%	75%	95%
1000	0.1	38111	139843	53367	30736	25029
500	0.2	32716	102460	43771	27052	22479
250	0.4	27950	73486	35780	23680	20067
200	0.5	26537	65132	33504	22656	19318
100	1.0	22489	45164	27237	19651	17070
50	2.0	18908	31803	22027	16890	14932
20	5.0	14786	20596	16468	13562	12247
10	10.0	12053	15192	13071	11241	10291
5	20.0	9575	11335	10198	9034	8340
2	50.0	6489	7339	6819	6173	5728
1.25	80.0	4687	5234	4896	4489	4209
1.111111111	90.0	4049	4487	4230	3859	3549
1.052631579	95	3631	4085	3824	3424	3091
1.01010101	99	3040	3745	3318	2771	2392

Statistic Summary	
Statistic	Value
Mean	*3.832*
Standard Deviation	*0.188*
Station Skew	*0.627*
Regional Skew	
Weighted Skew	
Adopted Skew	*0.627*

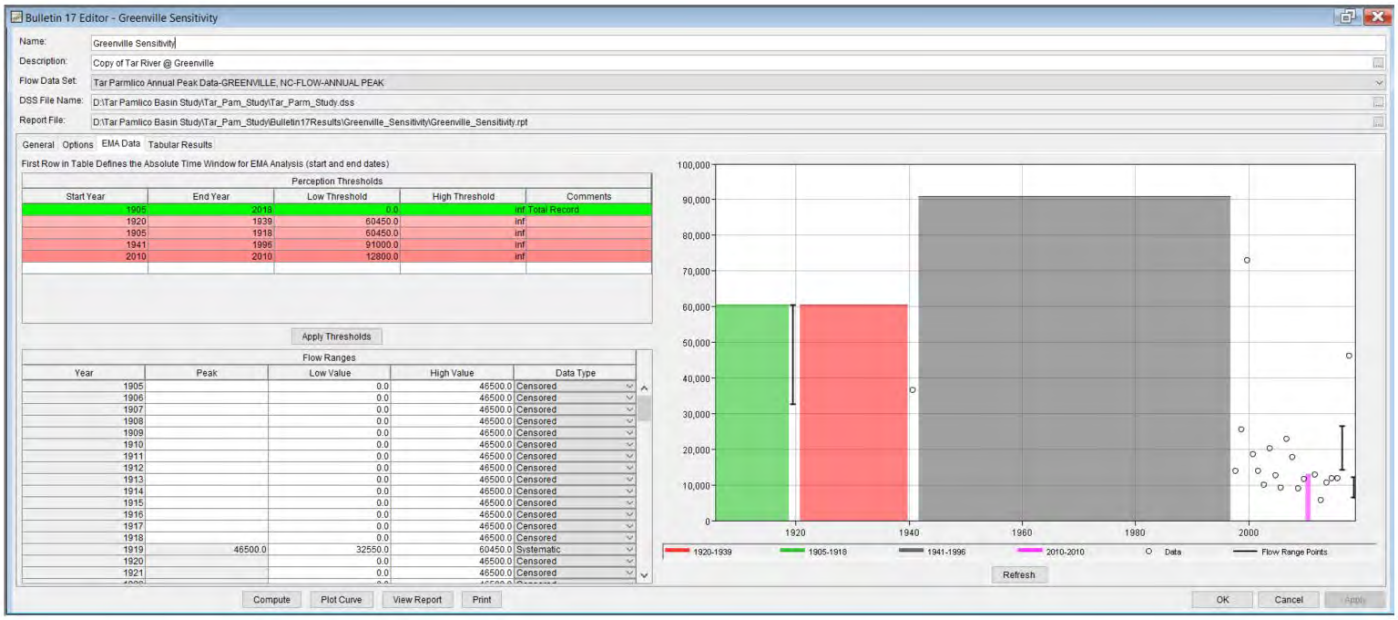
Period of Record Event Details	
Histric Events	*0*
High Outliers	
Low Outliers and Zero Flows	*0*
Missing Flows	*9*
Systematic Events	*43*
Historic Period	*52*

Footnote 13 All discharges shown in this table are in cubic feet per second

3.3 Sensitivity Analysis

A sensitivity analysis was performed on each gage using the results from the Bulletin 17C analysis. This was achieved by taking the tabular results for each gage and exporting them into excel. Located in the tabular results there are computed flows and their percent chance exceedance which is what was compared in the sensitivity analysis to predict just how sensitive the perception threshold was in the Bulletin 17C. A second Bulletin 17C analysis was ran for each gage with identical inputs except for the changes in the EMA data tab. Each perception threshold that was added to each gage was increased by 30%. An example of the EMA data tab with increased perception thresholds is shown below in Figure 7.

Figure 7: Sensitivity Analysis EMA Data with 30% Test to Threshold Entry



The computed results of this new EMA data was imported into excel. Both sets of results are represented side by side, so that the difference in percent can be found for each percent chance exceedance. Using excel the difference was calculated and converted to a percent as shown is Table 19 below. The significant cells are highlighted, and a graph was made as a visual aid to represent the difference.

Table 19: Sensitivity Analysis Results Example for Greenville, NC Gage

AEP	Computed	Lower 95%, Discharge, CFS	Upper 95%, Discharge, CFS
0.5	324	168	624
0.2	624	327	1190
0.1	859	441	1670
0.04	1180	581	2400
0.02	1460	692	3080
0.01	1770	806	3890
0.005	2050	895	4690
0.002	2490	1030	6040

Footnote 14: Green Mill Run has a total drainage area of 13.33 sq. miles at its mouth

The results from this analysis show that the smaller watersheds within the basin are the most sensitive to this change. These findings were used to inform uncertainty the flow frequency estimates using gage records throughout the study area of interest.

3.4 Ungauged Hydrologic Methods

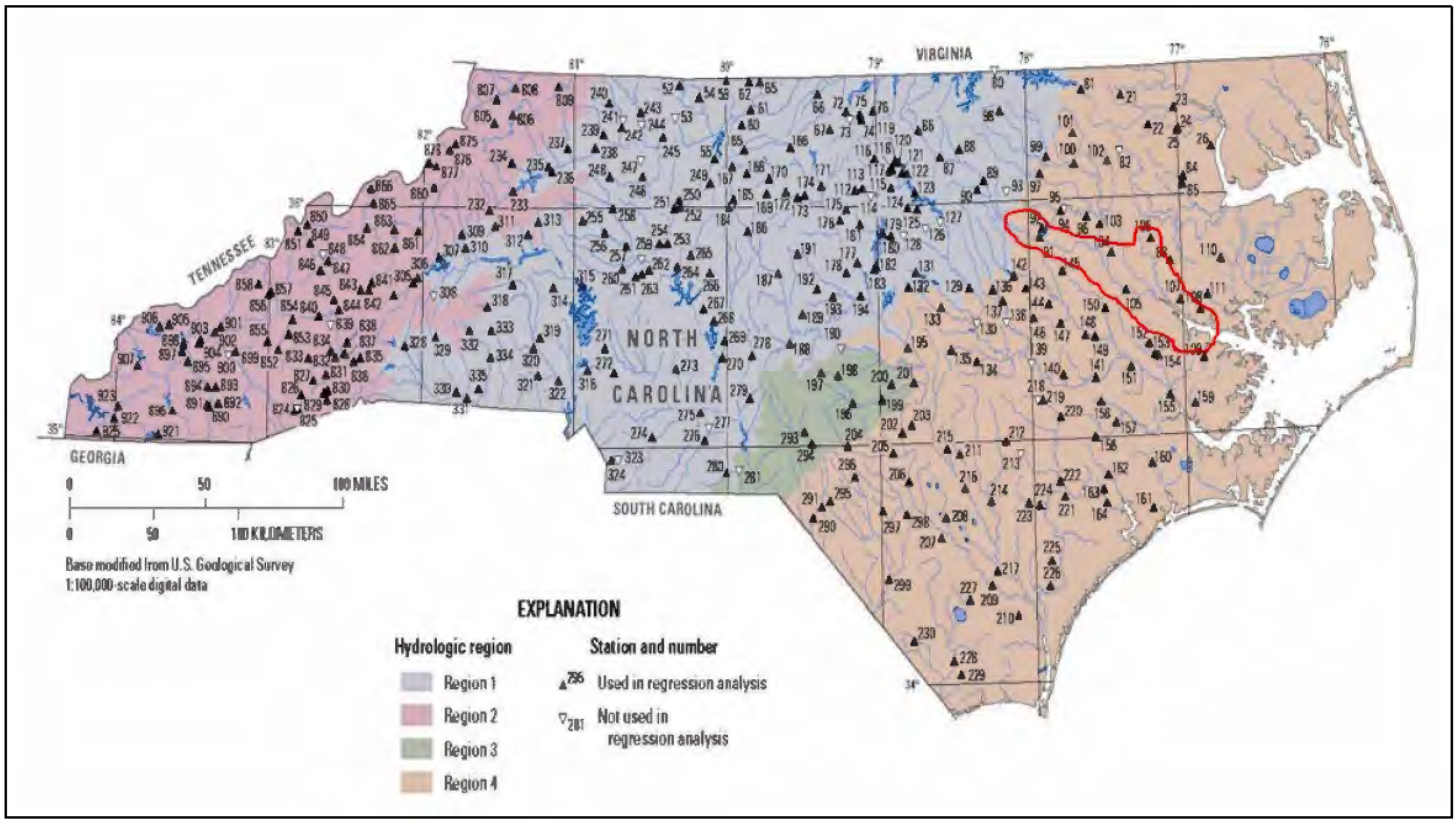
Various instances required the estimation of discharge located at an ungauged location, therefore preliminary estimates for discharge were based on the simplist approach and best available data at the time. One location in the basin requiring ungauged hydrologic methods for estimating flow frequency for the Green Mill-Run tributary (Southeast of Greenville, NC). The USGS Flood-Frequency applications tool, version 1.3 (2011) for use on streams in Georgia, South Carolina, and North Carolina was used to estimate discharges that were ungagged. The excel spreadsheet tool is designed for the purpose of computing flood-frequencies as well as prediction intervals depicting upper and lower uncertainties. The Tar Pamlico Watershed falls within the Region 4 to use the tool; this determination must be made.

Percent annual exceedance probability	Hydrologic Region (shown in fig. 2)	
	4	†5
	$0.10\ mi^2 \leq DRNAREA \leq 53.5\ mi^2$	$0.20\ mi^2 \leq DRNAREA \leq 10\ mi^2$
50	$26.3(DRNAREA)^{0.5908}10^{(0.0173*IMPNLCD06)}10^{(0.0515*I24H50Y)}$	$165(DRNAREA)^{0.537}$
20	$40.6(DRNAREA)^{0.5958}10^{(0.0125*IMPNLCD06)}10^{(0.0623*I24H50Y)}$	$265(DRNAREA)^{0.583}$
10	$51.8(DRNAREA)^{0.6004}10^{(0.0101*IMPNLCD06)}10^{(0.0666*I24H50Y)}$	$349(DRNAREA)^{0.600}$
4	$67.1(DRNAREA)^{0.6067}10^{(0.0075*IMPNLCD06)}10^{(0.0708*I24H50Y)}$	$473(DRNAREA)^{0.615}$
2	$78.4(DRNAREA)^{0.6111}10^{(0.0058*IMPNLCD06)}10^{(0.0738*I24H50Y)}$	$574(DRNAREA)^{0.624}$
1	$90.5(DRNAREA)^{0.6154}10^{(0.0043*IMPNLCD06)}10^{(0.0762*I24H50Y)}$	$684(DRNAREA)^{0.632}$
0.5	$103(DRNAREA)^{0.6201}10^{(0.0029*IMPNLCD06)}10^{(0.0785*I24H50Y)}$	$804(DRNAREA)^{0.639}$
0.2	$119(DRNAREA)^{0.6261}10^{(0.0012*IMPNLCD06)}10^{(0.0813*I24H50Y)}$	$971(DRNAREA)^{0.649}$

†From Gotvald and Knaak, 2011.

Figure 8: Equation used to estimate ungagged hydrologic locations, Project in Region 4

Figure 9: Hydrologic Region Map for Estimating ungauged flow frequency estimates.



Footnote 15: Tar Pamlico Watershed is indicated by the red boundary line.

Table 20: Discharge frequency estimate based on USGS regression for Green Mill Run Tributary

AEP	Computed	Lower 95%, Discharge, CFS	Upper 95%, Discharge, CFS
0.5	324	168	624
0.2	624	327	1190
0.1	859	441	1670
0.04	1180	581	2400
0.02	1460	692	3080
0.01	1770	806	3890
0.005	2050	895	4690
0.002	2490	1030	6040

Footnote 16: Green Mill Run has a total drainage area of 13.33 sq. miles at its mouth

4. Hydrologic Model

Hydrologic Engineering Center HEC-HMS software version 4.8 was used to perform hydrologic analysis on the basin wide scale. Specific needs during the study, specifically structurally based detention measures required the use of rainfall runoff predictions that simulate and predict hydrograph runoff timing and duration. The numerical modeling methods chosen were selected based on data availability, the physical characteristics for the watershed, develop an understanding of the hydrologic uncertainty and their ability to reach satisfactory calibration leading to defensible model predictions.

Given the nature of study, the periods of record are relatively large equating to an average of and given that discharge probability is adequately defined through gage-based statistical methods, a second cross validation to compare frequency-based rainfall runoff was pursued. The following section describe the approaches used to complete the hydrologic model analysis.

4.1 Model Formulation

The hydrologic model was created by first identifying the specific targeted events selected based upon discharge magnitude and data availability. The Wilmington District provided gridded rainfall that encompassed the watershed for four of the largest events since 2016. Hurricane Matthew was chosen as the calibration event as it was identified as a representative base event at which initial parameterization and similitude could be established.

Flood events experienced by the watershed range in peak discharge magnitude from small to extreme, however events that satisfied the requirements for consideration in calibration/validation were chosen with a basin wide calibration effort in mind. All records for the watershed were downloaded and inspected for completeness and error. Figure 9 was created to summarize the selection of calibration and validation events. The events labeled in red were considered for calibration/validation for the following reasons:

- Events had sufficient flow observations covering the study reaches.
- Hurricane Matthew was an event that caused substantial damage and life loss.
- Events chosen were the largest on record since 2016.
- Events had gridded precipitation available from the national weather service from 2016 to present as provided by the Wilmington District (USACE 2021).

The following sections describe the individual selections required to determine the methods to complete the numerical modeling.

Hurricane Matthew

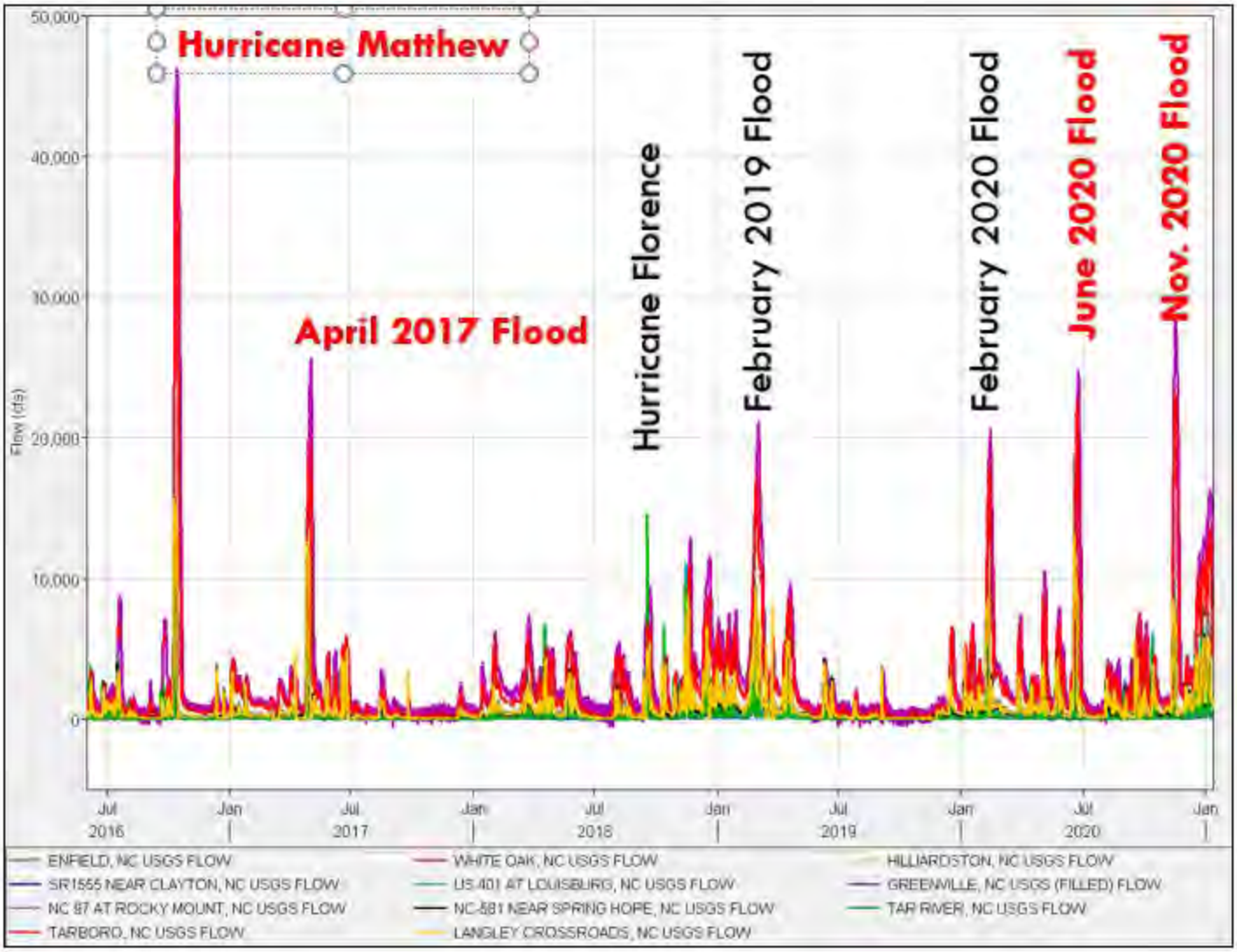
This flood event caused widespread flooding throughout the Tar Pamlico watershed. This flood event was chosen as the calibration events due to its size, coverage, and typical basin response. The Hurricane Matthew Flood event was an event that was chosen as calibration event because it was the best candidate for simulating a design storm event needed to determine measure effectiveness and flood magnitude and eventual hydraulic model calibration.

Widespread media coverage of this event produces drone footage during the flood event to best gain an understanding of the existing hydrology.

Radar Mosaic: 2016/10/08 06:30 UTC
Greenville
Raleigh
Jacksonville
Wilmington
Valdosta
Gainesville

Hurricane Matthew
September 28 - October 9, 2016
Category 1
October 8
Category 2
October 7
Category 3
October 5
Category 4
October 1
Category 5
September 30
Category 1
September 29
Richmond
Norfolk
Greensboro
Raleigh
Charlotte
South Carolina
Miami
CUBA
Port-au-Prince
Santo Domingo
San Juan
Kingston
Fort-de-France

Figure 10: Calibration and Validation Events



Footnote 17: The RED labels indicate the event was chosen for Calibration and/or Validation

4.2 Model Development

Initial parameterization was achieved through first principle hydrologic characterization. Subbasin elements, routing reaches, and baseflow predictions were achieved through direct physically based properties by using the HMS model functionality which produces explanatory variables as summarized in the following table.

Table 21: Physically based subbasin properties for initial parameterization

Full Name	Longest Flowpath	Longest Flowpath Slope	Centroidal Flowpath Length	Centroidal Flowpath Slope	10-85 Flowpath Length	10-85 Flowpath Slope	Basin Slope	Basin Relief	Relief Ratio	Elongation Ratio
(TEXT)	(MILES)	-	(MILES)	-	(MILES)	-	-	(FEET)	-	-
Subbasin-4	33.7	0.008	16.2	0.001	25.3	0.002	0.137	1455.6	0.008	0.432
Subbasin-10	45.4	0.006	19.3	0.000	34.1	0.007	0.170	1463.9	0.006	0.407
Subbasin-14	46.5	0.006	22.9	0.009	34.9	0.006	0.143	1437.4	0.006	0.380
Subbasin-17	23.9	0.010	13.6	0.001	18.0	0.001	0.286	1206.7	0.010	0.477
Subbasin-19	2.3	0.088	1.1	0.001	1.8	0.113	0.486	1090.2	0.088	0.639
Subbasin-7	35.1	0.007	21.1	0.001	26.3	0.008	0.127	1327.4	0.007	0.348
Subbasin-20	10.2	0.021	6.1	0.033	7.6	0.027	0.131	1155.8	0.021	0.557
Subbasin-21	3.2	0.064	1.3	0.151	2.4	0.003	0.386	1092.4	0.065	0.514
Subbasin-5	53.6	0.005	29.6	0.007	40.2	0.006	0.127	1403.0	0.005	0.271
Subbasin-12	45.7	0.005	21.8	0.000	34.3	0.000	0.199	1282.3	0.005	0.255
Subbasin-22	33.2	0.007	19.5	0.000	24.9	0.008	0.136	1184.8	0.007	0.331
Subbasin-1	42.1	0.006	20.7	0.010	31.5	0.007	0.208	1355.8	0.006	0.358
Subbasin-2	55.5	0.005	32.1	0.001	41.6	0.001	0.210	1417.8	0.005	0.322
Subbasin-11	9.7	0.023	5.0	0.039	7.2	0.028	0.250	1163.8	0.023	0.365
Subbasin-13	29.1	0.008	11.3	0.018	21.8	0.010	0.111	1290.7	0.008	0.371
Subbasin-3	46.1	0.003	21.1	0.005	34.6	0.001	0.027	330.4	0.001	0.324
Subbasin-15	23.8	0.009	14.1	0.000	17.8	0.011	0.255	1108.8	0.009	0.293
Subbasin-6	32.5	0.007	15.2	0.001	24.4	0.008	0.143	1122.0	0.007	0.352
Subbasin-16	20.8	0.010	10.1	0.000	15.6	0.013	0.175	1113.3	0.010	0.372
Subbasin-23	9.6	0.022	5.3	0.000	7.2	0.027	0.458	1104.2	0.022	0.313
Subbasin-18	0.4	0.435	0.2	1.116	0.3	0.577	1.918	1020.0	0.436	0.686
Subbasin-24	16.7	0.012	4.1	0.048	12.5	0.016	0.108	1091.1	0.012	0.392
Subbasin-8	39.3	0.006	20.4	0.000	29.5	0.007	0.105	1176.8	0.006	0.406
Subbasin-25	13.4	0.016	5.9	0.000	10.1	0.020	0.131	1123.6	0.016	0.460
Subbasin-26	38.7	0.005	18.2	0.000	29.0	0.000	0.098	1159.1	0.006	0.449
Subbasin-9	51.5	0.004	26.9	0.000	38.6	0.005	0.079	1097.7	0.004	0.344
Subbasin-27	44.9	0.005	14.3	0.014	33.6	0.006	0.100	1123.6	0.005	0.374
Subbasin-28	5.0	0.040	1.0	0.183	3.7	0.053	0.212	1047.1	0.040	0.421

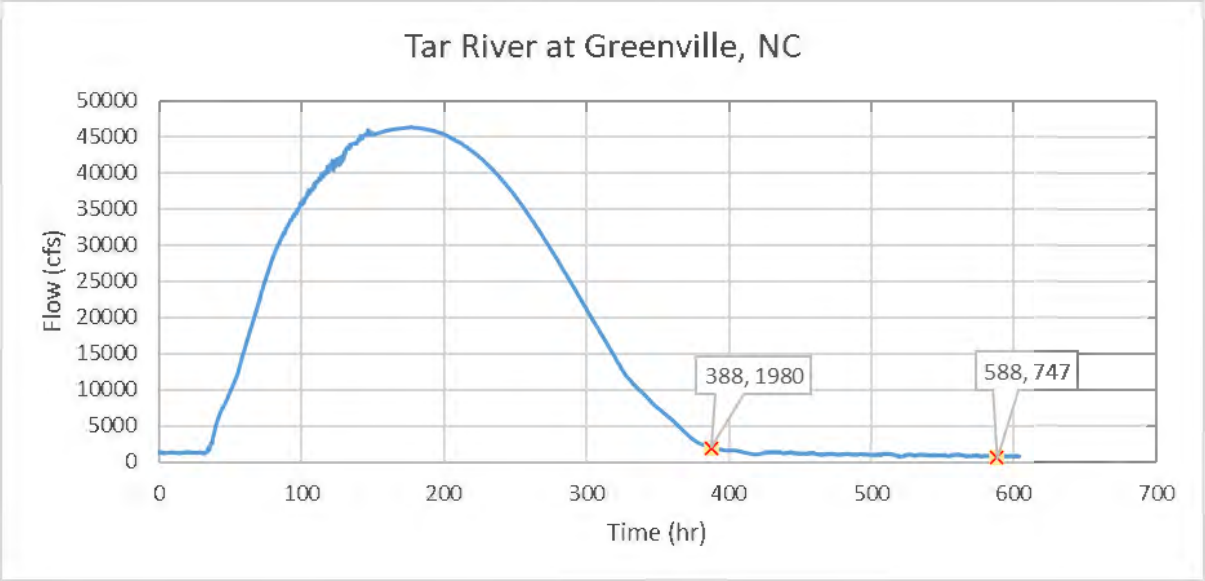
4.2.1 Baseflow Method

Recession constant and ratio to peak was chosen as the method for estimating baseflow. These baseflow parameters were computed by plotting observed hydrographs on a logarithmic scale and computing the average slope of the log form on the receding limb of the hydrographs. The resultant recession constant was then lumped using gage proximity to subbasins in the vicinity. The ratio to peak was computed as the proportion of the maximum discharge of the hydrograph divided by first inflection of the falling hydrograph limb.

Table 22: Baseflow estimate sample calculation.

T1	388	Q1	1980
T2	588	Q2	747
Recession Constant		0.89	
Ratio to Peak		0.04	

Figure 11: Graphical selections for estimating baseflow at the Greenville location



4.2.2 Loss Method and Transform

The curve number method was chosen to model rainfall loss in the basin. National land use grids as well as soil survey polygons shapefiles were used to generate a weighted average for each subbasin. For each subbasin a runoff curve grid was created then zonal statistics were used to compute average curve numbers for each subbasin.

The Modified Clark Transform method was chosen to model subbasin hydrologic response. Two methods were used to initialize time of concentration and storage coefficient. The first method uses an empirically based trend selected based on land use classification as shown in Figure 12 (Sabol, 1987 and 1993). A majority of the subbasins within the basis were determined to fall within the “Agricultural” definition for land use. The second method was referenced in the HEC-HMS user manual as shown in Figure 13.

Figure 12: Empirical equations chosen to estimate time of concentration

Agricultural

$$T_c = 7.2\, A^{.1}\, L^{.25}\, L_{ca}^{.25}\, S^{-.2}$$

Urban

$$T_c = 3.2\, A^{.1}\, L^{.25}\, L_{ca}^{.25}\, S^{-.14}\, RTIMP^{-.36}$$

where T_c = time of concentration, in hours

A = area, in square miles

S = watercourse slope, in ft/mile

L = length of the watercourse to the hydraulically most distant point, in miles

L_{ca} = length measured from the concentration point along L to a point on L that is perpendicular to the watershed centroid, in miles, and

RTIMP = effective impervious area, in percent. (Note: RTIMP must be greater than 1 percent.)

Storage Coefficient: The storage coefficient relates the effects of direct runoff storage in the watershed to unit hydrograph shape. The equation for estimating the storage coefficient (R) is:

$$R = 0.37\, T_c^{1.11}\, L^{.80}\, A^{-.57}$$

where R is in hours and the variables are as defined for the T_c equations.

Figure 13: HEC-HMS Reference Manual empirical equations for Tc and R

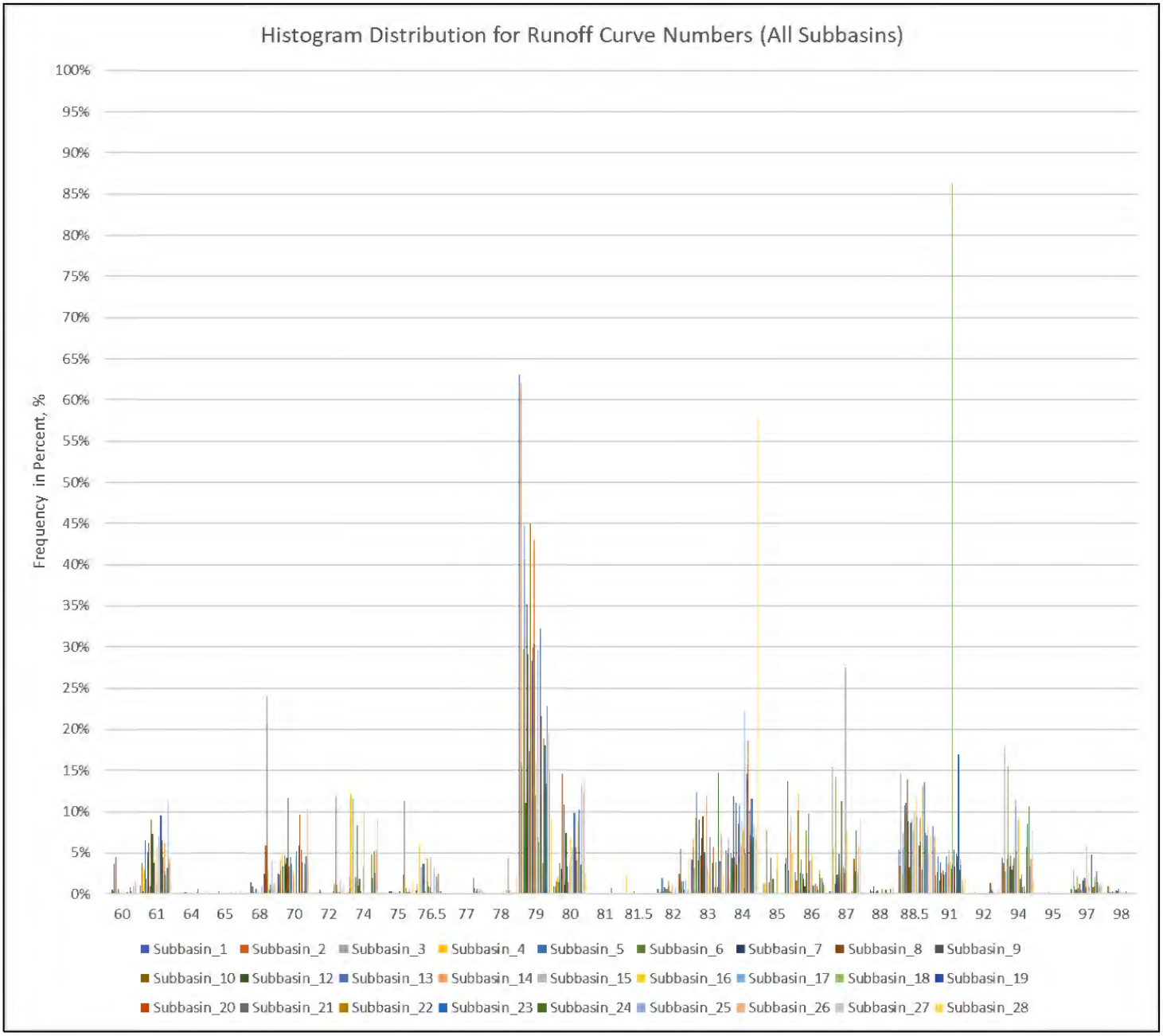
$$T_c = 2.2 * (\frac{L * L_C}{\sqrt{Slope_{10-85}}})^{0.3}$$

where T_c = time of concentration (hrs); L = longest flow path (mi); L_c = Centroidal flow path (mi); $Slope_{10-85}$ = average slope of the flow path represented by 10 to 85 percent of the longest flow path (ft/mi).

Once the time of concentration is estimated, the storage coefficient will be estimated using the following relationship from nearby watersheds:

$$\frac{R}{T_c + R} = 0.65$$

Figure 14: Cover variability by subbasin of the runoff potential



4.2.3 Routing Reach Properties

Eight-point cross sections were generated using the digital elevation model developed in HEC – RAS for the master hydraulic manual as well as the following parameters computed using the DEM in the HMS model.

Figure 15: Routing reach parameters estimated using HEC-HMS GIS features

Reach Name	Length, miles	Length, feet	Slope	Relief (FT)	Sinuosity
Reach-5	24.75169	130700	0.00018	23	2.17
Reach-9	7.48183	39500	0.00023	9	2.18
Reach-11	6.2862	33200	0.00033	11	1.26
Reach-12	1.80645	9500	0.00262	25	1.31
Reach-13	18.7902	99200	0.00038	38	1.65
Reach-14	1.87593	9900	0.00081	8	1.68
Reach-15	21.20613	112000	0.00033	37	2.00
Reach-7	41.30593	218100	0.00047	103	1.88
Reach-2	4.79077	25300	0.00036	9	1.82
Reach-6	29.98821	158300	0.00028	44	1.61
Reach-8	16.17382	85400	0.0004	34	1.60
Reach-10	0.33809	1800	0	0	1.59
Reach-4	7.19117	38000	0.00032	12	2.02
Reach-3	26.4465	139600	0.0009	125	1.52
Reach-16	17.15473	90600	0.00021	19	1.91
Reach-17	1.65538	8700	0	0	1.10
Reach-18	20.38327	107600	0.00007	7	1.23
Reach-19	7.81632	41300	0.0001	4	1.10
Reach-1	20.17913	106500	0.00002	2	1.28

4.3 Rainfall Runoff Calibration/Validation Procedure

After the initial best estimates are computed for the hydrologic model, the basin model was provided instantaneous observation discharges at known gage locations identified as having legitimate and reasonable data. Several iterations were pursued that sought to accurately produce the best model performance as described in 4.4.1 Model Evaluation Metrics section. Each computational node and subsequent parameter i.e. runoff curve numbers, time of concentration/storage coefficient, reach routing variables within the basin were adjusted to achieve satisfactory model performance while simultaneously falling within acceptable ranges of physical bounds of reality.

The following sections describes the targeted calibration/validation performance metrics used to determine model performance.

4.4 Calibration and Validation

4.4.1 Model Evaluation Metrics

A “weight-of-evidence approach, where both statistical tests and graphical comparisons were employed, were used for evaluating model performance. The following statistical methods describe the nature of explanatory metrics as well as performance rankings used to evaluate the model calibration and validation.

4.4.1.1 Coefficient of Determination (R^2)

The coefficient of determination (R^2) describes the degree of collinearity between simulated (prediction/model) and observed data. R^2 describes the proportion of the variance in measured data explained by the model prediction. R^2 is oversensitive to outliers and insensitive to additive

proportional differences between model predictions and measured data. It is properly demonstrated in equation form by the following:

Equation 1: Coefficient of Determination (R^2)

$$R^2 = \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - \bar{Y}^{obs})(Y_i^{sim} - \bar{Y}^{sim})}{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - \bar{Y}^{obs})^2} \sqrt{\sum_{i=1}^{n} (Y_i^{sim} - \bar{Y}^{sim})^2}} \right]^2$$

Where Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith simulated value for the constituent being evaluated, Y_i^{obs} is the mean of observed data for the constituent being evaluated, Y_i^{sim} is the mean of simulated data for the constituent being evaluated, and n is the total number of observations. It is the square of the Pearson correlation coefficient between the simulated and observed data.

4.4.1.2 Nash Sutcliffe Efficiency (NSE)

The Nash Sutcliffe Efficiency (NSE) measures the relative magnitude of the residual variance compared to the measured data variance. NSE ranges between negative infinity and 1.0 (1 inclusive), where NSE = 1 is optimal. Values of NSE less than or equal to 0.0 indicate the mean observed value is a better predictor than the simulated value, meaning that the performance is acceptable. Nash Sutcliffe Efficiency is computed by the following equation:

Equation 2: Nash Sutcliffe Efficiency

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^{n} (Y_i^{obs} - \bar{Y}^{obs})^2} \right]$$

4.4.1.3 Root Mean Square Error (RMSE) – Observed Standard Deviation Ratio (RSR)

The root mean square error (RMSE) is valuable because it indicates the error in the units of the constituent of interest, where the lower the RMSE the better the model performance. The RMSE-Observed Standard Deviation Ratio (RSR) normalizes the root mean square error by using the standard devaiation of the observations, incorporating the benefits of error index statistics so that the resulting statistic can be applied to various constituents. RSR is computed by the following equation:

Equation 3: Observed Standard Deviation Ratio (RSR)

$$RSR = \frac{RSME}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - \bar{Y}^{obs})^2} \right]}$$

4.4.1.4 Percent Bias (PBIAS)

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than the observed data. The optimal value for PBIAS is 0.0, with low absolute percent bias indicating accurate model simulation. Positive values mean the model underestimates bias when compared to the observed, whereas negative values indicate the model overestimation bias. PBIAS was computed for peak inflows and cumulative inflows. Percent Bias (PBIAS) is computed by the following equation:

Equation 4: Percent Bias (PBIAS)

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim}) \times 100}{\sum_{i=1}^{n}(Y_i^{obs})}\right]$$

4.4.1.4 Performance Rating for Model Evaluation Metrics

Model performance statistics were evaluated on an hourly time step for the model calibration and validation. For the purposes of accessing model performance, hourly performance statistics are evaluated using the performance ratings as shown in Table 23. The selected performance ratings shown below, and the are consistent with standard industry best practices.

Table 23: Performance Ratings for Hydrologic Model Calibration/Validation

Performance Rating	R^2	NSE	RSR	PBIAS
Very Good	$0.65 < R^2 \leq 1.00$	$0.65 < NSE \leq 1.00$	$0.00 < RSR \leq 0.60$	$PBIAS < \pm 15$
Good	$0.55 < R^2 \leq 0.65$	$0.55 < NSE \leq 0.65$	$0.60 < RSR \leq 0.70$	$\pm 15 \leq PBIAS < \pm 20$
Satisfactory	$0.40 < R^2 \leq 0.55$	$0.40 < NSE \leq 0.55$	$0.70 < RSR \leq 0.80$	$\pm 20 \leq PBIAS < \pm 30$
Unsatisfactory	$R^2 \leq 0.40$	$NSE \leq 0.40$	$RSR > 0.80$	$PBIAS \geq \pm 30$

4.4.2 Model Calibration Results

Table 24: Hurricane Matthew Rainfall Runoff Calibration Results

Calibration: Hurricane Matthew	R^2	NSE	RSR	PBIAS-V	PBIAS-P
Tar River, USGS 02081500	0.99	0.95	0.23	-13.46	-17.57
Louisburg, USGS 02081747	0.95	0.91	0.30	-27.50	-7.13
Spring Hope, USGS 02081942	0.90	0.89	0.33	-13.54	7.74
Tar Reservoir BL, USGS 02082506	0.82	0.81	0.43	-9.79	11.42
Rocky Mount, USGS 02082585	0.91	0.91	0.30	-3.49	-12.87
Hilliardston, USGS 02082770	0.95	0.94	0.24	0.75	24.13
White Oak, USGS 02082950	0.97	0.97	0.17	1.25	8.21
Enfield, USGS 02083000	0.96	0.96	0.21	-1.74	16.23
Tarboro, USGS 02083500	0.96	0.96	0.21	-1.74	16.23
Greenville, USGS 02084000	0.96	0.95	0.22	-6.07	0.44

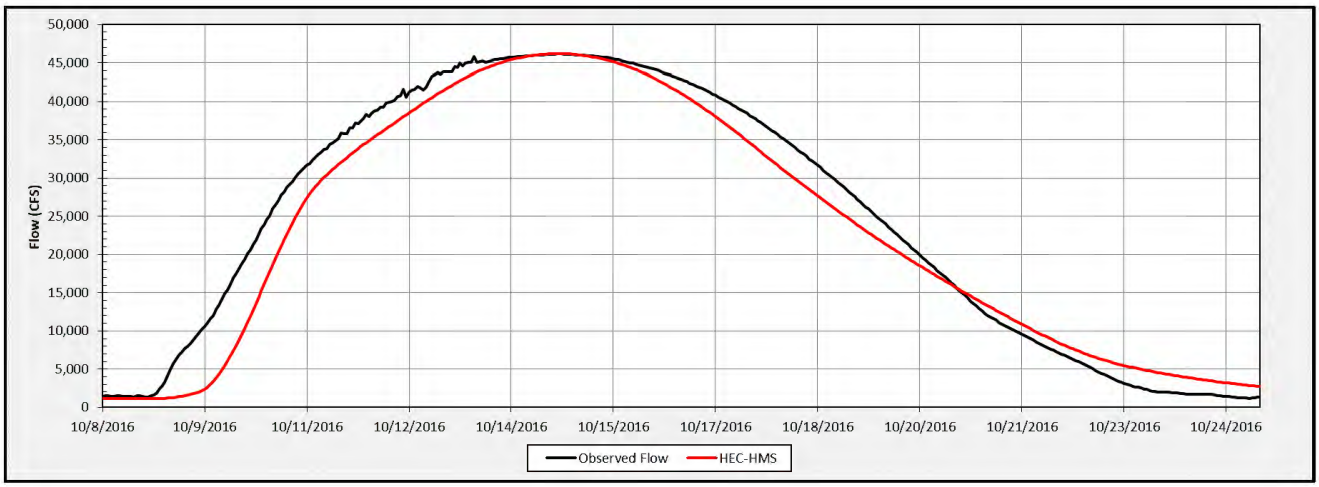


Figure 16: Hurricane Matthew Calibration Results Greenville, NC

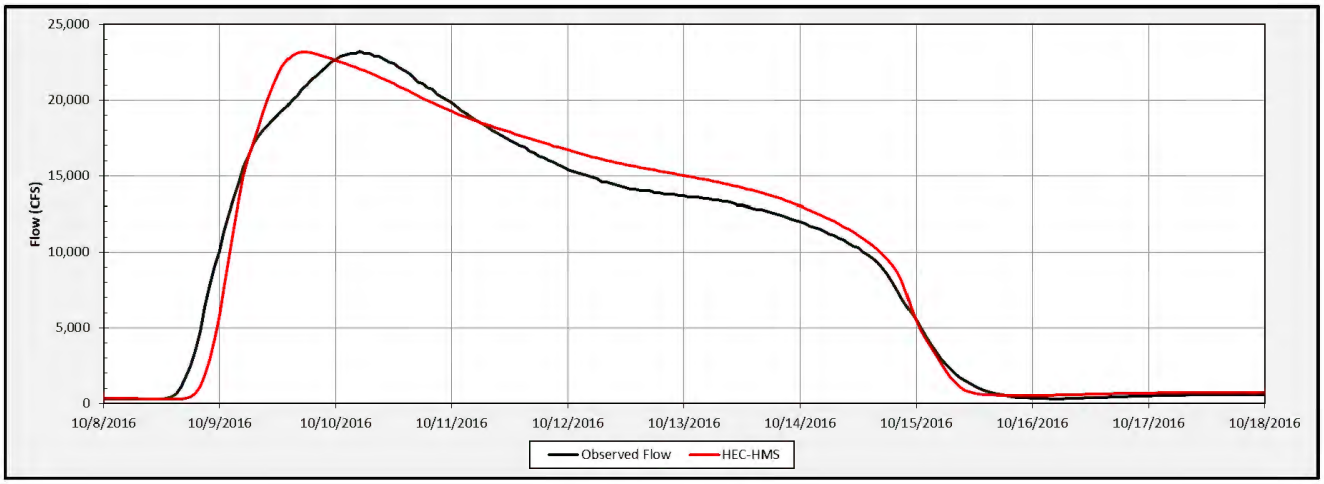


Figure 17: Hurricane Matthew Calibration Results Rocky Mount, NC

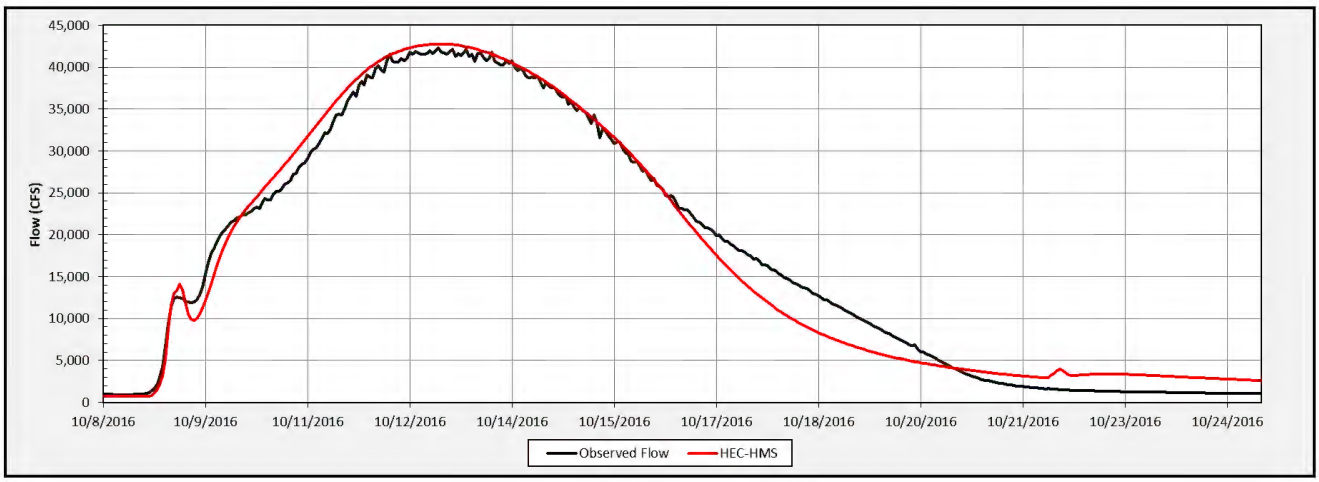


Figure 18: Hurricane Matthew Calibration Results for Tarboro, NC

4.4.3 Model Validation Results

Table 25: Model Validation Overall Performance (November 2020, April 2017, June 2020)

Average Validation Performance	R^2	NSE	RSR	PBIAS-V	PBIAS-P
Tar River, USGS 02081500	0.91	0.25	0.67	40.01	29.36
Louisburg, USGS 02081747	0.88	0.78	0.47	-17.25	7.90
Spring Hope, USGS 02081942	0.83	0.58	0.64	-6.90	57.28
Tar Reservoir BL, USGS 02082506	0.76	0.64	0.60	-15.63	23.98
Rocky Mount, USGS 02082585	0.87	0.75	0.50	-11.41	-3.45
Hilliardston, USGS 02082770	0.80	0.65	0.57	-17.52	26.55
White Oak, USGS 02082950	0.83	0.38	0.76	34.30	66.47
Enfield, USGS 02083000	0.83	0.80	0.44	-6.30	-2.80
Tarboro, USGS 02083500	0.94	0.80	0.43	2.61	19.56
Greenville, USGS 02084000	0.94	0.88	0.33	3.54	9.57

Table 26: Model Validation Results; November 2020 Event

November 2020: Validation	R^2	NSE	RSR	PBIAS-V	PBIAS-P
Tar River, USGS 02081500	0.98	0.97	0.18	-8.70	-3.39
Louisburg, USGS 02081747	0.91	0.75	0.50	-46.51	-15.82
Spring Hope, USGS 02081942	0.85	0.70	0.55	-41.67	4.29
Tar Reservoir BL, USGS 02082506	0.73	0.58	0.65	-42.96	-12.10
Rocky Mount, USGS 02082585	0.92	0.70	0.55	-38.84	-38.05
Hilliardston, USGS 02082770	0.87	0.81	0.44	-30.17	-8.82
White Oak, USGS 02082950	0.89	0.80	0.45	9.44	39.70
Enfield, USGS 02083000	0.89	0.86	0.38	-22.60	-7.35
Tarboro, USGS 02083500	0.97	0.90	0.31	-18.87	-17.18
Greenville, USGS 02084000	0.98	0.96	0.20	-9.44	-7.39

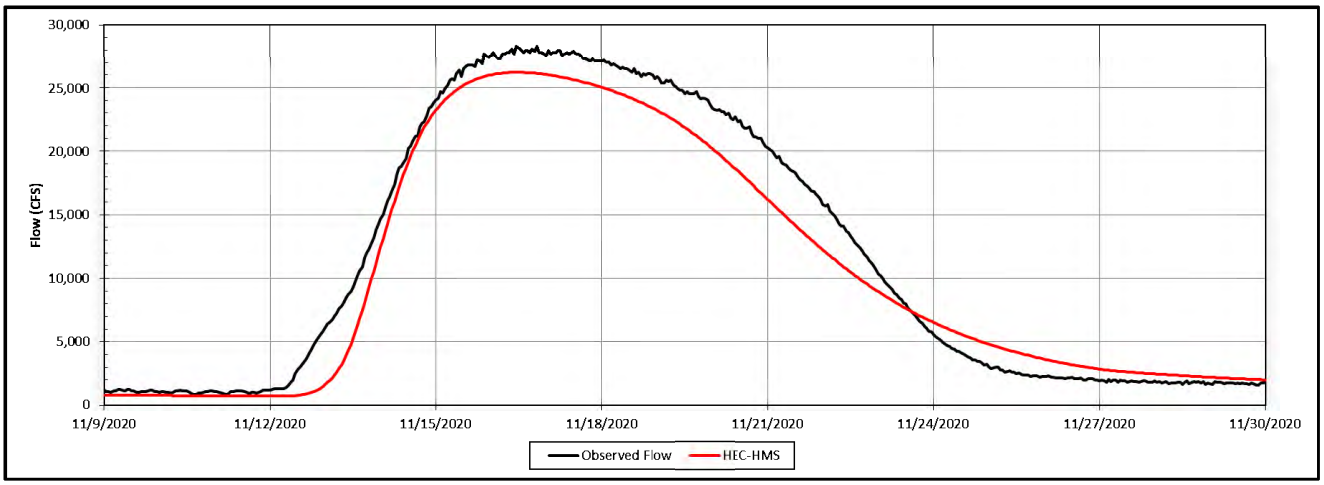


Figure 19: November 2020 Validation Event for Tar Mainstem near Greenville, NC

Table 27: Model Validation Results; April 2017 Event

April 2017: Validation	R^2	NSE	RSR	PBIAS-V	PBIAS-P
Tar River, USGS 02081500	0.86	0.86	0.38	-18.18	-0.65
Louisburg, USGS 02081747	0.82	0.77	0.48	-28.78	7.54
Spring Hope, USGS 02081942	0.83	0.60	0.64	-10.83	66.10
Tar Reservoir BL, USGS 02082506	0.79	0.71	0.54	-19.36	45.02
Rocky Mount, USGS 02082585	0.86	0.76	0.49	-15.16	28.10
Hilliardston, USGS 02082770	0.69	0.40	0.78	-7.22	60.36
White Oak, USGS 02082950	0.86	0.26	0.86	24.72	99.88
Enfield, USGS 02083000	0.84	0.80	0.45	-11.41	22.80
Tarboro, USGS 02083500	0.91	0.66	0.59	0.91	54.06
Greenville, USGS 02084000	0.94	0.86	0.37	-2.15	20.75

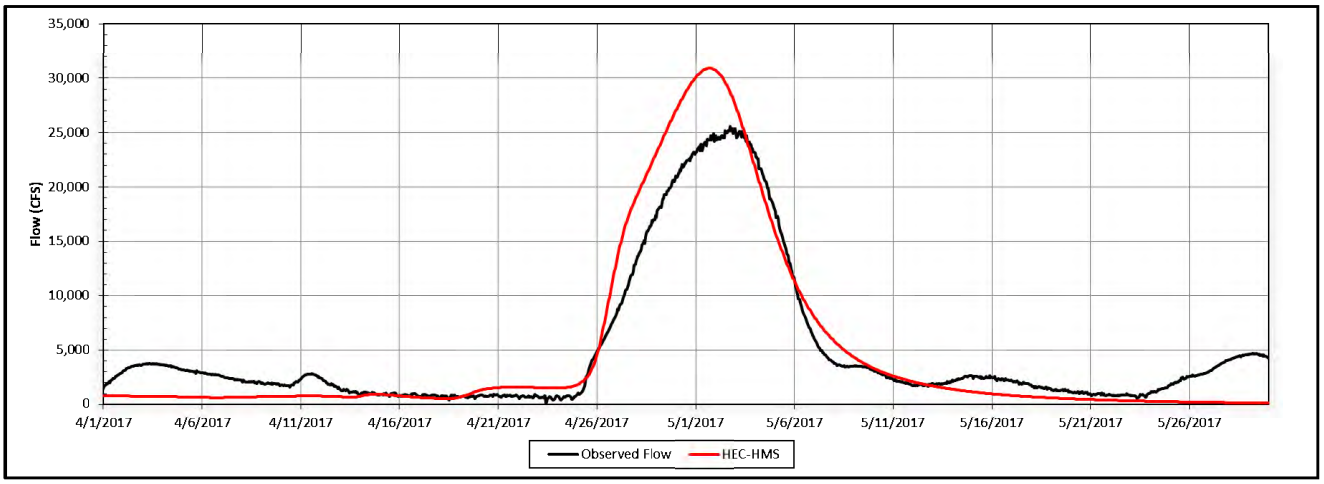
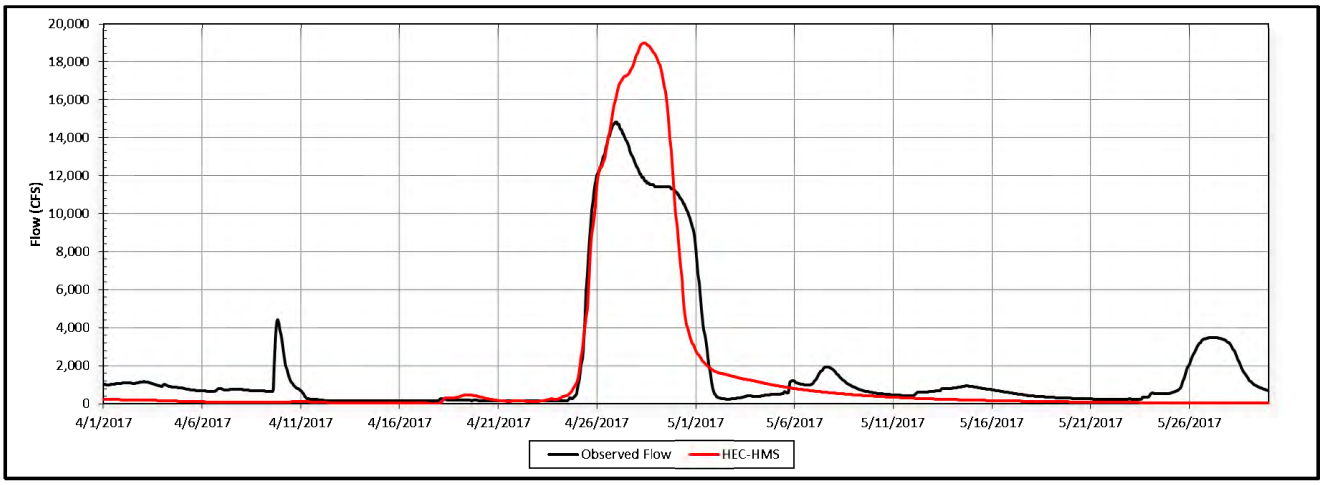


Figure 20: April 2017 Validation Event for Greenville, NC



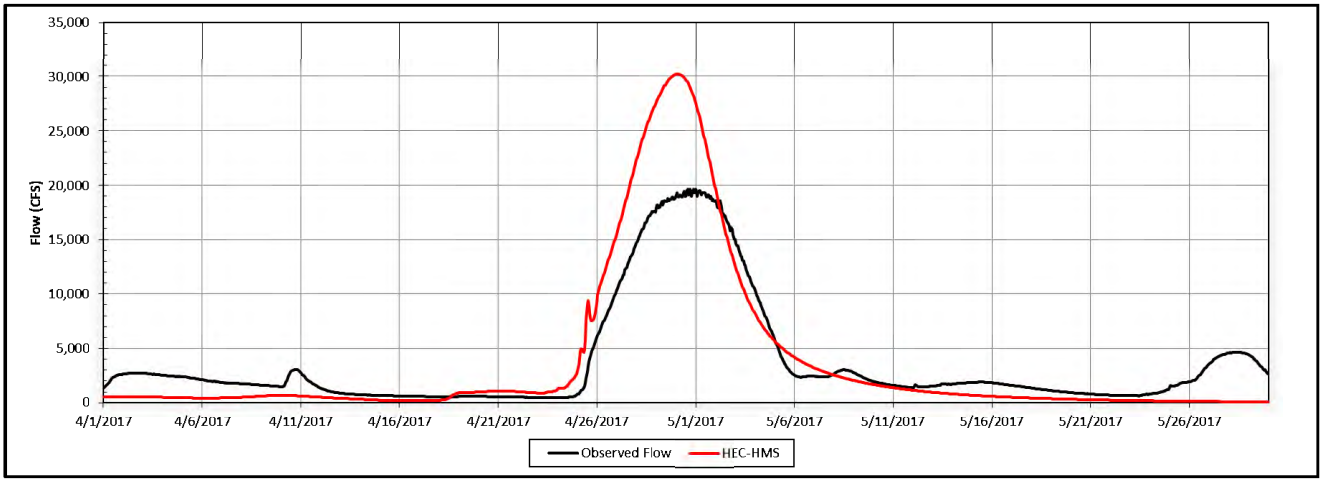


Figure 21: April 2017 Validation Event for Tarboro, NC

Table 28: Model Validation Results; June 2020 Event

June 2020: Validation	R^2	NSE	RSR	PBIAS-V	PBIAS-P
Tar River, USGS 02081500	0.88	-1.07	1.44	146.90	92.11
Louisburg, USGS 02081747	0.90	0.82	0.42	23.54	31.99
Spring Hope, USGS 02081942	0.80	0.46	0.73	31.81	101.44
Tar Reservoir BL, USGS 02082506	0.75	0.64	0.60	15.42	39.02
Rocky Mount, USGS 02082585	0.82	0.78	0.47	19.77	-0.38
Hilliardston, USGS 02082770	0.86	0.76	0.49	-15.16	28.10
White Oak, USGS 02082950	0.73	0.09	0.95	68.74	59.81
Enfield, USGS 02083000	0.75	0.75	0.50	15.11	-23.84
Tarboro, USGS 02083500	0.93	0.84	0.39	25.77	21.80
Greenville, USGS 02084000	0.91	0.82	0.43	22.21	15.37

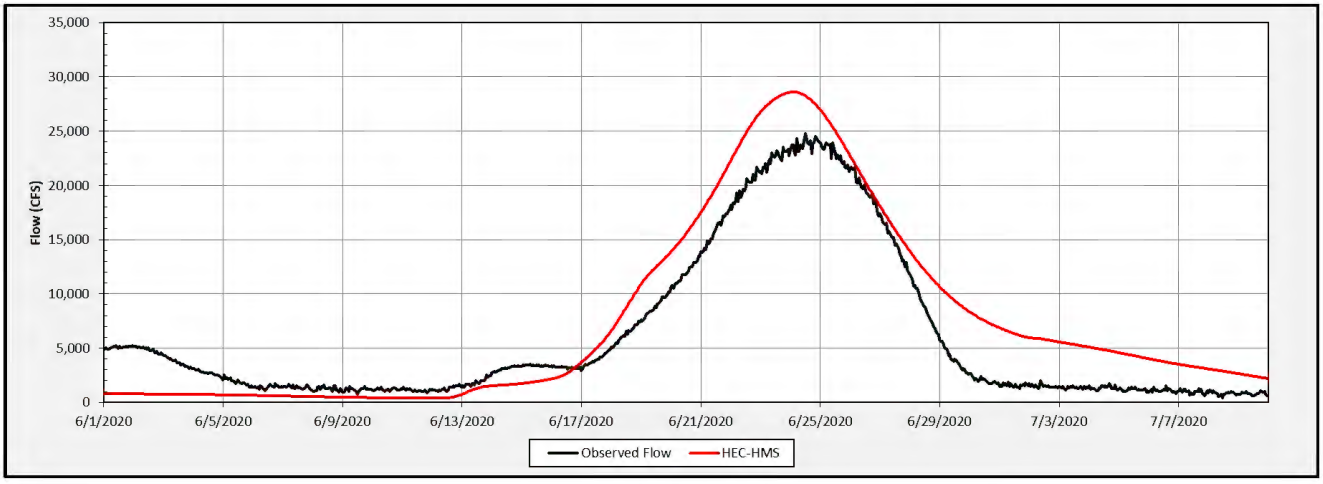


Figure 22: June 2020 Validation Event for Greenville, NC

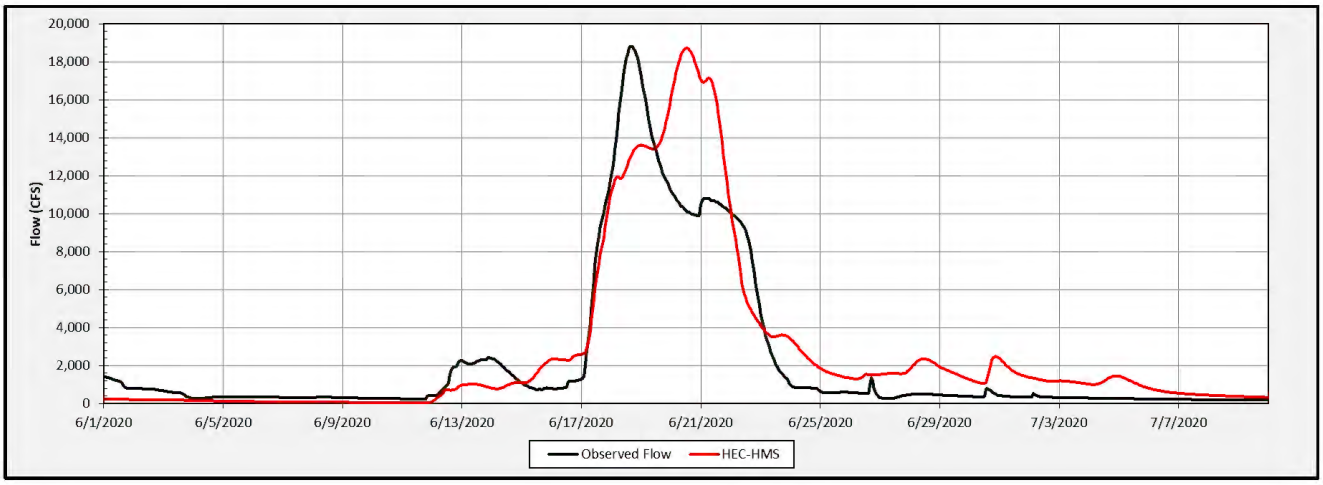


Figure 23: June 2020 Validation Event for Rocky Mount, NC

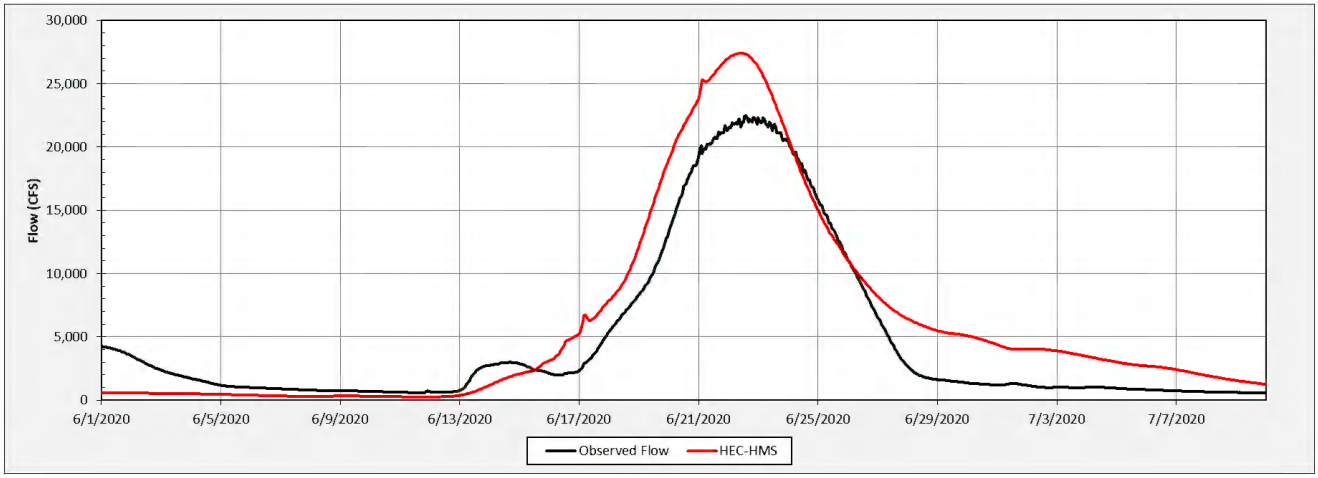


Figure 24: June 2020 Validation Event for Tarboro, NC

The validation results were conservative regarding peak discharges, due to the antecedent conditions present prior to storm events such as Hurricane Matthew and April 2017 events. These events received precipitation that saturated the hydrologic soils present. Given this assumption conservative validation results are consistent for use in determining potential flood damage reduction benefits.

4.5 Calibrated Hydrologic Parameter Sets

4.5.1 Calibrated Loss and Transform Parameters

Table 29: Calibrated Loss and Transform Parameters based on Hurricane Matthew Event

Subbasin	Area (sq.miles)	Curve Number	% Impervious	Time of Concentration (hr)	Storage Coefficient (hr)
Subbasin-4	166.69	79	0.89	20.0	12.5
Subbasin-10	267.83	65	0.47	20.0	20.0
Subbasin-14	245.28	62	0.00	30.0	25.0
Subbasin-17	102.37	62	0.21	20.0	80.0
Subbasin-19	1.7652	62	0.36	4.1	7.6
Subbasin-7	117.31	74	0.29	17.1	31.7
Subbasin-20	25.312	75	0.09	6.8	12.6
Subbasin-21	2.1302	77	0.00	7.9	14.7
Subbasin-5	165.41	70	0.22	20.0	35.0
Subbasin-12	106.5	82	0.36	55.5	102.9
Subbasin-22	94.373	83	0.25	31.5	58.5
Subbasin-1	177.89	83	0.11	37.5	21.8
Subbasin-2	250.64	50	0.07	61.2	113.6
Subbasin-11	9.7732	75	0.10	12.0	22.3
Subbasin-13	91.497	98	0.61	20.2	37.7
Subbasin-3	175.87	85	0.98	53.6	99.5
Subbasin-15	38.201	85	0.20	12.6	12.6
Subbasin-6	103.32	84	0.24	16.2	20.0
Subbasin-16	46.836	82	0.14	10.7	10.7
Subbasin-23	7.0521	68	0.09	3.0	3.0
Subbasin-18	0.0725	90	0.00	1.1	1.1
Subbasin-24	33.516	67	0.12	3.0	3.0
Subbasin-8	199.94	88	0.19	34.4	63.8
Subbasin-25	29.942	89	0.06	14.6	27.1
Subbasin-26	237.09	88	0.12	51.9	96.3
Subbasin-9	247.29	75	0.07	51.0	94.6
Subbasin-27	220.68	78	0.12	39.6	73.4
Subbasin-28	3.4291	83	0.00	6.7	12.5

4.5.2 Adopted Baseflow Parameters

Table 30: Adopted Baseflow Parameters

Full Name	Baseflow Recession Constant	Baseflow Ratio to Peak	Associated Baseflow Gage Site
(TEXT)	(UNITLESS)	(UNITLESS)	(TEXT)
Subbasin-4	0.77	0.04	Tar River
Subbasin-10	0.82	0.06	Louisburg
Subbasin-14	0.87	0.06	Spring Hope
Subbasin-17	0.87	0.06	Spring Hope
Subbasin-19	0.87	0.06	Spring Hope
Subbasin-7	0.81	0.05	Hilliardston
Subbasin-20	0.87	0.06	Spring Hope
Subbasin-21	0.87	0.06	Spring Hope
Subbasin-5	0.81	0.05	Hilliardston
Subbasin-12	0.81	0.05	Hilliardston
Subbasin-22	0.87	0.06	Spring Hope
Subbasin-1	0.79	0.03	WhiteOak
Subbasin-2	0.79	0.03	WhiteOak
Subbasin-11	0.79	0.03	WhiteOak
Subbasin-13	0.88	0.04	Enfield
Subbasin-3	0.88	0.04	Enfield
Subbasin-15	0.88	0.04	Enfield
Subbasin-6	0.88	0.04	Enfield
Subbasin-16	0.88	0.04	Enfield
Subbasin-23	0.88	0.04	Enfield
Subbasin-18	0.88	0.05	Tarboro
Subbasin-24	0.88	0.05	Tarboro
Subbasin-8	0.88	0.05	Tarboro
Subbasin-25	0.88	0.05	Tarboro
Subbasin-26	0.89	0.04	Greenville
Subbasin-9	0.89	0.04	Greenville
Subbasin-27	0.89	0.04	Greenville
Subbasin-28	0.89	0.04	Greenville

4.5.3 Calibrated Routing Method Parameters

Table 31: Calibrated Routing Reach Parameters (1 of 2)

Reach	Routing Method	Lag Time (mins)	Lag Time (hours)	K Constant (hours)	Length (ft)	Slope (FT/FT)	Manning's (CH)
Reach-5	Lag Time	1550	N/A		N/A	N/A	N/A
Reach-9	Lag Time	2200	N/A		N/A	N/A	N/A
Reach-15	Lag & K	N/A	8	28	N/A	N/A	N/A
Reach-7	Lag & K	N/A	14	49	N/A	N/A	N/A
Reach-2	Lag & K	N/A	2	7	N/A	N/A	N/A
Reach-10	Lag & K	N/A	7	24.5	N/A	N/A	N/A
Reach-4	Lag & K	N/A	6	21	N/A	N/A	N/A
Reach-3	Lag & K	N/A	0	0	N/A	N/A	N/A
Reach-16	Lag & K	N/A	3	10.5	N/A	N/A	N/A
Reach-17	Lag & K	N/A	3.58	12.77	N/A	N/A	N/A
Reach-18	Lag & K	N/A	9.05	28.68	N/A	N/A	N/A
Reach-19	Lag & K	N/A	9	30.2	N/A	N/A	N/A
Reach-1	Lag & K	N/A	0.7	2.2	N/A	N/A	N/A
Reach-11	Muskingum-Cunge	N/A	N/A	N/A	33200	0.00036	0.035
Reach-12	Muskingum-Cunge	N/A	N/A	N/A	9500	0.00066	0.04
Reach-13	Muskingum-Cunge	N/A	N/A	N/A	99200	0.00026	0.04
Reach-14	Muskingum-Cunge	N/A	N/A	N/A	9500	0.00256	0.06
Reach-6	Muskingum-Cunge	N/A	N/A	N/A	158300	0.00043	0.04
Reach-8	Muskingum-Cunge	N/A	N/A	N/A	85400	0.00037	0.045

Table 32: Calibrated Routing Reach Parameters (2 of 2)

Reach	Routing Method	Space-Time Method	Subreaches	Index Flow (CFS)	Manning's LT	Manning's RT	Shape
Reach-5	Lag Time	N/A	N/A	N/A	N/A	N/A	N/A
Reach-9	Lag Time	N/A	N/A	N/A	N/A	N/A	N/A
Reach-15	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-7	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-2	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-10	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-4	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-3	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-16	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-17	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-18	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-19	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-1	Lag & K	N/A	N/A	N/A	N/A	N/A	N/A
Reach-11	Muskingum-Cunge	Auto DX Auto DT		8680	0.06	0.06	Eight Point
Reach-12	Muskingum-Cunge	Auto DX Auto DT		11207	0.1	0.1	Eight Point
Reach-13	Muskingum-Cunge	Specified DX Auto DT	3	11321	0.1	0.1	Eight Point
Reach-14	Muskingum-Cunge	Specified DX Auto DT	3	13067	0.08	0.08	Eight Point
Reach-6	Muskingum-Cunge	Specified DX Auto DT	8	2907	0.1	0.1	Eight Point
Reach-8	Muskingum-Cunge	Specified DX Auto DT	8	4674	0.08	0.08	Eight Point

4.6 Recommended Synthetic Events for Hydrograph Needs

The Hydrologic parameters developed in calibration and validation procedure are used to inform the hydrologic model for defining the synthetic frequency-based events used to simulate the conditions present for flow hydrographs. Various instances require the study need to evaluate hydrograph storage and the timing of excess rainfall in a large size basin such as the Tar/Pamlico Sound. Synthetic Frequency Storm was used in HEC HMS to simulate flow hydrographs. These results are necessary for any time dependent measure requiring an estimate of storage reduction potential.

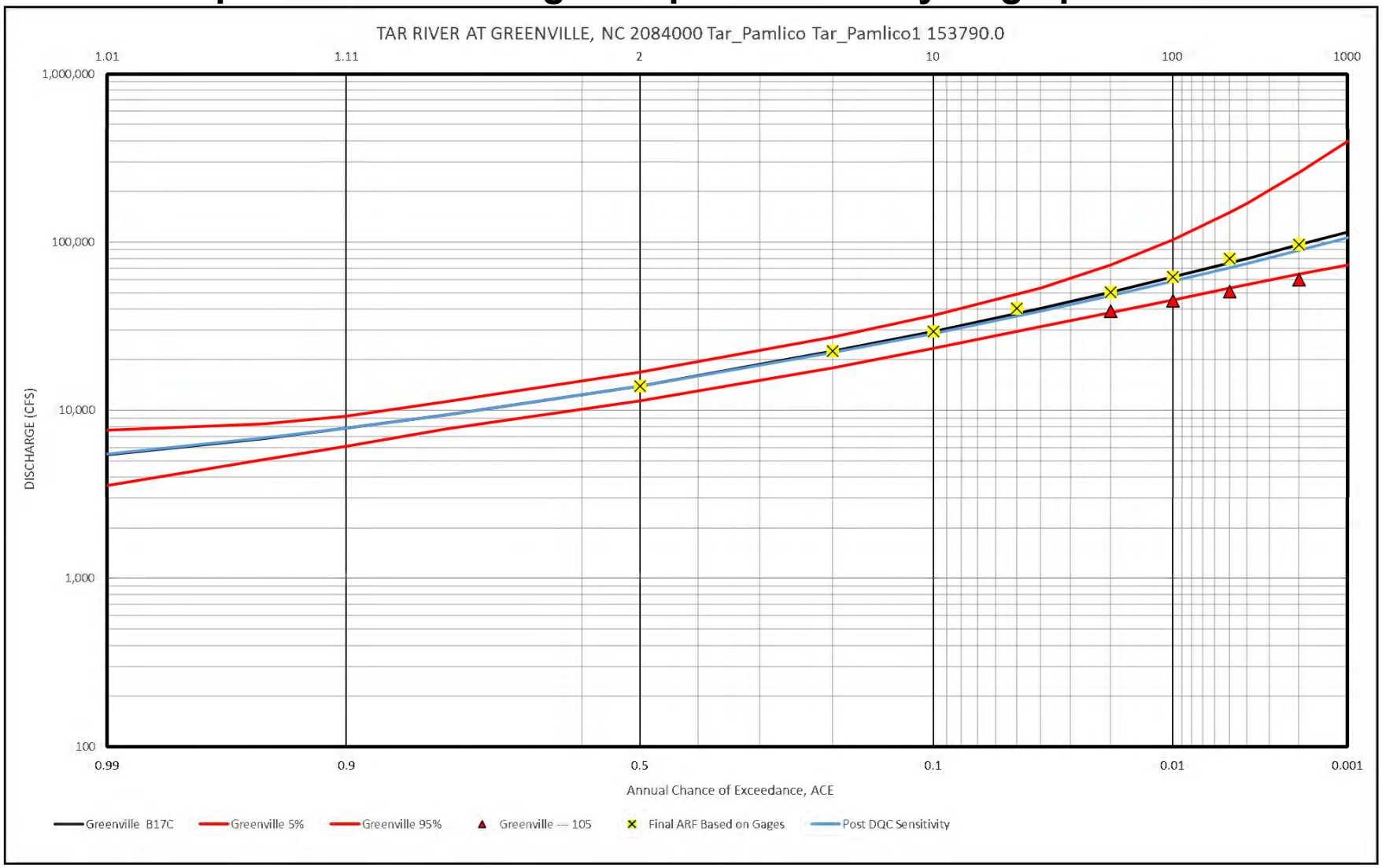
4.6.1 Hypothetical Rainfall

Frequency based depth-duration rainfall depths were provided to the frequency storm meteorological model to simulate excess rainfall using the simulation runs for each of the frequencies necessary for study. Extraction detail regarding rainfall depths used in the study can be found in Table 33.

Table 33: Pertinent Rainfall Frequency Depth Details

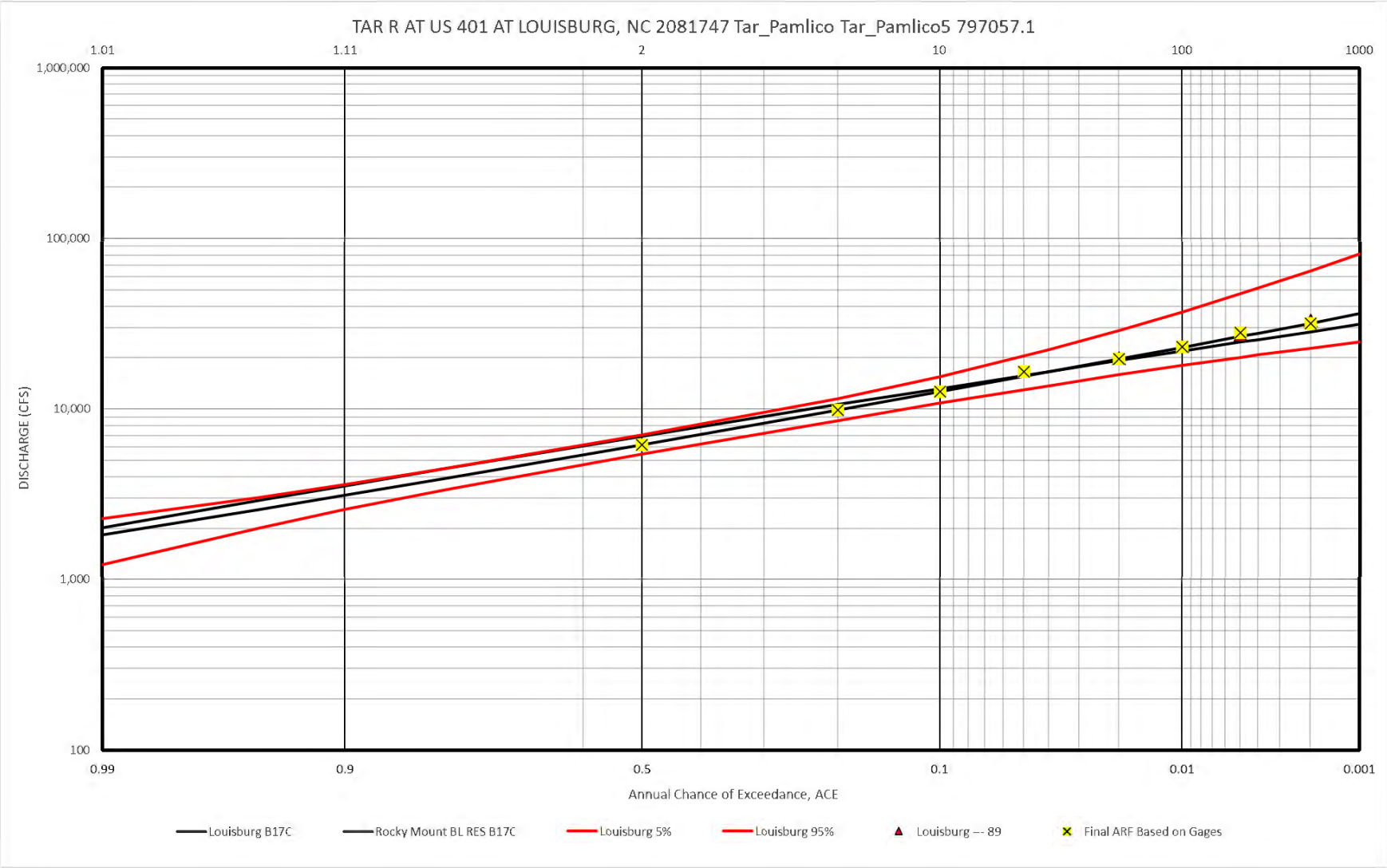
Data Source Name:	Point precipitation frequency estimates (inches)
Data Source Region/Version:	NOAA Atlas 14 Volume 2 Version 3
Data Type:	Precipitation depth
Data Format:	Annual maximum
Location Name (ESRI Maps):	Battleboro, North Carolina
Accessed:	15-Oct-21
Latitude:	36.0320°
Longitude:	-77.8613°
Elevation (USGS):	Elevation (USGS): 188.44 ft

4.7 Adopted Peak Discharge Frequencies for Hydrograph Estimates



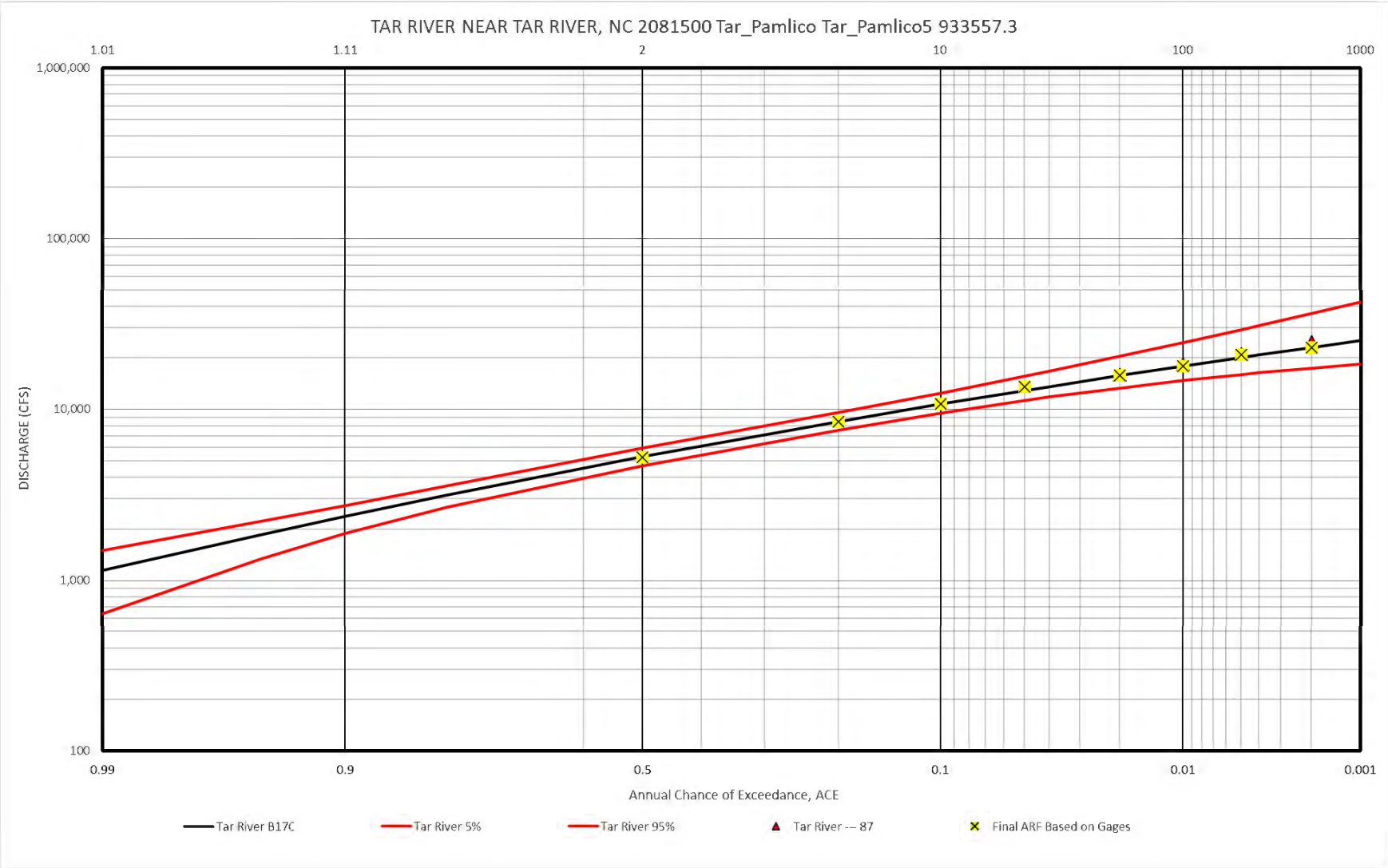
Footnote 18* Red triangles were taken from FEMA FIS Study

Figure 25: Peak Flow Frequency Results for Greenville, NC of the Tar River



Footnote 19* Red triangles were taken from FEMA FIS Study

Figure 26: Peak Flow Frequency Results for Louisburg, NC of the Tar River



Footnote 20* Red triangles were taken from FEMA FIS Study

Figure 27: Peak Flow Frequency Results for most upstream Tar River USGS gage

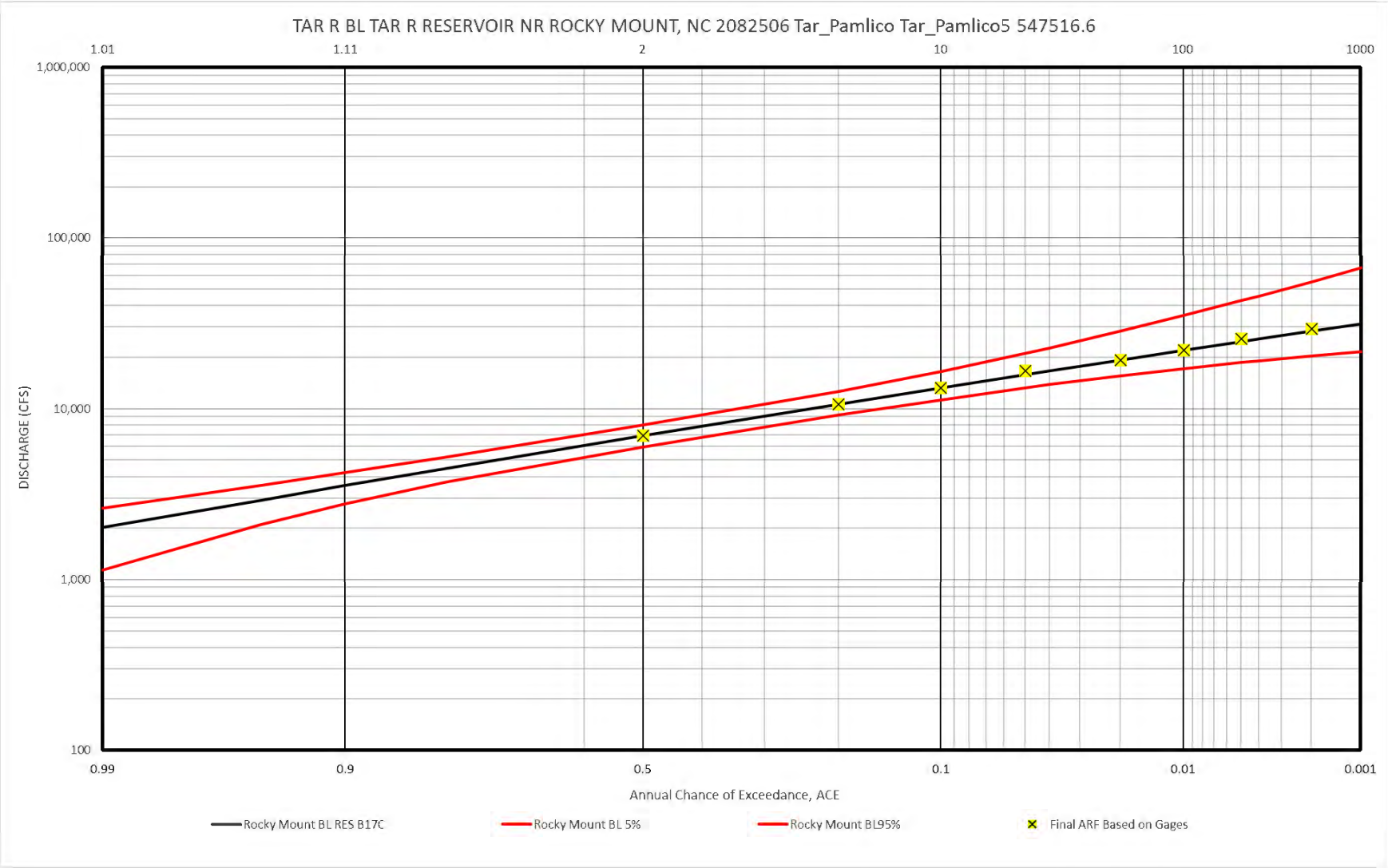
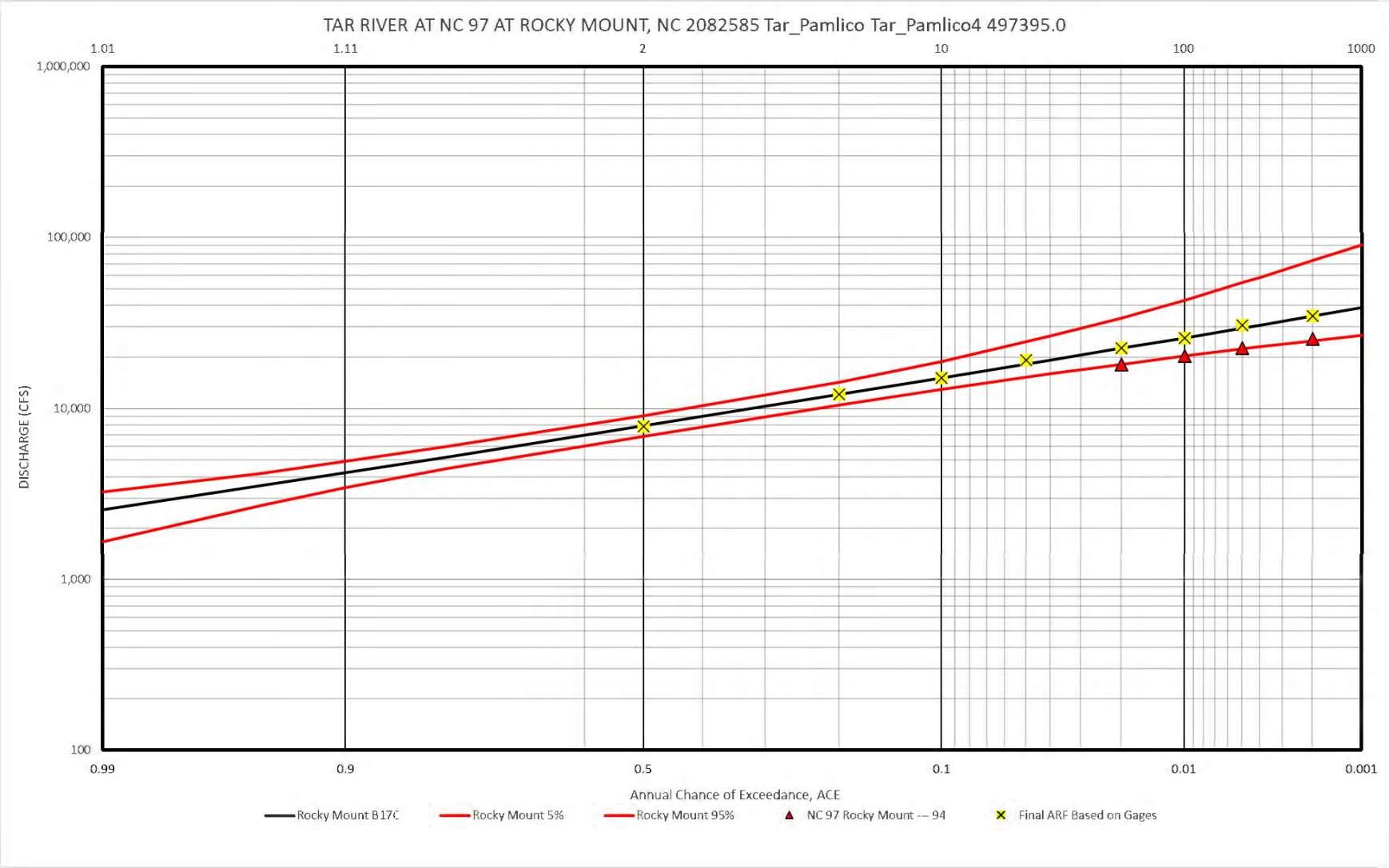
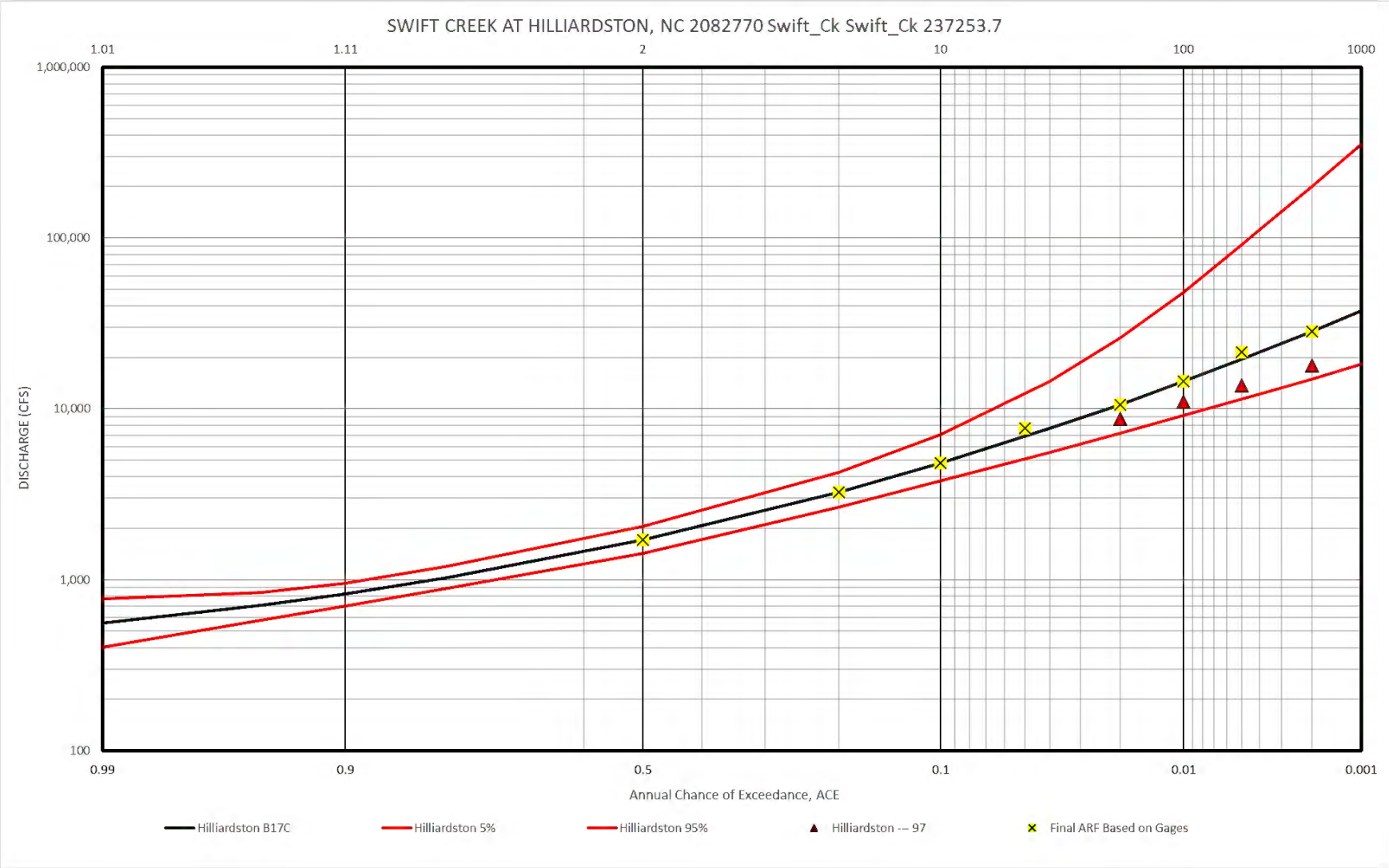


Figure 28: Peak flow frequency results for Rocky Mount, NC of the Tar River Reservoir Outflow



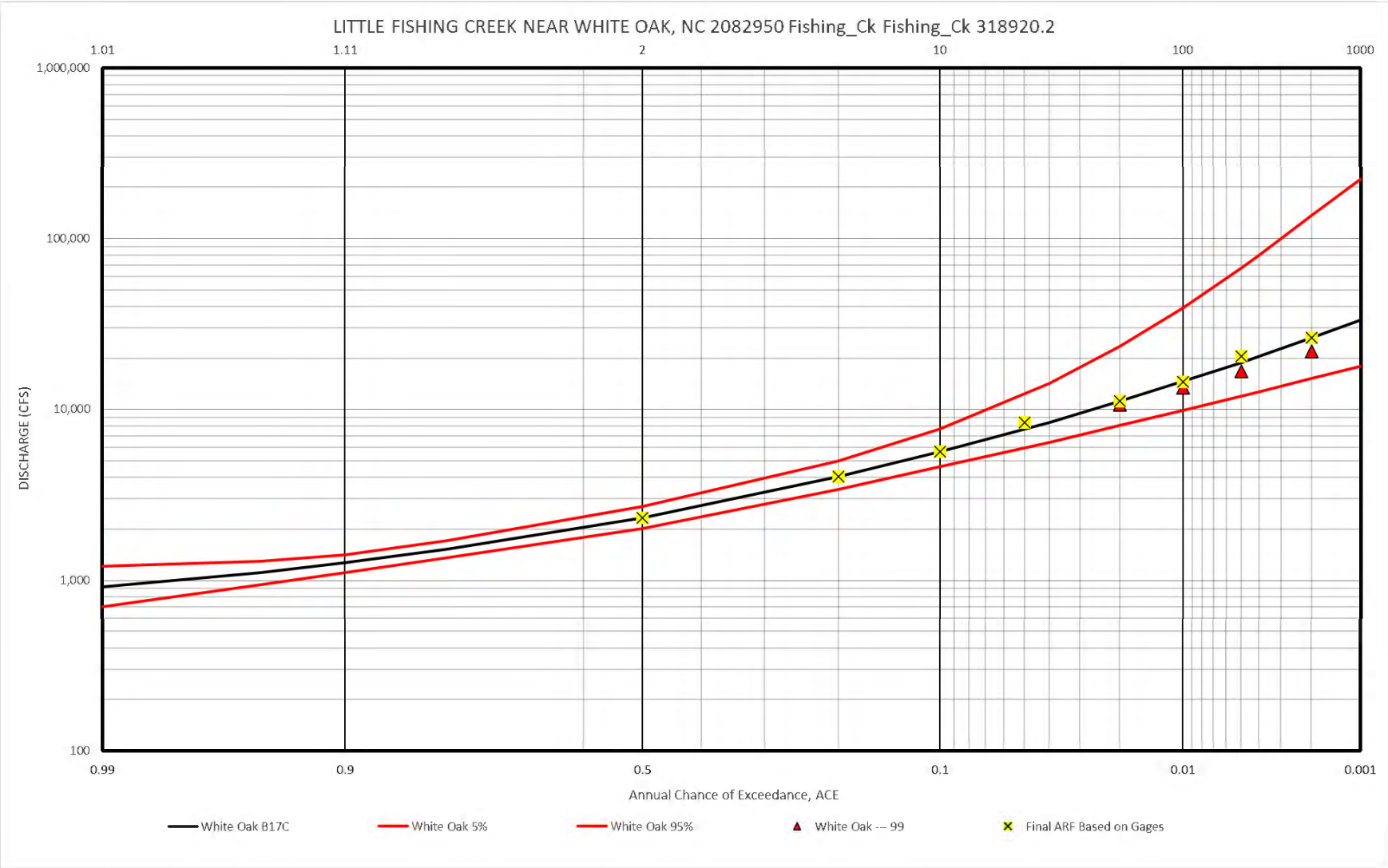
Footnote 21* Red triangles were taken from FEMA FIS Study

Figure 29: Peak Flow Frequency Results for Rocky Mount, NC of the Tar River



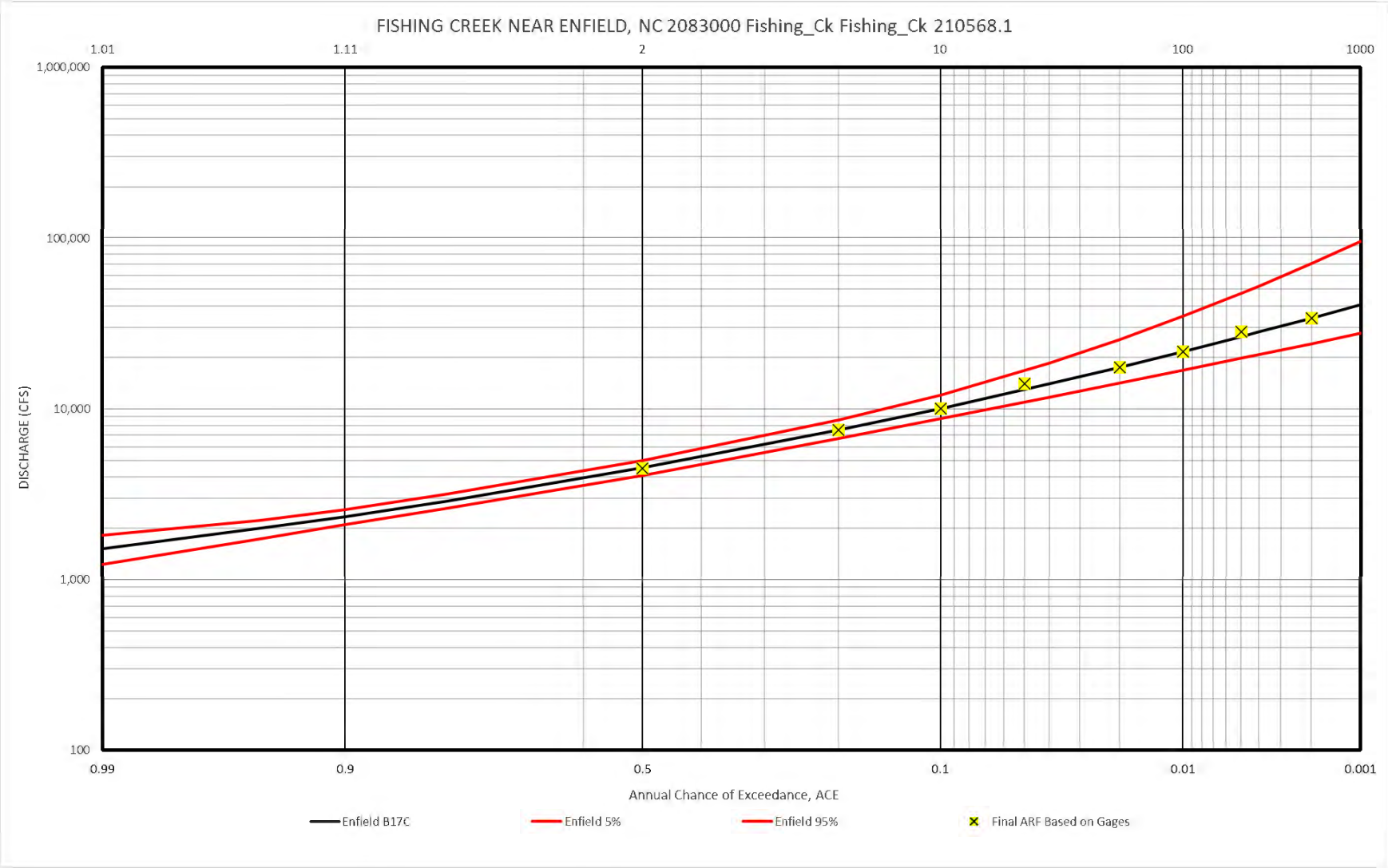
Footnote 22* Red triangles were taken from FEMA FIS Study

Figure 30: Peak Flow Frequency Results for Hilliardston, NC of Swift Creek



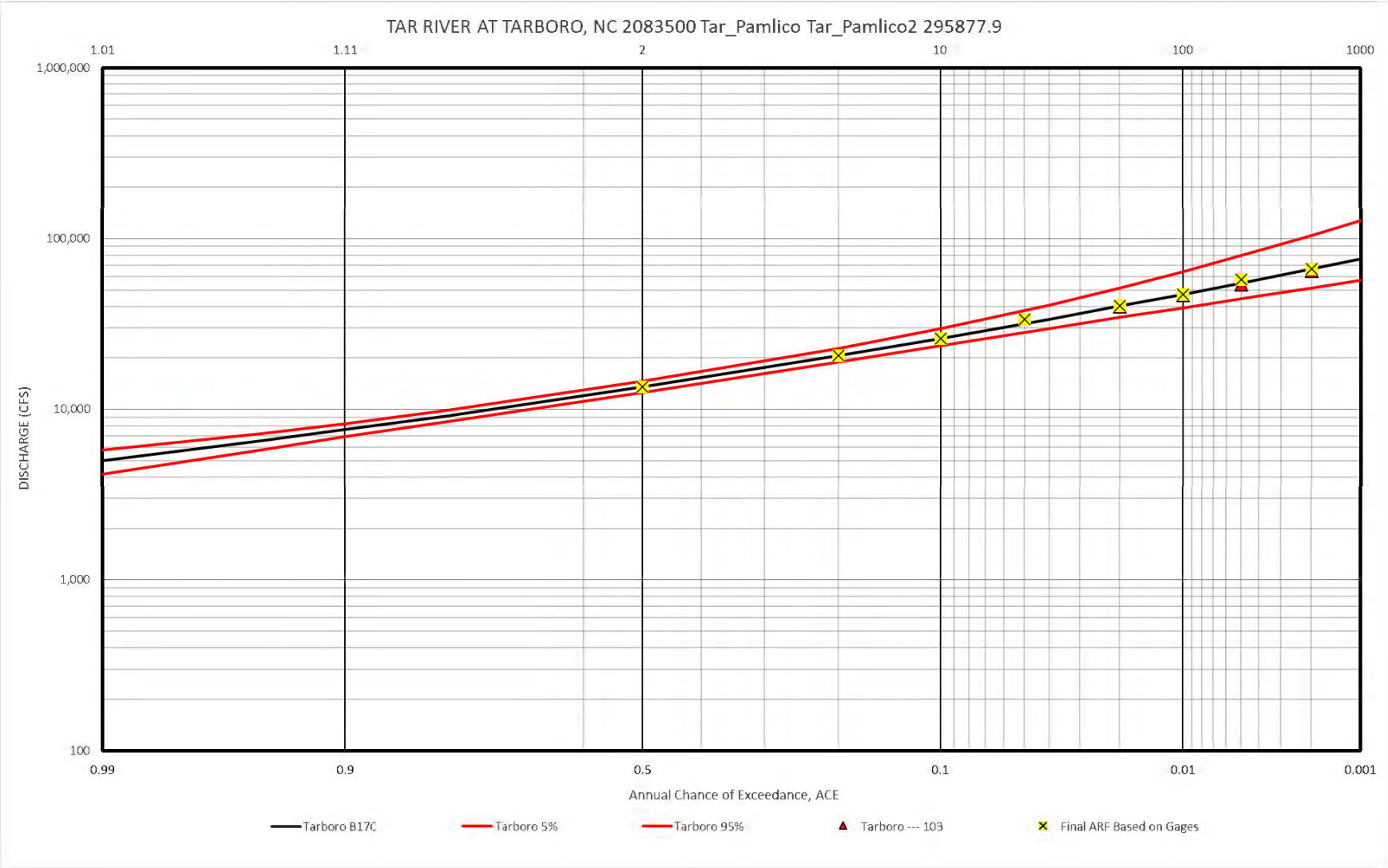
Footnote 23* Red triangles were taken from FEMA FIS Study

Figure 31: Peak Flow Frequency Results for White Oak, NC of Little Fishing Creek



Footnote 24* Red triangles were taken from FEMA FIS Study

Figure 32: Peak Flow Frequency Results for Enfield, NC of Fishing Creek



Footnote 25* Red triangles were taken from FEMA FIS Study

Figure 33: Peak Flow Frequency Results for Tarboro, NC of the Tar River

4.8 Limitations and Uncertainty

Hurricane Matthew impact were primarily due to the historical rainfall depth observed over the affected areas. It's estimated that between 12 and 18 inches of cumulative rainfall following an intense climatic wet period. The rainfall intensity for the storm event ranged to 1 to 2 inches which held constant for most of the event. A complete summary of the appropriate uncertainty can be found in Table 34.

Methods for conveying hydrologic uncertainty was primarily based on frequency analysis based on in stream observations at gage locations which support the TSP were only used. Few locations required additional flow estimates as the tributary was too small for similitude of characteristics shared among other gaged subbasins sites, but ultimately were used as order of magnitude estimates for alternative screening.

Table 34: Comprehensive summary of the basis for adopted flow frequency uncertainty

RAS Reach	TSP_Name	Discharge Uncertainty Basis	Period of Record	Mean	Standard Deviation	Skew
Tar_Pamlico1	TarPam2	Greenville Gage Analysis	114	4.168	0.228	0.576
Stony_Ck	StonyCk	Ungaged Hydrologic Approach: Rainfall Runoff	Equivalent Record Length should be 15 years according to Table 4-5: EM 1619.			
Tar_Pamlico5	TarPam10	Tar River Gage Below Reservoir	39	3.838	0.223	-0.096
Tar_Pamlico5	TarPam12	Louisburg Gage Analysis	56	3.795	0.237	0.094
Swift_Ck	SwiftCk	Swift Creek Hilliardston Gage	56	3.275	0.306	0.803
Tar_Pamlico4	TarPam9	Rocky Mount Gage Analysis	43	3.901	0.216	0.073
Tar_Pamlico3	TarPam8	Nearest Gages are Rocky Mount and Tarboro	Equivalent Record Length should be 15 years according to Table 4-5: EM 1619.			
Fishing_Ck	FishingCk	Fishing Creek Enfield Gage	105	3.673	0.249	0.47
Tar_Pamlico2	TarPam7	Nearest Gage is Louisburg	Equivalent Record Length should be 15 years according to Table 4-5: EM 1619.			
Tar_Pamlico2	TarPam4	Tarboro Gage Analysis	123	4.141	0.21	0.299
Conetoe_Ck	ContoeCk	Conetoe Gage Analysis	44	2.947	0.28	1.736
Tar_Pamlico1	TarPam1	Greenville Gage Analysis	114	4.168	0.228	0.576
Tar_Pamlico2	TarPam6R	N/A, this area Tarboro Overbank	This may not require a confidence estimate.			
Tar_Pamlico2	TarPam5L	N/A, this area is Princeville Levee	This may not require a confidence estimate.			
Tar_Pamlico1	TarPam3	Greenville Gage Analysis	114	4.168	0.228	0.576
Tar_Pamlico5	TarPam11	Nearest Gage is Louisburg	Equivalent Record Length should be 15 years according to Table 4-5: EM 1619.			
Tar_Pamlico5	TarPam14	Tar River Gage Analysis	80	3.71	0.257	-0.286
Tar_Pamlico1	GreenMill	Ungaged Hydrology; Regional Regression Equations	See Table "USGS Regression Estimates" for the Green Mill Run Lower and Upper 95			
Tar_Pamlico5	TarPam13	Louisburg Gage Analysis	56	3.795	0.237	0.094

5. Hydraulic Analysis

5.1 Model Geometry

The final comprehensive model, (basin-wide inundation coverage), developed for the Tar River River Watershed was developed in HEC-RAS 6.3.1. The model geometry contains seventeen reaches, 2,686 cross sections, 189 storage areas and 382 hydraulic structures i.e., lateral structures, levees, or inline structures. River and reach naming associations with corresponding damage reaches can be found in Table 35 and shown in Figure 35.

Table 35: Rivers and reaches defined in model geometry

River	Reach	TSP Damage Reach Association
Conetoe_Ck	Conetoe_Ck	ContoeCk
Fishing_Ck	Fishing_Ck	FishingCk
Green Mill Run	Reach-1	GreenMill
jack_Creek	jack_Creek3A	N/A, occurs in Coastal Hazard Zone
jack_Creek	jack_Creek2A	N/A, occurs in Coastal Hazard Zone
jack_Creek	jack_Creek3B	N/A, occurs in Coastal Hazard Zone
jack_Creek	jack_Creek2B	N/A, occurs in Coastal Hazard Zone
jack_Creek	jack_Creek1	N/A, occurs in Coastal Hazard Zone
Stony_Ck	Stony_Ck	StonyCk
Swift_Ck	Swift_Ck	SwiftCk
Tar_Pamlico	Tar_Pamlico5	TarPam13
Tar_Pamlico	Tar_Pamlico4	TarPam9
Tar_Pamlico	Tar_Pamlico3	TarPam8
Tar_Pamlico	Tar_Pamlico2	TarPam7 & TarPam5L
Tar_Pamlico	Tar_Pamlico1	N/A, occurs in Coastal Hazard Zone
Tar_Pamlico	Tar_Pamlico1A	N/A, occurs in Coastal Hazard Zone
Tar_Pamlico	Tar_Pamlico1B	N/A, occurs in Coastal Hazard Zone

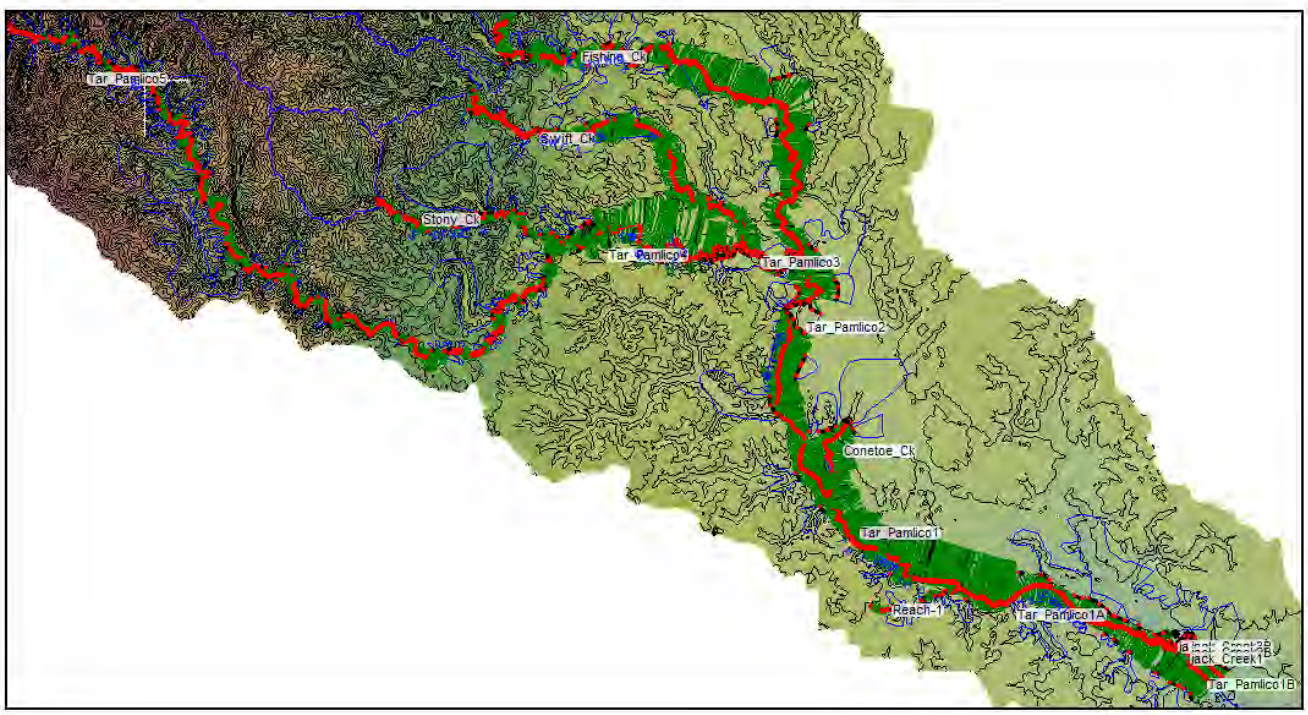


Figure 34: HEC-RAS Hydraulic Model (Steady State)

5.2 Boundary Conditions

Peak flows developed in HEC-SSP Version 2.2 Bulletin 17C Frequency Analysis were used as inflows to the river watershed HEC-RAS model at the upstream end of reaches and at lateral inflows from contributing sub-basins. Table 8-1 provides a summary of the unsteady boundary conditions, file names, and file paths.

The most downstream extents of the hydraulic model were chosen to be approximately 2 miles downstream of the Runyon Creek confluence near Washington, NC. This distance was chosen based three classes based on magnitude (stream length), prior experience (institutional knowledge), and the considerations for the study extent (riverine flood risks). Known WSEL was chosen for both calibrations run as well as the synthetic frequency profiles i.e. 0.01 AEP.

Sensitivity analysis was used to quantify the uncertainty in the water surface profiles as well as better understand the tidal boundary influences propagated upstream. See the Uncertainties section of the hydraulic water surface profiles for a more detailed description of specifying uncertainty in the lower Tar Pamlico sound region of the water surface profiles.

Table 36: Boundary conditions for the Tar River Mainstem and Tributaries (Steady Flow)

HMS Element Name	Drainage Area	Flow Source	Hydraulic Model Reach	River	Reach	XS
<TEXT>	<Sq. Miles>	<TEXT>	<TEXT>	<TEXT>	<TEXT>	River Station
tarRiver	166.7	Tar River Gage, B17C/HMS	US Boundary For Tar_Pamlico5 Reach	Tar_Pamlico	Tar_Pamlico5	933557.3
louisburg	434.5	Louisburg Gage, B17C/HMS	Internal Flow For Tar_Pamlico5 Reach	Tar_Pamlico	Tar_Pamlico5	797057.1
tarReservoir	782.2			Tar_Pamlico	Tar_Pamlico5	556938.7
tarReservoirOutflow	783.9	Tar River BL Res Gage, B17C/HMS	Internal Flow For Tar_Pamlico5 Reach	Tar_Pamlico	Tar_Pamlico5	548873.5
Junction-6	926.6	Tar/Stoney Confluence, HMS Only	US Boundary For Tar_Pamlico4 Reach	Tar_Pamlico	Tar_Pamlico4	507822.7
rockyMount	928.7	Rocky Mount Gage, B17C/HMS	Internal Flow For Tar_Pamlico4 Reach	Tar_Pamlico	Tar_Pamlico4	499025
Junction-2	1295.0			Tar_Pamlico	Tar_Pamlico3	371057
Junction-17	2029.4	Confluence of Tar/Fishing Creek	US Boundary For Tar_Pamlico2	Tar_Pamlico	Tar_Pamlico2	333044.2
Junction-3	894.0			Fishing_Ck	Fishing_Ck	2522.707
Junction-4	743.9			Fishing_Ck	Fishing_Ck	94814.6
fishingEnfield	529.8	Enfield Gage, B17C/HMS	Internal Flow For Fishing Creek Reach	Fishing_Ck	Fishing_Ck	212783
Junction-7	438.3			Fishing_Ck	Fishing_Ck	294894.3
littleFishingWhiteOak	177.9	White Oak Gage, B17C/HMS	Internal Flow For Fishing Creek Reach	Fishing_Ck	Fishing_Ck	318920.2
tarboro	2062.9	Tarboro Gage, B17C/HMS		Tar_Pamlico	Tar_Pamlico2	294888
Junction-5	2292.8			Tar_Pamlico	Tar_Pamlico2	258765
greenville	2529.9	Greenville Gage, B17C/HMS	Internal Flow For Tar_Pamlico_1 Reach	Tar_Pamlico	Tar_Pamlico1	153790
Junction-1	2997.9			Tar_Pamlico	Tar_Pamlico1A	66576
hilliardston	165.4	Hilliardston Gage, B17C/HMS	US Boundary For Swift Creek Reach	Swift_Ck	Swift_Ck	236656.6
Sink-1	3168.0			Tar_Pamlico	Tar_Pamlico1A	49475.84
springHope	679.8	Spring Hope Junction, HMS Only		Tar_Pamlico	Tar_Pamlico5	649363.4
Stony2	103.9	Stony Creek, HMS Only	Internal Flow for Stony Reach	Stony_Ck	Stony_Ck	45818.84
Swift2	190.893			Swift_Ck	Swift_Ck	191844.2
Fishing2	452.5602	Fishing Creek, HMS Only	Internal Flow Between White Oak/Enfield	Fishing_Ck	Fishing_Ck	272835.7
Tar2	679.81	Upper Tar Node, HMS Only	Internal Flow Between Louisburg/Spring Hope	Tar_Pamlico	Tar_Pamlico5	716101.4

5.3 Model Parameters

Terrain model was developed from high resolution digital elevation models sourced from Lidar for areas of identified flood problems as well as locations that appeared to require additional detail required for hydraulic modeling. The detailed 1-meter resolution terrain was provided by the State of North Carolina sufficiently covering the entire basin; however, the dataset was impractically large to be processed by GIS software for the 3,200 sq. mile basin. Given the challenge regarding the limitations of the dataset size, the extents falling outside the aforementioned areas were added having 10-meter terrain resolution accessed by the USGS.

Numerous hydraulic models provided by the State of North Carolina were used to extract hydraulic structures which all fall in the following categories: bridges, culverts, railway, roadway, and pedestrian transportation stream crossings.

Upstream of bridges, ineffective flow areas were set to the minimum elevation of the road (high chord). Downstream of bridges, ineffective flow areas were set to the minimum elevation of the bridge opening (low chord). During calibration, adjustments were made to the bridge structures that appeared to have debris concerns either from aerial photographs or choke points along the centerline of conveyance.

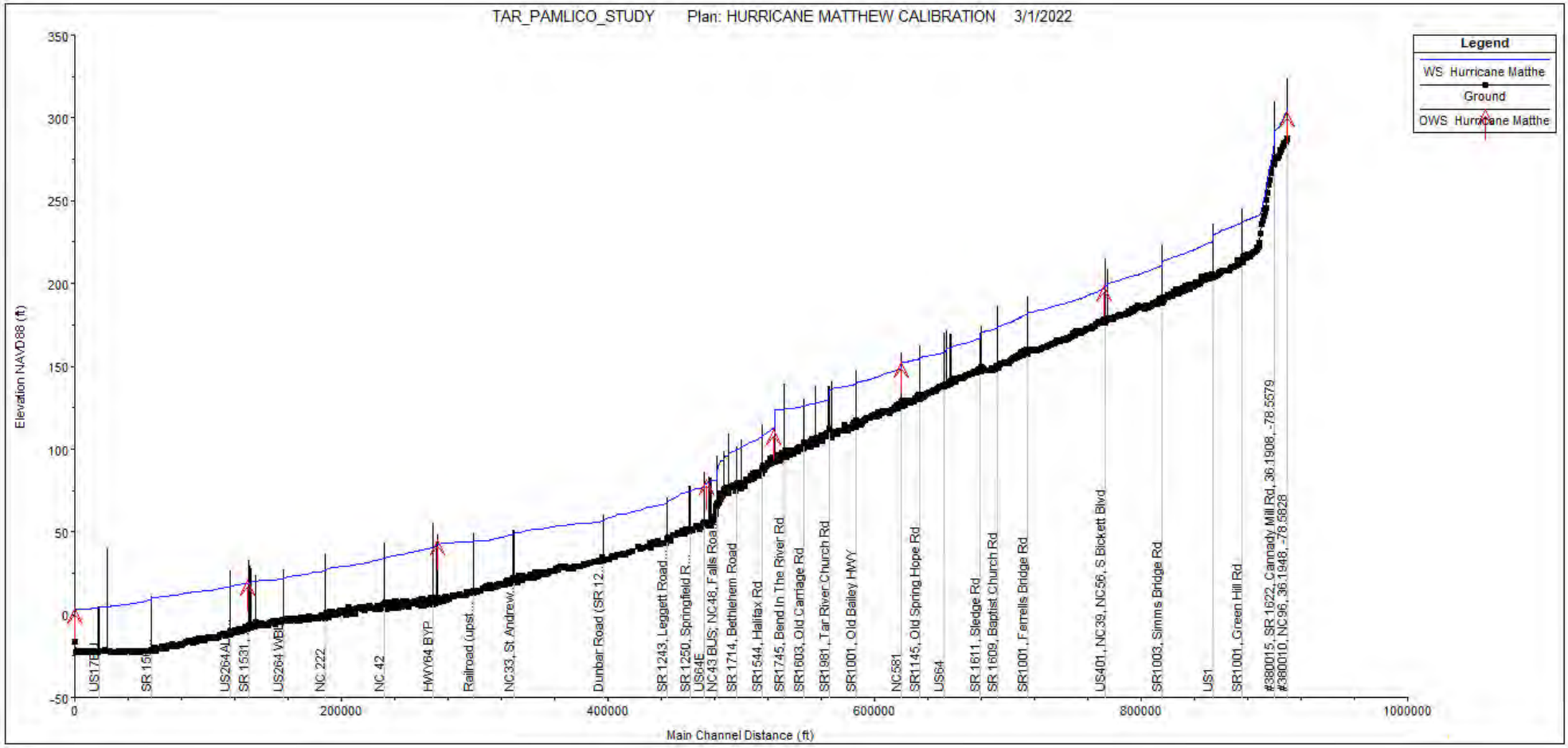
Ineffective areas were also used in the overbanks where floodwaters are stagnant. The Fishing Creek watershed is an example of a reach that has low depressed storage within the floodplain, therefore ineffective area placement was completed to represent these areas along each reach. The Princeville Levee is a location that was treated as a levee point which prevents flows from entering the floodplain until which time overtopping occurs. This method was chosen as most appropriate to model the existing levee.

Manning's "*n*" values along each reach were initially assigned values for reasonableness regarding acceptable ranges of left, channel, and overbank roughness values. All were provided a visual assignment of manning's roughness value based on an approximate 1000-foot scale. Justifications for manning's roughness selection as explanatory variable used for calibration are described in the Model Calibration Section.

5.4 Model Calibration

The gage locations used for calibrations are shown in . Hurricane Matthew was chosen as a representative flood peak of which could easily be referred to as a design flood. High water marks were extracted from the USGS gages that provided stage data. Additionally, high water marks were searched for within the USGS database repository. High water mark data was recovered for the Hurricane Matthew event however were not located within the study area boundary, therefore, the calibration stages used were taken only from riverine gage locations.

Table 37: Water Surface Profile with High Water Marks (Tar River Mainstem)



Footnote 26 – Elevations in this figure are reported in NAVD88 vertical datum

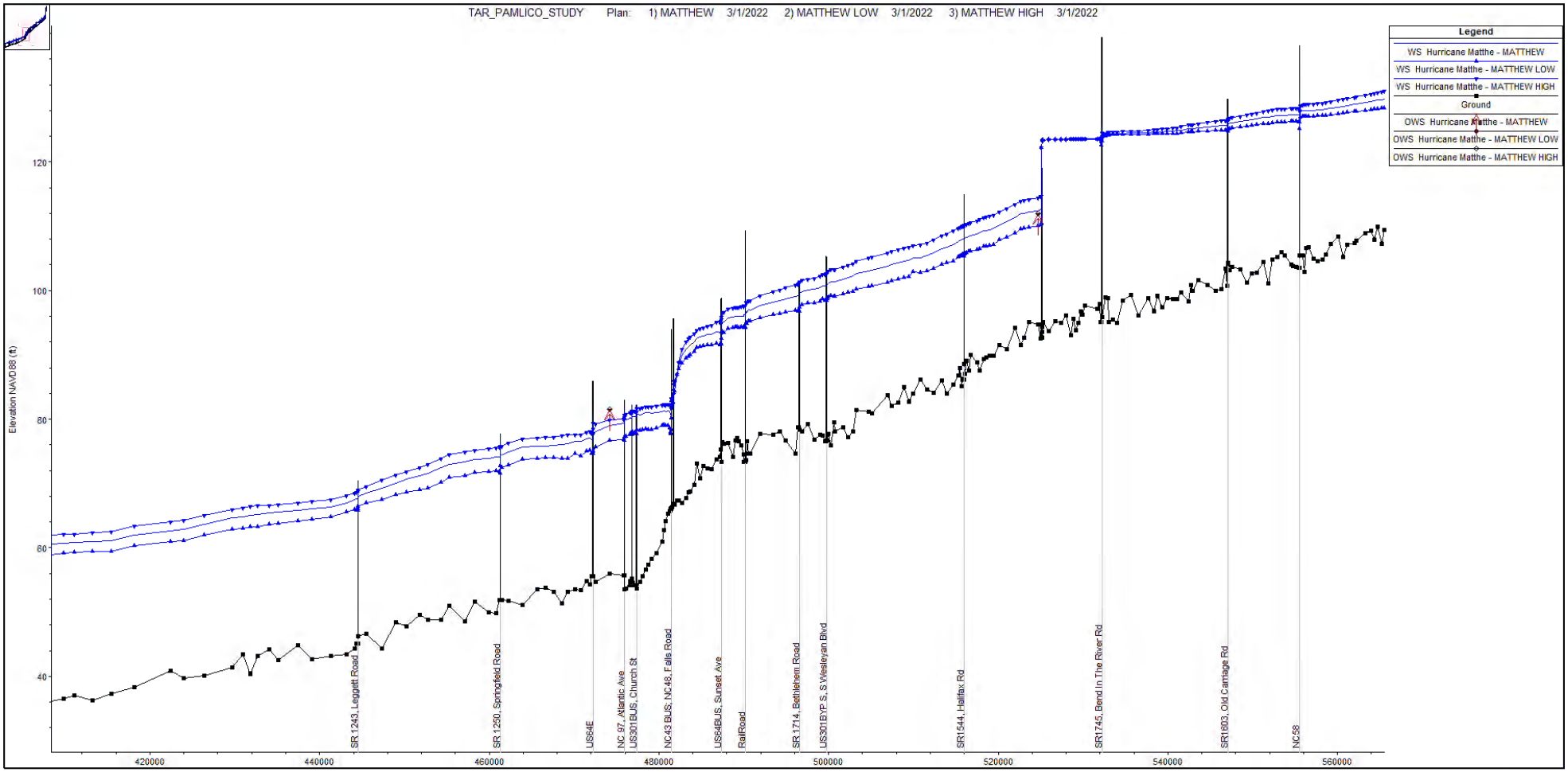


Figure 35: Low, best estimate, and high bounds depicting the stage variability due to roughness bounds

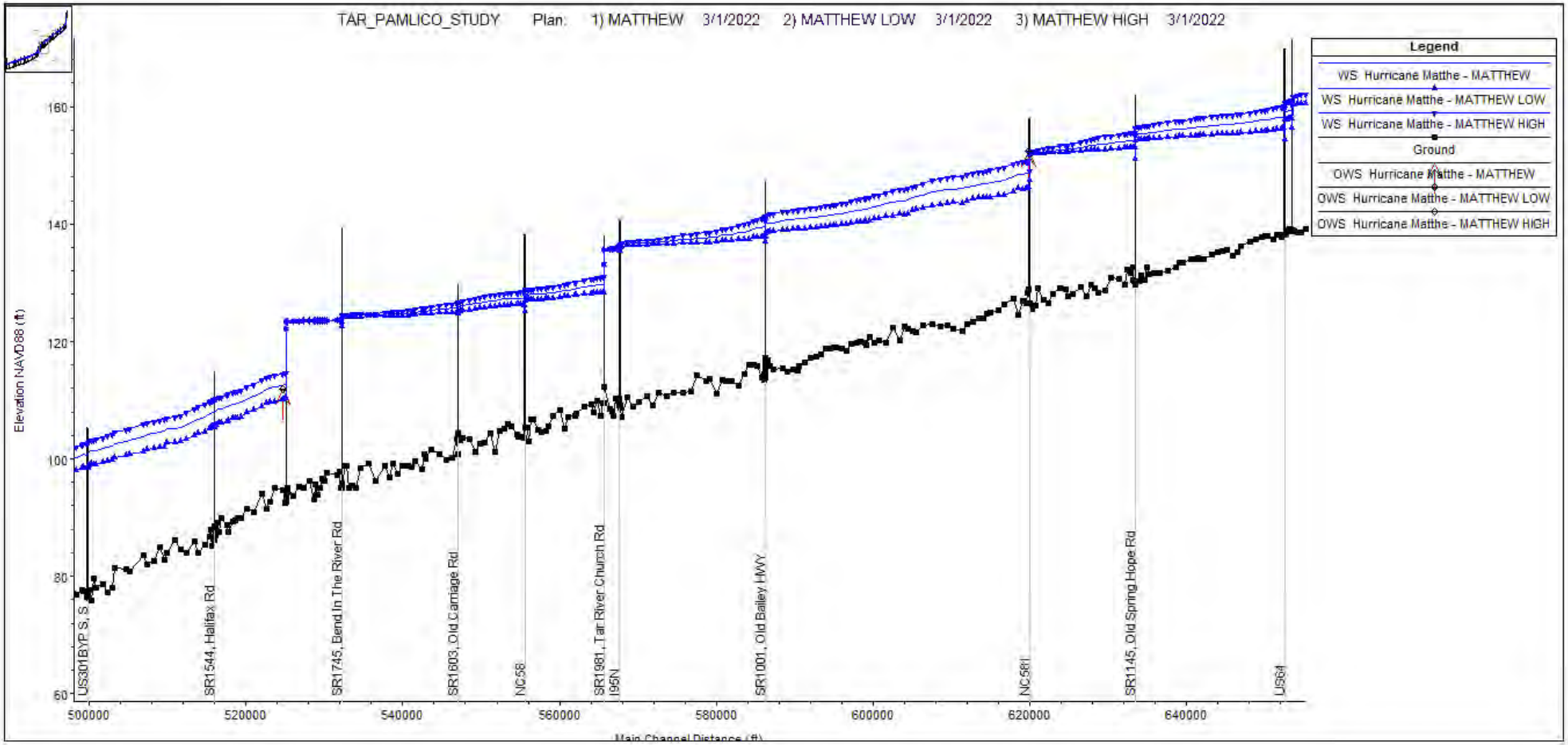


Figure 36: Tar river reservoir tailwater and NC581 USGS gauge of the Tar River 4 reach variance

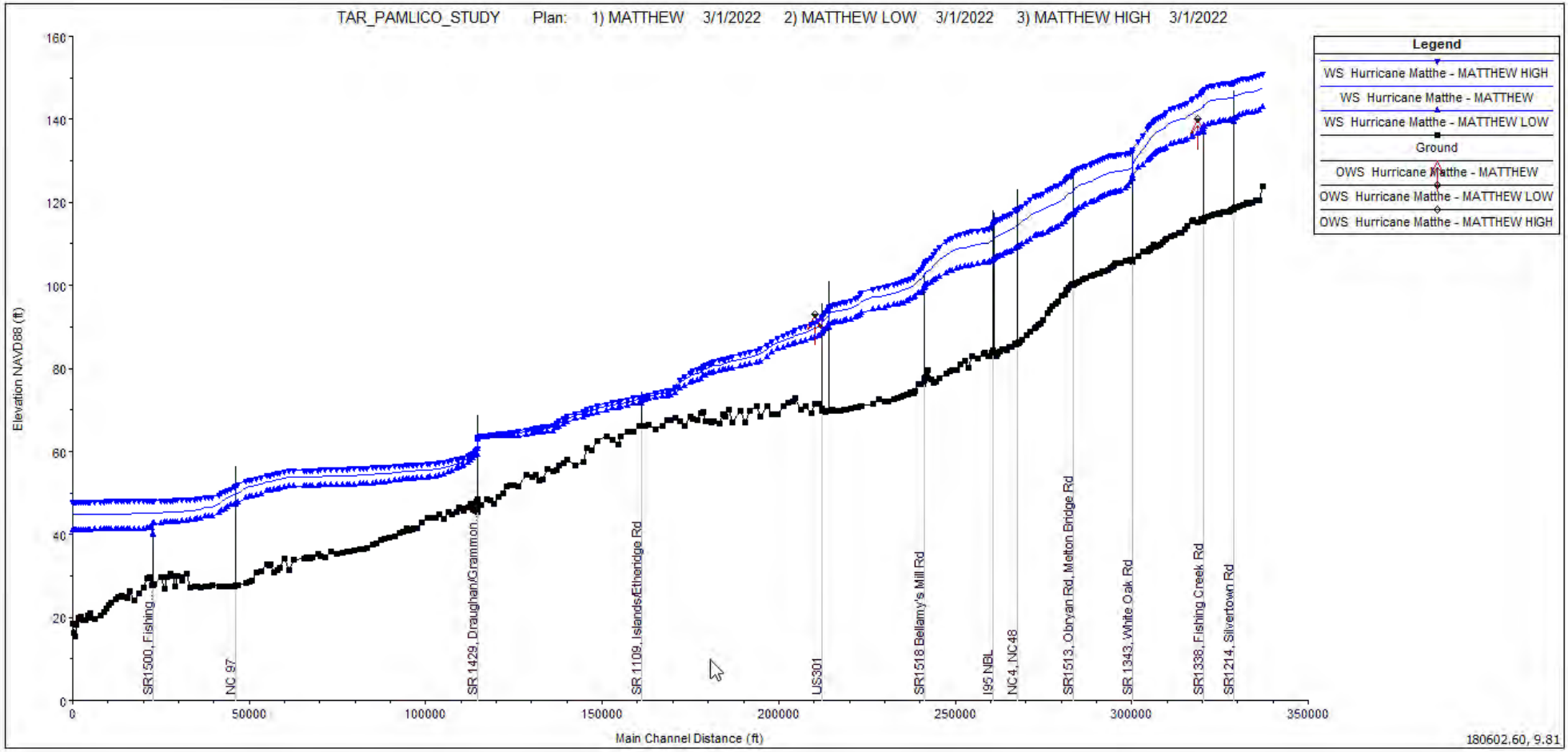


Figure 37: Fishing Creek stage uncertainty and variance

Table 38: Hurricane Matthew event model comparison for WSEL

Location Name	Observed WSEL	Modeled WSEL	Difference (ft-Variance)	Difference (in-Variance
Tar River upstream of Louisburg, NC	304.02	303.90	-0.1	-1
Tar River near Louisburg, NC	198.96	197.66	-1.3	-16
Tar River near NC-581 Spring Hope, NC	152.50	151.84	-0.7	-8
Tar River Langley Crossroads, NC	111.96	112.42	0.5	6
Tar River at NC-97 Rocky Mount, NC	81.54	79.01	-2.5	-30
Tar River at Tarboro, NC	45.61	42.40	-3.2	-39
Tar River at Greenville, NC	20.92	18.76	-2.2	-26
Tar River at Washington, NC	OBSERVED WSEL		NO CHANGE	NO CHANGE

Footnote 27: All elevations are shown in feet - NAVD88

5.5 Uncertainty Analysis

Calibration results informed the hydraulic uncertainty of the water surface profiles by taking High and Low manning's roughness estimates as upper and lower bounds. The water surface elevation differences between the Low and High were then used to compute average standard deviation of error between reaches that share uncertainty related to each gage location. Various reaches in the hydraulic model were ungauged in which case the selection of as specified by (EM 1619). Each justification regarding the selections of standard deviation computed/adopted for study.

River	Reach	Standard Deviation Adopted	Rationale and Estimate Basis
Conetoe_Ck	Conetoe_Ck	1.60	Computed based on High/Low Water Surface Elevation Standard Deviation
Fishing_Ck	Fishing_Ck	2.89	Computed based on High/Low Water Surface Elevation Standard Deviation
Green Mill Run	Reach-1	1.50	Default Minimum Standard Deviation of Error in Stage, due to no high water mark data
jack_Creek	jack_Creek3A	1.50	Default Minimum Standard Deviation of Error in Stage, due to no high water mark data
jack_Creek	jack_Creek1	1.50	Default Minimum Standard Deviation of Error in Stage, due to no high water mark data
Stony_Ck	Stony_Ck	1.50	Default Minimum Standard Deviation of Error in Stage, due to no high water mark data
Swift_Ck	Swift_Ck	1.68	Computed based on High/Low Water Surface Elevation Standard Deviation
Tar_Pamlico	Tar_Pamlico5	1.50	Default Minimum Standard Deviation of Error in Stage, due to no high water mark data
Tar_Pamlico	Tar_Pamlico4	2.06	Computed based on High/Low Water Surface Elevation Standard Deviation
Tar_Pamlico	Tar_Pamlico3	3.58	Computed based on High/Low Water Surface Elevation Standard Deviation
Tar_Pamlico	Tar_Pamlico2	3.08	Computed based on High/Low Water Surface Elevation Standard Deviation
Tar_Pamlico	Tar_Pamlico1	2.35	Computed based on High/Low Water Surface Elevation Standard Deviation
Tar_Pamlico	Tar_Pamlico1A	1.50	Default Minimum Standard Deviation of Error in Stage, due to no high water mark data
Tar_Pamlico	Tar_Pamlico1B	1.50	Default Minimum Standard Deviation of Error in Stage, due to no high water mark data

5.6 Additional 2D Hydraulic Modeling for Inundation Refinement

Needs for refining a complex spread of flow through the Tar River 4 reach and the lowest portions of both the Stoney Creek Reach and Tar River 5 Reach were established by the PDT. The flow paths vary significantly within the limits that a 2-dimensional hydraulic model would provide a better water surface elevation for each structure within the vicinity of the complex flow region as shown in Figure 40.

The 2D hydraulic model consisted of approximately 408,000 cells with nominal cell spacing of 100 feet and average cell size of 4,500 square feet with an average cell face length of 70 feet. The mesh refinement included culvert and bridge information provided by an online GIS portal. Culverts over 54” and under 54” were considered, however many culverts within the inventory were not required due to a lack of influence to flood inundation results. Approximately 26 culverts were added to the 2D hydraulic model added to nearly 22 Internal 2D connections.

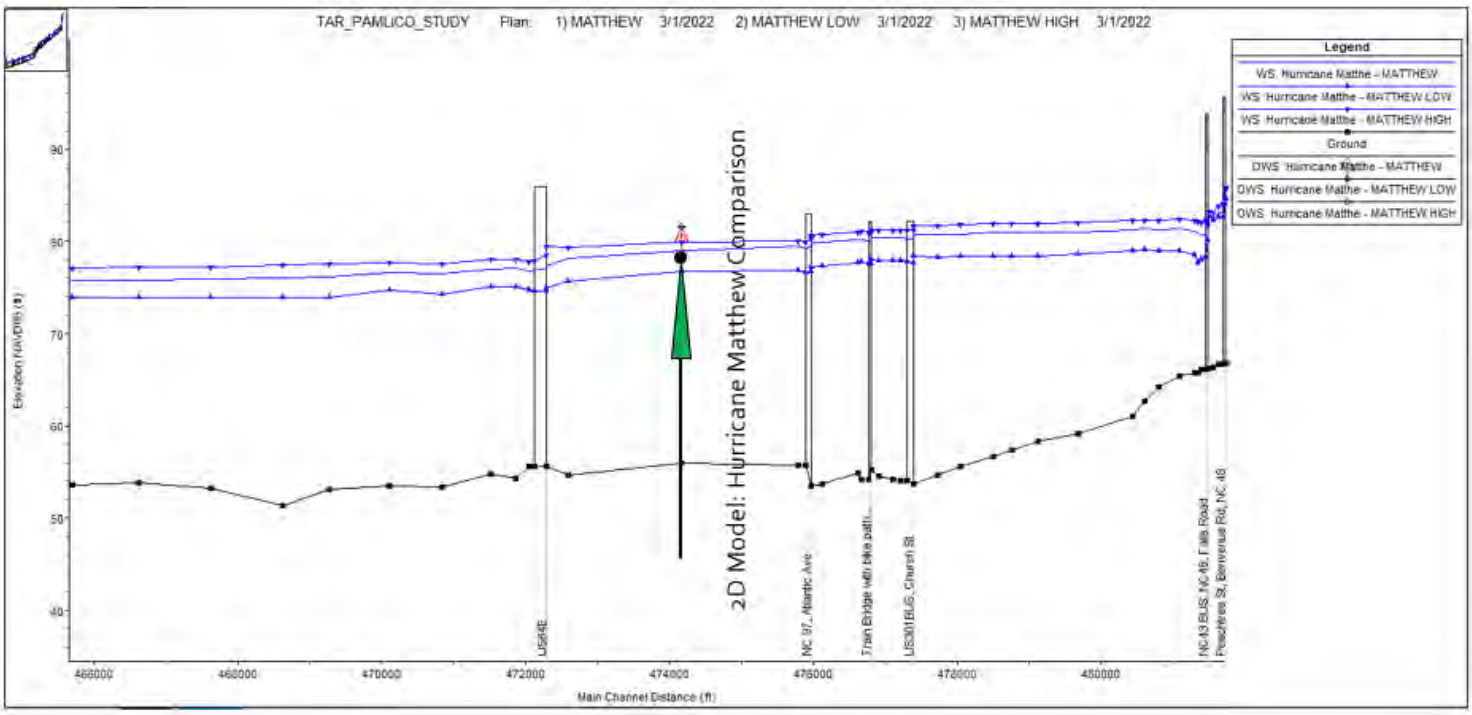


Figure 38: Peak Water Surface Elevation comparison to existing water surface elevations

The refinements associated with the 2D hydraulic model area were improved minimally for the high water mark elevation located at the USGS gage which included a calibration zone downstream on the Tar Pamlico Reach 4. The 1D hydraulic model underpredicted Hurricane Matthew’s peak which corresponded to 2.06 standard deviation of error which was computed using variance. During the calibration of 1D model manning’s roughness values were elevation in a manner that would 1) promote water surface elevation increases while also not exceeding physical maximums for the cover types observed in the reach.

The largest refinement improvement in the 2D hydraulic model is that bi-directional flow was present and the 1D cross section in the hydraulic model was assigning flow depth values in areas that were disconnected. The 2D hydraulic model was better capable of modeling these remote areas by inserting culverts and other conveyance structures that were contributing to the flooding in the area.

Given these findings, it is recommended that the uncertainty remains consistent for the Tar Mainstem, however significant improvement to overbank areas were significantly improved. See Figure 42 for a comparison of the inundation results. Furthermore, inundation grids were generated using the calibrated Hurricane Matthew flows, with frequency simulation runs informed by the DSS connections from the final synthetic frequency hydrographs.

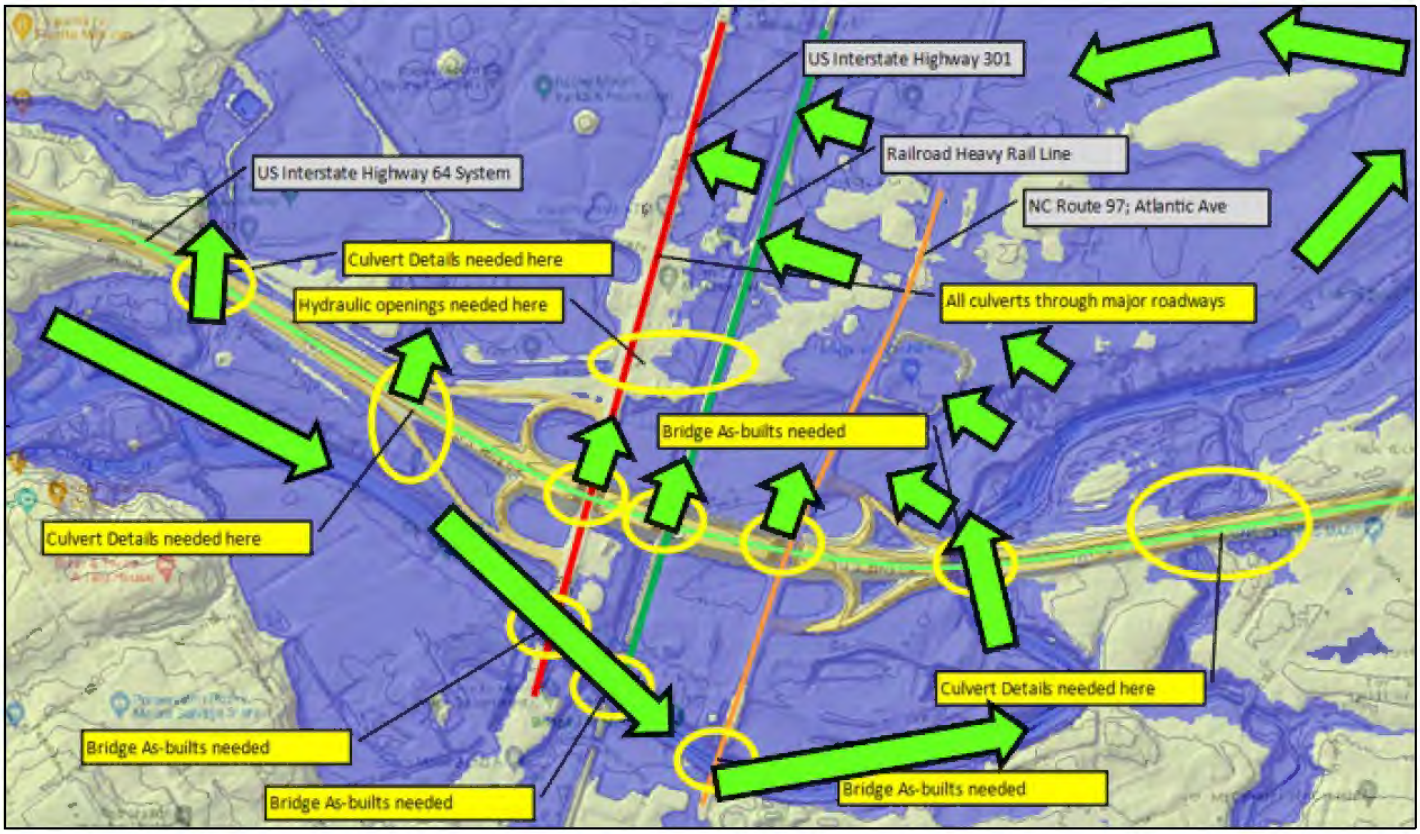


Figure 39: Schematic demonstrating the complex flow paths and integrated transportation network

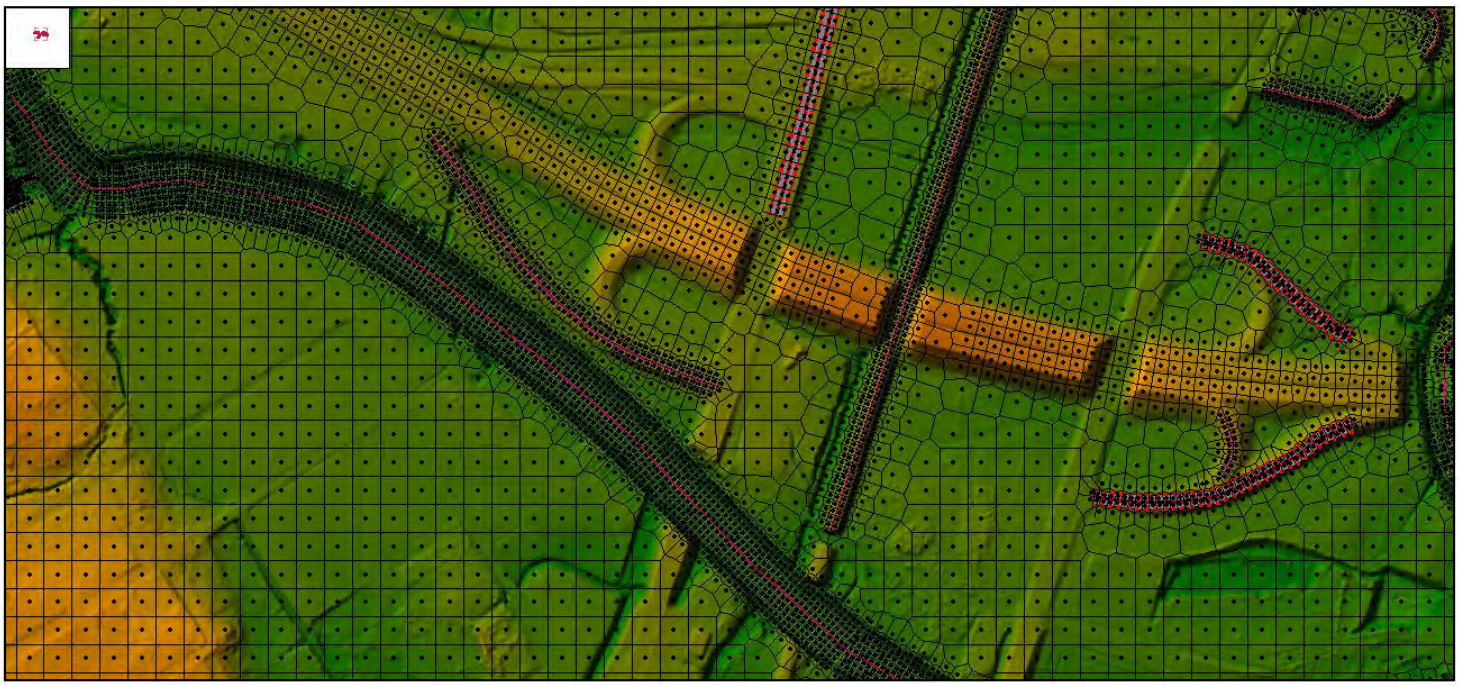


Figure 40: 2D Hydraulic model representative example of mesh

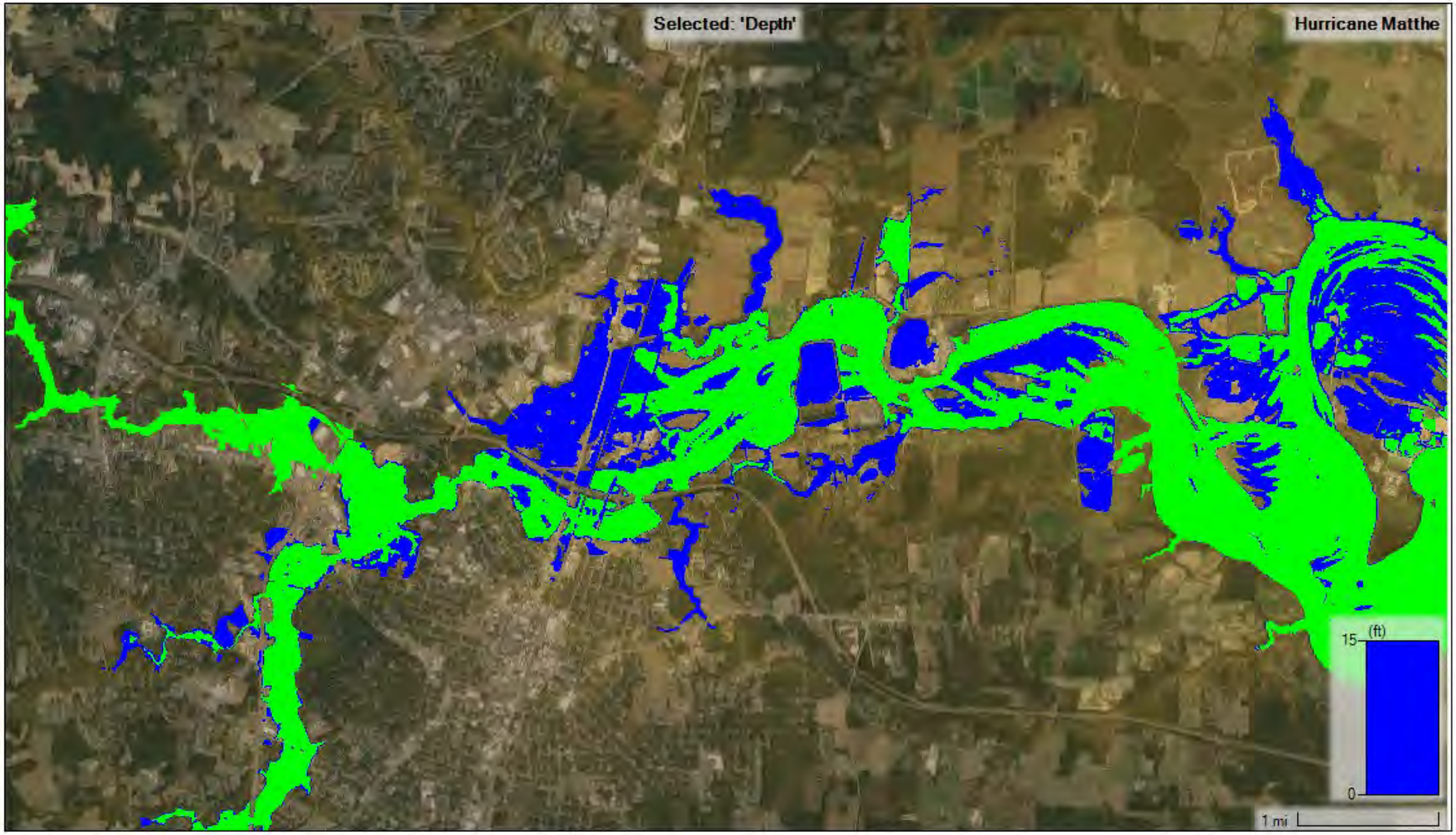


Figure 41: Inundation maps showing improvements to areas in floodplain areas (Green – 2D Results & Blue – 1D Results)

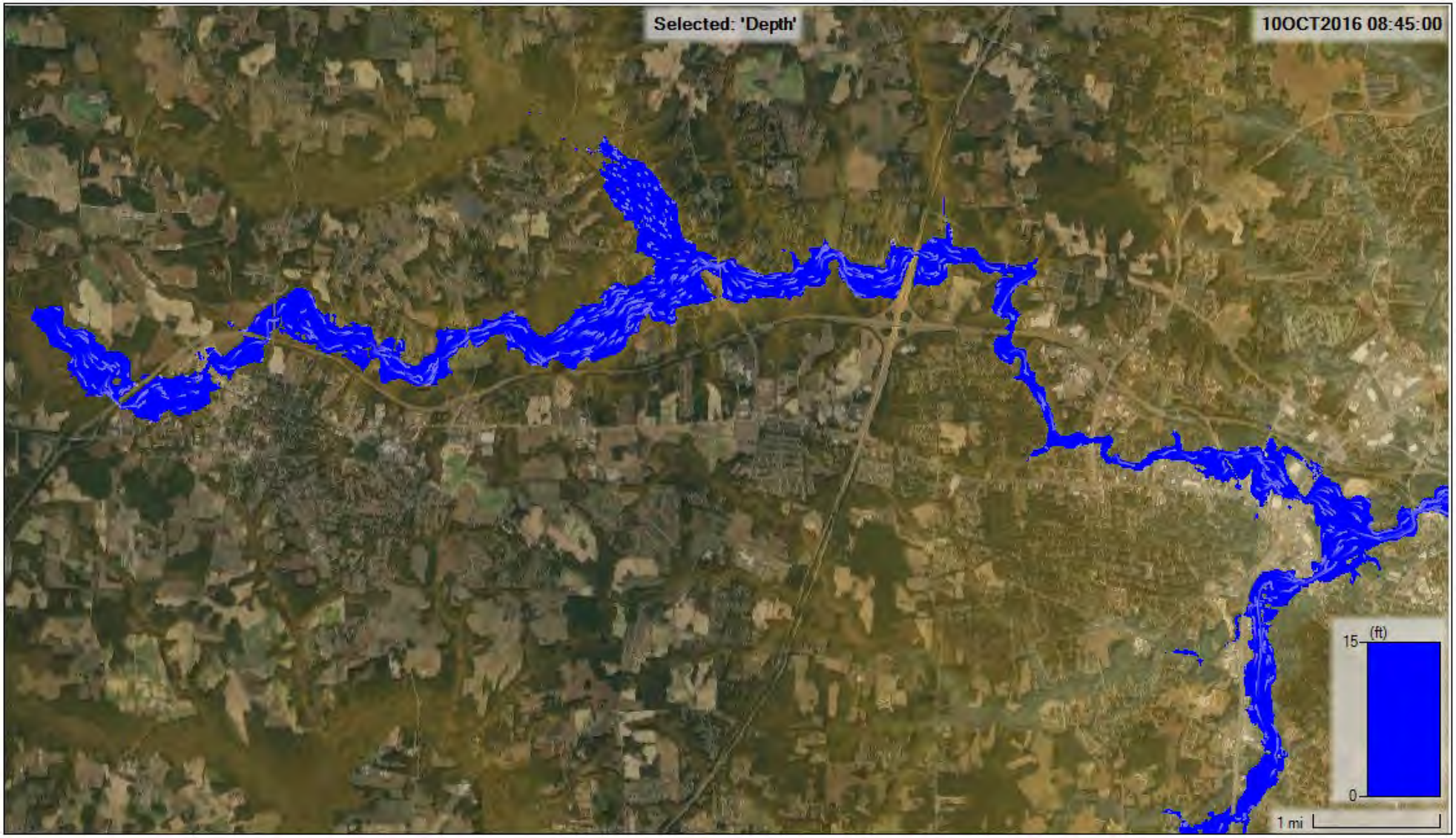


Figure 42: Fishing creek reach FWoP flowpaths

Figure 43: Typical flowpath patterns for the lower Tar Pamlico 5 reach

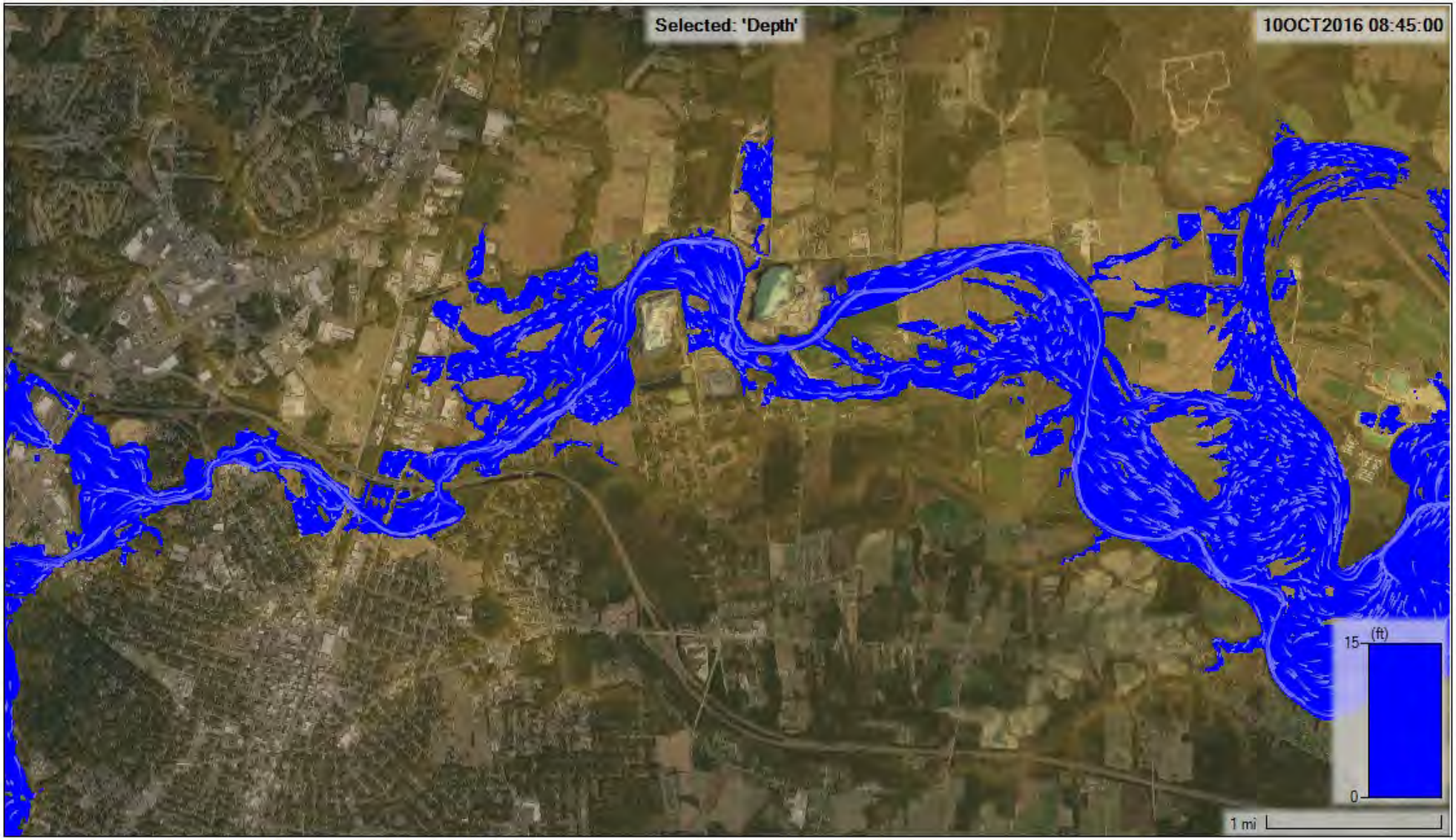


Figure 44: Typical flowpath patterns observed during Hurricane Matthew for the Tar Pamlico 4 reach

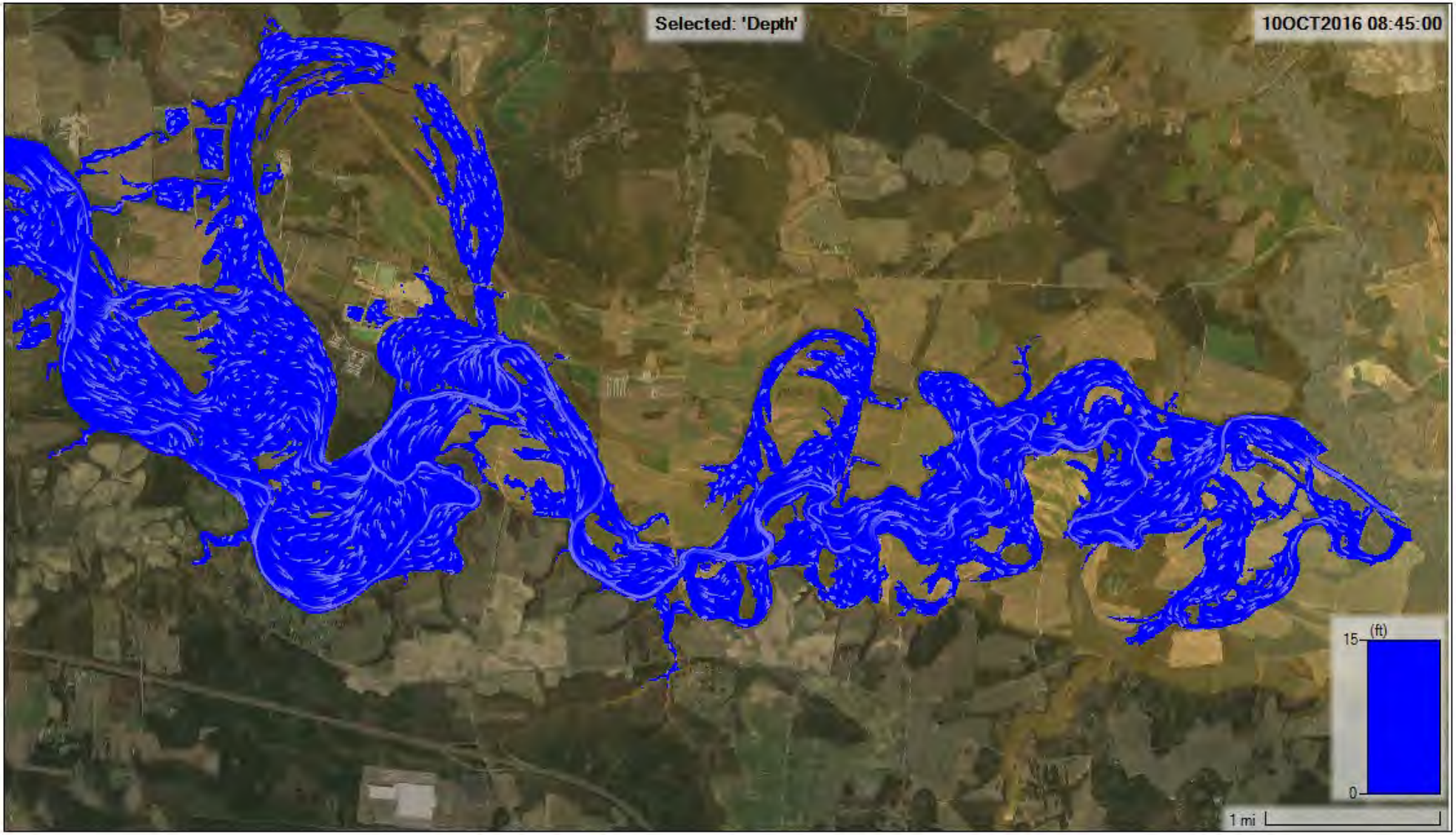


Figure 45: Tar Pamlico 4 reach typical flow patterns just upstream of the Swift Creek confluence

6. Feasibility Alternative Analysis

Listing of alternatives that received hydraulic or hydrologic modeling. The level of detail remained consistent for comparisons of impact in the immediate locality of the remediation but also systematic influences resulting in alternative implementation Future Without Project Conditions FWoP. This study resulted in having no structural features moving forward therefore the TSP includes a combination of non-structural improvements only. The following sections are meant to describe the screening techniques pursued by the Hydraulics and Hydrology to rule out measures from economics benefits. The Tentatively Selected Plan (TSP) is the alternative that includes flood dry proofing, elevating, and flood venting.

Screened Alternative ID	Overarching Alternative Name
S26	Transportation Modification and Debris Management at Major Constrictions
S25	Transportation Modifications
S28	Rocky Mount Run of River Modification
S11	Channel Modification #4 (Tarboro)
Screened	Potential Channel Modifications Pending Task 5 Results
S12 to S15	Braided Channels Above Tarboro
S10	Nashville Auxiliary Channel (Stony Creek)
S10	Nashville West Washington Street Bridge Modification
NNB2	Offline Detention (Water Farming)
S1 to S3	Dry Dams

Footnote 28: This table is a summary of the alternatives modeled with detail; for a comprehensive listing of measures screened see the Planning Appendix A

6.1 Transportation Modifications and Debris Impacts (S26)

The goal of this alternative is assessing the effects of implementing a debris management plan to several bridges throughout the watershed. The intention of this assessment is to determine if preventing debris buildup at crossings could potentially alleviate flooding and determine the effectiveness of a debris management plan providing the benefit of decreased infrastructure damage. USACE's Tar-Pamlico & Neuse River Basins, NC – Geomorphic Summary report (USACE, 2021) indicates that there are concentrated sites of debris accumulation in the meander bends of the rivers surrounding urban areas and at bridge crossings throughout the watershed.

Large woody debris is common along the main stem of the Tar River Mainstem, the Feasibility Study team feels that debris accumulations would occur on the rising limb of flood hydrographs. Debris management and removal operations would likely not be completed during flood events and would be best performed post flood conditions. See Figure 47 for a picture of typical large woody debris along the mainstem of the Tar River.

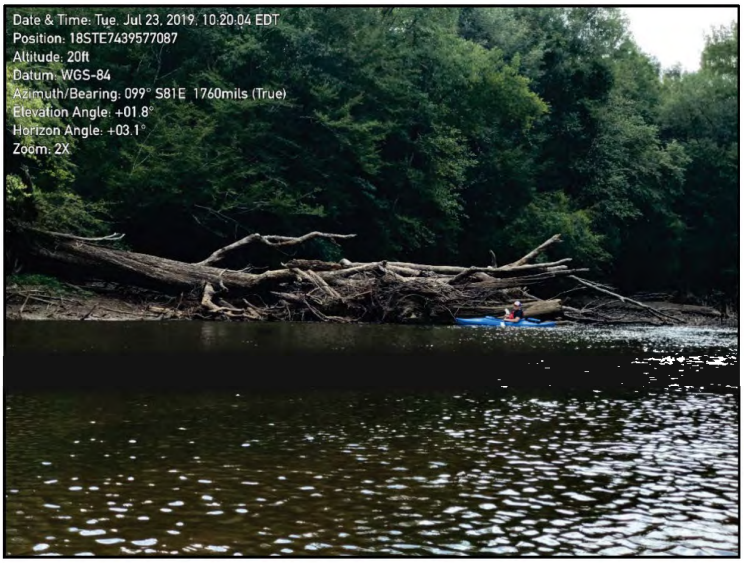


Figure 46: Large pile of Large Woody Debris in The Tar River near Tarboro, NC

Approach & Methodology

The first step was to identify certain bridge(s) that could potentially yield lower flood elevations under a debris management plan. To accomplish this a first pass assessment was conducted by eliminating all debris blockages on all bridge crossing piers in the existing conditions HEC-RAS model. This essentially allowed for a best-case flooding scenario to ascertain two key factors. One factor being how much flood reduction, if any all, occurs with debris removed from bridges. The second factor also being if any reductions occur in urban and/or residential areas where flood damage reduction is more greatly realized. For the first pass assessment only the 100-year.

After running the model with all debris removed the results were analyzed to determine a smaller subset of bridges that would be further analyzed. This subset of bridges was limited to urban/residential areas, and where flood reductions were around 0.5 feet or more. Two additional HEC-RAS model runs were created with this smaller subset of bridges. One model was run with the subset of bridges completely clear of debris. This was done to see if the results differed from when all bridges in the model were cleared of debris. The second model run was conducted with the subset of bridges having 50% of debris removed from their piers.

Results

Results from the HEC-RAS model where all bridges were removed of debris show that there was zero change in flood elevations for Conetoe Creek, Fishing Creek, Green Mill Run, and Jack Creek.

Results showed that there were areas of reduced flood stage within urban/residential areas of Stony Creek, Swift Creek, and the Tar Pamlico River. The Tar Pamlico River especially showed areas a large flood reduction. Unfortunately, most of these large reductions were in rural areas and/or towards the upstream end of the river. Full results for this analysis can be found in Appendix X. Using the provided results from the model run a handful of bridges on Stony Creek, Swift Creek, and the Tar Pamlico River mainstem were selected for further analysis. Table 39 shows which bridges were chosen for debris removal.

Table 39: Bridge Crossings for Debris Removal

River	HEC-RAS STA	Road Name
Tar Pamlico	741019.0	SR 1001, Ferrells Bridge Road
	797947.2	U.S. 401, S. Bickett Boulevard
	799733.6	SR 1229, S. Main Street
	840453.5	SR 1003, Simms Bridge Road
Swift Creek	176467.3	NC4, NC48
	178277.1	I-95 (SB)
	200780.6	SR 1003, Red Oak Road
Stony Creek	3823.341	US 301 Bypass, Wesleyan Boulevard
	4105.634	Tarrytown Center
	7031.708	SR 1616, Country Club Road
	8852.217	US 64 BUS
	14220.71	Jones Road
	16428.41	SR 1613, Winstead Ave
	23767.63	US 64 Bypass
	29307.08	SR1544, Halifax Road
	45240.22	SR 1603, Od Carriage Road
	59886.89	SR 1003, Red Oak Road
	66587.48	SR 1670, 1st Street
	73736.27	SR 1435, Wonble Road
	74974.13	US 64 (WB)
	75061.1	US 64 (EB)
	78094.67	NC 58, W. Washington St
	85124.11	US 64 Bypass (WB)
	101416.7	SR 1320, Vick Road

Figure 48 through Figure 50 show the locations of each of the bridges analyzed for debris removal.

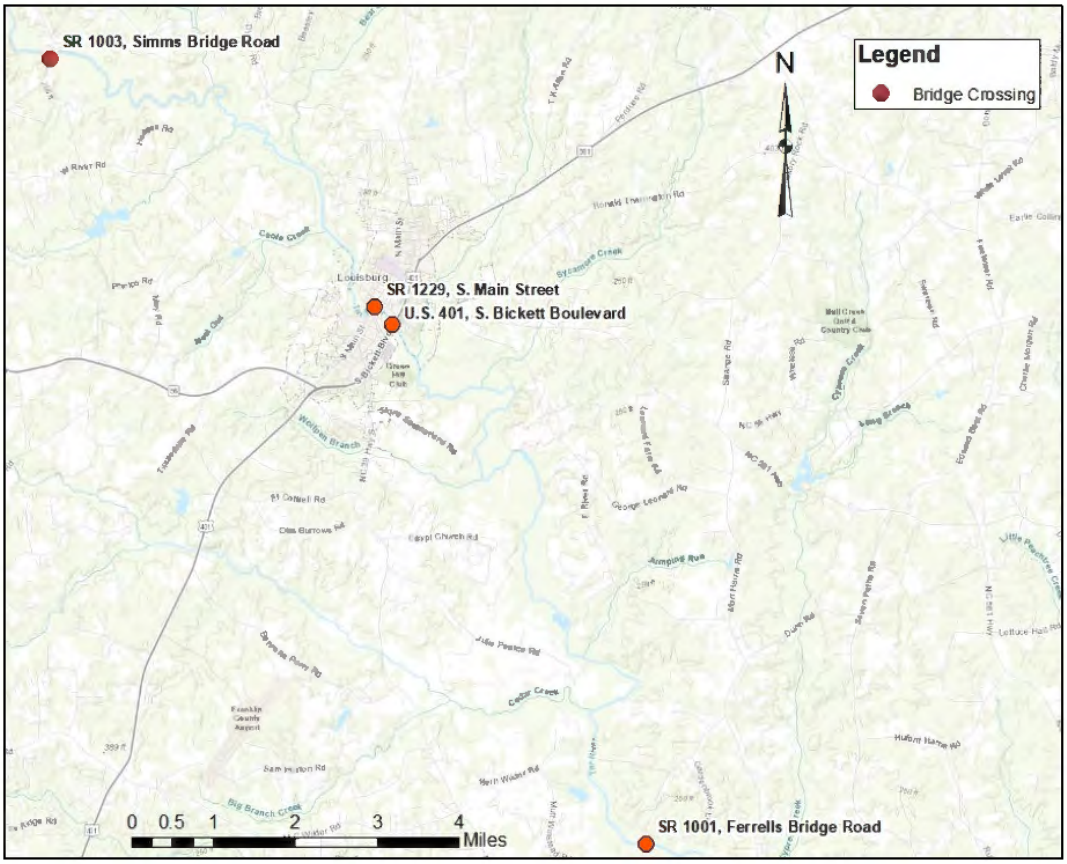


Figure 47: Tar Pamlico Bridge Crossings for Debris Removal

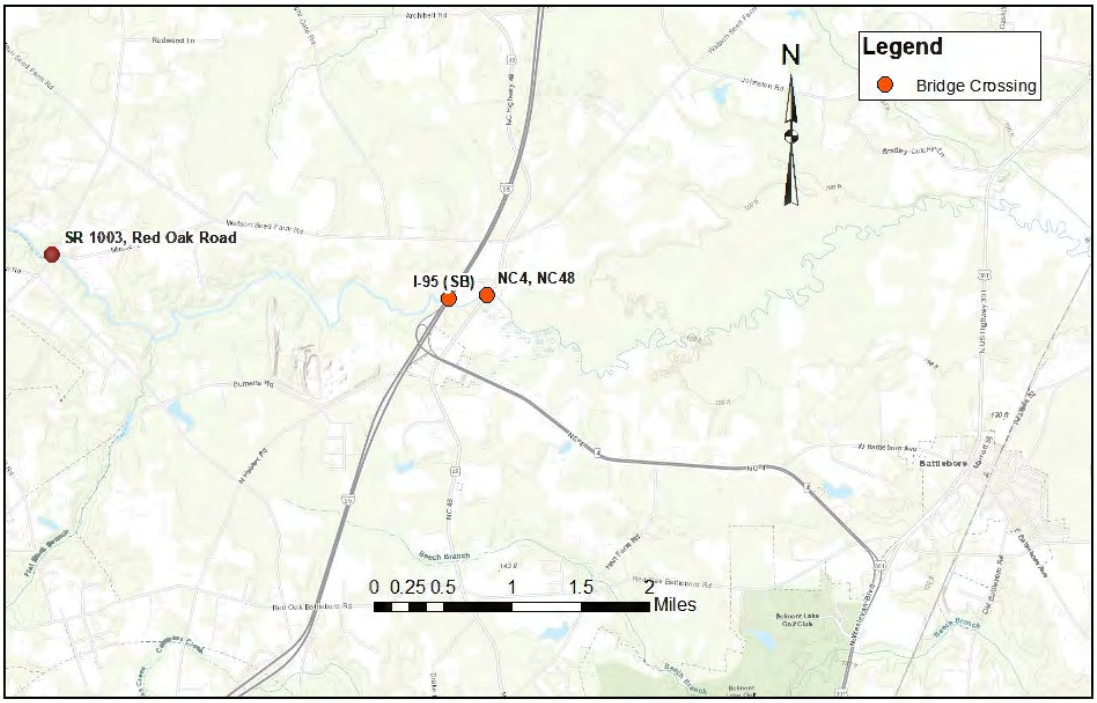


Figure 48: Swift Creek Bridge Crossings for Debris Removal

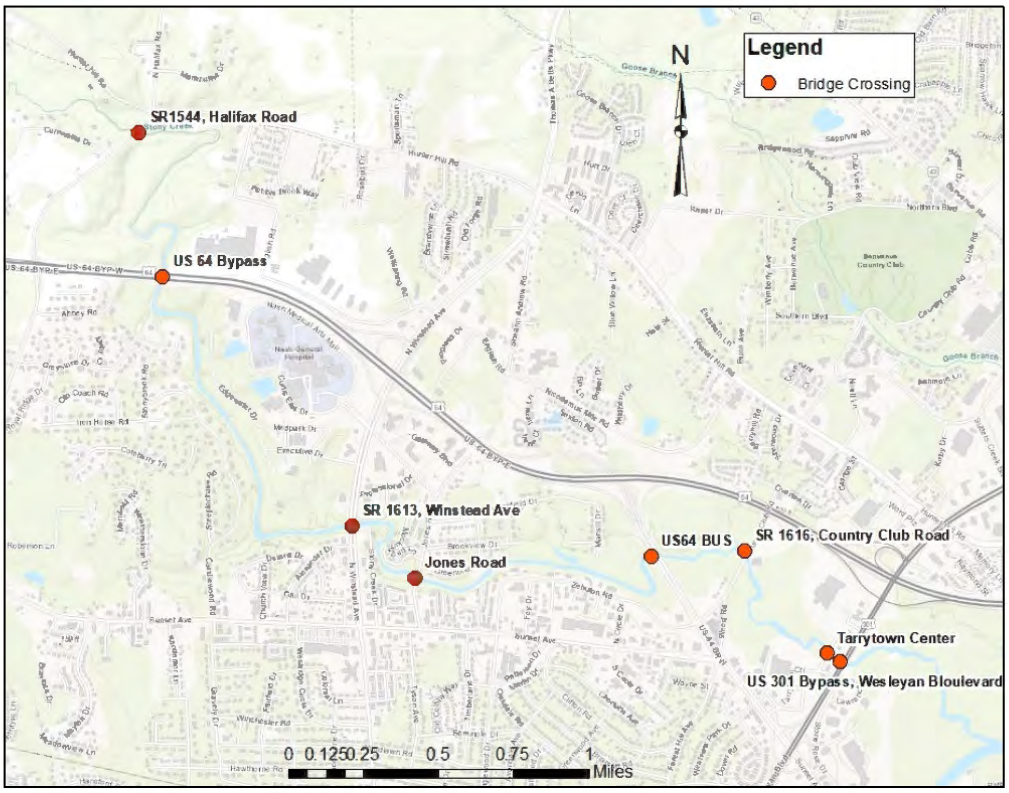


Figure 49: Tar Pamlico Bridge Crossings for Debris Removal

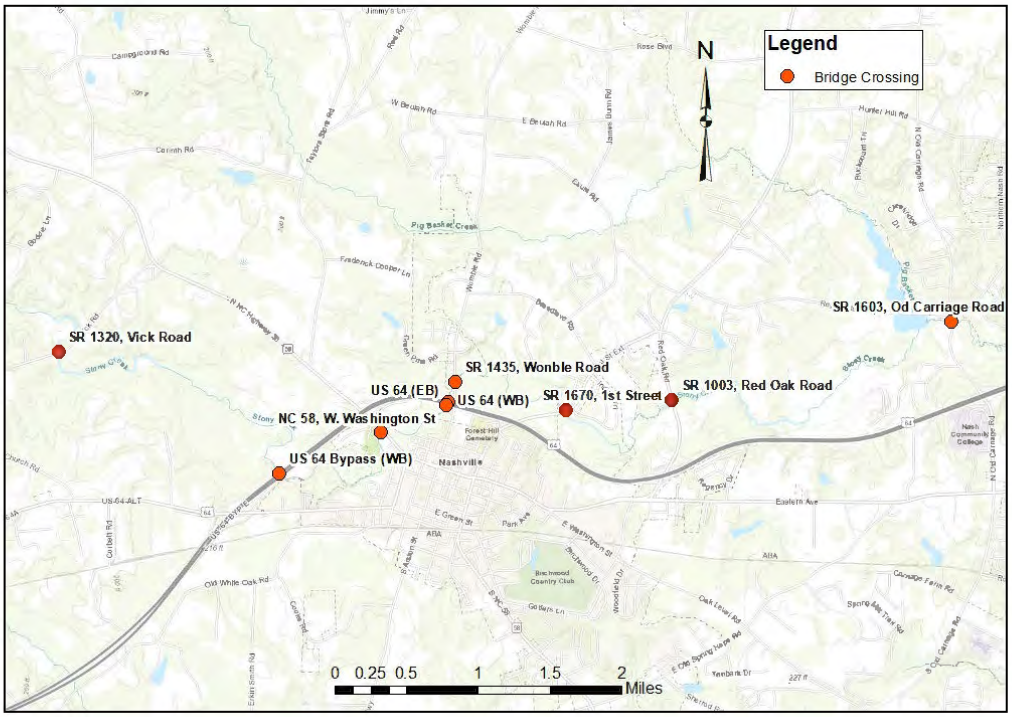


Figure 50: Tar Pamlico Bridge Crossings for Debris Removal

Table 40 shows the resulting decrease (negative number) in water surface elevation from 100% removal of debris when compared to the existing calibrated model. Full model results can be found in HEC – RAS Model.

Table 40: WSEL Differences with 100% Debris Removal

River	HEC-RAS STA	Effected Population Center	Return Period	Max. Δ WSEL (ft)	Avg. Δ WSEL (ft)
Tar Pamlico	840620.8 To 739026.9	Louisburg, NC	2-YR	-1.59	-0.44
			5-YR	-1.69	-0.35
			10-YR	-2.09	-0.37
			20-YR	-2.43	-0.40
			50-YR	-2.68	-0.45
			100-YR	-2.88	-0.49
			250-YR	-3.13	-0.54
			500-YR	-3.33	-0.58
Swift Creek	201074.0 To 175708.5	Battleboro, NC	2-YR	-0.11	-0.02
			5-YR	-0.18	-0.03
			10-YR	-0.36	-0.06
			25-YR	-0.60	-0.10
			50-YR	-0.65	-0.14
			100-YR	-1.23	-0.10
			250-YR	-0.51	-0.15
			500-YR	-0.68	-0.06
Stony Creek	101575.3 To 3702.674	Rocky Mount & Nashville, NC	2-YR	-0.09	-0.01
			5-YR	-0.20	-0.02
			10-YR	-0.37	-0.03
			25-YR	-0.71	-0.05
			50-YR	-1.44	-0.09
			100-YR	-1.95	-0.14
			250-YR	-2.12	-0.24
			500-YR	-1.88	-0.12

Table 41 shows the resulting decrease (negative number) in water surface elevation from 50% removal of debris when compared to the existing calibrated model. Full model results can be found in HEC-RAS Model.

Table 41: WSEL Difference with 50% Debris Removal

River	HEC-RAS STA	Effected Population Center	Return Period	Max. Δ WSEL (ft)	Avg. Δ WSEL (ft)
Tar Pamlico	840620.8 To 739026.9	Louisburg, NC	2-YR	-1.54	-0.42
			5-YR	-1.61	-0.33
			10-YR	-1.99	-0.34
			25-YR	-2.31	-0.37
			50-YR	-2.54	-0.41
			100-YR	-2.72	-0.44
			250-YR	-2.94	-0.48
			500-YR	-3.09	-0.52
Swift Creek	201074.0 To 175708.5	Battleboro, NC	2-YR	-0.09	-0.01
			5-YR	-0.16	-0.02
			10-YR	-0.32	-0.05
			25-YR	-0.55	-0.09
			50-YR	-0.61	-0.13
			100-YR	-1.22	-0.09
			250-YR	-0.52	-0.15
			500-YR	-0.55	-0.05
Stony Creek	101575.3 To 3702.674	Rocky Mount & Nashville, NC	2-YR	-0.06	-0.01
			5-YR	-0.13	-0.01
			10-YR	-0.26	-0.02
			25-YR	-0.55	-0.04
			50-YR	-1.22	-0.07
			100-YR	-1.06	-0.11
			250-YR	-2.02	-0.19
			500-YR	-1.75	-0.10

6.2 Alternative 5A- Channel Diversions (S11 & Other Screened Locations)

The goal of this alternative was to evaluate the water surface profile changes due to a constructed diversion channel, Diversion Channel #4 while not inducing flood damage or transferred flood risk to the surrounding public at large. Diversion Channel #4 is located south of Tarboro and Princeville, NC and runs roughly parallel to the Tar Pamlico River for approximately 3.6 miles, see Figure 52.

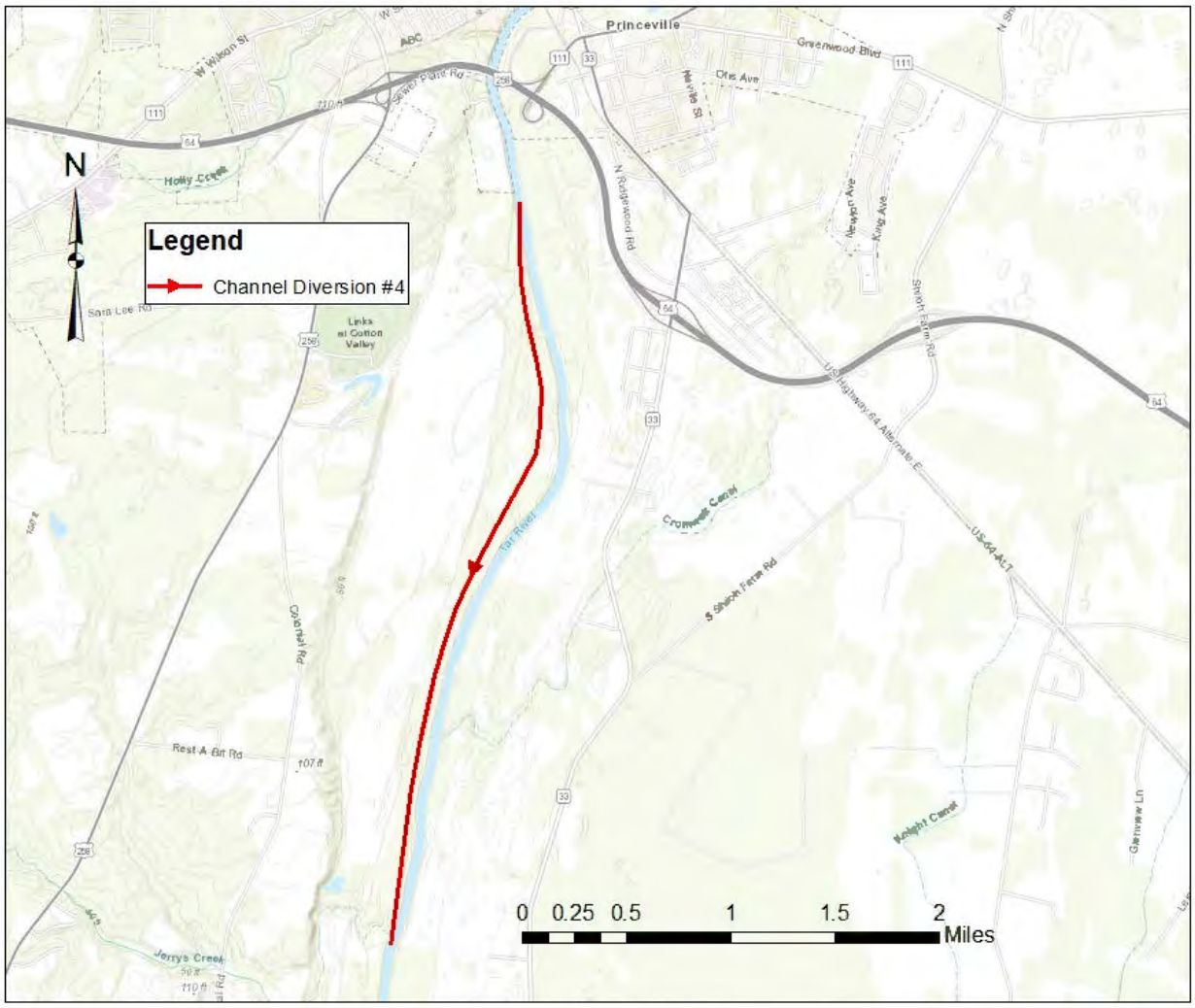


Figure 51: Diversion Channel #4 Location Map

Approach & Methodology

The scope of this assessment called for evaluating the water profile drop for the construction of a diversion channel that has roughly the same channel capacity of the existing Tar River. The existing conditions terrain used to calibrate the model show the Tar River in this area to be roughly 160 feet wide with side slopes approximately at 1V:5H, see Figure 53.

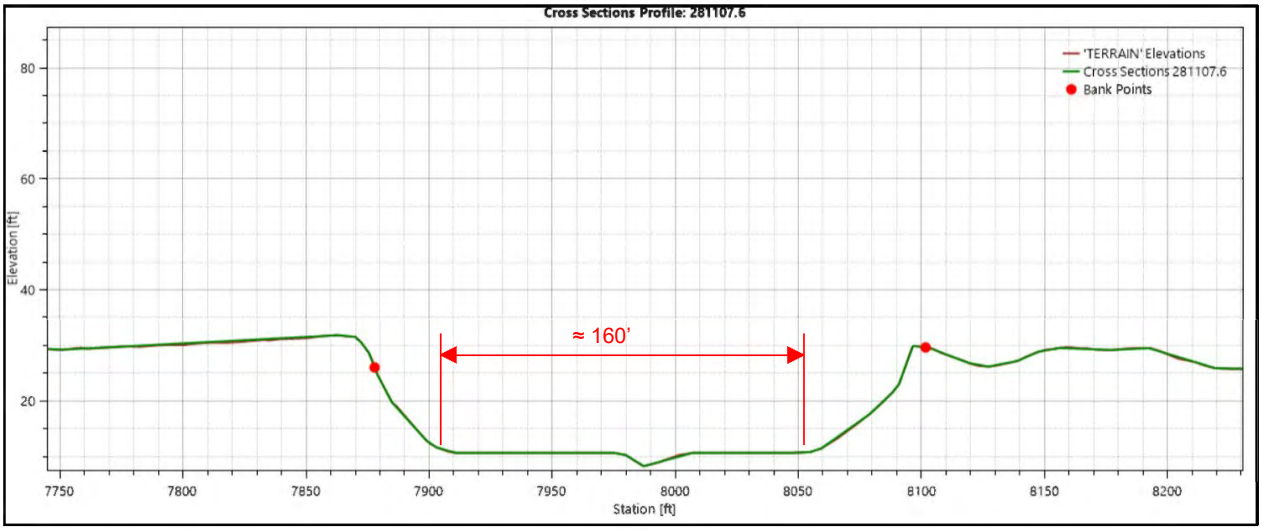


Figure 52: Tar River Existing Cross Section

Given the geometry of the existing channel, a Diversion Channel #4 having a trapezoid cross section with a width of 160 feet and 1V:5H side slopes was entered in to HEC-RAS cross sections 289972.2 through 272426. The channel was then assigned a Manning's n value of 0.05, matching that of the existing conditions model for the Tar River, see Figure 54. It should be noted that the channel geometry and Manning's n value was selected only based on replicating the existing Tar River. This diversion channel does not in any way reflect a stable channel design and/or reflect a Manning's n representative of a constructed channel material.

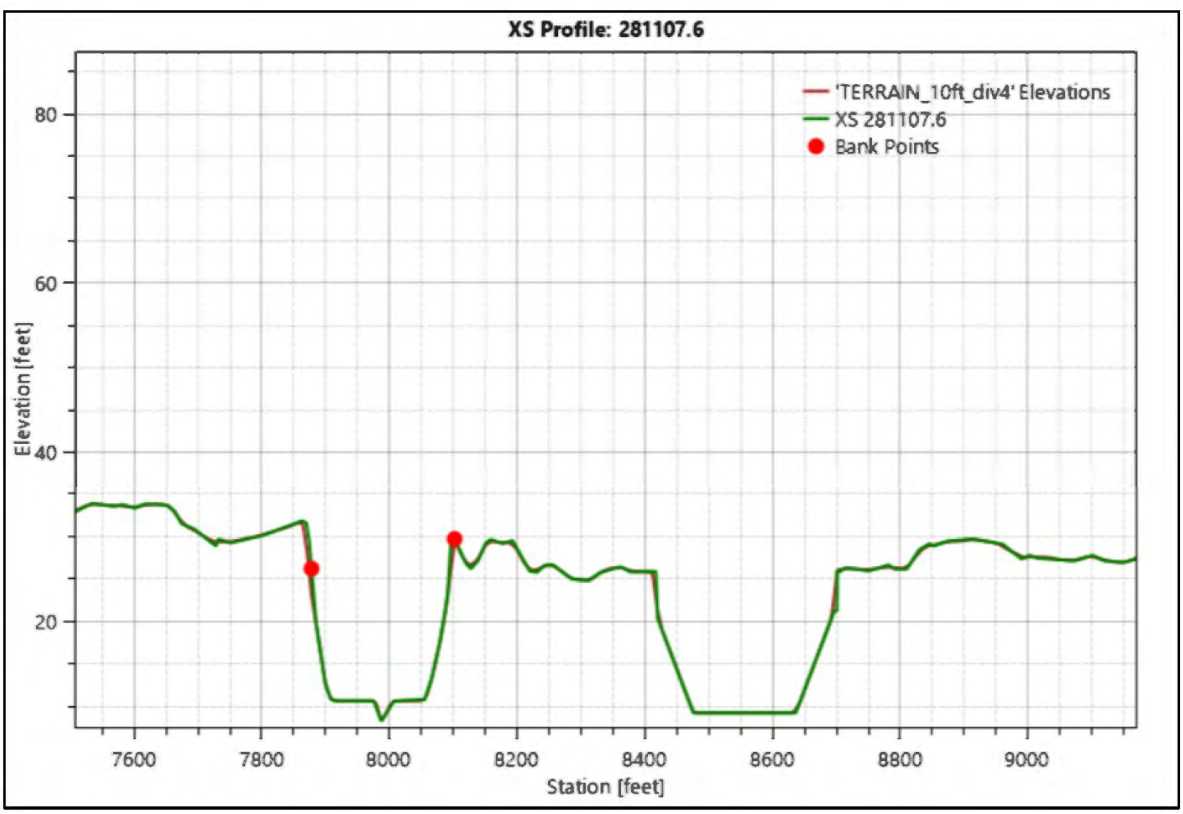


Figure 53: Tar River with Diversion Channel #4 Cross Section

The diversion channel was not modeled to receive high water over a levee or modeled separately as its own reach within HEC-RAS. It was simplistically modeled to be serve as extra conveyance for the main Tar River. HEC-RAS' levee feature was added to the high ground between the main Tar River and the diversion channel to simulate flow in the diversion channel only when flood waters are high enough.

Results

Figure 55 shows the resulting water surface profiles for the evaluation of Diversion Channel #4. The diversion channels are shown against the existing conditions model. The profiles shown are for the 5-year and 100-year events. These two events were shown to provide examples of the flood water reductions due to Diversion Channel #4. One can see that there is larger difference in water surface elevations for larger (less common) events compared to smaller (more frequent events). Complete model results can be found in HEC-RAS Model.

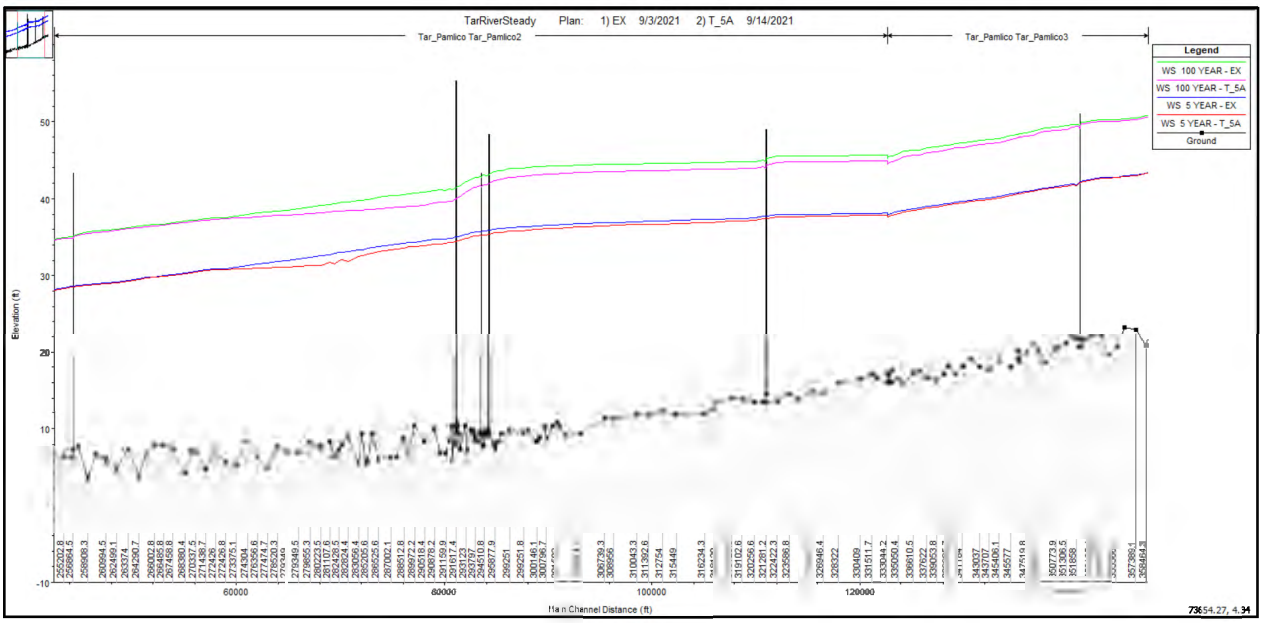


Figure 54: Example Water Surface Profile Reductions

Table 42: WSEL Difference with 50% Debris Removal

River	HEC-RAS STA	Effected Population Center	Return Period	Max. Δ WSEL (ft)	Avg. Δ WSEL (ft)
Tar Pamlico	362338.4 To 272426	Princeville/Rocky Mount, NC	2-YR	-1.29	-0.37
			5-YR	-1.33	-0.41
			10-YR	-1.67	-0.65
			25-YR	-1.60	-0.71
			50-YR	-1.66	-0.88

River	HEC-RAS STA	Effected Population Center	Return Period	Max. Δ WSEL (ft)	Avg. Δ WSEL (ft)
			100-YR	-1.66	-0.88
			250-YR	-1.57	-0.88
			500-YR	-1.45	-0.76

6.3 Transportation Modification Increase in Structure Conveyance (S25 & S10)

The transportation modification alternative seeks to identify major hydraulic structures that have the most opportunity for increased conveyance by consideration of additional culverts, bridge removal, and/or modification to bridge span/culvert. The predominant goal is to maximize water surface elevation reduction around urbanized areas where inundation from flooding is likely to have negative impacts.

Selection of hydraulic structures locations that would give the most benefit to reduction of flood inundation were determined through a collection of several different strategies. The first being a visual inspection of each modeled bridge using different frequency profiles to determine which structures significantly increase water surface elevation Figure 56.

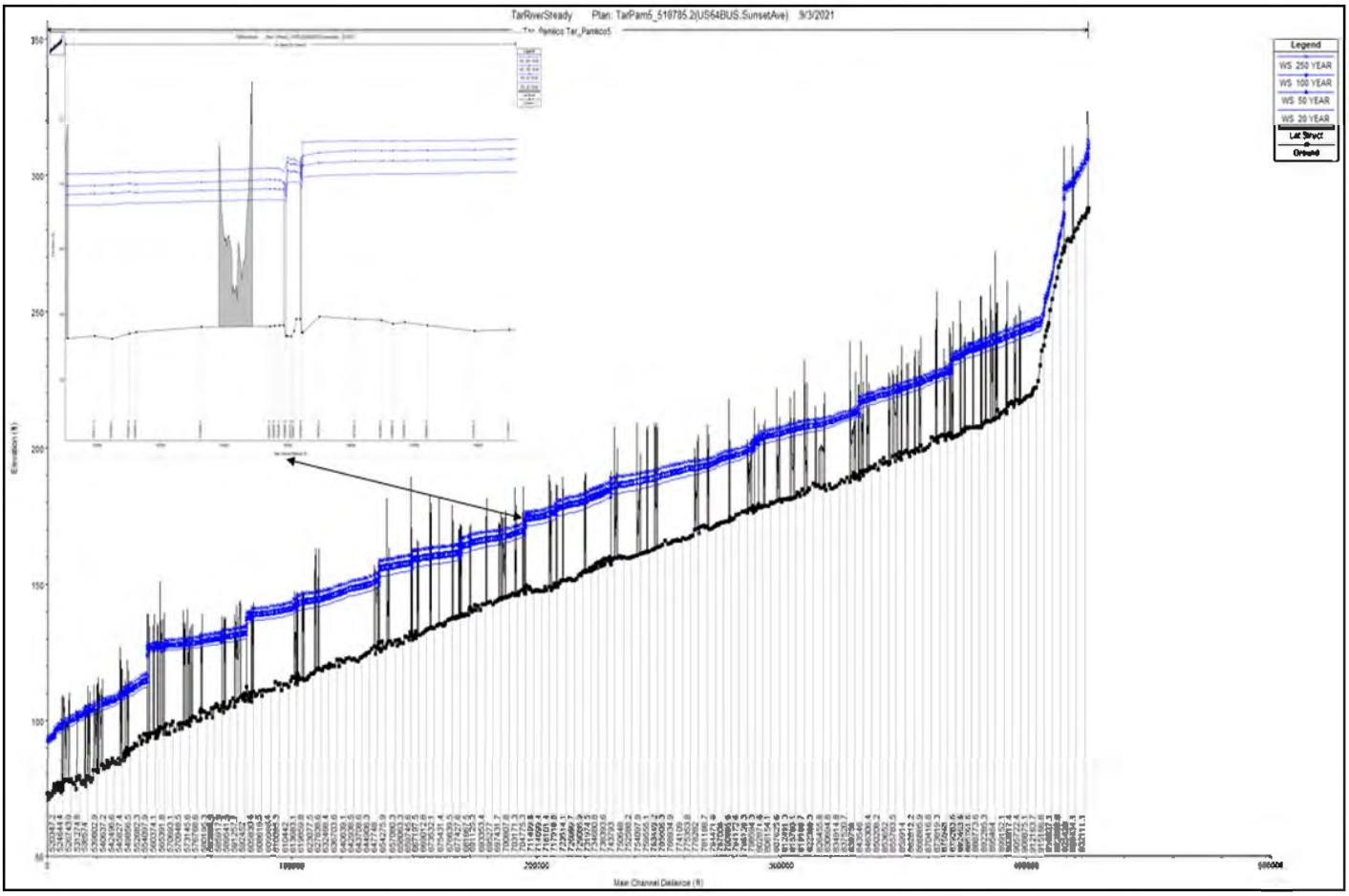


Figure 55: Water Surface Elevation Profile Inspection near Hydraulic Structures

Noted locations of interest were then compared with structure/municipal data to make final determinations of which hydraulic structures would be best suited for modification. An example location shown in Figure 2 shows a potential restriction from two bridges on Stoney Creek. Red points signify structures that could be negatively impacted by this restriction and therefore was analyzed in task 2N and 2O (See Table 1).

The same approach was used throughout the entire model which identified a total of seventeen bridge locations where increased water surface elevation in urbanized areas are susceptible to flood inundation (see Table 1). To verify the magnitude of impact that each hydraulic structure on areas of interest, a steady state hydraulic model was created using HEC-RAS.

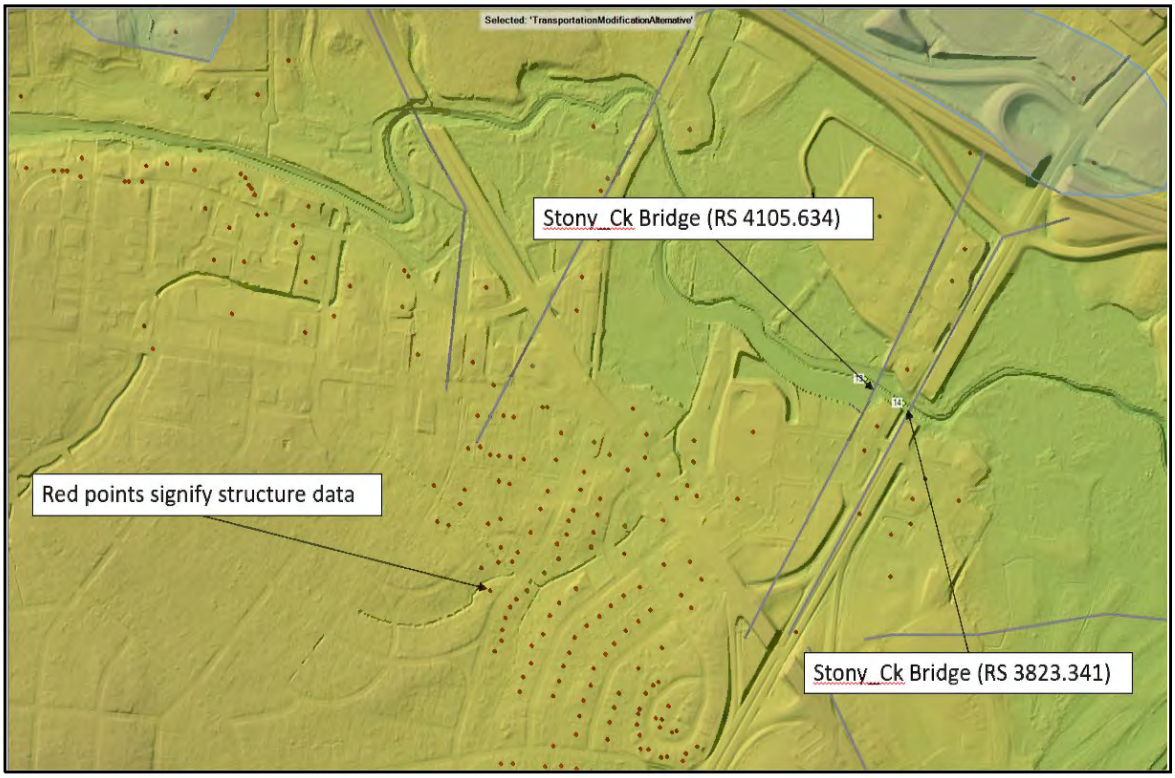


Figure 56: Area of interest example

Table 43: Identified Hydraulic Structure Locations – Task 2 (S25) Sub-Alternatives

ALT ID	Geometry Name	Reach	River Station	Description
2A	TarPam5_799733.6(SR 1229, S. Main St.)	Tar_Pamlico5	799733.6	SR 1229, S. Main St.
2B	TarPam5_797947.2(US401 NC39, S.Bickett)	Tar_Pamlico5	797947.2	US401, NC 39, S Bickett Blvd.
2C	TarPam5_705499.8(AbandonedRailroad)	Tar_Pamlico5	705499.8	Railroad
2D	TarPam5_593213.3(SR 1981, TarRiverChrRd)	Tar_Pamlico5	593213.3	SR 1981, Tar River Church Rd.
2E	TarPam5_518785.2(US644BUS,SunsetAve)	Tar_Pamlico5	518785.2	US64BUS, Sunset Ave.
2F	TarPam4_505350.2(PeachtreeSt,Benvenue)	Tar_Pamlico4	505350.8	Peachtree St, Benvenue Rd, NC48
2G	TarPam4_505110.2(NC43BUS,NC48,FallsRd)	Tar_Pamlico4	505110.2	NC43 BUS, NC48, Falls Rd.
2H	TarPam4_495459.8(US64E)	Tar_Pamlico4	495459.8	US64E
2I	TarPam2_29176.2(Hwy64BYP)	Tar_Pamlico2	291762.5	Hwy. 64 BYP
2J	TarPam1_180732.2(US264,WBL)	Tar_Pamlico1	180732.2	US264 WBL
2K	TarPam1A_88182(SR1565,GrimeslandBrRd)	Tar_Pamlico1A	88182	SR 1565, Grimesland Bridge Rd.
2L	StonyCr_78094.67(NC58,W.WashingtonSt)	Stony_Ck	78094.67	NC58, W. Washington Street
2M	StonyCr_59886.89(SR1003)	Stony_Ck	59886.89	SR 1003
2N	StonyCr_4105.634(LoopRd,TarryTn,Gotham)	Stony_Ck	4105.634	Loop Rd. Tarrytown Center, Gotham Ln.
2O	StonyCr_3823.341(US30ISBYP,WesleyanBlv)	Stony_Ck	3823.341	US301SBYP, Wesleyan Blvd.
2P	Fishing_214506.3(Railroad)	Fishing_Ck	214506.3	Railroad
2Q	Fishing_212720.6(US301)	Fishing_Ck	212720.6	US301

To fully maximize conveyance a HEC-RAS geometry file was created for each location of interest to first analyze the effect of bridge removal. Each of the geometry simulations removed only one bridge,

and results compared to an existing condition water surface profile for frequency events ranging from 20 year to 250 year. The figure below shows task 2K (Figure 3). In this scenario the green inundation is shown to be slightly less than the existing condition model for the 100-year frequency

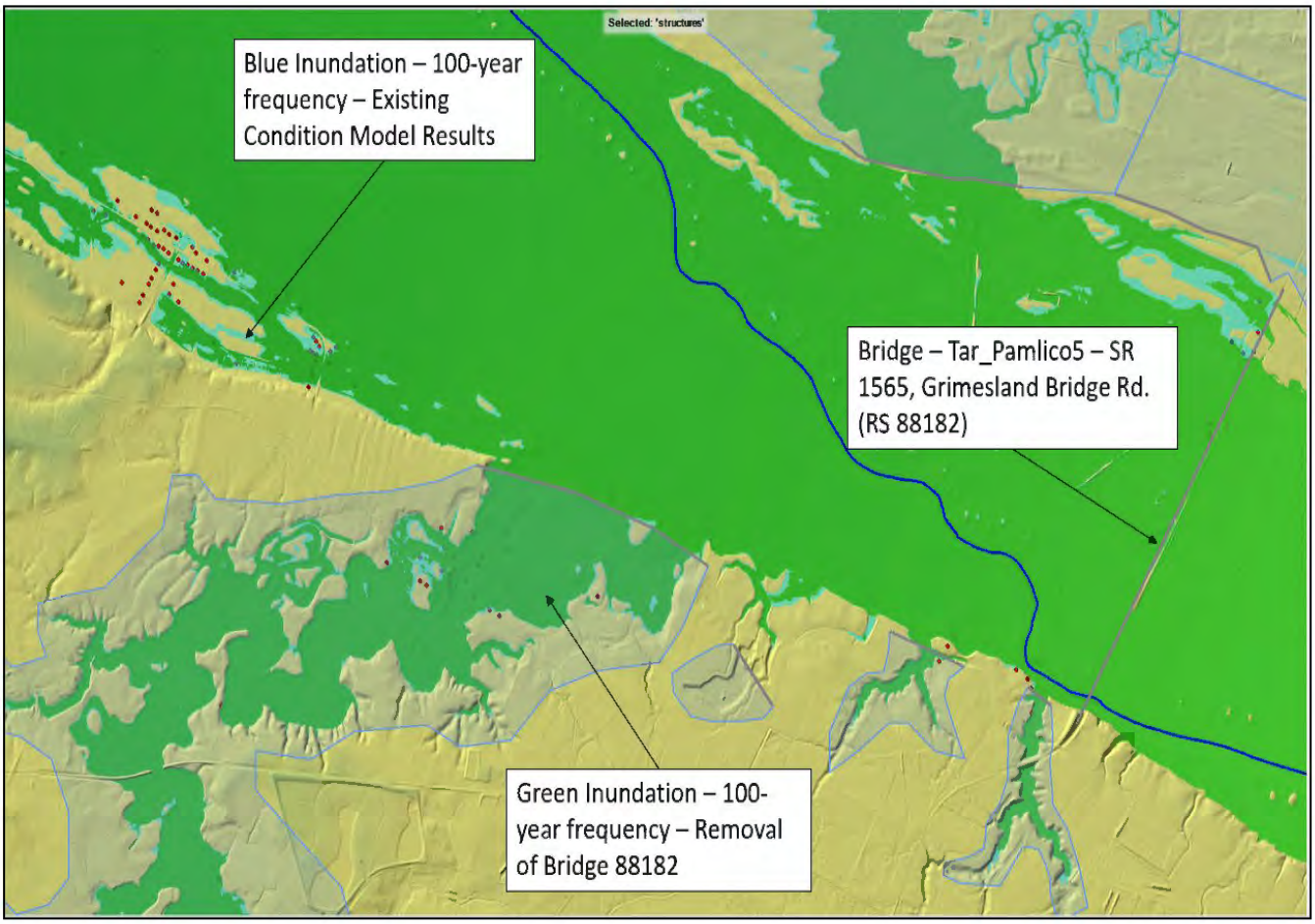


Figure 57: Changes in water surface elevation compared to FWOP inundation (Task 2K)

Each bridge removal scenario, like the one shown in Figure c, when compared against the existing condition scenario were found to be negligible in all cases. Only three bridges were found to have any improvement to inundation around structure data. Those three bridges are listed in Table 44 below.

Table 44: Identified hydraulic structure locations for Task 2 evaluation

Task Identifier	**Geometry Name**	**Reach**	**River Station**	**Description**
2D	TarPam5_593213.3(SR 1981, TarRiverChrRd)	Tar_Pamlico5	593213.3	SR 1981, Tar River Church Rd.
2J	TarPam1_180732.2(US264,WBL)	Tar_Pamlico1	180732.2	US264 WBL
2K	TarPam1A_88182(S R1565,GrimeslandBr Rd)	Tar_Pamlico1A	88182	SR 1565, Grimesland Bridge Rd.

For each of the locations mentioned in Table 43, a comparison of water surface profile differences to the existing condition were analyzed.

An example of this is the Grimesland Bridge, located approximately 7 miles west of Washington, NC. A water surface elevation comparison for the 100-year frequency gives a -1.64 ft difference if the bridge were totally removed. It should also be noted that the effects of bridge removal are noticed approximately 10 miles upstream, the biggest difference (-1.64 ft) being at the bridge location. This can be seen in Figure 48 and 49 below. A list of all water surface elevation comparisons can be found in Table 44.

Removal of the bridge causes a reduction upstream of the bridge, but a 0.76 ft increase in water surface downstream, which would ultimately transfer flood risks, therefore this alternative has been screened for 1) effectiveness, and 2) transference of flood risk. As for the other two scenarios the water surface difference was present upstream but did not seem to affect the water surface downstream.

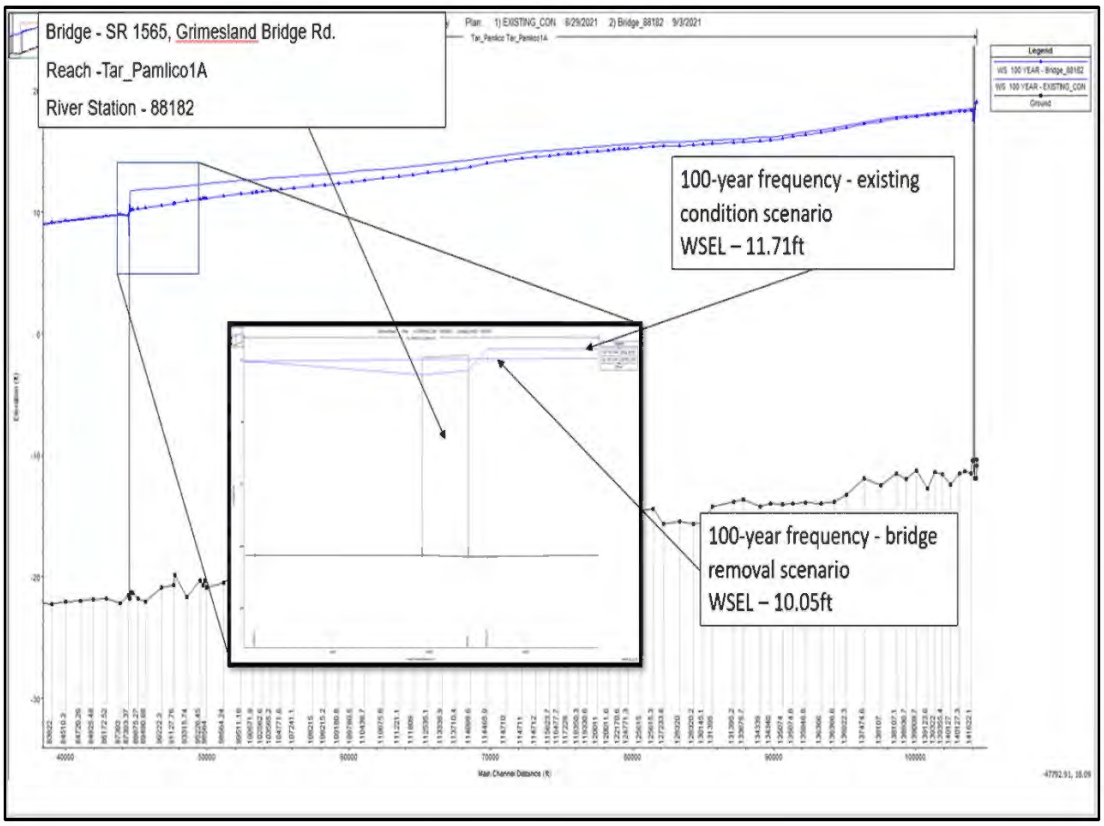


Figure 58: Changes in WSEL compared to FWoP (Task 2K)

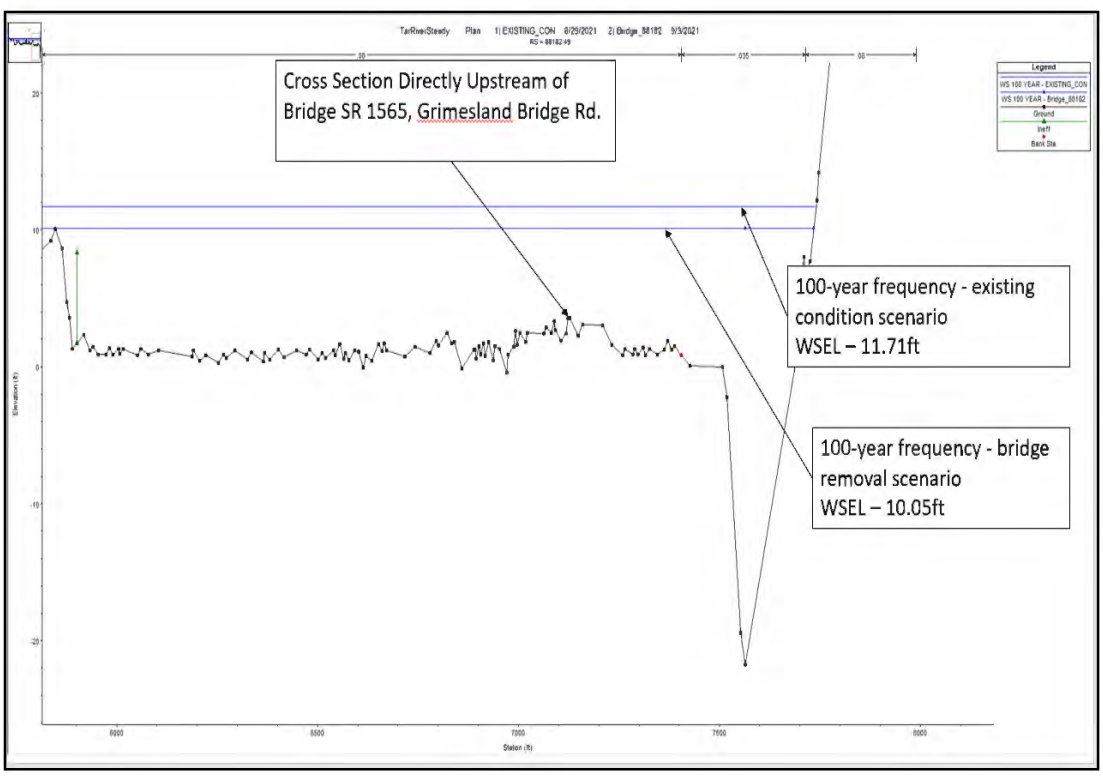


Figure 59: Cross section US of Bridge WSEL Comparison (Task 2K)

Table 45: Water surface elevation comparisons

Location Reference	Cross Section Reference	Recurrence Interval	WSEL Comparison (feet)	Distance from Bridge (miles)
10 miles southwest of Rocky Mount	Tar_Pamlico5 593213.3	25-year	-5.45	US – 1.13 DS – 1.28
		50-year	-5.21	
		100-year	-5.02	
		250-year	-5.11	
		500-year	-5.02	
3 miles west of Greenville	Tar_Pamlico1 180732.2	25-year	-0.278	US – 5.66 DS – 3.68
		50-year	-0.366	
		100-year	-0.422	
		250-year	-0.563	
		500-year	-1.07	
7 miles west of Washington	Tar_Pamlico1A 88182	25-year	-0.456	US – 9.55 DS – 4.45
		50-year	-1.07	
		100-year	-1.64	
		250-year	-2.79	
		500-year	-1.07	

Although improvement did occur for some structures throughout the model domain, the overall benefit is negligible and does not address solutions to basin wide flooding that effects residential and commercial structures. Because total removal of hydraulic structures did not address a feasible solution, assessment of structure improvements to enhance conveyance was not analyzed.

6.4 Rocky Mount Run of River Removal (S28)

The Rocky Mount run of river modification alternative seeks to estimate water surface elevation reductions for each annual chance exceedance probability by removing the low head hydraulic structure. The Rocky Mount Mill Dam is a low head dam located just downstream of Falls Road (see Figure 1 below).

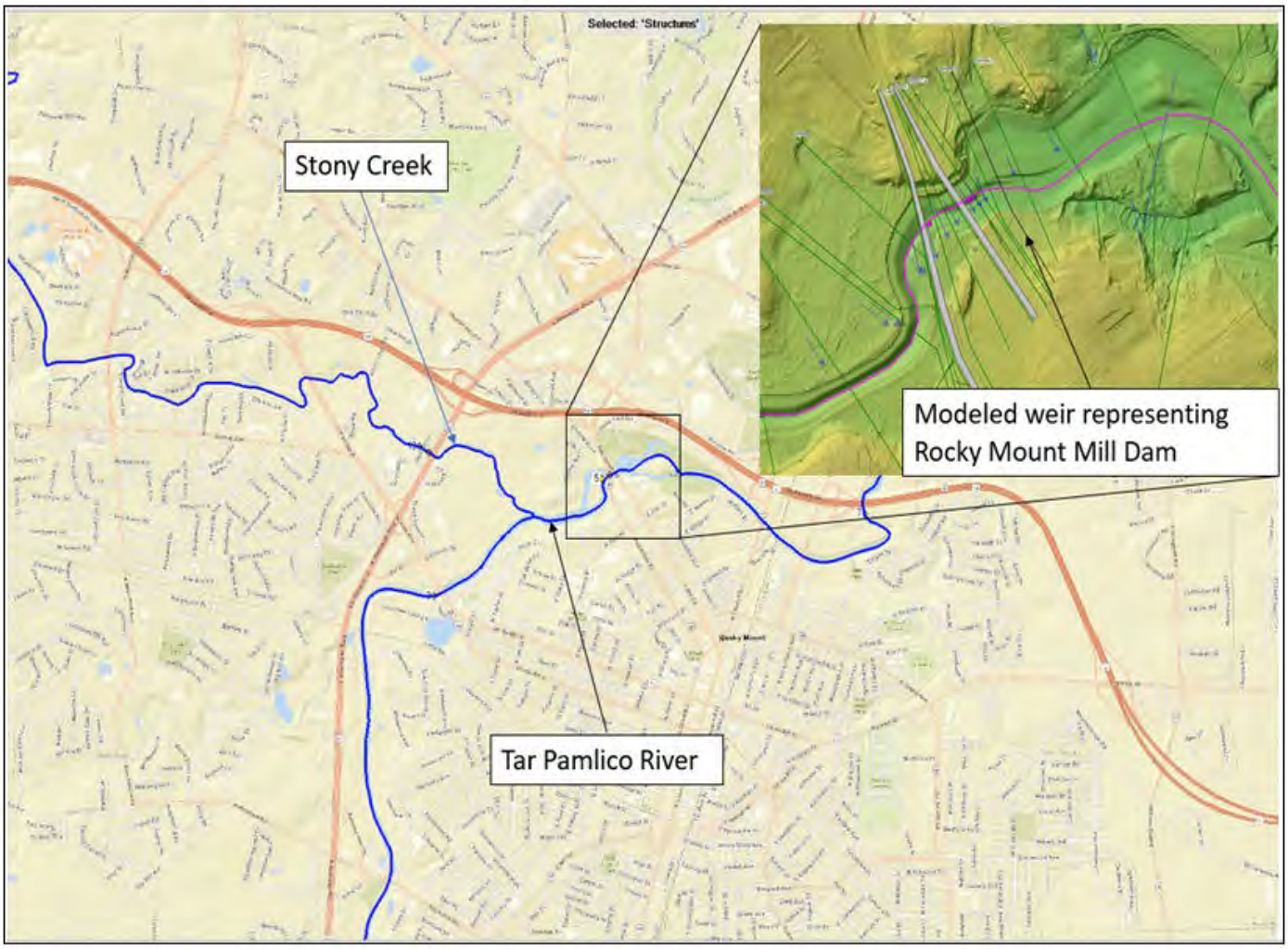


Figure 60: Location of Rocky Mount Mill Dam

A similar assessment was performed in a 2018 Tar River Basin Food Analysis and Mitigation Strategies Study conducted by North Carolina Emergency Management and the North Carolina Department of Transportation (NCDOT). In mitigation scenario 10 named Rocky Mount Mill Dam Removal, it was noted removal of the dam can decrease flooding in the Tar Pamlico River for various frequency profiles. This seemed to be especially true for lower magnitude events.

Impacts of dam removal were also considered as part of the 2018 study. It was found that removal of the dam would cause lower water levels necessary for the City of Rocky Mount water intake and water treatment plant on Sunset Avenue. Finding show that during low flow periods the plant would not be able to extract sufficient water volume at the plant intake. As a result, the existing water treatment plant would have to be relocated to a new site, although cost and location were not estimated. Pertinent data associated with the structure was received by the municipality shown in Table 46.

Table 46: Rocky Mount Low Head Dam pertinent data

Dam Type	Stone Masonry
Dam Height (Max Section)	15 ft
Dam Hydraulic Height (Max Section)	15 ft
Dam Crest Length	740 ft (including abutments) 600 ft per NC Dam Inventory
Dam Crest Width	4 ft
Dam Crest Elevation (1981 Phase 1 Report) Dam Crest Elevation 2015 Mack Gay Survey	EL 84.1 (assumed NGVD29 datum) EL 83.2 (NAVD88)
Dam Upstream Slope	Assumed Vertical
Dam Downstream Slope	Vertical
Normal – August Mean[2]	EL 83.5
Normal – March Mean[2]	EL 84.4
Spillway Type	Straight Drop with Max Drop of 15 ft
Bottom Drain	2 Sluice Gates, Electro-Mechanically Operated, 10 ft wide by 10 ft tall
Storage Capacity at Top of Dam	224 acre-ft

The existing model used as part of the existing conditions steady state model was found to not have the Rocky Mount Mill low head dam modeled as part of the geometry. Because of this, this alternative steady state HEC-RAS model compared an existing condition geometry, that excluded the weir, to a modified geometry that includes the weir.

Modeling results show that maximum water surface elevations for frequencies ranging from 20-year to 250-year have a negligible impact between the two scenarios. The largest difference occurs at lower frequencies, which in the case shown in Figure 2 is a 20-year event with a 0.3 ft difference. This difference in water surface elevation spans from the Falls Road Bridge to the Rocky Mount low head dam, which is about 300 ft. Peak discharge profiles upstream and downstream of these two locations converge and appear to be the same.

6.5 Offline Detention, Water Farming (NNB2)

The offline detention alternative seeks to identify potential sites for increased storage in the overbanks with the primary objective of estimating required storage to reduce water surface elevation for the 100-year frequency event.

Before any offline storage was estimated, site locations were first established where detention basins are thought to be most effective for reduces water surface elevations. These locations include Fishing Creek, Stony Creek, Swift Creek, and the Tar Pamlico River from Rocky Mount to Conetoe Creek. Other considerations within these locations include areas were there would be limited impacts to existing structures, bridges, and major highway systems. Once each site had been identified, all

locations were presented to the Project Delivery Team (PDT) for further discussion. Using this approach, a total of ten locations were selected and listed in Table 46 below.

Table 47: Identified detention basin locations

Task	Location	Reach	Near River Station	Proposed Basin Area (sq. mi.)
10A	Swift Creek (Wake Stone Corps)	Swift_Ck	186822.8	0.43
10B	Fishing Creek (Downstream of Franklington)	Fishing_Ck	179771.7	7.36
10C	TarPam4 (Adjacent to Pittman Grove)	Tar_Pamlico4	467337	1.87
10D	TarPam3 (Adjacent to Belvedere)	Tar_Pamlico4	380939	2.77
10E	TarPam2 (Adjacent to West Tarboro)	Tar_Pamlico2	311392.6	17.65
10G	Upstream of the US301 Bridge	Fishing_Ck	234058.8	0.33
10F	Downstream of the SR 1343, White Oak Rd Bridge	Fishing_Ck	300526.2	0.29
10H	Hanson Aggregates near Rock Mount	Tar_Pamlico4	48120	0.12
10I	Hanson Aggregates near Rock Mount	Tar_Pamlico4	480345	0.08
10J	Upstream/Downstream of the SR 1243, Leggett Road Bridge	Tar_Pamlico4	477500	1.49

Out of the ten locations mentioned in Table 1, only five were selected for further analysis as conceivable sites for detention basin storage. Most excluded locations (Task 10G to 10I) had a negligible reduction in total inflow volume, which was estimated to be five percent or less of the total volume. Only one of the excluded locations (Task 10J) was ruled out specifically for the exceptional number of impacted structures, roads, and bridges. A location near that of Task 10J was selected because of this (see Task 10C). Locations selected for further analysis (Task 10A to 10E) based on reduction in total volume and a potential for lesser number of economic impacts are shown in Table 2 below.

Table 48: Detention basin locations for further analysis

Task	Location	Reach	Near River Station	Proposed Basin Area (sq. mi.)
10A	Swift Creek (Wake Stone Corps)	Swift_Ck	186822.8	0.43
10B	Fishing Creek (Downstream of Franklington)	Fishing_Ck	179771.7	7.36
10C	TarPam4 (Adjacent to Pittman Grove)	Tar_Pamlico4	467337	1.87
10D	TarPam3 (Adjacent to Belvedere)	Tar_Pamlico4	380939	2.77
10E	TarPam2 (Adjacent to West Tarboro)	Tar_Pamlico2	311392.6	17.65

For each identified location, shown in Table 2, detention basin dimensions were estimated purposely to determine peak storage volumes primarily for the 100-year frequency. Estimates were made with a few necessary assumptions, particularly that each detention basin is thirty foot in depth with a 3:1 side slope. This was the assumption for all Tasks in Table 2, except for Task 10A, Swift Creek. For Task 10A the area in and around the Wake Stone Corporation was assumed to be excavated to

elevation forty feet above sea level, which on average is about eighty foot below the existing ground surface in most locations.

Using these assumptions, along with a detention basin calculator from the Federal Highways Administration, an elevation-storage-discharge was developed individually for each site. An example of the resulting storage curve can be seen in Figure A below, which shows calculated storage for Task 10A, Swift Creek.

Total storage for each task was constructed using similar methods as those described for Task 10A above, with results displayed in Table 3 below. With each storage curve, a simplified HEC-HMS model was created with the aim of diverting flow exclusively to maximize total detention basin storage, thus reducing the peak water surface elevation for the 100-year frequency event in downstream locations. A diversion in the HEC-HMS modeling software is an element with two outflows, main and diverted, and one or more inflows.

Inflow hydrographs used in the simplified model analysis came from an already existing basin wide HEC-HMS model described in previous sections. The synthetic hydrographs were developed using precipitation-based methods for various frequency-based events To resolve this, inflow hydrograph peaks in the existing HEC-HMS were scaled to be like that of those peaks in HEC-RAS. This ensures that when the diversion is maximized in simplified HEC-HMS, the reduction in peak flow is then used to compare water surface elevations in the HEC-RAS steady state model.

Table 49: Detention basin total storage used in HEC-HMS diversion

Task	**Location**	**Reach**	**Total Estimated Storage (Acre-ft)**	**Assumed Detention Basin Depth (feet)**	**Proposed Basin Area (sq. mi.)**	**Inflow volume reduction (Percent)**
10A	Swift Creek (Wake Stone Corps)	Swift_Ck	22,605	80	0.43	38%
10B	Fishing Creek (Downstream of Franklington)	Fishing_Ck	26,000	10	7.36	17%
10C	TarPam4 (Adjacent to Pittman Grove)	Tar_Pamlico4	35,921	30	1.87	16%
10D	TarPam3 (Adjacent to Belvedere)	Tar_Pamlico4	37,368	30	2.77	16%
10E	TarPam2 (Adjacent to West Tarboro)	Tar_Pamlico2	339,125	30	17.65	51%

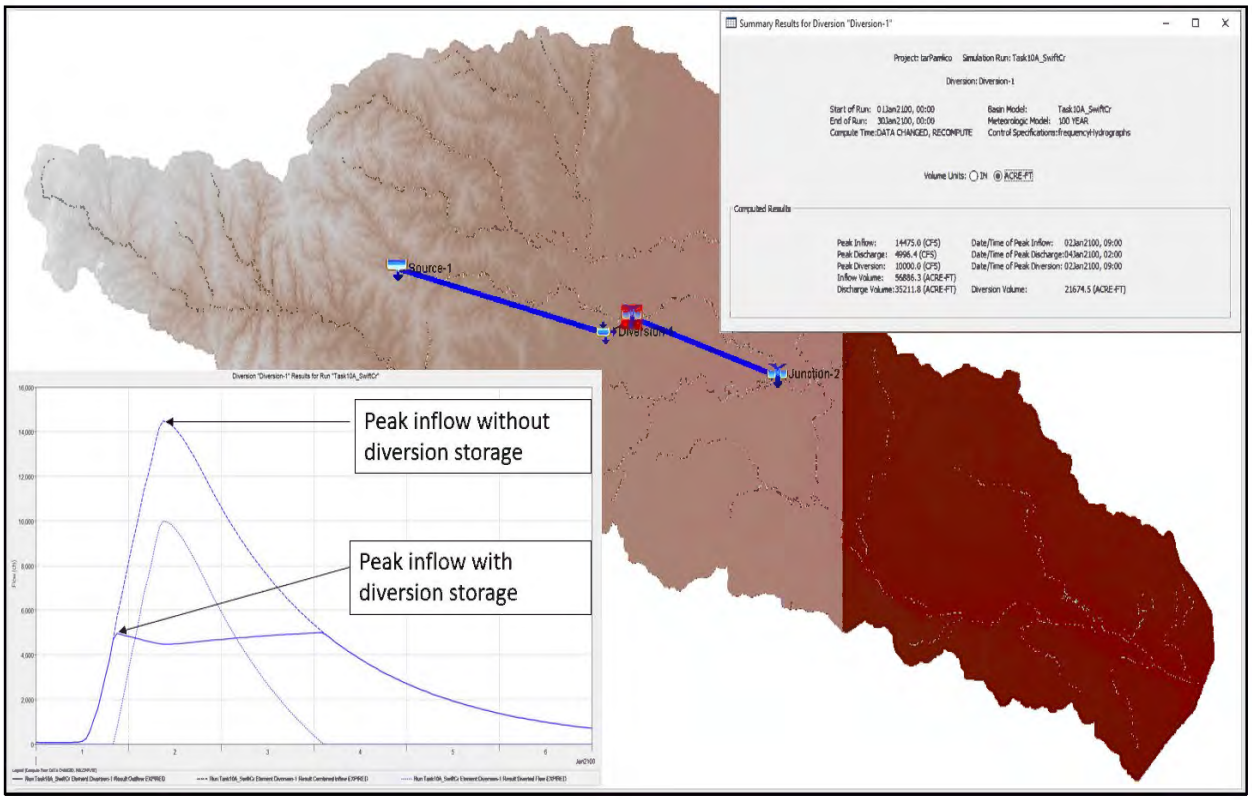


Figure 61: Task 10A reduced peak from diverted inflow

In the example of Task 10A shown in Figure 2, peak inflow was reduced because of diverted storage from 14,475 cfs to approximately 5,000 cfs. Maximum benefit to reduce the peak inflow was detected through an iterative process that was dependent on when detention storage was initiated. For instance, in the example of Task 10A, the maximum reduction was achieved when flow was diverted beginning at 5,000 cfs. It was observed that diverted flow was not as efficient in peak reduction of the inflow hydrograph if initiation began before or after 5,000 cfs. Each task was done similarly to achieve maximum inflow reductions that would eventually be incorporated in the HEC-RAS steady state model.

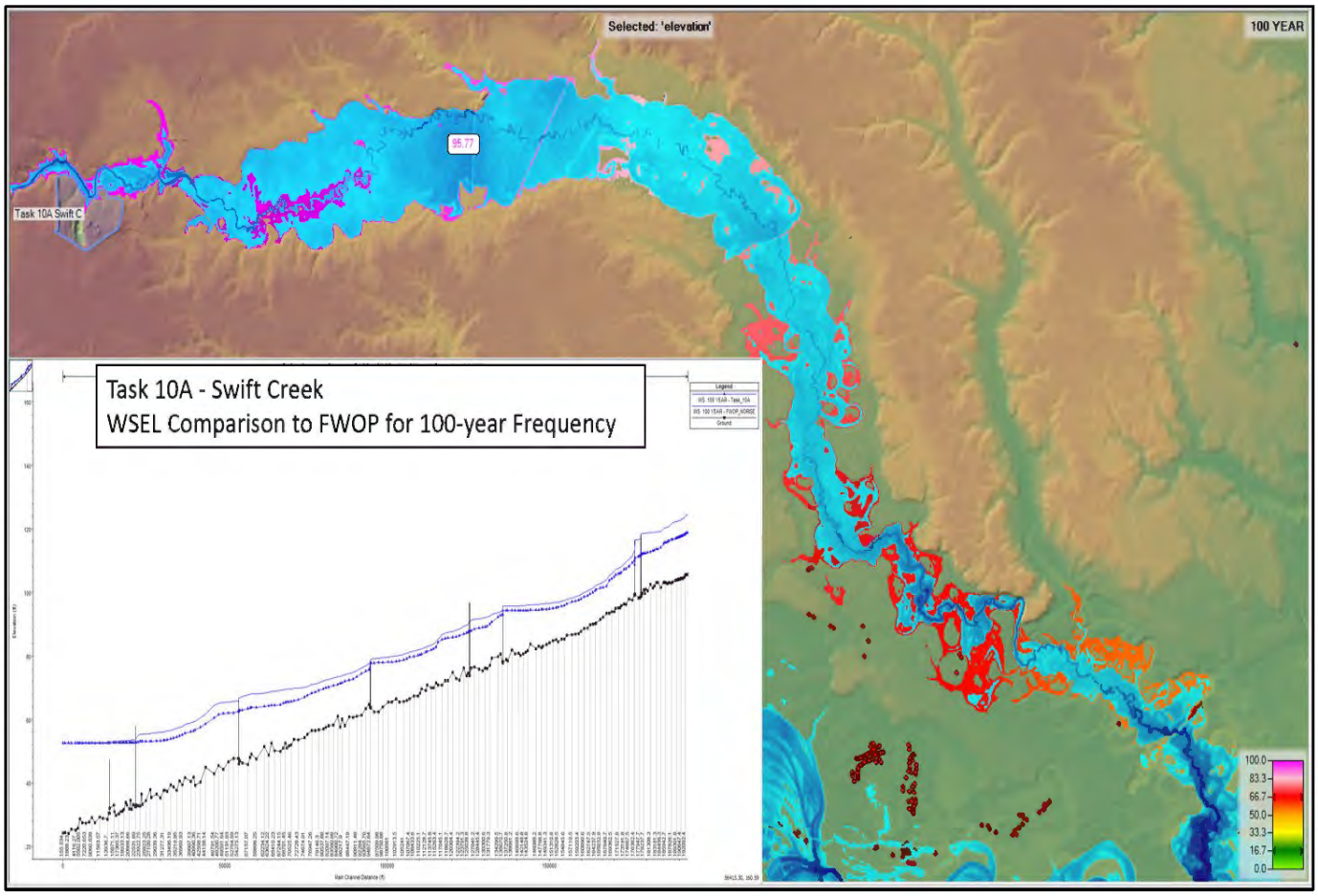


Figure 62: WSEL Comparison of Task 10 to FWoP

In HEC-RAS the steady flow editor was updated with the new peak inflow from the simplified HEC-HMS model. The updated water surface elevation profiles were then compared to an existing future without project condition scenario. The water surface differences can be seen in Figure 3 below for Task 10A. Some areas in Swift Creek have water surface elevation reductions as much as 6.5 foot, and 3.25 feet on average. The difference in water surface elevation steadily goes to zero near the confluence of Swift Creek and the Tar Pamlico River as shown in the profile in Figure 3. Differences in water surface elevation for each scenario, along with potential impacts to structures, bridges, and highways due to detention basin installment are given in Table 4 below.

Table 50: Detention basin impacts

Task	Location	Average WSEL Difference (Feet)	Estimated Excavation Volume (Acre-ft)	Estimated Impacted Structures, Bridges, and Highways from Installation of Detention Basin
10A	Swift Creek (Aggregate and Agricultural Company)	-3.25	13,500	Wake Stone Corporation – Aggregate and Agricultural Company
10B	Fishing Creek (Downstream of Franklington)	-1.71	26,000	Various Farms/Farmland Roads - Islands Road, Douglas Hill Farm Road, and Bam Hill Road

				Bridges - SR 1109, Islands/Etheridge Rd, and SR 1429, Draughan/Grammon Rd
10C	TarPam4 (Adjacent to Pittman Grove)	-0.85	35,921	Various Farms/Farmland Roads- There does not appear to be any official roads, only dirt roads throughout farmland.
10D	TarPam3 (Adjacent to Belvedere)	-1.91	37,368	Various Farms/Farmland Roads – Penders Mill Run
10E	TarPam2 (Adjacent to West Tarboro)	-0.14	339,125	Various Farms, Farmland, and Bussiness – Dail Strawberries, Dickens Funeral Services, Weeping Mary Church, Thee Thicket, Church of God Seventh Day Roads – US Hwy 64, S Shiloh Farm Road, Chinquapin Road, Burnette Farm Road, Tripple Jones Lane,

Although improvement did occur in water surface elevation for some structures downstream of detention locations, the overall benefit does not appear to address solutions to basin wide flooding that effect residential and commercial structures. If an area is determined acceptable for offline detention, then a much more precise analysis would be required to properly size an inflow/outflow weir.

This analysis assumes that maximization of weir dimensions has been designed and offline detention is operating at maximum efficiency. Rough estimates were made to size an inflow/outflow weir based on peak inflow. This was done by using the weir equation in formula (Equation 1), with adjustment in weir length as the variable for optimization of peak flows.

Equation:1 Weir Equation

$$Q = CLH^{\frac{3}{2}}$$

$$Q - Flow\ (cfs)$$

$$L - Weir\ Length$$

$$H - Head$$

Table 51: Estimated weir length

Task	Location	Peak Flow (cfs)	Flow at Invert (cfs)	Weir Length (feet)
10A	Swift Creek (Aggregate and Agricultural Company)	10,000	5000	414
10B	Fishing Creek (Downstream of Franklington)	7,380	11000	2676
10C	TarPam4 (Adjacent to Pittman Grove)	13,852	20000	7175

10D	TarPam3 (Adjacent to Belvedere)	9,107	14000	279
10E	TarPam2 (Adjacent to West Tarboro)	24,168	25000	636

6.6 Dry Dams (S1 to S3)

PDT discussions occurred to reduce the full 22 reservoir sites into a number of specified reservoirs that would have appreciable effect to the reduction of flood stages. This was preliminary achieved by taking the Hydrologic Modeling System and “disconnecting” entire tributaries. Pursuing this approach improved the overall efficiency for developing an understanding of the systematic impacts to contributing areas. This narrowed the teams focus to three primary reservoir locations the Upper Tar River Reservoir, Stony Creek, and Fishing Creek Site No. 2. Reservoir locations shown overlaid to subbasin layout from HMS model is shown in Figure 64.

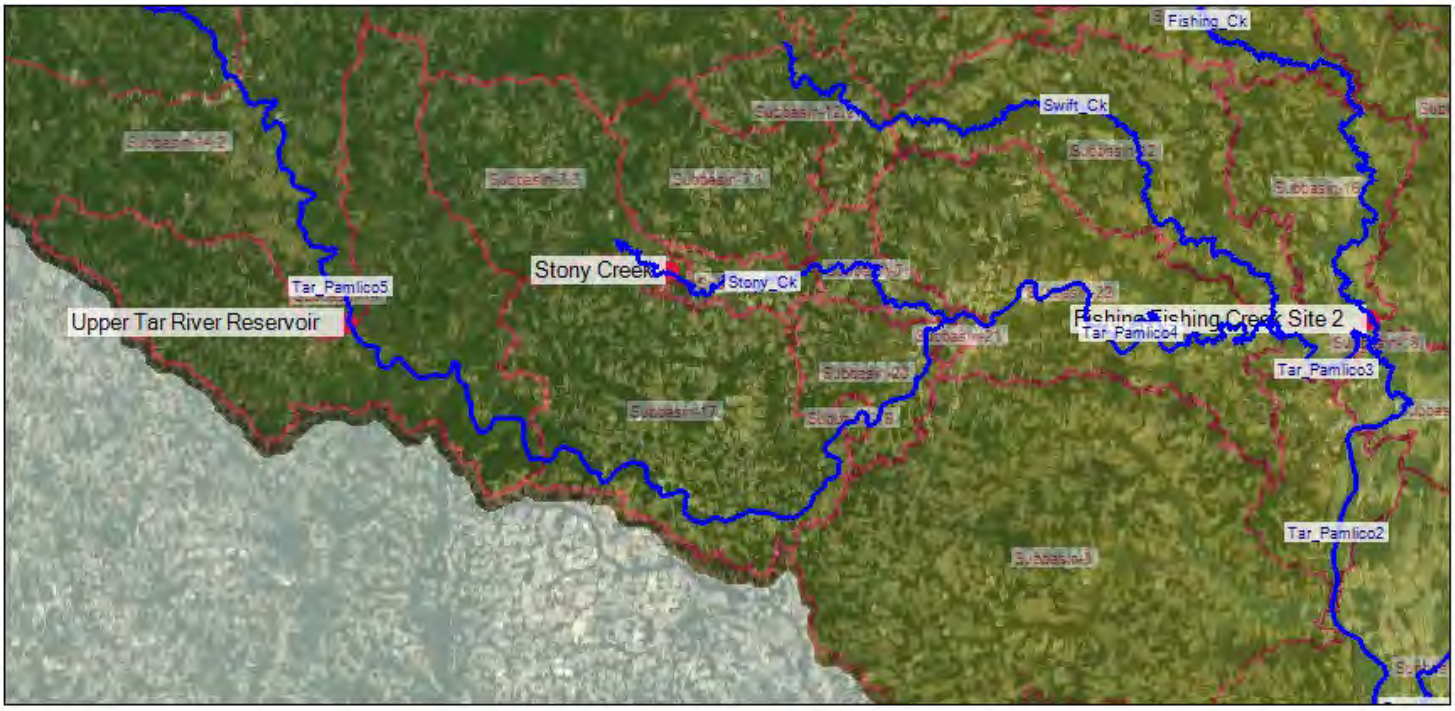


Figure 63: Map with HEC -RAS Reaches and dry dam/reservoir locations.

Each of the three reservoir sites were identified as potentially viable from high level reach screening perspective, therefore a sample design was chosen as representative for weighing the benefits of reservoir attenuation. Assumptions for the reservoir style design was based on the layout of Dover Reservoir located in the Huntington District Corps of Engineers. The notion that a significant number of reservoirs within the national inventory have spillway plotting frequencies of approximately 1/250 year or 0.004 AEP was carried forward to estimate the reduction potential storage up to the 250 year level of event magnitude. This assumption was established with the secondary notion that if reservoirs do not provide benefits at the 250 year level the design costs would likely outweigh the benefits.

The other parameter as identified as cost sensitive is top of dam elevation. Each top of dam elevation was set to not allow an preliminary estimate of probable maximum inflow at each site. Each of the three reservoir sites received an abbreviated estimate for the routing volume into the watershed using the calibrated hydrologic model. Storm orientation parameters were varied to achieve peak inflows at the reservoir. The top of dam elevation was then established as elevation not allowing overtopping. A summary of the pertinent data can be found in the following tables. After the conceptual design was drafted, HEC-HMS reservoir elements were added at junction locations for each of the sites. The entire HMS model DSS file output records were then used to process the reduction potential at each node which provided discharge time series. HMS RAS Calculator tool was used that identified functions such as VLookup, HLookup to post-process the hydrologic modeling results. The HEC RAS

flow file was then modified to include the discharge reduction points through all impact of the watershed. Water surface profiles associated with each alternative upstream of each reservoir site had a peak reservoir frequency elevation observed in the hydraulic model. The only purpose for including the reservoir elevations was to gain an understanding of the environmental impacts as well as a provisional look at reservoir pool footprints.

Table 52: Alternative 14B – Fishing Creek Site No. 2

Fishing Creek Dry Dam - Pertinent Design Data		
General Items		
River	Fishing Creek	
County and State	Edgecombe and Halifax, North Carolina	
Dam Location	Latitude: 36.109141°	Longitude: -77.548968°
Closest Downstream Population Center	Tarboro, North Carolina	
Watershed Area Above Dam	744 square miles	
Main Dam		
Type	Rolled Earth Embankment with Gravity Spillway Monoliths	
Maximum Dam Height	48.2 feet	
Estimated Maximum Flood Storage	754,300 acre-feet	
Top of Dam Elevation (NAVD 1929)	103.0 feet	
Top of Dam Length	30,000 feet	
Estimated Normal Pool Elevation	Dry Dam	
Spillway		
Type	Uncontrolled Ogee Service Spillway	
Spillway Crest Elevation	87.7 feet	
Spillway Crest Width	400 feet	
Estimated PMF Design Discharge	40,400 cubic feet per second	
Outlet Works		
Type	Gated Sluices with Stilling Basin	
Invert Elevation	56 feet	
Marsh Dike Embankment		
Maximum Height	26 feet	
Length	4,300 feet	
Halifax Dike Embankment		
Maximum Height	9 feet	
Length	2,600 feet	
Enfield Dike Embankment		
Maximum Height	5 feet	
Length	7,100 feet	

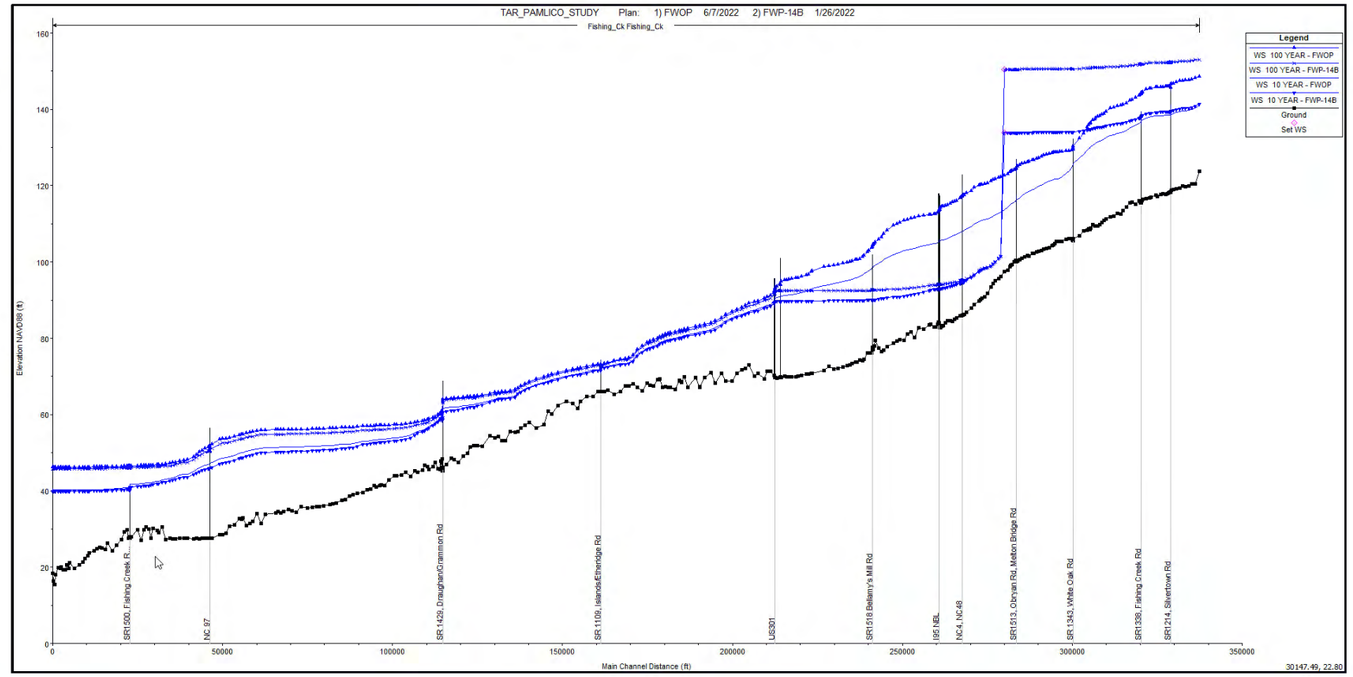


Figure 64: Water surface profile comparisons for the Fishing Creek flood reductions

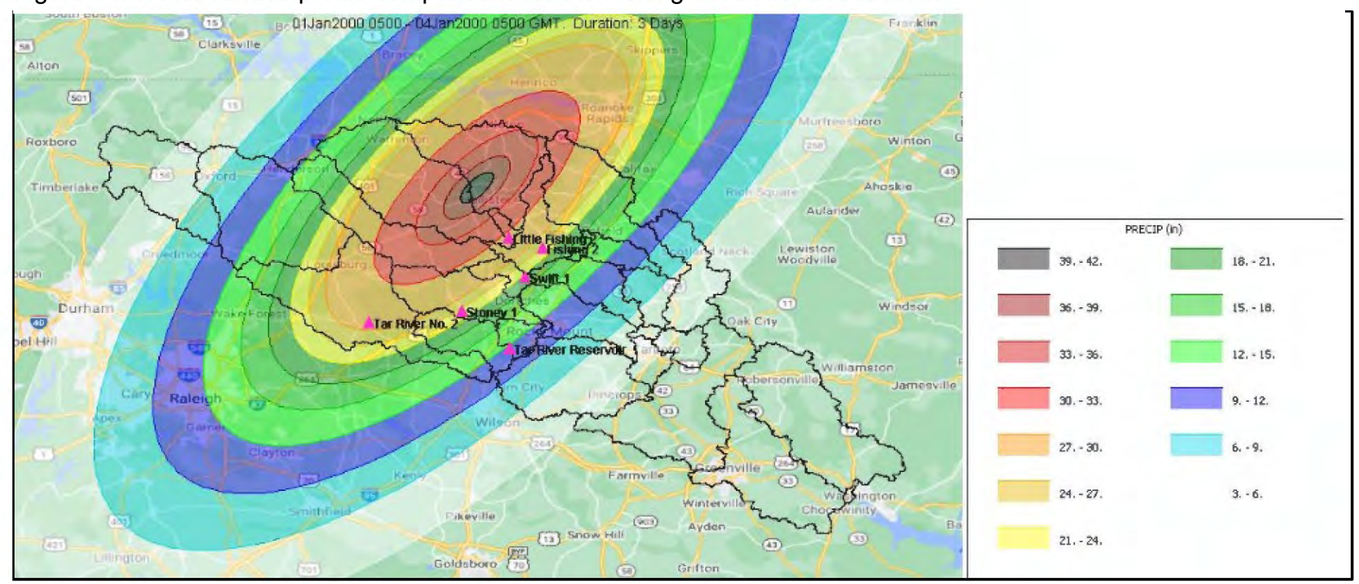
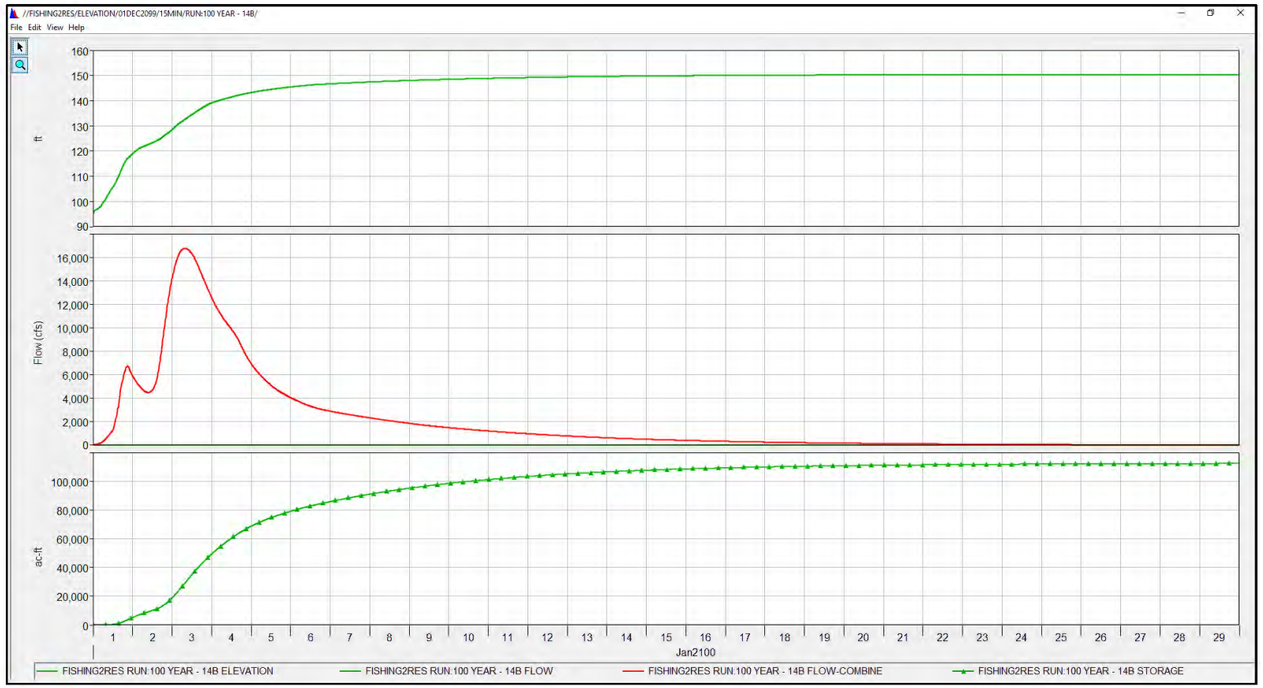
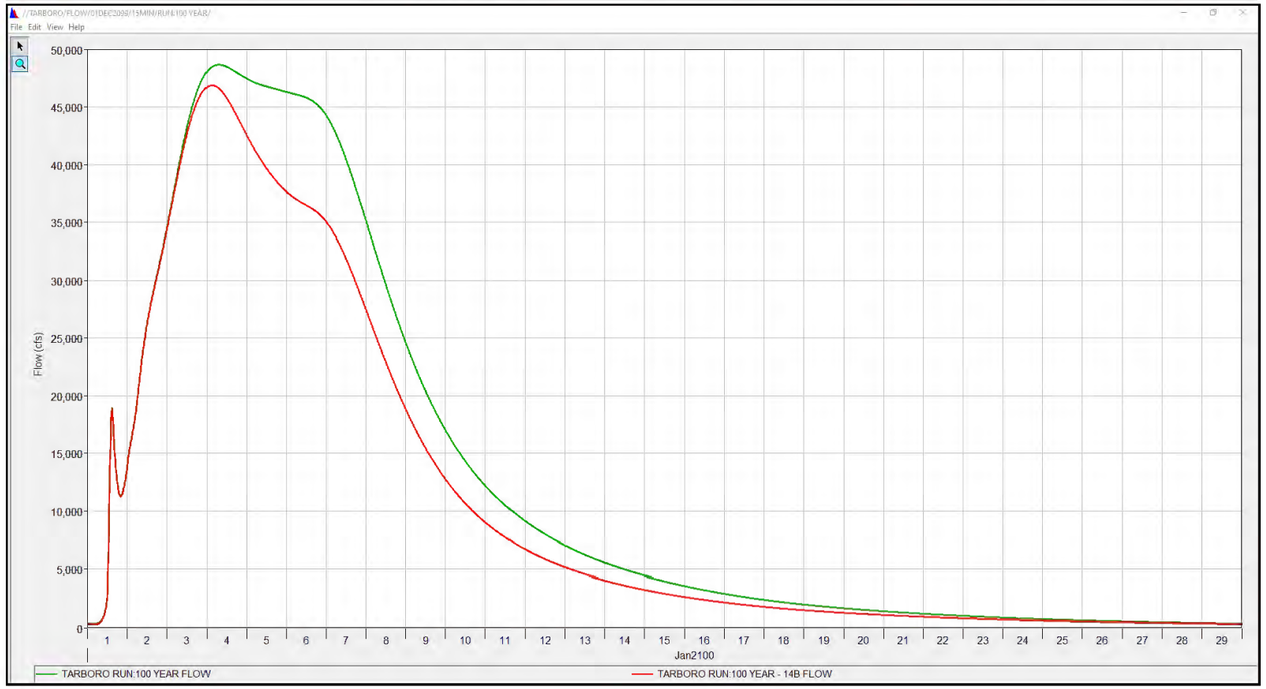


Figure 65: HMR 51/52 Simulated Storm Pattern Distribution for Fishing Site No. 2

Figure 66: Routing Chart for the Fishing 2 Reservoir Site (above), 100 YEAR Routing With and Without Project at Tarboro, NC





Footnote 29: Red Line Reflects With Project Conditions and Green is Future Without Project Conditions

Table 53: Alternative 14F Stony Creek Site

Stony Creek Dry Dam - Pertinent Design Data		
General Items		
River	Stony Creek	
County and State	Nash, North Carolina	
Dam Location	Latitude: 35.988743°	Longitude: -77.997743°
Closest Downstream Population Center	Nashville, North Carolina	
Watershed Area Above Dam	52.3 square miles	
Main Dam		
Type	Rolled Earth Embankment with Gravity Spillway Monoliths	
Maximum Dam Height	57 feet	
Estimated Maximum Flood Storage	54,000 acre-feet	
Top of Dam Elevation (NAVD 1929)	198.8 feet	
Top of Dam Length	8,800 feet	
Estimated Normal Pool Elevation	Dry Dam	
Spillway		
Type	Uncontrolled Ogee Service Spillway	
Spillway Crest Elevation	195.8 feet	
Spillway Crest Width	400 feet	
Estimated PMF Design Discharge	23,400 cubic feet per second	
Outlet Works		
Type	Gated Sluices with Stilling Basin	
Invert Elevation	143 feet	

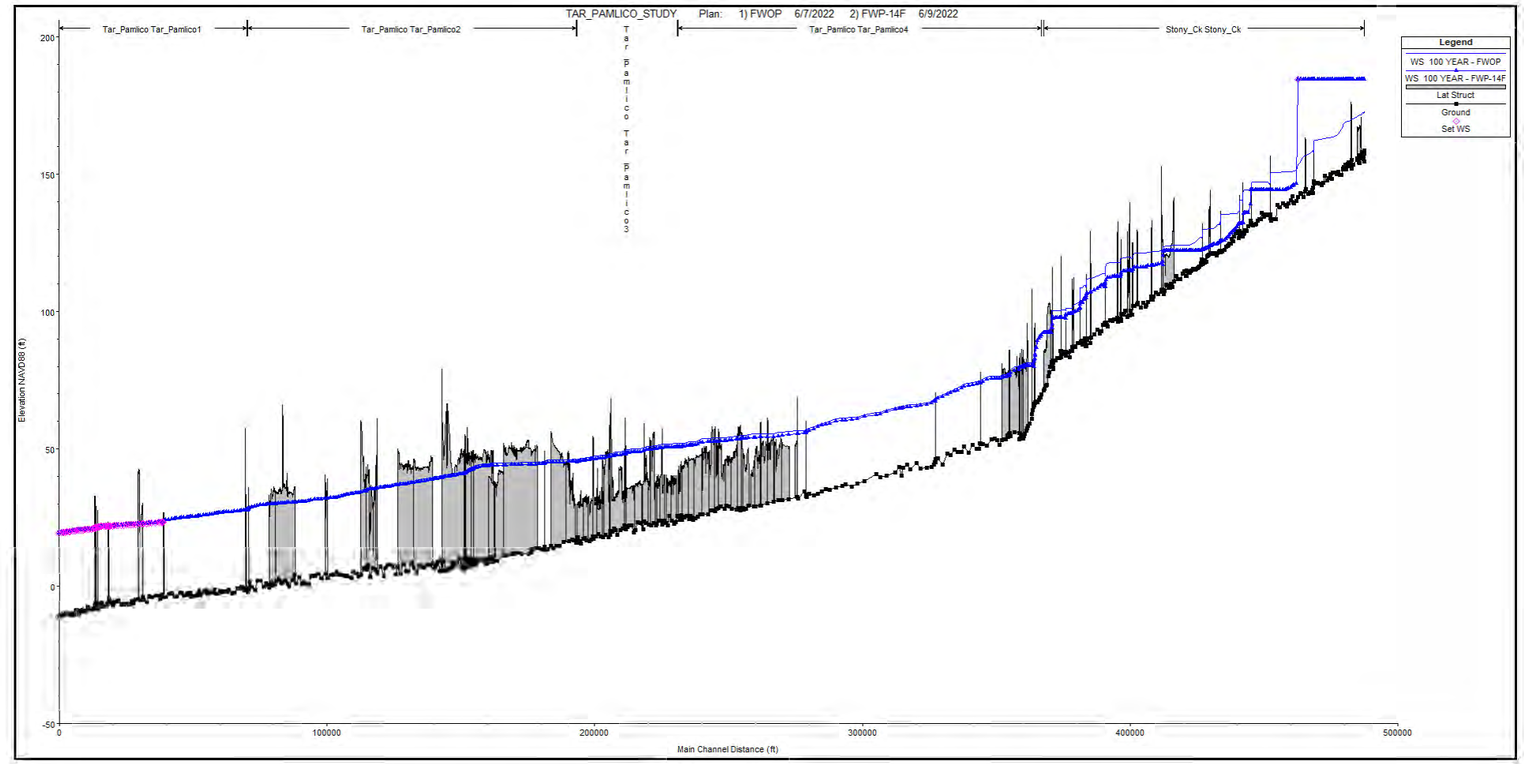
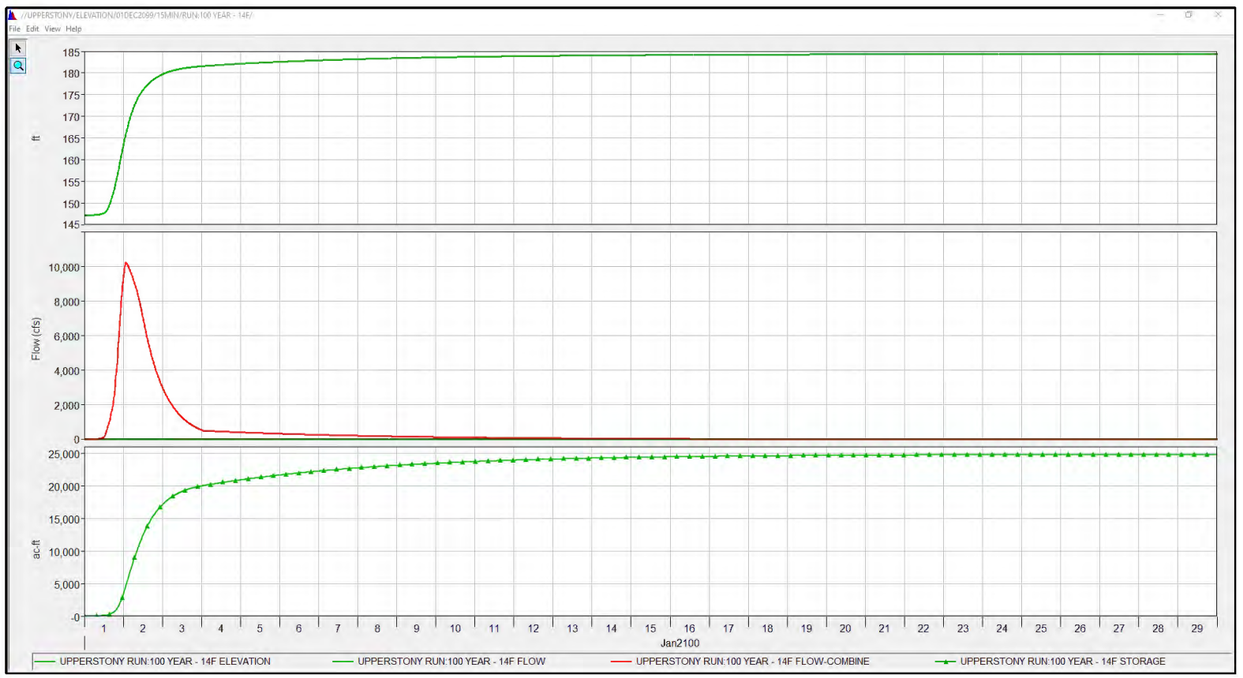
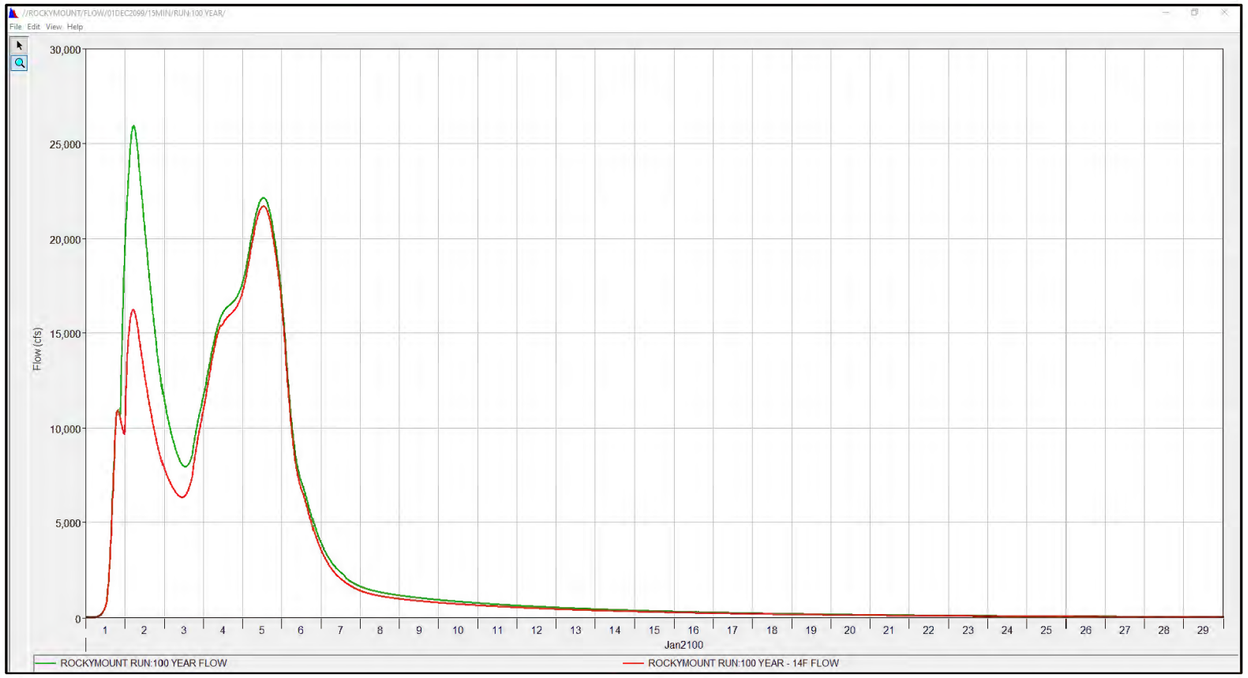


Figure 67: Water surface profile comparison for the Stony Creek Reservoir

Figure 68: Routing Chart for the Fishing 2 Reservoir Site (above), 100 YEAR Routing With and Without Project measured at Rocky Mount PAR

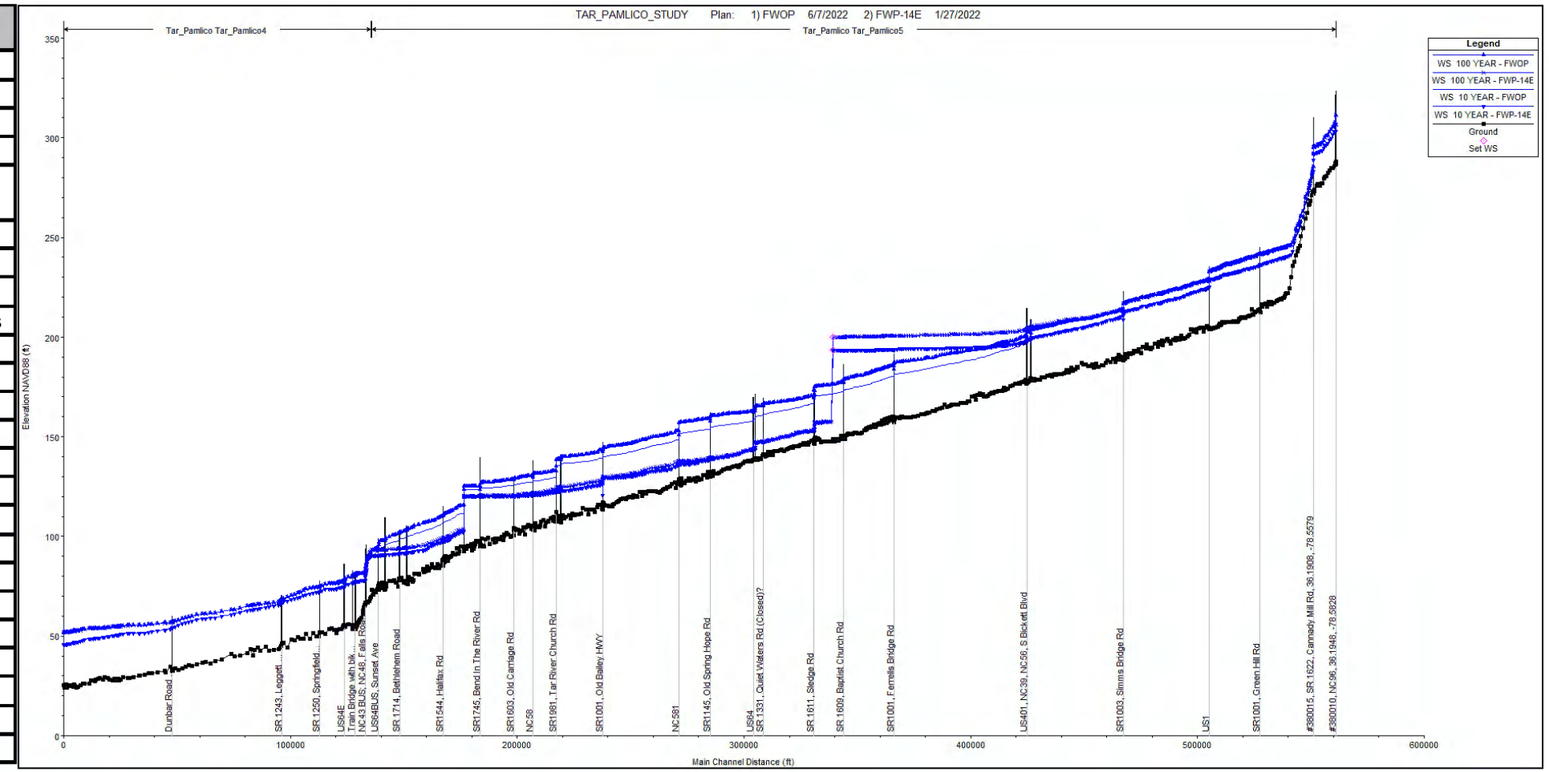




Footnote 30: Red Line Reflects With Project Conditions and Green is Future Without Project Conditions

Table 54: Alternative 14E – Upper Tar River Reservoir

Upper Tar River Dry Dam - Pertinent Design Data		
General Items		
River	Tar River	
County and State	Franklin, North Carolina	
Dam Location	Latitude: 35.953198°	Longitude: -78.218756°
Closest Downstream Population Center	Spring Hope, North Carolina	
Watershed Area Above Dam	553 square miles	
Main Dam		
Type	Rolled Earth Embankment with Gravity Spillway Monoliths	
Maximum Dam Height	79.2 feet	
Estimated Maximum Flood Storage	344,000 acre-feet	
Top of Dam Elevation (NAVD 1929)	227.3 feet	
Top of Dam Length	3,100 feet	
Estimated Normal Pool Elevation	Dry Dam	
Spillway		
Type	Uncontrolled Ogee Service Spillway	
Spillway Crest Elevation	200.0 feet	
Spillway Crest Width	400 feet	
Estimated PMF Design Discharge	122,400 cubic feet per second	
Outlet Works		
Type	Gated Sluices with Stilling Basin	
Invert Elevation	149 feet	



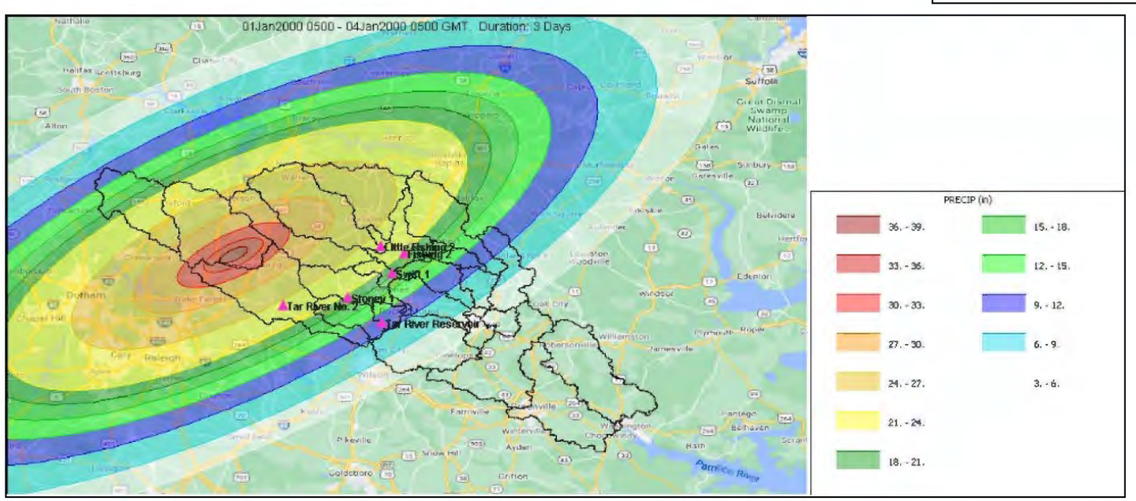
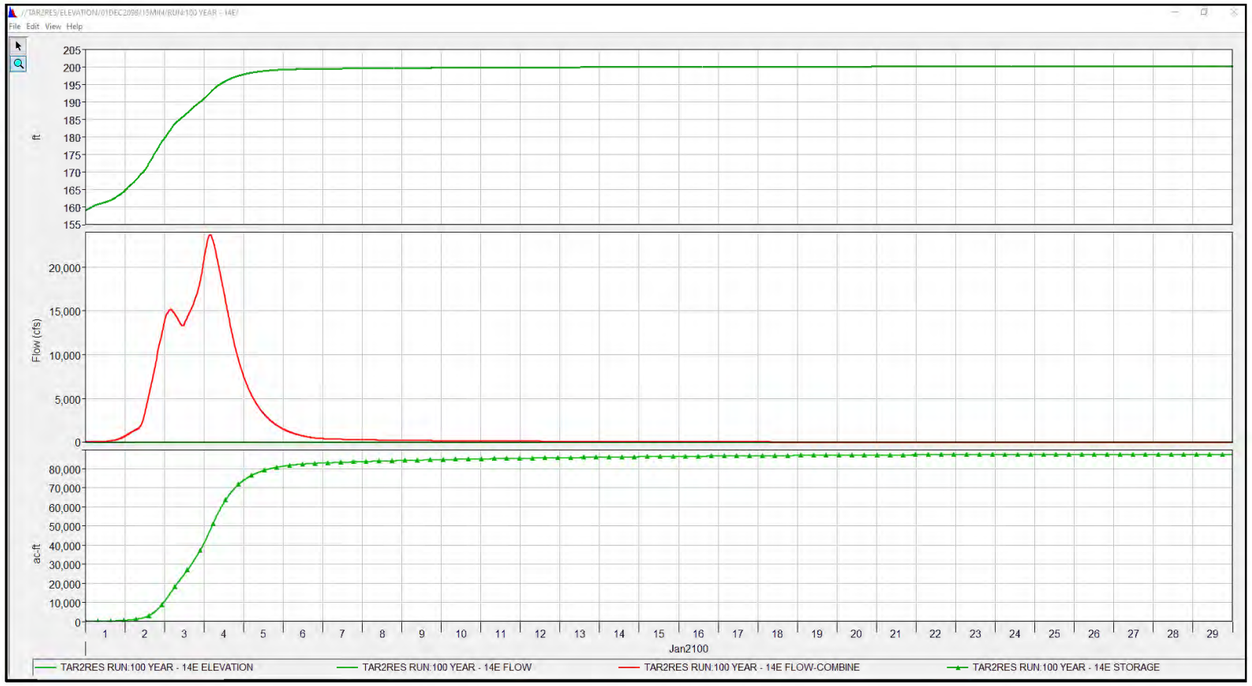
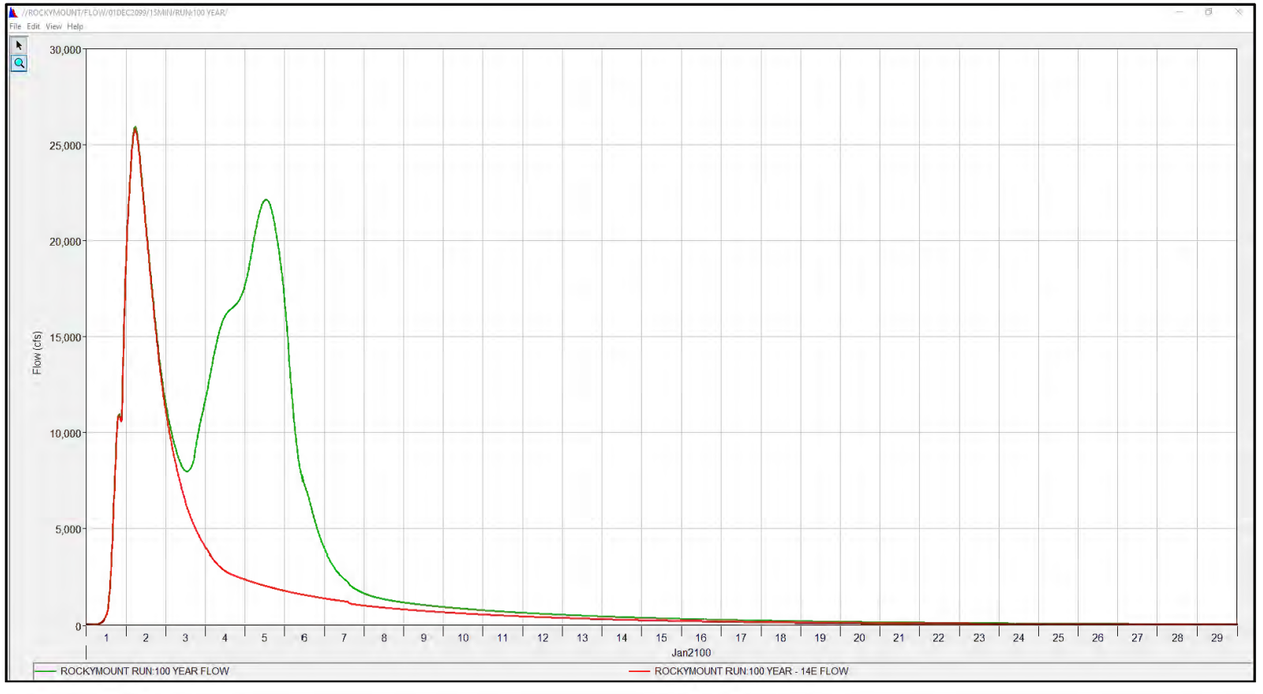


Figure 69: Storm orientation for HMR 51/52 for Probable Maximum Flood Estimate

Figure 70: Routing Chart for the Fishing 2 Reservoir Site (above), 100 YEAR Routing With and Without Project measured at Rocky Mount PAR





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Appendix A

Comprehensive Climate Assessment Report

Tar Pamlico River Basin
North Carolina

Date Prepared: February 11, 2021
Performed by: Timothy “Alex” Toler, CELRD-LRH

Introduction and Background

This qualitative assessment of climate change impacts is required by U.S. Army Corps of Engineers (USACE, “the Corps”) Engineering and Construction Bulletin (ECB) 2018-14, “Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects.” This assessment documents the qualitative effects of climate change on the hydrology in the region. The ECB 2018-14 analysis is targeted at identifying potential impacts and risks to the Tar-Pamlico Basin Feasibility Analysis Study due to climate change.

USACE projects, programs, missions, and operations have generally proven to be robust enough to accommodate the range of natural climate variability over their operating life spans. However, recent scientific evidence shows that in some places and for some impacts relevant to USACE operations, climate change is shifting the baseline about which that natural climate variability occurs and may be changing the range of that variability as well. This is relevant to USACE because the assumptions of stationary climate conditions and a fixed range of natural variability, as captured in the historic hydrologic record may no longer apply. Consequently, historic hydrologic records may no longer be appropriately applied to carry out hydrologic assessments for flood risk management in watersheds such as the Tar-Pamlico Basin.

Tar-Pamlico River Basin Description

The Tar-Pamlico River basin is the fourth largest river basin in North Carolina and is one of only four river basins whose boundaries are located entirely within the state. The Tar River originates in north central North Carolina in Person, Granville and Vance counties and flows southeasterly until it reaches tidal waters near Washington and becomes the Pamlico River. The river empties into the Pamlico Sound. The Pamlico River is a tidal estuary that flows into the Pamlico Sound. Major tributaries of the Tar River include Fishing Creek, Swift Creek, Little Fishing Creek, Town Creek, Conetoe Creek, Chicod Creek, Tranters Creek and the Pungo River. Based on the 2011 National Land Cover Data, the Tar-Pamlico River Basin's estimated developed area is ~7%, agriculture ~29%, wetlands ~23% grassland/scrub ~12% and forest ~27%. Development and population growth centers around Greenville, Rocky Mount, Washington and in rural areas within commuting distance to Raleigh.

The Tar River Basin begins in the Piedmont of North Carolina and extends 215 miles southeast through the Coastal Plan and flows to the Pamlico Sound estuary. The basin covers about 6,100 square miles. The basin encompasses all or part of 18 counties. Major population centers in the study area include the cities of Louisburg, Rocky Mount, Greenville, Tarboro, and Princeville, NC.

Tar-Pamlico Basin Gage Data

The Tar-Pamlico Basin has 13 stream gage sites, of which 8 are located along the Tar River mainstem. Listed below in **Table 1** are the USGS gages that are within the Tar-Pamlico Basin.

Table 1: Summary of Available USGS gages located in the Tar-Pamlico Basin

USGS NO.	Gage Name and Location	DA, mi^2	Latitude	Longitude	Water Quality Data	Start of Record	Latest Record
02081500	Tar River near Tar River, NC	165	36.1942	-78.5831	Yes	1939	2020
02081747	Tar R at Us 401 At Louisburg, NC	435	36.0931	-78.2961	Yes	1934	2020
02082000	Tar River near Nashville, NC	708	35.8493	-77.9305	Yes	1929	1970
02082506	Tar R Bl Tar R Reservoir near Rocky Mount, NC	784	35.9006	-77.8656	Yes	1971	2012
02082585	Tar River at Nc 97 At Rocky Mount, NC	933	35.9547	-77.7872	No	1977	2020
02082770	Swift Creek at Hilliardston, NC	173	36.1122	-77.9200	Yes	1924	2020
02082950	Little Fishing Creek near White Oak, NC	178	36.1833	-77.8761	Yes	1960	2020
02083000	Fishing Creek near Enfield, NC	530	36.1506	-77.6931	Yes	1910	2020
02083500	Tar River at Tarboro, NC	2,222	35.8944	-77.5331	Yes	1897	2020
02083800	Conetoe Creek near Bethel, NC	72	35.7760	-77.4622	Yes	1955	2002
02084000	Tar River at Greenville, NC	2,697	35.6167	-77.3728	Yes	1887	2020
02084160	Chicod Cr at SR1760 Near Simpson, NC	42	35.5617	-77.2308	Yes	1976	2020
02084472	Pamlico River at Washington, NC	3,200	N/A	N/A	Yes	1999	2020

Observed Trends in Current Climate and Climate Change

Literature Review of Observed Climate Changes

The Tar Pamlico River Basin is located in Water Resource Region (i.e. HUC-2 watershed) number 03, the South Atlantic-Gulf Region. A January 2015 report conducted by the USACE Institute for Water Resources (USACE 2015b) summarizes the available climate change literature for this region, covering both observed and projected changes. This summary is represented in **Figure 1** below.

The results presented in this review indicate a mild upward trending in temperature and a mild downward trending in streamflow in the South Atlantic-Gulf Region, particularly since the 1970s. However, clear consensus does not exist for either. Studies on precipitation show mixed results but with more findings showing an upward, rather than downward, pattern over the past 50 to 100 years.

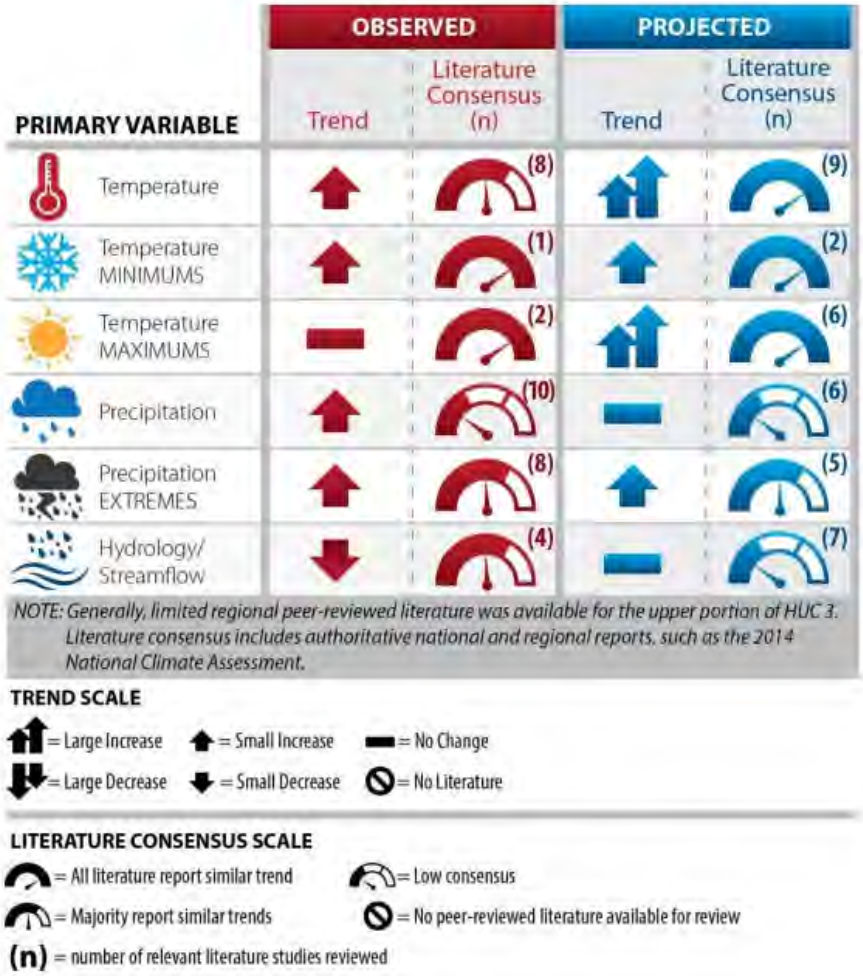

Figure 1: Summary matrix of observed and projected climate trends

Temperature

Several studies focusing on observed trends in historical temperatures were reviewed for this report. These include both national scale studies inclusive of results relevant to Water Resources Region 03 and regional studies focusing more specifically and exclusively on the area. Results from both types of studies are discussed below.

A 2009 study by Wang et al. examined historical climate trends across the continental United States. Gridded (0.5 degrees x 0.5 degrees) mean monthly climate data for the period 1950 – 2000 were used. The focus of this work was on the link between observed seasonality and regionality of trends and sea surface temperature variability. The authors identified positive statistically significant trends in recent observed mean air temperature for most of the U.S. (**Figure 2**). For the South Atlantic-Gulf Region, mixed results are presented. A positive, but mild, warming trend is identified for most of the area in the spring and summer. For the fall months, the southern portion of the area is shown to be warming while mild cooling is shown in the northern portion of the area. For the winter months, the divide appears to be more east-west, with warming in the east and cooling in the western portion of

the area. A later study by Westby et al. (2013), using data from the period 1949 – 2011, moderately contradicted these findings, presenting a general winter cooling trend for the entire region for this time period. The third NCA report (Carter et al., 2014) presents historical annual average temperatures for the southeast region. Their southeast study region is larger than, but inclusive of the South Atlantic-Gulf Region. For this area, historical data generally shows mild warming of average annual temperatures in the early part of the 20th century, followed by a few decades of cooling, and is now showing indications of warming. However, though a seasonal breakdown is not presented, the NCA report cites an overall lack of trend in mean annual temperature in the region for the past century. Details on statistical significance are not provided.

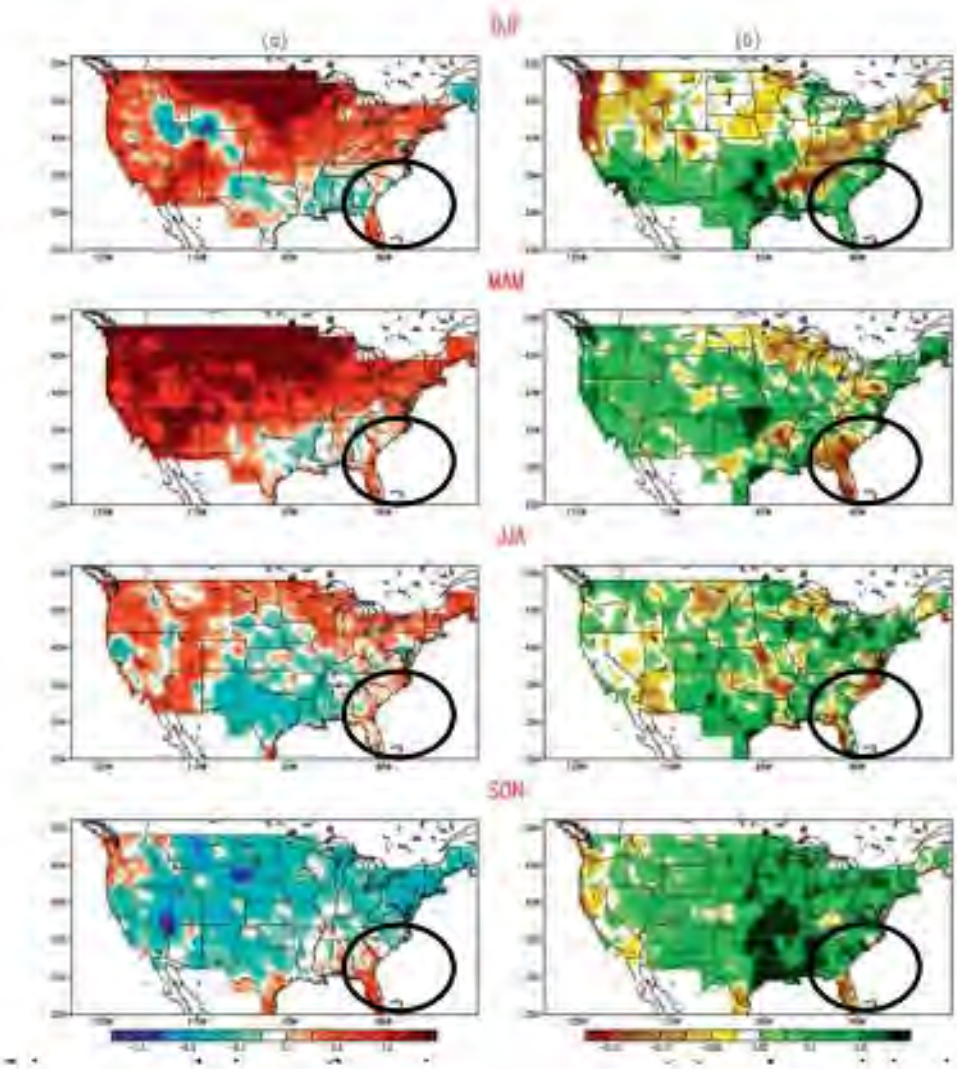

Figure 2: Trends in surface air temperature (a) and precipitation (b) over the United States, 1950 – 2000. The South Atlantic-Gulf Region is within the black oval (Wang et al., 2009)

A 2012 study by Patterson et al. focused exclusively on historical climate and streamflow trends in the South Atlantic region. Monthly and annual trends were analyzed for several stations distributed throughout the South Atlantic-Gulf Region for the period 1934 – 2005. Results (**Figure 3**) identified a

largely cooling trend for the first half of the historical period and the period as a whole. However, the second half of the study period (1970 – 2005) exhibits a clear warming trend with nearly half of the stations showing statistically significant warming over the period (average increase of 0.7 ºC). The circa 1970 “transition” point for climate and streamflow in the U.S. has been noted elsewhere, including Carter et al. (2014). Trends in overnight minimum temperatures (Tmin) and daily maximum (Tmax) temperatures for the southeast U.S. were the subject of a study by Misra et al. (2012). Their study region encompasses nearly the full extent of the South Atlantic-Gulf Region and used data from 1948 to 2010. Results of this study show increasing trends in both Tmin and Tmax throughout most of the study region. The authors attribute at least a portion of these changes to the impacts of urbanization and irrigation.

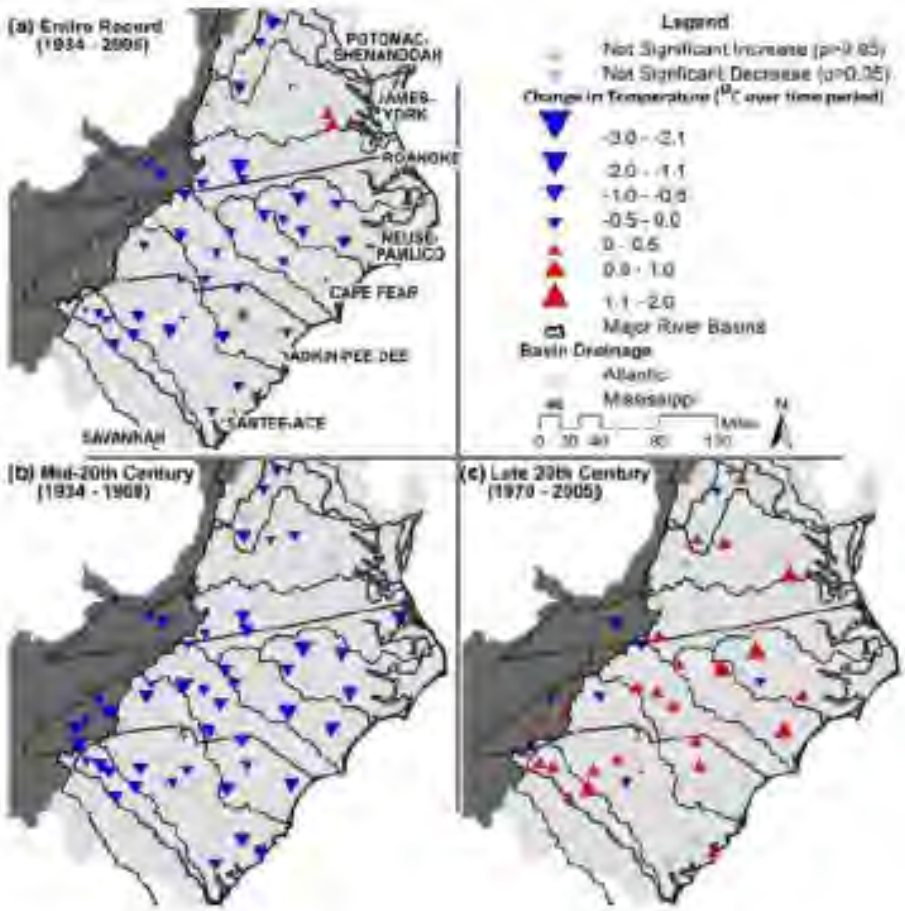

Figure 3: Historical annual temperature trends for the South Atlantic Region, 1934 – 2005. Triangles point in the direction of the trend, size reflects the magnitude of the change. Blue indicates a decreasing temperature trend. Red indicates an increasing temperature trend (Patterson et al., 2012)

Precipitation

Palecki et al. (2005) examined historical precipitation data from across the continental United States. They quantified trends in precipitation for the period 1972 – 2002 using NCDC 15- minute rainfall

data. For the South Atlantic-Gulf Region, statistically significant increases in winter storm intensity (mm per hour) and fall storm totals were identified for the southernmost portion of South Atlantic-Gulf Region. Additionally, a statistically significant decrease in summer storm intensity was identified for the northern portion of the area.

A 2011 study by McRoberts and Nielsen-Gammon used a new continuous and homogenous data set to perform precipitation trend analyses for sub-basins across the United States. The extended data period used for the analysis was 1895 – 2009. Linear positive trends in annual precipitation were identified for most of the U.S (**Figure 4**). For the South Atlantic-Gulf Region, results were mixed with some areas showing mild decreases in precipitation and others showing mild increases. No clear trend for the area is evident from these results.

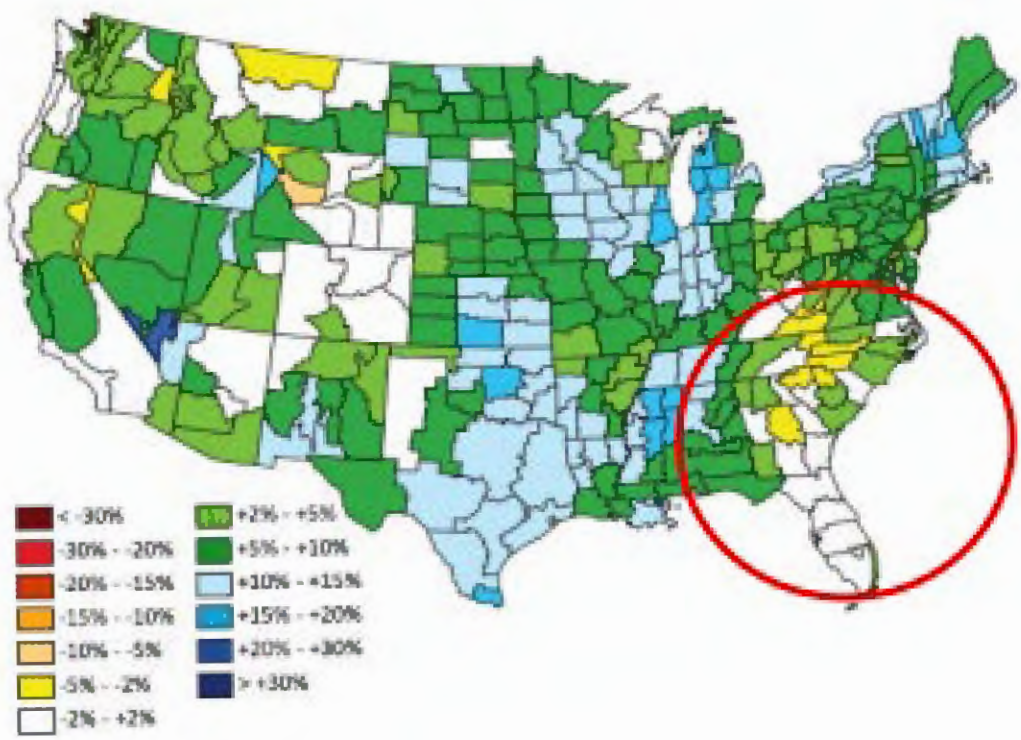

Figure 4: Gulf Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

Changes in extreme precipitation events observed in recent historical data have been the focus of a number of studies. Studies of extreme events have focused on intensity, frequency, and/or duration of such events. Wang and Zhang (2008) used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. Statistically

significant increases in the frequency of the 20-year storm event were quantified across the southern and central U.S., in both the recent historical data and the long-term future projections (described below). For the South Atlantic-Gulf Region, significant changes in the recurrence of this storm were identified for the period 1977 – 1999 compared to the period 1949 – 1976. An increase in frequency of approximately 25 to 50% was quantified.

In North Carolina (at the Coweeta Laboratory), changes in precipitation variability have been observed (Laseter et al., 2012) (**Figure 5**). These changes include wetter wet years and dryer dry years compared to the middle of the 20th century. As an example, the wettest year on record occurred in 2009 at Coweeta, and only two years earlier (2007) the driest year on record was observed. This pattern of change is supported by the NCA report (Carter et al., 2014), which states that, “summers have been either increasingly dry or extremely wet” in the southeast region. This assessment is based on analysis of data dating back to the turn of the 20th century.

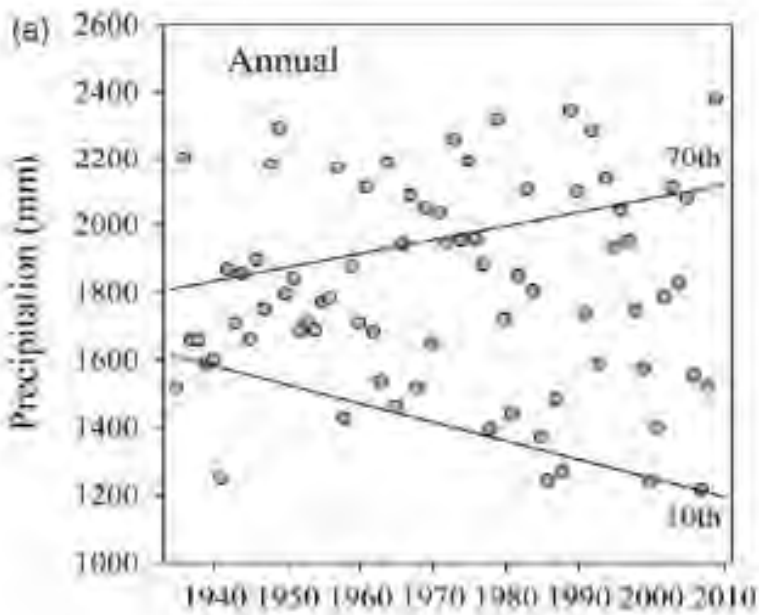

Figure 5: Total annual precipitation at Coweeta Laboratory (North Carolina). Lines show modeled 10th and 90th quantiles as a function of time, 1940 – 2010. (Laseter et al., 2012).

A 2012 study by Patterson et al. focused exclusively on the South Atlantic Region, investigating historical climate and streamflow trends. Monthly and annual trends were analyzed for several stations distributed throughout the South Atlantic-Gul Region for the period 1934 – 2005. Results identified little, if any, patterns of precipitation change in the area over this period. Some sites showed increasing trends, others showed decreasing trends. Overall, and for the full period of record, more sites exhibited mild increases in precipitation than decreases.

Hydrology

Kalra et al. (2008) found statistically negative trends in annual and seasonal streamflow for a large number of stream gages in the South Atlantic-Gulf Region, analyzed in aggregate, for the historical period 1952 – 2001. This study also identified a statistically significant stepwise change occurring in the mid-1970s, concurrent with the warming climate "transition" period previously noted in Section 2.1, Temperature. These findings are supported by a regional study by Small et al. (2006). This study, using HCDN data for the period 1948 – 1997, identified statistically significant negative trends in annual low flow for multiple stations distributed throughout the South Atlantic-Gulf Region (but even more stations exhibited no significant trend at all).

The Patterson et al. (2012) study also observed a "transition" period occurring around 1970, as well as identified significant decreasing trends in streamflow in the South Atlantic-Gulf Region for the period 1970 – 2005 (Figure 6). Results were mixed for an earlier time period (1934 – 1969), with some decreasing and some increasing trends. These results again highlight the noted transition period of the 1970s.

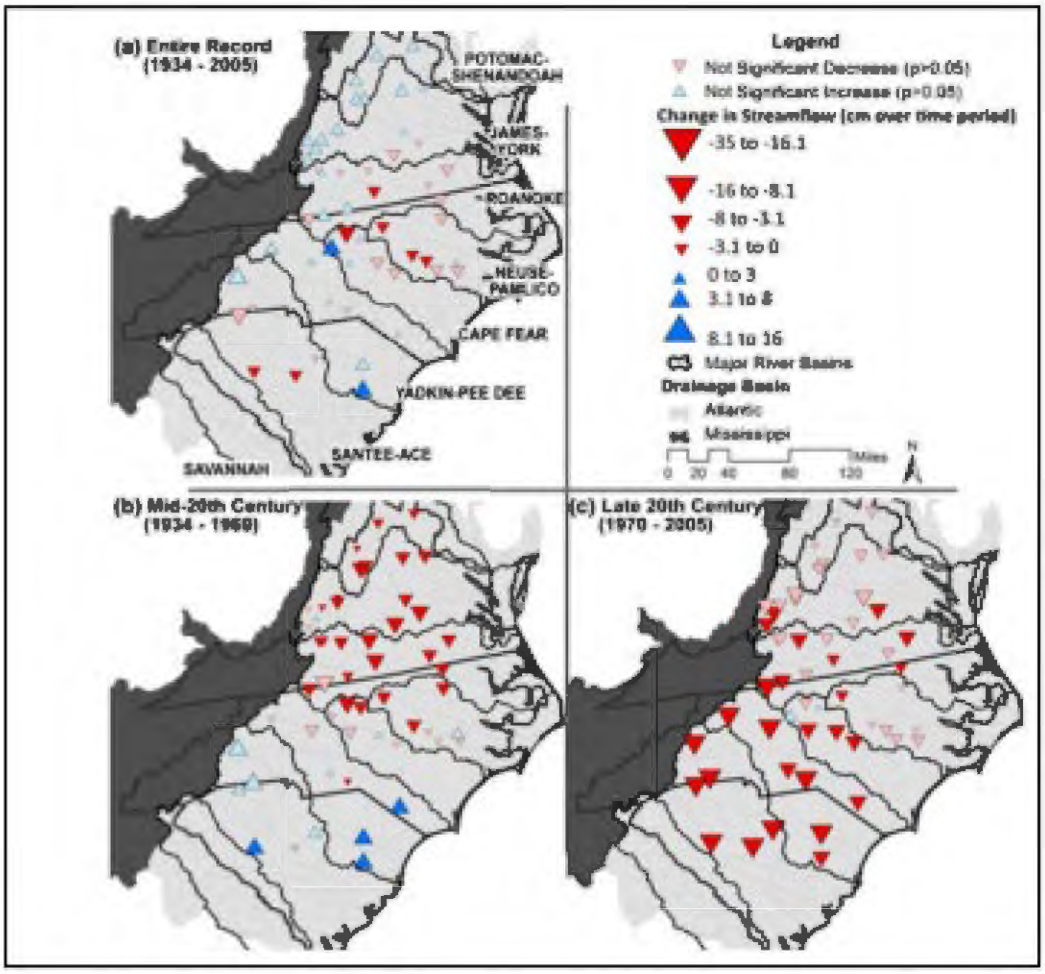

Figure 6: Observed changes in annual streamflow, South Atlantic Region, 1934 – 2005. Triangles point in the direction of the trend, size reflects the magnitude of the change. Blue indicates a decreasing streamflow trend. Red indicates and increasing streamflow trend. (Patterson et al., 2012).

Summary of Observed Climate Findings

The consensus in the recent literature points toward mild increases in annual temperature in the South Atlantic-Gulf Region over the past century, particularly over the past 40 years. While much of the area is located within the so-called “warming hole” identified by various researchers (including Carter et al., 2014), recent studies have demonstrated significant warming for other parts of the area (particularly northern portions) since the 1970s. Annual precipitation totals have become more variable in recent years compared to earlier in the 20th century. Evidence has also been presented, but with limited consensus, of mildly increasing trends in the magnitude of annual and seasonal precipitation for parts of the study area. These results are seemingly contradicted by a number of studies that have shown decreasing trends in streamflow throughout the area, particularly since the 1970s. This paradox is discussed by Small et al. (2006), who attribute it largely to seasonal differences in the timing of the changes in precipitation vs. streamflow. The study authors evaluated watersheds that experienced minimal water withdrawals and/or transfers. Results presented here also suggest that increasing temperatures may also play a role in decreasing streamflows, despite the lack of corresponding precipitation decline.

Climate Hydrology Assessment Tool

The Climate Hydrology Assessment Tool (CHAT) developed by USACE and was utilized to examine trends in observed annual peak streamflow for the various gage locations shown in **Table 1**. The CHAT tool is used to fit a linear regression to the peak streamflow data in addition to providing a p-value indicating the statistical significance of a given trend.

A summary of the regression trends and their statistical significance is shown in **Table 2** below. Individual graphical output for all gages and period of record data analyzed is shown in Figures 7-14. Every gage that was analyzed via CHAT did not have a statistically significant linear trend. A few of the gages were not within the CHAT and the Tar River at Greenville, NC gage did not have the 30-year period of record needed to perform the analysis, so it was not analyzed either. There were no statistically significant trends detected in either gage that would indicate significant changes in observed streamflow due to climate change, long-term natural climate trends, or land use/land cover changes. These results will be further analyzed and checked with the nonstationairity detection tool in the next section.

Climate Hydrology Assessment Tool Results

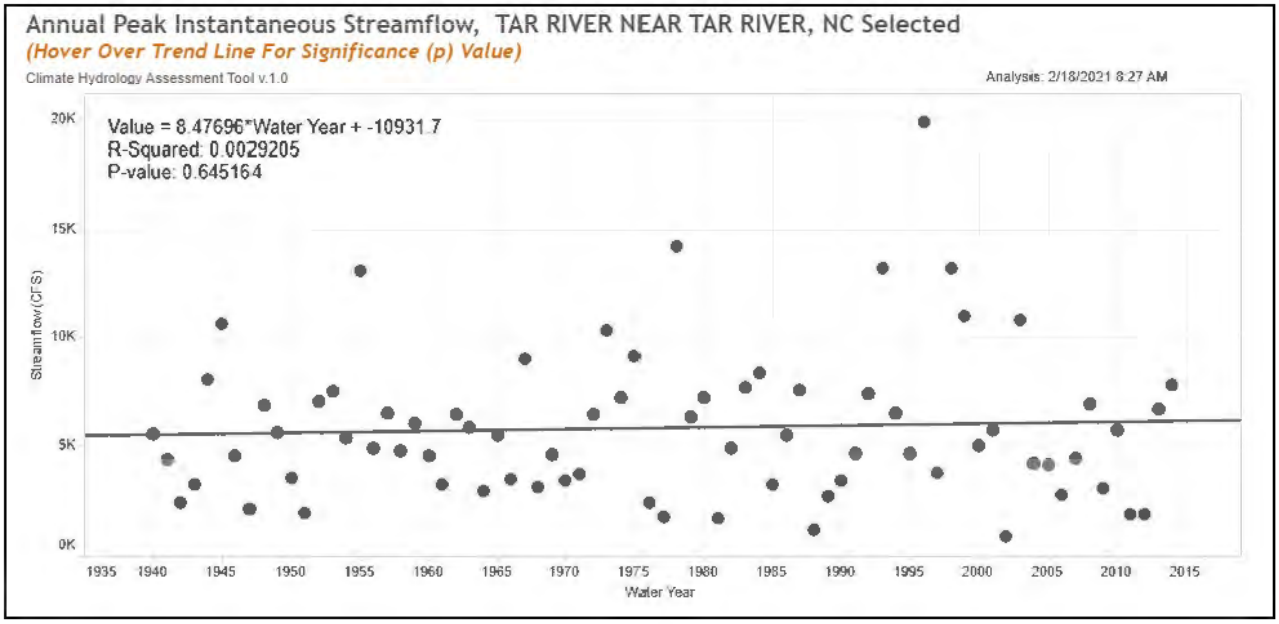

Figure 7: CHAT Results for Gage 02081500 Tar River near Tar River, NC

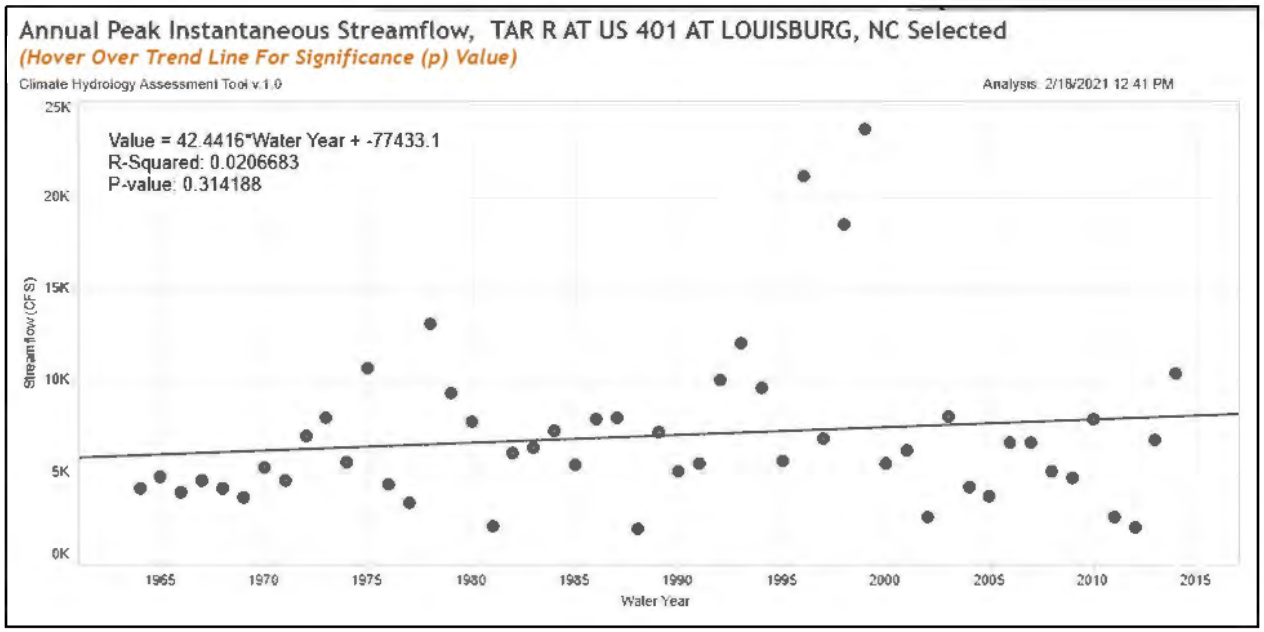

Figure 8: CHAT Results for Gage 02081747 Tar River at US 401 at Louisburg, NC

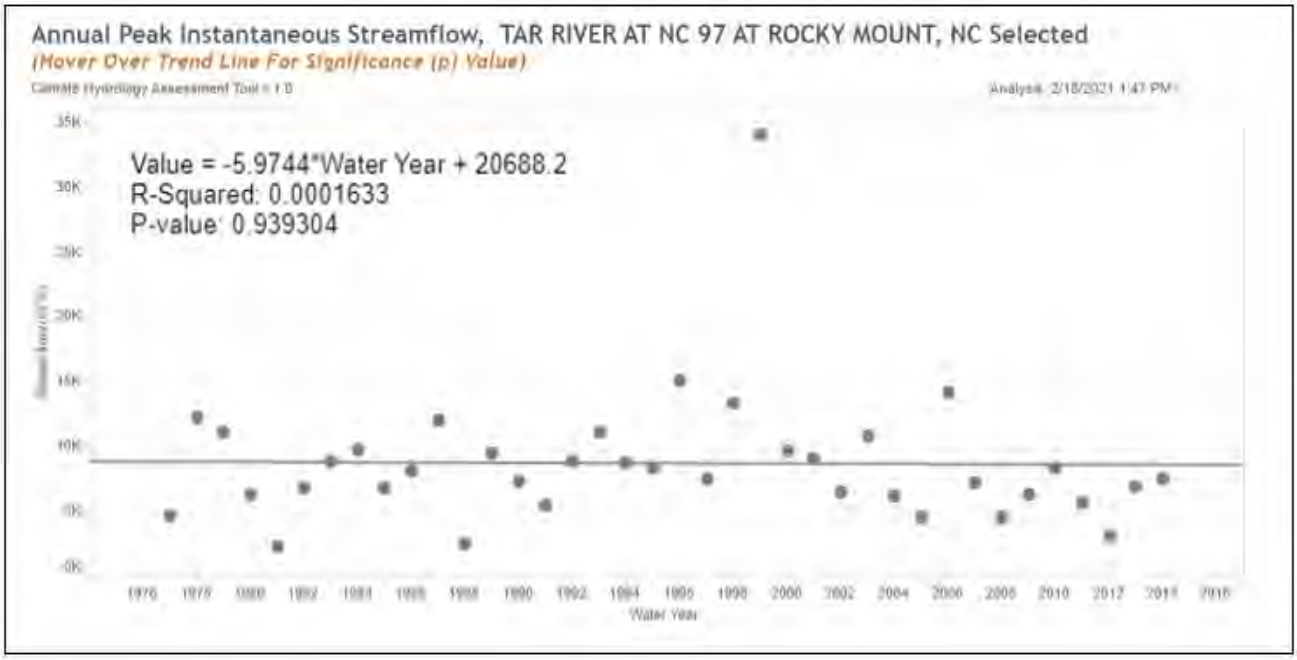

Figure 9: CHAT Results for Gage 02082585 Tar River at NC 97 at Rocky Mount, NC

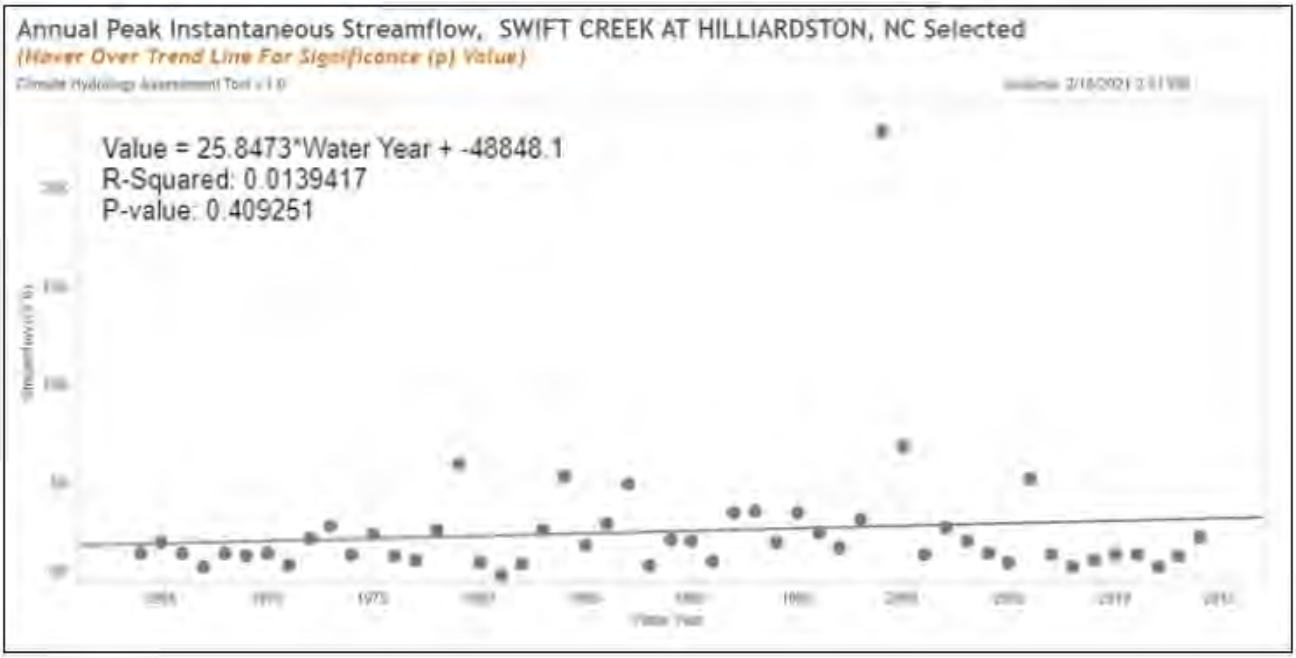

Figure 10: CHAT Results for Gage 02082770 Swift Creek at Hilliardston, NC

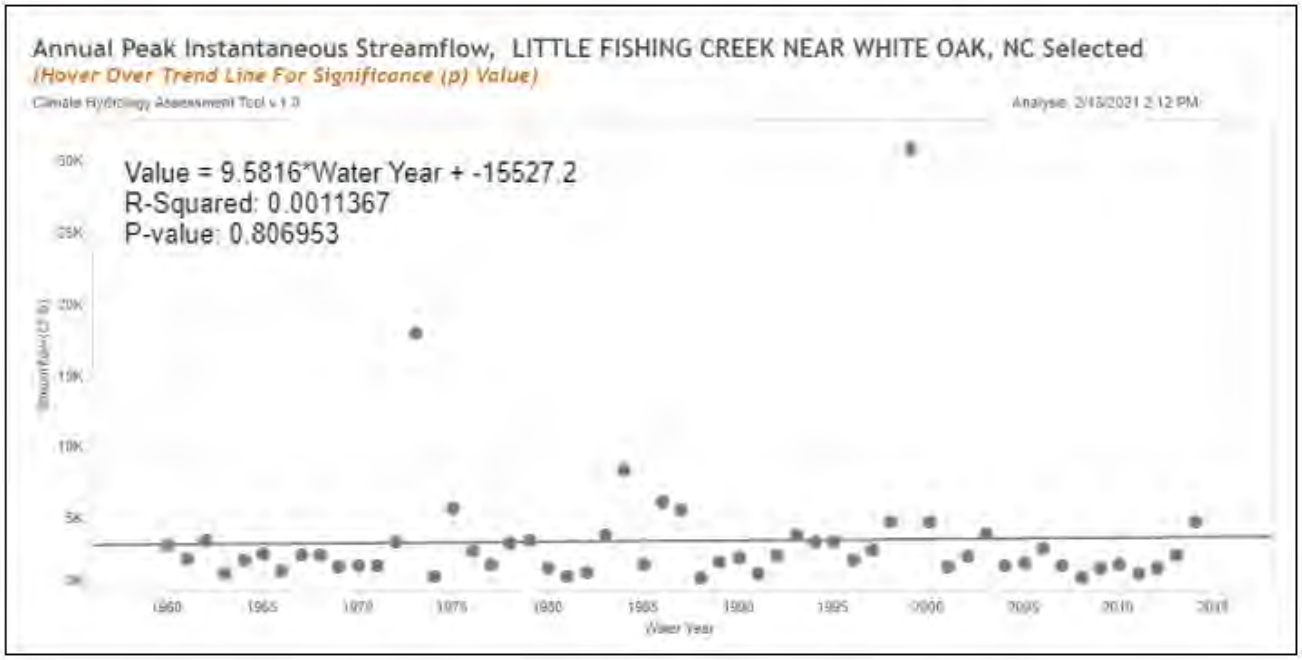

Figure 11: CHAT Results for Gage 02082950 Little Fishing Creek near White Oak, NC

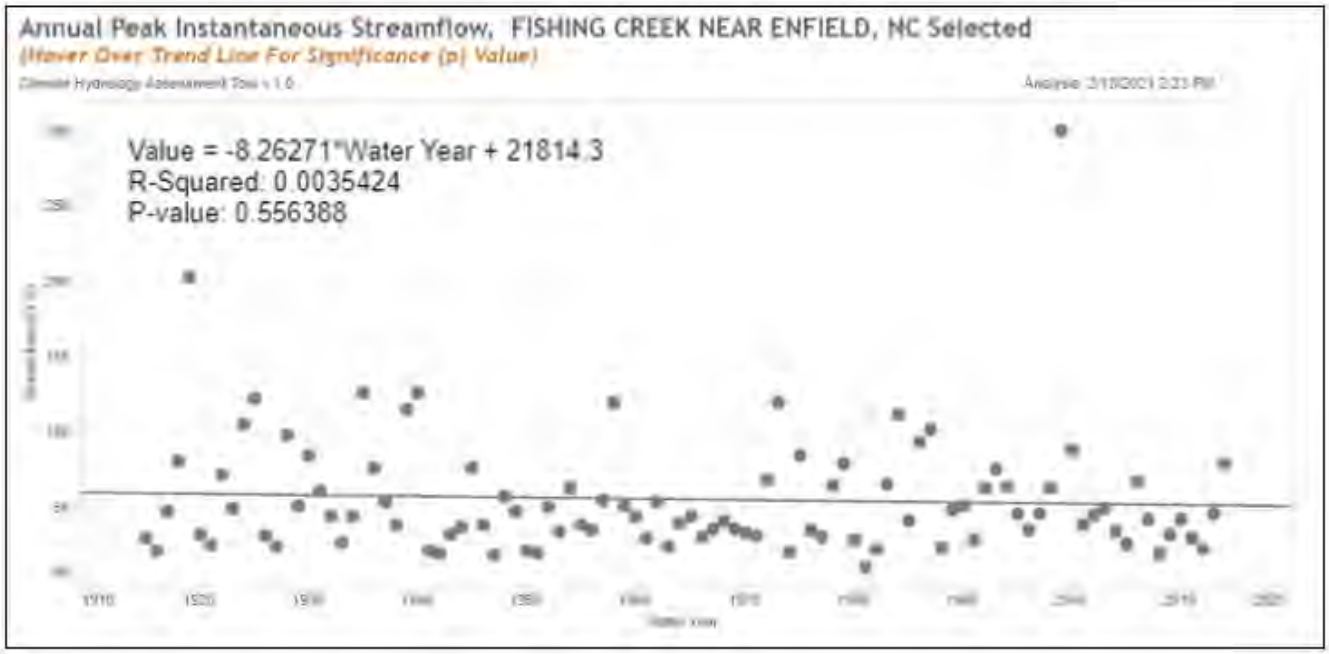

Figure 12: CHAT Results for Gage 02083000 Fishing Creek near Enfield, NC

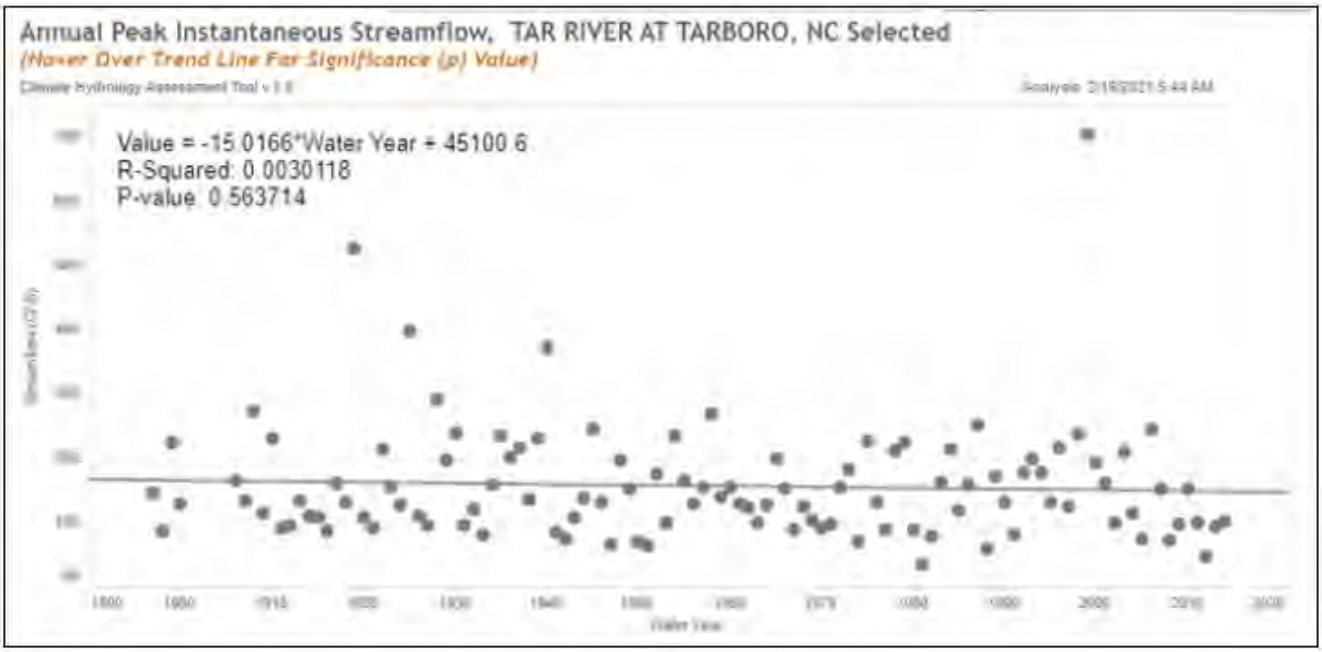

Figure 13: CHAT Results for Gage 02083500 Tar River at Tarboro, NC

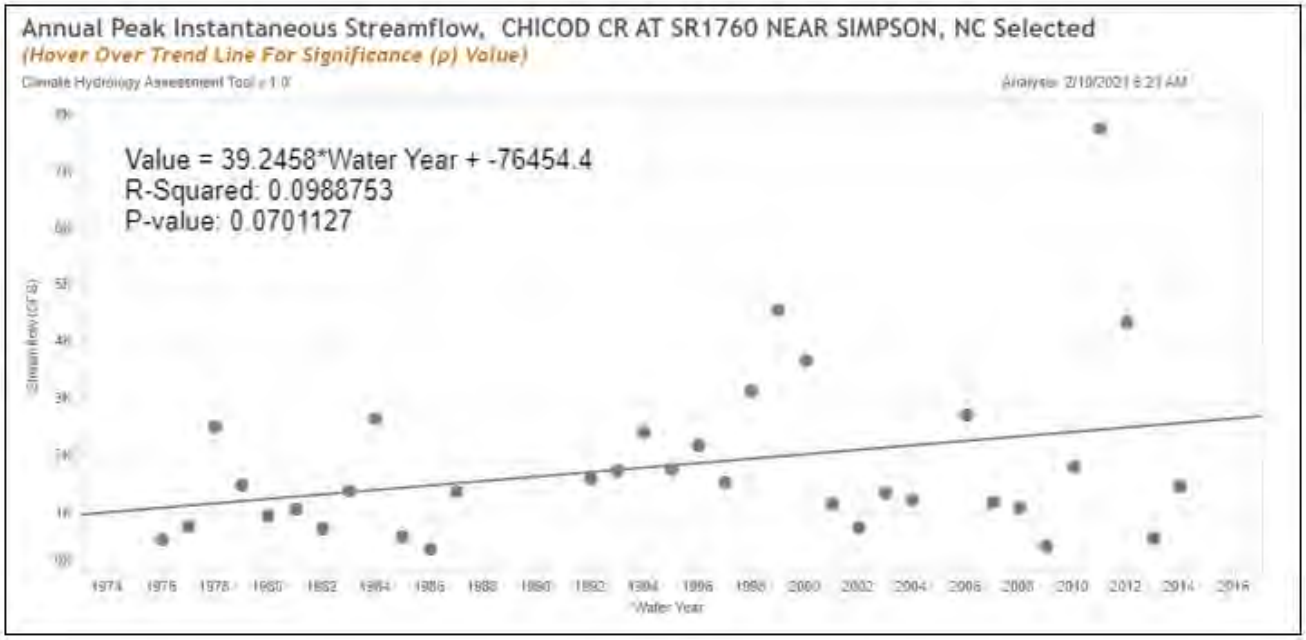

Figure 14: CHAT Results for Gage 02084160 Chicod Creek at SR1760 near Simpson, NC

Table 2: Summary of Observed Streamflow Trends in Annual Peak Streamflow using CHAT

Gage Number	Gage Name and Location	POR for CHAT	POR for NSD	POR Note	Regression Slope	P-Value	Trend Direction	Significance
02081500	Tar River near Tar River, NC	1940-2014	1940-2014	Complete	8.477	0.645	Upward	Insignificant
02081747	Tar R at US 401 at Louisburg, NC	1964-2014	1964-2014	Complete	42.442	0.314	Upward	Insignificant
02082000	Tar River near Nashville, NC	N/A	N/A	Not in CHAT or NSD	N/A	N/A	N/A	N/A
02082506	Tar River below Tar R Reservoir near Rocky Mount, NC	N/A	N/A	Not in CHAT or NSD	N/A	N/A	N/A	N/A
02082585	Tar River at NC 97 at Rocky Mount, NC	1977-2014	1977-2014	Complete	-5.974	0.939	Downward	Insignificant
02082770	Swift Creek at Hilliardston, NC	1964-2014	1964-2014	Complete	25.847	0.409	Upward	Insignificant
02082950	Little Fishing Creek near White Oak, NC	1960-2014	1960-2014	Complete	9.582	0.807	Upward	Insignificant
02083000	Fishing Creek near Enfield, NC	1915-2014	1915-2014	Complete	-8.263	0.556	Downward	Insignificant

02083500	Tar River at Tarboro, NC	1895-2014	1906-2014	Complete	-15.017	0.564	Downward	Insignificant
02083800	Conetoe Creek near Bethel, NC	N/A	N/A	Not in CHAT or NSD	N/A	N/A	N/A	N/A
02084000	Tar River at Greenville, NC	1997-2014	1997-2014	Length not sufficient	N/A	N/A	N/A	N/A
02084160	Chicod Creek at SR1760 near Simpson, NC	1976-2014	1976-2014	Complete, minus gap (1988-91)	39.246	0.07	Upward	Insignificant
02084472	Pamlico River at Washington, NC	N/A	N/A	Not in CHAT or NSD	N/A	N/A	N/A	N/A

Nonstationairity Detection Tool

The USACE Nonstationarity Detection (NSD) Tool was used to assess whether the assumption of stationarity, which is the assumption that the statistical characteristics of a time-series dataset are constant over the period of record, is valid for a given hydrologic time-series dataset. The nonstationarity detection tool (NSD) was used to assess stationarity in annual instantaneous peak stream flow & gage height data series. At the time this study began, the NSD was the standard tool used to assess climate nonstationarity by the USACE. This tool has been superseded by the Time Series Tool (TST) in later studies. The use of the NSD tool here was maintained through the study. The PDT does not feel that improved estimates regarding sea level would otherwise impact the water surface elevations for the TSP chosen because the sensitivities did not produce any differences in water surface elevations far enough upstream to make impact regardless. Nonstationarities are detected through the use of 12 different statistical tests which examine how the statistical characteristics of the dataset change with time (Engineering Technical Letter (ETL) 1100-2-3, *Guidance for Detection of Nonstationarities in Annual Maximum Discharges*; *Nonstationarity Detection Tool User Manual*, version 1.2). Abbreviations of the 12 statistical tests are shown in **Table 3** below.

Table 3: NSD Statistical Test Abbreviations

Nonstationarity Detection Method Abbreviation	Statistical Test Name
CVM	Cramer-Von-Mises (CPM)
KS	Kolmogorov-Smirnov (CPM)
LP	LePage (CPM)
END	Energy Divisive Method
LW	Lombard Wilcoxon
PT	Pettitt
MW	Mann-Whitney (CPM)
BAY	Bayesian
LM	Lombard Mood
MD	Mood (CPM)
SLW	Smooth Lombard Wilcoxon
SLM	Smooth Lombard Mood

A nonstationarity can be considered “strong” when it exhibits consensus among multiple nonstationarity detection methods, robustness in detection of changes in statistical properties, and a relatively large change in the magnitude of a dataset’s statistical properties. Many of the statistical tests used to detect nonstationarities rely on statistical change points, these are points within the time series data where there is a break in the statistical properties of the data, such that data before and after the change point cannot be described by the same statistical characteristics. Similar to nonstationarities, change points must also exhibit consensus, robustness, and significant magnitude of change.

A summary of the NSD results can be found in **Table 4** below. Only one stream gage produced a nonstationairity and it is the 020817747 Tar R at US 401 at Louisburg, NC gage. The NSD calculated that a consensus of distribution occurred in 1971 by the CVM and KS methods, but the calculations presented no robustness. All other gages either did not have enough data to perform an analysis or the data that was found on USGS was not recent enough to be feasible for the analysis.

Non-stationarity Detection Tool Results

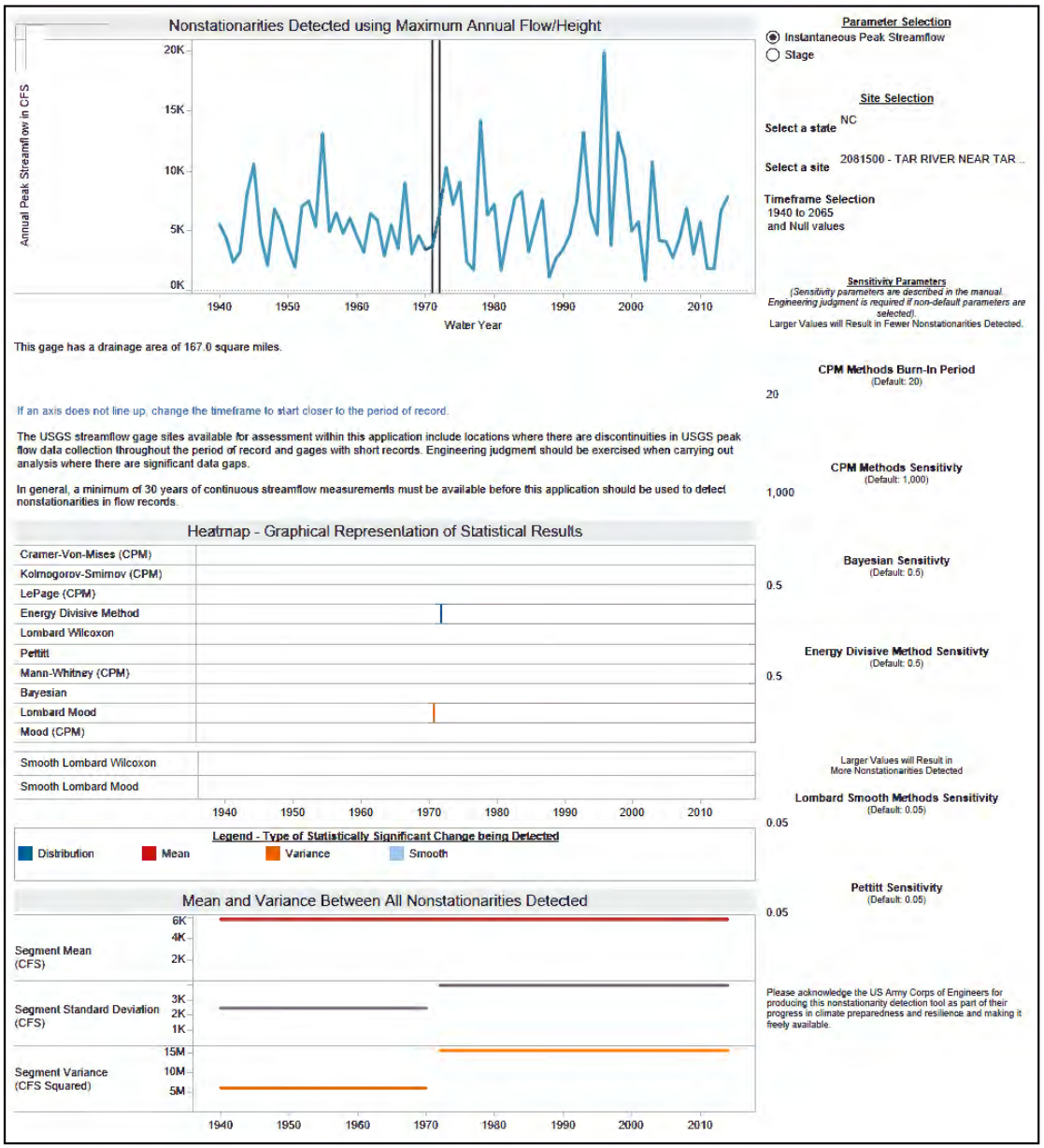

Figure 15: Nonstationairity Detection Results for Gage 02081500 Tar River near Tar River, NC

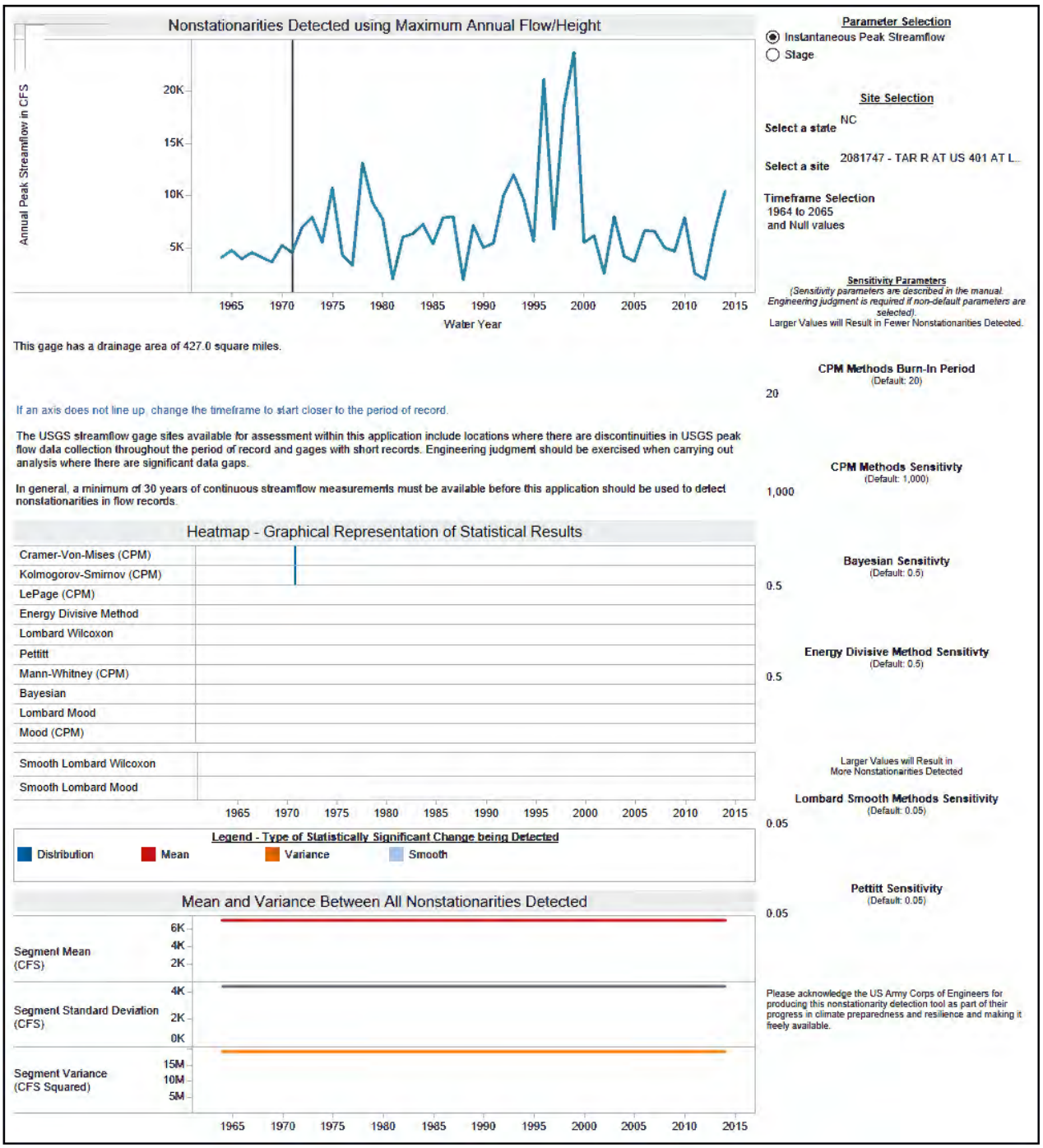

Figure 16: Nonstationairity Detection Results for Gage 02081747 Tar River at US 401 at Louisburg, NC

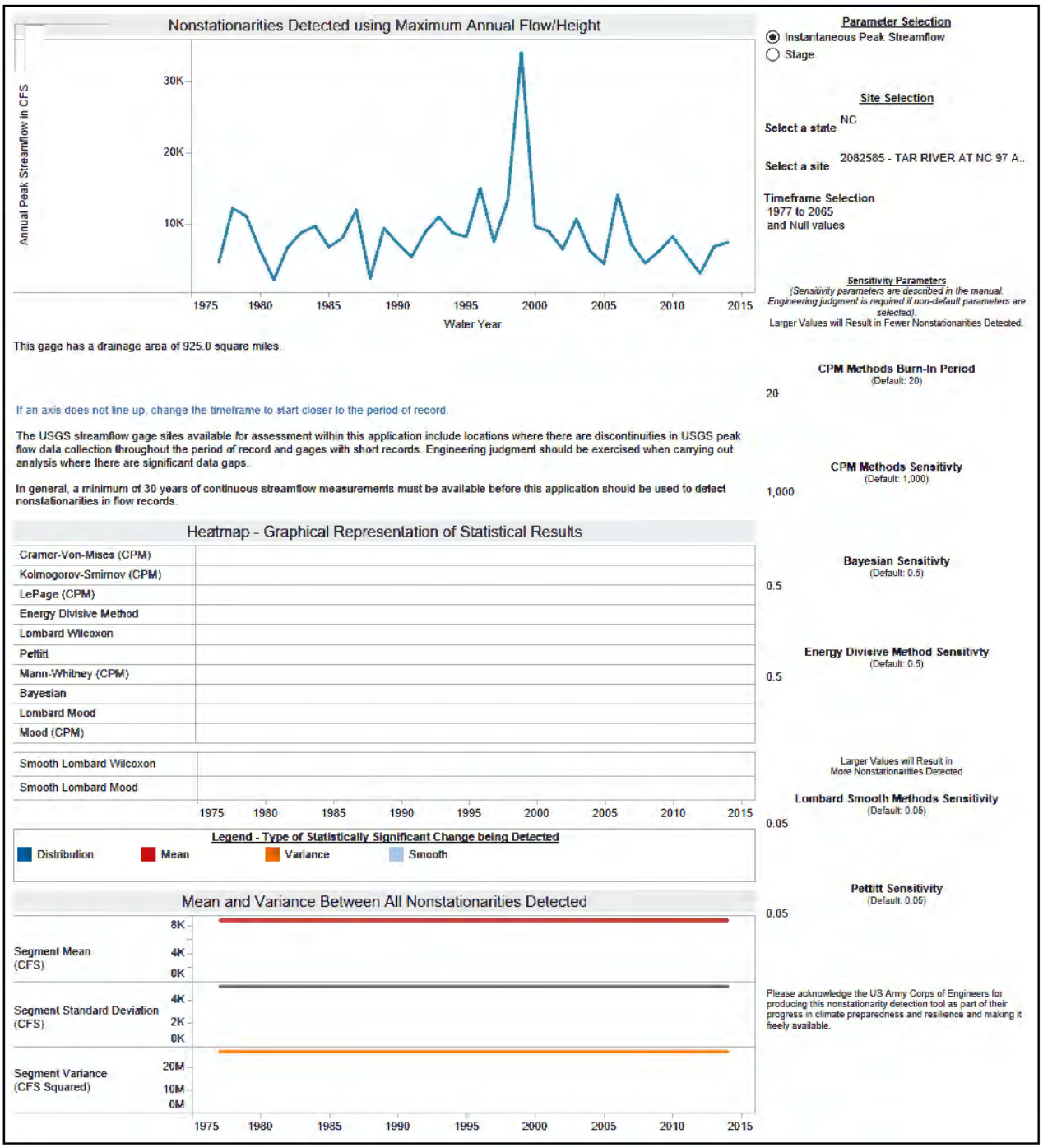

Figure 17: Nonstationairity Detection Results for Gage 02082585 Tar River at NC 97 at Rocky Mount, NC

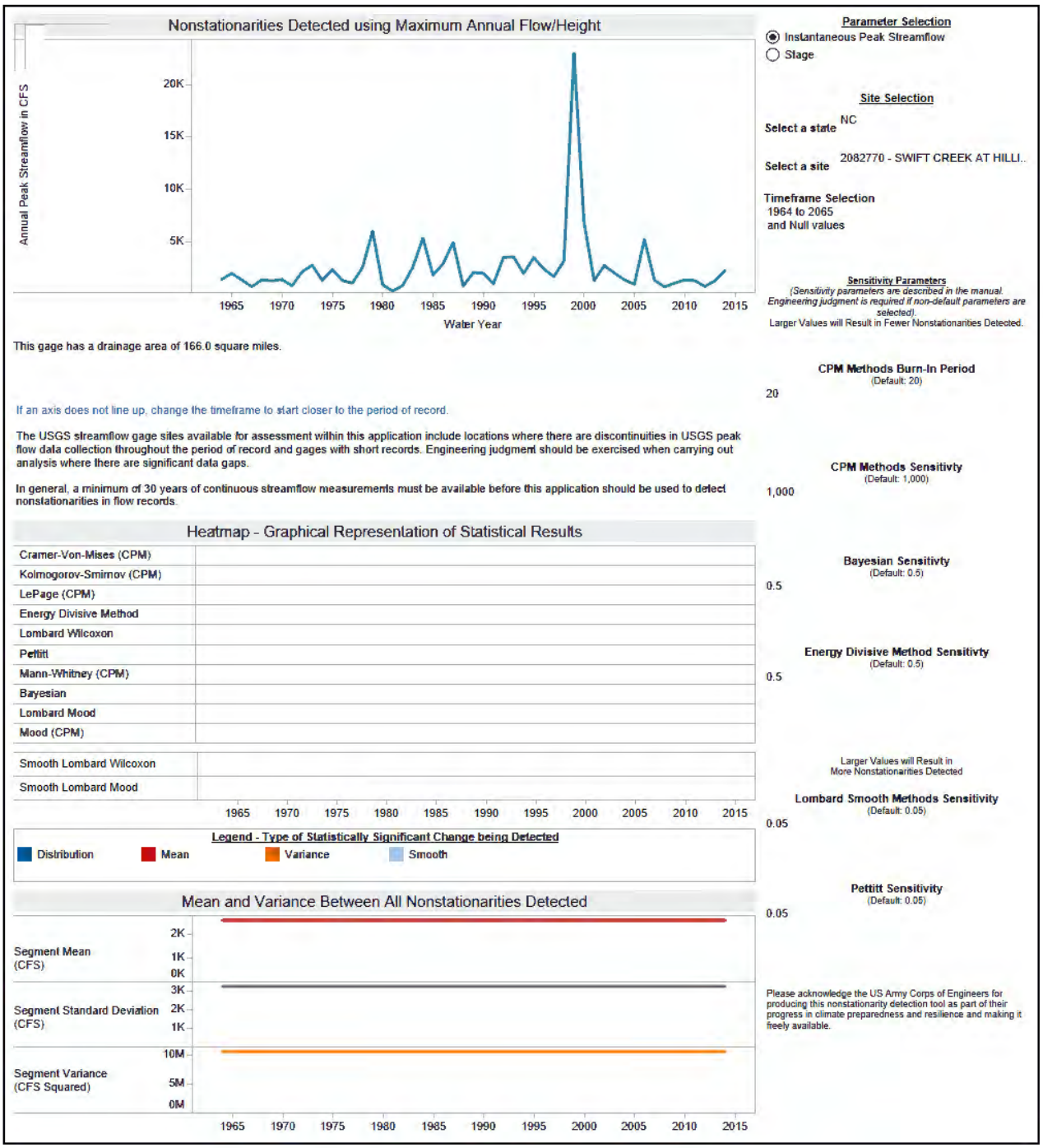

Figure 18: Nonstationairity Detection Results for Gage 02082770 Swift Creek at Hilliardston, NC

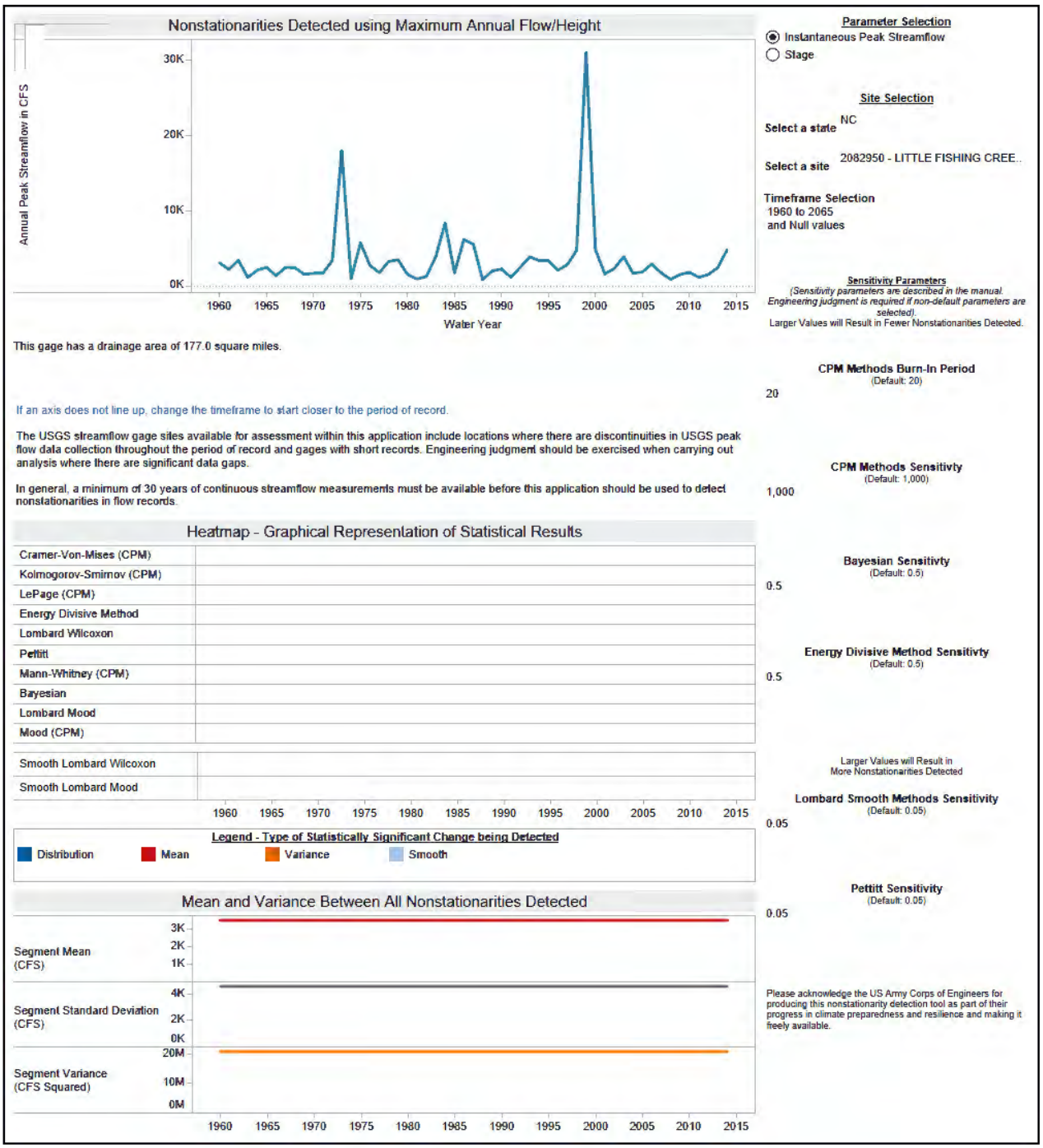

Figure 19: Nonstationairity Detection Results for Gage 02082950 Little Fishing Creek near White Oak, NC

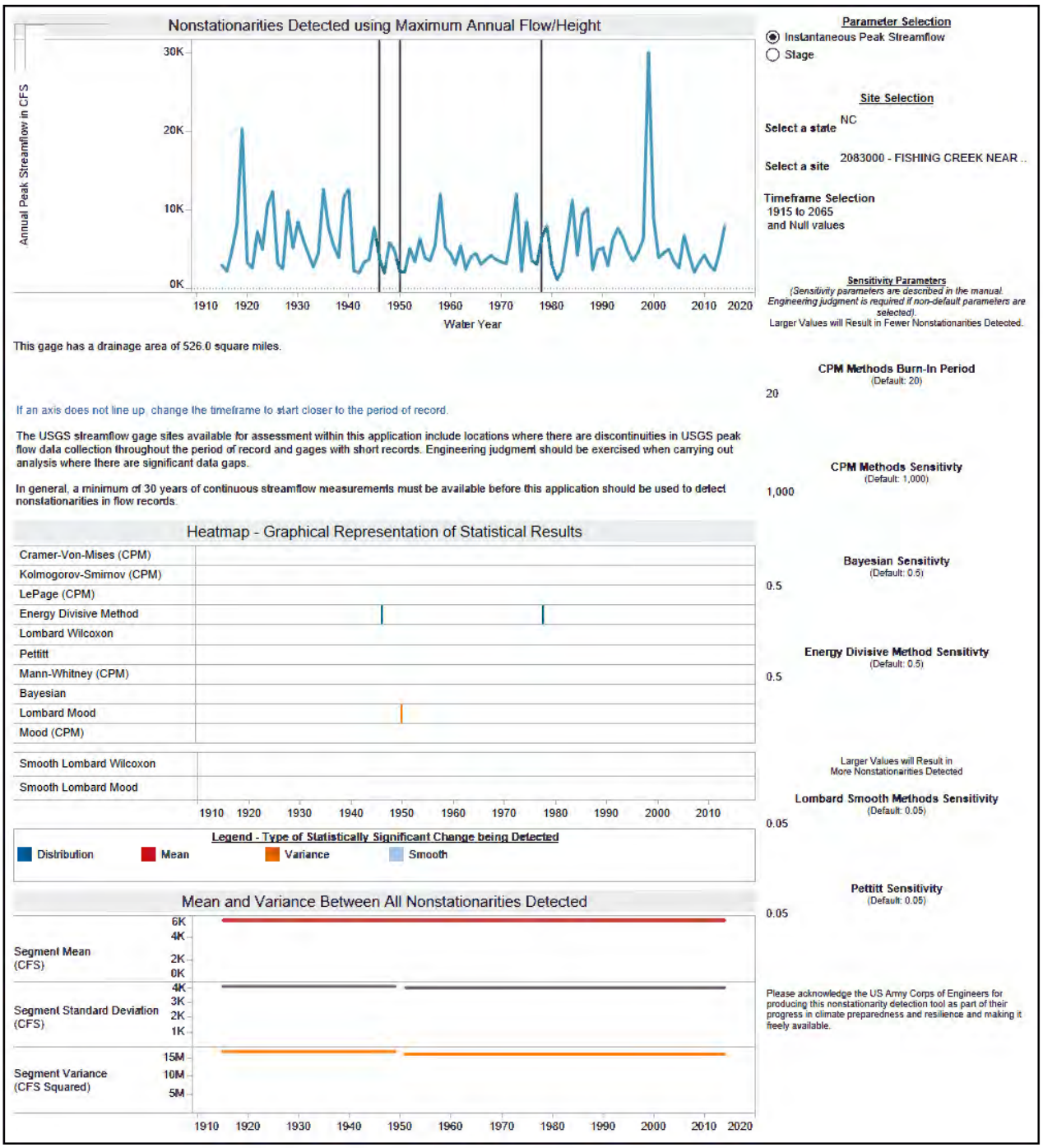

Figure 20: Nonstationairity Detection Results for Gage 02083000 Fishing Creek near Enfield, NC

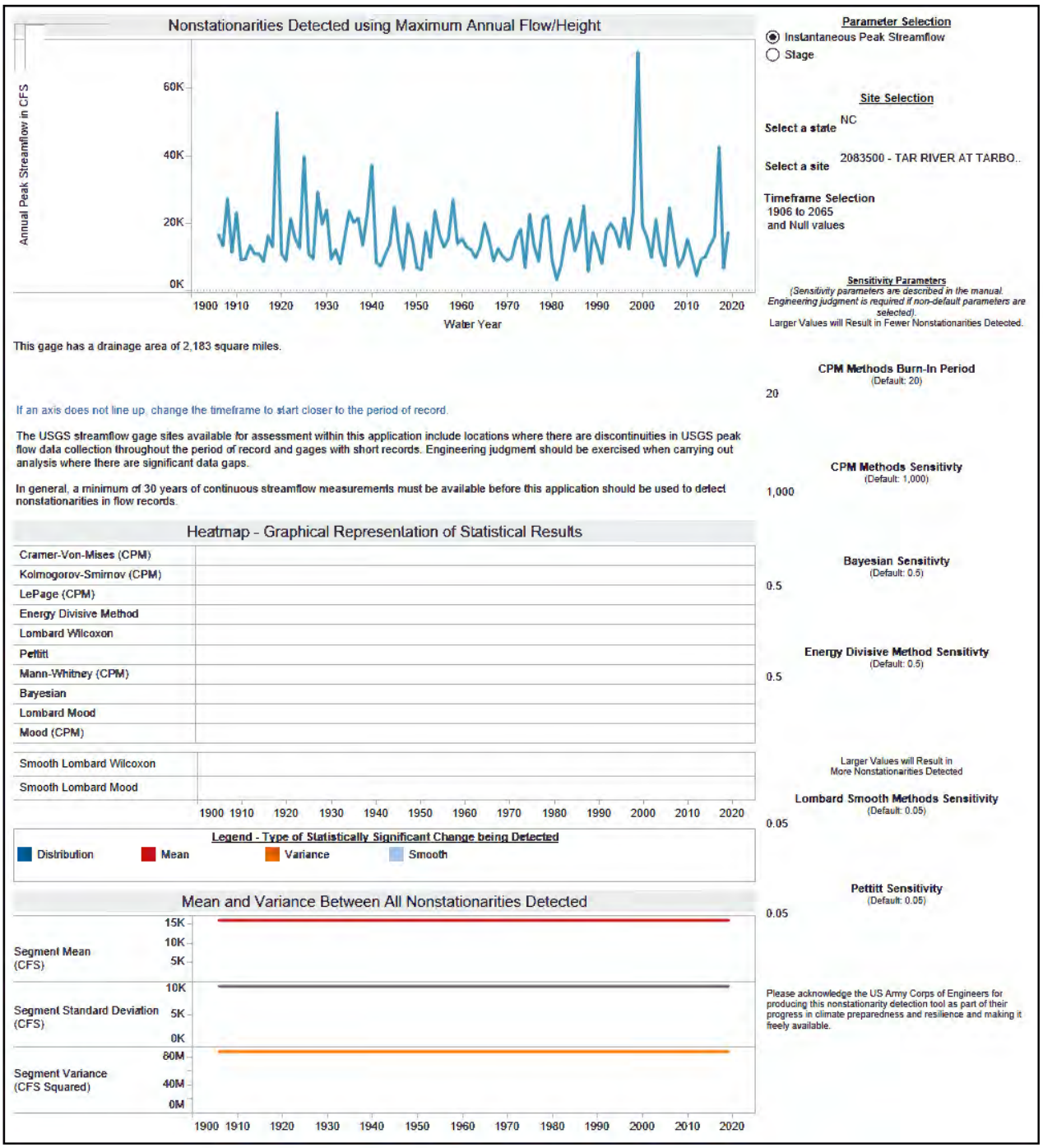

Figure 21: Nonstationairity Detection Results for Gage 02083500 Tar River at Tarboro, NC

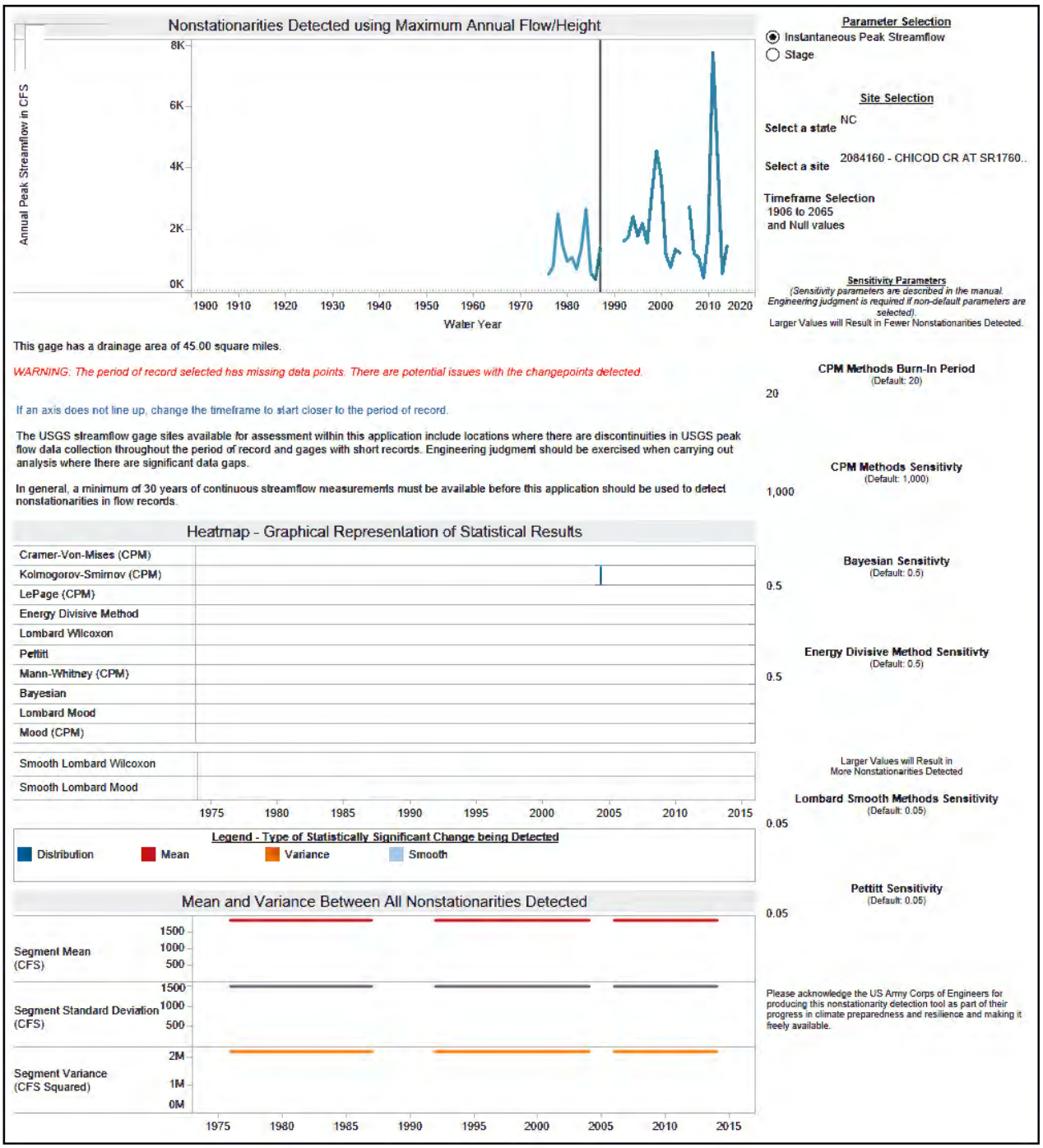

Figure 22: Nonstationairity Detection Results for Gage 02084160 Chicod Creek at SR 1760 near Simpson, NC

Table 4: Summary of Observed Streamflow Trends in Annual Peak Streamflow using NSD

Gage Number	Gage Name and Location	POR for CHAT	POR for NSD	POR Note	Consensus	Robustness	Conclusion
02081500	Tar River near Tar River, NC	1940-2014	1940-2014	Complete	No	No	None
02081747	Tar R at US 401 at Louisburg, NC	1964-2014	1964-2014	Complete	Yes	No	CVM & KS in 1971
02082000	Tar River near Nashville, NC	N/A	N/A	Not in CHAT or NSD (ended in 1970)	N/A	N/A	N/A
02082506	Tar River below Tar R Reservoir near Rocky Mount, NC	N/A	N/A	Not in CHAT or NSD (ended in 2010)	N/A	N/A	N/A
02082585	Tar River at NC 97 at Rocky Mount, NC	1977-2014	1977-2014	Complete	No	No	None
02082770	Swift Creek at Hilliardston, NC	1964-2014	1964-2014	Complete	No	No	None
02082950	Little Fishing Creek near White Oak, NC	1960-2014	1960-2014	Complete	No	No	None
02083000	Fishing Creek near Enfield, NC	1915-2014	1915-2014	Complete	No	No	None

02083500	Tar River at Tarboro, NC	1895-2014	1906-2014	Complete	No	No	None
02083800	Conetoe Creek near Bethel, NC	N/A	N/A	Not in CHAT or NSD (ended in 2001)	N/A	N/A	N/A
02084000	Tar River at Greenville, NC	1997-2014	1997-2014	Length not sufficient	N/A	N/A	N/A
02084160	Chicod Creek at SR1760 near Simpson, NC	1976-2014	1976-2014	Complete, minus gap (1988-91)	No	No	None
02084472	Pamlico River at Washington, NC	N/A	N/A	Not in CHAT or NSD (length not sufficient)	N/A	N/A	N/A

Projected Trends in Future Climate and Climate Change

Literature Review of Projected Climate Changes

While historical data is essential to understanding current and future climate, non-stationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2008). Consequently, the scientific and engineering communities are actively using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed global climate models (GCMs), are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

Temperature

Maximum air temperature projections were investigated by Liu et al. (2013) using a single GCM and assuming an A2 greenhouse gas emissions scenario (worst case). The results of their study, specific to the South Atlantic-Gulf Region, show a projected increase in winter and spring maximum air temperature of about 2 ºC for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (**Figure 23**). They show projected increases of up to 3.5 ºC for summer and fall temperatures.

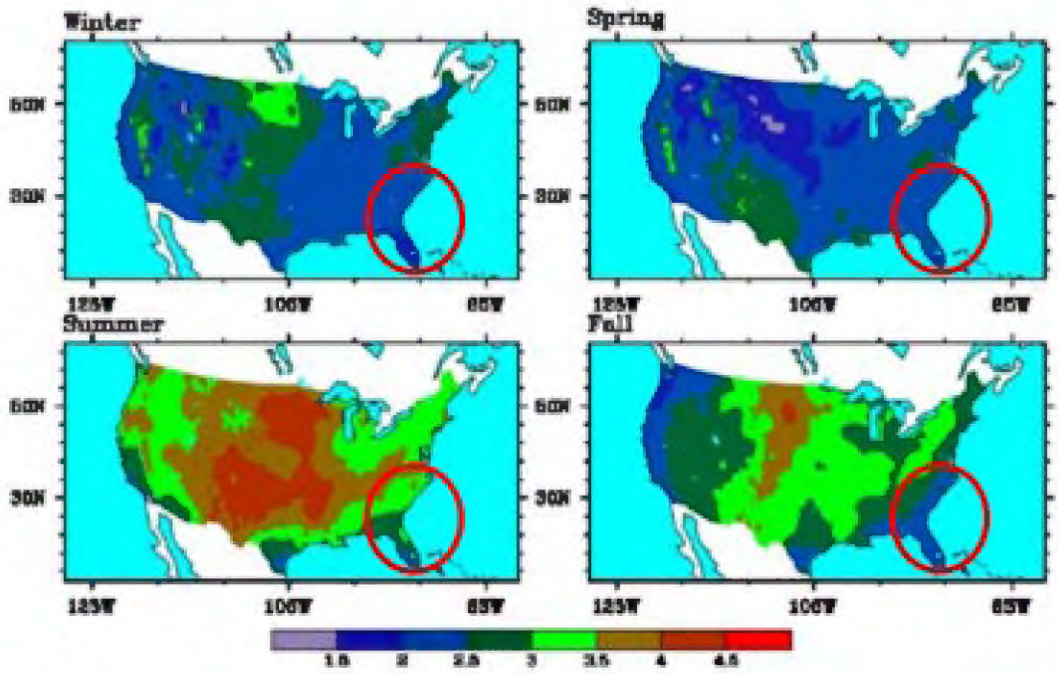

Figure 23: Projected changes in seasonal maximum air temperature, ºC, 2041-2070 vs. 1971-2000. The South Atlantic-Gulf Region is within the red oval (Liu et al., 2013).

Elguindi and Grundstein (2013) present results of regional climate modeling of the U.S. focused on the Thornthwaite climate type – a measure of the combination of relative temperature and precipitation projections. For the South Atlantic-Gulf Region, results show a shift from primarily warm wet or warm moist climate type in the latter decades of the 20th century to a much larger proportion of hot moist or hot dry climate type areas by the period 2041 – 2070 (**Figure 24**).

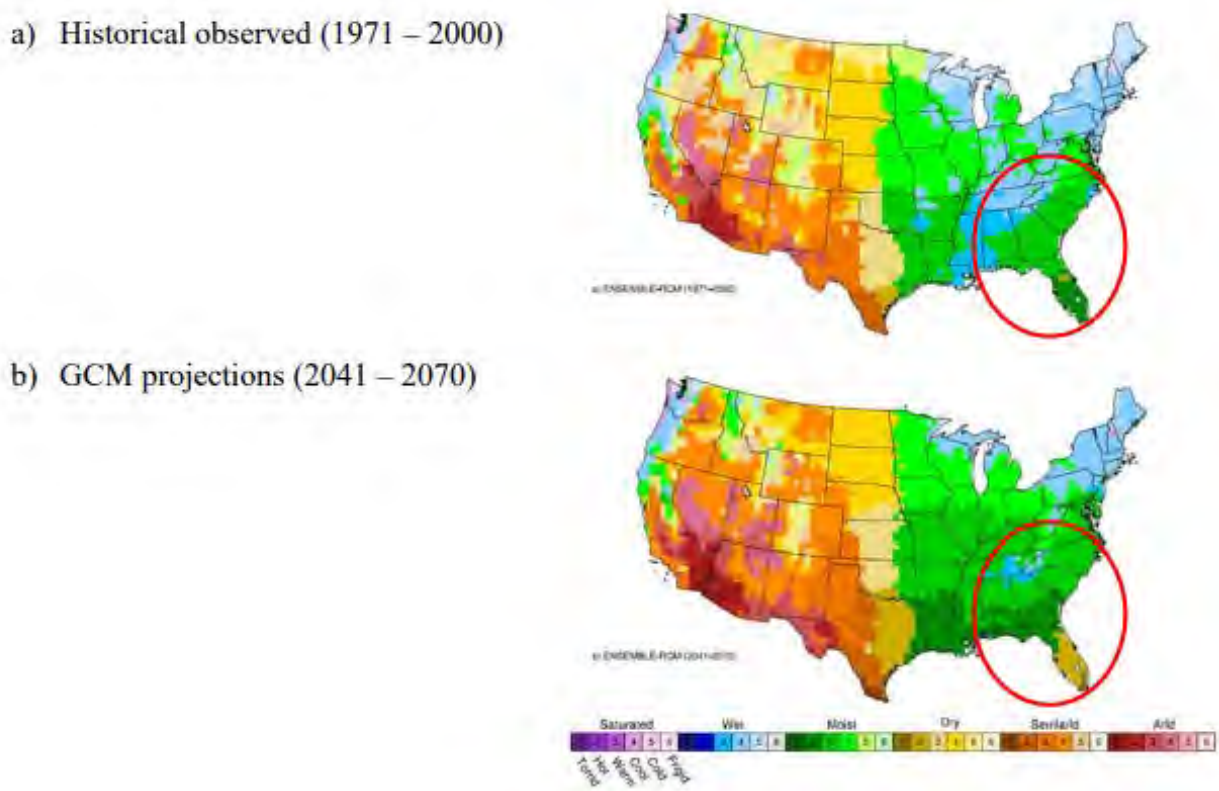

Figure 24: Revised Thornthwaite climate types projected by regional climate models. The South Atlantic-Gulf Region is within the red oval (Elguindi and Grundstein, 2013).

Projections of changes in temperature extremes have been the subject of many recent studies performed at a national scale. A 2006 study by Tebaldi et al. applied nine GCMs at a global scale focused on extreme precipitation and temperature projections. Model projections of climate at the end of the century (2080 – 2099) were compared to historical data for the period 1980 – 1999. For the general southeastern U.S., inclusive of the South Atlantic-Gulf Region, the authors identified small increases in the projected extreme temperature range (annual high minus annual low temperature), a moderate increase in a heat wave duration index (increase of 3 to 4 days per year that temperatures continuously exceeds the historical norm by at least 5 ºC), and a moderate increase in the number of warm nights (6 to 7% increase in the percentage of times in the year when minimum temperature is above the 90th percentile of the climatological distribution for the given calendar year), compared to the baseline period.

At a regional scale, Qi et al. (2009) used two GCMs (CGC1 and HadCMSul2) in combination with hydrologic modeling to project streamflow changes in the Trent River

(North Carolina). Temperature projections from these two climate models (**Figure 25**) show increases of approximately 2 to 4 ºC by the end of the 21st century for their study area.

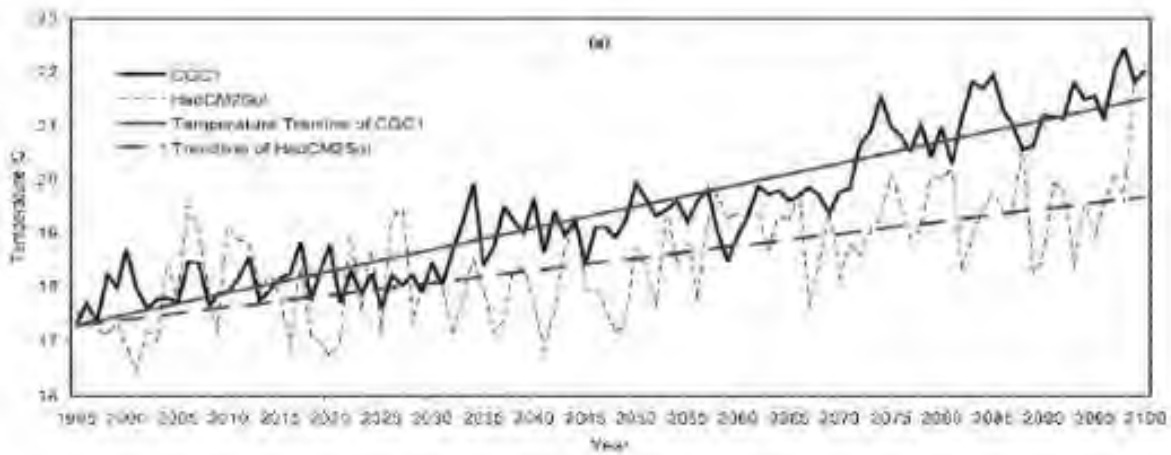

Figure 25: Projected annual average air temperature, Trent River basin, North Carolina, 1995–2100. (Qi et al., 2009).

Precipitation

Qi et al. (2009) present two differing GCM projections for their coastal North Carolina watershed (**Figure 26**). One projects an approximate 15% increase in precipitation by the end of the 21st century, while the other projects an approximate 20% decrease.

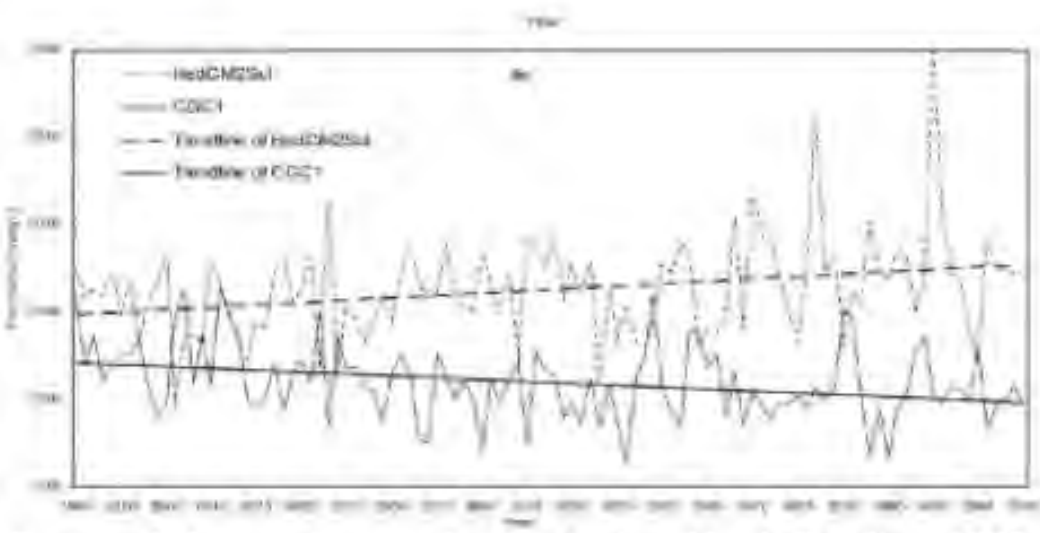

Figure 26: Projected changes in annual precipitation, North Carolina, 1995 – 2100. (Qi et al., 2009).

Future projections of extreme events, including storm events and droughts, are the subject of studies by Tebaldi et al. (2006), Wang and Zhang (2008), Gao et al. (2012), and Wang et al. (2013a). The first authors, as part of a global study, compared an ensemble of GCM projections for the southeast U.S. and a 2090 planning horizon with historical baseline data (1980 – 1999). They report small increases in the number of high (> 10 mm) precipitation days for the region, the number of storm events greater than the 95th percentile of the historical record, and the daily precipitation intensity index (annual total precipitation divided by number of wet days). In other words, the projections forecast small increases in the occurrence and intensity of storm events by the end of the 21st century for the general study region. In addition to the historical data trend analyses by Wang and Zhang (2008) described above, these authors also used downscaled GCMs to look at potential future changes in precipitation events across North America. They used an ensemble of GCMs and a single high emissions scenario (A2) to quantify a significant increase (c. 30 to 50%) in the recurrence of the current 20-year 24-hour storm event for their future planning horizon (2075) and the general South Atlantic-Gulf Region (**Figure 27**). The projected increases in storm frequency presented by Wang and Zhang appear to be more significant than those projected by Tebaldi et al. (2006), but there is agreement on the general trend.

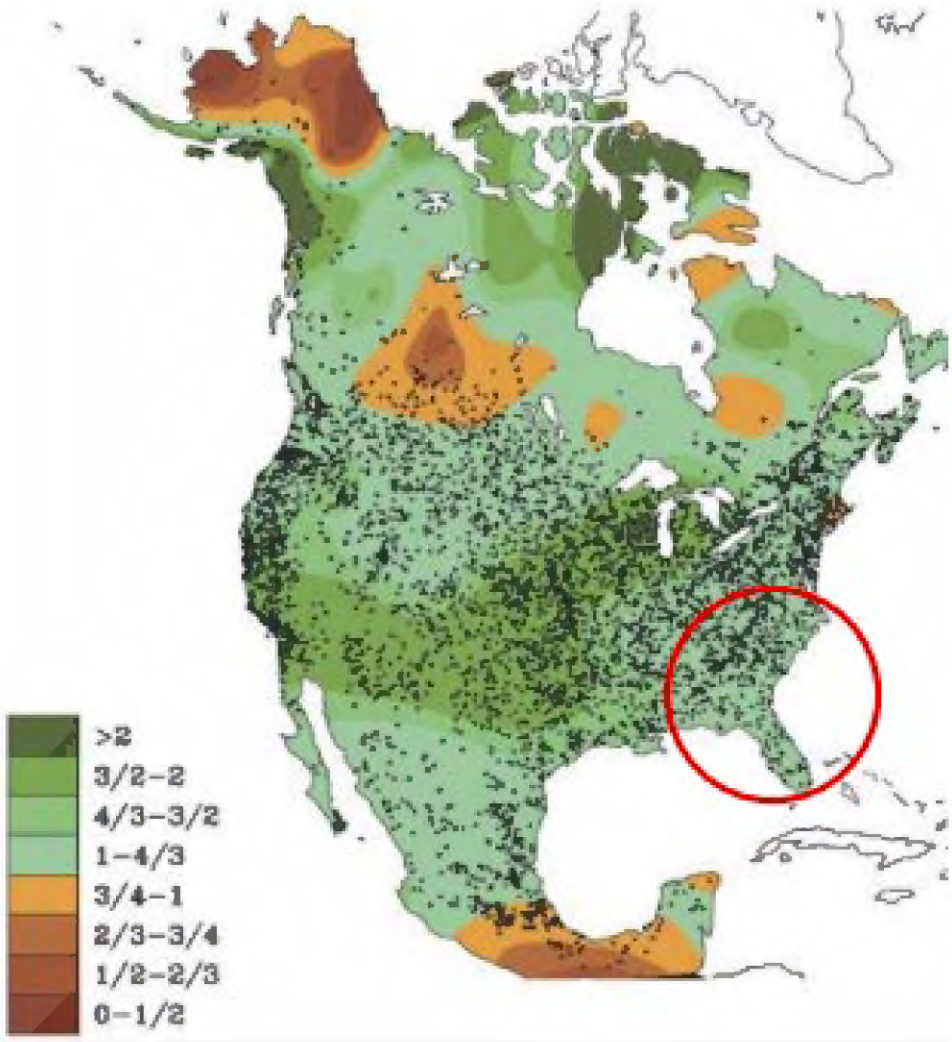

Figure 27: Projected risk of current 20-year 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The South Atlantic Gulf Region is within the red oval (Wang and Zhang, 2008).

Hydrology

A number of global and national scale studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro-scale hydrologic models. These studies include projections of potential hydrologic changes in the South Atlantic-Gulf Region. Thomson et al. (2005) applied two GCMs, across a range of varying input assumptions, in combination with the macro-scale Hydrologic Unit Model to quantify potential changes in water yield across the United States. Results are presented for both continuous spatial profiles across the country (**Figure 28**) and for

individual HUCs. For the South Atlantic-Gulf Region, contradictory results are generated by the two GCMs. For the same set of input assumptions, one model predicts significant decreases in water yield, the other projects significant increases in water yield.

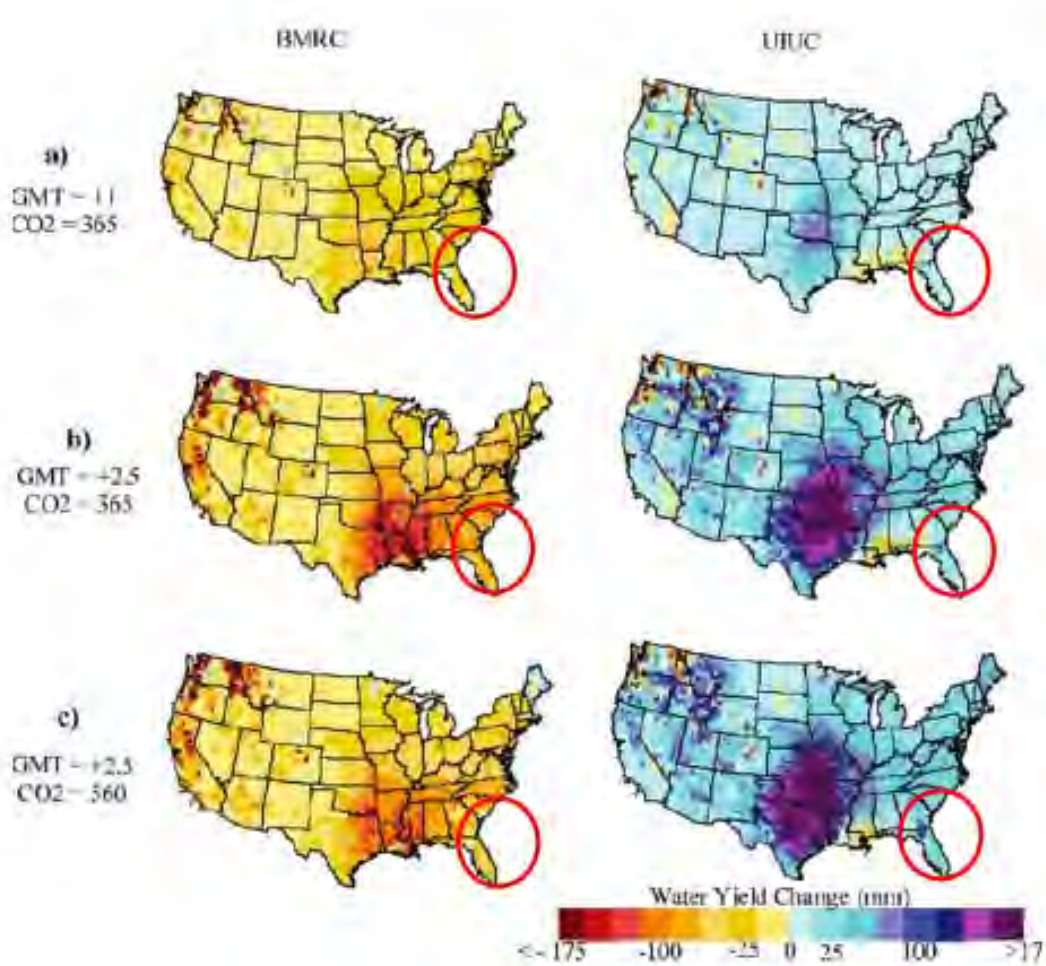

Figure 28: Projected change in water yield (from historical baseline), under various climate change scenarios based on 2 GCM projections. The South Atlantic-Gulf Region is within the red oval (Thomson et al., 2005).

The results presented by Thomson et al. (2005), described above, highlight the significant uncertainties associated with global climate modeling, particularly with respect to hydrologic parameters. Additional uncertainty is generated when these climate models are combined with hydrologic models that carry their own uncertainty. This comparison and quantification of uncertainty is the subject of a 2013 study by Hagemann et al. In this study, the authors apply three GCMs, across two emission scenarios to seed eight different hydrologic models for projecting precipitation, ET, and runoff on a global scale. Their findings, in agreement with CDM Smith (2012), indicate that the uncertainty associated with macro-scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections

from Hagemann et al. (2013) for the general South Atlantic-Gulf Region show an overall decrease in runoff by approximately 200 mm per year for their future planning horizon (2071 – 2100) compared to the recent historical baseline (1971 – 2000) (**Figure 29**), assuming an A2 emissions scenario.

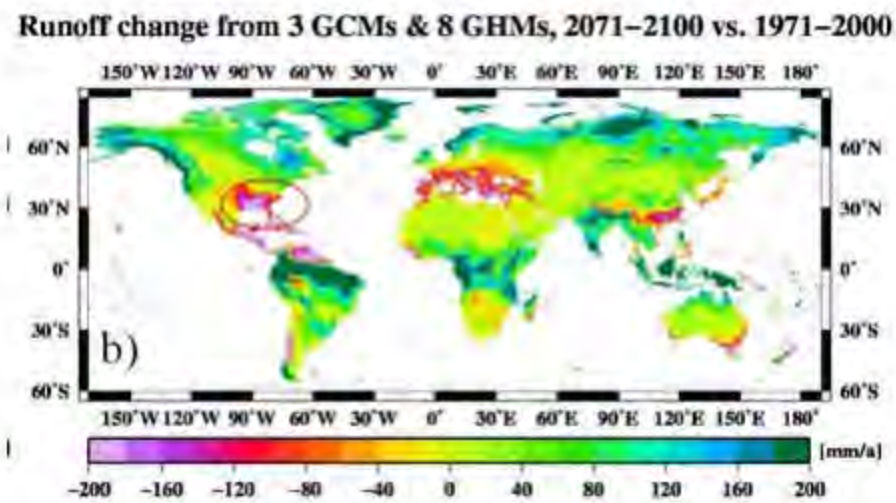

Figure 29: Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The South Atlantic-Gulf Region is within the red oval (Hagemann et al., 2013).

No clear consensus was found in projected streamflow changes in the South Atlantic-Gulf Region. Some studies point toward mild increases in flow, others point toward mild decreases in flow.

Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the study area, and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of approximately 2 to 4 ºC by the latter half of the 21st century for the South Atlantic-Gulf Region. The largest increases are projected for the summer months. Reasonable consensus is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves in the long-term future compared to the recent past. Projections of precipitation in the study area are less certain than those associated with air temperature. Results of the studies reviewed here are roughly evenly split with respect to projected increases vs. decreases in future annual precipitation. This is not unexpected as, according to the recently released NCA (Carter et al., 2014); the southeast region of the country (inclusive of the South Atlantic-Gulf Region) appears to be located in a “transition zone” between the projected wetter

conditions to the north and dryer conditions to the west. There is, however, moderate consensus among the reviewed studies that future storm events in the region will be more intense and more frequent compared to the recent past. Similarly, clear consensus is lacking in the hydrologic projection literature. Projections generated by coupling GCMs with macro-scale hydrologic models in some cases indicate a reduction in future streamflows but in other cases indicate a potential increase in streamflows in the study region. Of the limited number of studies reviewed here, results are approximately evenly split between the two.

Climate Hydrology Assessment Tool

The USACE Climate Hydrology Assessment Tool (CHAT) was used to assess projected, future trends within the Neuse-Pamlico watershed, HUC-0302. The tool displays the range of projected annual maximum monthly streamflows from 1950 - 2099, with the projections from 1950 – 1999 representing hindcast projections and 2000 – 2099 representing forecasted projections.

Figure 30 displays the range of projections for 93 combinations of CMIP5 GCMs and RCPs produced using BCSD statistical downscaling. These flows are simulated using an unregulated VIC hydrologic model at the outlet of HUC 0302 Neuse-Pamlico. It should be noted that the hindcast projections do not replicate historically observed precipitation or streamflow and should therefore not be compared directly with historical observations. This is in part because observed streamflows are impacted by regulation, while the VIC model used to produce the results displayed in **Figure 30** is representative of the unregulated condition.

Upon examination of the range of model results, there is a clear increasing trend in the higher projections, whereas the lower projections appear to be relatively stable and unchanging through time. The spread of the model results also increases with time, which is to be expected as uncertainty in future projection increases as time moves away from the model initiation point. Sources of variation and the significant uncertainty associated with these models include the boundary conditions applied to the GCMs, as well as variation between GCMs and selection of RCPs applied. Each GCM and RCP independently incorporate significant assumptions regarding future conditions, thus

introducing more uncertainty into the climate changed projected hydrology. Climate model downscaling and a limited temporal resolution further contribute to the uncertainty associated with CHAT results. There is also uncertainty associated with the hydrologic models. The large spread of results shown in **Figure 30** highlights current climatic and hydrologic modeling limitations and associated uncertainty.

Figure 31 displays only the mean result of the range of the 93 projections of future, climate changed hydrology which are shown in **Figure 30**. A linear regression line was fit to this mean and displays an increasing trend with a slope of approximately 28.5 cfs/yr. It should be noted that the p-value associated with this trend is less than 0.0001, indicating that the trend should be considered as statistically significant.

These outputs from the CHAT qualitatively suggest that annual maximum monthly flows, and therefore annual peak flows, are expected to increase in the future relative to the current time.

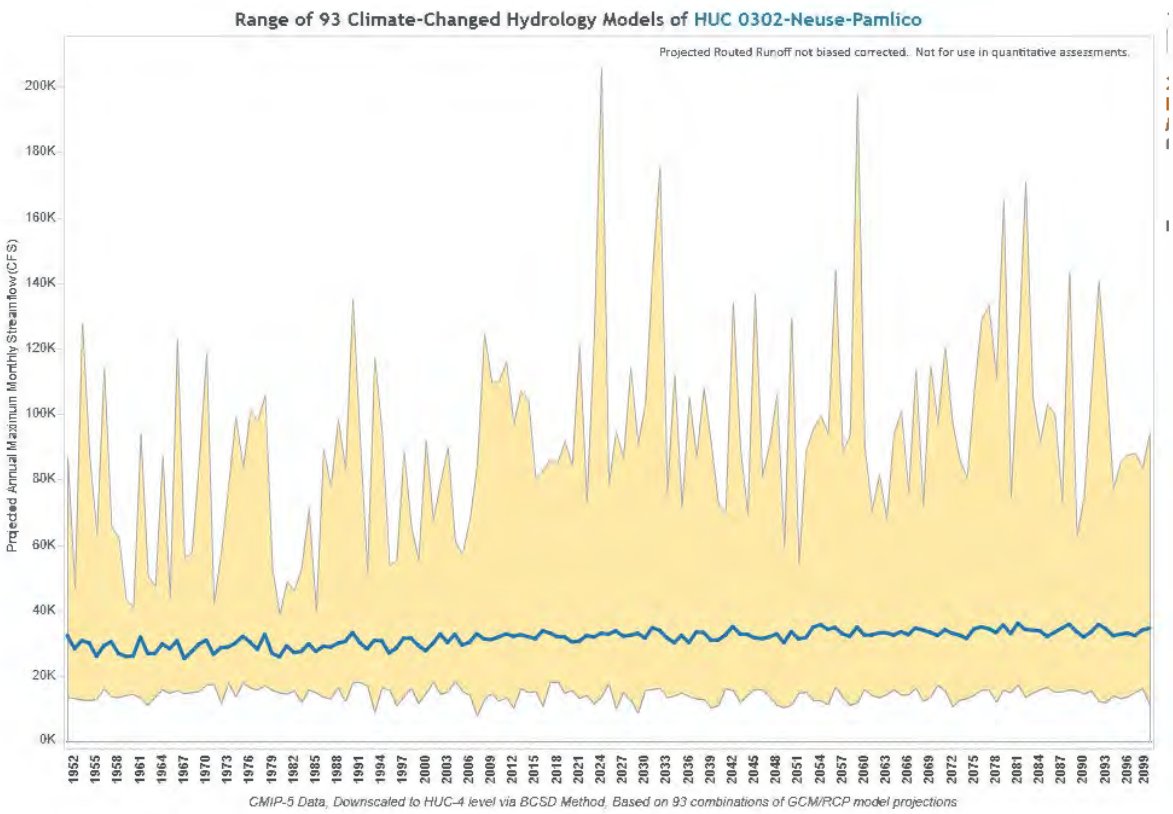

Figure 30: Range of GCM/RCP Projections for the HUC-0302 Neuse-Pamlico.

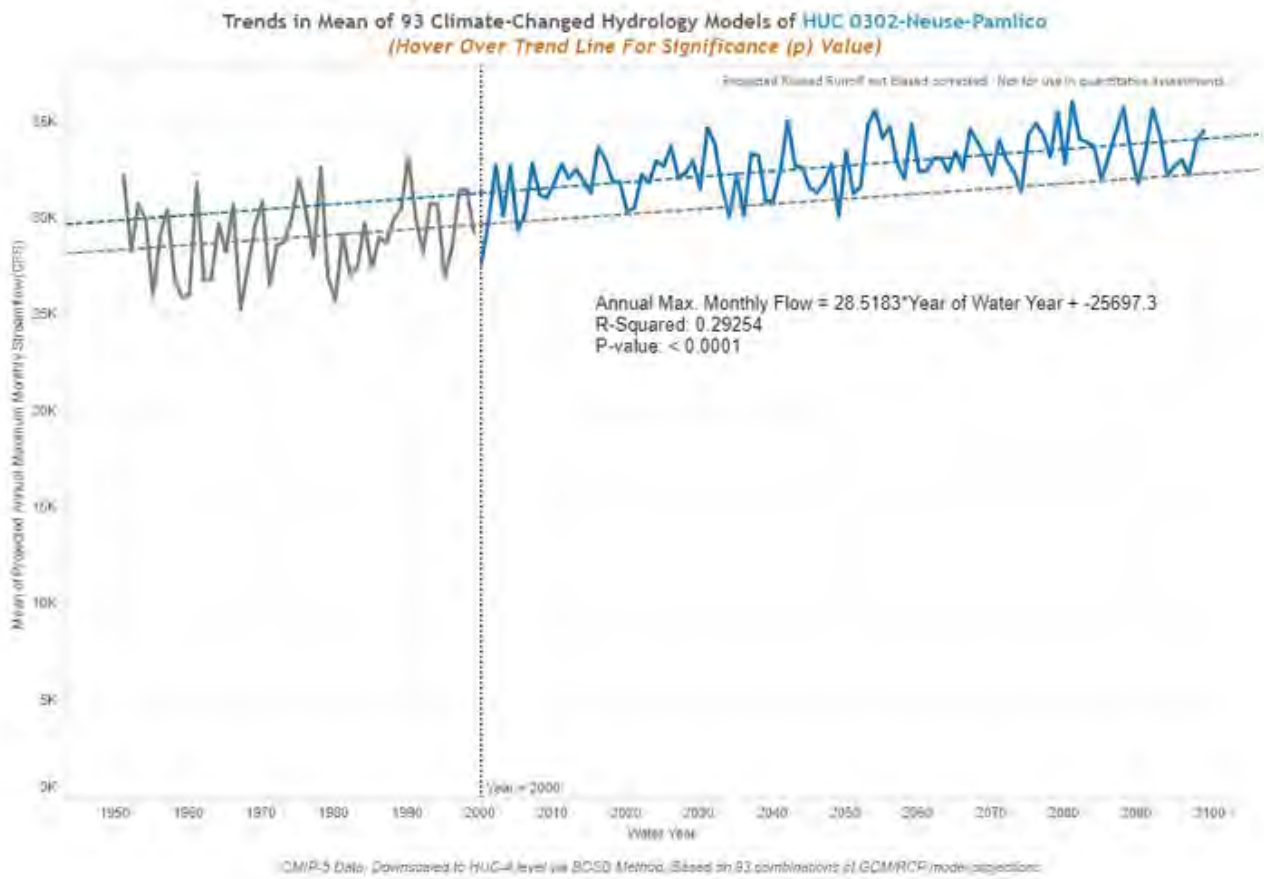

Figure 31: Mean of GCM/RCP Projections for the HUC-0302 Nuese-Pamlico.

Vulnerability Assessment

The USACE Watershed Climate Vulnerability Assessment Tool (VA Tool) facilitates a screening level, comparative assessment of how vulnerable a given HUC-4 watershed is to the impacts of climate change relative to the other 202 HUC-4 watersheds within the continental United States (CONUS). The tool can be used to assess the vulnerability of a specific USACE business line such as “Flood Risk Reduction” or “Navigation” to projected climate change impacts. Assessments using this tool help to identify and characterize specific climate threats and particular sensitivities or vulnerabilities, at least in a relative sense, across regions and business lines. The tool uses the Weighted Ordered Weighted Average (WOWA) method to represent a composite index of how vulnerable a given HUC-4 watershed (Vulnerability Score) is to climate change specific to a given business line. The HUC-4 watersheds with the top 20% of WOWA scores are flagged as being vulnerable.

Flood risk reduction is the most relevant business line for the Tar Pamlico River Basin Feasibility Study and is the primary business line analyzed with the USACE Climate Vulnerability Assessment Tool. Other business lines included in the VA Tool are ecosystem restoration, emergency management, hydropower, navigation, recreation, regulatory, and water supply. While the flood risk reduction is the main business line discussed in detail, all other business lines were analyzed as well.

When assessing future risk projected by climate change, the USACE Climate Vulnerability Assessment Tool makes an assessment for two 30-year epochs of analysis centered at 2050 and 2085. These two periods were selected to be consistent with many of the other national and international analyses. The Vulnerability tool assesses how vulnerable a given HUC-4 watershed is to the impacts of climate change for a given business line using climate hydrology based on a combination of projected climate outputs from the general circulation models (GCMs) and representative concentration pathway (RCPs) resulting in 100 traces per watershed per time period. The top 50% of the traces is called “wet” and the bottom 50% of the traces is called “dry.” Meteorological data projected by the GCMs is translated into runoff using the Variable Infiltration Capacity (VIC) macro-scale hydrologic model. For this assessment, the default National Standards Settings are used to carry out the vulnerability assessment.

For the Flood Risk Management business line, the HUC 0302 Neuse-Pamlico Basin is not within the top 20% of vulnerable watersheds within the CONUS for any of the four scenarios, which is not to say that vulnerability to future climate change does not exist within the basin. **Table 5** displays the overall vulnerability scores for the business line relevant to this study under both wet and dry scenarios and under both time epochs. The indicators driving the residual vulnerability for the flood risk management business line is shown in **Figure 32**. **Table 5** and **Table 6** display the indicators contributing to vulnerability within the Neuse-Pamlico Basin for the flood risk reduction business line; the tables are generally sorted from largest to smallest average indicator contribution to vulnerability. Additionally, the tables display the indicator code, name, and a brief description of the indicator’s meaning.

Regarding the Flood Risk Reduction business line, the primary indicators driving vulnerability within the watershed are the flood magnification factor (indicator 568C), and the large elasticity between rainfall and runoff (indicator 277). The flood magnification factor represents how the monthly flow exceeded 10% of the time is predicted to change in the future; a value greater than 1 indicates flood flow is predicted to increase, which is true for the Neuse-Pamlico Basin. The rainfall/runoff elasticity (indicator 277) measures the tendency for small changes in precipitation to result in large changes in runoff.

Note that some of the indicators contain a suffix of “L” (local) or “C” (cumulative). Indicators with an “L” suffix reflect flow generated within only one HUC-4 watershed, whereas indicators with a “C” suffix reflect flow generated within a HUC-4 watershed and any upstream watersheds.

It is important to note the variability displayed in the VA tool’s results (**Table 5**, **Table 6**) highlights some of the uncertainty associated with the projected climate change data used as an input to the VA tool. Because the wet and dry scenarios each represent an average of 50% of the GCM outputs, the variability between the wet and dry scenarios underestimates the larger variability between all the underlying projected climate changed hydrology estimates. This variability can also be seen between the 2050 and 2085 epochs, as well as various other analysis within this report, such as output from the CHAT (**Figure 30**).

Table 5: Overall Vulnerability Score for Epochs and Selected Scenarios

Business Line	**Flood Risk Reduction**	
Epoch	**2050**	**2085**
Dry	45.13	47.59
Wet	48.16	51.99

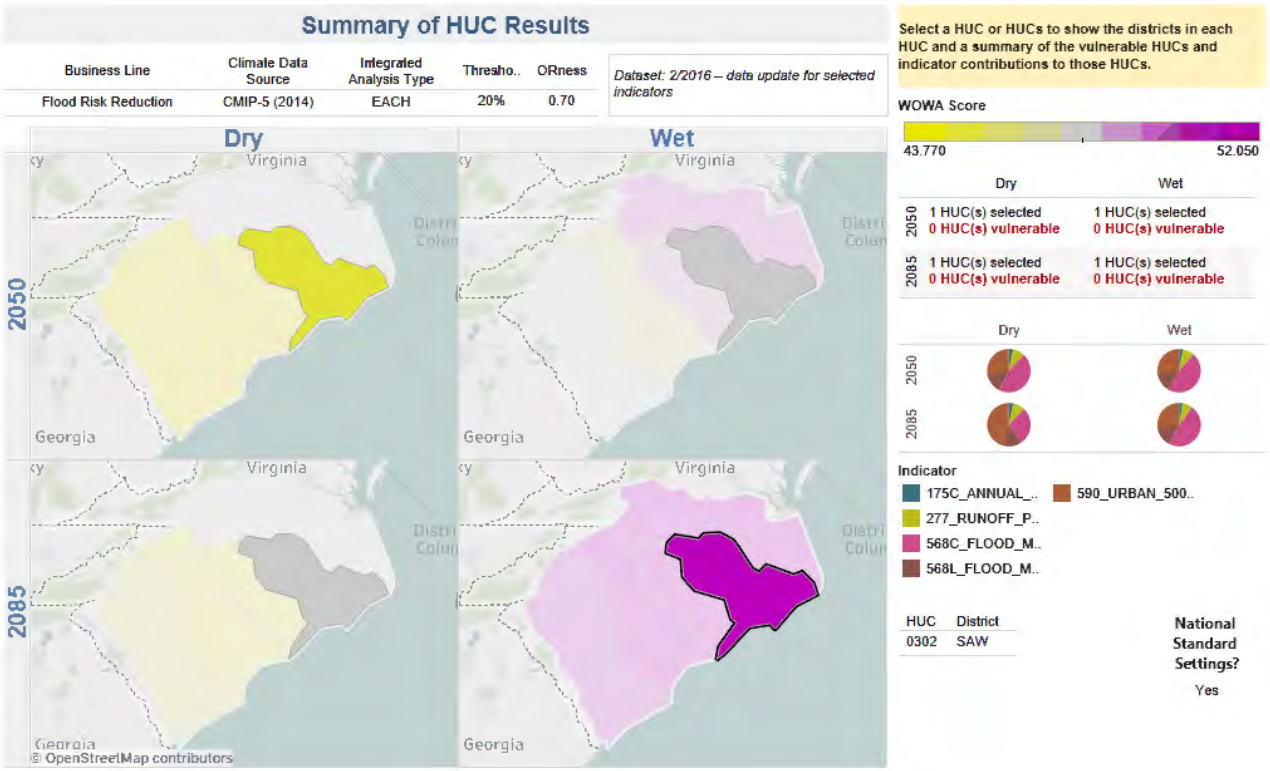

Figure 32: VA Tool Summary of HUC Results for Flood Risk Reduction Business Line

Table 6: Vulnerability Indicators for Flood Risk Reduction Business Line

Flood Risk Reduction			2050	2050	2085	2085
Indicator Code	**Indicator Name**	**Description**	**Dry**	**Wet**	**Dry**	**Wet**
568C	Cumulative Flood Magnification Factor	Change in flood runoff: ratio of indicator 571C (monthly runoff exceeded 10% of the time, including upstream freshwater inputs) to 571C in base period.	45.15%	46.92%	28.07%	47.18%
277	Percent Change in Runoff Divided by the Percent Change in Precipitation	Median of: deviation of runoff from monthly mean times average monthly runoff divided by deviation of precipitation from monthly mean times average monthly precipitation.	8.84%	8.45%	8.94%	7.66%
568L	Local Food Magnification Factor	Change in flood runoff: Ratio of indicator 571L (monthly runoff exceeded 10% of the time, excluding upstream freshwater inputs) to 571L in base period.	14.82%	15.40%	14.18%	15.49%
175C	Cumulative Annual Covariance of Unregulated Runoff	Long-term variability in hydrology: ratio of the standard deviation of annual runoff to the annual runoff mean. Includes upstream freshwater inputs (cumulative).	3.18%	2.97%	3.28%	2.72%
590	Acres of Urban Area Within 500-Year Floodplain	Acres of urban area within the 500-year floodplain.	28.01%	26.25%	45.54%	26.96%

Sea Level Change Assessment

Using the USACE Sea-Level Change Curve Calculator (Version 2019.21) historical rates and future rates are calculated for the Beaufort, NC Gage 8656483, location shown in **Figure 33**. According to ER 1100-2-8162 these rates are then used by the calculator to produce three curves which are the *USACE Low Curve*, *USACE Intermediate Curve*, and the *USACE High Curve*. The *USACE Low Curve* is calculated using the historic rate of sea-level change for each given location. The *USACE Intermediate Curve* is computed from the modified National Research Council (NRC) Curve I considering both the most recent Intergovernmental Panel on Climate Change (IPCC) projections and modified NRC projections with the local rate of vertical movement added. The *USACE High Curve* is computed from the modified NRC Curve III considering both the most recent IPCC projections and modified NRC projections with the local rate of vertical land movement added. The results for Beaufort, NC gage can be found in **Figure 34** and **Table 7** in both graphical and tabular form for each curve. The results of the calculator for the year 2100 are as follows: Low Curve is 0.91ft, Intermediate Curve is 1.95ft, and High Curve is 5.24ft.

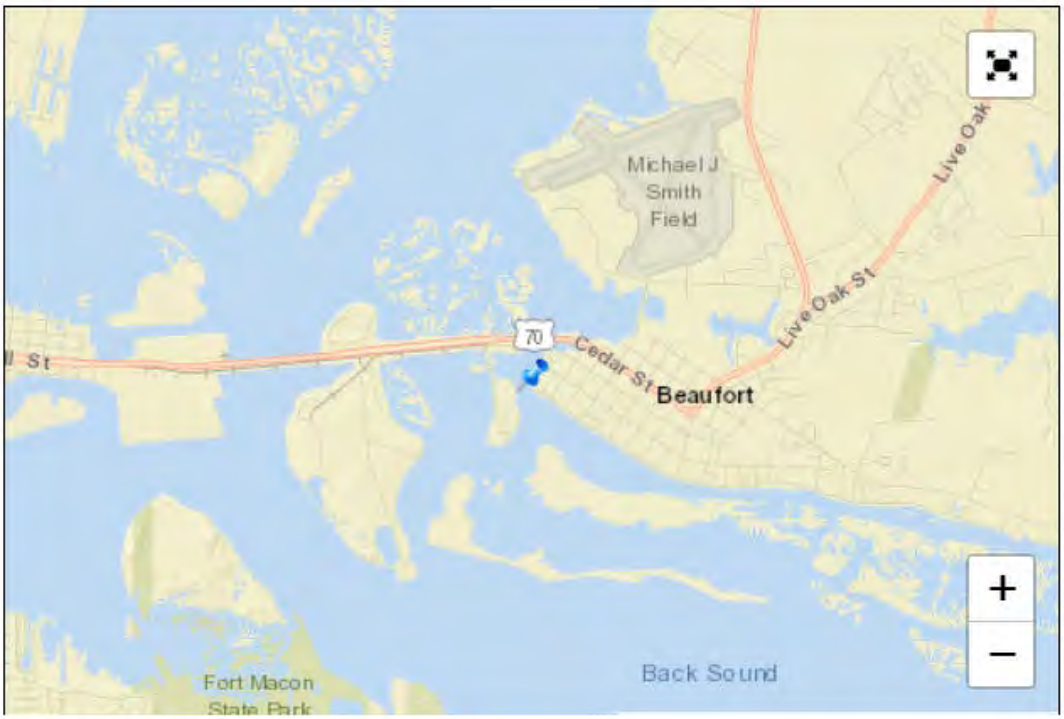

Figure 33: Location of Beaufort, NC Gage 8656483

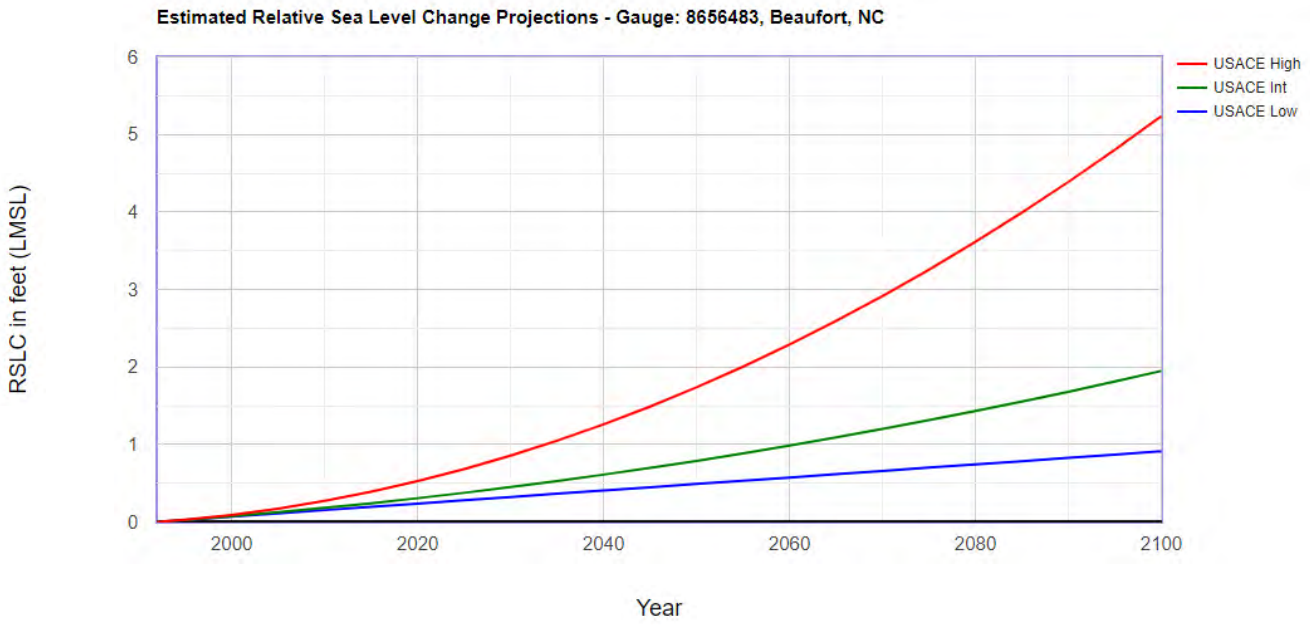

Figure 34: Estimated Relative Sea Level Change Projection Curves Beaufort, NC Gage 8656483

Table 7: Estimated Relative Sea Level Change Projection Tabular Data Beaufort, NC Gage 8656483

8656483, Beaufort, NC
NOAA's 2006 Published Rate: 0.00843 feet/yr
All values are expressed in feet relative to LMSL

Year	USACE Low	USACE Int	USACE High
1992	0.00	0.00	0.00
1995	0.03	0.03	0.03
2000	0.07	0.07	0.09
2005	0.11	0.13	0.17
2010	0.15	0.18	0.27
2015	0.19	0.24	0.39
2020	0.24	0.31	0.53
2025	0.28	0.38	0.68
2030	0.32	0.45	0.86
2035	0.36	0.53	1.05
2040	0.41	0.61	1.26
2045	0.45	0.70	1.49
2050	0.49	0.79	1.74
2055	0.53	0.88	2.00
2060	0.57	0.98	2.29
2065	0.62	1.09	2.59
2070	0.66	1.20	2.91
2075	0.70	1.31	3.25
2080	0.74	1.43	3.61
2085	0.78	1.55	3.99
2090	0.83	1.68	4.39
2095	0.87	1.81	4.80
2100	0.91	1.95	5.24

Summary and Conclusions

Based on the observed literature review, there is a consistent consensus that points toward mild increases in annual temperature in the South Atlantic-Gulf Region over the past century, particularly over the past 40 years. Annual precipitation totals have become more variable in recent years compared to earlier in the 20th century. Evidence has also been presented, but with limited consensus, of mildly increasing trends in the magnitude of annual and seasonal precipitation for parts of the study area. These results are seemingly contradicted by several studies that have shown decreasing trends in streamflow throughout the area, particularly since the 1970s. The study authors evaluated watersheds that experienced minimal water withdrawals and/or transfers. Results presented here also suggest that increasing temperatures may also play a role in decreasing streamflows, despite the lack of corresponding precipitation decline.

Every gage that was analyzed via Climate Hydrology Assessment Tool did not have a statistically significant linear trend. A few of the gages were not within the CHAT and the Tar River at Greenville, NC gage did not have the 30-year period of record needed to perform the analysis, so it was not analyzed either. There were no statistically significant trends detected in either gage that would indicate significant changes in observed streamflow due to climate change, long-term natural climate trends, or land use/land cover changes.

Using the Nonstationairity Detection Tool only one stream gage produced a nonstationairity and it is the 020817747 Tar R at US 401 at Louisburg, NC gage. The NSD calculated that a consensus of distribution occurred in 1971 by the CVM and KS methods, but the calculations presented no robustness. All other gages either did not have enough data to perform an analysis or the data that was found on USGS was not recent enough to be feasible for the analysis.

Projected Trends Summary and Conclusions

Based on the projected literature review, there is strong consensus in the literature that air temperatures will increase in the study area, and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of approximately 2 to 4 ºC by the latter half of the 21st century for the South Atlantic-Gulf Region. Projections of precipitation in the study area are less certain than those associated with air temperature. Results of the studies reviewed here are roughly evenly split with respect to projected increases vs. decreases in future annual precipitation. Projections generated by coupling GCMs with macro-scale hydrologic models in some cases indicate a reduction in future streamflows but in other cases indicate a potential increase in streamflows in the study region. Of the limited number of studies reviewed here, results are approximately evenly split between the two.

Upon examination of the range of model results from the Climate Hydrology Assessment Tool, there is a clear increasing trend in the higher projections, whereas the lower projections appear to be relatively stable and unchanging through time. The spread of the model results also increases with time, which is to be expected as uncertainty in future projection increases as time moves away from the model initiation point. Sources of variation and the significant uncertainty associated with these models include the boundary conditions applied to the GCMs, as well as variation between GCMs and selection of RCPs applied. Climate model downscaling and a limited temporal resolution further contribute to the uncertainty associated with CHAT results. There is also uncertainty associated with the hydrologic models. The large spread of results shown in

Figure 30 highlights current climatic and hydrologic modeling limitations and associated uncertainty. **Figure 31** displays only the mean result of the range of the 93 projections of future, climate changed hydrology which are shown in **Figure 30**. A linear regression line was fit to this mean and displays an increasing trend with a slope of approximately 28.5 cfs/yr. It should be noted that the p-value associated with this trend is less than 0.0001, indicating that the trend should be considered as statistically significant.

Results from the USACE Vulnerability Assessment tool were analyzed for the project area and found no outstanding vulnerabilities compared with other HUCs across the continental United States. While the project area is not within the top 20% of vulnerable HUCs nationally, that does not imply that vulnerability to climate change does not exist. The VA tool indicates that the change in flood runoff (cumulative), combined with the acres of urban area within 500-year floodplain, are driving flood risk reduction vulnerability.

Based on the USACE Sea-Level Change Curve Calculator for the Beaufort, NC Gage the Tar-Pamlico River Basin will be affected by sea-level rise over the next century. The results of the calculator for the year 2100 are as follows: Low Curve is 0.91ft, Intermediate Curve is 1.95ft, and High Curve is 5.24ft. These results can be found in **Table 7.**

Residual Risks					
Project Feature	*Trigger*	*Hazard*	*Harm*	*Qualitative Likelihood Rating*	*Justification for Rating*
Alternative 3A: Maximum Net Economic Benefits/NED Plan	Storm event magnitude that initiates flood damages	Future knowledge of large floods could increase the frequency of flow	Future flood risk may be characterized by floods that have not occurred yet, floods will continue to occur however protected from damages	Unlikely	The industry best practices in statistical hydrology were used to compute confidence bounds and uncertainty was provided to the Flood Damage Analysis through standard deviation of error
Alternative 3B: Comprehensive Benefits Plan	Storm event magnitude that initiates flood damages	Future knowledge of large floods could change the flow frequencies experienced	Future flood risk may be characterized by floods that have not occurred yet, floods will continue to occur however protected from damages	Unlikely	Trends noted during the climate impact analysis does not conclude that increasing precipitation or stream flow records indicate a rise in flood magnitudes, nor is larger floods i.e. Hurricane Matthew expected to be more frequent
Dry Flood Proofing	Relative sea level rise increases to the extent that impact the riverine water surface profiles	Higher downstream stages in Pamlico Sound would increase the impact of backwater up the Tar River Mainstem	Dry flood proofing would not be sufficent to deliver flood damage reduction	Unlikely	Through in depth sensitivity analysis using known wsel, normal depth, RSLR applied, it was determined that no combination of loading given the tide frequency impact would go further upstream than the US264 Bypass Bridge
Install dwelling vents	Relative sea level rise increases to the extent that impact the riverine water surface profiles	Higher downstream stages in Pamlico Sound would increase the impact of backwater up the Tar River Mainstem	Dry flood proofing would not be sufficent to deliver flood damage reduction	Unlikely	Through in depth sensitivity analysis using known wsel, normal depth, RSLR applied, it was determined that no combination of loading given the tide frequency impact would go further upstream than the US264 Bypass Bridge