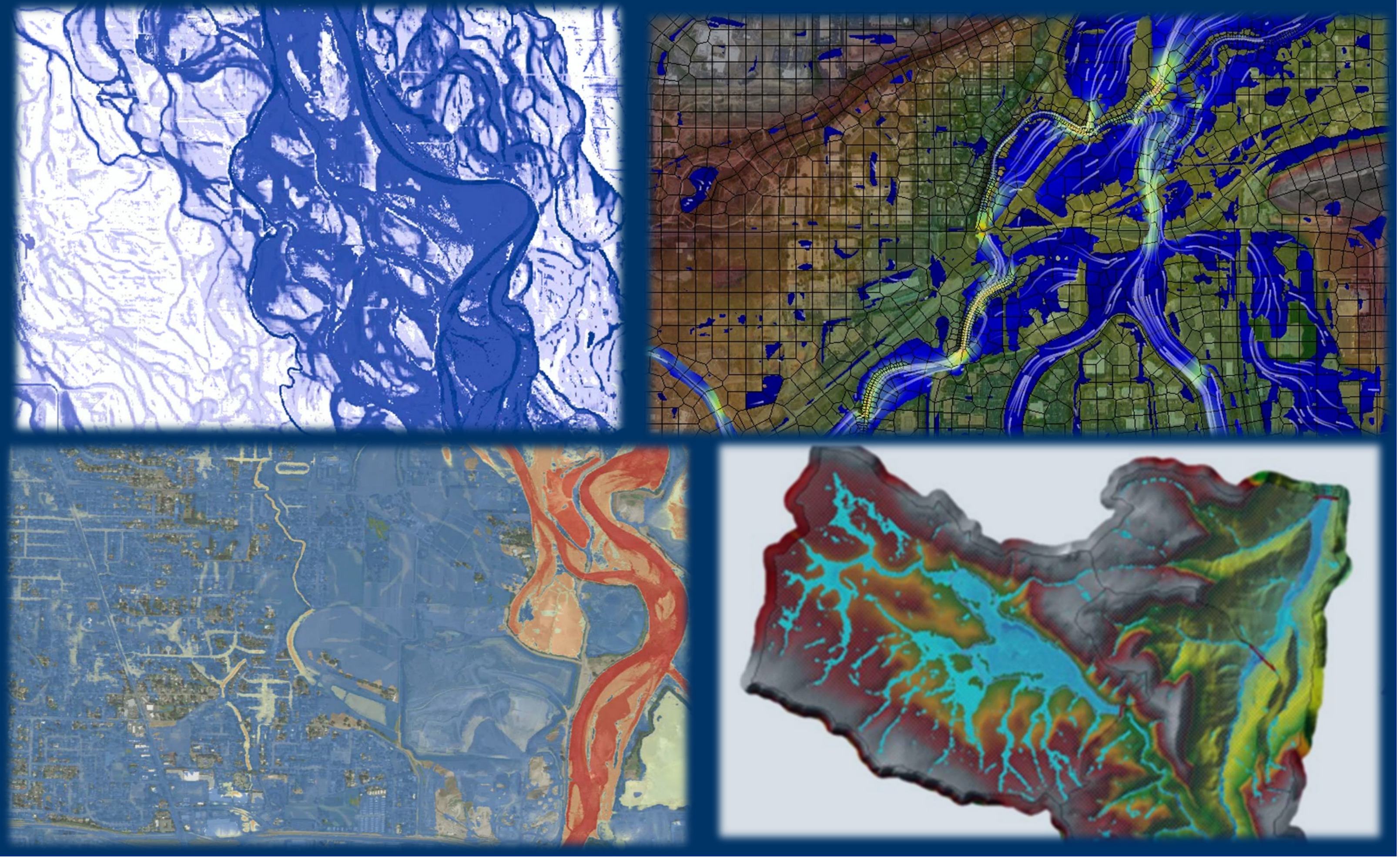


2D Watershed Modeling in HEC-RAS Recommended Practices

November 2021

FEMA

STARR II Strategic Alliance for Risk Reduction

compass
Identify, Interpret, Integrate

Key Definitions

Annual Exceedance Probability (AEP): The probability that the given event will be equaled or exceeded in any given year (e.g., 1-percent-annual-chance).

Areal Reduction Factors (ARFs): An adjustment factor used to generate spatially averaged precipitation totals based on areal extent and point precipitation frequency data. In general, the areal reduction factor adjustment for larger watershed areas results in lower spatially averaged depths compared to watersheds with smaller areal extents.

Average-Annualized Loss (AAL): The long-term average loss, in terms of damage to an asset expected in any one year, for the cause of loss being modeled. AAL is also referred to as the catastrophe loss cost, or pure premium, and is typically expressed as the expected loss per unit of exposure.

Base Level Engineering (BLE): An automated and cost-effective engineering approach that uses high-tech modeling software and high-resolution ground data to provide communities with a baseline understanding of their flood hazards. BLE represents the base level of engineering methodology and investment needed for all flood study efforts FEMA will undertake.

Headwater Watersheds: Watershed areas with one outflow location and no inflow locations.

Fluvial Flooding: Flooding experienced when flows and water surface elevations exceed the channel or stream bank capacities, resulting in riverine flooding.

Model Mesh: The spatial extent of a hydraulic model within which numerical computations are performed.

Precipitation Boundary Condition: An external or meteorological boundary condition that applies rainfall or runoff (rainfall minus losses due to interception / infiltration) directly to cells in the 2D model mesh.

Pluvial Flooding: Flooding produced from direct precipitation, which is also known as local intense precipitation. Pluvial flooding occurs when precipitation rates exceed the infiltration capacity of soils and the drainage capacity of stormwater infrastructure, resulting in excess runoff that causes ponding and overland flow.

Receiving Watersheds: Watershed areas with one outflow location and at least one inflow location.

Recurrence Interval: An average time or an estimated average time between events based on the probability that the given event will be equaled or exceeded in any given year.

Spatially Varying Precipitation: Precipitation applied to the model mesh are based on a hypothetical or empirical storm event data that accounts for storm shape, orientation, size, and spatial variable precipitation intensity.

Uniform Spatial Precipitation: Precipitation applied to the model mesh are based on point precipitation data from a specific annual exceedance probability event.

Two-Dimensional Watershed Modeling: A two-dimensional model that represents the physical conditions and characteristics of a watershed to simulate hydrologic and hydraulic processes.

1.1 BACKGROUND

Two-dimensional (2D) watershed modeling approaches in HEC-RAS are being used increasingly across the nation to provide economical estimates of flood hazards. These methods, by offering the ability to characterize both pluvial and fluvial hazards, can also contribute to increasing coverage of floodplain mapping and graduated hazard identification products.

To date, 2D watershed models have been produced for the NFIP, at a variety of scales ranging from smaller than HUC-12 to larger than HUC-8. Additionally, the development of these models to support Base Level Engineering (BLE) studies has varied across the FEMA regions as the uses and capabilities of HEC-RAS expanded. The timeline of 2D-related initiatives below demonstrates how the scale and use of these models has evolved over time.

HEC-RAS v5

- **Early 2D BLE projects (2016)**
  - HUC-8 scale
- **Subsequent 2D BLE projects (2017)**
  - HUC-12 or larger in area
- **PFRA (2018-2019)**
  - Probabilistically derived graduated hazard/risk data
  - HUC-12 scale or larger in area
- **Scaling 2D BLE to Probabilistic Innovation (2020)**
  - Validation of the reusability of 2D BLE models to support probabilistic/graduated analyses
- **HEC-RAS v6 Release (2021)**

1.2 BENEFITS OF 2D WATERSHED MODELING

In several ways, 2D watershed modeling satisfies traditional deterministic modeling needs and provides an opportunity for FEMA to explore scenario-based and probabilistic flood risk analyses. A number of subjective parameters required for one-dimensional (1D) hydraulic modeling such as determining ineffective flow areas, Manning's n values, and contraction / expansion ratios, are all accounted for directly by the detailed representation of the geomorphology in the 2D model, freeing the engineer to spend more time refining the physical representation of the model mesh as well as the hydrologic boundary parameters.

If the 2D model mesh is developed in a way that closely reflects the physical conditions of the watershed, then it can be used for a multitude of hydrologic and hydraulic purposes with only modest further effort (in the case of additional hydrologic events) or at least much more efficiently than creating a new model for each analysis. These models can have a long shelf life due to their modularity and upgradeability by many stakeholders, which offers directbenefits for map maintenance. Given the upgradable nature of 2D watershed model meshes, it's possible to use them as the base for a library of national flood models to provide probabilistic flood risk information, capture future conditions, forecast inundation, and support other example use cases identified in Figure 1 below.

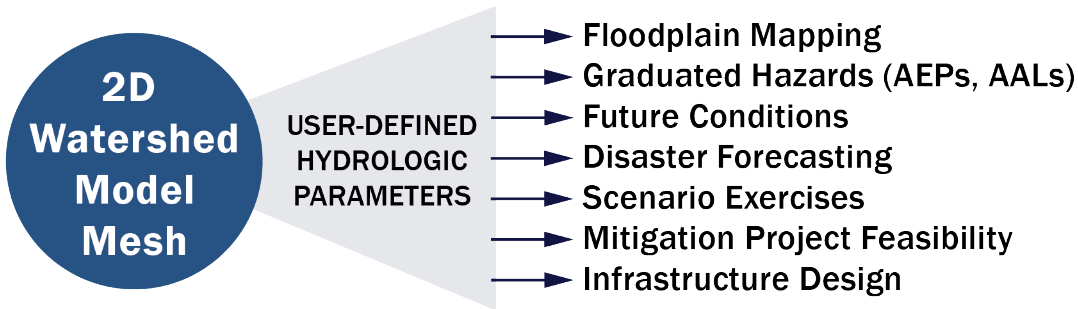


Figure 1. Potential Use Cases of 2D Watershed Model Mesh

1.3 DOCUMENT GOALS

This document provides recommended practices relating to the development of 2D HEC-RAS inputs and outputs for watershed modeling. The following three main goals were used to generate these recommendations.

1. **Consistent Methods for Mesh Development:** Provide consistent methods for generating computational meshes in 2D HEC-RAS that are foundational for the long-term needs of the program, such as graduated hazard and risk identification.
2. **Model Reusability:** Promote practices that support model reusability given anticipated advancements in climatological, topographic, and land use data, as well as advancements in 2D modeling software.
3. **Risk MAP Protocols for 2D Watershed Modeling:** Document protocols recommended for 2D watershed modeling that are not fully covered by HEC-RAS Reference Manuals or FEMA Guidelines.

This section provides recommendations for the consistent development of watershed models using 2D HEC-RAS. The following recommendations were prepared based on a review of existing 2D watershed models developed by FEMA and its mapping partners, a project that looked at scaling 2D watershed models to probabilistic datasets, literature reviews, and tests of the latest techniques in 2D watershed modeling.

The following model mesh development practices are listed in order of importance in supporting long-term investments in 2D watershed modeling:

- Watershed Model Mesh Scale
- Watershed Model Mesh Connectivity and Delineation
- Mesh Hydro-Enforcement and Refinement
- Topography
- Event Selection
- Representation of Levee Systems

2.1 WATERSHED MODEL MESH SCALE

When uniform spatial precipitation is applied in a 2D model, the recommended model mesh size for most areas of the nation is HUC-12 scale (20-60 mi^2). This recommendation is based on the following guiding principle being met:

Guiding Principle for Setting Model Mesh Scale with Uniform Spatial Precipitation

1) The study team must have confidence that the runoff (flows) and total runoff volume computed for each stream in the watershed is representative of the desired recurrence interval.

In mountainous areas of the country such as the pacific northwest, the spatial variability of precipitation frequency data can be extreme and warrant smaller watershed model sizes than HUC-12. In other cases, HUC-10 scale watershed models can be acceptable where the networking pattern of the ground surface controls the flood frequency rather than the variability of spatial rainfall. A transition to probabilistic methodologies or spatially varying precipitation methods will help address this limitation and allow for the use of larger 2D model domains, on average.

For additional context, Table 1 summarizes qualitative challenges and complexity in validating water surface elevations (WSELs), peak flows, and runoff volumes from examination of existing uniform spatial precipitation watershed models in Illinois and Louisiana against gage and FIS data. As the watershed area size increased, Areal Reduction Factors (ARFs) were applied to adjust the point precipitation values over large areas, which ultimately made it difficult to validate the hazard characteristics for smaller tributaries within the watershed. If ARFs were not applied, then the model would have made it difficult to validate the hazard characteristics for mainstem streams. For example, a value of “Low” in the table indicates that it is less challenging and complex to validate uniform spatial precipitation models in locations where observed or reported data is available for that particular model domain size, whereas values of "High" denote model domain sizes where it is more challenging and complex to perform model validation of the WSELs, peak flows, and/or runoff volume against other available data.

Table 1. Challenges and complexity in validating watershed-wide results against gage and FIS data in uniform spatial precipitation 2D models.

Watershed Area Size (mi^2)	HUC Levels	WSELs	Peak Flows	Total Runoff Volume
0-50	HUC-12	Low	Low	Low
50-150	HUC-12 / HUC10	Low	Low	Medium
150-300	HUC-10	Medium	Medium	High
300+	HUC-10 / HUC-8	High	High	High

2.2 WATERSHED MODEL MESH CONNECTIVITY AND DELINEATION

Where a project area includes inflows from upstream watersheds, the relationship between inflow and in-watershed hydrologic conditions must be examined. Figure 2 below illustrates the difference between headwater and receiving watershed areas. The study team should follow either the decoupled or coupled approaches provided in Section 4.5 of this document to simulate flood event conditions for receiving watershed areas.

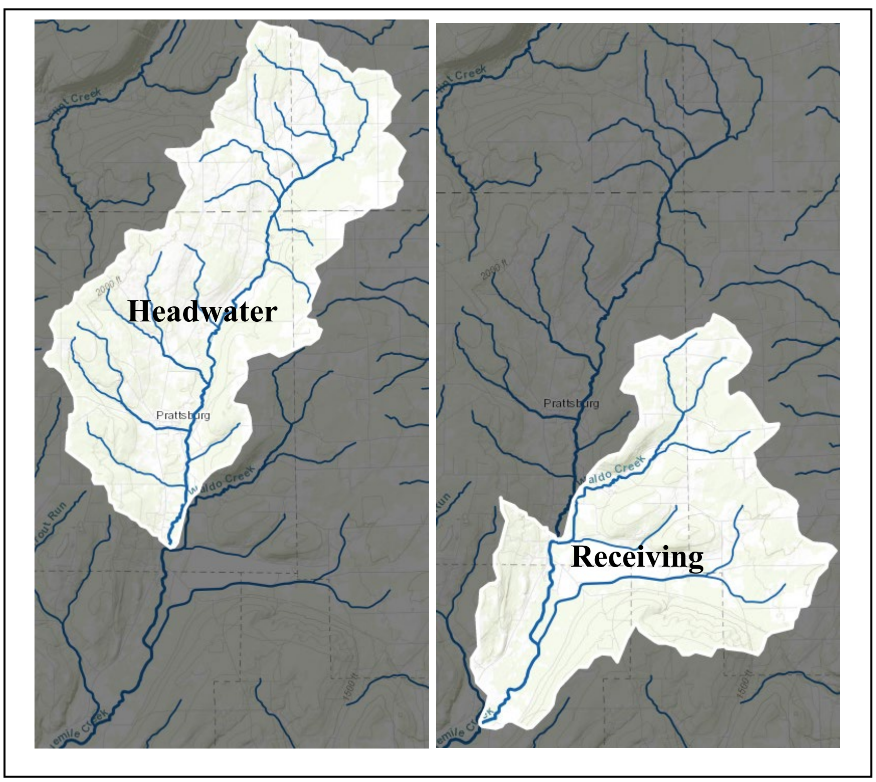


Figure 2. Headwater vs receiving watershed areas.

Delineating consistent boundaries among watershed areas is also critical for modeling and mapping flood hazards across large project areas. The USGS WBD HUC boundaries must be adjusted based on the model input topography to capture the true watershed area before being used as a model mesh boundary. The differences between the original USGS and redelineated watershed based on the model topography (e.g., DEM) can be significant (see Figure 3).

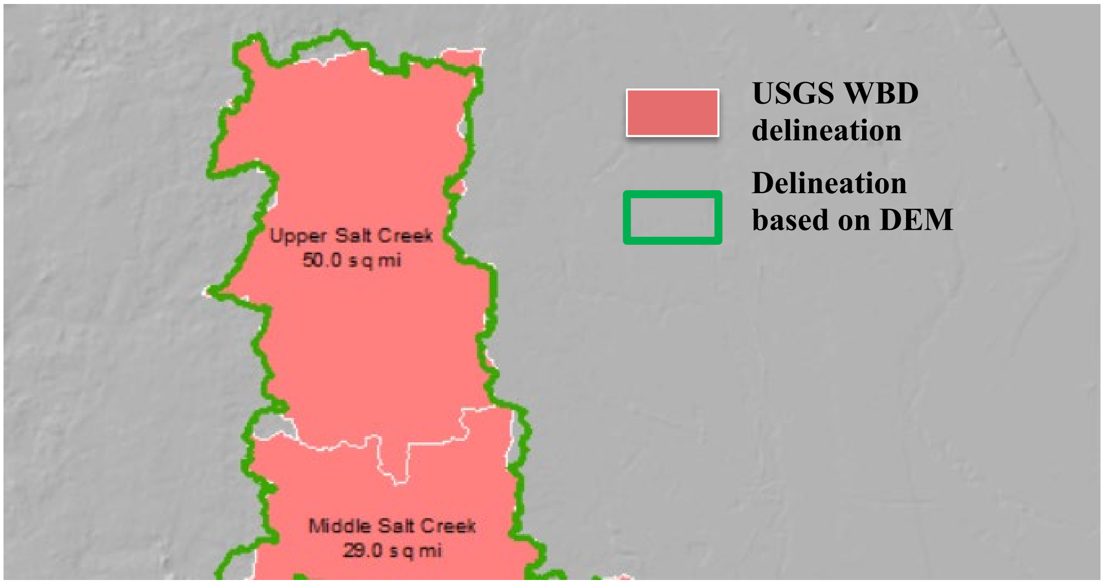


Figure 3. Comparison of redelineated watershed area with WBD HUC delineation.

In the past, study teams have buffered the USGS WBD HUC boundaries (typically by 1000-2000 ft) to capture any additional watershed area, and then add outflow boundary conditions along the perimeter of the watershed area to allow areas that drain away from the watershed to exit the model mesh. This approach provides sound results within the true watershed area but it causes spatial overlapping of mapping results across multiple watershed areas that requires post-processing to resolve and is therefore not recommended.

2.3 MESH HYDRO-ENFORCEMENT AND REFINEMENT

One advantage of 2D watershed modeling is that the model mesh can be reconfigured by the user iteratively more easily than 1D modeling. This iterative process is useful for using initial model results to inform mesh configuration. Once the initial model mesh is set and modeling results are available, hydro-enforcement and refinement regions should be applied.

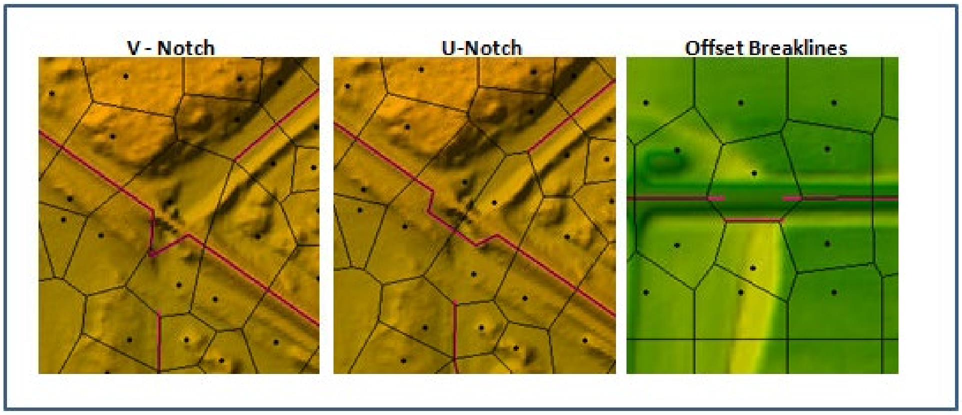
2.3.1 Hydro-Enforcing Stream Channels

The most critical step in model mesh development is to hydro-enforce the mesh so that the channel capacity of the stream can be realized during flow routing and hydraulic calculations. This includes areas where there is assumed hydraulic connectivity through high ground (e.g., roadways, railroads, and dams) using breaklines or 2D area connections to simulate the effect of culverts, spillways, etc. Mesh breaklines should also be added along channel bank features that affect channel overflow. Effective practices for developing a hydro-enforced model mesh are listed in Table 2 below.

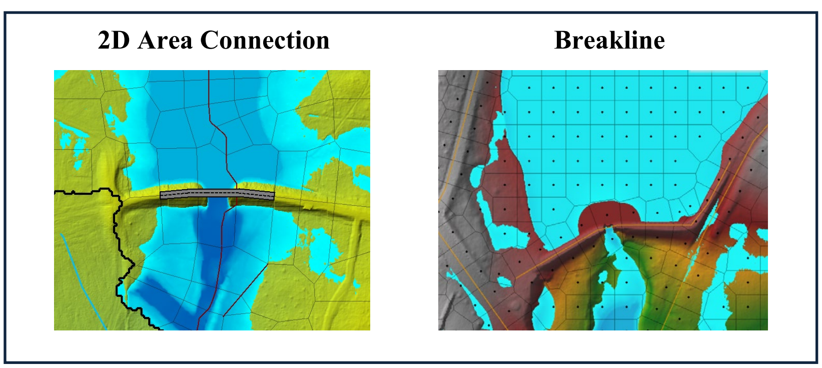
Table 2. Hydro-enforcing effective practices.

Hydro-Enforcing Effective Practices List

1. Hydro-enforcing should be accomplished through the addition of refinement regions, breaklines, or terrain modification.
2. Hydro-enforcing through v-notch, u-notch, or offset breaklines should be enforced with a cell protection radius prior to enforcing any stream centerline or channel bank breaklines so that the hydroenforcing is preserved as the mesh is refined. Alternatively, stream centerline or channel bank breaklines can be clipped to not interfere with hydro-enforcing breaklines.



3. Users should avoid manual edits to individual computation nodes and should instead use breaklines to reshape the mesh. Manual node edits cannot be re-enforced in a consistent manner.
4. 2D area connections or [terrain modification approximations of the channel] can be used to simulate flows through these embankments. These methods are particularly useful for embankments that are wider than the local cell size.
5. 2D area connections should be used to represent dams. Breaklines can be more easily interfered with during model refinement and are dependent on the underlying terrain to accurately capture the spillway geometry. Rating curve information from the dam operator, USACE, BLM, or other agencies can also be incorporated with the 2D area connection.



6. Confirm successful hydro-enforcing by simulating a low flow precipitation event (e.g., 50-pct or 10-pct) and review the total volume accounting to confirm that the expected amount of influx of water is drained to the channel and then through outlet. Users can also visually inspect this process by reviewing the max arrival times layer or the depth

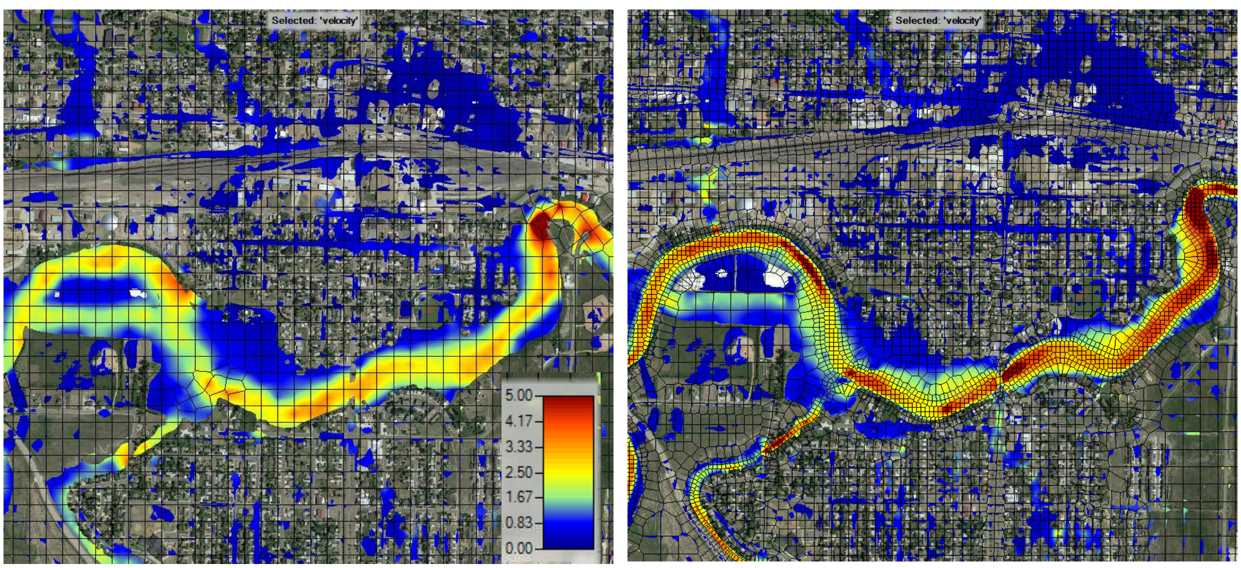
at the final timestep of the model. Upstream areas with high max arrival time values or excessive depths at the end of the simulation indicate that the runoff is collecting and not draining away.

Additionally, comparing the hydrographs at 2D area connections and outflow locations against the expected shape of a standard unit hydrograph can help identify areas where flow routing is being restricted erroneously.

2.3.2 Model Mesh Cell Sizes

Generally, computation points are created with a cell spacing of 200’ x 200’. This ensures that the cell count is low enough for manageable computation times but detailed enough to pass water through the model. Refinement regions should be added to the model to define populous areas, and steep areas, typically at 50’ x 50’ cell spacing. If the entire watershed area requires smaller cell spacing then the initial model mesh can be set at 100’ x 100’ or 50’ x 50’ cell spacing.

Please note that mesh refinement areas may be desired for reasons beyond their effect on the water surface elevation. For example, the detail of velocity output is significantly improved with the additional mesh refinement as shown in Figure 4. As velocity and other flooding characteristics are being considered for future floodplain management initiatives, the need for accurate representation of channel characteristics increases.



200’ grids ***Refined 100’ and 50’ grids***

Figure 4: Velocity (ft/s) Comparison Map

2.3.3 Model Mesh Along Streams and Roadways

Applying refinement regions and breaklines to stream channels typically helps better capture terrain features in the conveyance calculations. Aligning mesh cell edges along channel banks can be important to properly account for the transfer of water between channel and floodplain, especially if those channel banks are perched or raised relative to the adjacent overbanks. Stream centerlines and roads/railroads should also be captured, typically as breaklines with 50’ spacing. Just as important is to capture areas of conveyance through or over channel banks and roads/railroads (e.g., from culverts, openings, low points) so that the model can account for flow exchange across these features.

If after refinement, the density of cells within the stream channel banks is more than two, the HEC-RAS solver should likely be switched to the full momentum equation; otherwise the velocity values within the channel can be unrealistically high. The full momentum equation should be used in these cases because the diffusion wave equation disregards certain components of fluid dynamics, such as local acceleration of velocity with time, advective acceleration, and viscosity terms that are important for modeling flow separations and eddies between 2D cells within the channel.

2.4 TOPOGRAPHY

Using QL2 or better terrain data for 2D watershed modeling provides improvements in hydrology and hydraulics. This recommendation is more restrictive than the current FEMA Standards (SID # 43); however, detailed terrain data improves confidence in the output well beyond that seen in 1D modeling because HEC-RAS 2D relies on the terrain for the flow routing as well as hydraulics. Additionally, the finer resolution of QL2 terrain is particularly important for results related to more frequent recurrence interval events such as the 50- or 10-percent-annual-chance recurrence event because it better captures the channel flow capacity.

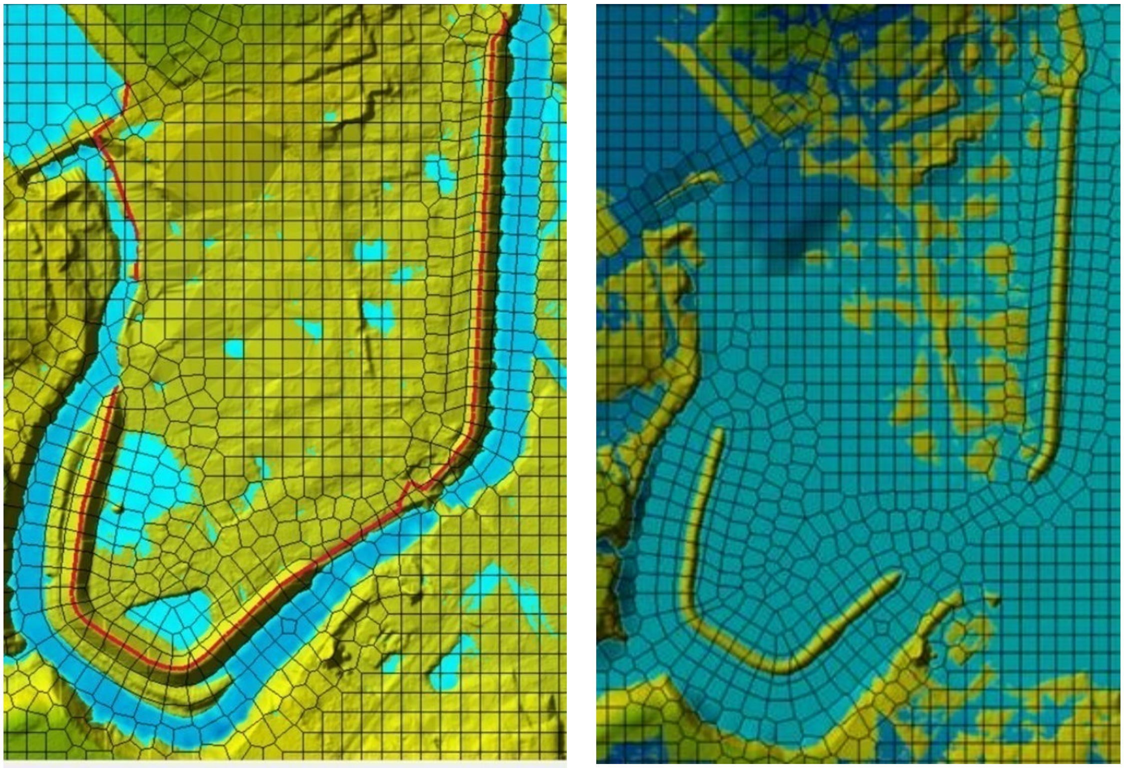
2.5 EVENT SELECTION

Including the nine NOAA published recurrence interval events from the 50-percent to the 0.1-percent-annual-chance event for 2D watershed models provides several benefits to the mesh development process. Currently, FEMA standard SID# 84 includes recurrence intervals from the 10-percent to the 0.2-percent-annual-chance event, but there is little effort required to include these additional events since the point precipitation frequency totals are published directly by NOAA and can be applied directly to the model as a meteorological condition in HEC-RAS v6. These additional events provide useful information about low flow routing for hydro-enforcing, assist with developing flows for downstream watersheds, and confirms that the model can perform well if scaled to probabilistic assessments which use a large range of storm event scenarios to calculate risk.

2.6 REPRESENTATION OF LEVEE SYSTEMS

Where there are levees in a watershed model, two model meshes should be created. One with the mesh updated to account for crest elevations of the levee systems and one with the mesh updated to eliminate any effects of the levee systems (natural valley) as shown in Figure 5.

Applying this process for each system within the project footprint provides insight into the range of possible flood hazard outcomes for each event. This can be used as a starting point for communications with the communities about FEMA's ~~levee~~ analysis and mapping procedures for levees and can also support risk identification when coupled with fragility curves.



Levee Crest Included ***Natural Valley***

Figure 5: With Levee and Natural Valley Models

This section is provided to guide study teams toward developing 2D watershed models that can be reused by FEMA and its stakeholders for continued hazard and risk identification. The following list of effective practices allow efficient upgrades to the model mesh as new data becomes available (e.g., topography or land use) or enhanced analyses are desired (i.e., Zone AE study and graduated flood hazard analyses):

- Model Coordinate Systems and Units
- Organization and Storage of Input and Output Data
- Model Validation / Calibration

3.1 MODEL COORDINATE SYSTEMS AND UNITS

3.1.1 Selection of a Project Coordinate System

A project area may span multiple coordinate projection systems. The study team should select one consistent coordinate system and use the same .prj file for all watershed models within the project footprint to avoid variations or mismatching of input and output data.

If a single coordinate system for a project area is not possible, an effective practice is to include the coordinate system projection file within the folder that contains the model files so that the .prj file is retained with the model inputs and outputs (see Section 3.2 for additional information).

3.1.2 Projection Units

Projections based on US customary units should be used. Certain coordinate systems like UTM use meters as their standard unit of measurement and need to be adjusted to US Feet to align with the default HEC-RAS system units of US customary.

3.2 ORGANIZATION AND STORAGE OF INPUT AND OUTPUT DATA

Consistent management of the 2D HEC-RAS input and output data is important for the reusability of the model. The following information guides users to develop data in a format that is easily recognizable, storage efficient, and user-friendly for uploading and downloading the data.

3.2.1 Recommended Model Naming Convention

Users should use this information as a basis for naming HEC-RAS models, plans, and other modeling components to be consistent and self-explanatory. The objective of this convention is to allow users to locate and understand the modeling data components quickly, which is especially useful for studies that cover large scales with large file sizes.

General Convention

The general rules in Table 3 are useful for consistent labeling of modeling data. Also, this convention will allow users to easily relate modeling results to FIRM Database Standards such as the D_Event Table.

Table 3. General notation.

General Convention Recommendations
Use (1/ recurrence interval in years) ×100 followed by "_pct" to describe the event. Carry decimals to the tenths (e.g., for the 10-percent event, use 10.0_pct).
Use lowercase characters throughout.
Use underscores rather than spaces

Model Names

The recommended naming convention in Table 4 allows users to quickly identify the project and geographic location (HUC or stream).

Table 4. Recommended model naming convention

Name	Example
Project Name + HUC code	amite_0807020204
Project Name + mainstem stream name	amite_comito_river

Plan Names

The following recommended plan naming convention allows users to determine the inflow conditions for each plan and determine if it is a fluvial or pluvial plan.

Table 5. Recommended plan naming convention.

Description	Name	Example	Short ID
Precipitation boundary models	Temporal distribution + event + "pct"	noaaq1_1.0_pct	precip_1.0_pct
Inflow hydrograph models	inflow stream name + event + "pct"	comito_river_1.0_pct	comito_1.0_pct
Coupled inflow hydrograph models with joint probability pluvial condition	inflow stream name + event + "pct" + _jp"	comito_river_1.0_pct_jp	comito_1.0_pct_jp

Geometry Names

The recommended geometry naming convention in Table 6 provides indicators (flags) to describe the cell spacing, and other important mesh characteristics.

Table 6. Recommended geometry naming convention.

Description	Name	Example	Geometry Flags
Geometry flags dependent on hydraulic method. Order of flags in name does not matter. The identifier may be the HUC code or stream name. Active geometry flags should be explained in the Plan description.	identifier + "flags_" + geometry flags	0807020204_flags_ 200n50b100rih	#n: nominal cell spacing (e.g., 200n) [required] #b: breaklines applied and minimum associated cell size (e.g., 50b) #r: refinement regions applied and minimum associate cell size (e.g., 100r) i: infiltration in model h: hexagonal cell configuration

Hydrologic Input Names

The type of hydrologic inflow and outflow boundary conditions depends on the methodologies selected for preparing the 2D HEC-RAS models. Consistent naming conventions should be agreed upon prior to the initiation of a project. This consistency is critical for when adjacent or upstream watershed areas are being used as inflow conditions. Examples for several types of boundary conditions are provided in Table 7 for reference.

Table 7. Recommended hydrologic input naming convention.

Description	Hydrologic Input	Example
Precipitation boundary hyetograph	Precipitation boundary conditions	noaaq1_1.0_pct
Indicate the inflow HUC or stream (if applicable).	Inflow boundary conditions	inflow_from_071200040402
Indicate the downstream HUC or stream.	Downstream outfall boundary conditions	outfall_to_071200040402
Only applicable if there is floodplain overflow into an adjacent basin.	Overflow boundary conditions	overflow_to_071200040401. If there is more than one overflow, append an alphabetical suffix (e.g., _a)

3.2.2 Folder Organization

The modeling components listed in this section should be located within a single folder per watershed area along with the associated files listed in Table 8.

Table 8. Associated files to be included in model folder.

Additional files list
1. Projection file used to set the model coordinate system
2. Terrain files – Source terrain digital elevation model raster files (e.g., .tif) – HEC-RAS associated .hdf and .vrt files

Additional files list
3. Soil and land use and classification files used to develop Manning's n & Infiltration layers – Source raster or vector file (e.g., .tif or .shp) – HEC-RAS associated .hdf file
4. DSS input files used for the model
5. Gridded rainfall source information (if applicable)
6. GIS data that was used to develop breaklines and 2D area connection data

3.2.3 Recommended Model Output Settings

Model output parameters contribute to the output file sizes and can be adjusted in the plan window of HEC-RAS. Table 9 provides recommended ranges for output settings to balance usability of the output and file size.

Table 9. Recommended model output settings.

Model Output Setting	Recommended Range	Justifications
Hydrograph output interval	5-30 minutes	-Reviewing the shape of outflow hydrographs is a good means to confirm the model is routing flow as expected. -Including a shorter output interval does not increase file sizes significantly.
Mapping output interval	15 minutes – 1 hour	-An initial shorter interval like 30 minutes is useful for reviewing the progression of mapping data to refine the mesh. -A longer output interval for all remaining plans and simulations can preserve memory but will lose the ability to see flow hydrograph shapes within the model. - If only Max WSEL is needed, then an option of "Max Profile" is acceptable.
Detailed output interval	None	Applies to 1D elements and can be ignored in 2D only RAS.

Certain model outputs can be excluded during file transfer if desired. Model output is stored in several files, but most of the output information is stored in HEC-RAS plan output HDF files (e.g., p.01.hdf). Please note that the other HEC-RAS HDF files related to the terrain, land use, and geometry are required as model input and cannot be excluded. The model plan outputs can be reproduced after file transfer by simulating each plan as needed. Excluding other plan results can be particularly useful if external users are only seeking the 1-percent-annual-chance event results.

3.3 MODEL VALIDATION / CALIBRATION

Validation and calibration of rainfall-runoff models provide confidence in model results. While the flow routing component of 2D HEC-RAS is much more detailed than a typical rainfall-runoff model, the placement of breaklines and the development of CNs and Manning's n values need to be validated and calibrated (where possible) to confirm realistic results.

3.3.1 Velocity Validation

Users should inspect the maximum velocities along the stream channels and near hydraulic structures to confirm the reasonability of the results. Typically, velocity issues can be resolved by the adjustment of 2D area connections, addition of breaklines, or use of the full momentum solver. The timing of the maximum velocity is also important to consider. In some cases high velocities may occur during the initial precipitation time step as shown in Figure 6. This case is not necessarily an indication of poor velocity validation because the spike in velocity does not affect the peak depth during the storm event.

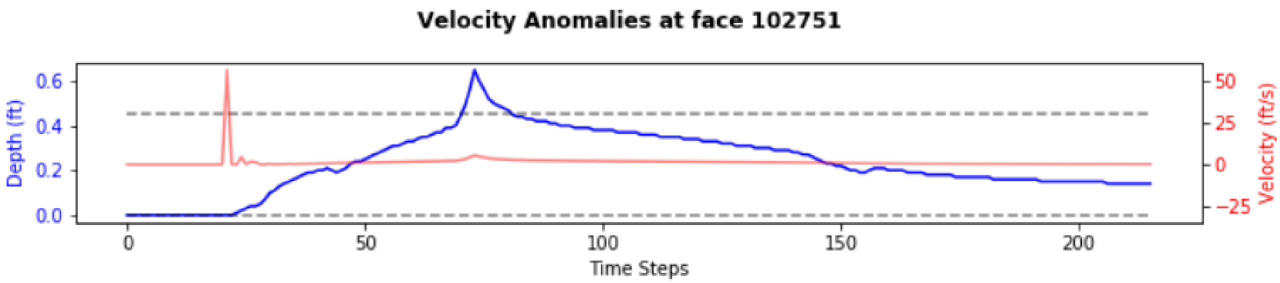


Figure 6. Spike in velocity during initial precipitation time step.

3.3.2 Peak Flow Validation

Modeling in 2D HEC-RAS is an iterative process. After each simulation, the results should be analyzed and adjustments made to verify that the model produces the expected results. Breaklines can significantly influence flow routing and should be modified to allow water to pass through (i.e., hydro-enforcing) the model in a realistic way. For example, if water is known to pond behind high ground, this behavior should be consistent with how the mesh and terrain allow the area to drain. After each iteration of mesh refinement, stage and flow hydrograph results in HEC-RAS should be compared to flow and water surface elevation data calculated with USGS gages, regression equations, and rating curves for validation.

3.3.3 Curve Number Calibration / Validation

Validating / calibration of the Curve Number (CN) confirms that the model is producing the volume of runoff expected for the watershed area. This validation is an important first step before calibrating peak flows. There are two practices recommended for calibrating the CN based on gage records.

3.3.3.1 Data Derived CN Calibration Method

The draft update to the *National Engineering Handbook - Part 630 Hydrology, Chapter 10* (16 October 2017 Updated Revision) proposes several changes to the application of the CN method. Being able to calibrate the CN with local gage data can provide improved confidence in the results of modeling because it allows comparing the volume of runoff to the volume of precipitation for a long range of historic storm events. The procedure involves utilizing local precipitation and stream gages in headwater watersheds to refine CN values to fit local conditions.

Figure 7 demonstrates how the national CN calculated book value (78) for the watershed is well above the gage derived CN value within the local watershed. Using this information, the engineer can scale down the land use / soil type CNs to be calibrated to fit the recorded rainfall runoff conditions for extreme storm events (50mm -300mm of rainfall).

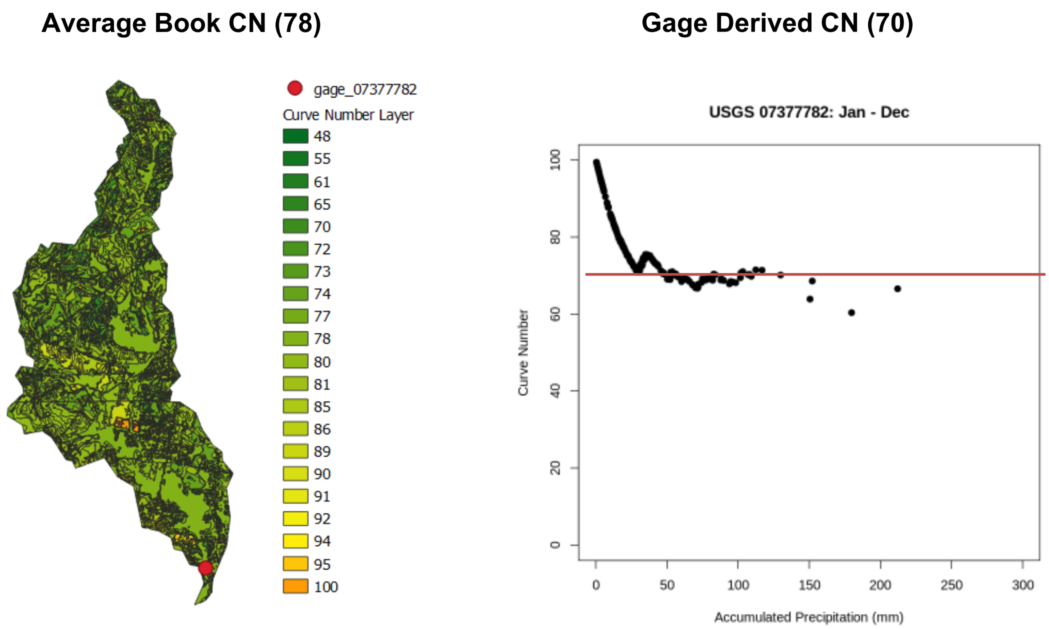


Figure 7. Comparison of book CN and calibrated CN.

3.3.3.2 Validation to Observed Storms

Validation to observed storm events allows the modeler to compare volume, time to peak, and other indices in addition to stage and flow, but should not be used to calibrate the resulting curve number for the watershed. The antecedent soil moisture conditions will vary and may not capture the expected maximum retention conditions of the watershed.

2D watershed modeling is an emerging practice and leverages relatively new modeling capabilities of HEC-RAS. The latest available documentation regarding the HEC-RAS 2D User's Manual, Hydraulic Reference Manual, and HEC-RAS Mapper User's Manual is currently available at https://www.hec.usace.army.mil/confluence/rasdocs/. When developing 2D watershed modeling, users should refer to the latest RAS documentation as well as the latest FEMA Guidance for Hydrology: Rainfall-Runoff Analysis and Hydraulics: Two-Dimensional Analysis.

Until incorporated into FEMA guidance, this document provides information to clarify existing guidance, highlight new benefits, and provide new protocols for the following topics:

- Spatial Precipitation
- Spatial Infiltration
- Areal Reduction Factors
- Calculating the 1-percent plus and minus storm events
- Modeling Inflows from Upstream Watersheds
- Stream Profiles
- Floodplain Mapping

4.1 SPATIAL PRECIPITATION

Clarification: Spatial precipitation in HEC-RAS v6 is functionally different than the excess precipitation approaches previously used in HEC-RAS v5. A summary of the major differences between models is provided in the following table.

Table 10. Spatial precipitation vs excess precipitation

Function	HEC-RAS v6 (Spatial Precipitation)	HEC-RAS v5 (Excess Precipitation)
Boundary Condition	Global (Meteorological Data tab)	External (Boundary Conditions tab)
Input format	Grid based temporal distributions or point gage hyetograph input	Direct hyetograph input
Expected DSS Input Data Type	Rainfall (period-cumulative)	Runoff (instantaneous value)
Infiltration	Performed during simulation	Performed prior to simulation

Spatial precipitation allows direct application of precipitation and infiltration in the model but is more complex to format than an excess precipitation. There are two available options to apply spatial precipitation: gridded or point gage input. Under either approach, the user should use the precipitation accumulation map and plot functionality in RAS Mapper (shown in Figure 8) to confirm that the precipitation totals match the expected precipitation depth frequency values.

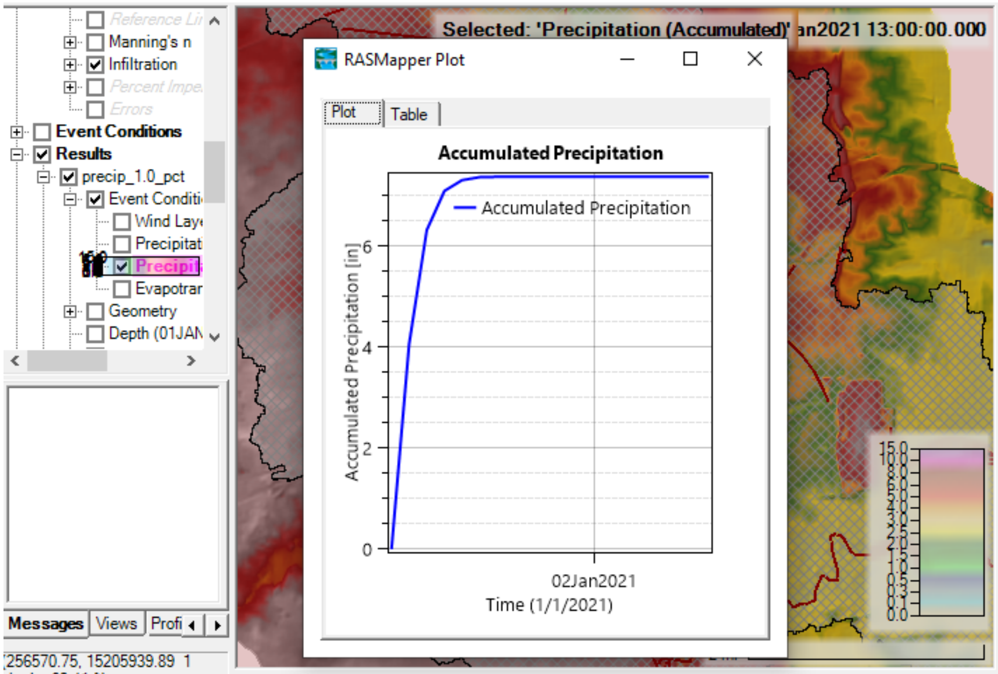


Figure 8. Precipitation accumulation map and plot.

4.2 SPATIAL INFILTRATION

New Benefits: Available in HEC-RAS v6, in-model spatial infiltration provides a site-specific flood hazard assessment compared to the application of runoff (excess rainfall). The example below highlights the benefit of using spatial infiltration and WSELs are affected by local infiltration rates.

Figure 9 and Figure 10 show the difference in WSELs with spatial infiltration. For this watershed the average weighted curve number (CN) is 70, but the local CN is less on the south side and has lower WSELs shown in orange. The CN for the ponding areas shown in green is higher and has higher WSELs than the uniform infiltration model. The site-specific infiltration is limited by the maximum potential retention value; therefore, the value of performing spatial infiltration decreases with the more extreme recurrence intervals as shown when comparing Figure 9 and Figure 10.

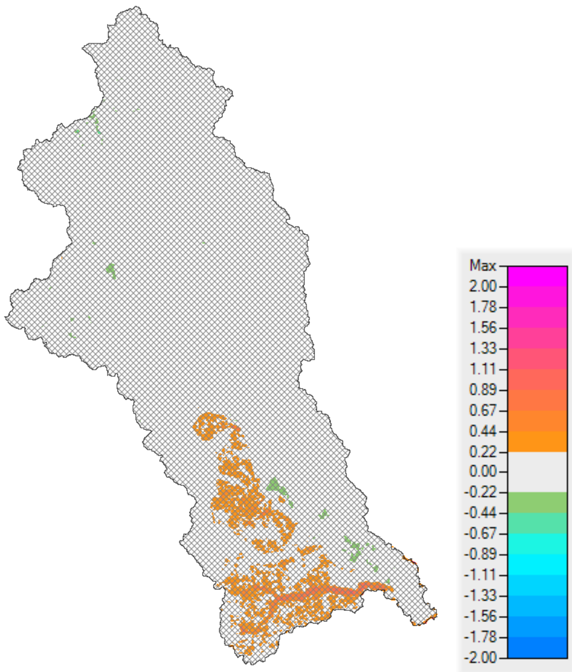


Figure 9. WSEL difference between uniform infiltration model and spatial infiltration model (20 pct event).

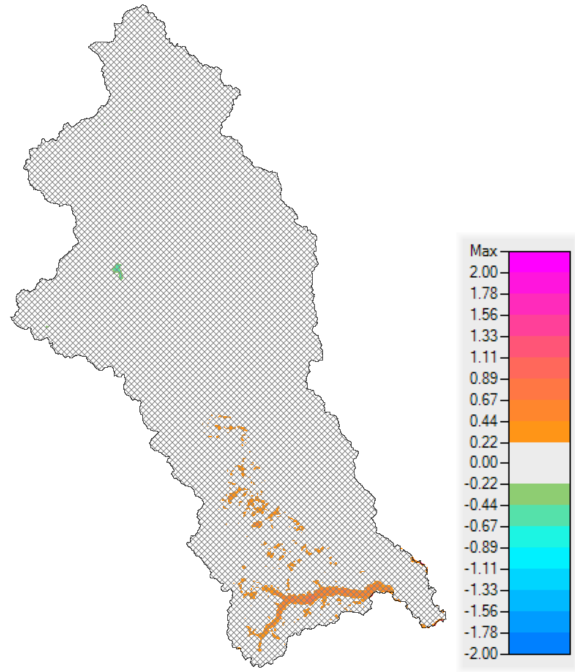


Figure 10. WSEL difference between uniform infiltration model and spatial infiltration model (1 pct event).

4.3 AREAL REDUCTION FACTORS

Clarification: Areal reduction factors transform precipitation point depths into an effective mean precipitation depth for a given watershed area. The reduction is an approximate method to account for the spatial variability of rainfall over large watershed areas and is based on empirical data from rain gages. The most commonly used method is the National Weather Service Bureau's TP-29 prepared in 1954 which is based on gage data east of the Mississippi. Several other methods have been derived from more recent academic studies that better account for storm magnitude, geographic location, and storm orientation.

Users should consider utilizing any locally developed areal reduction factors or more sophisticated methods than TP-29 that take into consideration the frequency of the event and shape of the watershed. Also, note that use of an areal reduction factor will produce pluvial hazards that are less severe in headwater areas and should be considered when setting watershed model mesh scale.

4.4 CALCULATING THE 1-PERCENT-PLUS AND MINUS PRECIPITATION EVENTS

New protocol: For a 2D watershed model, the 1-percent-plus (upper 84-percent confidence limit) needs to be based on the precipitation data since the flows are implicitly calculated in the model at every cell. The recommended approach to prepare the 1-percent-plus precipitation totals using available data from NOAA is described below. This process assumes the log of the precipitation uncertainty is normally distributed and uses the quantile function to transform the 90% confidence intervals into the 1-percent plus and minus precipitation values.

1. Given precipitation values (lower 90%, median, and upper 90%) from NOAA
2. Calculate μ (natural log of median rainfall)
    - μ = ln(median)
3. Calculate σ_{max} (the max natural log of the standard deviation of the data):
    - $\sigma_{lower} = (\mu - ln(lower\ 90\%))/1.645$
    - $\sigma_{upper} = (ln(upper\ 90\%) - \mu)/1.645$
    - $\sigma_{max} = max(\sigma_{lower}, \sigma_{upper})$
4. Calculate the 1-percent plus and minus precipitation values:
    - $1\text{-}percent\ plus = exp\ (\mu + \sigma_{max} \times \sqrt{2} \times erfinv(2 \times 0.84 - 1))$
      $= exp\ (\mu + \sigma_{max} \times 0.994)$
    - $1\text{-}percent\ minus = exp\ (\mu + \sigma_{max} \times \sqrt{2} * erfinv(2 \times 0.16 - 1))$
      $= exp\ (\mu + \sigma_{max} \times -0.994)$

*Note: $erfinv$ is the inverse error function also denoted as erf^{-1}

4.5 MODELING INFLOWS FROM UPSTREAM WATERSHEDS

New protocol: Receiving watershed areas need to include fluvial hazards from upstream runoff. The two current approaches for modeling the hazards associated with upstream inflows in 2D watershed models are summarized below with full workflows and examples included in Appendix A and Appendix B.

4.5.1 Decoupled fluvial and pluvial models

This approach uses separate modeling plans for the pluvial condition and the fluvial flooding condition. In the example shown in Figure 11 (pluvial conditions) and Figure 12 (fluvial conditions) there is a single upstream inflow location, but multiple inflow locations can be modeled this same procedure.

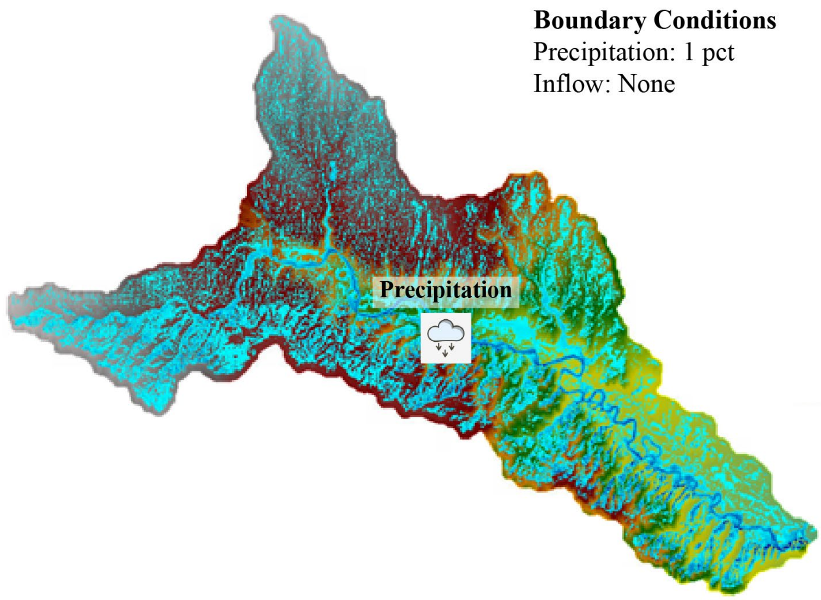


Figure 11. Pluvial decoupled plan.

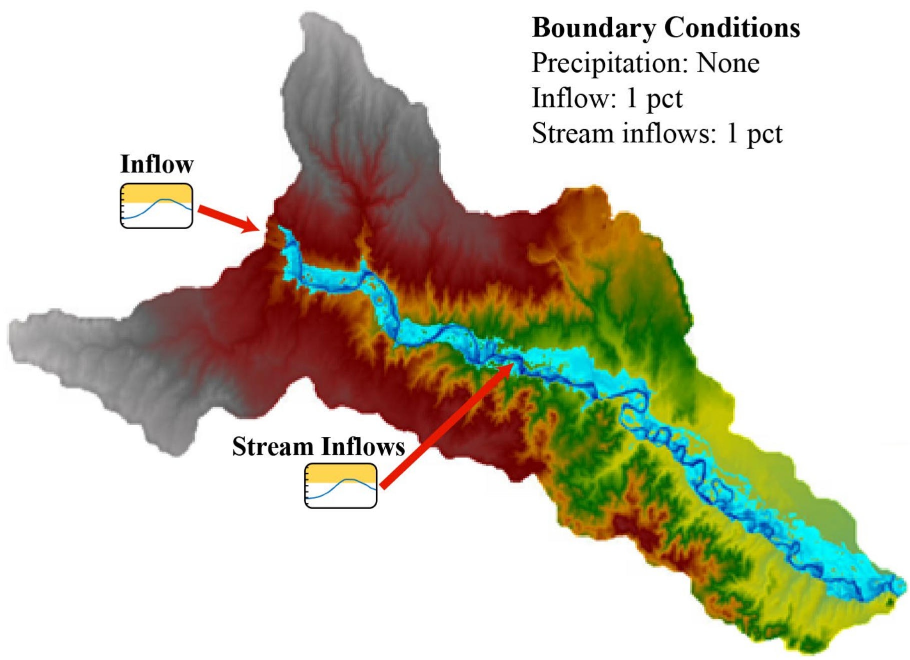


Figure 12. Fluvial decoupled plan.

The pluvial plan follows the same general approach as in headwater areas. A zero-value inflow boundary condition hydrograph where the upstream basin is entering the watershed needs to be created so that the same model mesh can be used for the fluvial plan.

The fluvial approach is analogous to a 1D model where the flows at key points are determined and used as inputs to the hydraulic model. Therefore, decoupled fluvial plans start with a peak inflow and a hydrograph from an appropriate source, such as a USGS stream gage within the watershed, regional regression equations, or a stream gage upstream or downstream of the watershed.

A flow frequency analysis is applied to a local stream gage, and several major flood events are analyzed to estimate a gage-based dimensionless unit hydrograph. The peak flows at the gage are then transferred upstream and downstream to calculate the upstream inflow and downstream target outflow using drainage area ratio techniques. If flows are developed using regression equations or some other source because no stream gage is available, unit hydrographs will have to be developed using some other method.

An inflow hydrograph is then prepared and can be added along the stream centerline to account for the variability in flows between the upstream and downstream boundary conditions. The development of the inflow hydrograph requires an analysis of flow attenuation within the model and the additional contributing flow required to match the downstream peak flow.

The final floodplain would be produced by taking the larger water surface elevation of either the pluvial or fluvial event at each cell. See Appendix A for an example use case of this procedure.

4.5.2 Coupled fluvial and pluvial models using joint probability

This approach routes the upstream headwater outflows as an inflow hydrograph through the receiving watershed areas while applying coincident precipitation conditions based on joint probability. The basis for the joint probability estimates is from the report *Estimating Joint Probabilities of Design Coincident Flows at Stream Confluences* (National Cooperative Highway Research Program, 2013). Figure 13 illustrates how precipitation and inflow information are used together to identify pluvial and fluvial hazards.

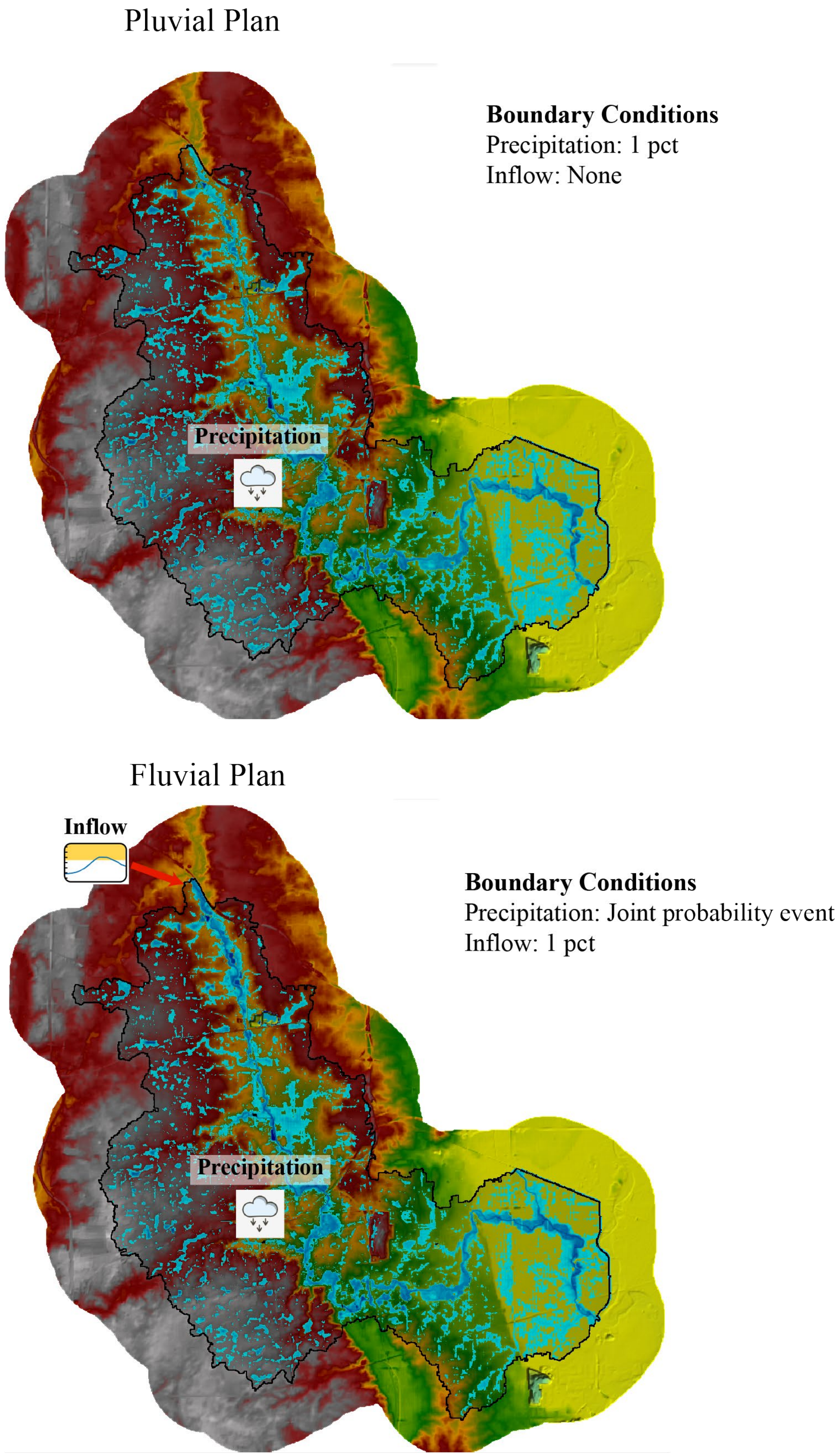


Figure 13. Watershed area of coupled pluvial and fluvial plans with joint probability (JP) events.

To determine the appropriate joint probability for precipitation and inflow events, the contributing drainage areas at each inflow are compared against the total watershed area. The ratios of the total area to the contributing watershed area are then used as parameters to characterize the relationship between inflows and ultimately a representative joint probability event. The joint probability events must be time-adjusted in the model so that the peak flows occur coincidently at the confluence.

The final floodplain would be produced by taking the larger water surface elevation of among the joint probability plans at each cell. See *Appendix B* for an example use case of this procedure.

4.6 STREAM PROFILES

New protocol: Zone AE streams or other streams where a flood profile will be produced should apply the stream profile line as a breakline in the model mesh so that the WSELs along the profile are smooth. The addition of the breakline forces the profile to be based on calculated cell face values rather than interpolated values between several cells. This application is particularly important for narrow floodplains on smaller tributaries as is shown in the example shown in Figure 14 and Figure 15.

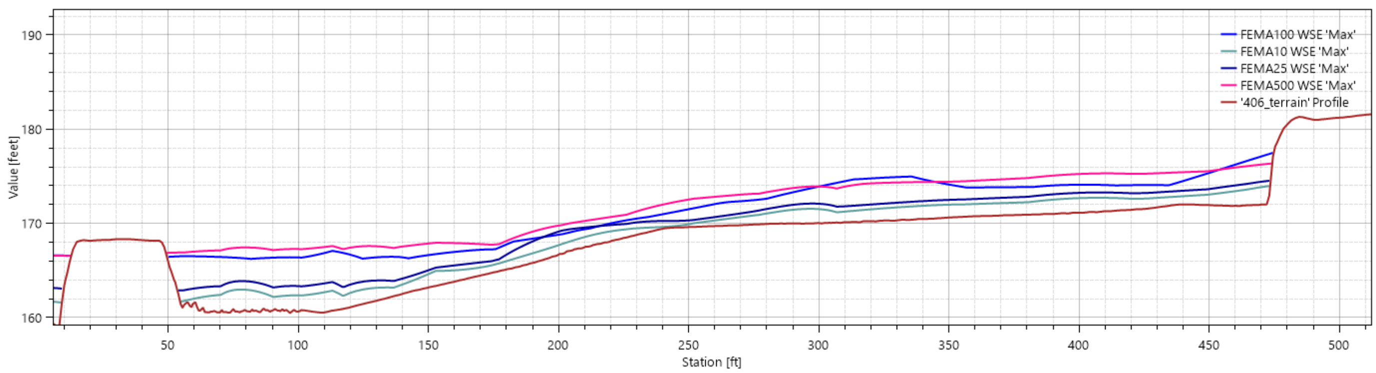


Figure 14. No breakline along stream profile.

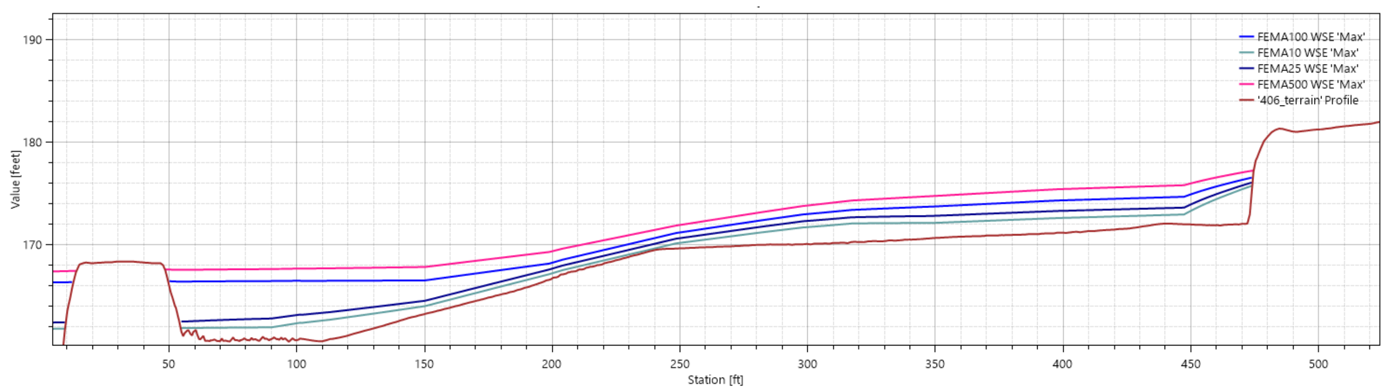


Figure 15. Breakline along stream profile.

4.7 FLOODPLAIN MAPPING

Clarification: The sub-cell computation approach employed by 2D HEC-RAS allows the user to use larger computational cells and still retain some of the geometric and hydraulic property information based on the high-resolution topography underlying the cells. This provides a good compromise between model accuracy and runtime; however, only one water surface elevation is calculated for each cell center which can lead to erroneous mapping results when interpolating between cells. The rendering mode options in HEC-RAS also affect how the program interpolates these values.

4.7.1 HEC-RAS Rendering Mode Options

The "sloping" rendering mode in RAS Mapper is most like the conventional 1D interpolated floodplain mapping process used in Risk MAP studies and should generally be used for interacting with the data prior to generating the regulatory floodplain and associated grids. The default in RAS Mapper is "hybrid," which is useful for models with detailed grid sizes but more frequently presents patchwork floodplains compared to the sloping method.

4.7.2 Resolving Erroneous Floodplain Mapping Results

Erroneous mapping occurs when RAS Mapper attempts to interpolate between adjacent cells to "slope" the water surface, but in doing so, steep canyon walls or bluffs on the floodplain fringe can artificially cause the water surface to be interpolated upstream, resulting in significant areas of inundation where there should really be no inundation. This erroneous mapping result is referred to herein as "cupping." Figure 16 shows several areas of significant cupping on the south side of the main channel.

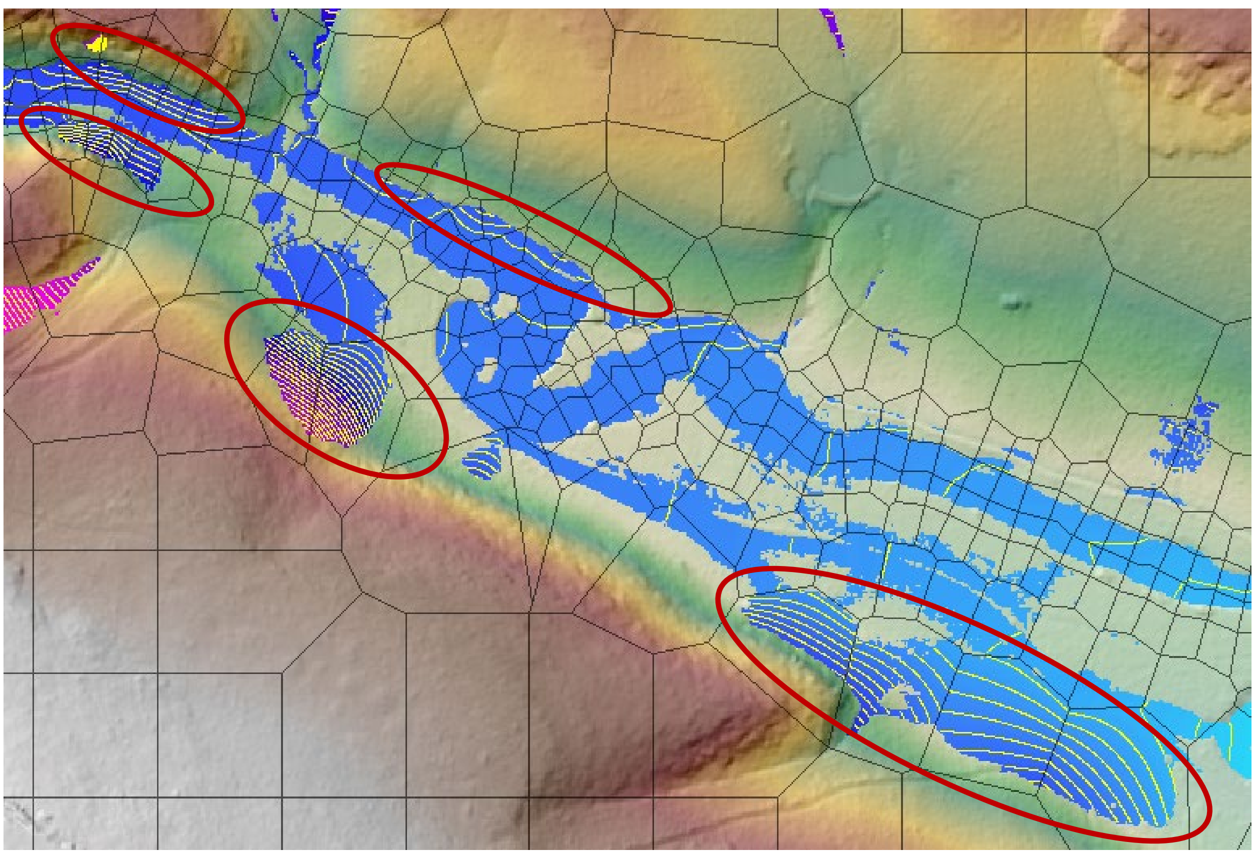


Figure 16. Maximum WSEL plotted on 2' contours showing mapping issues due to "cupping."

4.7.2.1 In-model techniques to resolve cupping

This section provides model development methods that reduce the cupping issues in the sloping render mode. These methods represent good modeling practices for model development, but ultimately do not completely eliminate the problem consistently enough to recommend using the results as exported by RASMapper.

The most basic technique is to use the streamlines as breaklines with reduced cell size around the stream channel. This is a fast and simple method to create a mesh, which usually still results in significant cupping issues, especially in steeper watersheds; a small tributary exhibiting "V-shaped" cupping after applying a stream centerline breakline is shown in Figure 17.

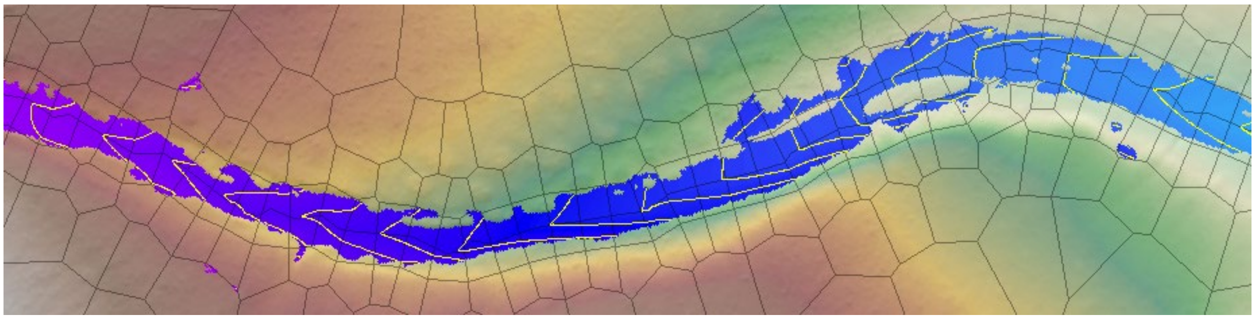


Figure 17. "V-shaped" cupping in a small tributary.

This can be reduced by centering the cells along the streamline through the use of a refinement region created by buffering the streamline by 25-ft on both sides (for a 50-ft cell). This refinement region is then applied to the mesh with 50-ft internal cell spacing to center the cells along the channel.

One drawback of this approach is that these large and skinny refinement regions are difficult to enforce correctly in HEC-RAS. The method usually requires a significant amount of time troubleshooting. A simpler alternative to this is create a breakline that is offset from the main channel by 25-ft in one direction. Then this offset stream breakline is enforced in the mesh with 50-ft cells aiming to center the cells on the channel. This method achieves a very similar mesh to the stream refinement region and is much easier to enforce within HEC-RAS.

4.7.2.2 External processing techniques to resolve cupping

Because none of the modeling fixes can consistently resolve these erroneous mapped values based on the available HEC-RAS rendering options, an external process should be used to generate or clean the floodplain boundaries and depth/water surface grids when developing a regulatory product.

There are several different external mapping techniques being used throughout the country to address cupping issues. These processes typically require multi-step GIS techniques, which can be time intensive and result in mapping that is slightly different from the HEC-RAS modeling output. Any external mapping process used to produce regulatory boundaries should be thoroughly documented by the mapping partner.

Appendix A – Workflow & Example Decoupled Pluvial and Fluvial Model

This approach uses separate modeling plan for the pluvial condition and the fluvial flooding condition. The pluvial plan follows the same general approach as in headwater areas. The fluvial plan is analogous to a 1D model where the flows at key points are determined and used as inputs to the hydraulic model.

WORKFLOW

The steps for developing a pluvial model are as follows:

- In a non-headwater watershed area, create an inflow boundary condition and set the hydrograph to a zero value (or some small amount of base flow if appropriate). This allows for a single geometry that HEC-RAS can use in both the 1% pluvial and the 1% fluvial plan runs.
- Perform precipitation based pluvial simulations for every watershed to include the recommended recurrence interval events:

The steps for developing a fluvial model are as follows:

1. Determine peak flows at outlet and at any inlets using gage analysis or another applicable technique.
2. Develop a representative unit hydrograph for the stream reach within the watershed model.
3. Create stream centerline hydrographs for each event. The stream centerline inflow can be estimated as the difference between the outflow and the inflow to start.
4. Iteratively scale the stream centerline hydrograph until the model outflow matches the goal flow at the outlet
5. Use the maximum WSELs between the fluvial and pluvial plans for flood hazard mapping

EXAMPLE

In this procedure, a Bulletin 17C analysis was applied to USGS stream gage 07145500 Ninnescah River near Peck, KS, and several major flood events were analyzed to estimate a gage-based dimensionless unit hydrograph. The peak flows at the gage were then transferred upstream and downstream to calculate the upstream inflow and downstream target outflow using drainage area ratio techniques.

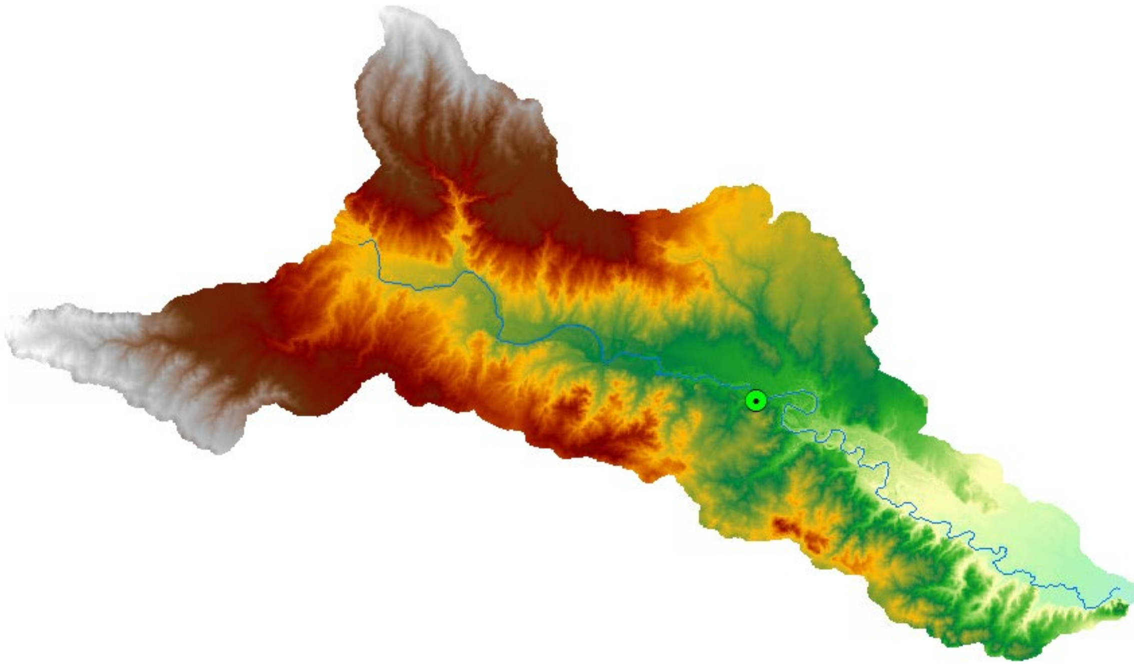


Figure A1: Watershed area for testing decoupled pluvial and fluvial modeling with USGS stream gage shown

For a 1% peak flow of 52,070 cubic feet per second (cfs), the applied upstream peak flow was 48,621 cfs and the target peak outflow was 57,181 cfs. From this, it was determined that an additional flow of 8,559 cfs was required to represent the additional drainage area within the basin, which was applied as an internal flow hydrograph BC line along the stream centerline. The initial hydrograph for this additional flow was determined simply by subtracting the inflow hydrograph from the outflow hydrograph.

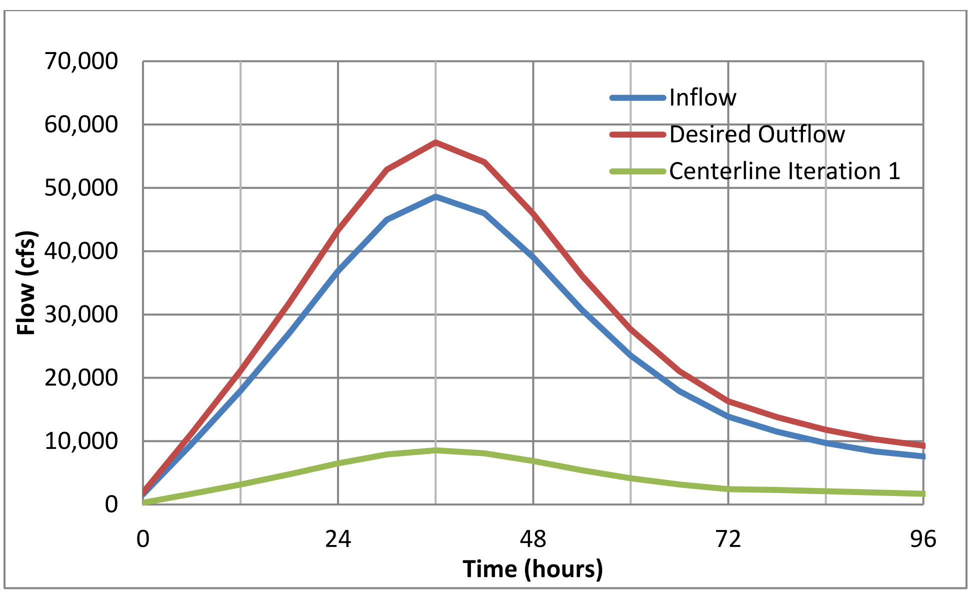


Figure A2: Initial stream centerline hydrograph

When this initial stream centerline hydrograph was added to the model, the peak outflow was only 52,198 cfs due to attenuation within the stream corridor; therefore, additional flow beyond the 8,559 cfs was needed. To determine the amount of outflow that could be attributed to the inflow, the model was run with only the inflow boundary condition active as shown in Figure 3.

The 48,621 cfs at the upstream end was attenuated down to about 45,000 cfs, which means that about 85% of the stream centerline inflow (7,268 of 8,559 cfs) goes towards increasing the peak.

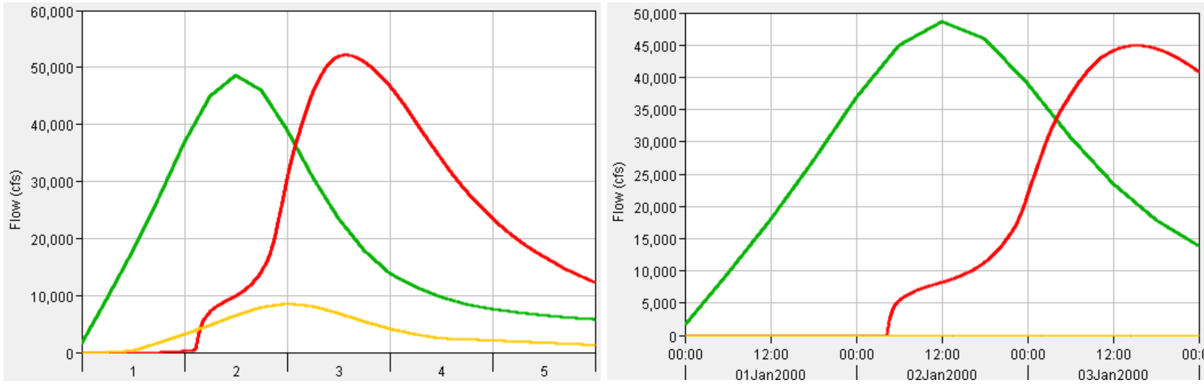


Figure A3: Initial Inflow and Outflow Hydrographs

Based on the upstream inflows-only run, the stream centerline inflow needed to contribute 12,251 cfs to the peak at the downstream end. Based on this roughly 85% rate, a hydrograph with a peak of 14,500 cfs was added along the stream centerline to achieve outflows within 1% of the target value from the gage transfer.

Table A1: Target and Applied Peak Flows

Peaks	Target	Iteration 1	US Inflow Only	Final Inflow
US Inflow	48,621	48,621	48,621	48,621
Stream Centerline		8,559	0	14,500
Outflow	57,181	52,198	44,930	56,757

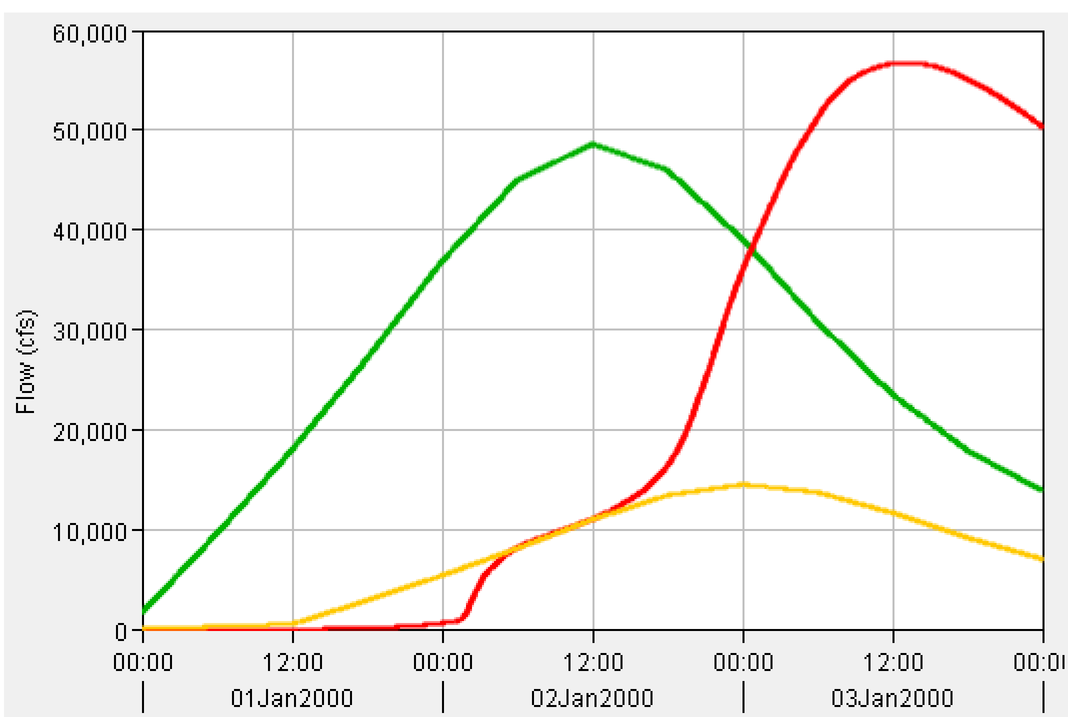


Figure A4: Final Inflow and Outflow Hydrographs

Appendix B – Workflow & Example Coupled Pluvial and Fluvial Model

This approach routes the upstream headwater outflows as inflow hydrograph through the receiving watershed areas while applying coincident precipitation conditions based on joint probability. The basis for the joint probability estimates is from the report *Estimating Joint Probabilities of Design Coincident Flows at Stream Confluences* (National Cooperative Highway Research Program, 2013).

WORKFLOW

1. In a non-headwater watershed area, create an inflow boundary condition and set the hydrograph to a zero value. This allows for a single geometry that HEC-RAS can use in both the 1% pluvial and the 1% fluvial plan runs.

2. Perform precipitation based pluvial simulations for every watershed to include the recommended recurrence interval events:

3. Compute the following factors for every upstream watershed inflow location:
   - The total watershed area, $\mathbf{A_{TOT}}$, is computed by summing the drainage area of the inflow and all other areas upstream of the confluence (a + b).
   - The drainage area ratio, $\mathbf{R_A}$, is computed by dividing the drainage area of the total watershed (a + b) by the drainage area of the inflow (a).

     (a) = Drainage area of inflow
     (b) = Drainage area of all other upstream areas draining to confluence

4. Based on R_A and A_{TOT}, assign the upstream watershed one of four categories (see Table B1, which is based on Table H.2 of the NCHRP, 2013 report).

Table B1. Watershed Categories

		Total Watershed Area	
		$A_{TOT} < 350$ mi^2	$A_{TOT} \geq 350$ mi^2
Drainage Area Ratio	$R_A < 7$	SS	SL
	$R_A \geq 7$	LS	LL

5. For each event, use Tables B2-B6 to identify the representative joint probability event for each inflow combination. These tables were created based on a simplification of Tables H.3 – H.7 in NCHRP, 2013 report. Users should review NCHRP, 2013 prior to use.

Table B2. 10-percent-annual-chance joint probability combinations

Category	Joint Probability Events		
	Representative	Reduced for Calibration	Increased for Calibration
SS	**50-percent**	-	20-percent
SL	**50-percent**	-	20-percent
LS	**50-percent**	-	20-percent
LL	**50-percent**	-	20-percent

Table B3. 4-percent-annual-chance joint probability combinations

Category	Joint Probability Events		
	Representative	Reduced for Calibration	Increased for Calibration
SS	**20-percent**	50-percent	10-percent
SL	**50-percent**	-	10-percent
LS	**20-percent**	50-percent	10-percent
LL	**50-percent**	-	10-percent

Table B4. 2-percent-annual-chance joint probability combinations

Category	Joint Probability Events		
	Representative	Reduced for Calibration	Increased for Calibration
SS	**10-percent**	20-percent	4-percent
SL	**20-percent**	50-percent	4-percent
LS	**10-percent**	20-percent	4-percent
LL	**50-percent**	-	20-percent

Table B5. 1-percent-annual-chance joint probability combinations

Category	Joint Probability Events		
	Representative	Reduced for Calibration	Increased for Calibration
SS	**4-percent**	10-percent	2-percent
SL	**10-percent**	20-percent	2-percent
LS	**4-percent**	10-percent	2-percent
LL	**50-percent**	-	10-percent

Table B6. 0.2-percent-annual-chance joint probability combinations

Category	Joint Probability Events		
	Representative	Reduced for Calibration	Increased for Calibration
SS	**1-percent**	2-percent	0.5-percent
SL	**2-percent**	4-percent	1-percent
LS	**1-percent**	2-percent	0.5-percent
LL	**20-percent**	50-percent	4-percent

6. Simulate each joint probability condition (precipitation and inflow events) independently to identify the timing of the peak at the confluence of the main watershed and upstream watershed.
7. Retain the peak timing of the precipitation event and adjust the inflow timing so that all inflow events will peak at the confluence concurrently. The timing of the inflow events can be shifted using HEC DSSVue.
8. Compare the coincident joint probability modeling results to available gage records and use the reduced or increased for calibration information in Tables B2-B6 to increase or decrease flows to better match gage records.
9. Utilize the maximum WSELs between the fluvial and pluvial plans for flood hazard mapping and utilize the plan that produces the max peak flow for the next downstream watershed model.

EXAMPLE

In this example 1-percent-annual-chance joint probability information was developed for two inflow locations for the Lower Salt Creek HUC-12 watershed in Illinois. This process requires additional plans depending on the number of inflow locations. See Figure B1 for a project area map.

HUC-12 #	Basin Name	Number of Inflow Locations
071200040404	Lower Salt Creek	2

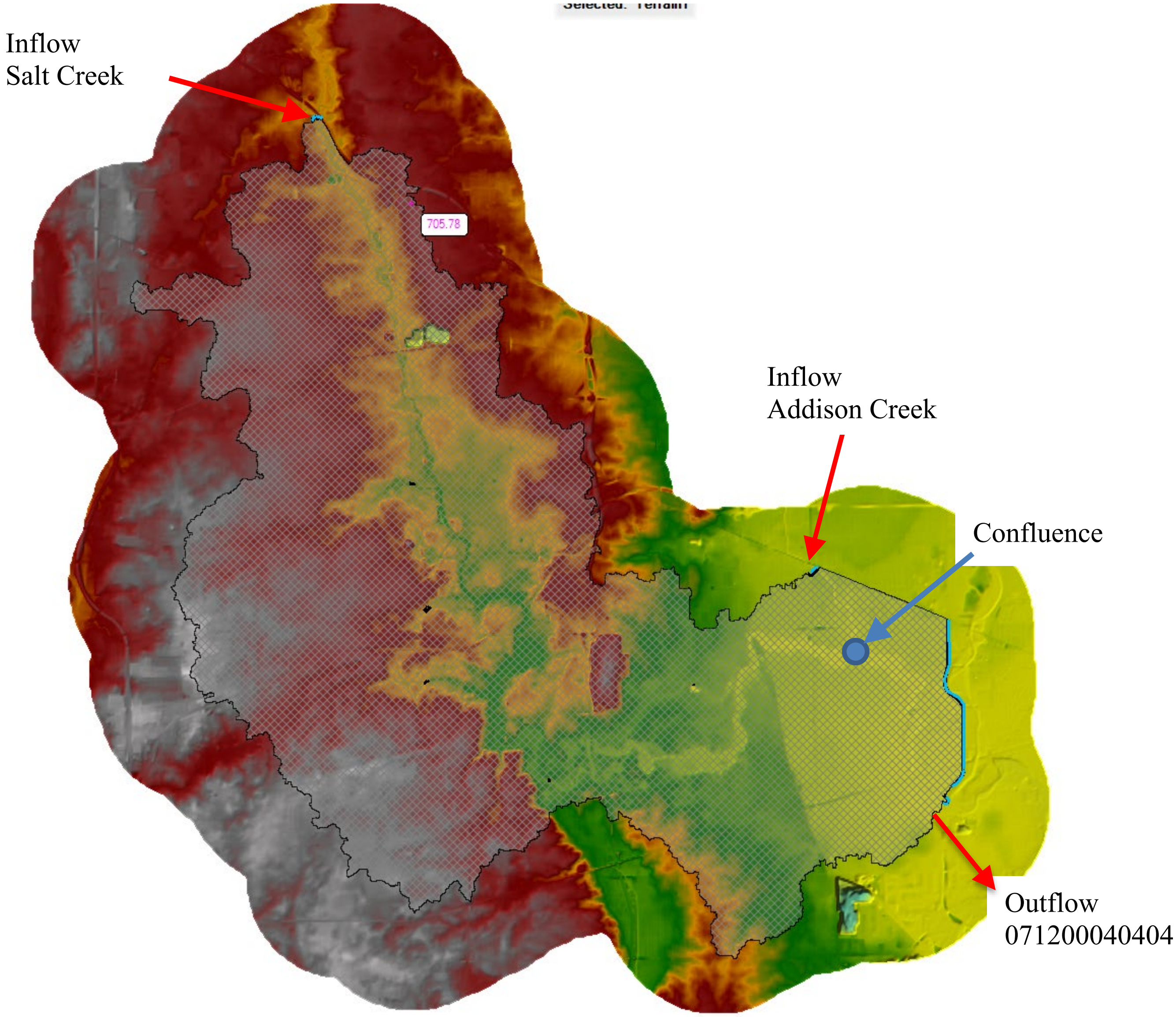


Figure B1. Project Area Map

Values for Atot, Ra were calculated based on the watershed areas. Watershed categories and a representative joint probability event were then determined for the two inflow watersheds based on Table B1 and Table B5. Results are shown in the below.

Inflow Point of interest	Inflow drainage area (mi^2)	Atot - Total drainage area upstream of confluence (mi^2)	Ra	Watershed Category	Representative Joint Probability Event
Salt Creek	79	149	1.9	**SS**	**4-pct**
Addison Creek	24	149	6.2	**SS**	**4-pct**

The DSS outputs from the inflow location models were copied into the local model folder to be used as inflow boundary conditions. The 1-pct and 4-pct inflow events were applied independently as model plans to identify the timing of the peak flows for each event at the confluence (see Figure B2 below showing the timing of the peak flows)

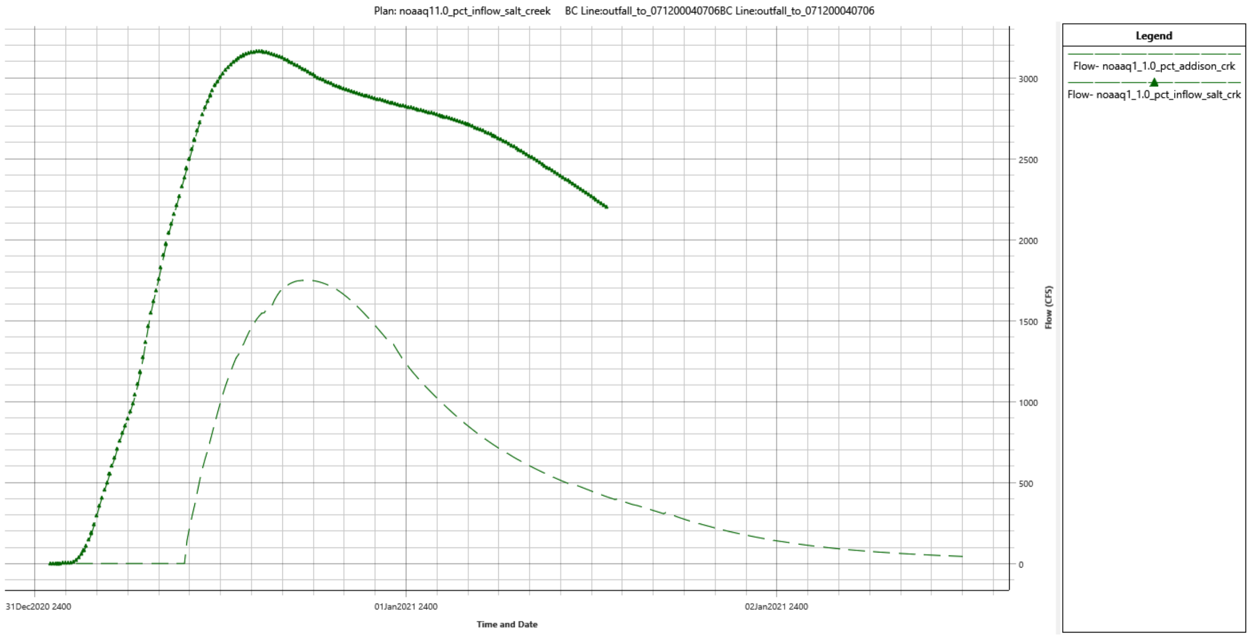


Figure B2. Timing of Peak flows with Inflow conditions only

These results were then compared with the peak timing of the 1-pct and 4-pct precipitation only plans so that the inflow timing can be shifted so that the following peaks occur coincidently. The table below summarizes the inputs used for each joint probability plan.

Plan Name	Joint Probability Events for Watershed 071200040404			Max CFS at confluence
	Salt Creek Inflow event	**Addison Creek Inflow event**	**071200040404 Precipitation event**	
noaaq1_1.0_pct	-	-	*1-percent*	2721.25
addison_creek_1.0_pct_jp	*4-percent*	*1-percent*	*4-percent*	3390.22
salt_creek_1.0_pct_jp	*1-percent*	*4-percent*	*4-percent*	**3588.28**

Based on the three plans above, the maximum flow condition at the confluence occurs in the salt creek 1-percent joint probability plan. This plan was then compared with local gage data and FIS data to determine if adjustments to the joint probability information needed to be revised. See Figures B3 and B4. In this case the initial results match well with the gage and FIS data, so no adjustments are required. This joint probability plan would then be used as the inflow condition for the next downstream watershed.

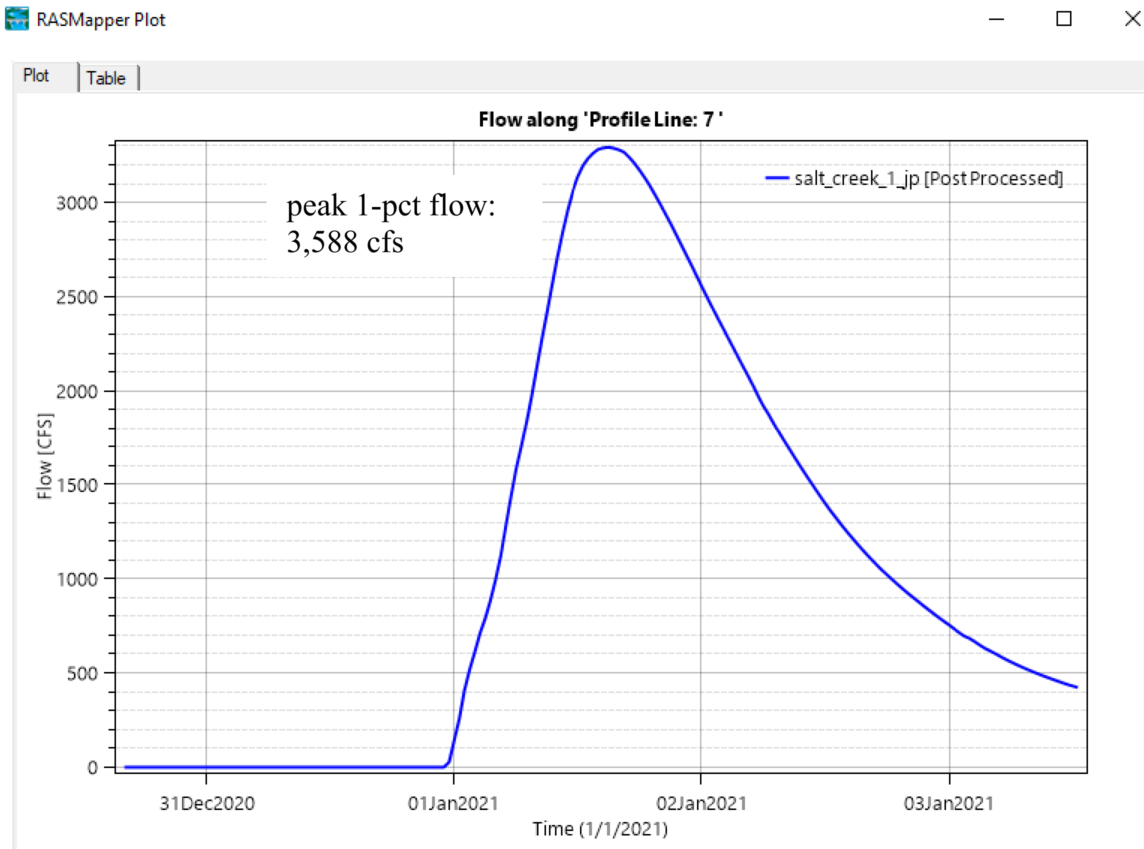


Figure B3: Joint probability plan results at local gage

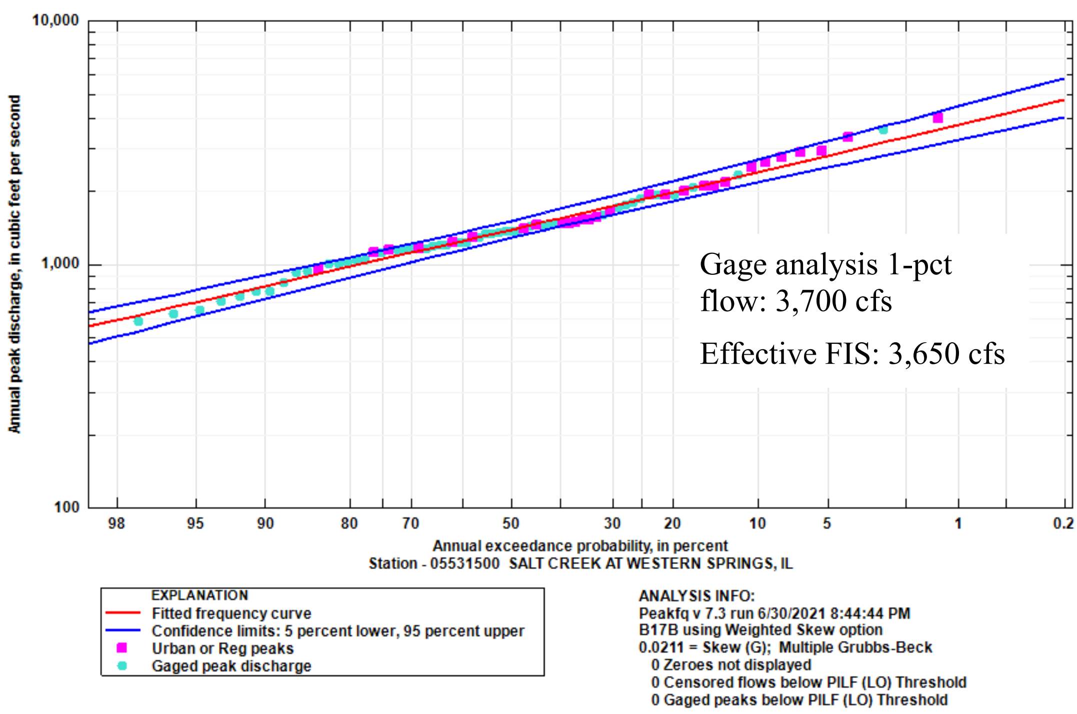


Figure B3: Local gage frequency analysis and FIS data