NORTH CAROLINA
Department of Environmental Quality

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Subtask 3.5, 3.6, 3.7: Recommendations: Open Access H&H Modeling, Storm Frequencies, and Climate Forecast Models Support Tools

North Carolina Flood Resiliency Blueprint

Prepared for the North Carolina Department of Environmental Quality by AECOM, ESP Associates, and Insight

December 2023

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Definitions

A comprehensive list of definitions applicable to multiple Flood Resiliency Blueprint documents is provided in a separate document.

Acronyms

AAL Average Annual Loss

ADCIRC Advanced Circulation Model

AR5 & AR6 Assessment Reports 5 and 6

CISA climate informed science approach

CMIP5 Coupled Model Intercomparison Project Phase 5

CMIP6 Coupled Model Intercomparison Project Phase 6

DMS Division of Mitigation Services within NCDEQ

DSS Data Storage System

FEMA **Federal Emergency Management Agency**

FORE-SCE Forecasting Scenarios

FFRMS Federal Flood Risk Management Standard

FVA freeboard value approach

GHG greenhouse gas

GIS Geographic Information System

HEC Hydrologic Engineering Center

HMS Hydrologic Modeling System

IPCC Intergovernmental Panel on Climate Change

LOCA Localized Constructed Analogs

MACA Multivariate Adaptive Constructed Analogs

MODFLOW **Modular three-dimensional finite-difference ground-water flow model**

NCORR North Carolina Office of Resilience and Recovery

NCDEQ North Carolina Department of Environmental Quality

NCDOT North Carolina Department of Transportation

NCFMP **North Carolina Floodplain Mapping Program**

NCSU North Carolina State University

NOAA National Oceanic and Atmospheric Administration

RAPT Resilience Analysis and Planning Tool

RAS River Analysis System

RCPs Representative Concentration Pathways

SLR sea level rise

SSPs Shared Socioeconomic Pathways

SWAN **Simulating Waves Nearshore**

UASCE US Army Corps of Engineers

USGS US Geological Survey

UNC **University of North Carolina**

1 Introduction

Task 3 of the Phase 1 development of the North Carolina Flood Resiliency Blueprint (Blueprint) includes modeling recommendations based on Stakeholder Engagement (Task 1) and the Gap Analysis (Task 2).

1.1 Purpose

The purpose of this document is to summarize the following Phase 1 recommendations.

- Recommendations for open access hydrologic and hydraulic (H&H) modeling software and approaches including how various models can be leveraged and cross-utilized.
- Recommendations regarding model scale.
- Recommendations regarding storm frequency options.
- Recommendation regarding climate forecast model(s) selection.

North Carolina is a data-rich state, including statewide foundational datasets that lend themselves to supporting development of models for different stakeholders with unique needs and goals. These datasets and models have been identified and documented as part of the Task 2 deliverables. This document will provide recommendations for open access H&H modeling use, application of storm frequency options, and selection of climate forecast models.

1.2 Open Access H&H Modeling

This section provides recommendations associated with open access H&H modeling. Factors considered in developing the recommendations include existing model use and acceptance, inventory of existing modeling that can be leveraged, and efficiencies in model production and foundational dataset usage that can be exploited at scale.

1.2.1 Model Use and Acceptance

One of, if not the most widely used and accepted open access riverine H&H models is the River Analysis System (RAS), developed by the US Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) – commonly referred to as HEC-RAS (see Figure 1-1 below). The HEC-RAS software offers both one-dimensional (1D) and two-dimensional (2D) modeling capabilities. Traditionally, one dimensional modeling has been the industry standard for hydrologic and hydraulic modeling as well as flood mitigation alternative evaluation. Over the past decade, innovations in model input data and modeling software have increased the industry prevalence of two-dimensional modeling. The two-dimensional modeling options in HEC-RAS offers enhanced modeling including advanced spatially distributed model output variables such as flood depth, flood velocity, flow direction and others. These two-dimensional capabilities include the analysis of fluvial (high-water levels in river channels) and pluvial (rainfall intensity exceeding soil infiltration capacity) flooding conditions.

The Cooperating Technical Partners (CTP) Program is an innovative approach to creating partnerships between FEMA and participating NFIP communities, regional agencies, state agencies, tribes and universities that have the interest and capability to become active participants in the FEMA flood hazard mapping program. HEC-RAS is approved for use and has been used by FEMA and CTPs across the nation to identify and analyze flood hazards since its development in 1995 as a successor to the command-prompt based HEC-2 model. The latest version as of this report is version 6.4[1].

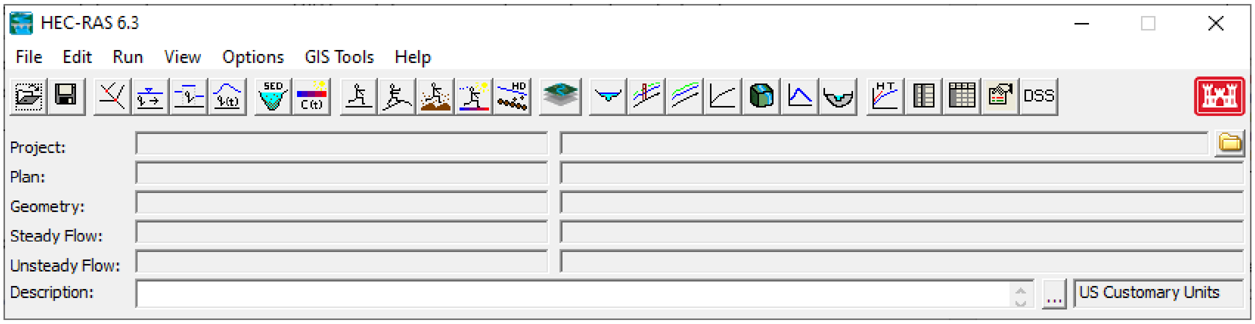

Figure 1-1: HEC-RAS Version 6.3 Main Window

Various stakeholders including the Department of Transportation and local governments utilize HEC-RAS for planning, design, alternatives development, and in support of benefit-cost analyses when evaluating flood mitigation options.

Subtask 2.5 presented coastal models available within North Carolina. The most common model noted that is used for FEMA and the North Carolina Floodplain Mapping program flood studies, coastal resiliency efforts, and real-time flood event modeling is ADCIRC. This coastal surge model is easily paired with wave models such as SWAN to fully analyze coastal hazards from both surge and wave action. Using combined probability, ADCIRC model results can also be paired with riverine modeling for accurate flood hazard identification. This interaction of models can be further developed using unsteady 2D H&H modeling such as HEC-RAS that provides both fluvial and pluvial flooding analysis. Especially in locations prone to hurricane activity such as North Carolina, it is important to use models (or pairings of models) that could force fluvial, pluvial, tidal, wind and wave driven processes since the interaction of all those processes at the coast enhances flooding extents and depths.

Although the ADCIRC model is open source, typically a proprietary software such as SMS is considered necessary for model runs. Processing of ADCIRC models does require the use of high-end computing clusters (super computers). Advanced models like ADCIRC (but also Delft3D FM, MIKE or similar) are often accurate but slow due to the computational power required to run them, therefore, when there is a need to model multiple frequency events (full probabilistic approach or even for testing flood hazard reduction measures), or for early warning applications, it is important to have models that are computationally efficient. Models such as SFINCS or similar could be an alternative when accuracy and speed are relevant[2].

Subtask 2.5 emphasized the importance of incorporating groundwater emergence and shoaling resulting from rising sea levels into the mapping of future coastal flooding. This phenomenon can lead to inland areas experiencing flooding well before coastal defenses are breached or overtopped. To address this, the US Geological Survey (USGS) has utilized the MODFLOW model to simulate and predict groundwater conditions and interactions between groundwater and surface water in North

[1] https://www.hec.usace.army.mil/software/hec-ras/download.aspx
[2] https://www.worldscientific.com/doi/10.1142/9789811275135_0242, https://sfincs.readthedocs.io/en/latest/overview.html#introduction-to-sfincs

Carolina[3]. This involved utilizing general assumptions and a range of sea level rise scenarios, offering valuable insights for long-term coastal adaptation and planning efforts. Establishing collaborative partnerships with USGS, aimed at enhancing MODFLOW modeling accuracy, for instance, by incorporating more precise soil information, could greatly benefit the state's goal of increasing the resilience of coastal communities in the face of climate change.

1.2.2 Inventory of Existing Modeling

The North Carolina floodplain mapping program's statewide regulatory modeling dataset is predominantly comprised of one-dimensional (1D) HEC-RAS models for riverine areas and ADCIRC models for coastal areas. No other H&H modeling dataset within the state matches its scale and overall level of detail. As documented in section 2.4, these datasets are updated as annual funding is available, however, these updates only cover a relatively small percent of the state's stream miles. Models are based on the best available topography(lidar) and bathymetry available at the time of the model development and include either field survey or measurements of hydraulic structures (bridges, culverts, dams) depending on the level of detail implemented. The associated "FLOOD" database managed by the NCFMP houses spatial features associated with the models (streamlines, cross sections, transects, survey points, flow breaks, etc.) as well as model results for the various flood events analyzed.

As documented in section 2.4, the NCFMP is also working to develop advisory two-dimensional (2D) HEC-RAS modeling. Unlike the regulatory 1D riverine modeling, the purpose of the 2D models is to provide enhanced awareness of potential fluvial and pluvial flooding beyond the limits of the regulatory 1D models (see Figure 2 below) and to evaluate more extreme events (up to the 0.1% or 1,000-yr event[4] as well as future rainfall considerations).

[3] https://cmgds.marine.usgs.gov/data-releases/datarelease/10.5066-P9W91314/

[4] The term 0.1% or 1,000-yr event means that a flood of that magnitude (or greater) has a chance of 1 in 1,000 of occurring in any given year.

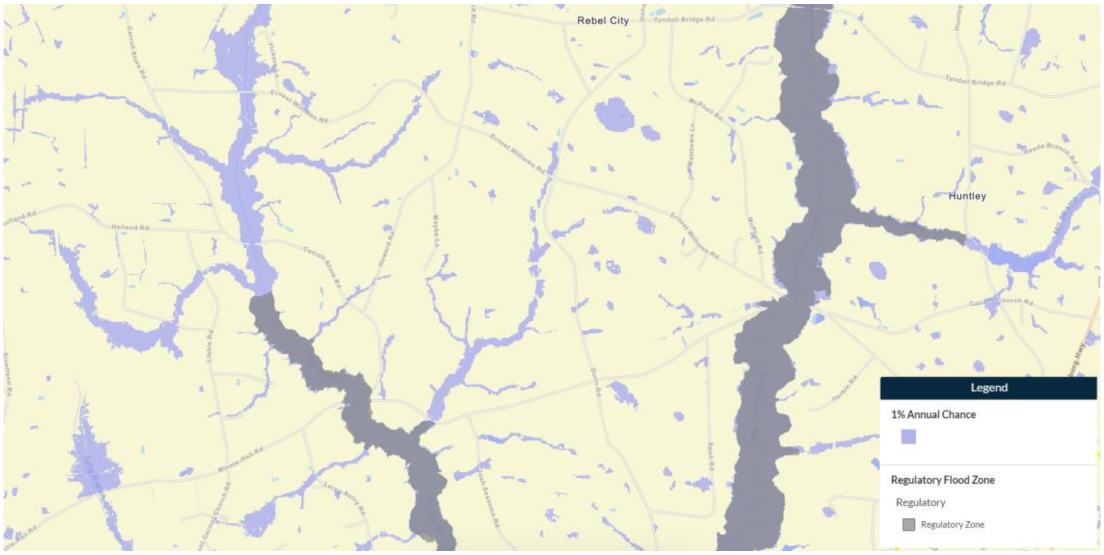

Figure 1-2: Advisory 1% annual chance flood hazard mapping overlaid with regulatory flood hazard mapping available on the NC Floodplain Mapping Program's Advisory 2D Flood Hazard Mapping Viewer

These models are not intended to replace the regulatory 1D models where they exist. Because of that, mainstem flooding from one basin model to another is not maintained and a standard baseflow is applied instead. Although this approach provides better awareness of the localized flood risk along smaller streams (due to not having significant backwater effects from the mainstem), the resulting model and products are not dependable to analyze flood impacts or effects of mitigation efforts within the basin along the mainstem where the more substantial flood impacts would be expected during larger events. Since 2020, NC Emergency Management (NCEM) has been performing this advisory 2D modeling on an annual basis organized by major river basins. As of the date of this report NCEM has completed or has in progress 25,000 square miles of 2D advisory modeling and mapping covering approximately 47% of the State (Figure 1-3). Although the coverage of the advisory 2D dataset is limited within the state, efforts continue for statewide expansion.

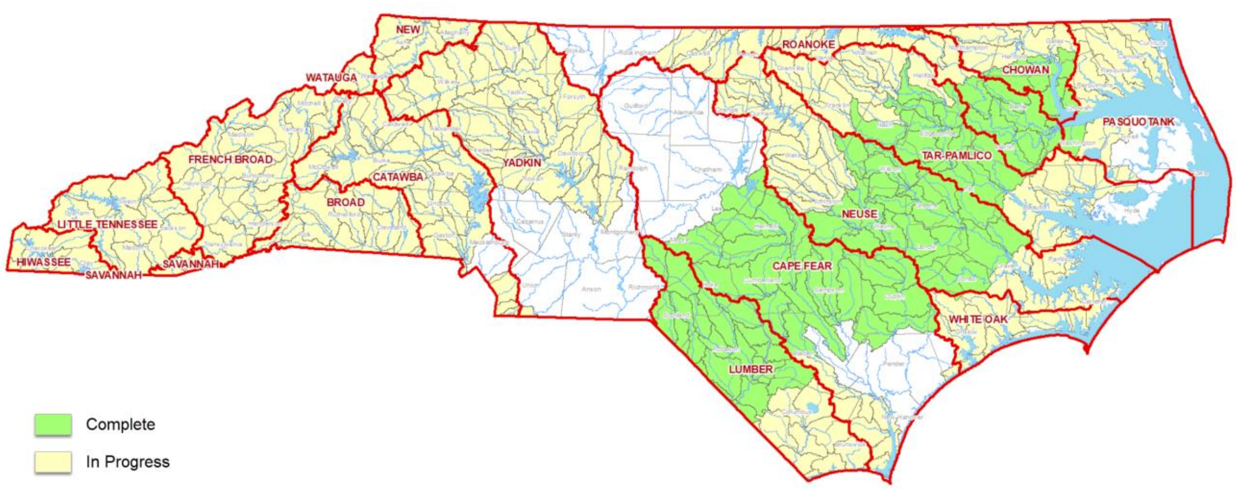

Figure 1-3: Current Status of Completed (12,700 square miles / 26%) and In Progress (27,000 square miles / 56%) of 2D advisory mapping in North Carolina .

1.2.3 Model Production Efficiencies

In order to achieve scalable and efficient model production the selected model must be able to easily integrate foundational datasets. HEC-RAS offers "RAS Mapper" which functions as a geographic information system (GIS) within the open access model. This feature enables necessary pre-processing of input datasets as well as post-processing of H&H model results without the use of proprietary GIS software. One of the most important input datasets for model production is high quality terrain data. HEC-RAS works seamlessly with the available statewide lidar datasets in North Carolina and enables terrain modifications that are often needed in the 2D model production workflow and when evaluating alternatives for designs that modify the terrain (e.g., levees, seawalls, etc.).

HEC-RAS is able to link to other HEC models such as the hydrologic model HEC-HMS using a Data Storage System (DSS) database. This connection allows for reduced manual effort and near seamless ingestion of model results from one platform to another (for example, sourcing in flow hydrographs developed in HEC-HMS). More recently, HEC-RAS has offered the capability to perform runoff calculations directly in the RAS model, reducing the need for a separate hydrologic model in some cases (such as rain-on-grid 2D modeling). HEC-RAS is also capable of ingesting raster rainfall data with varied distribution and intensity over time. This feature enables the reproduction of specific storm events for model calibration purposes. This feature also allows the modeling of future occurrences of past events (reproducing Hurricane Florence in 2100 for example) based on climate modeling results.

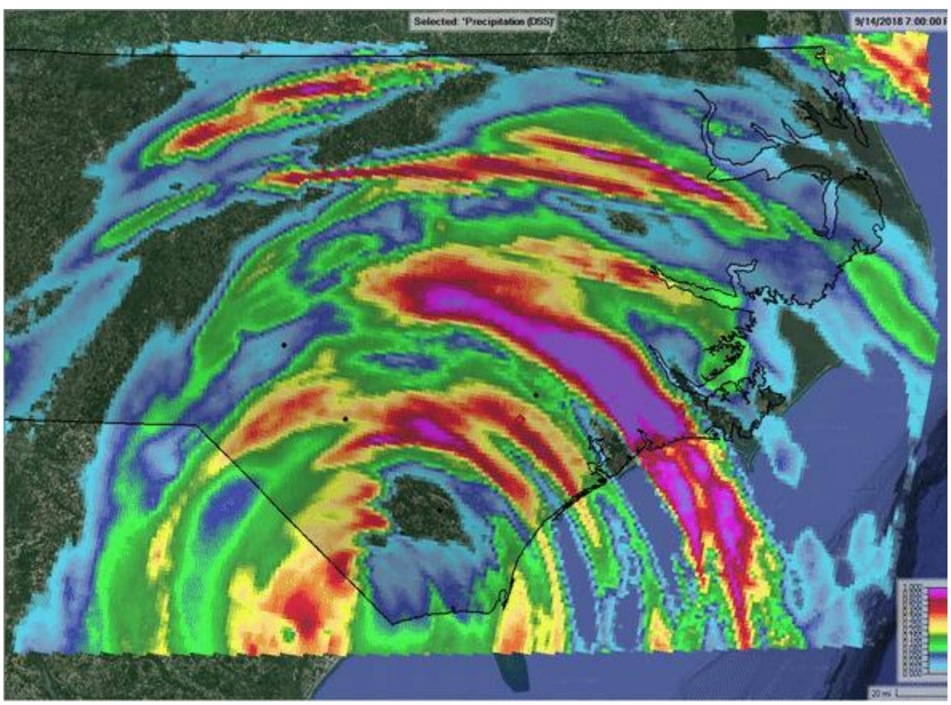

Figure 1-4: Example of Spatially Varied Rainfall in HEC-RAS

With the available inventory of 1D regulatory HEC-RAS models and supporting data housed in the FLOOD database from the NCFMP, an opportunity exists to leverage that data. Working within the common HEC-RAS environment, base-level HEC-RAS 2D models can be improved with the addition of survey data for channels and hydraulic structures.

1.2.4 Blueprint Recommendations

This report provides the following recommendations with respect to open-source H&H modeling approaches and scale:

- Utilize 2D H&H modeling methods using the open-source HEC-RAS model (and associated RAS Mapper GIS) and the rain-on-grid approach that integrates hydrology and hydraulics in the same model platform as the basis for Blueprint modeling efforts.
- Leverage available HEC-RAS model geometry developed from field survey of channels and hydraulic structures that is available in the NCFMP FLOOD database to implement targeted and scalable improvements to base-level 2D models.
- Reanalyze the available advisory 2D modeling from NCFMP to allow mainstem flow to propagate downstream and provide valid flood impact results for the mainstem within the model.
- Utilize 2D HEC-RAS models to evaluate basin-wide effects of implementing potential mitigation strategies at different recurrence intervals within targeted basins.
- Leverage RAS Mapper terrain modifications to efficiently model mitigation alternatives including structural and nature-based alternatives (e.g., channel modifications/improvements, diversions/re-alignment, detention/retention basins, wetland restoration).
- Utilize RAS Mapper within HEC-RAS for initial floodplain mapping generation and development of raster products including water surface elevation rasters that allow for building level risk assessments needed to inform benefit-cost analyses for potential mitigation strategies.
- Utilize spatial-varied precipitation data within HEC-RAS to calibrate 2D rain-on-grid models to known events to improve model accuracy and to model future events derived from climate models.
- Leverage stakeholder relationships with USACE, USGS and UNC RENCI center for coastal modeling needs using ADCIRC or similar.
- Use ADCIRC coastal modeling results (or similar) as boundary conditions for upland riverine 2D models to provide combined flood hazard awareness of fluvial, pluvial, and coastal flooding.
- Leverage stakeholder relationships with USGS for Groundwater modeling using MODFLOW or similar.

Optional Enhancement: Probabilistic Flood Risk Analysis

In addition, as an optional enhancement/upgrade to the H&H modeling, this report recommends conducting a pilot analysis considering a probabilistic analysis in addition to the deterministic analysis described above. The ***Probabilistic Flood Risk Analysis (PFRA)*** method is an alternative to the deterministic modeling of the 2D rain on grid hydrologic and hydraulic methodology. The PFRA approach leverages the existing and developed 2D modeling as a baseline input dataset. The difference in the probabilistic modeling utilizes an array of rainfall events based on varying storm frequencies, duration, and intensity. Hundreds of rainfall events are modeled using the PFRA approach. Additional statistical analyses are performed on these model results to yield a more probabilistic floodplain boundary and enhanced risk products (including 3D flood elevations and depths).

This approach is computation heavy and requires a cloud-based computing and modeling system to perform the model storm iterations.

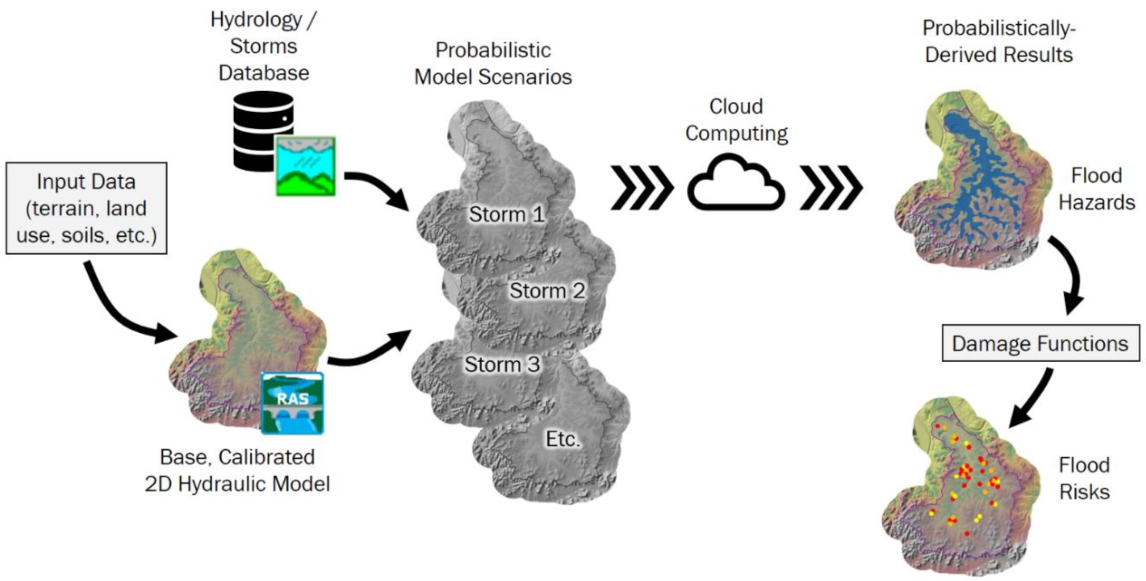

Figure 1-5: PFRA Process

The PFRA approach is more labor and computational time intensive but provides a more comprehensive depiction of the flood hazards. The additional datasets allow for a more refined computation of flood risk (including annualized damages) and the evaluation of mitigation alternatives.

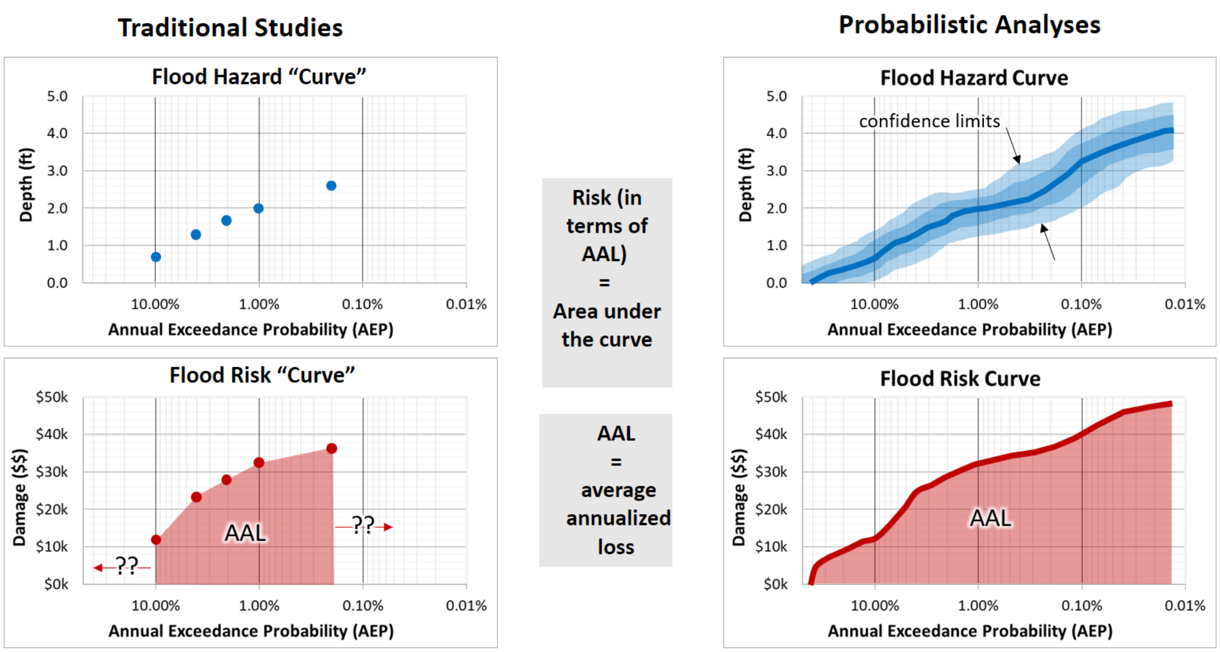

Figure 1-6: The PFRA modeling approach allows for an expanded range of Annual Exceedance Probability (AEP) simulations for more accurate Average Annualized Loss (AAL) calculations.

One drawback of the development the PFRA approach described above is cost. Currently, the cost increase to develop PFRA models compared to deterministic 2D modeling is approximately 300% higher. However, the deterministic 2D hydrologic and hydraulic modeling can be leveraged in the future if the State of North Carolina expands the modeling methods to include PFRA.

1.3 Decision Tool Storm Frequency Options

This section provides recommendations associated with decision tool storm frequency options.

For various reasons including natural topography, human-caused development, and socio-economic conditions, among others, the severity of flood impacts varies across the state with event frequency. While some areas may see significant flood impacts to residential areas at a 2% annual chance of exceedance event (50-yr event) other areas may have no impacts during a 0.2% annual chance of exceedance event (500-yr event). In addition, some flood mitigation strategies are designed to only be effective and target certain levels of flooding events (local stormwater regulations for runoff detention for example). Therefore, in order to properly evaluate the effectiveness of flood mitigation alternatives in areas with existing flood impacts, or plan for avoiding flood impacts in areas of future development, it is important to evaluate a wide range of storm frequencies. Analysis of flood impacts for multiple frequencies also allows for the calculation of risk metrics such as the Average Annual Loss (AAL) which represents the average economic loss in dollars resulting from flooding each year[5]. AAL can then be used as a component in benefit-cost-analyses to evaluate the viability of implementing targeted mitigation strategies.

The NCFMP models the 10, 4, 2, 1, and 0.2% (10-, 25-, 50-, 100-, and 500-yr) events in their 1D regulatory modeling. For advisory 2D modeling, they have expanded the frequencies analyzed to the 20, 10, 4, 2, 1, 0.5, 0.2, and 0.1 (5-, 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-yr) events as well as the 1%+ (the statistical upper bounds of the 1% event) and three "future" conditions events by increasing the 1% rainfall by 10, 20, and 30% (see Figure 3 below).

Event
20% Annual Chance *(5-Year Flood)*
10% Annual Chance *(10-Year Flood)*
4% Annual Chance *(25-Year Flood)*
2% Annual Chance *(50-Year Flood)*
1% Annual Chance *(100-Year Flood)*
1% Rainfall Depth Plus *(100-Year Flood (Upper Confidence Bound))*
1% Rainfall Depth Plus 10% *(Median 1% Annual Chance Rainfall Depth plus 10%)*
1% Rainfall Depth Plus 20% *(Median 1% Annual Chance Rainfall Depth plus 20%)*
1% Rainfall Depth Plus 30% *(Median 1% Annual Chance Rainfall Depth plus 30%)*
.5% Annual Chance *(200-Year Flood)*
.2% Annual Chance *(500-Year Flood)*
.1% Annual Chance *(1000-Year Flood)*

Figure 1-7: Storm Frequency Results Available in the NCFMP Advisory 2D Flood Viewer

Federal Agencies have begun implementing the Federal Flood Risk Management Standard (FFRMS). The goal of this standard is to build a more flood resilient future. The standard, at one time revoked, was reinstated through Executive Order 14030, Climate-Related Financial Risk and requires agencies to prepare for and protect federally funded buildings and projects from flood risk. The standard

[5] The AAL is established through the integration of the resulting damage-probability curve, which can be constructed by plotting flood probabilities (e.g., 0.1%, 0.2%, etc.) and their associated damages.

provides flexibility for implementation with three options to establish the flood hazard to be used for projects. The options include a detailed climate informed science approach (CISA), freeboard value approach (FVA), and the 0.2% annual chance event (500-yr) floodplain.

1.3.1 Blueprint Recommendations

This report provides the following recommendation with respect to decision tool storm frequency options:

- Maintain consistency with the wide range of storm frequencies currently being modeled for the Advisory 2D mapping effort undertaken by the NC Floodplain Mapping Program.
- This will include the 20, 10, 4, 2, 1, 0.5, 0.2, and 0.1 (5-, 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-yr) events as well as the 1%+/- (the statistical upper and lower bounds of the 1% event) and three "future" conditions events by increasing the 1% rainfall by 10, 20, and 30%.

Table 1-1: Recommended Storm Frequency Annual Exceedance Probabilities

Storm Frequency Annual Exceedance Probability AEP	Description / Commonly Used Alternative Name
INDUSTRY STANDARD FREQUENCIES	
20%	5-year flood event
10%	10-year flood event
4%	25-year flood event
2%	50-year flood event
1%	100-year flood event
0.5%	200-year flood event
0.2%	500-year flood event
0.2%	1000-year flood event
ENHANCED FREQUENCIES / SIMULATIONS	
1% "minus"	The statical ***lower*** limit of the 1% AEP event (100-year) [1]
1% "plus"	The statical ***upper*** limit of the 1% AEP event (100-year)
Future 10%	Future conditions modeling of the 1% AEP rainfall increase by 10%
Future 20%	Future conditions modeling of the 1% AEP rainfall increase by 20%
Future 30%	Future conditions modeling of the 1% AEP rainfall increase by 30%
1: Note that the NC Floodplain Mapping Program is considering not including this frequency model run because FEMA no longer requires it.	

- Model mapping criteria should be developed in conjunction with relevant inputs on the fate and transport of hazardous contaminants.

- Coordinate with FEMA Region IV on the ongoing work with the FFRMS FVA approach recommended to integrate two additional flood events by adding 2-feet and 3-feet to the regulatory 1% annual chance flood elevations. Care should be taken to avoid duplication of effort by the FEMA FFRMS production teams.

1.4 Climate Forecast Model Selection

This section provides recommendations associated with climate forecast model selection.

A key component of developing a Blueprint for flood resiliency is accounting for future conditions which may experience more extreme rainfall, sea level rise, and ultimately increased flood impacts. Consideration of future conditions when evaluating potential flood mitigation alternatives is critical. It helps ensure wise investments in solutions that can provide benefits in a changing climate. Subtask 2.5 of the Blueprint inventoried a variety of information and datasets to be considered when analyzing future flood hazards.

Development of flows based on future conditions cannot use many of the methods currently utilized for traditional flood studies. A common approach for developing flows for various storm frequencies are regional regression equations developed by USGS. These equations are developed using measurements from stream gauges. Within North Carolina, the equations have typically relied on few variables (predominantly drainage area) and limited or no climate factors such as rainfall. Development of future condition flows cannot be gauge dominated or reliant on factors that do not account for changing climate conditions. Hydrologic modeling that uses precipitation as an input such as the HEC-RAS 2D rain-on-grid method recommended above provides an opportunity for direct consideration of a changing climate. Development of precipitation data in future scenarios must be handled using climate models.

As documented in subtask 2.5, the Intergovernmental Panel on Climate Change (IPCC) has released Assessment Reports 5 and 6 (AR5 and AR6) in 2014 and 2023 respectively, covering Coupled Model Intercomparison Project Phases 5 and 6 (CMIP5 and CMIP6). These reports presented experiments that simulated on a global scale how the atmosphere might change based on future greenhouse gas (GHG) emission scenarios. In 2014, AR5 used Representative Concentration Pathways (RCPs) with four scenarios that ranged from RCP2.6 with ambitious GHG reductions to RCP8.5 that reflected no policy changes for GHG emission reductions. The newer AR6 in 2023 updated the RCPs and coupled them with Shared Socioeconomic Pathways (SSPs) that included factors linked to climate change such as population growth, urbanization, and technological advances. The SSPs developed included five scenarios ranging from SSP1-1.9 that reflected CO2 emissions declining to net zero by 2050 to SSP5-8.5 that reflected CO2 emissions roughly doubling from current levels by 2050. CMIP5 has been frequently used within the United States and has many associated datasets for use in evaluating future conditions flooding. CMIP6, although newer, has fewer datasets currently available. The global results from these studies can be downscaled using different techniques such as Localized Constructed Analogs (LOCA) and Multivariate Adaptive Constructed Analogs (MACA) to produce regional and local information for H&H modeling and planning.

One such example of the potential uses of this data for planning is to visualize how past events would develop in the future. Recently, the North Carolina State Climate Office at NCSU used RCP8.5 to develop precipitation data for Hurricane Florence in the year 2094 to support NCDOT planning efforts. The resulting precipitation was then used to create maps depicting estimated recurrence intervals of the actual precipitation that fell during Hurricane Florence in September 2018 and projections of what an event similar to Hurricane Florence would produce in 2094 based on RCP 8.5. These maps can be seen below in Figures 1-8 and 1-9.

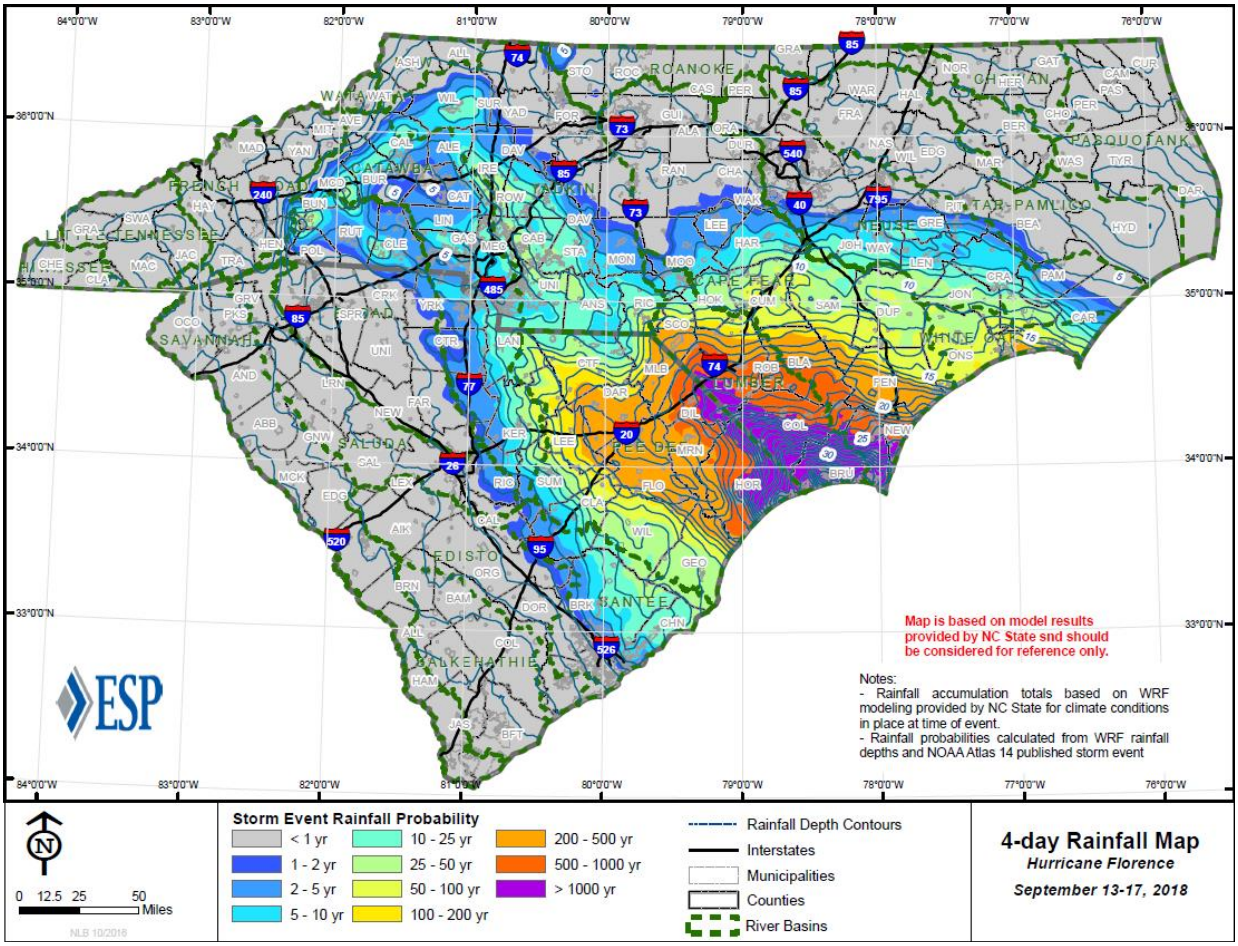

Figure 1-8: Estimated Recurrence Intervals of Hurricane Florence Rainfall

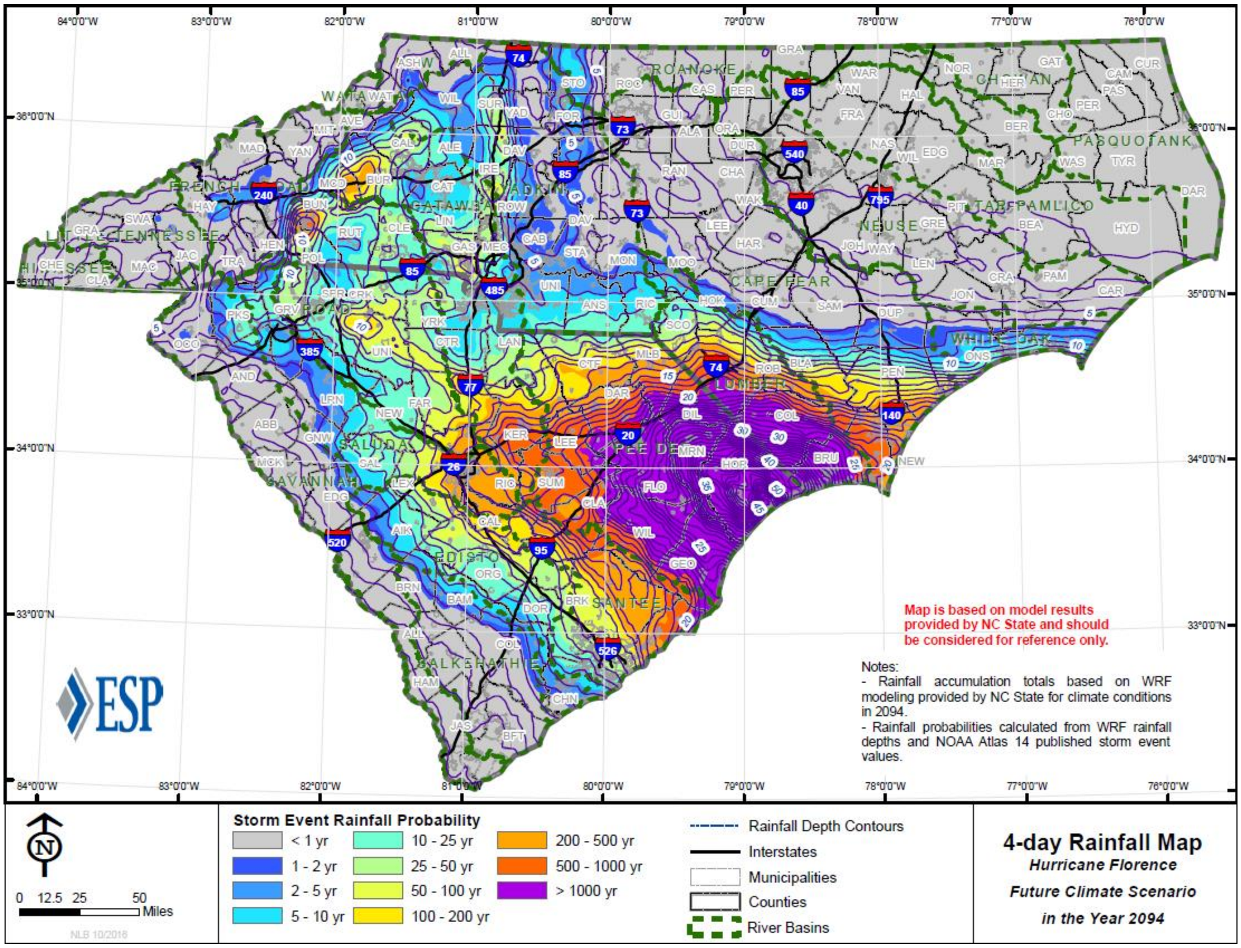

Figure 1-9: Recurrence Intervals for Rainfall from a Hurricane Florence Level Event in 2094

The National Weather Service Office of Water Prediction published the NOAA Atlas 14 Precipitation-Frequency Atlas of the United States (Atlas 14). Atlas 14 provides a wide range of precipitation estimates for various durations and frequencies. These estimates are used to plan and design various projects including transportation infrastructure and local stormwater control measures. An update to Atlas 14 is currently being developed and will be referred to as Atlas 15. Volume 1 of Atlas 15 will provide updates to rainfall estimates based on temporal trends in historical observations while Volume 2 will use future climate model projections to develop adjustment factors for Volume 1. Atlas 15 is not anticipated to be available until 2025-2026.

Climate change modeling must also consider sea level rise (SLR) which will impact H&H model boundary conditions and ultimately increase flood hazards. NOAA’s “2022 Sea Level Rise Technical Report” provides the latest information on SLR. In addition, for future planning purposes it is important to model future land use and land cover (as a consequence of climate change and future socio-economic drivers) since soil characteristics are used in almost all H&H models to obtain floodplains and flood depths. Section 2.5 mentions among others the FORE-SCE model[6] from USGS which could be used to facilitate planning and climate mitigation efforts.

1.4.1 Blueprint Recommendations

The following recommendations are provided with respect to climate forecast model selection:

- Utilize the MACA CMIP5 RCP8.5 statistically downscaled climate projections to develop an envelope of four future climate conditions. RCP4.5 mean and upper statistical bounds for mid-century and RCP8.5 mean and upper statistical bounds for end of century will provide four potential scenarios of varying conservatism. Although CMIP6 includes a newer approach with SSP scenarios that include factors such as population growth, urbanization, and technological advances there are far fewer datasets readily available than CMIP5. Utilization of RCP4.5 and 8.5 factors for future rainfall is already being performed by NCEM for 2-D advisory rain-on-grid modeling. Perform comparisons of the downscaled rainfall to the pre-defined future condition profiles outlined above (1% +10-, 20-, and 30%) to determine if additional H&H modeling profiles are needed to analyze future conditions flooding more fully.
- Additional future conditions analysis of 40%, 50% and 60% is recommended to cover the full range of climate change scenarios.
- Climate modeling is constantly changing and evolving with new data and technology. The Blueprint must allow for refreshes/updates as new data (such as additional variables for downscaled CMIP6 projections which are not available yet) become available.
- Statistically downscaled global climate model projections can provide an initial high-level estimate of potential future rainfall across the state. When progressing from high-level estimates to design of potential mitigation alternatives, Volume 2 of Atlas 15 (when available) should be utilized for improved detail for future rainfall projections.
- Include SLR estimates based on NOAA's 2022 Technical Report when setting downstream boundary conditions for H&H models in coastal environments.
- All additional modeling including HEC-RAS models, GIS support data, floodplain mapping, building level loss estimates should be shared with the NC Floodplain Mapping program utilizing a database schema matching the current Advisory Flood database. This data sharing will maximize the cross department uses of this data for both mitigation, hazard communication and floodplain management.

1.5 Hydrologic and Hydraulic Modeling Tiers

A two-tiered approach for model scale, extents and detail is recommended. The following is a summary of the recommended modeling approaches for analyzing and ranking mitigation alternatives.

[6] https://www.usgs.gov/special-topics/land-use-land-cover-modeling/science/land-cover-modeling-methodology-fore-sce-model

1.5.1 Large Scale Basin Wide 2D Modeling (Tier 1):

It is recommended that the Tier 1 modeling be performed at the HUC-10 river basin scale similar in scope to the recommendations and methods outlined above. This scale of modeling is appropriate for the following:

- The development of cost-effective hazard identification and floodplain mapping for areas covered by current regulatory mapping and many flooding sources have never been modeled or mapped.
- Building and asset-based risk assessment, loss calculation, flood risk score and average annualized loss estimated for all impacted assets in the studied basins.
- Developing geospatial products to better communicate the flood hazards, consequences and risk Stakeholders via the display of flood extents, depths, building impacts (depths, structure and content losses, etc.). These products can assist with outreach.
- The development of site/building specific flood mitigation measures including structure elevation, floodproofing, relocation and or acquisition including the computation of the cost benefit ratio for each of the building specific mitigation alternatives.
- Tier 1 modeling will include the annual exceedance probabilities discussed above and will include the same methodology for incorporating hydraulic structures (bridges and culverts) and the current NC Floodplain Mapping Advisory modeling.

It should be noted that while the large-scale basin wide 2D modeling is beneficial for flood hazard identification and existing conditions risk assessment, the ability to perform mitigation alternative analysis (pre/post conditions) is limited due to the scale, model size and lack of site specific data inputs. The Tier 1 modeling should serve as the initial starting modeling dataset for enhanced, smaller scale modeling of regional and site specific / grey infrastructure alternatives where the need arises.

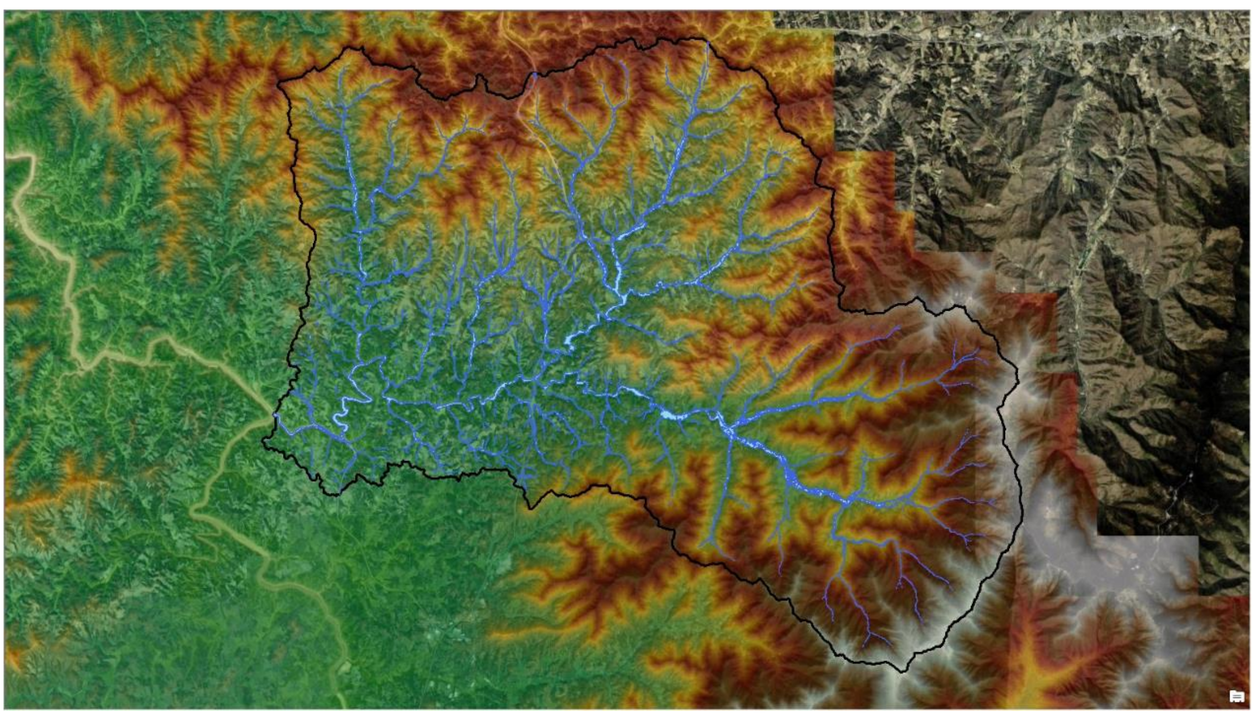

Figure 1-10: Example of Tier 1 Basin Wide Modeling and Risk Assessment

1.5.2 Project/Site Specific Detailed Modeling Alternative Analysis (Tier 2)

Following the Tier 1 (Large Scale) Modeling, stakeholder and engagement meetings should be conducted to review the following datasets resulting from the Tier 1 modeling:

- Multi return period and future conditions flood hazards and impacts.
- Pre-computed building-specific mitigation alternative measures that are viable for consideration,
- Other resilience/mitigation actions that can be recommended at this stage using the large scale modeling.
- Existing mitigation actions identified in the current Hazard Mitigation Plans, regional or local resiliency plans, municipal Capital Improvement Projects, Army Corp studies, and other identified actions.
- Determination of hazard / impact areas within the sub-basin where additional modeling may be required for mitigation alternative evaluation.

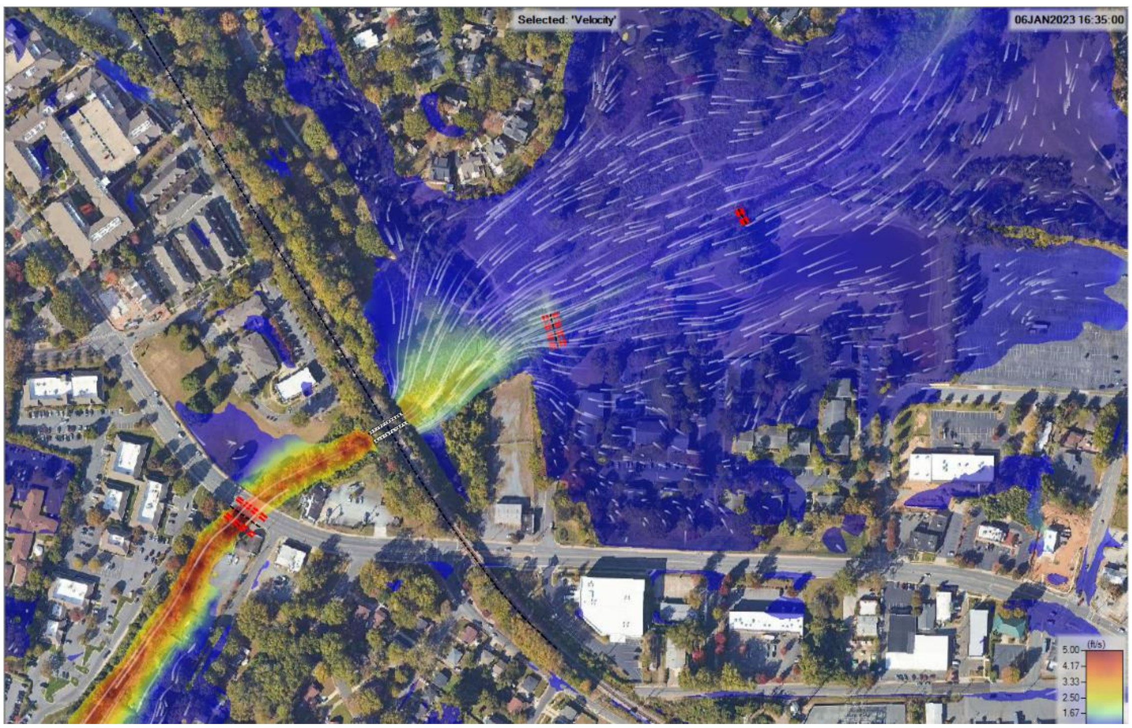

Figure 1-11: Example of Tier 2 Modeling (Project/Site Specific Mitigation Alternative Analysis)

The Tier 2 Modeling footprints will be smaller and site specific and will likely include additional details (geometries, elevations, etc.) for hydraulic structures.

The outcome of these engagement meetings will include a prioritized list for additional mitigation alternative consideration for the smaller-scale Tier 2 analysis (Project / Site Specific analysis). Modeling can be conducted at this point or flagged for future efforts to evaluate alternatives (such as grey and green infrastructure) that may provide reductions in flood hazard and impacts. These mitigation alternatives will be evaluated for cost, benefits such as loss avoidance, environmental and social justice and other factors. Evaluated mitigation alternatives will be stored in the Blueprint decision support tool for subsequent stakeholder engagement and prioritization.