RIVER BASIN FLOOD STUDY

Texas GLO River Basin Flood Studies

Standard Operating Procedures for Baseline Flood Modeling

RIVER BASIN FLOOD STUDY

Revision Table

version	date	description of changes	point of contact
1	08/15/2022	N/A	
2	10/03/2022	modified language in section 5	The Water Institute
3	11/04/2022	Modified language in sections 1 and 5; Revised Fig 5-4.	The Water Institute
4	01/18/2023	Appendix B, sec 1.1 and reference list	The Water Institute
5	07/25/2023	Added Section 2.6 – Folder structure; Updated Section 3.12 and 4.11 for consistency	Freese and Nichols
6	1/16/25	Deleted reference on Pg 181 which became Appendix B	DEC

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1. Overview

This standard operating procedure (SOP) document will guide the development of baseline flood modeling conducted as part of the Texas General Land Office (GLO) River Basin Flood Study (RBFS). This baseline modeling will be conducted during Phase 3 of the GLO RBFS project by riverine and coastal modeling teams for the West Region, Central Region, East Region, and Lower Rio Grande Valley Region. The US Army Corps of Engineers (USACE) is serving as the GLO's technical reviewer for this project.

The SOP is divided into four sections described below.

- **Section 2 – Submittal and Review Process**: Defines the submittal and review process that the modeling teams and USACE will follow during Phase 3, including the contents of each submittal, the procedure for submitting models for USACE's review, and the process to resolve and close technical comments received from USACE.
- **Section 3 – Hydrology**: Defines hydrologic modeling standards for the study.
- **Section 4** – **Hydraulics**: Defines hydraulic modeling standards for the study.
- **Section 5 – Coastal and Compound Flooding**: Defines additional hydrologic and hydraulic modeling standards unique to watersheds with coastal influences on flooding conditions.

The SOP was developed collaboratively by the four regional teams based on information in each team's Phase 2 scope of work, in USACE's *Minimum Standards for Hydrologic, Hydraulic, and Coastal Analysis* document dated December 17, 2020 (hereinafter referred to as the *USACE Minimum Standards*), and in the associated USACE model review checklists. The regional teams leveraged their experiences from the pilot studies in Phase 2 and feedback received from USACE and GLO to customize the contents of this SOP to the needs of the RBFS project. For the purposes of this study, this SOP supersedes the *USACE Minimum Standards*. During Phase 3 of the GLO RBFS project, this SOP may be revised to guide the development of alternatives analysis during Phase 4. These revisions should not significantly impact the scope, level of effort, or deliverables that each modeling team has scoped for Phase 3.

1.1. Study Level of Detail

This SOP documents all analyses and processes that may be applicable to a watershed included in the GLO RBFS. However, models will be built to varying levels of detail based on the degree of existing flood risk in a watershed and the potential for flood risk mitigation projects. In general, areas with high risk or where there is a high potential for mitigation projects may warrant a higher level of detail than areas with low risk. Therefore, this SOP distinguishes applicable methodologies and elements according to a model's proposed level of detail as described below and in **Table 3-1**, **Table 4-1**, and **Table 5-1**.

In the context of hydrology, the level of detail generally applies to an entire contiguous hydrologic model. In the context of hydraulics and coastal modeling, the level of detail can vary between individual modeled streams; that is, a single hydraulic or coastal model may include low-detail areas and medium-detail areas within the same model domain.

Additional detail can be added in future phases of this project. For example, if a low- or medium-detail model depicts significant flood risk that could be mitigated by a USACE-funded project, that model could be upgraded to a high-detail model as part of future Phase 4 alternatives analysis effort.

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1.1.1.Low Detail

In general, Low Detail studies involve the development of HEC-RAS 2D rain-on-mesh (ROM) models, similar in scope and purpose to 2D Base Level Engineering (BLE) models prepared by FEMA and the Texas Water Development Board (TWDB). The intent of these models is to define the approximate runoff response and flooding extents for a range of frequency storms with limited effort. Bridges and culverts are typically not included or are included with minimal detail. Hydrologic loss and hydraulic roughness parameters may be calibrated at a high level if observed data are available.

If a 2D BLE model exists, it will be used as the basis for a Low Detail model. If there is no 2D BLE model, a new rain-on-mesh HEC-RAS model will be created to a similar standard as described in **Section 3.2** and **Section 4.7**, with the intent of defining the runoff response of each study area and approximating the hydraulic response within the area. This rain-on-mesh HEC-RAS model will also serve as the Low Detail hydrologic model; a standalone HEC-HMS model will not be created (except as necessary to prepare any rainfall input hyetographs).

In riverine areas requiring medium- or high-detail analysis, a low detail rain-on-mesh HEC-RAS model may still be created but will only be considered an intermediate calculation to inform the development of other model parameters. In this case, a complete set of rain-on-mesh model runs will not be provided in final deliverable package.

In coastal watersheds, rain-on-mesh modeling is required. Low detail coastal models will be constructed in the same manner as riverine watersheds but will include additional coastal specific analyses described in **Section 5**.

1.1.2.Medium Detail

In general, Medium Detail studies involve the development of georeferenced HEC-HMS and HEC-RAS rainfall-runoff models based on Atlas 14 rainfall data. Additional hydrology items such as statistical stream gage analysis and calibration are also necessary where data is available. Medium Detail hydraulic models include georeferenced HEC-RAS models with structures along the streams identified in the corresponding hydrologic model. All structures downstream of hydrologic inflows will be included in the model; however, some of the structures may include only a minimal level of detail.

Existing hydrologic models from previous studies will be updated to use Atlas 14 rainfall data, and existing stream gage analyses will be extended to account for new data available since the previous analysis was completed or to take advantage of the new Bulletin 17C analysis methodology. Existing hydraulic models from previous studies will be used to provide structure data, channel roughness, and bathymetric data where feasible. Items such as calibration, sensitivity and uncertainty analysis can be considered optional or limited for Medium Detail streams depending on available data. Existing models will also be updated to align with this SOP as needed and according to engineering judgement.

SOP elements considered beyond the scope of Medium Detail models typically include Elliptical Storm Analysis, Future Land Use Conditions Assessment, Storm Shifting, or new Reservoir Analysis, unless their use is justified due to very large drainage areas, site specific conditions, or to reconcile discrepancies in the final frequency results. Detailed sensitivity and uncertainty analysis as described in **Section 4.9** are also beyond the scope of Medium Detail streams.

In coastal watersheds, rain-on-mesh modeling is required. Medium detail coastal models will consist solely of georeferenced HEC-RAS rain-on-mesh models, where hydrologic losses are modeled using gridded infiltration in HEC-RAS. HEC-HMS models will not be created for coastal watersheds.

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1.1.3.High Detail

In general, High Detail models will include all the applicable components listed in the SOP. During Phase 3, High Detail models will only be used to analyze large-scale flood risk reduction projects with the potential for USACE funding, and therefore may include additional efforts to increase the confidence in flow estimates for large basins with such techniques as Elliptical Storm Analysis, selection of appropriate Areal Reduction Factors, Storm Shifting, and Reservoir Analysis, as applicable. High detail hydraulics streams will include all levees, dams, and other significant structures, especially in areas likely to be impacted by flooding events and/or that would benefit from potential projects. Detailed calibration, sensitivity, and uncertainty analyses are also expected to be included for High Detail streams.

In coastal watersheds, rain-on-mesh modeling is required. High detail coastal models will consist solely of georeferenced HEC-RAS rain-on-mesh models, where hydrologic losses are modeled using gridded infiltration in HEC-RAS. HEC-HMS models will not be created for coastal watersheds.

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2. Submittal and Review Process

Each region's modeling team will be responsible for determining a submittal schedule at the beginning of each study and must communicate it to GLO/USACE prior to the first submittal. GLO/USACE will generally have a two-week turnaround time on comments for each submittal.

The following describes the review process to be used for each study:

1. Study team provides an initial submittal, including a report, applicable models and supporting data, and blank hydrology, hydraulics, and coastal Quality Control (QC) checklist spreadsheets, along with a general description of the report and files submitted. Each QC checklist will be a cumulative document containing all comment/response documentation for the entire study.

2. USACE reviews the submittal, provides comments on the hydrology, hydraulics, and coastal QC checklist spreadsheets, and provides the checklist spreadsheets to the study team, generally within 2 weeks.

    a. USACE should provide all comments, including report comments, on the checklist spreadsheet for tracking purposes. The comments may be supplemented with pasted screen captures of models, figures, or exhibits where appropriate.
    b. If USACE provides additional files in support of their comments (such as marked-up PDFs, reference information, or other supplementary data), these should be referenced in checklist spreadsheet comments for tracking purposes.

3. Study team provides draft comment responses and/or sets up an informal screen-sharing session with USACE reviewers to discuss a plan for resolution, generally within 1 week.

    a. For minor or straightforward comments, these steps may be unnecessary.
    b. For more substantial comments, a screen-sharing session should provide sufficient clarification that the study team will fully address all comments with the subsequent submittal.
    c. For major issues, the study team and GLO Project Manager may opt to re-submit a portion of the submittal to resolve the issues before the next submittal; however, the goal is that such re-submittals be minimized.

4. Study team addresses comments and provides final responses on the QC checklist spreadsheets with the next submittal.

    a. Substantial changes to items that had previously been reviewed and closed should be brought to the attention of the reviewer by creating a new comment line for that item and adding a note to the "Review Item Description" field describing the need for re-opening that review item. A highlight in the transmittal email to reviewers may also be appropriate.

5. USACE backchecks comment responses and closes comments while reviewing the next submittal. Comments that remain open after the next submittal's backcheck may require additional coordination between the study team and USACE to resolve and should be prioritized by the study team.

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The following sections summarize the contents of each planned submittal. The study team should review the submittal guidelines during the study to ensure each submittal is complete.

The study team should deliver submittals for review via the latest electronic file transfer methods approved by USACE. The study team should also refer to the SOP for methods to limit file size, particularly as it relates to hydrologic and hydraulic models. Excessively large file sizes may be prohibitive to future transmission of the data.

The report should be submitted in PDF format with bookmarks. The report should include all sections in the RBFS report outlines below, even if those sections are not relevant to this study area or if those sections are not part of this report submittal. Sections not relevant should include a single line stating that they are not part of the study scope and/or an explanation of why they are excluded, if appropriate. Future sections may include a single line indicating which submittal is anticipated to have that section completed. This will minimize changes in section numbering that may impede comparisons of different report versions.

Model submittals should be complete and include all terrain, land use, results, and other supporting data necessary for the reviewer to open the model and view model results without having to re-run the model.

All supporting data should be included with each submittal, even if it has not changed since the last submittal. For example, a HEC-SSP analysis may not have changed between the 50% and 75% submittals but should be included as part of the 75% submittal to provide a complete product and avoid reviewers having to search for previously submitted information.

While the summary tables include all items discussed in the SOP, every item may not be applicable to each study area. For example, a low-detail model may not include calibration, and a watershed lacking gage data would not require statistical analysis. Items that may not be applicable to a study area due to the study's level of detail or due to lack of applicability in general are tagged with "*".

Each study's report may include minor changes to specific deliverable contents from this standard submittal guideline (e.g., initial calibration results could be provided during the 50% submittal, or a report section may be written early).

2.1. 25% Draft Modeling Milestone

The 25% draft modeling milestone for each study area will build on the information provided in the Phase 3 Baseline Modeling work plans or Flood Model Implementation Plans (FMIPs) and will form the basis for the hydrologic, hydraulic, and coastal reports to be delivered at the 50%, 75%, and final modeling milestones. In general, the 25% report will provide an overview of the study area and document the analysis to be performed for the study area. This report will also include a preliminary discussion of coastal boundary conditions as applicable including wind forcing and rainfall-surge pairings. The report may be worded as appropriate for the final deliverable, referencing things that have not yet done as if they have been completed, to prevent re-writing sections later. Comments or parentheticals may be added as appropriate to help the reviewer understand the actual progress.

The 25% report should specify what submittals are anticipated and the expected contents of the submittals. Some watersheds may not include a separate 50% and 75% submittal (for example, low/medium-detail studies). This would effectively combine the 50% and 75% submittals into one submittal, with USACE reviewing checklist items for both milestones as appropriate.

The study team will not necessarily submit supporting data from standard data sources (e.g., Texas Natural Resources Information System [TNRIS] Light Detection and Ranging [LiDAR], National Land Cover Dataset [NLCD], or Soil Survey Geographic Database [SSURGO]). Locally sourced, non-standard data sources will be submitted for review by USACE.

The 25% deliverable will include blank QC Checklist spreadsheets with the basic project information filled in, ready for USACE to add 25% comments during review.

A list of the report sections and supporting data to be included in the 25% deliverable is shown in **Table 2-1**.

Table 2-1. 25% Draft Modeling Milestone

Report Section/Subsection	*Applicable SOP Section(s)*	*Supporting Data to be Submitted at 25%*
General – Study Purpose and Overview		
- **Watershed Details, Communities, Level of Detail**		
- **Previous Studies, Previously Identified Projects**	3.1, 4.2, 4.4, 5.2	Identified project/previous study shapefile; existing models, reports, other relevant data
- **Gage Data**	3.1, 3.6.2, 4.8.2	Gage location shapefile
- **Flood History and Calibration Events**	3.1, 3.6.2, 4.8.2	
- **Deviations from Work Plan or FMIP***		
General – Data Collection		
- **Terrain and Bathymetry**	3.1, 4.2.3, 5.6	Terrain and bathymetric data
- **Land Cover & Impervious Cover**	3.1, 3.2, 4.3	Land cover and impervious cover shapefiles or rasters
- **Soil Data**	3.5	Soil shapefile
- **Structure Data (e.g., bridges, reservoirs, levees)**	3.10, 4.6	Hydraulic structures shapefile
- **Precipitation**	3.4	Gridded rainfall data (historical storms)
- **Coastal Storm Surge***	5.4, 5.6	Observed and simulated storm surge data, including salinity data when appropriate/available
- **Wind***	5.4, 5.6	Wind fields (historical storms)
Hydrology – Preliminary Frequency Flows		
- **Methodology (e.g., rain-on-mesh, regression)**	3.1, 3.2	
Coastal Rainfall – Surge Pairing*	5.3	
Hydrology – Rainfall-Runoff Model Methodology	3.4	Initial HEC-HMS model layout with subbasins, reaches, junctions, and potentially reservoirs, sinks, diversions
- **Existing Models and Proposed Improvements**	3.1	
- **Soil Loss**	3.5	
- **Transform**	3.5	

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Table 2-1. 25% Draft Modeling Milestone *(continued)*

Report Section/Subsection	*Applicable SOP Section(s)*	*Supporting Data to be Submitted at 25%*
- **Channel Routing**	3.5	
- **Reservoirs, Dams, Levees***	3.10	
- **Hydrologic Calibration and Validation***	3.6	
- **Frequency Event Precipitation**		Atlas 14 Depths, Elliptical Storms*, Areal Reduction*, etc.
Hydraulics – Hydraulic Model Methodology		
- **Model Type and Extents (Extents and Level of Detail, General Boundary Conditions)**	4.1, 5.1	Shapefile of streams with level of detail
- **Incorporation of Available Data***	4.2	Shapefile of existing model extents, if any, and extents to be updated
- **Hydraulic Features Bridges/Culverts, Dams, Levees, Reservoirs, Pump Stations**	4.6	Shapefile of bridge/culvert/dam/levee/reservoir/pump station locations
- **Hydraulic Calibration and Validation***	4.8, 5.7	Stream gage elevation and flow data for selected calibration events
- **Coastal Inundation Uncertainty Analysis***	5.8	

* Item may not be applicable to all studies but should still be included in the report structure, as described above. Items in blue text are new to the current milestone. Items in black for later milestones are items carried over from previous milestones and may include some minor updates as part of the current milestone.

2.2. 50% Draft Modeling Milestone

The 50% draft modeling milestone for each study area will include the first draft of the hydrologic and hydraulic analysis. This deliverable will include HEC-HMS and HEC-RAS models with initial draft geometry and draft flows. The models should run but may contain some instabilities or other minor issues that will be resolved with the 75% submittal. Depending on available data or model level of detail, this submittal may be combined with the 75% draft, followed by the final draft. In such cases, all items for both the 50% and 75% submittals would be submitted together.

A list of the report sections and models and supporting data to be included in the 50% deliverable is shown in **Table 2-2**. Sections listed in blue represent new or substantial additions to the report at the 50% milestone. If significant changes were made to sections of the report that USACE had previously reviewed and closed, the modeling team should summarize the changes for the reviewers' benefit by adding a new line in the QC checklist and/or the transmittal email, as appropriate.

The 50% deliverable will include the QC checklist spreadsheets with responses addressing all comments, ready for backcheck by USACE to close the 25% comments and add new 50% comments.

Table 2-2. 50% Draft Modeling Milestone

Report Section/Subsection	*Applicable SOP Section(s)*	*Models and Supporting Data to be Submitted at 50%*
General – Study Purpose and Overview		
- **Watershed Details, Communities, Level of Detail**		

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Table 2-2. 50% Draft Modeling Milestone (continued)

Report Section/Subsection	*Applicable SOP Section(s)*	*Models and Supporting Data to be Submitted at 50%*
- **Previous Studies, Previously Identified Projects**	3.1, 4.2, 4.4, 5.2	
- **Gage Data**	3.1, 3.6.2, 4.8.2	
- **Flood History and Calibration Events**	3.1, 3.6.2, 4.8.2	
- **Deviations from Work Plan or FMIP***		
General – Data Collection		
- **Terrain and Bathymetry**	3.1, 4.2.3, 5.6	
- **Land Cover & Impervious Cover**	3.1, 3.2, 4.3	
- **Soil Data**	3.5	
- **Structure Data (e.g., bridges, reservoirs, levees)**	3.10, 4.6	
- **Precipitation**	3.4	
- **Coastal Storm Surge***	5.4, 5.6	
- **Wind***	5.4, 5.6	
Hydrology – Preliminary Frequency Flows		
- **Methodology (e.g., rain-on-mesh, regression)**	3.1, 3.2	
- **Comparison of Results**	3.11	
Hydrology – Statistical Hydrology*	3.3	HEC-SSP model*
- **Gage Locations and Period of Record**	3.3	Observed peak flow data*
- **Rating Curve Investigation/Adjustment**	3.3	Rating curve adjustment calculations*
- **Bulletin 17C**	3.3	
- **Bulletin 17C Expanding Time Window**	3.3	
Hydrology – Rainfall-Runoff Model	3.4	HEC-HMS model with preliminary frequency events and uncalibrated historical events, if applicable
- **Existing Models and Modifications***	3.1	
- **Model Extents and Calculation Points**	3.4	Hydrologic feature shapefiles (subbasins, reaches, etc.)
- **Soil Loss Parameters**	3.5	Loss data shapefiles or rasters (soil groups, textures, losses, etc.), calculation spreadsheet
- **Transform Parameters**	3.5	Transform shapefiles (flowpaths, etc.), calculation spreadsheet
- **Channel Routing**	3.5	Channel routing data shapefiles (reaches) and calculations (storage-discharge, Muskingum sections, etc.)
- **Reservoirs, Dams, Levees***	3.10	Reservoir/dam/levee location shapefiles, gate operations, storage curves, as-built data, survey, etc.*
- **Areal Reduction and Elliptical Storms***	3.9	HEC-MetVue model*; spreadsheet summarizing evaluated storms, depth-area reduction curves, and other elliptical parameters
- **Historical Event Precipitation and Results (uncalibrated)**	3.4, 3.11	

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Table 2-2. 50% Draft Modeling Milestone (continued)

Report Section/Subsection	*Applicable SOP Section(s)*	*Models and Supporting Data to be Submitted at 50%*
- **Frequency Event Precipitation and Results (uncalibrated)**	3.4, 3.5, 3.11	
- **Results, Comparisons, and Summary (uncalibrated)**	3.11	
- **Uncertainty Analysis***	3.11, 4.9	
Coastal Rainfall-Surge Pairing*	5.3	Summary of statistical analysis, joint probability methods, and production simulations
Hydraulics – Hydraulic Model		HEC-RAS model with preliminary frequency events; uncalibrated historical events, if applicable; ROM/sensitivity analysis runs
- **Model Type and Extents (Extents and Level of Detail, General Boundary Conditions)**	4.1, 5.1	
- **Incorporation of Available Data***	4.2	
- **Hydraulic Parameter Development (General considerations, Manning Roughness, Cross-Sections, 2D Areas)**	4.3, 5.6	Initial HEC-RAS model with model boundary, breaklines, cross section, banklines, flowpaths, land cover, mesh size, etc.
- **Hydraulic Model Inflows**	4.4, 5.5, 5.6	Initial HEC-RAS model with inflow boundary condition lines
- **External Boundary Conditions**	4.5, 5.5, 5.6	Initial HEC-RAS model with external boundary condition lines
- **Hydraulic Features Bridges/Culverts, Dams, Levees, Reservoirs, Pump Stations**	4.6	Source data for gate operations, storage curves, as-built data, survey, etc.
- **Hydraulic Calibration and Validation***	4.8, 5.7	Uncalibrated results comparison
- **Hydraulic Sensitivity (numerical sensitivity and physical parameter sensitivity*)**	4.9, 5.8	Include numerical and physical parameter sensitivity analyses.
- **Hydraulics Results Comparisons and Evaluation (uncalibrated)**	4.10	
- **Uncertainty Analysis* and Model Limitations**	4.9, 5.8	Initial discussion of Model Limitations will be addressed at 50%. Uncertainty analysis, if any, should be performed using calibrated models at 75%.

* Item may not be applicable to all studies but should still be included in the report structure, as described above. Items in blue text are new to the current milestone. Items in black are carried over from previous milestones and may include some minor updates as part of the current milestone.

2.3. 75% Draft Modeling Milestone

The 75% draft modeling milestone for each study area will include the second draft of the hydrologic and hydraulic models, adding calibration, validation, storm shifting, and/or areal reduction and elliptical storms, as applicable. The 75% draft modeling milestone will also incorporate all coastal production runs with varying rainfall and surge pairings. Depending on available data or model level of detail, this submittal may be combined with the 50% draft and be followed by the final draft. In such cases, all items for both the 50% and 75% submittals would be submitted together.

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A list of the report sections and models and supporting data included in the 75% deliverable is shown in **Table 2-3**. Sections listed in blue represent new or substantial additions at the 75% milestone. If significant changes were made to sections of the report that USACE had previously reviewed and closed, the modeling team should summarize the changes for the reviewers' benefit by adding a new line in the QC checklist and/or the transmittal email, as appropriate.

The 75% deliverable will include the QC checklist spreadsheets with responses addressing all comments, ready for backcheck by USACE to close outstanding 25% and 50% comments and add new 75% comments.

Table 2-3. 75% Draft Modeling Milestone

Report Section/Subsection	*Applicable SOP Section(s)*	*Models and Supporting Data to be Submitted at 75%*
General – Study Purpose and Overview		
- **Watershed Details, Communities, Level of Detail**		
- **Previous Studies, Previously Identified Projects**	3.1, 4.2, 4.4, 5.2	
- **Gage Data**	3.1, 3.6.2, 4.8.2	
- **Flood History and Calibration Events**	3.1, 3.6.2, 4.8.2	
- **Deviations from Work Plan or FMIP***		
General – Data Collection		
- **Terrain and Bathymetry**	3.1, 4.2.3, 5.6	
- **Land Cover & Impervious Cover**	3.1, 3.2, 4.3	
- **Soil Data**	3.5	
- **Structure Data (e.g., bridges, reservoirs, levees)**	3.10, 4.6	
- **Precipitation**	3.4	
- **Coastal Storm Surge***	5.4, 5.6	
- **Wind***	5.4, 5.6	
Hydrology – Preliminary Frequency Flows		
- **Methodology (e.g., rain-on-mesh, regression)**	3.1, 3.2	
- **Comparison of Results**	3.11	
Hydrology – Statistical Hydrology*	3.3	HEC-SSP model with adjustments for reservoirs and shifted storms*
- **Gage Locations and Period of Record**	3.3	
- **Rating Curve Investigation/Adjustment**	3.3	
- **Bulletin 17C**	3.3	
- **Bulletin 17C Expanding Time Window**	3.3	
Hydrology – Rainfall-Runoff Model	3.4	HEC-HMS model with <u>calibrated</u> historical events, if applicable, and updated frequency events
- **Existing Models and Modifications***	3.1	
- **Model Extents and Calculation Points**	3.4	

Table 2-3. 75% Draft Modeling Milestone *(continued)*

Report Section/Subsection	*Applicable*	*Models and Supporting Data to*

	SOP Section(s)	*be Submitted at 75%*
- **Transform Parameters**	3.5	Transform data shapefiles (flowpaths, etc.), calculation spreadsheet
- **Channel Routing**	3.5	Channel routing data shapefiles (reaches) and calculations (storage-discharge, Muskingum sections, etc.)
- **Reservoirs, Dams, Levees***	3.10	Reservoir models (e.g., HEC-RESSim, RMC-RFA, etc.)*
- **Historical Event Calibration and Validation***	3.6	
- **Frequency Event Precipitation and Results**	3.5, 3.6, 3.11	
- **Future Land Use***	3.7	Future land use shapefile or raster source data, transform/loss calculation spreadsheet
- **Storm Shifting Methodology and Results***	3.8	HEC-MetVue model*, spreadsheet summarizing shifted storms
- **Results, Comparisons, and Summary**	3.11	
- **Uncertainty Analysis***	3.11, 4.9	
- Coastal Rainfall-Surge Pairing*	5.3	
- Hydraulics – Hydraulic Model		HEC-RAS model with <u>calibrated</u> historical events, if applicable, updated frequency events, and ROM/sensitivity analysis runs
- **Model Type and Extents (Extents and Level of Detail, General Boundary Conditions)**	4.1, 5.1	
- **Incorporation of Available Data***	4.2	
- **Hydraulic Parameter Development (General considerations, Manning Roughness, Cross-Sections, 2D Areas)**	4.3, 5.6	
- **Hydraulic Model Inflows**	4.4, 5.5, 5.6	
- **External Boundary Conditions**	4.5, 5.5, 5.6	
- **Hydraulic Features Bridges/Culverts, Dams, Levees, Reservoirs, Pump Stations**	4.6	HEC-RAS model with all hydraulic features
- **Hydraulic Calibration and Validation***	4.8, 5.7	Spreadsheet with calculated vs observed values for calibrated models and validation events, if any
- **Hydraulic Sensitivity (numerical sensitivity and physical parameter sensitivity*)**	4.9, 5.8	Some additional sensitivity testing associated with structures may be added for the 75% submittal

Table 2-3. 75% Draft Modeling Milestone *(continued)*

Report Section/Subsection	*Applicable SOP Section(s)*	*Models and Supporting Data to be Submitted at 75%*

- **Hydraulics Results Comparisons and Evaluation**	4.10	
- **Uncertainty Analysis* and Model Limitations**	4.9, 5.8	Uncertainty analysis, if any, should be performed using calibrated models at 75%
- **Future Conditions Runs***	3.7, 5.4	
- **Final Hydraulic Products, including Flood Risk Mapping**	4.11, 5.9	Draft versions of final hydraulic products focusing on the 1% event only (historical and frequency event inundation depth rasters, WSEL rasters, and inundation boundary shapefiles for other events to be included with the Final Draft Submittal), draft presentation materials for GLO and stakeholders in the basin

* Item may not be applicable to all studies but should still be included in the report structure, as described above. Items in blue text are new to the current milestone. Items in black are carried over from previous milestones and may include some minor updates as part of the current milestone.

2.4. Final Draft Modeling Milestone

The Final Draft deliverable will include the report, models, supporting data, and flood risk mapping files, including historical and frequency event inundation depth rasters, water surface elevation (WSEL) rasters, and inundation boundary shapefiles for all models within the study area, as well as final presentation materials for GLO and stakeholders in the basin.

The QC checklist spreadsheets should include responses addressing all outstanding comments, ready for backcheck by USACE.

2.5. Final Modeling Milestone

After USACE has closed all outstanding comments, the final milestone can be submitted. This will include the signed and sealed report, models, supporting data, and flood risk mapping files.

2.6. Folder Structure

Each submittal should generally follow the folder structure example presented below. This example represents a 50% deliverable submitted on yyyy-mm-dd for the Big Creek/Upper-Middle Oyster watershed. This folder structure should be typical for most study area submittals; however, vendor teams are free to deviate from this structure where appropriate for more intuitive naming or organization.

- Big Creek, Upper-Middle Oyster 50pct (yyyy-mm-dd).zip
    - HEC-HMSv410
        - BigCreek_UpperMiddleOyster
    - HEC-RASv63
        - BigCreek_UpperMiddleOyster1
        - BigCreek_UpperMiddleOyster2
    - QC Documentation
    - Spatial Data or Spatial Data.gdb [a folder and/or geodatabase with example subfolders or feature datasets listed below, as applicable]
        - Gage Locations
        - Hydraulic Features
        - Hydrologic Features
        - Land Cover and Soils
        - Projection
        - Results
        - Terrain
        - Wind [coastal studies only]
    - Supplemental Data
        - Bivariate Analysis [coastal studies only]
        - Elliptical Storms
        - Hydraulic Calculations
        - Hydrologic Calculations
        - Previous Studies
        - Reservoirs
        - Statistical Hydrology

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3. Hydrology

This SOP document is intended to provide structure and standard processes for baseline flood model development during Phase 3 of the Texas GLO RBFS project. This document outlines modeling approaches to support consistent application between the four study regions. This section of the SOP covers hydrologic model development, including development of model parameters, model setup, calibration and validation, and documentation, and it shares common elements with the USACE's *Minimum Standards for Baseline and Future Without Project Hydrologic, Hydraulic, and Coastal Analysis* document dated December 17, 2020 (hereinafter referred to as the *USACE Minimum Standards*).

This SOP is not organized according to the expected sequence of work. The locations of some sections within the narrative are selected for thematic grouping and convenience, but do not necessarily reflect the order in which work will be performed.

During Phase 3, the SOP will be updated to include processes for consequence analysis and alternatives analysis, potentially including future without project conditions and with project conditions.

Table 3-1 summarizes how the specified level of detail might affect the application of specific components of the SOP. Refer to **Section 1.1** for an overview of the level of detail concept.

Table 3-1. Breakdown of Hydrologic Analysis Components by Study Level of Detail

Section	Hydrologic Analysis Components	Study Level of Detail		
		Low	Medium	High
1.1	Selection Factors for Level of Detail	Minimal Identified Risks, No Identified Projects	Identified Risks, Potential Projects	Identified USACE Project
3.1	Relevant Previous Study Types	2D BLE	2D BLE, Georeferenced HMS/RAS (InFRM, FEMA FIS, etc.)	
3.2	Rain-on-Mesh	Final Deliverable	Upland Riverine Areas: Interim Tool to Support Model Parameterization Coastal Zone: Final Deliverable (see Section 5)	
3.3	Statistical Hydrology	Limited USGS Flow Adjustments	USGS Flow Adjustments per Rating Curves, Period of Record Extension, etc.	
3.4	Avg. Subbasin Size	N/A	< 10 sq. mi.	< 5 sq. mi.
3.5	Model Parameterization	N/A	Validate Existing Studies w/Some Updates or New Study	Significant Updates or New Study
3.6	Calibration & Validation	Optional	Optional	3 Calibration & 2 Validation Events
3.7	Future Land Use	N/A	Phase 4	Phase 3 (Potentially)
3.8	Storm Shifting	N/A	Optional	Reconcile Discrepancies w/ Statistical Hydrology
3.9	Elliptical Storms	N/A	Optional Considered for Areas > 1,000 sq. mi.	Considered for Areas > 400 sq. mi. Required for Areas > 1,000 sq. mi.
3.10	Reservoir Analysis	N/A	Optional	If Affecting Proposed Projects
3.11	Results Evaluation	Compare to Relevant Previous Studies and Statistical Hydrology		
3.12	Deliverables	Refer to GLO RBFS Submittal and Review Process		

3.1. General Hydrologic Features and Background Data

This section documents the general hydrologic features and background data prepared during the early stages of hydrologic analysis, including data sources that should be examined for existing data, potential upgrades to existing data, and the preliminary frequency flow analysis for the watershed.

These items were originally outlined in Section 1.2 – 'Initial Data Collection for Baseline Hydrology' and Section 1.3 – 'Preliminary Frequency Flow Analysis' of the *USACE Minimum Standards*.

3.1.1. Existing Data Collection

An initial collection of available data, models, and previous studies that may pertain to the hydrologic analysis in question should be performed. At a minimum, the data collection should consider the following:

- Base Level Engineering (BLE) models and spatial data
- InFRM Watershed Hydrology Assessment (WHA) data, models, and results
- USACE Corps Water Management System (CWMS) models
- FEMA Flood Insurance Study (FIS) frequency flow values, methods, and models
- Best available LiDAR terrain data, land use, and other spatial data
- Best available hydraulic models to inform hydrologic routing
- Reservoir Data (as-builts, gate operations, storage curves, etc.)
- Other existing studies or models

Data collection is expected to be ongoing during the development of hydrologic and hydraulic data for this study. In some cases, relevant data may be collected after significant work has been completed for a given watershed. For Phase 3 baseline modeling purposes, collected data to be used in the study will be documented in the 25% deliverable; additional data collected or provided after approval of the 25% deliverable may not be incorporated until a future phase if needed to support alternatives analysis.

3.1.2. Existing HEC-HMS Models and Potential Upgrades

Existing models collected for the watershed should be assessed for the need for upgrades. The suitability of existing models will ultimately be up to the engineer, but the items listed below may be considered for upgrades.

Model Version – Newly developed hydrologic models should use the most recent fully released version (non-beta) of HEC-HMS. Any existing studies likely use an older version. At a minimum, existing models that use version 4.2.1 or older should be upgraded to a more recent version of HEC-HMS. Older versions of HEC-HMS models may need to be georeferenced to take advantage of newer features of the software.

Rainfall – Existing models should be evaluated to ensure National Oceanic and Atmospheric Administration (NOAA) Atlas 14 precipitation depths are being used. If the hydrologic model included historical rainfall events, the methods used to generate the historical rainfall should be assessed.

Terrain – The terrain should be compared to recent datasets from Texas Natural Resources Information System (TNRIS), US Geological Survey (USGS), and National Elevation Dataset (NED). If more recent data is available, the quality of the existing terrain should be verified. If the more recent data is of higher quality, the terrain should be upgraded. In addition to base topographic datasets, bathymetric data should be considered, where necessary.

Subbasin Delineation – The existing subbasin boundaries and stream centerlines should be evaluated to ensure that they accurately reflect the direction and accumulation of flow in the watershed and that they contain a sufficient level of detail to support the hydraulic modeling for the stream reaches of interest. Revisions or additional detail should be made to the subbasin delineations and routing reaches as needed.

Land Use – New studies will primarily use the most recent NLCD dataset available at the beginning of the study. Hydrologic parameters should be updated as needed based on the NLCD dataset or other best available data.

Hydrologic Equations – The preferred hydrologic loss methods for this study are Initial Deficit and Constant Loss or Green-Ampt. The preferred transform methods are Snyder's Unit Hydrograph (UH), Clark UH, and ModClark UH. Depending on the level of detail to be provided in the model, it may be necessary to update the hydrologic methods to match one of the preferred methods. Changes to hydrologic equations should be calibrated to gage data, if available, or previous model results.

Hydrologic Routing Methods – The preferred hydrologic routing methods for this study are Modified Puls and Muskingum-Cunge. Depending on the level of detail to be provided in the model, it may be necessary to update the hydrologic routing methods to match one of the preferred methods. Changes to hydrologic routing methods should be calibrated to gage data, if available, or previous model results.

3.1.3. Other Existing Models

If other hydrologic models are available for the study area that are not related to rainfall-runoff modeling (i.e., HEC-HMS), the models should be reviewed for required upgrades. Some examples of other existing models include, but are not limited to:

- HEC Reservoir System Simulation (HEC-ResSim)
- USACE Risk Management Center Reservoir Frequency Analysis (RMC-RFA)
- HEC Statistical Software Package (HEC-SSP)

Details regarding the requirements for these types of models are included in **Section 3.3** and **Section 3.10**.

3.1.4. Coordinate System and Vertical Datum

For newly developed models, the North American Datum of 1983 Texas Centric Mapping System Albers Equal Area projection in US Survey Feet 'NAD_1983_TCMS_Albers_FtUS' should be used. The preferred vertical datum is the North American Vertical Datum of 1988 (NAVD88) using GEOID12B. This vertical datum should be consistent with available terrain data and vertical units should be in feet. Conversions between datums should be clearly documented, including comparisons of surveyed reference markers, as available. If the National American-Pacific Geopotential Datum of 2022 (NAPGD2022) is published prior to the completion of the study, information and instructions for converting to the new datum should be included.

When an existing model is being used, the projection that was used to develop the model may continue to be used if it is generally accepted by industry standards. Decisions regarding whether to maintain the existing datum should be clearly documented. When the projection used in the existing model is not acceptable, it should be updated to 'NAD_1983_TCMS_Albers_FtUS'.

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Likewise, if an existing model was developed using a generally accepted vertical datum, that vertical datum should be documented and may continue to be used. Local vertical datum adjustments may also be considered to account for localized phenomena such as subsidence.

3.1.5. Preliminary Frequency Flow Analysis

The engineer should prepare preliminary frequency flow estimates for the hydrologic stream reaches within the watershed. These flows can be estimated based on results from previously completed studies or newly generated using a HEC-RAS 2D rain-on-mesh model. The following sections describe the process for generating preliminary frequency flows for each scenario.

Existing Studies

There are several categories of existing studies that may be available in each watershed. It is ultimately up to the engineer's judgement to select which study is most appropriate to use for preliminary estimates, but the following list can be used to rank each type of study from most preferable to least preferable.

1. InFRM Watershed Hydrology Assessments
2. Other Existing Detailed Studies
3. Published frequency discharge from FEMA FIS
4. Existing BLE hydrologic results

For each applicable study type, a comparison of frequency flows produced by each study should be provided. The summary of frequency flows should include flows calculated for each subbasin along with major comparison points the models may have in common (e.g., confluences, roadways). The selected data source used to estimate frequency flows should be clearly documented, along with the hydrologic methods, hydrologic equations, rainfall, and meaningful elements of uncertainty in the analysis.

In some instances, a more recent analysis may supersede FIS discharges or BLE hydrologic results.

Other Analyses

If available data do not exist or existing studies for the watershed in question are significantly out-of-date, two simplified analyses are also acceptable to determine preliminary frequency flows.

1. Statistical flow frequency analysis using latest available data (see **Section 3.3**)
2. Regression equations

In most cases, the lack of existing studies should lead to additional modeling, as described in the Rain-on-Mesh paragraph, below, but the simplified analyses may be adequate for low-detail modeling or in other edge cases.

Rain-on-Mesh

In the absence of existing detailed models, or where 2D BLE models are available, a preliminary rain-on-mesh HEC-RAS model can be developed to generate preliminary frequency flows. This model can also be leveraged as a tool to inform the early stage of hydrologic model development and increase the efficiency of calibrating hydrologic and hydraulic models during later stages. If the study produces a higher level of detail in a later stage of the project, the rain-on-mesh model will be considered an interim

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product and will not be part of the final deliverable. **Section 3.2** and **Section 4.7** include guidelines for developing low detail rain-on-mesh models that are suitable for this purpose.

3.1.6. Documentation

For each task described in the SOP, supporting documentation should be included with the final hydrologic report. The sections below summarize the necessary documentation for each task. The engineer should take care to include additional documentation not listed in this SOP as unique or edge cases are encountered.

Existing Data Collection

A general summary of the background data collected for the study area should be provided. Examples that should generally apply to each watershed are listed below.

1. List of existing studies and accompanying models, including general background information (e.g., date completed, study/model extents, etc.)
2. List of spatial data collected, including its date and source (e.g., NLCD Land Cover, USGS 2018 LiDAR, etc.)
3. Other watershed specific data (e.g., reservoir operations, levees, etc.)

For each base dataset collected (e.g., land cover, soils, etc.) a watershed wide exhibit should be developed. Additionally, exhibits that document the extents of existing models along with areas that will be upgraded with newer baseline data should be provided.

Upgrades to Existing Models

If multiple existing models are available, decision-making criteria for selection of a preferred model should be documented. For the selected model, it is recommended to evaluate whether upgrades are possible for each data source. An example table is shown below in **Table 3-2**, which includes existing and proposed data sources.

Table 3-2. Existing Model Upgrades Example

Upgrade Item	Existing	Proposed Upgrade
Hydrologic Model Version	HEC-HMS v3.5	HEC-HMS v4.8
Land Cover	NLCD 2011	NLCD 2016
Hydrologic Loss Method	Curve Number	Green & Ampt
…	…	…

Preliminary Frequency Flow Analysis

Preliminary frequency flows should be summarized in tabular format at key locations within the study area (e.g., major bridges, stream confluences). The methods and data sources used to generate the flows should also be documented. If the preliminary frequency flows are newly generated (i.e., from Other Analyses or Preliminary ROM), a brief report chapter that describes the methods and data sources used to arrive at the preliminary frequency flows should be developed. An example summary table is shown below in **Table 3-3**.

Table 3-3. Preliminary Frequency Flow Example

Stream	Location		Frequency Event Flows (cfs)

		Drainage Area, sq. mi.	**50%**	**20%**	**10%**	**…**
Mill Creek	SH 36	###	400	600	800	…
East Mill Creek	FM 109	###	100	200	300	…
…		…	…	…	…	…

3.2. Rain-on-Mesh Modeling

Rain-on-mesh HEC-RAS models will be used in varying capacities throughout the GLO RBFS, including:

- Coastal Watersheds
  - Rain-on-mesh HEC-RAS models will be the final product for all coastal models – Low, Medium, and High Detail. No HEC-HMS models will be created for coastal watersheds.
- Riverine Watersheds
  - Low Detail Models – Rain-on-mesh HEC-RAS models will be the final product.
  - Medium/High Detail Models – Rain-on-mesh HEC-RAS models will be an interim product used to inform the final HEC-HMS and HEC-RAS models. Rain-on-mesh HEC-RAS models will not be part of the final deliverable.

In watersheds where Low Detail models are used as the final product or where rain-on-mesh is used as an interim tool, less model detail than is typically required will be adequate. These models will generally be comparable to 2D BLE models. This section will discuss some elements where a relaxed level of detail is appropriate. Reference **Section 3.2**, **Table 3-1**, **Table 4-1**, and **Section 4.7** for additional information on low detail rain-on-mesh models.

Existing 2D BLE models, where available, will satisfy the purposes of the Low Detail hydrologic model with a few minor adjustments. If a BLE model does not use spatial infiltration because of a limitation in the version of HEC-RAS used at the time of the BLE study, then the model version should be updated to HEC-RAS v6.1 or newer, and spatial infiltration should be set up to reduce the number of assumptions.

In Medium and High Detail Coastal watersheds, the final HEC-HMS and HEC-RAS models should be developed according to the remaining standards presented in the SOP, excluding low detail sections.

3.2.1. HEC-RAS Model Setup

2D Boundary – The study area watershed should be merged into a single feature and imported into the HEC-RAS model as the 2D boundary. In general, basins should be no larger than a HUC-10 or HUC-8. The 2D boundary should generally cover the entire studied watershed but does not need to follow the exact boundary limits determined from the terrain. The boundary should be simplified to remove extraneous detail in the form of vertices.

Land Cover & Manning's Roughness – Land cover datasets will typically be generated from the most recent NLCD dataset. Coastal watersheds will need to incorporate additional land cover data, as described in **Section 4.3.3**. The land cover can be imported to the HEC-RAS model using RAS Mapper by associating the NLCD grid codes with Manning's roughness values, per **Table 3-4**. Values were derived from guidance provided in the USACE *HEC-RAS 2D User's Manual* (for channel and floodplain roughness) and National Resources Conservation Service (NRCS) *TR-55* (for shallow overland roughness).

The *HEC-RAS 2D User's Manual* states that the channel and floodplain roughness values are intended for "appreciable depths of flow," while shallow overland roughness values are "generally much higher due

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to the relative roughness compared to the flow depth.” For the purposes of this study, the threshold separating shallow overland and channel/floodplain roughness values is a flow depth of 1 to 3 inches. The spatial extents of the two sets of roughness values should be determined based on a preliminary 1%-annual exceedance probability (AEP) simulation using only channel/floodplain roughness values. Areas with a maximum flow depth below 1 to 3 inches should be assigned the shallow overland roughness values.

A range of appropriate roughness values for each NLCD code, followed by a suggested value, is shown in the table below. In addition, an “Impervious Percentage” raster should be generated based on the most recent NLCD Impervious data. The relative extents of shallow overland versus channel/floodplain roughness values can be determined from depths from a preliminary simulation.

Table 3-4. HEC-RAS Land Cover - NLCD

NLCD Gridcode	Land Cover Classification	Channel and Floodplain Roughness	Shallow Overland Roughness
0	NoData	0.035	0.035
11	Open Water	0.025–0.05 (0.035)	0.035
21	Developed, Open Space	0.03–0.05 (0.04)	0.15–0.41 (0.41)
22	Developed, Low Intensity	0.06–0.12 (0.08)	0.15–0.41 (0.41)
23	Developed, Medium Intensity	0.08–0.16 (0.12)	0.15–0.41 (0.24)
24	Developed, High Intensity	0.12–0.20 (0.15)	0.011–0.41 (0.011)
31	Barren Land (Rock/Sand/Clay)	0.023–0.03 (0.03)	0.011
41	Deciduous Forest	0.10–0.20 (0.10)	0.40–0.80 (0.40)
42	Evergreen Forest	0.08–0.16 (0.15)	0.40–0.80 (0.40)
43	Mixed Forest	0.08–0.20 (0.12)	0.40–0.80 (0.40)
52	Shrub/Scrub	0.07–0.16 (0.08)	0.13
71	Grassland/Herbaceous	0.025–0.05 (0.04)	0.15–0.24 (0.24)
81	Pasture/Hay	0.025–0.05 (0.045)	0.15
82	Cultivated Crops	0.02–0.05 (0.05)	0.06–0.17 (0.17)
90	Woody Wetlands	0.045–0.15 (0.07)	0.40–0.80 (0.80)
95	Emergent Herbaceous Wetlands	0.05–0.085 (0.05)	0.40–0.80 (0.80)

Gridded Infiltration – HEC-RAS can be used to implement hydrologic losses. RAS Mapper can be used to generate an infiltration layer based on the land cover and soils layers. The available loss methods in HEC-RAS are Deficit-Constant, Green-Ampt, and SCS Curve Number. The SCS Curve Number method is not recommended for the purposes of this study; however, if an existing 2D BLE model uses spatially varying SCS Curve Number infiltration, the modeling team may choose to keep that methodology. Hydrologic loss parameters can be applied based on SSURGO soil textures or hydrologic soil groups. **Section 3.5.1** includes guidelines for estimating loss parameters for each method.

Mesh Detail – 2D mesh refinements should be incorporated through the addition of breaklines and/or refinement regions near main areas of conveyance and at hydraulic structures. Medium and High Detail Rain-on-Mesh models are subject to the same mesh detail requirements as Rainfall-Runoff models, as described in **Section 4.3.7**. Descriptions of appropriate mesh detail for Low Detail models can be found in **Section 4.7**. For all levels of detail, modelers should aim to create a mesh that generates without the need for manual edits.

3.2.2. Rainfall Data and Initial Conditions

Various types of rainfall events will be applicable to the rain-on-mesh model depending on its intended use (i.e., low-detail vs. interim product vs. coastal). In coastal watersheds or areas where low-detail

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modeling will be the final product, all frequency events are applicable, and historical events are optional depending on the scope of a particular watershed. In watersheds where a low-detail model is used as an interim tool, the engineer may decide which rainfall events are most useful to their overall analysis. More detail on developing rainfall data can be found in **Section 3.4**.

Frequency Event – Zonal statistics can be used to calculate spatially averaged NOAA Atlas 14 precipitation depths across the study area for all durations between 5 minutes and 24 hours. For each duration, the spatially averaged depths should be compared to the maximum and minimum depths across the study area to verify that the average rainfall depth values do not vary from the maximum and minimum depths by more than 10%. If the average depths vary from the maximum and minimum depths by more than 10%, the study area should be subdivided into smaller subbasins.

It is recommended to create a dummy HEC-HMS model to generate a precipitation time series dataset that can be applied to HEC-RAS. Specifically, the frequency storm option within the meteorologic model can be used to develop precipitation hyetographs for each recurrence interval.

Areal Reduction –Point rainfall depths will be assumed to be sufficient for the purposes of Phase 3 baseline modeling. Appropriate depth-area reductions and/or elliptical storms will only be applied to High Detail models, as defined in the Phase 3 work plans or FMIPs. If a specific project is identified for detailed analysis, areal reduction may be applied in support of that project during Phase 4 alternatives analysis.

Historical/Calibration Event(s) – Stream gage stage/flow data, historical precipitation data, and NOAA Atlas 14 24-hr precipitation depths can be used to support selection of historical events. For a preliminary calibration of a low detail model, it is recommended to use an event that is comparable to the 1% AEP frequency event or the best available large event. Potential data sources are highly dependent on the date of the event and the location of the study area, but NOAA Stage IV, Multi-Radar/Multi-Resolution (MRMS) Quantitative Precipitation Estimation (QPE) w/ Gage Bias Correction and Gage-Adjusted Radar Rainfall (GARR) are examples of readily available historical rainfall datasets. Once the rainfall data has been downloaded, it can be converted into a HEC-DSS gridded file format that can be used in HEC-RAS. The links listed below describe this process in detail. Refer to **Section 3.4.2** for additional information.

1. HEC-HMS Gridded Rainfall Guide – https://www.hec.usace.army.mil/confluence/hmsdocs/hmsguides/creating-gridded-boundary-conditions-for-hec-hms
2. Vortex Software – https://github.com/HydrologicEngineeringCenter/Vortex

Initial Conditions – An initial run may be considered to fill depressions within 2D cells to avoid overestimating initial loss values. The model state at the end of a hypothetical run can be saved and referenced as a restart file.

3.2.3. Validation of Low Detail Models

Validation is typically not included or only minimally analyzed for Low Detail models. If validation is deemed necessary for a Low Detail model, it should only be included at a high-level to ensure the model is producing reasonable results. The study team can validate the model based on gage analysis or through the simulation of historical events. The following sections outline the parameters of interest for validation of Low Detail models.

Runoff Volume
If validating a Low Detail model through the simulation of an historical event, loss parameters should be adjusted within the infiltration layer so that the total runoff volume in the HEC-RAS model matches the observed data at the gage. At this stage, the shapes of the modeled and observed hydrographs likely do not agree, but the goal of this step is only to adjust losses so that the area under each hydrograph (i.e., the runoff volume) is approximately equal. For example, although the two hydrographs shown in **Figure 3-1** do not have the same peak flow, they have approximately equal runoff volumes. The modeler should take care to account for any stranded water that may be present at the end of the simulation. Failing to account for this volume may lead to an incorrect hydrologic loss calibration.

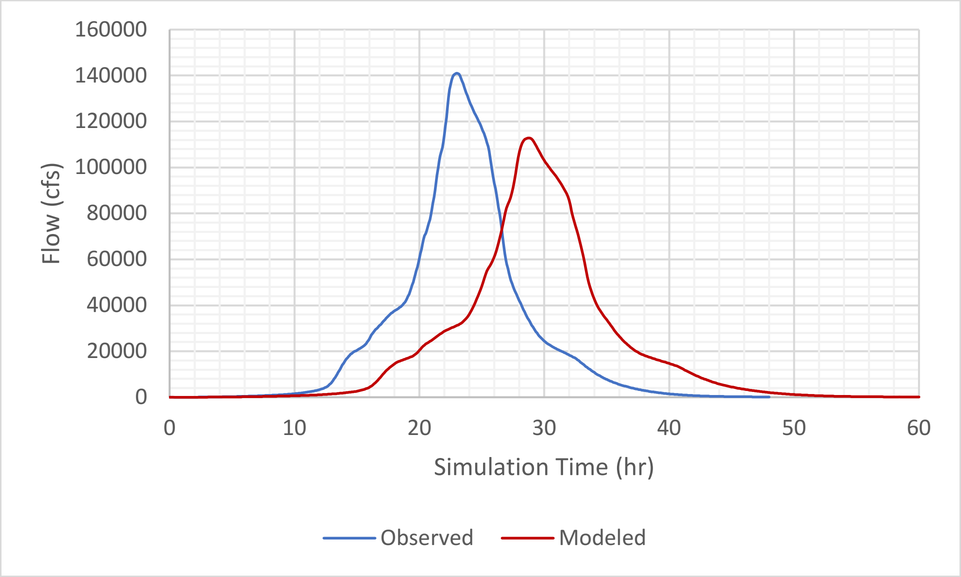

Figure 3-1. Observed vs Modeled Discharge Hydrographs

Peak Flow/Stage
Peak stages and flows can be compared to statistical gage analysis or observed data recorded by a stream gage during a historical event. If a modeler chooses to only compare the Low Detail model results to statistical gage analysis, hydrologic parameters within the infiltration layer and manning's roughness parameters in the land cover layer may be adjusted to better match the calculated values. The modeler may also use the published rating curve at relevant stream gages as an additional comparison point for the Low Detail model's stage and flow response.

For validation through the simulation of historical events, the modeler should first adjust hydrologic parameters to match the total observed runoff volume, as described in the previous section. Then, manning's roughness parameters may be adjusted to better match peak data. The modeler should note that hydraulic structures can significantly impact the stage and flow measurements recorded by stream gages, given that gages are generally placed near hydraulic structures.

3.3. Statistical Hydrology
Statistical hydrology provides a key reference point for validating results of the hydrologic and hydraulic analyses. This section provides guidelines for assessing statistical hydrology at stream gages and was inspired from the descriptions in Section 1.5 – Statistical Hydrology of the *USACE Minimum Standards*.

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Recommendations are also provided for reviewing USGS rating curves and field measurements. In some cases, limited period of record or other flow measurement issues may reduce confidence in the results of the flow frequency analysis. Additional investigation of stream gage measurements can provide insights to better understand the data and clarify discrepancies with model results.

3.3.1.Rating Curves and Field Measurement Data

The USGS publishes rating curves and field measurement data for most stream gages. Rating curves are periodically updated over time to account for new field measurement data, particularly following significant events. Rating curves can be obtained from the USGS website at the following address.

- USGS Rating Curves - https://waterdata.usgs.gov/nwisweb/get_ratings?site_no=XXXXXXXX&file_type=exsa.

Field measurement data published by USGS can improve understanding of historical flow measurements and provide context if there are uncertainties with a rating curve. Field measurement data typically includes the type, quality, and time of measurement, and may include other variables such as the channel width, area, and flow velocity.

Several factors can affect the consistency and quality of flow measurements. The magnitude of flows can affect the feasibility of capturing accurate flow measurements. For major events, broad floodplains may create the potential to over- or under-estimate flows when velocity-area measurements are aggregated. There is also variation in the underlying accuracy of various types of flow measurements. The timing of the flow measurement can also be significant, depending on whether it occurred during the rising or falling limb of the hydrograph. Tailwater effects can also play a role if the gage was affected by elevated stages from a receiving stream or waterbody. Standard techniques and methods for stage measurement, discharge measurement, and levels at gaging stations are described in the USGS *Techniques and Methods 3-A7, 3-A8,* and *3-A19* publications.

According to TM3-A7, a qualitatively "excellent" measurement can be characterized by the following factors.

1. The cross section is smooth, firm, and uniform
2. The velocity is smooth and evenly distributed
3. The equipment is in good condition
4. The two-point velocity measurement method was used
5. Weather conditions are good (no wind or ice)

Otherwise, the measurement rating may be downgraded as unfavorable qualitative factors are identified. **Table 3-5** lists approximate accuracies associated with each qualitative rating.

Table 3-5. Approximate Accuracies for USGS Field Measurement Ratings

Rating	Accuracy
Excellent	2%
Good	5%
Fair	8%
Poor/Very Poor	8-20%

Field measurements can be obtained from the USGS website at the following address.

- USGS Field Measurements - https://waterdata.usgs.gov/nwis/measurements?site_no=XXXXXXXX&agency_cd=USGS&format=rdb_expanded

3.3.2.Flow Frequency Analysis

The USGS *Bulletin 17C Guidelines for Determining Flood Flow Frequency* is recommended for performing statistical analysis of stream gage data. The latest version of HEC-SSP is recommended to standardize implementation of the Bulletin 17C approach. Flow frequency analyses will be performed for stream gage locations with at least 20 years of record. Key steps in the HEC-SSP Bulletin 17C analysis are described below.

1. Create a new study for the stream gage(s) in question. Name the study according to the stream gage name and include a brief description of the analysis being performed (e.g., engineer, gage location, stream, watershed, etc.).

    a. Import Time Series Annual Peak Flow data from USGS site for the selected station. The values imported from USGS may need to be modified, especially in the following situationsTo add historic flood data from other (non-USGS) sources
    b. To exclude non-homogeneous portions of the record
    c. To change point flow estimates to intervals to better estimate uncertainty in the rating curve

2. Create a new Bulletin 17 Analysis and name it based on the USGS station.

    a. Select the imported Flow Data Set from the drop-down menu
    b. Ensure Method is “17C EMA”
    c. Use the station skew option for sufficiently long periods-of-record. When period-of-record is shorter, the weighted skew option may be preferrable.

3. Check “Use Values from Table Below” on the “Options” tab and ensure table contains desired frequencies (i.e., 0.2%, 0.5%, 1%, 2%, 4%, 10%, 20%, and 50% AEPs).

4. Check for data gaps on the “EMA Data” tab.

    a. If missing data from specific year ranges, add each missing period as a row to the “Perception Thresholds” table.

    b. Include a “Low Threshold,” with the default being the Multiple Grubbs-Beck (MGBT) method. User evaluation of the gage period of record and information from adjacent gages should be considered to verify the low threshold. In some cases, the low threshold may be set to equal the smallest observed flow from the systematic period of record. Correlation with data from adjacent gages with a longer period of record can also be used to set the low threshold. The USACE *HEC-SSP User’s Manual* and InFRM WHA studies include additional background and examples for selecting a low threshold.

    c. Set the “High Threshold” to “inf.”

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   d. Execute the computation. Save the SSP file and results in the designated folder for the USGS station. Specific deliverables to export from SSP are described in the 'Documentation' section, below.

5. Perform a quality check on the SSP results to verify a satisfactory fit of the computed curve to the recorded data, especially for high discharge events. Checks should also compare computed station skew to regional skew values. Where deviations are significant, adjustments to the assumptions should be considered.

An additional analysis should be performed to show how the statistical flow frequency results change over time as years are added to the period of record. Flow frequencies should be estimated for the 50%, 10%, 1%, and 0.2% AEP events. The analysis should include a minimum of 10 years and proceed year-by-year until the end of the period of record. The beta version of HEC-SSP v2.3 includes an option to "compute using expanding window" that can be used to perform the analysis. Study teams should use the most recent version of HEC-SSP available at the commencement of each study and maintain the version throughout the duration of the study. For Phase 3 of the GLO RBFS, this is HEC-SSP 2.3 Beta, released November 2021.

It should be noted that results of the statistical frequency analysis are predicated on stationary hydrologic conditions. Statistical analyses, such as the Kendall's tau test, may be beneficial to identify statistical trends in streamflow over time. Factors affecting stationarity should be identified and accounted for, such as changes in regulation of the watershed (e.g., construction of a dam). Other data sources, such as paleo and historical flood data, can also be considered for incorporation in the Bulletin 17C analysis. **Sections 3.10.3** and **3.10.6** include guidelines for period-of-record extension and evaluating the effects of regulation.

3.3.3. Documentation

An exhibit depicting the location of USGS gages should be included. The symbology for the gages should indicate whether a Bulletin 17C analysis was performed. A table should be prepared listing the stream gages that were analyzed, including the station number, name, period of analysis, contributing drainage area, and low flow outlier threshold, like the format of **Table 3-6**.

Table 3-6. Summary of Selected USGS Gages

Number	Name	Drainage Area (sq. mi.)	Period of Analysis	Low Flow Outlier Threshold (cfs)
08111700	Mill Creek nr Bellville, TX	400	1955-2021	999
XXXXXXXX	Example Gage #2	1,200	1940-2021	333

A table of flow frequency results for the 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% AEPs should be prepared, including the upper and lower 95% confidence interval (CI) estimates, like the format of **Table 3-7**. Flows should be rounded to the nearest whole number value.

Table 3-7. Bulletin 17C Analysis Results

Station	Peak Streamflow (cfs) by Annual Exceedance Probability							
	50%	**20%**	**10%**	**4%**	**2%**	**1%**	**0.5%**	**0.2%**
08111700 Mill Creek nr Bellville, TX								
Lower 95%-CI	1	11	111	1,111	11,111	111,111	1,111,111	11,111,111
Estimate	**2**	**22**	**222**	**2,222**	**22,222**	**222,222**	**2,222,222**	**22,222,222**
Upper 95%-CI	3	33	333	3,333	33,333	333,333	3,333,333	33,333,333
XXXXXXXX Example Gage #2								
Lower 95%-CI	3	33	333	3,333	33,333	333,333	3,333,333	33,333,333
Estimate	**6**	**66**	**666**	**6,666**	**66,666**	**666,666**	**6,666,666**	**66,666,666**
Upper 95%-CI	9	99	999	9,999	99,999	999,999	9,999,999	99,999,999

Graphical plots from the Bulletin 17C analysis should be incorporated in the technical report, including a plot of the annual peak streamflow data (see **Figure 3-2**) and a plot of the flow frequency curve (see **Figure 3-3**). A brief discussion should be included for each gage to describe unique considerations or assumptions, including gages omitted from the analysis. The standard report generated by HEC-SSP should be saved as a PDF file and included with the digital deliverables.

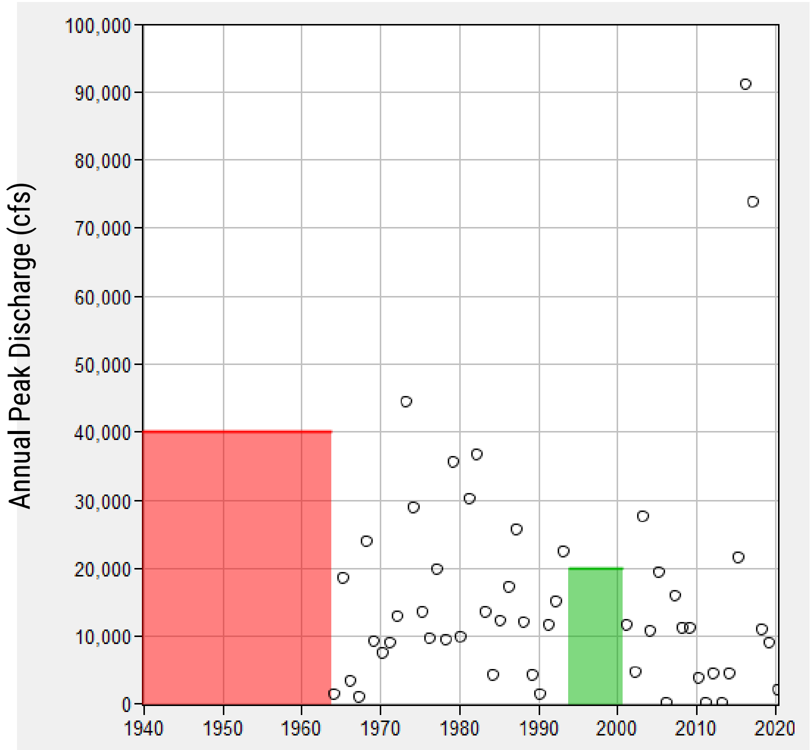

Figure 3-2. Annual Peak Streamflow Data for USGS Gage 08111700 Mill Creek near Bellville, TX

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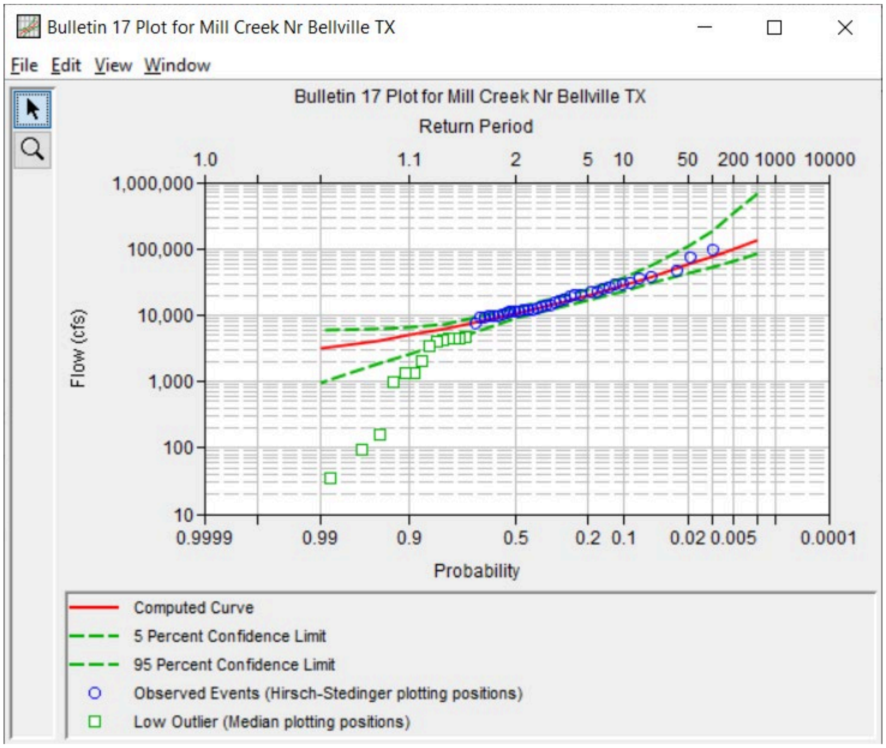

Figure 3-3. Bulletin 17C Annual Exceedance Probability Plot for USGS Gage 08111700 Mill Creek near Bellville, TX

Change over time plots for the flow frequency analysis should be provided for each gage, similar to the format of **Figure 3-4**, below.

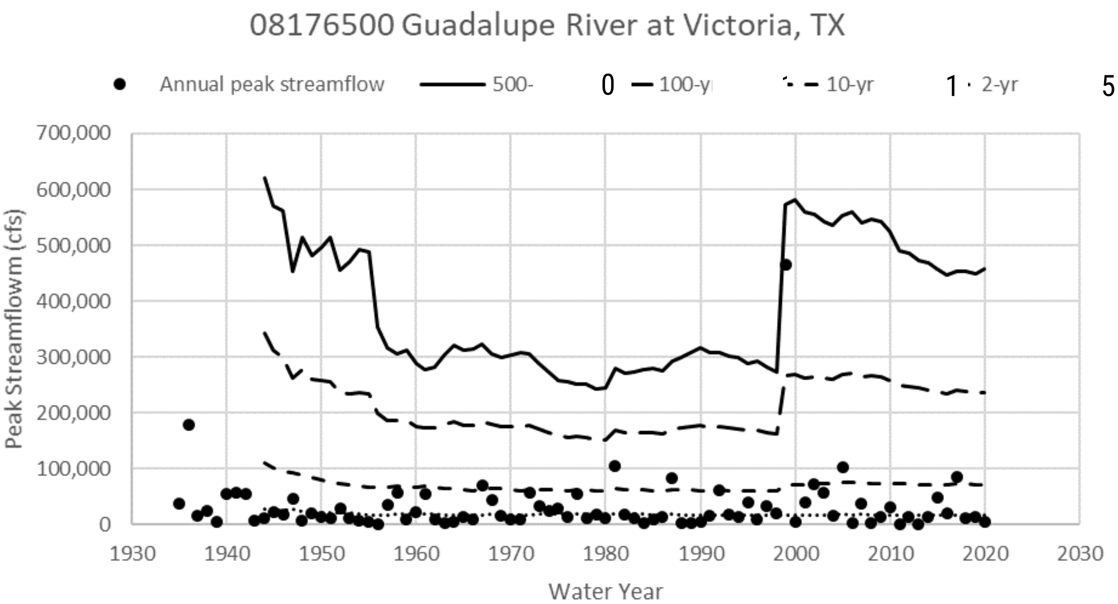

Figure 3-4. Example Flow Frequency Change Over Time Plot

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Rating curve and field measurement information can be assembled in tabular and graphical formats. The example plot, below (see **Figure 3-5**), compares rating curve and field measurement data symbolized by the reported accuracy rating. If preliminary hydraulic modeling results are available, it is recommended to include a plot of the simulated rating curve at the location of the gage. The simulated rating curve may be beneficial for identifying looped rating curves where tailwater conditions may affect the magnitude of flows for a given stage.

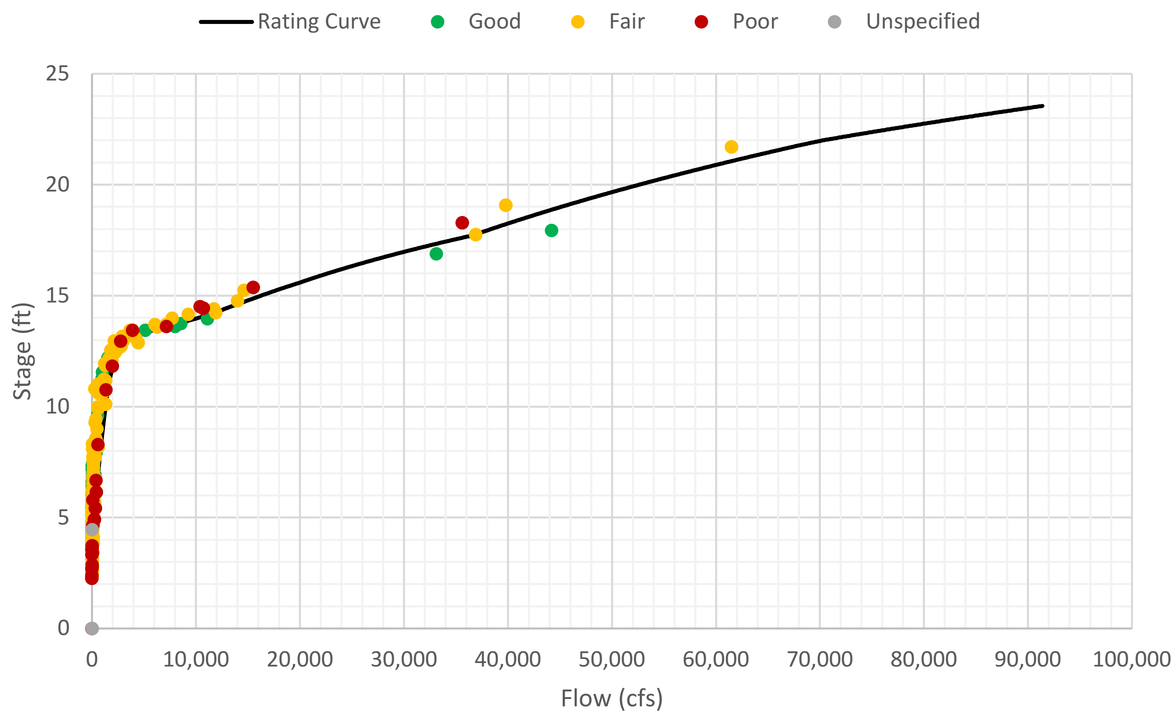

Figure 3-5. Comparison of USGS Rating Curve and Field Measurements at 08111700 Mill Creek near Bellville, TX

The MGBT low flow outlier threshold can be used to screen field measurements to assess the accuracy rating of measurements within the range of flows used in the frequency analysis, as shown in **Table 3-8**.

Table 3-8. Count of USGS Field Measurements by Accuracy Rating for Low and High Flows at 08111700 Mill Creek near Bellville, TX

Accuracy Rating	Low Flow Threshold (7,400 cfs)		Total
	Above	Below	
Good	5	181	186
Fair	13	239	252
Poor	9	28	37
Unspecified	0	3	3
Total	27	451	478

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3.4. Calculation Points and Events for Rainfall Runoff Modeling

This section documents the procedures that will be used to generate hydrologic calculation points (i.e., subbasins) and rainfall events. Processes include delineation of hydrologic features, manipulation of rainfall data, and initial hydrologic model setup. This section was inspired from the items outlined in Section 1.4 – 'Detailed Hydrologic Analysis Work Plan' and Section 1.6 – 'Rainfall Runoff Modeling' of the *USACE Minimum Standards*.

3.4.1. Calculation Points

Hydrologic delineations (e.g., subbasins, longest flow paths, etc.) can be either be obtained and modified using existing models or newly developed during this study. This section will describe the process that can be used for each source.

Existing Models

Existing subbasins and other hydrologic delineations should be reviewed for accuracy and whether they will support the expected level of hydraulic model detail to be completed during the study. If the existing model used outdated terrain data, delineations should be compared to more recent topography data and updated as necessary.

BLE Models

BLE models are expected to be available for most of the study areas. Subbasin delineations for BLE models may be too detailed for the purposes of this study. BLE subbasin delineations can be used as a baseline; alternatively, subbasins can be merged until they are an appropriate size for the study. For a HUC-10 or HUC-12 scale study area, subbasin sizes are generally expected to range from 5 to 10 square miles.

New Models

In the recent releases of HEC-HMS, hydrologic elements traditionally delineated using HEC-GeoHMS can now be fully developed within HEC-HMS. The process to develop hydrologic elements using HEC-HMS is outlined below. While using HEC-HMS to generate hydrologic delineations is expected to be more efficient than the traditional process using ArcGIS, either approach is acceptable, as similar results can be achieved with either method. General background information about the Geographic Information System (GIS) capabilities of HEC-HMS can be found at the link below.

- HEC-HMS User's Manual – https://www.hec.usace.army.mil/confluence/hmsdocs/hmsum/4.9/geographic-information/gis-menu

Terrain Data – The base terrain to be used for hydrologic and hydraulic modeling should have a finer resolution than is necessary to complete hydrologic delineations in HEC-HMS. It is recommended to resample the terrain to an appropriate cell size (e.g., 3'x3' to 30'x30'). The terrain can be added to the model using Components > Terrain Data Manager.

Terrain Conditioning – HEC-HMS versions 4.8 and later can create a hydrologically conditioned terrain, which includes processes for Building Walls, Burning Streams, Preprocessing Sinks, and Preprocessing Drainage. The "Preprocessing Drainage" step is equivalent to generating the flow direction and flow accumulation rasters in ArcGIS. Building walls is an optional step the engineer may take to enforce pre-determined subbasin boundaries. The other three terrain pre-processing steps are key in achieving accurate delineations. Depending on the size of the study area, these steps may require significant processing time. Consider modifying HEC-HMS program settings to use multiple Central Processing Unit (CPU) cores to reduce processing time.

Basin Model and Coordinate System – The terrain can be associated with the basin model file. Upon selecting the terrain, a pop-up window should appear requesting a coordinate system for the basin. Select “Skip” to automatically use the same coordinate system as the terrain. Alternatively, the user can select a coordinate system under GIS > Coordinate System.

Identify Streams – The GIS > Identify Streams function can be used to define stream centerlines for the basin model. A pop-up window will ask the user to enter a drainage area threshold (e.g., 5 miles). At a minimum, streams should be identified for every reach where channel routing will be applied. The appropriate drainage area threshold will differ for each basin. This process and the subsequent “Delineate Elements” step described below will likely be iterative until the user is satisfied with stream and subbasin delineations. Consider starting with a larger drainage area threshold than is ultimately desired, such as 10 square miles instead of 5 square miles, and slowly work down to the desired area.

Break Points – After completing the stream identification process, the user has the option to manually set break points using the break point creation tool. Break points force hydrologic elements to terminate at specific locations. At a minimum, break points should be added at the watershed outlet and any stream gages. The *USACE Minimum Standards* suggest adding break points at substantial hydraulic structures, such as NRCS flood control structures and major highways. Applying break points at each hydraulic structure may lead to an excessively detailed hydrologic model. The engineer should use discretion when determining which structures to represent with break points. HEC-HMS creates a subbasin break when a tributary exceeding the threshold enters a channel. For long, narrow watersheds, a long subbasin may be delineated near the channel that is significantly larger than the designated threshold. Break points can be added to address this situation.

Delineate Elements – After streams have been identified and break points have been set, the GIS > Delineate Elements function can be used to perform hydrologic delineations. A preliminary naming convention must be specified for the model in the pop-up window, as shown in **Figure 3-6**. After selecting “Delineate,” HEC-HMS will generate fully geo-referenced model elements, as shown in **Figure 3-7**.

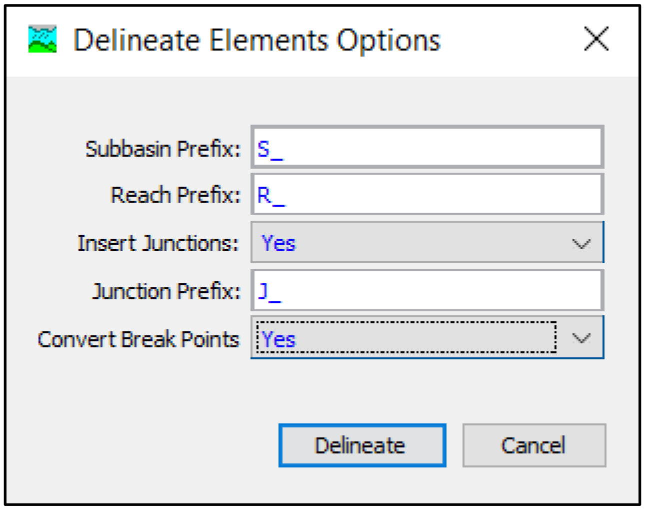

Figure 3-6. Delineate Elements Pop-Up

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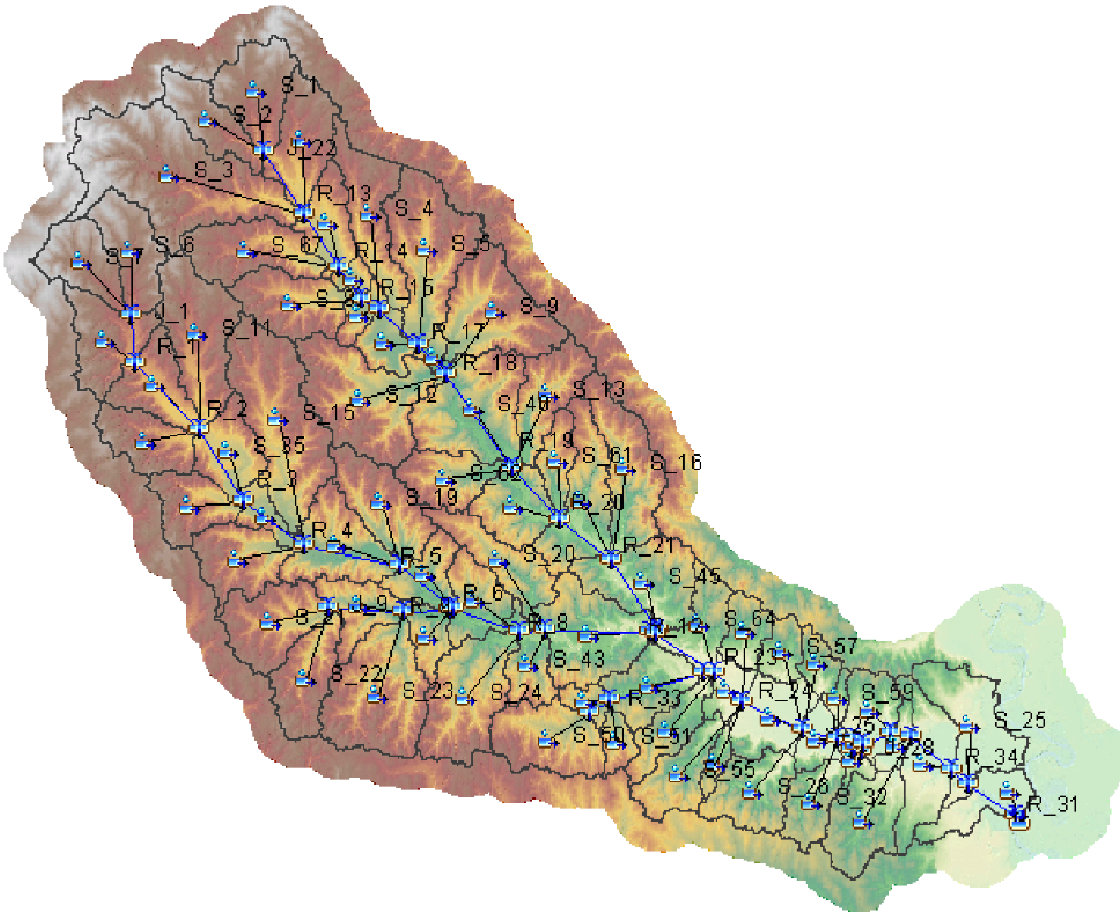

Figure 3-7. Preliminary Basin Model

Further Refinements – HEC-HMS allows for additional refinements to hydrologic delineations through the "Split Elements" and "Merge Elements" tools (see **Figure 3-8**). Both processes work similarly. The *HEC-HMS User's Manual* provides detailed instructions.

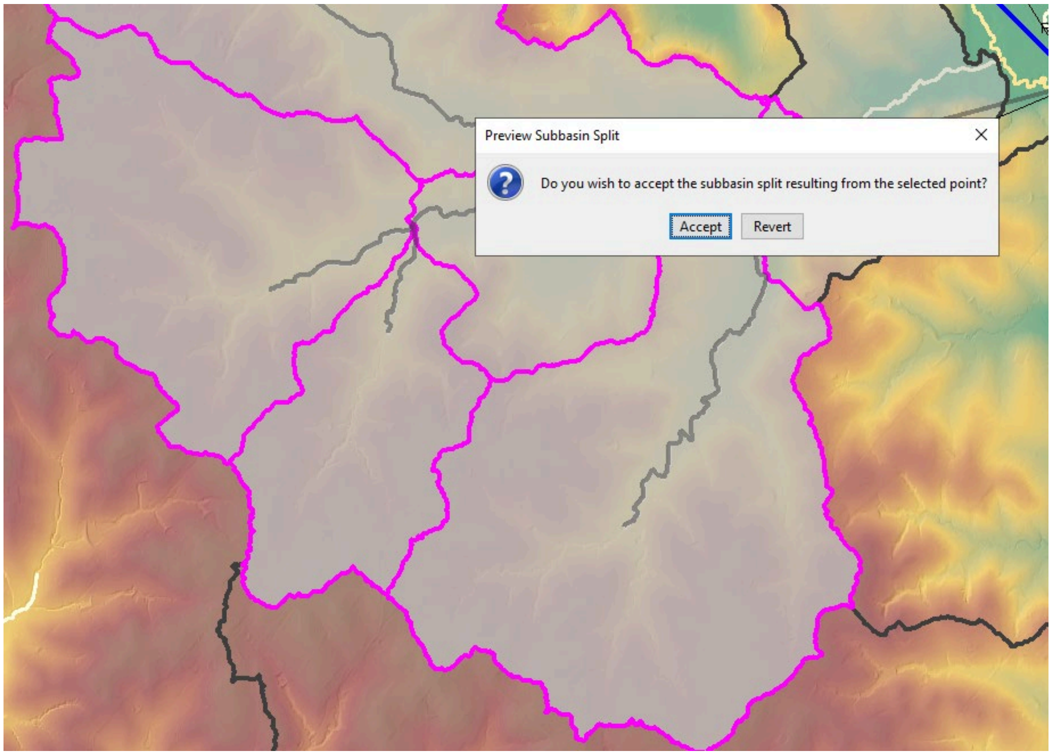

Figure 3-8. Split Elements Example

After sufficiently detailed delineations have been completed in HEC-HMS, a quality check of the initial subbasin and stream delineations should be performed in reference to the detailed terrain and aerial imagery. To perform this check, the subbasins can be exported to a shapefile. Manual edits can be performed in GIS and re-imported to the subbasins in the HEC-HMS model using the "Import Georeferenced Elements" tool.

Element Naming Convention – For newly developed models, the following naming convention should be used. If working from an existing detailed model, the existing naming convention can be maintained.

- **Hydrologic Elements:** Hydrologic elements should be named according to their type and receiving stream, followed by a numeral. Subbasins, reaches, and junctions should begin with the prefix "S," "R," and "J," respectively. The prefix should be followed by a two to three letter abbreviation for the receiving stream. For example, "West Mill Creek" could be abbreviated as "WMC." Lastly, the elements should be numbered sequentially from downstream to upstream. An example of the complete naming convention is "S_WMC_01" for the most downstream subbasin of West Mill Creek. Descriptions may be included for individual elements to capture additional information. For example, if subbasin "S_WMC_01" represented a named tributary to West Mill Creek, the description "*Tributary Name* to West Mill Creek" could be included.

Junctions: Junctions representing stream gage locations should be appended with "_GAGE" and include descriptions that identify the owning agency and gage identifier

Other: Less common hydrologic elements, such as diversions, sinks, and sources, should aim to use a naming convention similar to what will be used for the subbasins, junctions, and reaches. However, these elements may benefit from more descriptive names that are specific to the study area. Reservoirs do not need to follow an abbreviated naming convention and should use their proper names (e.g., Lake Somerville)

Other Hydrologic Delineations
HEC-HMS also supports delineation of other hydrologic parameters, including Longest Flowpath, Centroidal Flowpath, 10-85 Flowpath, and Subbasin Centroid.

Before these parameters can be exported to a shapefile, they must be calculated, as available through the Parameters > Characteristics > Subbasin menu option. After the calculations are complete, the layers can be exported to a shapefile using GIS > Export Layers. Delineations should be reviewed for accuracy and adjusted in GIS, as necessary.

HEC-HMS supports the calculation of hydrologic routing parameters, including Length, Slope, Relief, and Sinuosity.

If the automated HEC-HMS processes were not utilized, or if working from an existing subbasin data set, hydrologic reaches that agree with the conditioned terrain can be developed using the "Identify Streams" tool in HEC-HMS. Appropriate thresholds are required to extend streams through areas where reaches will be modeled. Features can be exported to ArcGIS if adjustments are needed. If features are subsequently imported from GIS, it is recommended to explode and re-merge the features to avoid issues with start and end vertices. Reaches can be split at subbasin intersections then re-imported to HEC-HMS.

3.4.2.Rainfall

Frequency Events
Precipitation data for frequency events will be based on NOAA Atlas 14 Annual Duration precipitation depths. Annual duration data supports consistent comparison with statistical flow frequency analyses. Future work may use Partial Duration precipitation depths to better define the benefit-cost ratio of proposed projects where smaller storms are relevant. This section outlines steps to apply the frequency event depths to the hydrologic model.

Rainfall Data – NOAA Atlas 14 rainfall rasters can be downloaded directly through the National Weather Service (NWS) website at the location below.

- NOAA Atlas 14 Precipitation – https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html

Duration – The appropriate duration to use for downloading precipitation depth rasters will vary by study area. For large watersheds, it is recommended to test a storm duration that exceeds the time of concentration for the drainage basin. In most cases, the 24-hr storm is expected to be used, but longer durations may be applicable for large watersheds. The precipitation rasters should be stored locally within the model file structure. The rasters can be used to visualize how the Atlas 14 rainfall totals vary across the watershed to support selection of values to be used in the analysis. Rasters for shorter durations (e.g., 1-hr, 3-hr, 6-hr, etc.) may also be beneficial to review, since the intense portions of the storm can have a significant effect on flood risk. It is generally recommended to use the frequency storm precipitation method within HEC-HMS and input a single set of rainfall depths for the watershed. Alternatively, multiple discrete zones can be identified for large watersheds. Elliptical storms may be considered for high detail studies of large watersheds, as described in **Section 3.9**.

Intensity Duration – An intensity duration of 5 minutes is typically appropriate for most study areas. The intensity duration should be less than the time of concentration of the smallest subbasin. The intensity position should be evaluated based on engineering judgement, historical storm events, and watershed response characteristics. Recommendations regarding areal reduction are provided in **Section 3.9**.

Historical Events
Historical rainfall events to be used for calibration and validation should be selected through analysis of stream gage stage/flow data and precipitation gage data near the study area. The engineer should aim to select a range of storms that represent various climatological and hydrological conditions of the watershed, such as:

1. Different seasons/dates to capture variability in storm types, atmospheric, and antecedent soil moisture conditions.
2. Ranges of total rainfall and intensity of rainfall to capture various scales of flooding events (e.g., channel discharge, bank-full discharge, overbank flooding) with the highest priority being to select large flood events similar to a 1% AEP flood.
3. Extreme events (e.g., Hurricane Harvey).
4. Recent events.
5. Different storm durations.

Data Sources – There are multiple radar-based products that are readily available, namely, the NWS Stage IV QPE and the MRMS QPE w/ Gage Bias Correction. Rainfall data from either of these sources will generally be the preferred source for historical events. Both datasets are NOAA products, and a summary of each dataset is shown in **Table 3-9**.

Table 3-9. Historical Rainfall Data Source Summary

Data Source	Period of Record	Spatial Resolution	Temporal Resolution
Stage IV–QPE	2002 - Present	4 km²	1-, 6-, 24-hr
–RMS	2012 - Present	1 km²	1-hr

The data from each source can be accessed at the following locations, including a guide for navigating the Iowa State University MRMS archive:

- NWS Stage IV QPE – http://data.eol.ucar.edu/codiac/dss/id=21.093
- MRMS w/ Gage Bias Correction – http://mtarchive.geol.iastate.edu
- HEC-HMS Guide on MRMS and Iowa State University– Archive - https://www.hec.usace.army.mil/confluence/hmsdocs/hmsguides/working-with-gridded-boundary-condition-data/importing-and-using-multi-radar-multi-sensor-mrms-precipitation-data

Other Considerations – Gage-adjusted radar rainfall from other sources (e.g., RainVieux data from Vieux & Associates) may be available for a given study area and can also be used. Which data source (i.e., Stage IV, MRMS, or GARR) to use for the historical events is ultimately up to the engineer's discretion, but the engineer should acquire rain gage observations (e.g., through the National Climatic Data Center [NCDC]) for comparison and validation of the radar data, regardless of the data source.

For years prior to 2002, the engineer should rely on early NWS Stage III QPE data or rain gage data available from various federal and state agencies (e.g., NWS, NCDC, USGS, USACE). For earlier events, NOAA Analysis of Record for Calibration (AORC) gridded precipitation data (4 km² resolution) may be also available. If one of these alternative sources is used, a quality assessment should be performed and documented, including any adjustments that were necessary.

Sub-daily gridded datasets can have precipitation volume errors, which tend to underestimate volume and can create calibration issues when attempting to match observed peak flows at gages. Daily Parameter elevation Regression on Independent Slopes Model (PRISM) grids are generally more reliable for volume estimates and can be used to correct errors using the Vortex normalizer tool, as documented in a tutorial on the HEC-HMS website.

- HEC-HMS Guide on Vortex Normalizer Tool – https://www.hec.usace.army.mil/confluence/hmsdocs/hmsguides/working-with-gridded-boundary-condition-data/correcting-precipitation-volume-with-the-normalizer-utility

HEC-DSS Conversion and Meteorologic Model Setup – Multiple tools (e.g., HEC-MetVue, Vortex, etc.) are available to convert radar rainfall data into a file format that can easily be used in hydrologic and hydraulic modeling. This section will document the use of Vortex to convert radar rainfall data into a HEC-DSS file format, but the engineer can use whichever tool/process is most efficient in the specific study case.

Vortex software and detailed instructions on using the software can be found at the following links. The HEC-HMS Gridded Rainfall Guide includes steps that can be used to create DSS files for each historical rainfall event. Each HEC-DSS file should be named according to the approximate date of the event (e.g., "May 2016").

- HEC-HMS Gridded Rainfall Guide –Creating Gridded Boundary Conditions for HEC-HMS (army.mil)
- Vortex Software – https://github.com/HydrologicEngineeringCenter/Vortex/releases

After setting up the source HEC-DSS files, separate gridsets and meteorologic models can be created in HEC-HMS for each event. Precipitation gridsets can be created for each event using the Create Component > Grid Data function. When creating precipitation grids, a consistent naming convention should be used, including the approximate date of the event and the data source (e.g., "May 2016-NWS Stage IV"). The description should be populated with precise dates and time intervals. The HEC-DSS file linked to the precipitation gridset should reference "HistoricalRainfall" in the file name or be contained within a "Historical Rainfall" folder within the hydrologic model folder structure.

Meteorologic models must use the "Gridded Precipitation" storm type and be connected to the appropriate precipitation gridset. Meteorologic models should be named according to the approximate date of the event (e.g., "May 2016").

Time Zone – When downloading spatially varied precipitation data from the sources listed above, the engineer should ensure the time standard for the rainfall data agrees with the observed stream gage data. Stream gages are often reported in local time, while precipitation data may be in Coordinated Universal Time (UTC). It is recommended that the user make minimal manual modifications to the downloaded data and corresponding Data System Storage (DSS) files, because HEC-HMS can make

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these adjustments. To adjust the time zone of rainfall data, use the "Time Shift" function available within the meteorologic model. It should be noted that the conversion from UTC to local time changes depending on the time of year due to daylight saving time.

Units – Historical rainfall data may use millimeters to measure precipitation depth rather than inches. As long as the units are specified in the DSS file, HEC-HMS can perform any conversions automatically. The engineer should check results to ensure any conversions are being performed correctly.

3.4.3. Hydrologic Model Setup

This section will review the primary components of HEC-HMS models and document the suggested naming convention for newly developed models. Each watershed will have unique elements that may not fit into the naming convention described in this section, so the engineer should take care to clearly name unique model components and include descriptions as needed. Some of the data in this section was touched upon in each respective section earlier in the document, but a complete naming convention is summarized here.

Coordinate System

If an existing model is being used as the base of this study, continue to use the projection that was used to develop the model if it is generally accepted by industry standards. For newly developed models, use the Albers Equal Area projection "NAD_1983_TCMS_Albers_FtUS." If the projection used in the existing model is not acceptable, update it to "NAD_1983_TCMS_Albers_FtUS."

Naming Conventions

Basin Model – The basin model should be named in reference to the overall watershed name, land use condition, and historical event associated with the basin. Examples of the expected basin models and naming convention typically included in the HEC-HMS model are shown below in **Table 3-10**.

Table 3-10. HEC-HMS Basin Models

Basin	Purpose
Mill Creek	Uncalibrated existing conditions
Mill Creek_August 2017	Calibration to August 2017 event
Mill Creek_Calibrated	Calibrated existing conditions

Control Specifications & Meteorological Models – Regardless of the storm type, Meteorological models should be named according to their frequency event or approximate date for historical event. Example naming conventions are shown in **Table 3-11**.

Table 3-11. Meteorological Model Naming Convention

Event Type	Naming Convention	Example
Hypothetical	Frequency_Duration	1PCT_24hr
Historical Event	Month_Year	August_2017

Control specifications should follow the standard described in **Table 3-12**. Control specifications for hypothetical events should describe the duration of the simulation, and historical events should be given the same name as the meteorological model they will be associated with.

Table 3-12. Control Specifications Naming Convention

Event Type	Naming Convention	Example

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Hypothetical	#_Day	3_Day
Historical Event	Month_Year	August_2017

Hydrologic Elements – Hydrologic elements should be named according to their type and receiving stream, followed by a numeral. Subbasins, reaches, and junctions should begin with the prefix "S," "R," and "J," respectively. The prefix should be followed by a two- to three-letter abbreviation for the receiving stream. For example, "West Mill Creek" could be abbreviated as "WMC." Lastly, the elements should be numbered from downstream to upstream in increasing numerical order. Include descriptions within elements as needed. For example, if subbasin "S_WMC_01" represents a named tributary to West Mill Creek, include a description like "*Tributary Name* to West Mill Creek."

Table 3-13. Hydrologic Element Naming Convention

Element Type	Naming Convention	Example
Subbasin	S_Abbrv. Stream_##	S_WMC_01, …
Reach	R_Abbrv. Stream_##	R_WMC_01, …
Junction	J_Abbrv. Stream_##	J_WMC_01, …
Reservoir	Proper Name	Lake Somerville
Any Gaged Data	Name + _GAGE	J_WMC_01_GAGE, Lake Somerville_GAGE…

Paired Data – Paired data should be named according to the hydrologic element it will be associated with. For example, a storage-discharge relationship for a routing reach should follow the routing reach naming convention described in **Table 3-13**. Any items associated with reservoirs should be given the same name as the reservoir.

Grid Data – There are multiple types of grid data that may be applied to the HEC-HMS model. In general, each grid should be named according to the parameter it represents. For example, a precipitation grid for a historical storm may be called "August_2017", or a percolation rate grid representing hydraulic conductivity for uncalibrated conditions may be called "Ksat_Uncalibrated." If gridded data is extensively used for historical events, add tags to each grid type noting the approximate date of the event (e.g., Ksat_August_2017).

3.4.4. Documentation

Supporting documentation for each main task associated with this SOP should be provided with the final hydrologic report. The sections below summarize the necessary documentation for each task. The engineer should take care to include additional data not listed in this SOP as unique or edge cases are encountered.

Calculation Points

A geospatial database should be compiled that includes, at a minimum, the following spatial data. In addition, an exhibit should be provided to show relevant delineations used to establish hydrologic parameters, such as subbasins and flow paths.

1. Base Terrain (No hydrologic conditioning)
2. Hydrologically Conditioned Terrain
3. Subbasins
4. Longest Flowpath, Centroidal Flowpath
5. Subbasin Centroids

6. Hydrologic Reaches
7. HEC-HMS Junctions
8. Gage Locations

Rainfall

The following data should be provided for the frequency and historical events.

<u>Frequency</u>

1. Map of NOAA Atlas 14 1% 24-hr grid across study area.
2. Table summarizing the frequency depth-duration values as described in Section 0 – ‘Frequency Events.’ This should include all sub-areas, if applicable.
3. Geospatial database that includes the study area subdivisions described in the ‘Frequency Events’ section.

<u>Historical</u>

1. Table summarizing the chosen historical events and their purpose (i.e., calibration or validation). The table should document the data sources, resolution, meteorological model name (e.g., “May 2016”), approximate dates (e.g., May 10 – May 24), and total rainfall (e.g., 12.50 inches), and simulated peak discharges at USGS gages.
2. Figures that display the distribution of cumulative rainfall for each historical event, similar to what is shown in **Figure 3-9**.

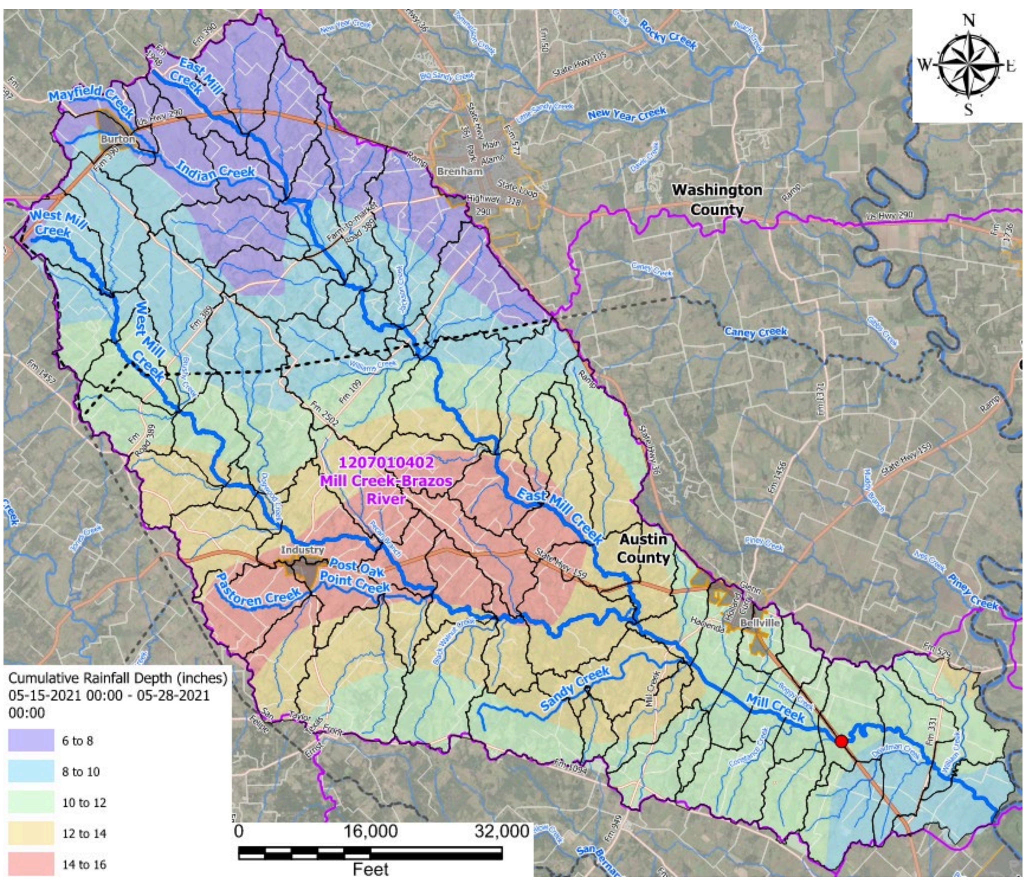

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Figure 3-9. Cumulative Precipitation Depth - Example

3.5. Hydrologic Methods and Equations

This section describes guidelines for hydrologic calculations and model development and was inspired from the items outlined in Section 1.6 – 'Rainfall Runoff Modeling' of the USACE Minimum Standards.

3.5.1. Hydrologic Loss Methods

For all HEC-HMS models developed, two hydrologic loss methods are acceptable — Initial and Constant or Green-Ampt. For consistency, the same methodology and parameter set (Gridded or Lumped) should be used within a given model area. Generally, SSURGO soils data are used to parameterize hydrologic loss parameters and the NLCD Impervious area dataset is used to define the impervious area not subject to infiltration.

The Initial and Constant loss method has been applied broadly across Texas as part of the InFRM Watershed Hydrology Assessments. The USACE Fort Worth District has developed recommended parameters for 24-hour frequency events, as described below. Parameters are dependent on the magnitude and duration of the storm event, requiring separate versions of the HEC-HMS basin file for each event that is evaluated. The insights from calibration to historical storm events may be limited if the magnitudes and durations do not align well with the selected frequency events.

The Green-Ampt methodology is physically based, and calibrated parameters are generally applicable across a range of storm event magnitudes and durations. A single HEC-HMS basin file can typically be used for multiple events. The Green-Ampt methodology has been applied for some previous studies within the GLO regions but not across as broad a spectrum of geographies relative to the Initial and Constant loss methodology. Initial estimates of parameters values are provided below; however, calibration is essential to determine appropriate values for frequency event analysis.

Depending on the original data source, hydrologic losses may initially be calculated in metric units. Prior to incorporation to the model or report, all data should be converted to U.S. Customary units.

Soils Data

Soils data is available from the US Department of Agriculture (USDA) SSURGO soils database. The data includes spatial features for unique soil map units. Hydrologic soil group (HSG) delineations classify the runoff potential into four groups (i.e., A, B, C, or D), with Group A having the lowest runoff potential and Group D having the highest. The HEC-HMS reference manual includes recommended ranges of infiltration rates for each soil group, as described below.

As part of the InFRM Watershed Hydrology Assessments, the USACE Fort Worth District developed a geospatial grid of percent sand for the state of Texas, which can be used to support estimation of initial and constant loss rate parameters.

Initial and Constant Loss

The initial and constant loss infiltration method is a widely used hydrologic loss method that is appropriate for single storm events and can be calibrated efficiently for the wide range of loss rates that are experienced from wet to dry soil conditions. The Initial and Constant loss method has been applied to several river basins in Texas as part of the InFRM Watershed Hydrology Assessments.

The initial and constant loss method requires two input values: initial loss and constant loss. These parameters can be calculated based on soils data.

Initial loss – Represents interception and depression storage from surface cover and topographic features. Estimated initial losses are dependent on antecedent moisture conditions and the magnitude of the storm event being evaluated. For frequency events, this parameter should be set with a value representing "wet" antecedent conditions as a conservative measure.

Constant loss – Represents the rate at which precipitation infiltrates the soil layer and the rate of percolation of saturated soil. According to the *HEC-HMS Technical Reference Manual*, this parameter is typically related to saturated hydraulic conductivity, which should be used as an upper limit for the constant loss rate. Constant loss rates are expected to vary between historical events and should be a calibration point. Constant losses associated with frequency events should tend toward "wet" conditions (i.e., lower loss rates) and should generally be capped at 0.5 inches/hour.

As part of the InFRM Watershed Hydrology Assessments, USACE has developed recommended initial and constant loss values for 24-hour duration frequency events based on percent sand, as listed in **Table 3-14**.

Table 3-14. Initial and Constant Parameter Values by AEP Event from the USACE Fort Worth District Method

Annual Exceedance Probability (AEP)	Initial Loss (in) 0% Sand	Constant Loss (in/hr) 0% Sand	Initial Loss (in) 100% Sand	Constant Loss (in/hr) 100% Sand
50%	1.50	0.20	2.10	0.26
20%	1.30	0.16	1.80	0.21
10%	1.12	0.14	1.50	0.18
4%	0.95	0.12	1.30	0.15
2%	0.84	0.10	1.10	0.13
1%	0.75	0.07	0.90	0.10
0.4%	0.61	0.06	0.73	0.09
0.2%	0.50	0.05	0.60	0.08

Green-Ampt

The Green-Ampt method estimates infiltration based on the Richard's equation for unsteady flow in soil. HEC-HMS includes a simplified application of the Green-Ampt methodology based on four inputs derived from soil classifications. The approach estimates cumulative infiltration and does not support continuous simulation. Loss parameters can be estimated using either hydrologic soil groups or soil textures.

Table 3-15 lists recommended initial estimates and ranges of acceptable parameter values for each HSG. Final selected values should be supported by calibration results. For initial content, the recommended values correspond to the field capacity (i.e., 2 to 3 days after rain or irrigation). Acceptable values range from the residual water content, or wilting point (i.e., very dry conditions), to the saturated content from total porosity (Rawls 1982).

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Table 3-15. Green-Ampt Loss Parameters*

Hydrologic Soil Group	Initial Content	Saturated Content	Suction (in)	Hydraulic Conductivity (in/hr)
A	0.05 (0.02 – 0.44)	0.44	2	0.35 (0.30 – 0.45)
B	0.10 (0.04 – 0.45)	0.45	4	0.20 (0.15 – 0.30)
C	0.20 (0.07 – 0.46)	0.46	8	0.08 (0.05 – 0.15)
D	0.30 (0.09 – 0.47)	0.47	12	0.02 (0.00 – 0.05)

* Table lists recommended initial estimate, followed by range of acceptable values. Final selected values should be supported by calibration. Values sourced from *HEC-HMS Technical Reference Manual*, which cites SCS (1986); Skaggs and Khaleel (1982); and Rawls, Brakensiek, and Miller (1982); and from Rawls, Brakensiek, and Miller (1983).

For frequency storm events, initial content should be representative of wet hydrologic conditions, as informed by the calibration. If the calibration is inconclusive regarding the appropriate initial content for wet conditions, the saturated content can be used as a conservative assumption. A sensitivity analysis is recommended to understand the effect on resulting flood risk.

Conductivity values were sourced from Rawls (1983), summarized by HSG, and validated as part of the Central Region's calibration of the Mill Creek riverine pilot study. These values also align well with the USACE Fort Worth District's suggested cap on constant loss rates of 0.5 inches per hour and are also within the range suggested in the *HEC-RAS 2D User's Manual*, which references SCS (1986) and Sakaggs and Kaleel (1982).

Approximate values for suction were sourced from Rawls (1983), summarized by HSG, and validated as part of the Central Region's calibration of the Mill Creek riverine pilot study (note that Rawls 1983 values are lower than the values provided in Rawls 1982). During the riverine pilot study, suction was not found to be a significant factor in calibration. The most significant factors were found to be initial content and conductivity.

Lumped vs Gridded Green and Ampt

HEC-HMS has the capability to apply the Green and Ampt Loss methodology using a lumped (i.e., subbasin average) or gridded approach. While information on a gridded approach is included below and is an acceptable methodology for the GLO RBFS, study teams should evaluate the benefit to each study area prior to incorporating a gridded approach. Basin averaged parameters can provide adequate resolution for loss data and are generally simpler to develop than gridded losses. For a Green and Ampt lumped approach, a traditional area weighted average should be calculated for all parameters except Hydraulic Conductivity, which should instead be calculated using a logarithmic area weighted averaging approach, as described in the equation below.

$$\overline{} = 10^\wedge\left(\frac{\sum \qquad {}_{10}}{}\right)$$

Where:

— = composite watershed hydraulic conductivity, inches/hour
= hydraulic conductivity of a map unit, inches/hour
= watershed subarea
= watershed total area

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A gridded approach requires the input of the grids listed in **Table 3-16**.

Table 3-16. Gridded Green and Ampt Grid Types

Parameter	Grid Type
Initial Content	Water Content Grid
Saturated Content	Water Content Grid
Suction	Water Potential Grid
Hydraulic Conductivity	Percolation Rate Grid
Impervious	Impervious Area Grid

3.5.2.Hydrologic Transform Methods

The *USACE Minimum Standards* specify three preferred transform methods: Clark UH, ModClark UH, and Snyder UH. This section describes considerations for parameter development for each method. The engineer should take care to select a method that is regionally appropriate for the study watershed.

Clark UH

The Clark Unit Hydrograph method considers two processes of transformation from excess precipitation to runoff: translation and attenuation. Translation is defined as the movement of the excess precipitation from its origin to the outlet. Attenuation is the reduction in the peak discharge as excess volume is stored along the drainage path. The two input parameters used to define Clark's UH in HEC-HMS are Time of Concentration (TC) and the Storage Coefficient R.

Parameters – TC and R values can be estimated from the preliminary HEC-RAS Rain-on-Mesh model described in **Section 3.2**. The user should be careful to avoid over-calibrating the HEC-HMS parameters to the preliminary Rain-on-Mesh model since it is subject to change during the hydraulic analysis. In general, the 1% AEP storm can be used as the primary event to reference when setting parameter values. Alternatively, these values may be computed by regional regression equations, such as those in the *Fort Bend County Drainage Criteria Manual* and *Harris County Flood Control District Hydrology and Hydraulics Manual*, especially where needed to remain consistent with other, existing watershed models. Calculation of TC and R values by regional regression equations require detailed data to support each calculation.

Parameterization or Validation using Rain-on-Mesh Model – Time of concentration for Clark's UH is not directly measured from a rain-on-mesh hydraulic model, so multiple levels of calibration and comparison are described in this section. Engineering judgement is necessary when determining which level of comparison is appropriate for each subbasin. For subbasins where empirical values do not readily agree with rain-on-mesh results, the following method for estimating time of concentration from the rain-on-mesh model may be considered.

- The discharge hydrograph can be sampled from the rain-on-mesh model at the outlet of a given subbasin and compared to results from HEC-HMS. The TC and R values can be iteratively adjusted to increase or decrease the resulting peak flow and improve comparisons with the rain-on-mesh analysis results. In general, higher values of the storage coefficient, R, result in lower peak flows.

The ratio of R / (TC+R) should be consistent throughout a watershed and generally compatible with previous studies. Variations in this value within a watershed should be justified by a physical change in watershed characteristics. Values of this ratio should range from 0.1 for highly urbanized or flashy watersheds to 0.7 for sluggish/flat or swampy watersheds. Sample values are shown in **Table 3-17.** The initial estimates for TC and R should also be within 50% of each calibration event. A low detail rain-on-mesh model can be useful in determining this ratio if the documented values do not readily apply to a given study area.

Table 3-17. Typical R/(TC+R) Values

General Area Description	R/(TC+R)
Flat Coastal Prairies	0.65
Dallas/Fort Worth Metro Area	0.38
Steep Hill Country	0.27

ModClark UH

The ModClark Unit Hydrograph method is a quasi-distributed parameter model that accounts explicitly for variations in travel time for various regions within a subbasin. To implement the ModClark method in HEC-HMS, the time of concentration and storage coefficient of each subbasin must first be estimated according to the Clark UH methodology described above. Next, a discretization is established for each subbasin. The discretization requires multiple input parameters with the recommended approach shown below.

- Discretization Method – Structured
- Projection – Standard Hydrologic Grid (SHG)
- Cell size – Dependent on subbasin area; a resolution of 500 (0.5 km x 0.5 km) will generally be fine enough. Smaller watersheds/subbasins may require even finer resolutions.

Clark UH vs ModClark UH

Like losses, the Clark Unit Hydrograph may be computed using lumped parameters or gridded parameters. HEC-HMS includes the capability to account for the spatial variability of hydrologic phenomena (in this case, the distance to the outlet). Instead of relying on a single value of TC and R for each subbasin, the ModClark method indexes each grid cell value and allows for nonuniform hydrograph shapes within each subbasin. Either method is acceptable; however, if gridded losses are used, a gridded transform is preferred.

Snyder UH

The Snyder Unit Hydrograph transform method involves the estimation of two parameters: the lag time (T_p) and the peaking coefficient (C_p) to define the shape of the unit hydrograph. There are multiple formulas that can be used to define watershed characteristics. For this study, the Standard method or the USACE Fort Worth District method should be used.

Parameterization Using Standard Method – The T_p and C_p values for a specific watershed can be estimated either by calibrating a single subbasin HEC-HMS model to observed USGS streamflow data or by calibrating a single subbasin HEC-HMS model to rain-on-mesh results using hypothetical (i.e., 1% AEP) rainfall. A starting point for estimates may be found in the equations produced by the Texas Commission on Environmental Quality (TCEQ), “H&H Guidelines for Dams in Texas”:

$$= \left(\frac{*}{0.5}\right)^{0.38}$$

Where:

T_p = Lag Time (hours)

C_T = Dimensionless coefficient, calibrated. Generally, ranges from 0.7 to 3.0.

- L = Hydraulic length of watershed along longest flow path (mi)
- L_{CA} = Hydraulic length along the longest water course from the point under consideration to a point opposite the centroid of the drainage basin (mi)
- S = weighted slope of the basin (ft/mi), measured from the 85% to the 10% points along the longest stream path in the basin

The peaking coefficient (C_p) reflects the response characteristics of the basin and generally ranges between 0.4 (flat, slow responding) and 0.8 (steep, rapidly responding).

Parameterization Using USACE Fort Worth District Method – A regional regression equation specific to Texas was developed by the USACE Fort Worth District, as shown below, and is implemented as a standard option within HEC-HMS.

$$\log(\quad) = 0.383 * \log\left(\frac{*}{0.5}\right) + (\% \qquad * (\log(1.81) - \log(0.92)) + \log(0.92)) - \left(\quad * \frac{\%}{100}\right)$$

Where:

- T_p = Lag Time (hours)
- L = Longest flow path within subbasin (mi)
- L_{CA} = Distance along the stream from the subbasin centroid to outlet (mi)
- S = Stream slope (ft/mi), measured from the 85% to the 10% points along the longest stream path in the basin
- %Sand = Percentage of sand factor as related to the permeability of the soils (0% Sand = low permeability, 100% Sand = high permeability
- BW = $\log(T_p)$ bandwidth between 0% and 100% urbanization = 0.266 (log hours)
- %Urban = percentage urbanization factor, per NLCD data

Calibration Using Rain-on-Mesh Model – Lag time (T_p) for Snyder's UH is defined as the difference in time of the UH peak and the time of the centroid of the excess rainfall hyetograph. For a given subbasin, a plot can be generated that includes the excess rainfall hyetograph from HEC-HMS and the discharge hydrograph from the HEC-RAS rain-on-mesh model, as shown in **Figure 3-10**.

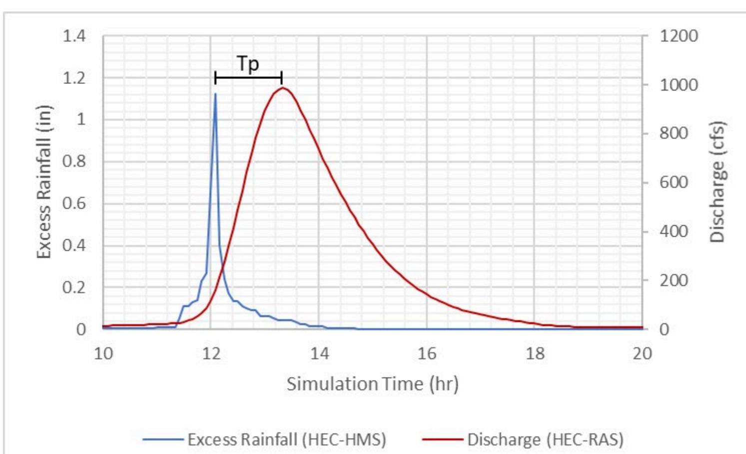

Figure 3-10. Snyder UH – Lag Time Calibration

The centroid of the excess rainfall hyetograph can be calculated through numerical integration. It is recommended to compare the graphically derived lag time with empirically calculated values. If the values reasonably agree, no adjustments are needed. If the two lag time values do not reasonably agree, the Snyder UH parameters (L, L_{CA}, C_T) should be reviewed and adjusted until any discrepancies are reconciled. The rain-on-mesh model is useful for evaluating if the longest flowpath delineation used in the empirical equation is representative of the subbasin. The C_T parameter is primarily found through calibration, so minor adjustments to this parameter may be sufficient to calibrate the lag time.

The peaking coefficient (C_p) can also be informed by the rain-on-mesh results. The peaking coefficient controls the intensity of the response hydrograph. The peak flows and hydrograph shapes from HEC-HMS can be compared with results from HEC-RAS. If peak flows and hydrograph shapes reasonably agree, no adjustments to C_p are needed. If the peak flows do not reasonably agree, C_p can be adjusted until the peak flows match. Bedient and Huber (1992) report that C_p typically ranges from 0.4 to 0.8, as stated in the *HEC-HMS Technical Reference Manual*.

Validation – Values for the C_p should be consistent within each watershed and generally compatible with previous studies, with sample values shown in **Table 3-18**. Deviations should be justified. The initial estimates for T_p and C_p should be within 50% of each calibration event.

Table 3-18. Typical Cp Values

General Area Description	C_p
Flat Coastal Prairies	0.40
Dallas/Fort Worth Metro Area	0.72
Steep Hill Country	0.80

3.5.3. Channel Routing

Channel routing is intended to be used to attenuate the combined runoff hydrographs between junctions and other hydrologic elements. The primary acceptable methods for use under this SOP include Modified Puls and Muskingum-Cunge 8-point.

HEC-HMS offers other methods to account for channel routing such as Lag, Kinematic Wave, and Muskingum. These methods are not recommended for this study; however, the engineer may use these simplified routing methods when detailed channel routing is not required for the watershed. Details on the other methods can be found in the *HEC-HMS Technical Reference Manual*.

Modified Puls

1D Model Process – Developing Modified Puls from 1D HEC-RAS models is a standard practice across the industry with significant background data readily available online. This section will provide a high-level overview of the process. First, a steady flow file should be developed, consisting of an array of flows that cover the expected normal range for the watershed and are large enough to capture the upper limit. A minimum of 15 to 20 flow values should be provided to cover low, in-channel flows up to 500-year and greater discharges. For longer streams, it may be necessary to stage the flow as it moves downstream, as shown in **Table 3-19**.

Table 3-19. Staged Steady –low Data - Example

River	Reach	RS	PF 1	PF 2	PF 3	PF 4	PF 5	PF 6	PF 7	PF 8	PF 9	PF 10	PF 11
River	Reach	10000	1	100	200	400	~~400~~	~~400~~	~~400~~	~~400~~	~~400~~	~~400~~	~~400~~
River	Reach	7500	1	100	200	400	600	~~600~~	~~600~~	~~600~~	~~600~~	~~600~~	~~600~~

River	Reach	RS	PF 1	PF 2	PF 3	PF 4	PF 5	PF 6	PF 7	PF 8	PF 9	PF 10	PF 11
River	Reach	5000	1	100	200	400	600	800	~~800~~	~~800~~	~~800~~	~~800~~	~~800~~
River	Reach	2000	1	100	200	400	600	800	1000	1200	~~1200~~	~~1200~~	~~1200~~
River	Reach	1000	1	100	200	400	600	800	1000	1200	1400	1600	1600
River	Reach	500	1	100	200	400	600	800	1000	1200	1400	1600	1800
River	Reach	100	1	100	200	400	600	800	1000	1200	1400	1600	1800

Based on the results of the staged flows, storage-discharge relationships for each reach can be generated using the "Storage-Outflow output" option in HEC-RAS or by manually inspecting the cumulative volume results parameter at the downstream end of each reach.

In the HEC-RAS routing model, the "Average Travel Time" standard output parameter can be used to estimate an <u>initial</u> number of subreaches. An appropriate profile for each reach should be selected. The difference in average travel time between the upstream and downstream cross sections is used to calculate the hydrograph travel time (K) and number of subreaches, as described below, per the *HEC-HMS Technical Reference Manual*. Results from a 1D or 2D unsteady flow model can also help determine the appropriate number of subreaches.

$$h \qquad (\ ) = \frac{(\text{min})}{1.5}$$

$$\# \qquad h = \frac{}{\Delta}$$

2D Model Process – In watersheds where 2D models are being developed or where 2D BLE models are available, hydraulic results from a preliminary model can be leveraged to develop storage-discharge relationships and calculate routing parameters for Modified Puls hydrologic routing. After completing a preliminary calibration of the rain-on-mesh, the following steps can be implemented to estimate Modified Puls routing parameters.

Stepped Hydrograph – For a given routing reach or set of routing reaches, a stepped inflow hydrograph that covers the range of expected flows can be applied at the upstream end of each reach. In this example, the stepped flow hydrograph uses the same set of flows from the steady-state analysis (described previously, see **Table 3-19**). **Figure 3-11** shows a plot of the stepped flow hydrograph.

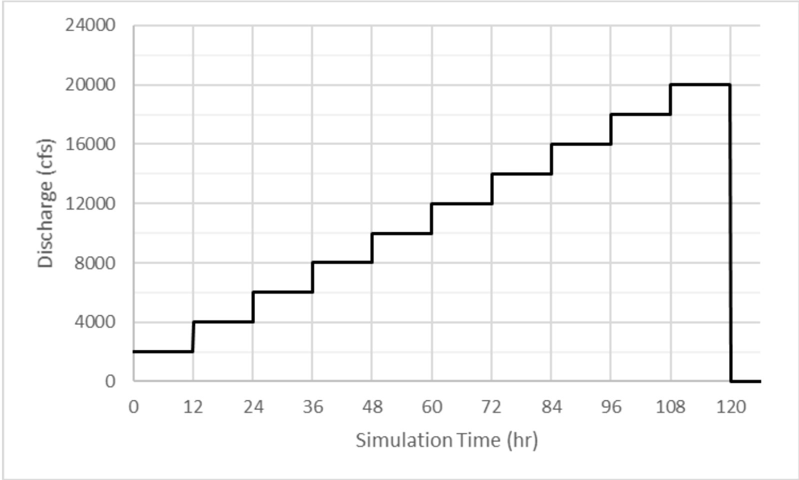

Figure 3-11. Stepped Hydrograph – 2D Modified Puls

A minimum of 15 to 20 flow values should be included in the stepped hydrograph to cover low, in-channel flows up to 500-year and greater discharges. In addition, the duration of each flow step should be sufficient to allow the total outflow at the downstream end of each reach to approach a constant value.

Storage-Discharge Relationship – Within HEC-RAS, reference lines can be added at the upstream and downstream end of each hydrologic reach, as shown in **Figure 3-12**. These will be used to generate flow hydrographs from which a storage-discharge relationship can be calculated.

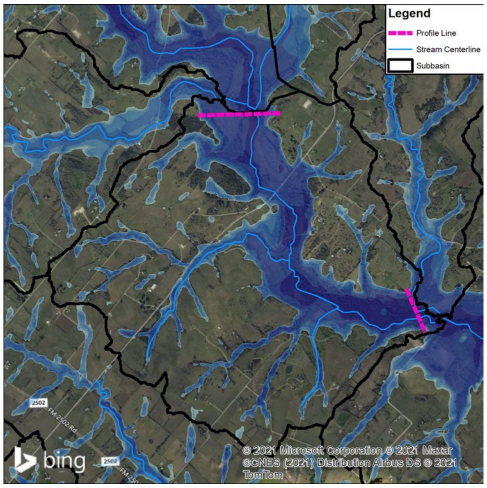

Figure 3-12. Routing Calculation – Reference Line Placement

The discharge time series for the upstream and downstream hydrographs are assembled in a spreadsheet that is used generate a storage-discharge relationship for the reach. An example is shown in **Table 3-20**. An example of the flow hydrographs produced from the reference lines is shown in **Figure 3-13**.

Table 3-20. Storage-Discharge Calculation

Time (hr)	In (cfs)	"Discharge" Out (cfs)	In - Out (cfs)	"Storage" In - Out (ac-ft)
0	0	0	0	0
1	100	20	80	6.6
2	400	100	300	24.8
3	600	200	400	33.1
4	1000	500	500	41.3
…	…	…	…	…

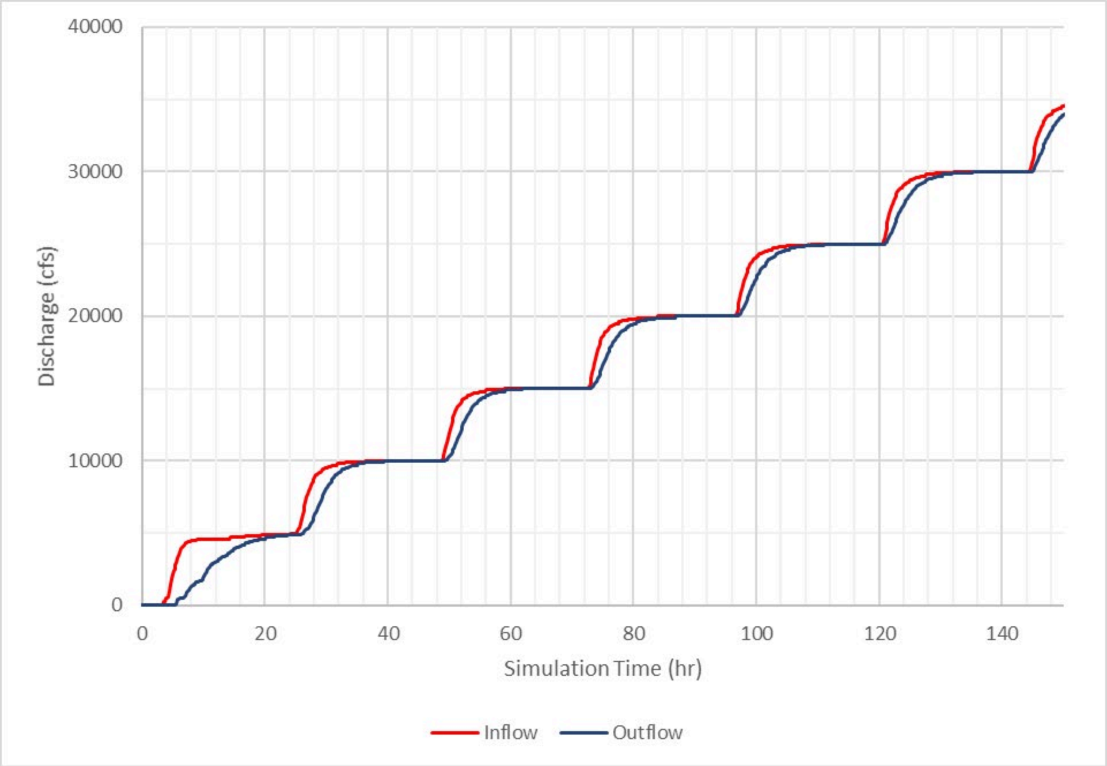

Figure 3-13. 2D Modified Puls Hydrographs

The incremental storage volume for a given discharge profile can be calculated as the area between the inflow (red) and outflow (blue) curves. The cumulative sum of the incremental storage values can be used to establish storage-discharge relationship for each reach. The curves generated by this process should be evaluated to ensure they produce reasonable attenuation and response characteristics in the discharge hydrographs. The storage volumes from this method should be compared against a 3D GIS calculation of the total water volume in the reach at a moment in time when the inflow = outflow. Differences should be less than 10% to be considered acceptable.

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Number of Subreaches Estimation – Results for the 10% AEP event from the preliminary rain-on-mesh model can be used to estimate the initial number of subreaches. Based on the results of the 10% AEP event, a representative profile can be selected for each hydrologic reach. Using the same flow hydrographs developed for the storage-discharge calculations, the travel time can be calculated for the representative profile as the time at which the downstream hydrograph reaches the designated flow rate minus the time at which the upstream hydrograph reaches the designated flow rate. The initial number of subreaches can then be calculated using the following equation:

$$\# \quad h = \frac{(\quad) * \frac{1}{1.5}}{- \quad (\quad)}$$

For either of the methods presented above, the engineer should use discretion in evaluating calculated parameter values by considering the following:

1. The number of subreaches affects the computed attenuation of the hydrograph. As the number of routing steps increases, the amount of attenuation decreases. The maximum attenuation corresponds to one subreach; this is commonly used for routing through ponds, lakes, wide and flat floodplains, and channels where flow is heavily controlled by downstream conditions.

2. This method tends to overestimate the number of subreaches when compared to observed data and should be considered the upper limit.

This method tends to produce a wide range of subreach values for neighboring reaches that have similar lengths and topographies. Initial estimates should be adjusted to produce a similar number of subreaches per mile for topographically similar reaches. It may be beneficial to include the number of subreaches per mile as a calibration parameter.

Muskingum Cunge 8-point
While Modified Puls is the preferred routing method, particularly for High and Medium Detail streams, the Muskingum Cunge 8-point routing method may be appropriate for Low Detail models or for areas of the model that are not critical to the study. This routing method requires three inputs: cross section, Manning's roughness, and channel slope. **Figure 3-14** provides an example from the *HEC-HMS Technical Reference Manual*.

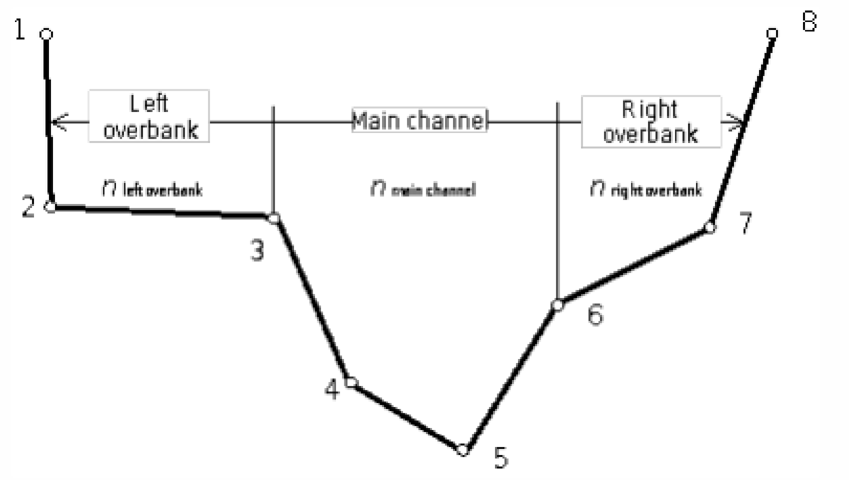

Figure 3-14. Format for Muskingum-Cunge Cross Section

3.5.4. Documentation

Supporting documentation for each main task within this SOP should be included with the final hydrologic report. The sections below summarize the necessary documentation for each task. The engineer should take to care to include additional documentation not covered in this SOP as unique or edge cases are encountered.

Hydrologic Loss Method

A brief report chapter should be provided to document the selected hydrologic loss method and how it was applied to the HEC-HMS model. A companion geospatial database should also be provided, along with the soils data and associated loss parameters used to develop loss rates for the watershed. In addition, any spreadsheets used to calculate loss rates should be provided. If a lumped approach was used for the study, summary tables of empirically calculated loss rates for each subbasin should be included.

Transform Method

The selected transform methodology and supporting calculations should be documented in a report chapter. Copies of spreadsheet calculations should be included. A geospatial database should be included with any physical parameters required for the methodology (e.g., longest flowpath).

Channel Routing

The methodology used to develop routing and supporting calculations should be documented in a report. The following should be included as applicable to the study area.

- Modified Puls – Storage-discharge relationships, calculations, and routing step calculations; profile line locations if developed from 2D.
- Muskingum 8-point – Geospatial database of cross sections and spreadsheets with station-elevation data.
- Routing Reaches – Geospatial database of routing reaches, with attributes noting relevant data such as routing method, length, slope, etc.
- Other – If other routing methods were applied, locations where they were applied, and any relevant calculations should be included.

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Transform Parameter Calibration

If transform parameters were adjusted based on the rain-on-mesh model, the materials listed below should be included. In addition to the plots and tables described below, a report that describes the calibration approach and results should be provided.

1. Plots
    a. Hydrographs – Uncalibrated HEC-HMS, Rain-on-Mesh, Calibrated (2D Informed) HEC-HMS.
2. Tables
    a. Excess Rainfall Centroid (time), Time to Peak (ROM), Uncalibrated Lag Time, Calibrated Lag Time.
    b. Uncalibrated TC, Rain-on-Mesh Lag Time, Calibrated TC.
    c. Uncalibrated Storage Coefficient, Calibrated Storage Coefficient.
    d. Snyder Peaking Coefficient, CP.

3.6. Hydrologic Calibration

This section documents the standard operating procedures for calibration and validation of hydrologic models. The HEC-HMS model of the watershed being studied should be the primary hydrologic model from which the flows are generated and input into the HEC-RAS hydraulic model. The HEC-HMS model should be calibrated with the observed data, where available, and compared with rain-on-mesh model output in areas where observed data is not available. The HEC-HMS model development process is described in detail in other sections of this SOP.

3.6.1. Storm Event Selection

Selection of storm events is important for hydrologic and hydraulic model calibration and validation. The following factors should be taken into consideration in the selection of storm events.

1. At least five (5) storm events should be used for this analysis. Three (3) storm events should be chosen for calibration and two (2) storm events should be chosen for validation. The storm events should be from the recent past, if possible.

2. The storm events should cover a range of intensities and durations to calibrate/validate to low flow, bank full, and overbank flooding conditions. At least one (1) extreme (low frequency) storm event should be chosen for calibration as well as validation. Similarly, at least one (1) small (high frequency) storm event should be chosen for calibration as well as validation. In areas where adequate data is not available or there have not been at least five storm events in the recorded history, then available storm events should be used, and appropriate documentation should be provided regarding the accuracy of the model.

The selected storm events should also reflect variability in seasons, antecedent soil moisture conditions, and baseflow conditions, as best as possible.

All the selected storm events should have adequate and reliable rainfall and flow gage data. Adequacy and reliability of data should be based on engineering judgment, but the general guidelines are as follows:

- The adequacy of the data is dependent on the data available for a particular watershed. Events should be selected which have reliable observed data at the greatest number of gages. Important storm events should be included.

Reliability of data can be evaluated based on corroboration of data from multiple sources. For example, the peak of the stage hydrograph can be compared to surveyed high-water marks. Similarly, gridded rainfall data can be compared to local rain gages.

Study teams should also note that low flow calibration events should evaluated with caution. During the hydraulic calibration process of the Central Region pilot study, both USACE and the modeling team observed a poor match to observed data for the beginning of the rising limb and end of the falling limb of the response hydrograph during historical events. A lack of bathymetric data was determined to be the primary cause of this behavior. While calibration to larger events will generally be prioritized within the GLO RBFS, study teams should consider incorporating bathymetric data where possible for a better calibration to low flow events.

3.6.2. Data Collection and Processing

Observed hydrologic and hydraulic data is needed to calibrate and validate model results for the selected storm events. The observed data should be gathered and organized to make it useable for the calibration and validation process. The observed data collection items and data organization process is described below.

Radar rainfall data – The underlying sources of rainfall data will be the NWS Stage IV QPE and the MRMS QPE w/ Gage Bias Correction. Customized gage adjusted radar rainfall data sources (e.g., RainVieux or similar) may also be used in cases where detailed modeling is desired or in smaller watersheds where a higher resolution of rainfall data may be needed for good calibration or validation. It should be noted that customized, commercial products must be purchased from third parties, whereas NWS data is free. There is also third-party processing time associated with acquiring customized data. Procedures for developing the rainfall data are presented in **Section 3.4.** When developing rainfall data, it is important to ensure that conversions are implemented to be consistent with gage data. Radar rainfall data is typically available in UTC, whereas the gage data is in local time, which is Central Standard Time (CST) for the region.

Areally averaged & gridded rainfall data – There are two options of incorporating rainfall data within HEC-HMS models: areal-averaged rainfall data and gridded rainfall data. For areal-averaged rainfall data, the spatially distributed rainfall data is averaged over each subbasin. In grided rainfall data, a 2D grid is used to define the rainfall over the watershed. In both cases, the rainfall data is developed in tabular format in HEC-DSS for use within HEC-HMS. Hydrologic Engineering Center's Meteorological Visualization Utility Engine (HEC-MetVue) or the Vortex tool can be used to process this rainfall data. This process of developing the data is documented in **Section 3.4** and **Section 3.9.** A maximum time interval of 1 hour should be used, though smaller time intervals may be preferred in some instances. For example, smaller time intervals may be needed in smaller subbasins that experience sharper peaks in flow so that the peaks are represented accurately. Reliability of the radar rainfall data should be evaluated through comparisons with gage data.

Observed stream flow and stage data – Flow and stage times series data should be gathered from the available gages for the selected storm events. Data should be organized in tabular and graphical formats for comparison with model results within and outside the models. The tabular format of observed flow data may be incorporated into HEC-DSS, which may be used to display the data within the HEC-HMS or HEC-RAS models for immediate comparisons with the model results. Typical sources for observed data include USGS, NOAA, USACE, counties, and municipalities. The observed flow data at gages is generally derived from observed stage data using the existing stage-discharge rating curves

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for the gage. Rating curves are generally updated over time, which can affect the consistency in how flows were estimated for different storm events. Therefore, field measurements of flow should also be acquired for comparisons with gage data and for addressing any discrepancies, as discussed in **Section 3.3**. Collecting gage data for the week preceding the storm event can help inform selection of initial conditions related to antecedent moisture conditions.

Reservoir operation data – Reservoir operation data may be required to accurately account for flows and stages in a particular reach. Reservoir data sources typically include USACE, states, counties, and municipalities. It may also be necessary to consider the effects of private dams. Procedures for acquiring and processing reservoir data are presented in **Section 3.10**. For reservoirs, the following data may be considered.

- Reservoir elevation vs area/volume data
- Reservoir time vs outflow data
- Reservoir time vs stage data
- Reservoir stage vs outflow data
- Reservoir gate/spillway geometry and operation data or rating curve data

Contemporaneous watershed characteristics – Contemporaneous watershed characteristics include data such as existing land use, seasonal vegetation, lake levels, etc. that were collected during the selected historical storm events. This information will be useful in developing accurate models representative of the conditions that existed during the selected storm events. This data may be acquired from historical aerials from Google Earth, National Agriculture Imagery Program (NAIP), or USDA. Other data sources include local land use maps, record drawings, etc.

3.6.3.HEC-HMS Model Preparation

The HEC-HMS model for the watershed should be updated with rainfall data from each of the selected historical storm events. If grided precipitation and infiltration are being used, the models should be updated accordingly. The hydrologic routing reaches should be updated with the Modified Puls Method or Muskingum-Cunge routing method for simplicity of calibration/validation of hydrologic routing. Reservoirs within the model should be updated with observed data.

3.6.4.HEC-HMS Model Calibration

Model calibration is performed by adjusting the parameters within HEC-HMS models to best match the HEC-HMS computed flow hydrographs with the observed flow hydrograph data in terms of peak flow, hydrograph volume, and hydrograph shape.

It should be noted that the observed flow hydrograph data at gages is generally derived from observed stage data using the stage-discharge rating curve for the gage. Field measurements are recorded infrequently. The rating curve is based on assumptions that may or may not be valid for certain ranges of flows/stages. Some portions of the rating curve may diverge from actual channel hydraulics. Therefore, before calibrating the hydrology to gaged flows, the rating curves should be compared to field flow measurements and adjusted as necessary. Inconsistencies in the rating curve should be noted for consideration during hydrologic calibration. It may also be beneficial to validate rating curves with results of the calibrated hydrologic/hydraulic models.

The following process is recommended for model calibration.

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Calibrating to gages at the downstream end of a subbasin

Subbasin parameter adjustment – If there is a single subbasin upstream of a gage, then the subbasin parameters should be adjusted to achieve best calibration. The hydrologic methods to be used are recommended below; however, other methods may be used if deemed necessary or beneficial.

Baseflow parameter adjustment – First, baseflow parameters should be adjusted using the Recession Method. The initial discharge parameter can be adjusted to match the observed flow at the start and end of each event. The recession constant can be adjusted to match the slope of the receding limb of the observed hydrograph and the ratio of the peak to observed flows at the end of the calibration event.

Infiltration parameter adjustment – The infiltration parameters should be adjusted to match the observed runoff hydrograph volume. Both the Initial Deficit and Constant Loss Method and the Green-Ampt method are recommended for calibration models. The initial deficit should be adjusted to reflect the antecedent moisture condition and to match the rising limb of the flow hydrograph. The constant loss should be adjusted to match the observed hydrograph volume. If the Green-Ampt method is used, similar adjustments to the initial content and conductivity should be implemented.

Hydrograph transformation parameter adjustment – The Clark UH, ModClark UH, or Snyder UH method should be used. The hydrograph transformation parameters should be adjusted to match the hydrograph shape and timing of the peak. The recommended process for the Clark UH Method is described below, and a similar approach can be implemented for other methods, with exceptions noted.

- The time of concentration should be adjusted to match the peak timing and the storage coefficient should be adjusted to match the hydrograph shape (see example comparison in **Figure 3-15**), particularly for the falling limb. Modification of the storage coefficient can have cascading effects downstream; therefore, the values should be adjusted systematically from upstream to downstream.

When using the Snyder UH method, the peaking coefficient and ratio of R/(Tc+R) should generally be consistent on a regional basis. The Snyder peaking coefficient generally ranges from 0.4 for sluggish watersheds to 0.8 for steep or urbanized watersheds. Values of the R/(Tc+R) ratio should generally range from 0.1 for highly urbanized or flashy watersheds to 0.7 for sluggish, flat, or swampy watersheds.

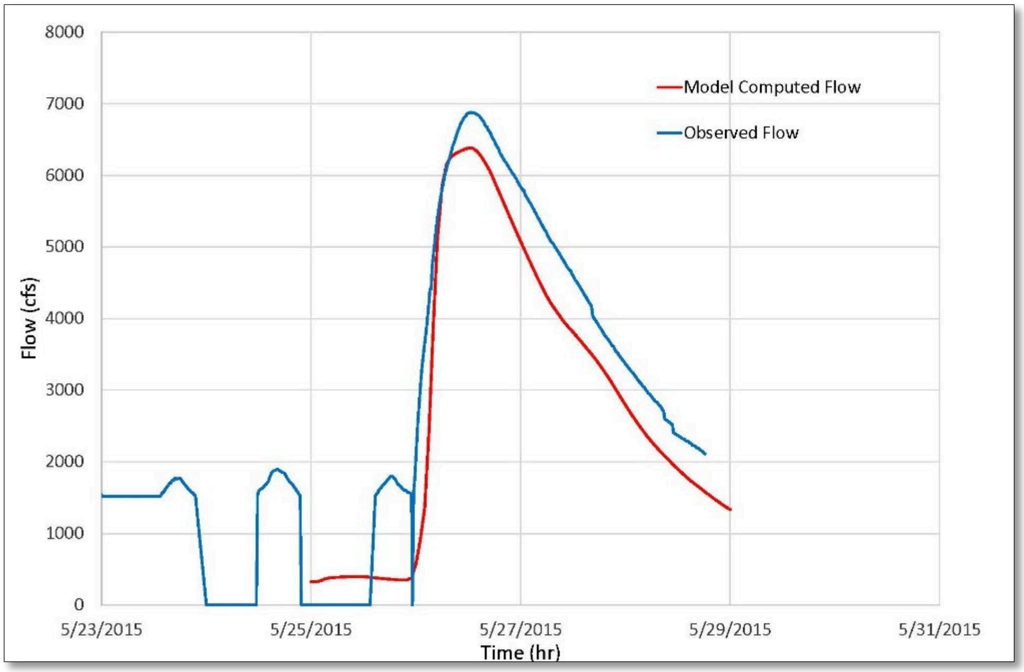

Figure 3-15. Example Modeled vs Observed Flow Hydrograph Comparison at a Gage Location

All parameters should be adjusted within reasonable limits. Refer to **Section 3.5** for reasonable parameter values.

Calibrating to gages along a reach junction
If the gage is located along a reach junction (i.e., HEC-HMS junction along a single reach or confluence of multiple reaches), then the hydrologic routing parameters should be adjusted in addition to the subbasin parameters. If reservoirs are present upstream of the observed gage, reservoir operation data should be included.

Upstream subbasin parameter adjustment – All upstream subbasin parameters should be adjusted uniformly, unless there is justification to use different parameters for specific subbasins (e.g., spring-fed subbasin or subbasins with varying soil conditions, antecedent moisture conditions, excessive surface ponding, etc.).

Hydrologic routing parameter adjustment – The Modified Puls or Muskingum-Cunge routing method is recommended for calibration. Approaches for developing Modified Puls routing parameters are described in **Section 3.5**.

- The number of sub-reaches within the Modified Puls method can be adjusted.
- The channel geometry, Manning's roughness, and slope can be adjusted for the Muskingum-Cunge method.

Reservoir routing parameter adjustment – Depending on the availability of data, this could include adjustments to outfall structures, outfall rating curves, storage curves, or other features associated with reservoir operations during the event.

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The parameters should be adjusted within reasonable limits. Refer to **Section 3.5** for reasonable parameter values. A rain-on-mesh model may be used for guidance if reasonable parameters are not yielding good calibration.

Developing parameters for validation events
After calibrating the subbasin and routing parameters for each event, there are two ways to develop parameters for validation events depending on the sensitivity of the parameters in a particular watershed:

- Parameters can be averaged for all calibration events.
- Parameters can be set equal to a particular calibration event that is similar in magnitude to the validation event.

Some parameters such as initial baseflow, initial loss, and constant loss are highly variable between storm events and will commonly require adjustment for validation events to reflect contemporaneous watershed conditions. The parameters may need further adjustment while performing hydraulic calibration (i.e., through known high-water marks).

Evaluation of calibration quality
Statistical metrics, numerical/graphical comparisons, and engineering judgement should be used to evaluate the quality of calibration.

Relevant statistical metrics – These include the Coefficient of Determination, Nash-Sutcliffe Efficiency Coefficient, Percent Bias (PBIAS), and Root Mean Square Error-Standard Deviation Ratio (RSR). Performance ratings associated with the statistical metrics are provided in **Table 3-21** and were developed as part of the InFRM WHAs.

- **Numerical comparisons** – These include differences in hydrograph volume, peak flow, and peak time (see
- **Table 3-22**).

Visual comparisons – These generally include hydrograph shape (rising and falling limbs), hydrograph peak, and peak timing (see **Figure 3-15**).

Engineering judgment – This involves understanding the sensitivity of parameters, discrepancies in observed rainfall and gage data, and limitations of the model in determining the best possible calibration.

Table 3-21. Statistical Model Performance Metrics

Performance Rating	NSE	PBIAS	RSR
Very Good	0.80 ≤ NSE < 1.00	PBIAS < ±15	0.00 < RSR ≤ 0.60
Good	0.70 ≤ NSE < 0.80	±15 ≤ PBIAS < ±20	0.60 < RSR ≤ 0.70
Satisfactory	0.50 ≤ NSE < 0.70	±20 ≤ PBIAS < ±30	0.70 < RSR ≤ 0.80
Unsatisfactory	NSE ≤ 0.50	±30 ≤ PBIAS	RSR > 0.80

Table 3-22. Modeled vs. Observed Peak Flow, Hydrograph Volume, and Time to Peak Comparisons at Gage Locations

		Storm Event 1

Gage Location	River Sta.	Model Q (cfs)	Observed Q (cfs)	% Diff.	Model Vol. (ac-ft)	Observed Vol. (ac-ft)	% Diff.	Model Peak Time (hr)	Observed Peak Time (hr)	% Diff.
Location 1	10,000	10,000	10,800	-7%	7,500	8,150	-8%	20	18.5	8%
Location 2	20,000	5,000	4,700	6%	3,300	3,400	-3%	16	17	-6%

3.6.5.Comparisons with Rain-on-Mesh Model

Typically, in upstream portions of the main channel and tributaries, gages (i.e., observed flow data) are not available for calibration. In such areas, flow hydrographs from the HEC-HMS model should be compared with the flow hydrographs from the rain-on-mesh 2D model to improve the reliability of the HEC-HMS model and to improve calibration at gage locations. The following process should be followed.

1. Comparisons between the HEC-HMS model and the rain-on-mesh 2D model should be made at key locations. Key locations include sub-basin outfalls, reach junction points, and stream confluences.

2. The rain-on-mesh 2D model development and application of boundary conditions should follow the guidelines provided in **Section 3.2**. A moderate level of detail is considered adequate for this task to avoid excessive run times.

   Gridded rainfall data developed for HEC-HMS based on procedures described above should be used within the rain-on-mesh 2D model.

3. Infiltration and hydrograph transformation parameters should be adjusted within the HEC-HMS subbasins to best match the rain-on-mesh flow hydrographs at subbasin outfalls using the process described above for calibration. To best match at reach junctions and stream confluences, Modified Puls or Muskingum-Cunge routing parameters within the routing reaches should be adjusted. Initial Modified Puls routing parameters can be obtained from RAS Mapper from the rain-on-mesh 2D model. The methodology for utilizing Modified Puls routing method is described in **Section 3.5**. Other routing methods may also be used as determined to be suitable.

3.6.6.Documentation

The following documentation should be prepared for all the storm events.

1. Plots
   a. Flow hydrograph comparison plots – HEC-HMS model vs observed data and HEC-HMS model vs rain-on-mesh 2D model (see **Figure 3-15**).

2. Tables
   a. Peak flow comparison tables – HEC-HMS model vs observed data and HEC-HMS model vs rain-on-mesh 2D model. The flow comparison tables should include percent difference values (see example
   b. **Table 3-22**).

   c. Hydrograph volume comparison tables – HEC-HMS model vs observed data and HEC-HMS model vs rain-on-mesh 2D model. The volume comparison tables should include percent difference values.
   d. Tables of calibration performance metrics – Tables such as the Coefficient of Determination, Nash-Sutcliffe Efficiency Coefficient, PBIAS, and RSR, as described in **Section 3.6.4**.
   e. Table of calibrated hydrologic parameters for each storm event and final calibrated parameters.

3. Other
   a. Explanation of deviations between HEC-HMS model flows and observed/rain-on-mesh 2D model flows.
   b. Documentation of statistical analysis and model performance.

3.7. Future Land Use Conditions

This section documents the standard procedure that will be used to address the simulation of future land use conditions for hydrologic model development.

The purpose of the future land use conditions assessment is to support the evaluation of future with-project and without-project scenarios. In areas where specific projects have already been identified, future without-project scenarios can be evaluated during Phase 3 baseline conditions modeling. In other areas where specific projects have not yet been identified, future conditions land use assessment should be postponed until the Phase 4 alternatives analysis. This approach is expected to be further developed during Phase 3 and more widely applied during Phase 4.

3.7.1. Future Land Use Conditions Assessment

If future without-project conditions are evaluated during Phase 3, hydrologic modeling should include a limited number of simulations (for example, just the 1% AEP for riverine flooding evaluation). This modeling will be useful in obtaining an initial assessment of future flood risk and may influence the decision for the location and type of future projects.

When a proposed project has been identified, the modeling team should run future conditions simulations for additional AEP events as appropriate, based on the location and type of project and the existing and future land use conditions of the watershed. For coastal influenced modeling, the need to consider future conditions will be assessed on a case-by-case scenario. The future conditions flooding assessment should begin after the existing conditions hydrologic models are 100% complete and the hydraulic models are at least 75% complete.

First, the modeling team should locate the most appropriate future land use conditions projections, published by a reliable source. Priority should be given to land use projections that have been published by local municipalities, authorities, and/or drainage districts within the study area. If this information is not available, then it is recommended to use USGS Conterminous US Land Cover Projections, which provide 17 land cover classes and annual land cover maps from 1992 to 2100. The benefit of this dataset is that it includes the same land use classifications as the NLCD database that is used for the assessment of existing conditions. The year that will be used for the analysis should be selected to match the latest projection of the sea level rise (SLR) projection. For example, if the latest SLR projection is for 2085, then the future conditions land use for the same year should be used. Near the coastal zone, the potential impacts that SLR will have on future land use should be taken into consideration, and engineering judgment should be used to determine if adjustments to the projected maps are required.

With adequate justification, the modeling team may choose to use a different projection year or a different source of land use projections, such as the Environmental Protection Agency (EPA)'s Integrated Climate and Land Use Scenarios dataset (ICLUS-Scenarios SSP2 RCP4.5), which includes land use projections for every decade. During Phase 4 pilot testing, the usability of the two datasets (i.e., USGS Conterminous Projections vs. EPA ICLUS) will be compared and a more informed recommendation will be made. The modeling teams should coordinate to ensure consistent datasets and projection years are used for each study area.

After the selection of the land use projection maps, the hydrologic analysis will be repeated with the future land cover. The primary model changes due to future land use will be the determination of infiltration parameters and (typically reduced) runoff response times. The exact application of the future land use will depend on the hydrologic method that is used. For impervious cover, since there is not a 1:1 correspondence with NLCD land use codes, it is recommended to apply the land use predictions as a 'difference' between the 2019 and 2085 projections, and then to add that difference to the 2019 NLCD. For models that use NRCS curve numbers (for example, an existing model from a previous study), the team will assess the 2019 to 2085 increase in curve number (CN) for a subbasin (or, possibly, gridded area) and add that value to the 2019 NLCD, limiting to no higher than the maximum allowable value. Where the values are indexed and not based on a numeric value like CN or percent impervious cover, the team will assign equivalent codes for the NLCD analysis in 2019 and 2085 and process the projected land cover in the same fashion as the base hydrology. Subsequently, the team will confirm that the 2019 results are similar to the NLCD 2019 results so that the 2085 differences are likewise reasonable.

After the hydrologic analysis for future conditions is complete, the modeler should consider changing the Manning's roughness in certain areas within the watershed. Because the resolution of the USGS land cover projections is low (i.e., 250m x 250m), it is not recommended to import the future maps directly in HEC-RAS. Instead, the modeler should review the maps and exercise judgment to adjust the roughness values for future conditions.

It is also recommended that any long-term hydraulic projects that have been announced by local or federal authorities be included in the future conditions hydraulic runs, as long as those projects have secured funding. Considerations about the assessment of future conditions in coastal influenced models are discussed in the **Section 5**.

- USGS Conterminous US Land Cover Projections 1992 to 2100 – https://www.sciencebase.gov/catalog/item/5b96c2f9e4b0702d0e826f6d
- EPA Integrated Climate and Land Use Scenarios – https://iclus.epa.gov/

3.8. Storm Shifting

Storm shifting can be used to produce "what-if" scenarios for watersheds, counties, and other municipalities that had near-misses from major storm events. It can also be useful to validate rainfall-runoff results, particularly if there are discrepancies with flow frequency analysis results. Storm shifting will only be used for High Detail studies.

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It is recommended that selected storms have rainfall depths similar in magnitude to a 1% or 0.2% AEP NOAA Atlas 14 depth for the location of interest.

3.8.1. Limitations

There are limitations that should be considered when shifting storm events, including meteorological and orthographical limits. Specific limits are not defined within this SOP and should be established at the discretion of the engineer. It is recommended that storms be translated only and not rotated, since this may diminish the plausibility of the storm-shifting scenario.

Guidelines from "Site-Specific PMP for North Texas: Bringing HMR 51 in to the 21st Century" (Kappel et al. 2012) may be considered in determining appropriate limits:

1. Storms must not be transposed to an elevation of +/- 1,000 feet from the storm location
2. Storms must not be transposed more than +/- 6 degrees of latitude
3. Storms within 50 miles of the coastline cannot be transposed

3.8.2. HEC-MetVue

HEC-MetVue is recommended for implementing storm shifting adjustments due to its ability to load different file formats (such as HDF, NetCDF, XMRG, ESRI ASCII grid, GRIB, and HEC-DSS). Final storm shifting outputs will be stored in HEC-DSS format or as subbasin average hyetographs.

3.8.3. Antecedent Moisture Conditions

Since storm shifting is intended to realize the effects of a near-miss situation, the calibrated loss rates from the same time period as the un-shifted historical storm will be used for the shifted storm, when available. When calibrated losses are not available for the time period of the historical storm, losses from the 1% AEP storm can be applied.

3.8.4. Documentation

Report Results Discussion

Storm shifting methods and results should be described in the final report document, including the source, file format, projection, and time zone information of the precipitation data. A description of the translation, as well as the goal of shifting the storm should be discussed to assist the reader in understanding the desired outcome and need for shifting the storm. Some reasons for shifting the storm may involve optimization trials for maximizing precipitation, flow, or elevation for a given point in a model. If automated processes were used, descriptions of the approach and results should be included.

Results to be documented in the report should include the basin totals and subbasin averages, which can be computed by HEC-MetVue natively.

Output data formats should be discussed to indicate whether subbasin hyetographs or gridded data were output for use in the hydrologic and/or hydraulic modeling.

3.9. Areal Reduction & Elliptical Storms

Areal reduction of point rainfall estimates is critical to producing realistic flow estimates based on the size of a storm. This SOP includes a standard approach for areal reduction for locations with small contributing drainage areas, as well as a more complex implementation of elliptical storms for locations with large contributing drainage areas. This section was inspired from the items outlined in Section 1.6 – 'Rainfall Runoff Modeling' of the *USACE Minimum Standards*.

Typically, areal reduction factors and elliptical storms have been implemented within the framework of steady-state flows. Each gage or node in the hydrologic network is evaluated using a separate areal reduction factor or elliptical storm, and the resulting peak flows are integrated in a single hydraulic model simulation.

For unsteady hydraulic modeling, a separate simulation is required for each areal reduction factor. Furthermore, adjustments to boundary conditions are necessary to enable integration of results from multiple simulations. Given the additional complexities associated with unsteady modeling, it is recommended to adopt a simplified approach for initial flood risk evaluations and to reserve site-specific evaluations for the alternatives analysis.

Specifically, it is recommended to run three scenarios for the initial flood risk evaluation: (1) no areal reduction, (2) uniform areal reduction using the contributing drainage area at the basin outfall, and (3) nonuniform areal reduction for junctions near High Detail communities with known projects for evaluation. Once mitigation alternatives have been identified and prioritized, refinements to the areal reduction factors or elliptical storms can be implemented, as necessary.

3.9.1. Methodology

The NOAA Atlas 14 precipitation frequency estimates are applicable to discrete spatial locations. When applying the precipitation frequency estimates across broader areas, reductions must be applied to account for the limited areal extents of actual storm events. The NWS Technical Paper 40 (TP-40) includes a recommended areal reduction curve based on a study from 1961, which is implemented in the HEC-HMS software for drainage areas up to 400 square miles. Although HEC-HMS can execute computations for drainage areas larger than 400 square miles, the areal reduction will be the same as that for a drainage area of 400 square miles. Analysis from the InFRM WHA for the Guadalupe River Basin determined that peak flow results from the uniform rainfall method were generally within 10% of the elliptical storm method for drainage areas up to 1,500 square miles. The InFRM WHA report concluded that this uniform areal reduction method could provide reasonable peak flow estimates for drainage areas up to 1,000 square miles.

For the GLO project, the TP-40 uniform areal reduction can be applied for contributing drainage areas up to 1,000 square miles. Elliptical storms should be applied for contributing drainage areas greater than 1,000 square miles. Elliptical storms may also be considered for contributing drainage areas between 400 and 1,000 square miles if there is a need to improve confidence in the results, such as in populated areas, locations with significant flood risks, or locations with proximity to an identified mitigation alternative.

The Depth-Area Analysis tool in HEC-HMS automates the process of developing a separate frequency storm or hypothetical storm for each evaluation point. The analysis requires the specification of an underlying basin model and meteorologic model. The depth-area analysis also requires the specification of analysis points. For existing conditions, the following analysis points should be considered:

1. No reduction
2. Watershed outlet (Full reduction)
3. Stream gage(s)

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4. Junctions near populated areas with known projects for evaluation

To create a new depth-area analysis, the following steps can be implemented:

1. Navigate to Compute > Create Compute > Depth-Area Analysis
2. Name the Depth-Area Analysis (e.g., "50% AEP")
3. Select appropriate Basin and Meteorologic Model
4. Add Analysis Points based on the above guidance (analysis points are associated with HEC-HMS elements)

3.9.2. Additional Considerations for Elliptical Storms

The InFRM WHAs cite extensive research to support recommended approaches and parameters for elliptical storm analysis. The InFRM WHA recommendations are adopted for this SOP as summarized below.

Point Precipitation Frequency Estimates – Point precipitation frequency estimates are sampled from NOAA Atlas 14 for the entire elliptical storm. Elliptical storms are developed for the 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, and 0.2% AEPs.

Area – A storm area of 10,000 square miles is used based on an analysis of storm sizes from the available catalog.

Ellipse Ratio – An ellipse ratio of 3:1 is recommended by default. Other ratios may be appropriate based on watershed shape. The InFRM WHA generally considered ratios between 2:1 and 3:1.

Temporal Pattern – The 50% intensity position for the HEC-HMS frequency storm is recommended by default. Other intensity positions or temporal distributions may be implemented if justified by analysis results or for consistency with prior studies.

Duration – A 24-hour storm duration is recommended by default. Longer durations may be implemented for large basins if justified by analysis results or for consistency with prior studies. It is recommended to test a duration that exceeds the time of concentration for the drainage basin.

Depth-Area Reduction – The depth-area reduction factors from the InFRM WHA studies for the Guadalupe, Trinity, or Neches River basins are recommended, as listed in **Table 3-23**. Comparisons to historical storm events in the study area should be developed for High Detail studies to validate or adjust the factors and should only be considered when gage statistics are inconsistent with frequency storms. If new factors are developed, note that these values are the most sensitive parameter for elliptical design storms. In this case, also consider historical storms that occurred near the watershed area. As part of the InFRM WHA studies, USACE has developed recommended approaches for developing depth-area reduction curves using HEC-MetVue.

Table 3-23. Adopted Depth-Area Reduction Factors from InFRM WHA for the Guadalupe, Trinity, and Neches River Basins

Storm Area (sq. mi.)	Guadalupe Reduction Factor	Trinity Reduction Factor	Neches Reduction Factor
10	0.987	1.000	1.000
30	0.967	0.977	0.970
50	0.953	0.960	0.957
100	0.930	0.940	0.936

Storm Area (sq. mi.)	Guadalupe Reduction Factor	Trinity Reduction Factor	Neches Reduction Factor
200	0.905	0.902	0.903
300	0.880	0.875	0.883
400	0.865	0.855	0.867
600	0.835	0.834	0.835
800	0.812	0.818	0.814
1,000	0.795	0.804	0.800
1,500	0.760	0.775	0.772
2,000	0.730	0.752	0.744
2,667	0.705	0.726	0.718
3,500	0.680	0.699	0.689
4,000	0.665	0.685	0.672
4,500	0.650	0.672	0.665
5,000	0.640	0.658	0.657
6,000	0.620	0.637	0.642
6,500	0.612	0.626	0.635
7,000	0.600	0.617	0.628
8,000	0.585	0.599	0.617
9,000	0.570	0.581	0.606
10,000	0.555	0.564	0.594

Optimization
The InFRM WHA approach is recommended for determining optimal elliptical storm locations and rotations. In summary, a shuffled, complex evolution global optimization program is used to determine the x and y coordinates and angle of the elliptical storm that produce the maximum peak flow at a point of interest. A separate optimization is performed for each point of interest for the 1% AEP event. The same locations and rotations are used for other AEP events, but more frequent storms may also need to be optimized in locations where a controlling hydraulic structure has a much lower capacity than the 1% AEP event.

The Fang Research Group at the University of Texas at Arlington developed scripts to automate most steps to develop elliptical storm runs, including generation of elliptical storm rasters, parameterization and execution of the HEC-HMS model, and implementation of global optimization routines. The USACE Hydrologic Engineering Center has continued development of the scripting tool. The latest version of the tool should be utilized to perform the analysis.

3.9.3. Documentation
Report documentation for Areal Reduction and Elliptical Storms should, at a minimum, include the information described below.

Areal Reduction
A brief report chapter should be included which discusses the overall approach to Areal Reduction in the studied watershed. At a minimum the following should be included in the report section:

- Description of Areal Reduction methodology (TP-40, InFRM DAR, etc.)
- Depth Area Reduction Curves
- Figure presenting the analysis points used for Areal Reduction
- Results comparisons between reduced and non-reduced scenarios

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Elliptical Storms
A report chapter should be included which discusses the approach to Elliptical Storms for the studied watershed, key analysis points, and the results the elliptical storm optimization. In addition to the discussion, the following tables and figures should be included, at a minimum.

- Table of Depth Area Reduction Factors
- Figure presenting all analysis points and critical storm center
- Figure presenting the ellipses of the critical elliptical storm
- Figure of point of interest used to determine critical storm center

3.10. Reservoir Analysis

Reservoirs have the potential to significantly alter the magnitude and timing of flows within a river basin. Accurate representations of reservoir features and operations are important to include in hydrologic and hydraulic analyses to properly develop flood risk information and flow frequency statistics.

The InFRM WHA guidance report (version 1.0, October 2019) serves as the primary source for the methodologies presented below, including information from the following sections:

- Section 3.3 – 'Period of Record Analysis with RiverWare'
- Section 3.4 – 'Reservoir Studies'

The USACE has developed several software programs and guidance materials in support of reservoir analysis. The USACE Risk Management Center (RMC) publishes guidance resources on its website.

- USACE RMC Guidance – https://www.rmc.usace.army.mil/Reference-Center/Risk-Assessment/

The following resources for semi-quantitative risk assessment are referenced in this section:

- **RMC-TR-2018-03:** Hydrologic Hazard Methodology for Semi-Quantitative Risk Assessments: An Inflow Volume-Based Approach to Estimating Stage-Frequency Curves for Dams.
- **RMC-TR-2021-02:** Estimating Flood Hazard for Dams and Levees with Upstream Regulation.

The general process for reservoir analysis is summarized as follows:

1. Identify reservoirs with the potential to affect flows at proposed mitigation projects, including reservoirs outside the detailed study area (see **Section 3.10.1**).

2. Collect available information for the reservoir to determine whether new or updated analyses are necessary. Document decision-making criteria and conclusions (**Section 3.10.2**).

Determine whether the period of record should be extended or adjusted for homogeneity. If so, use drainage area ratios and RiverWare to implement period of record adjustments. Document methodologies and results (**Section 3.10.6**).

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Evaluate the effects of regulation to guide which analysis methodologies should be applied. Document results and conclusions (**Section 3.10.6**).

For unregulated systems, use RMC Reservoir Frequency Analysis (RMC-RFA) to develop reservoir stage-frequency curves. If reservoir outlet structures and operations are too complex to be modeled in RMC-RFA, use deterministic modeling software, such as HEC-ResSim, to support coincident frequency analysis of reservoir stages in HEC-SSP (**Section 3.10.7**).

For regulated systems, use deterministic modeling of AEP events and empirical data to develop composite reservoir stage-frequency curves (**Section 3.10.8**).

3.10.1. Applicability

Several factors should be considered before undertaking the approaches described in this section.

First, there should be a proposed mitigation project for the area of interest. In accordance with the scope of the GLO study, if there is not a proposed mitigation project, then it may not be an efficient use of effort to refine flood risk information beyond initial evaluations or previous studies.

Next, the value of additional information that is gained from the analysis should be considered. Before extending the period of record, for example, the number of additional years relative to the original record should be considered. If the base period of record is already sufficiently long and extending the period of record would not have a significant effect on results, then it may not be worthwhile to undertake further analysis. When evaluating the effects of regulation, it is recommended to have at least 20 years in the period of record for the pre- and post-regulation datasets, respectively. If the regulation occurred in the middle of the period of record, then a minimum of 40 years would be necessary. Longer periods of record may be necessary depending on the timing of when regulation began. In any case, the uncertainty in statistical estimates should be considered and evaluated relative to relevant portions of the flow regime and associated effects on adjacent infrastructure.

Unique characteristics of each reservoir must also be considered, including the area of influence of the reservoir, the date the reservoir was constructed, the physical and operational characteristics of the reservoir (e.g., flood control, hydropower, water supply, etc.) and their corresponding effects on the flow regime, and any changes to reservoir operations that have occurred through time.

Finally, existing models and studies should be leveraged to the extent possible. The availability of existing models and studies may determine whether it is worthwhile to undertake reservoir analyses.

It may be necessary to consider the effects of reservoirs outside the area of detailed study. For example, although Lake Palestine is not within the GLO study area, it is a large reservoir that can have an impact on the Neches River. The modeler may wish to review the upstream reservoir outflow gage and compare to the downstream gages to better understand the relative contribution of reservoir flows versus flows from local drainage areas, as illustrated in **Figure 3-16**, below.

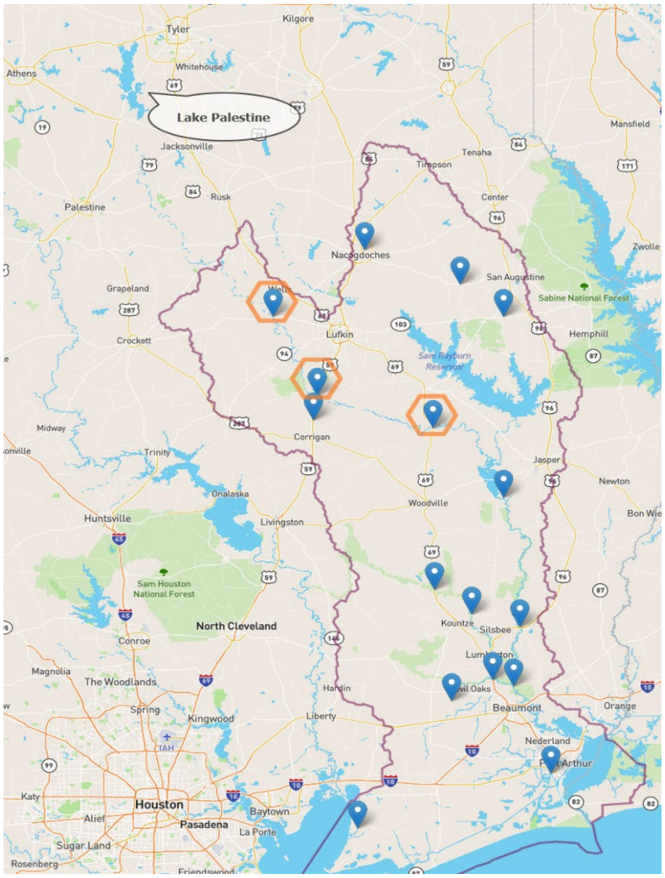

Figure 3-16. Example of Reservoir Outside of Study Area with Downstream Gages

3.10.2. Data Collection

The USACE maintains a National Inventory of Dams that can be referenced to identify reservoir proximity to a proposed mitigation project. Standard maps and aerial imagery can also be reviewed. The TWDB provides descriptive information for major reservoirs on its website.

- USACE National Inventory of Dams – https://nid.usace.army.mil/#/
- TWDB Major Reservoirs – http://www.twdb.texas.gov/surfacewater/rivers/reservoirs/index.asp

TWDB has performed most of the recent hydrographic surveys of Texas reservoirs. The reports for these surveys often contain useful information regarding the history of these projects. Historical reservoir diversions can be obtained from the TCEQ's Texas Water Rights Viewer.

- TCEQ Texas Water Rights Viewer – https://tceq.maps.arcgis.com/apps/webappviewer/index.html?id=44adc80d90b749cb85cf39e04027dbd

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3.10.3. Period of Record Extension

Extending the period of record for gages can reduce uncertainty in the computation of flow frequency and reservoir stage frequency metrics, improving confidence when the metrics are used to validate hydrologic and hydraulic model results. Period of record extension techniques can be used to generate data prior to the availability of recorded gage measurements or to adjust recorded gage measurements to account for non-stationarities that occur during the period of record, such as construction of a reservoir. The goal is to create a homogenous sequence of flows that reflects the current level of basin development, including reservoirs and other factors that could alter flood flows, for the full period of record.

The Drainage Area Ratio method can be used to extend or fill gaps in the period of record. For a gage with a limited period of record, other nearby gages with longer periods of record can be used to supplement missing data. The ratio of drainage areas between the gages can be used to calculate the flow at the gage with missing data based on flows at the gage with available data.

3.10.4. Software

The RiverWare software program, developed by the Center for Advanced Decision Support for Water and Environmental Systems, can be used to model river and reservoir systems. Inputs to RiverWare include USGS stream flow gage data; reservoir pool elevation gage data; drainage area data; records of reservoir inflows, outflows, pool elevations, storage, pumping, evaporation, and precipitation; reservoir elevation-area-capacity tables; discharge rating curves; and operational data from reservoir Water Control Manuals or other sources. Once the model has been calibrated to historical gaged flows, information about reservoir operations and water supply demands can be used to derive homogenous synthetic time series of regulated and unregulated flows for the full period of record. In Texas, USACE has developed RiverWare models within the Neches, Trinity, Brazos, Colorado, Guadalupe, and Red River basins. Other software programs can be used to perform similar analyses; however, RiverWare is generally recommended due to availability of existing models and for consistency with the InFRM WHA studies.

- RiverWare – https://www.riverware.org/

3.10.5. Model Inputs

Reservoir inflows are calculated using a mass balance approach, in which the inflow is set equal to the change in reservoir storage, plus evaporation, total releases out of the reservoir, and net pumpage out of the reservoir, less any water pumped into the reservoir. As a result of inaccuracies in the estimation of these parameters, calculated reservoir inflows are numerically smoothed by scaling positive inflows and rectifying negative inflows. Otherwise, there may be cases in which the reservoir inflows are less than zero. The InFRM WHA white papers include the set of equations and logic that are used to adjust inflows. Daily inflows are adjusted while maintaining monthly total volumes. RiverWare Functions have been developed by USACE in the RiverWare Programming Language to implement the smoothing equations and are available from the Water Resources Branch of the USACE Fort Worth District.

Simulated RiverWare reservoir pool elevations, releases, and flows at USGS gages are compared to historical observations to calibrate the model. Typically, a recent time period between 10 and 15 years is utilized to verify consistent and accurate reservoir operations and water supply demands. Detailed knowledge of reservoir features and operations and engineering judgement are required to interpret possible deviations from normal operations on account of factors such as meteorological forecasts, construction, or non-functional components.

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Daily time-step results from the RiverWare model must be converted to instantaneous flows to be used for frequency analyses. Typically, USGS gage data is used to develop a log-linear regression between daily average and peak instantaneous flows.

A mixed record of observed and simulated values is recommended to be used for flow frequency and reservoir stage frequency analyses. Generally, the observed flows should be used, and simulated flows would only be used for time periods for which observed data was not available or did not reflect current regulation.

3.10.6. Evaluating the Effects of Regulation

Flow frequency, reservoir stage frequency, and flood risk analyses are predicated on the assumption of the stationarity of the system being evaluated. Since reservoirs have the potential to significantly alter the flow regime within a river basin, their construction or change in operations represent non-stationarities which must be considered. Several approaches are available to identify and quantify the effects of regulation. Conclusions regarding the significance of the effects of regulation will determine which approaches can be applied for other types of analysis.

There may be cases where the effects of regulation are negligible or do not affect the portion of the flow regime for which a flood risk reduction project is being developed. A small reservoir, for example, may regulate flows for frequent events but allow large events to pass through unregulated.

For cases in which the effects of regulation are determined to be significant, adjustments to analysis approaches are necessary. Specific recommendations regarding reservoir stage-frequency analysis are provided in the section below. Bulletin 17C flow frequency analysis methodologies preclude the use of regulated flows, since regulation can introduce discontinuities in the flow regime that invalidate assumptions for underlying statistical curve-fitting functions.

The USGS publishes codes to indicate special conditions that affect interpretation of peak streamflow data.

- USGS Peak Streamflow Codes – https://nwis.waterdata.usgs.gov/nwis/peak?help#flow_qual_cd

The following codes indicate the potential for effects from regulation:

- Code 3 – Discharge affected by Dam Failure
- Code 6 – Discharge affected by Regulation or Diversion

Plots of annual peak streamflow can also help visualize non-homogeneities in the period of record caused by regulation. If there are significant peaks early in the period of record, but none after a certain point in time, for example, it may indicate that a reservoir was constructed upstream. Likewise, discontinuities in the trend of flows in a log-normal probability plot can indicate that regulation has occurred during the period of record.

The Kolmogorov-Smirnov test can be used to compare the empirical distribution functions between two samples to determine whether they come from the same population. The test can be applied to compare pre- and post-dam datasets or synthetic datasets of regulated and unregulated flows, such as are output from RiverWare. As detailed in RMC-TR-2021-02, the maximum difference between the empirical distributions is evaluated relative to a calculated variable to indicate whether the samples come from different populations.

Comparisons of cumulative frequency plots can also be beneficial to identify ranges of flows for which the differences in frequencies are greatest. This may clarify whether regulation affects the portion of the flow regime that is relevant for a proposed mitigation project.

3.10.7. Reservoir Stage-Frequency Analysis for Unregulated Flows

The USACE has developed the “Hydrologic Hazard Methodology for Semi-Quantitative Risk Assessments” to estimate reservoir pool elevation frequency curves and associated outflows. The reservoir stage-frequency curve is determined by fitting analytical distributions to stochastic simulation results, as implemented in the RMC-RFA software program. The RMC-RFA program routes inflow hydrographs through the reservoir for varying initial pool elevations, including considerations for seasonality. Statistical distributions of the model inputs are used to reflect natural variability and knowledge uncertainty. RMC-TR-2018-03 includes guidelines and step-by-step instructions for developing inputs and implementing analyses. Key inputs are summarized below.

Inflow Volume-Frequency Curve – This curve gives the frequency distribution of reservoir inflow volumes for the critical duration. The critical duration, or the duration which results in the highest reservoir stages, is typically determined through assessment of historical events. Inflow volumes are then determined for a specified duration. Typically, a “family” of curves for multiple durations is generated to determine whether statistical parameters should be smoothed for particular durations and to support development of hypothetical frequency events. It is required that inflows represent unregulated conditions, since regulation can invalidate curve-fitting assumptions for the analytical probability distributions.

Flood Seasonality Analysis – The relative frequency of flood events by season is determined empirically from the gage record using routines built into RMC-RFA.

Reservoir Starting Stage Duration Analysis – The percent of time that antecedent reservoir levels are exceeded are determined for the range of stages from the period of record. Separate duration curves are computed for each season by routines within RMC-RFA. Flood events are screened out of the historical gage data based on the rate of change in stage.

Reservoir Model – Modified Puls routing is implemented within RMC-RFA. Reservoir stage-storage-discharge relationships are provided to support routing calculations. Reservoir outlet structures can typically be simplified to approximate stage-discharge relationships. Analysis of gage measurements can also be used to develop stage-discharge relationships.

Inflow Hydrograph Shapes – Multiple inflow hydrograph shapes can be input and weighted. It is preferred to use historical storm events to capture response characteristics of the watershed.

Empirical Stage-Frequency Curve – The empirical stage-frequency curve from historical gage measurements is used to validate results. It can also be used to calibrate input parameters, such as the stage-discharge relationship. RMC-RFA includes capabilities to develop empirical stage-frequency curves using Weibull plotting positions.

The RMC-RFA program can simulate both the expected frequency curve and the median frequency curve. Median frequency curve results do not capture the full uncertainty in the analysis since the

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median does not reflect the effects of infrequent events at the tail of skewed distributions. The expected frequency references the mean and therefore provides a “best-estimate” of the probability of exceedance.

There may be cases in which the Modified Puls routing routines in RMC-RFA do not adequately capture the complexity of a reservoir outlet structure or its operational rules. In such cases, a coincident frequency analysis can be implemented in HEC-SSP as an alternate means to develop the reservoir stage-frequency curve. As described in RMC-TR-2018-03 Appendices A and B, the process involves routing multiple AEP balanced hydrographs through a deterministic model (e.g., HEC-HMS, HEC-ResSim, or RiverWare) for a range of starting pool elevations. The deterministic model results are then used to develop response curves for each starting stage, establishing a relationship between the AEP and reservoir stage.

3.10.8. Reservoir Stage-Frequency Analysis for Regulated Flows

A key requirement for the stochastic analyses implemented in RMC-RFA is the use of unregulated flow data and analytical probability distributions for the inflow volume-frequency curve. For regulated systems, two alternate options are available for developing a reservoir stage-frequency curve, as described in RMC-TR-2021-02. The alternate approaches include: (1) empirical stage-frequency curves and (2) deterministic modeling of AEP events. The empirical and deterministic stage-frequency curves can be blended to supplement one another.

Empirical stage-frequency curves are developed from historical gage data using Weibull plotting positions. The HEC-SSP General Frequency Analysis can be used to develop empirical frequency curves. Empirical curves should not be extrapolated beyond historical observations.

The deterministic modeling approach involves routing AEP events through the reservoir system using modeling software such as HEC-HMS, HEC-ResSim, or RiverWare. The simulated stages are paired with AEP results to define ordinates of the frequency curve.

3.10.9. Reservoir Simulation in HEC-ResSim

HEC-HMS is limited in its ability to accommodate complex operational rules for outlet structures. The HEC-ResSim software includes the ability to simulate rule-based operations. Prior to developing an HEC-ResSim model, existing models, including RiverWare, should be evaluated to determine whether they could be used to develop desired information. HEC-ResSim is organized into three separate modules: (1) Watershed Setup, (2) Reservoir Network, and (3) Simulation. The *HEC-ResSim User's Manual* includes guidelines for setting up and executing a model, as summarized below.

Watershed Setup Module

The Watershed Setup module includes definition of stream alignments and configuration of system features, such as reservoirs, diversions, and computation points. The stream alignment serves as the base structure to which other system elements are referenced. The stream network is composed of the starting/ending nodes, stream segments, and junctions within the watershed of interest. Computation points can be placed along the stream network to enable input and output of data from the model. Several project elements are available to represent features that regulate flow, including reservoirs, diversions, levees, channel modifications, off-channel storage, and other projects. Reservoirs are represented by a storage reach, pool, dam, and two or more configuration points. Routing reaches, diverted outlets, and diversions must be added to connect project elements. Multiple configurations of project elements can be created for comparison. The Network Connectivity Report and Node List summarize elements, sub-elements, and nodes within a reservoir network. Inflows are applied at junction nodes within the stream network. Nine methods are available to route flows through the reaches, including Muskingum, Modified Puls, and lag and attenuation. Multiple options are available to define diversions and losses, including user-defined functions, functions of computed variables, time series, and rules.

Reservoir Network Model

The Reservoir Network module includes specification of physical and operational parameters for reservoirs, as well as definition of the alternatives that will be simulated. A reservoir is made up of several components, including release elements and property elements. Release elements are features that take flows from the reservoir pool whereas property elements record physical properties. Required reservoir elements include the pool and dam. Optional reservoir elements include controlled outlets, uncontrolled outlets, power plants, pumps, outlet groups, diverted outlets, evaporation, seepage, leakage, tailwater elevation, and forebay head loss.

The structure for modeling reservoir operations was developed to support Guide Curve operation, as is typically implemented for USACE reservoirs. HEC-ResSim utilizes Operation Sets to describe the rules, or operational scheme, that will determine reservoir release decisions. The four basic features of an Operation Set are: Zones, Rules, Guide Curve, and Release Allocation.

Zones – The reservoir pool is subdivided into zones that govern the operational rules and constraints. The default zones in HEC-ResSim are Flood Control, Conservation, and Inactive. These zones are defined by reservoir levels and may be adjusted as needed to properly represent the reservoir system. The elevations governing the top and bottom of each zone are defined according to calendar dates to support seasonal adjustments. Conservation pool operations may support multiple purposes, such as water supply, instream flow maintenance, and recreation. The Inactive Zone corresponds to “dead” storage for which no releases can be made. Additional zones can be added as necessary, such as for the surcharge pool (i.e., uncontrolled storage capacity) or for further subdivision of the conservation pool. For each zone, a set of operating rules are defined to determine releases for each time step.

Rules – Rules represent the goals and constraints placed upon releases and typically vary depending on reservoir elevation (i.e., which zone is “active”). Rules are primarily defined using built-in functions and if statements; however, Python-based scripted rules are typically required to simulate more complex operational schemes. Release and downstream control functions and several types of variables are available to support development of operational rules. Rules are also prioritized to resolve conflicting operational goals.

Guide Curve – The Guide Curve concept is a key element in the release decision process. This curve is defined as the top of a specific zone. The basic rule is to get the reservoir pool elevation to the current guide curve level as quickly as possible within the physical and operational constraints of the outlets. For example, when the water surface elevation is within the flood control pool, the goal is to lower the water surface elevation back to the target elevation from the guide curve as quickly as possible within the provided operational constraints (typically to avoid downstream flooding). An operation set without any defined rules will simply follow the basic Guide Curve operations.

Release Allocation – Release allocation options define how releases will be distributed across multiple reservoir outlets such as power plants, gated spillways, diversions, etc. These options are intended to manage releases that are not specifically allocated by a rule to a given outlet. By default, HEC-ResSim uses a Balanced Release allocation that equally distributes releases across all available outlets. An alternative to this approach is the Sequential distribution, which maximizes releases from each outlet

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before making releases from the next available outlet. The order or priority of each outlet is established by the user. A third option, which essentially combines the first two, is also available.

Release Decision Intervals – Another important consideration when defining an Operation Set is the release decision interval. By default, HEC-ResSim determines a release decision for each time step of the simulation (as defined in the Run Control Tab). However, the decision schedule may be different from the model computational time step during real-time operations. A specific release decision frequency may be defined for each reservoir by activating the Decision Schedule feature. The selection of a proper release decision frequency is important to attain realistic results from the reservoir simulation.

Alternatives – Once all physical and operational parameters have been defined in the Reservoir Network, Alternatives may be defined to simulate the reservoir operation scenarios of interest. The main components of an alternative in HEC-ResSim include an operation set for each reservoir, definition of initial simulation conditions, and time series records assigned to pertinent locations. Each alternative follows a unique operation set.

Simulation Module

The Simulation module supports execution of computations and analysis of results. A simulation in HEC-ResSim occurs when a time window and time interval parameters are set for either a single alternative or a group of alternatives. Multiple alternatives (which could have different hydrologic inputs) can be tested under one simulation if they have the same simulation time window. For example, multiple frequency storms could be included in one simulation because their hypothetical hydrographs all start and finish on the same date. Separate simulations are needed for historical storm events since those occur on different dates.

Once results have been analyzed, the Trials feature can be used to test adjustments to parameters and refine operational schemes. Multiple trial simulations can be developed in the model. Each trial is a replica of its parent simulation and is saved separately in the model file structure. Therefore, changes to rules, zones, hydrologic inputs, initial conditions, etc. can be made without affecting the parent simulation. The user has the option of saving the adjusted parameters back to the parent simulation or keeping them as a separate trial simulation.

Multiple types of plots and reports can be reviewed and customized to support calibration and results evaluation. One of the most important reports generated by HEC-ResSim is the Release Decision Report. This report includes the reservoir's Active Zone, water surface elevation, and net inflow for each time step of the simulation. More importantly, this report provides the Active Rule and calculated releases from each reservoir outlet for each computational time step. It is highly recommended to carefully inspect the Release Decision Report for each reservoir element to ensure that results are reasonable and that all operational rules are being applied as intended by the user.

It should be noted that not all differences between the simulation and observed period of record pool elevations will match exactly, as real-world operations and emergency response may warrant deviations from the normal water control plan. Differences should be noted and explained, as applicable. Correspondence with the USACE Fort Worth District Water Management Section chief may be necessary.

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3.10.10. Documentation

It is recommended to document the factors that were considered in making the decision whether to undertake a detailed analysis for a particular reservoir. Documentation of key considerations will aid future reviewers in understanding why certain decisions or assumptions were made.

For any of the analyses described below, comparisons with previous studies should be included, as available. If existing models were utilized, a summary of changes that were implemented should be clearly documented, including justification for differences in results.

Period of Record Extension

For period of record extension, copies of the models should be included. A summary of the model inputs and results should be included to provide context for how the information was developed. Review comment logs should be maintained. The original source gage information, adjacent gages referenced as supplemental data, data or assumptions used to develop supplemental data (e.g., drainage area ratios), and final datasets should be provided and documented.

Effects of Regulation

Any flow data being used for reservoir analyses should be evaluated for effects from regulation, since it determines the available analysis approaches which can be applied. A summary of the analyses that were performed should be developed, including conclusions regarding whether the flow data was determined to be affected by regulation.

Reservoir Stage Frequency

Reservoir stage-frequency analyses inputs and results should be documented. Analysis results should include comparisons between the estimated analytical distributions and empirical distributions from gage data.

3.11. Hydrologic Results Comparisons and Evaluation

This section documents the standard operating procedure for evaluating the final hydrologic model results. This section was inspired from the items outlined in Section 1.0 – 'Hydrologic Analysis' of the *USACE Minimum Standards*.

3.11.1. Level of Detail

This SOP identifies the items required for submittal of a high level of detail RBFS model. While all levels of detail should have some comparison and/or validation of hydrologic results to prior studies and/or gage data, for a model using a lower level of detail, engineering judgment will be used to determine what aspects of the SOP may be relaxed, while still meeting the minimum standards required for the desired funding source.

3.11.2. Previously Completed Studies

Section 3.1 should be reviewed before evaluating the results of the revised studies. Existing flows may be from sources such as the following:

- Existing FEMA BLE studies
- Existing InFRM WHAs
- Existing USACE CWMS models
- Existing effective FEMA FIS frequency flow values, hydrologic methods, and
- available models

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- Other existing hydrologic study models, data and results for the study stream reaches

3.11.3. Statistical Hydrology

In cases where stream gages within or near an approved hydrologic stream reach have at least 20 years of peak annual stream flow data, a statistical hydrology analysis should be performed using Bulletin 17C guidelines. This is described further in **Section 3.3.** The resulting data from these analyses will be used in the comparisons and evaluations as discussed below.

3.11.4. Frequency Flow Comparison

Upon completion of the updated hydrologic analyses, the modeling team should compare results at common locations in both tabular and graphical formats for Peak Discharge vs Annual Exceedance Probability. The frequency curves from each hydrologic method analyzed should be plotted along with their associated confidence limits. Published flows from the associated effective FIS tables should also be plotted. In locations where gaged flows were assessed, the results of the flood frequency analysis should be added to the comparison. It should be noted that many older studies will likely not include the same flow events being studied in the RBFS models (i.e., 20% and 50% AEPs).

The following examples from previous USACE studies (see **Table 3-24**, **Figure 3-17**, and **Figure 3-18**) demonstrate potential approaches for comparing results with multiple methodologies; however, modeling teams should evaluate all available data to determine the best methods of presenting the data. Tabular and graphical information can help confirm that results from a new study are reasonable compared to previous studies and flow frequency analyses.

Table 3-24. Example Peak Flow Comparison from InFRM Trinity WHA

Location A Flow Comparison	50% AEP (cfs)	20% AEP (cfs)	10% AEP (cfs)	4% AEP (cfs)	2% AEP (cfs)	1% AEP (cfs)	0.2% AEP (cfs)
Effective FIS	-	-	103,000	-	147,000	164,000	202,000
–New Study - Method 1	50,060	76,500	93,480	114,000	131,800	148,300	187,400

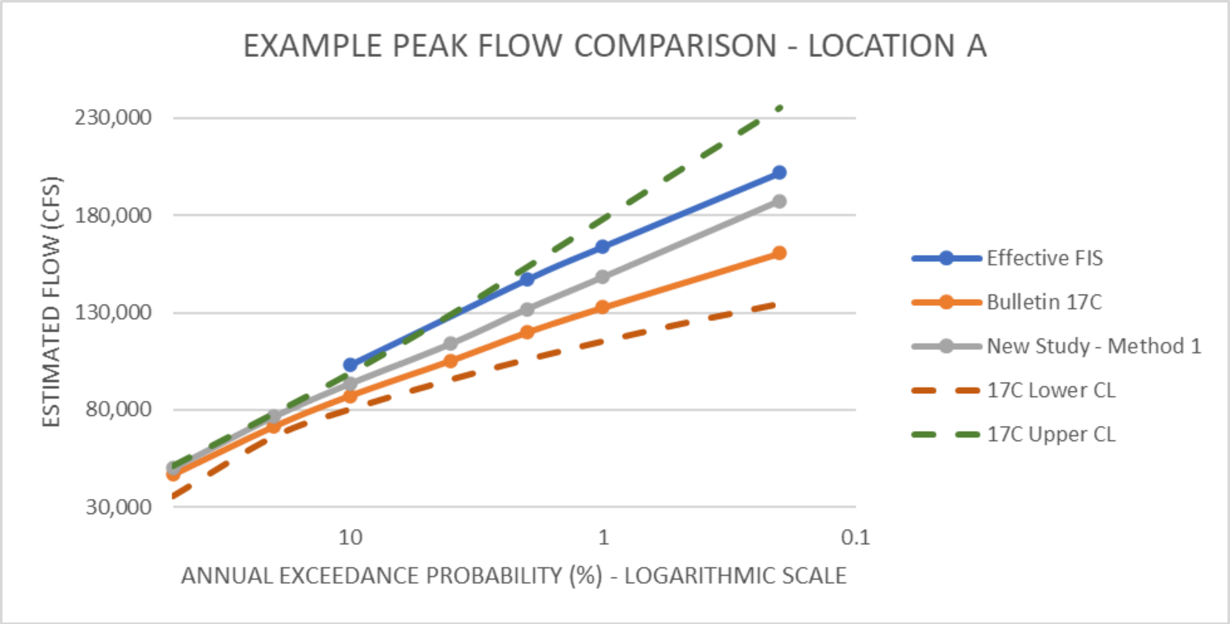

Figure 3-17. Example Peak Flow Comparison (Logarithmic) from InFRM Trinity WHA

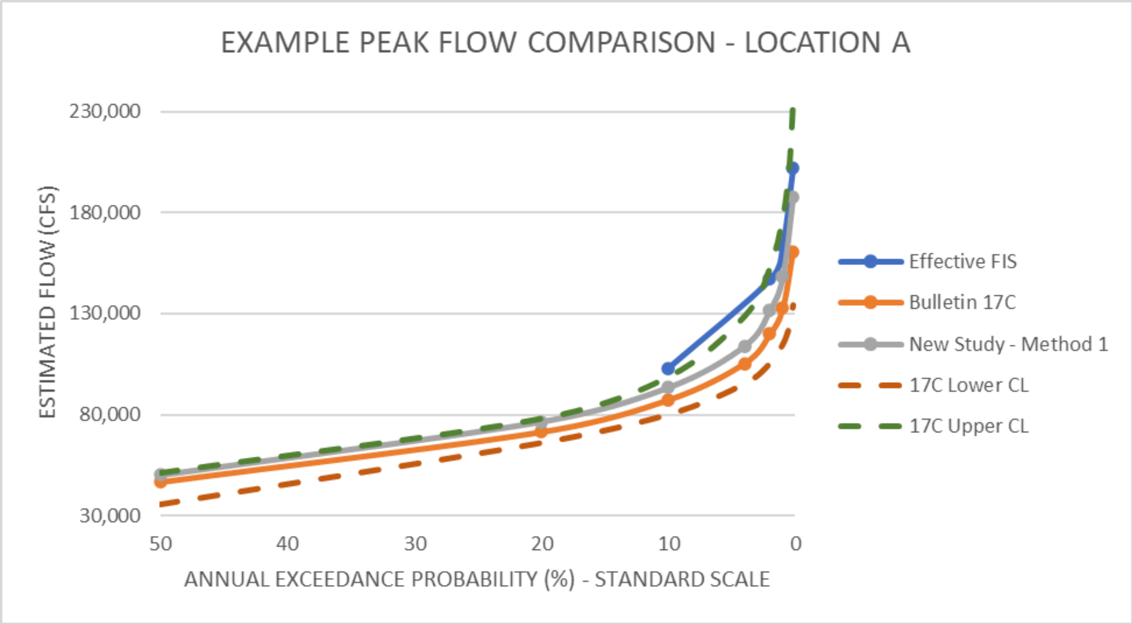

Figure 3-18. Example Peak Flow Comparison from InFRM Trinity WHA

High Detail studies should include a plot with the following (see **Figure 3-19** for an example).

1. 100-year statistical estimate over time
2. 100-year statistical estimate with 95% confidence limits
3. Annual Peak Flows, by year
4. 100-year sensitivity test, including shifted storms
5. 100-year 95% confidence interval, including shifted storms
6. 100-year USGS Regression equation and/or FIS flow

For cases in which there are discrepancies between the rainfall-runoff model results and flow frequency analysis results, a storm shifting analysis can be used for validation. In a USACE study of the Clear Fork Trinity River, for example, the estimated 100-year flow from the calibrated rainfall-runoff model was approximately three times higher than the estimated 100-year flow from the flow frequency analysis of historical gage data. Historical events from 1949 and June 2000 were shifted to simulate the watershed response if meteorological conditions had been slightly different. Shifting the June 2000 storm 15 miles north resulted in a peak flow similar in magnitude to the 100-year flow, helping validate the flow frequency results.

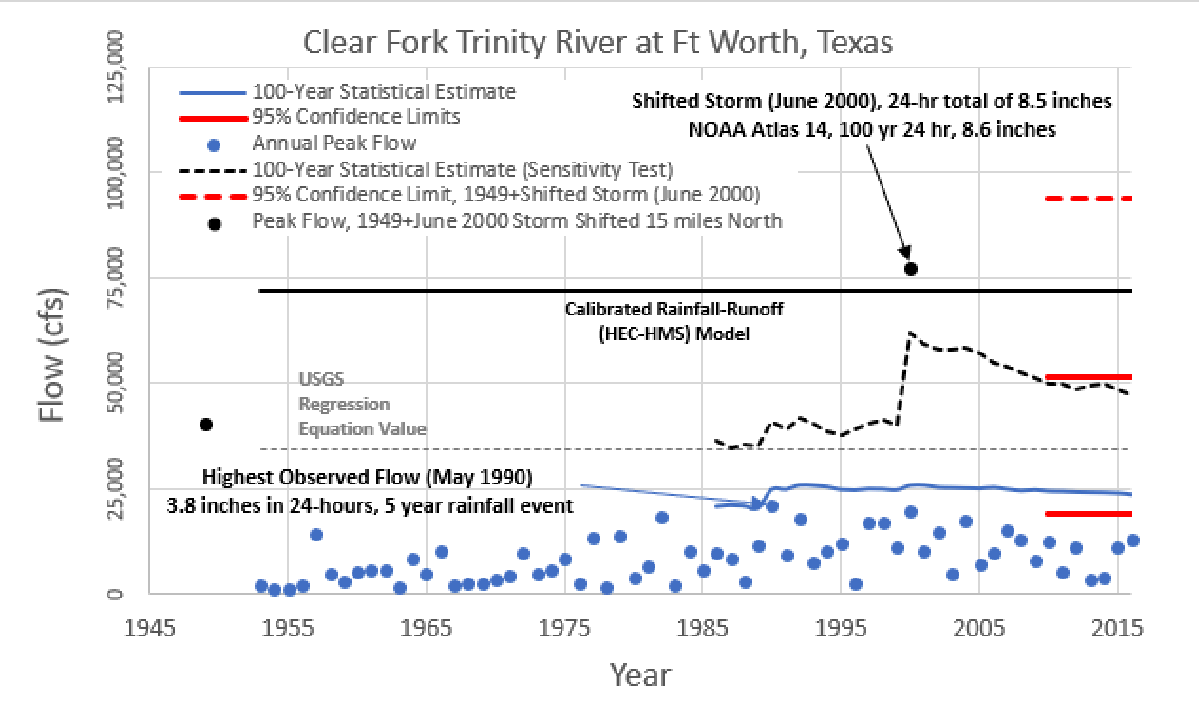

Figure 3-19. Example Flow Result Comparison for High Detail Studies

3.11.5. Calibration/Validation Results

Section 3.6 discusses the steps to be taken when performing calibration and validation of the hydrologic model and documentation to be prepared to demonstrate calibration and validation.

3.11.6. Areas of Uncertainty

Modeling teams will be required to investigate any significant differences between the various flow determination methods and submit a report chapter describing their findings. In some instances, the study team may need to revise the base assumptions if a suitable explanation is not available. The report chapter should include discussions on the strengths and weaknesses of each hydrologic method as well as justification for significant deviations from the effective published flows or previously completed studies.

3.12. Final Hydrologic Products

Individual components of the final hydrologic files will be developed and reviewed over the course of the modeling process. This section describes the final hydrologic submittal products for the RBFS hydrologic models. Section 2: Submittal and Review Processes and associated QC checklists provide a detailed outline of items required for each interim submittal.

The final report should document all assumptions and decisions made during the modeling process, as well as all backup data used, so that the results may be reproducible by future modelers. Section 2: Submittal and Review Process of the SOP outlines the data that should be included in the final submittal packages, as well as a recommended outline for the report and an example folder structure.

The final hydrology submittal should include all calculations, assumptions, results, and any other relevant documentation necessary to fulfill the USACE interim submittals described above. The

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hydrologic model and associated files (e.g., DSS) should be contained locally within the model folder so that it may be used by future modelers. The model should be cleaned of all extraneous files not directly relevant to the final simulations.

3.13. References

- Bedient, P.B., Huber, W.C. 1992. Hydrology and Floodplain Analysis, 3rd Edition.
- Center for Advanced Decision Support for Water and Environmental Systems (CADSWES). RiverWare, February 2022.
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4. Hydraulics

This section of the SOP covers hydraulic model development, including development of model parameters, model setup, model calibration and validation, and documentation, and shares common elements with the *USACE Minimum Standards*. The hydraulics section primarily describes best practices for the development of mid- to high-level of detail studies; however, it also describes approaches for developing simpler models with lower levels of detail. The low level of detail modeling approach is discussed in several sections within this document and provide the modeling teams with the flexibility to develop models that include components with varying levels of detail. Although the appropriate level of detail for any modeling component is also discussed in this document, it is expected that level of detail decisions will be made on a case-by-case basis and will be specified in the FMIP, work plan, or 25% Submittal of each study.

This SOP is not organized according to the expected sequence of work. The locations of some sections within the narrative are selected for thematic grouping and convenience, but do not necessarily reflect the order in which work will be performed.

During Phase 3, the SOP will be updated to include processes for consequence analysis and alternatives analysis, potentially including future without project conditions and with project conditions.

Table 4-1 summarizes how the specified level of detail might affect the application of specific components of the SOP. Refer to **Section 1.1** for an overview of the level of detail concept.

Table 4-1. Breakdown of Hydraulic Analysis Components by Study Level of Detail

Section	Hydraulic Analysis Components	Study Level of Detail		
		Low	Medium	High
1.1	Selection Factors for Level of Detail	Minimal Identified Risks, No Identified Projects	Identified Risks, Potential Projects	Identified USACE Project and/or Other Major Projects
4.1	Model Type and Extents	2D Rain-on-Mesh (ROM)	2D With Subbasins or 2D ROM	2D With Subbasins or 2D ROM
4.2	Incorporation of Available Data	Few Structures, Approximated from Aerials	Approximated Structures or from Existing Models, As-Builts	All Structures in Area, from Recent Models, As-Builts, Recon, or Survey
4.3	Hydraulic Parameters (e.g., Roughness)	Direct from source, no Calibration	Adjusted according to Calibration or Adopted from Previous Studies	Calibration for Multiple Events
4.4	Model Inflows	ROM	Subbasin Flows or ROM	Subbasin Flows or ROM
4.5	External Boundaries	Normal Depth acceptable for riverine	Coordinated with neighboring watersheds or coastal	Coordinated with neighboring watersheds or coastal
4.6	Hydraulic Features (Bridges/Culverts/Dams/Levees/Pump Stations)	Breaklines or mesh placement to include/exclude. No significant structure modeling	All features downstream of inflows included, but with approximate information	All structures included, with higher quality source information

Table 4-1. Breakdown of Hydraulic Analysis Components by Study Level of Detail *(continued)*

Section	Hydraulic Analysis Components	Study Level of Detail		
		Low	Medium	High
4.7	Low-Detail Hydraulic Modeling (ROM)	Expectations and Standards	Applicable to Low-Detail areas within a Medium-Detail model	Applicable to Low-Detail areas within a High-Detail model
4.8	Hydraulic Calibration	Minimal or No Calibration	Minimal Calibration or Calibration to Multiple Events	Multiple Calibration Events
4.9	Hydraulic Sensitivity	Minimal or No Sensitivity Analysis	Minimal or No Sensitivity Analysis	Sensitivity Analysis
4.10	Results Comparison and Evaluation	Minimal comparison to prior studies	Comparison to prior studies. Potential Validation Events	Validation Events. Potential Detailed Uncertainty Analysis
4.11	Final Hydraulic Products	Hydraulic Products as defined in the Work Plan (or FMIP) and SOP		

4.1. Model Type and Extents

4.1.1. Existing Model Availability

Prior to the development of the hydraulic modeling strategy, all existing models and reports for the region should be examined. The availability and quality of existing studies will influence key decisions such as the selection of model type, model extents, level of model detail, and processing and presentation of modeling results.

Collecting existing studies for every region/basin/stream is part of the data collection task and should be completed before the modeling task begins. Typical studies that may be available include, but are not limited to:

- 1D or 2D Base Level Engineering models
- InFRM Watershed Hydrology Assessment models and reports
- Local city/county-wide master drainage plans
- USACE Corps Water Management System models
- FEMA Flood Insurance Study frequency models and reports
- FEMA Letters of Map Revisions (LOMR) or similar models
- FEMA Levee Analysis and Mapping Process models
- Drainage models from local municipalities and drainage districts

The findings of the existing model review process will be documented in a comprehensive inventory. The inventory will include as many of the following inputs as possible: Study Title, Model Name, Model Version, Model Type (1D/2D), Model Developer Point of Contact (name, title, email), Model Extents, Model Report Availability, Model Development Year, Modeling Purpose, Model Calibration, and Validation Events. All models reviewed should be included in the inventory, even if no information from them is brought forward into the current analysis.

The final models will be built in HEC-HMS and HEC-RAS; however, the modeling teams should examine and consider adopting components from existing models built in other software such as SWMM, FLO-2D, InfoWorks, etc.

In general, modeling teams should focus on studies that have been published in the last 10 years; however, older studies or ongoing preliminary studies should also be taken into consideration and utilized, if possible. Specifically, existing studies can be used to extract data such as bridge/culvert/levee/weir geometry, stream bathymetry, pre-calibration model parameters, calibration data, and/or calibrated model parameters. Additionally, existing models can be used to extract flow/stage hydrographs and rating curves that may be used as boundary conditions in the new models (more insights regarding the boundary conditions are provided in **Section 4.4.4** and **Section 4.5**). The engineer should review the source models to determine if cross sections, reaches, 2D domains, structures, or other features are of sufficient quality to be used in the new models.
Existing hydraulic reports and supporting documentation should also be examined, as they may include useful information such as high-water mark (HWM) data, reservoir operation procedures, historical levee breach details, or general insights regarding the overall modeling setup. Overall, engineering judgement should be used to decide how existing analyses can be used or considered.

4.1.2. Consideration of Potential Projects

The types of proposed projects along a given stream may impact the modeling strategy for that reach. Information about potential projects can be identified during the data collection phase, leveraging inputs from local stakeholders and from documents such as hazard mitigation plans. When the location and type of a proposed project is known, the designated modeling team can make sure the model resolution is sufficient in the vicinity of the proposed project. Hydraulic models may include denser cross sections or smaller cell sizes, and hydrologic models may include smaller subbasins in these areas. This way, the analysis of proposed projects will require smaller changes to the base existing conditions model.

The funding source of a potential project may also have implications in the types of models that should be developed. In general, it is understood that projects funded by USACE typically require more detailed models than those funded by other agencies. Therefore, if it is known that a USACE-funded project may be developed in the area, the modeling team should develop a thoroughly calibrated and validated model. Furthermore, the modeling team should review modeling criteria dictated by any local communities and the funding source. These criteria may dictate the selection of specific modeling methodologies from those described by these SOPs.

Consideration of Planned Projects

Ongoing projects in the watershed that are expected to be completed in the near future and that may significantly impact overall flow patterns or flood risk in the watershed—for example, major bridges or culverts, channelization, or detention projects—should be included as if they had been completed in the existing conditions models. This should include only projects that have been announced by local or federal authorities and have secured funding.

Model Version

New RBFS models will be developed in the latest HEC-RAS release version of HEC-RAS available at model initiation (version 6.3 at the time of this publication). All documentation should clearly identify the model version used for the analysis.

While there are other hydraulic models available, this project focuses on analysis of riverine and coastal areas for which HEC-RAS 2D is a suitable model. Areas that require modeling extensive storm sewer systems to assess a project's viability are outside the scope of this project. It is anticipated that HEC will be releasing updates to HEC-RAS on a more frequent basis (e.g., about 4 months elapsed between version 6.0 and version 6.1, and 6 months between version 6.1 and version 6.2), which may necessitate changing the model version after model initiation. Once a study has been initiated, the engineer should assess whether the improvements in the new HEC-RAS version make it worthwhile to update the model to a more recent version. If the update can be made without significant effects on the project budget and schedule (i.e., if the release occurs prior to model calibration and there are no significant changes to HEC-RAS that would require re-work), it should be pursued. After calibration or if the version release notes indicate potential for significant disruption to the schedule or re-work, the engineer should use appropriate judgment for whether to update. After the 75% submittal, any version updates requested by GLO or USACE may be considered out of scope items.

Model Type

The type of hydraulic model for every area will depend on several factors, such as:

- Types of potential projects and funding
- Topography and flow characteristics of the stream and overbanks (1D/2D)
- Stream risk/priority
- Types of existing hydrologic and hydraulic models
- Number of models that will need to be developed for each region

Preferably, new models will include only 2D domains and will not include 1D segments or 1D channels connected to 2D floodplains with lateral structures. HEC-RAS 2D methods are deemed appropriate for large scale modeling that may include coastal influences and/or extensive surface runoff. While it is understood that a 1D or 1D/2D model may have shorter run times, the project goals, which include achieving full watershed coverage and the ability to extend/improve models in the future, favor development of full 2D models where possible. No new fully 1D or 1D/2D models with 1D channel and 2D overbanks will be developed; however, if there are existing, reliable 1D-only or 1D/2D models that can be adopted or updated with minor modifications, the designated modeling team may decide to continue using that model type for the base condition models. In some cases, it may be beneficial to build a detailed 2D domain near an area of greatest interest and connect it with 1D streams upstream and/or downstream to cover areas of lower interest. Modeling near the coastal zone will always require the development of 2D models for coastal and transition zones but may include 1D reaches for riverine areas upstream of transition zones.

Rain-on-mesh 2D models should typically be used only as auxiliary models to support the calibration and development of the final models or in coastal influence areas (see **Section 5**).

Details about the modeling setup, definition of hydraulic structures, and flow inputs are discussed in **Section 4.3**, **Section 4.4**, and **Section 4.6** respectively.

4.1.3. Model Extents

RBFS models will generally be developed to cover a model area that is manageable to work with, but still is of a sufficient extent to determine whether a potential project has impacts or benefits upstream and/or downstream. It is anticipated that most of the hydraulic models will cover at least a single HUC-12 sized watershed; however, in some cases, larger areas may be modeled as appropriate, especially if an area near a confluence includes a potential project.

For potential projects along larger streams, a portion of the larger watershed, including adjoining tributaries near the potential project that could be affected by the project, will form the basis for the hydraulic model. It is not anticipated that the entirety of a riverine basin (i.e., HUC-8 or HUC-10) would necessarily be included in a RBFS model to assess a potential project along the channel. Such a model would only be required if the potential project is extensive and is expected to have impacts and/or benefits along the entire channel reach.

In areas where there are coastal influences and/or interbasin flows, a large hydraulic model may be developed to cover the coastal and riverine zones for multiple reaches, with appropriate buffers outside the areas of focus. The buffers can be determined upon reviewing existing floodplain maps, the results of USACE's 2020 Coastal Texas Study Advanced Circulation (ADCIRC) storm surge model suite, existing hydrologic and hydraulic models, and the results of auxiliary ROM models. In some cases, this extensive model may be the final model; in other cases, it will be an auxiliary model that can inform the selection of the final model extents and can assist the development of boundary conditions for smaller models (more information regarding the boundary conditions can be found in **Section 4.4.4** and **Section 4.5**, as well as in **Section 5**).

In areas with riverine and coastal flooding, the selection of the model extents in the coastal region is discussed in **Section 5**.

The selection of model type and extents for each area modeled will be discussed in the FMIP, work plan or 25% submittal for that area, will be reviewed by GLO and USACE, and will form the scope of work for development of the base conditions model for that area. The boundaries of the hydraulic models should cover the entire Hydrologic Unit Code area included in the project work plan or FMIP.

4.2. Incorporation of Available Data and Selection Criteria for Data Sources

The RBFS project will leverage and incorporate available background data during the development of hydraulic models and flood assessments. This section describes criteria regarding the quality assessment of available data sources and incorporation of that existing data into the RBFS analysis. It also addresses which modeling components can be adopted from previous hydraulic models and reports, and how previous modeling analyses should be used to support new modeling. Information regarding potential sources of existing data has been included in **Section 4.1**. Study teams should be mindful to request data from outside entities as early as possible, so as not to delay the 25% submittal which will document the data collected for each study area.

4.2.1. General Consideration of Collected and Existing Data Quality and Assessment

The quality of collected and existing data for hydrologic and hydraulic models is critical for obtaining reliable model results with confidence. Throughout the RBFS, hydraulic modeling teams should work with hydrology teams to fully evaluate the collected and existing data for use in both hydrologic and hydraulic modeling, perform data quality evaluation for improvement, and use consistent data sets for both hydrologic and hydraulic models. It is recommended that modeling teams should implement the following steps to collect data and evaluate quality.

- Data Inventory
- Data Quality Assessment
- Data Quality Improvement

Data Inventory

The technical team should develop an inventory for all basic and major data collected and used for the model, including name of the data; sources of data; date or period of data for time series data; where and from whom the data was obtained; description of the data, including any issues or concerns; and data characteristics associated with specific data, such as resolution and projection, etc. A table or multiple tables can be used to summarize this information. These data include, but are not limited to:

1. Rainfall data
2. Land Use and Land Cover data
3. Terrain data
4. Bathymetric data for streams, ditches, or coastal areas
5. Current or Future Land Use data
6. Cross Section data
7. Entire HEC-RAS 1D Reaches or 2D Domains
8. Auxiliary Geospatial data from models, such as Breaklines within 2D HEC-RAS Domains
9. Hydraulic Structures data (from models, shapefiles, or as-builts)
10. Dam/Levee Breach data
11. Point Source Discharge
12. Stream gage data (e.g., observed flow and stage, rating curve, field measurement, etc.)
13. Reservoir data (e.g., elevation, release and operation rules, etc.)
14. Boundary conditions
15. Hydrologic and hydraulic results (e.g., flow/stage hydrographs, rating curves, peak flow/stage values, etc.)
16. Modeling parameters (e.g., Manning's n roughness, cell sizes, time steps, normal depth slopes, etc.)

Data Quality Assessment
The technical team should assess the accuracy, adequacy, and appropriateness of all data used in model development and calibration. The data in the above data list should be assessed and evaluated in detail for its quality, completion, accuracy, adequacy, and appropriateness based on the sources, date, where and from whom the data was acquired, and the data analysis and approach used.

For time series data, such as rainfall data, observed flow and gage data, point sources data, and reservoir elevation and release data, any data gaps, missing data, outliers, and abnormal data periods should be identified through visual and numerical analyses. Any methods selected for use to fill data gaps, supplement missing data, or to correct outliers and abnormal data should be described in the data quality assessment.

When assessing data quality and its impact on model performance, the technical team should keep in mind that following considerations need to be evaluated:

1. If "best information available" are utilized to develop and calibrate the model.
2. If there are any deficiencies regarding data availability, and if so, how the deficiencies can be improved.
3. If there is relevant information available that was discarded without appropriate justification and, if so, whether the use of discarded information significantly affects results.

Following are the examples of major data types and the focus of the data quality assessment. Similar assessments should be made for any other data not listed below. A full data quality assessment is only required if the data are to be incorporated into the RBFS model/analysis.

Land Use and Land Cover (LULC) data – The technical team should verify if the most recent or best available LULC data is used when developing the model and if correct or appropriate LULC data are used for different scenarios. For example, for modeling historical events, historical LULC data need to

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be used, while for modeling current conditions, current LULC data need to be used. Also, the technical team should verify that correct LULC data is used for a modeling period versus for a calibration and validation period, and identify major changes of LULC through the years, if possible.

Terrain data – The technical team should verify that the most recent or best available terrain data is used when developing the model and that appropriate terrain data is used for different scenarios. For example, for modeling a historical condition, historical terrain data may need to be used or terrain may need to be modified to reflect the historical condition. Also, the team should check if the terrain used is consistent with the condition for a modeling period or calibration and validation period and identify major changes of terrain through the modeling period, if possible. The modeling team should also verify that the terrain resolution meets the modeling purpose.

Channel Bathymetric data – For studies with allocated budget for survey, the technical team should verify channel bathymetric data with survey data, assess whether adequate survey was done to define channel bathymetry, and determine whether new bathymetric survey is needed. The technical team should assess whether development of bathymetric data based on information extracted from existing models will be sufficient for the project.

Cross Section data or Entire 1D Reaches – Refer to **Section 4.3.6**. The technical team should check sources and dates of cross section data for reliability and accuracy and verify with survey data. The technical team should check cross section spacing to see if it meets suggested spacing, since spacing may affect computation stability. Additionally, the team should check cross section widths to see if they are wide enough to contain various flow scenarios.

Hydraulic Structures data (e.g., bridge, dam, levee, culvert, inline structure, etc.) – Refer to **Section 4.6**. The technical team should verify the data sources, reliability, and quality; determine the potential to upgrade to newer existing data for hydraulic structures; and determine if further site visits or investigations are necessary to obtain more accurate data.

Dam/Levee Breach data – The technical team should check and verify if a dam or levee breach happened during any historical events and if measured breach data is available. Levee breach analysis is not required for hypothetical runs. The team may consider choosing a calibration event that includes a breach. However, if a breach occurred during a calibration event, it must be modeled. HEC-RAS contains several methods to estimate breach parameters in the breach module. USACE Models, Mapping, and Consequences has also developed procedures for estimating levee breach parameters that can be used as guidance: "Application of Simplified Physical Breach Method in HEC-RAS, FY2019 Standard Operating Procedure for Levee."

Point Source Discharge data – The technical team should identify permitted point sources, such as water withdrawals and returns, and wastewater treatment discharges. This should include identifying major point sources and minor point sources. Minor point sources can be aggregated. The technical team should assess whether point sources are significant and may affect the flooding potential, or whether they should be excluded from the RBFS.

Stream gage data (e.g., observed flow and stage, rating curve, field measurement etc.) – The technical team should identify data gaps, missing data, data outliers, and abnormal data periods for observed flow and stage through visual and numerical analyses. The technical team should determine if a rating curve needs to be adjusted by verifying it with available field measurements.

Reservoir data (e.g., elevation, release and operation rules, etc.) – The technical team should identify data gaps and missing data, data outliers, and abnormal data periods for observed elevation and release data through visual and numerical analyses. The team should verify operation rules with the appropriate water control manual or project operation manual.

Boundary conditions – If boundary conditions from an existing study are to be used, the technical team should evaluate the model boundary location, the boundary conditions, and the supporting data behind the selected boundary conditions.

Other data – Any other specific data for the project should be evaluated for quality and usefulness.

It is recommended that the modeling teams develop data quality evaluation metrics based on the above data quality assessment and engineering judgment. The metrics should include a data list and the data quality level (e.g., Poor, Good, Excellent, Reliable, Uncertain, With deficiency, etc.)

Data Quality Improvement

The technical team should propose measures, approaches, and methods to improve data quality. These may include methods to fill data gaps and correct data outliers and abnormal data; methods to estimate parameter values; approaches to modify data, such as LULC and terrain, site visits and survey data, empirical equations, similar project references, etc.

4.2.2. Criteria and Guidelines for Consideration and Incorporation of Existing Data

Prior to beginning the modeling effort on each study area, the engineer should determine a cutoff date at which data provided by an outside entity will no longer be required to be incorporated into the study. Existing models, reports, geospatial data, and drawings that are being considered for incorporation will require thorough review and evaluation. If there are uncertainties regarding the methodology, assumptions, or background information for existing data, the modeling teams may request additional information from the data developers to clarify any questions and increase confidence in the validity of the existing data. The modeling teams should confirm that they are using the latest published model, report, or drawing. It is recommended that modeling teams keep notes in a logbook with details about how any existing data is modified and used. The logbook will be used only for internal coordination and tracking purposes and will not be submitted for review.

HEC-RAS Models

Although all existing models and reports should be reviewed and evaluated, greater emphasis is expected to be placed on models developed in the last 10 years. Elements from older models, such as structure geometries and stream bathymetries, may be used if there are no better and newer data sources, and if the elements are reviewed and found suitable and representative of existing conditions.

As described in **Section 4.1**, steady state models will not be an acceptable model type for new models. The geometry information from existing steady state models may be incorporated into new unsteady flow models as appropriate. Similarly, as explained in the **Section 3**, regression equations are not an acceptable methodology for new hydrologic analyses; therefore, results from hydraulic models that have used regression equation inflows will not be incorporated into new models. If the designated modeling team wants to consider the outputs of such models, new simulations will need to be performed using newer hydrologic inputs developed using an acceptable methodology.

The preferred format for new models will be 2D-only models. However, if there are high-quality existing 1D or 1D/2D models, then the modeling team may decide to use them with minor updates. It is

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recommended that existing 1D or 1D/2D models that cover relatively small areas be converted to 2D-only models, even if they are deemed to be reliable. This will simplify the development of new models and should reduce model instabilities and runtime errors/warnings.

Where they are available, it is highly recommended that existing 2D BLE models be used as a starting basis for new models, unless a higher quality model is also available. In cases when the study area is not deemed of high priority, then the BLE models may be able to be used with minor modifications and with new hydrologic inputs. In other cases, these models may require additional modifications. If the existing models have been developed with older LiDAR datasets or land use data, the models will need to be adjusted to incorporate the newest topography or land use before they can be used. Care should be taken that breaklines and other 2D features follow the updated LiDAR ridges, and that manual edits to land use associated with channel geometry are preserved.

Hydraulic Results

Existing modeling results that have been found to be reliable can be used to define boundary conditions for new models. Specifically, the designated modeling team may choose to incorporate stage/flow hydrographs, peak water surface elevations, and/or rating curves from existing models located upstream or downstream of the new model. Similarly, if there are existing models that partially or fully cover the study area, then the existing results should be compared against the new modeling results and differences should be discussed in the final report. Additional discussion on the modeling extents and the use of existing models is provided in **Section 4.1**.

Modeling Components

Existing models and reports can guide the selection of key hydraulic parameters for the new models. Specifically, FIS reports or other reliable studies can be used to select preliminary, pre-calibration parameters such as channel roughness values, normal depth slopes, etc. Additionally, the modeling team may choose to consider the mesh resolution and time step from existing models in their analysis. Upon careful examination of the existing models, the modeling team may also want to copy breaklines, Storage Area (SA)/2D connections, levee centerlines, and lateral structures. Finally, although new hydraulic models should be developed in HEC-RAS, it may be beneficial to review existing models in different software such as SWMM, InfoWorks, etc. and incorporate selected data.

Geospatial Data and Drawings

It is expected that existing shapefiles, rasters, and as-builts will be used for the development of new models. High priority streams and hydraulically significant structures will require more detailed inputs; therefore, the modeling and data collection teams should work closely to locate any available background data for these features.

4.2.3. Terrain

Topographic data used for the basis of model development will be from the most recently published LiDAR data, usually available in a processed raster format. It is suggested that a digital elevation model (DEM) prepared using industry-standard post-processing steps, such as hydro-flattening, be used. The vertical datum should be NAVD88. The preferred horizontal coordinate system to be used is the North American Datum of 1983 (NAD 83), 2011 realization, Texas Centric Mapping System Albers (U.S. Survey Foot). Note that this horizontal coordinate system in units of U.S. Survey Foot is not a standard option in many GIS programs (e.g., ArcMap, ArcGIS Pro, QGIS, etc.).

Due to the sizes and extents of some of the areas to be modeled, multiple topographic data sources may need to be merged and/or stitched together. Care should be taken to verify that any gaps, areas of

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NoData, or other anomalies are remedied, and that conversion between coordinate systems does not create vertical or horizontal discontinuities. In addition, some areas may have coastal bathymetry available that should be merged and used. The metadata and reported vertical accuracies of each topographic source dataset should be maintained and described in the final report.

Some sources of topographic and bathymetric LiDAR data are:

- TNRIS StratMap –LiDAR Data - https://tnris.org/stratmap/elevation-lidar/
- NOAA Digital Coast Data Acc–ss Viewer - https://coast.noaa.gov/dataviewer/#/lidar/search/
- USGS National –ap Viewer - https://apps.nationalmap.gov/viewer/

The data may come in various cell sizes (e.g., 1-meter, 3-meter, 1/9-arcsecond, etc.). It is expected that the final topographic terrain will have a cell size of no greater than 10 feet, though many models will use the full resolution available from the source data. The final terrain cell size should not be smaller than supported by the source data. If the source data has a 1-meter cell size, the final cell size should be 3.3 ft, which will be the typical cell size for RBFS models. When performing terrain operations (for example, resampling to project coordinate system), snap the grid to the origin (0, 0). Snapping the terrains and using a consistent cell size will reduce problems if terrains or models are combined.

When creating the terrain within RAS Mapper from the source DEMs, a rounding value of 1/32 ft should be selected. This rounding value (about 0.03 ft) has been found by USACE to balance the need for accuracy in the terrain with file size and computational speed. This rounding should be done prior to model development, as weirs cut from un-rounded terrain may be lower than the rounded terrain, requiring model revisions later.

Terrain Modifications

HEC-RAS version 6.0 and later versions include options to perform modifications in a vector format to incorporate changes that may not have been picked up during the original LiDAR flight or may have been constructed recently. This method is meant to include vector-based elevation data, as opposed to raster- or cell-based elevation data. It is recommended to utilize this functionality by creating a virtual terrain within HEC-RAS RAS Mapper (right click the terrain and select the "Clone Terrain (Virtual)" option) and then adding specific modifications that should be represented in the terrain. A non-exhaustive list of examples that could be added if the level of detail is required includes: unique bridge piers (if not modeled using the bridge method), surveyed high points (e.g., embankments, accredited flood protection structures like floodwalls, etc.), any as-built data that would be better represented using vector-based features, or others.

For any as-built data that exists as a raster or triangulated irregular network (TIN) that is not included in the existing topographic data (e.g., effective LOMR, constructed projects that modify the terrain, etc.), completing data processing outside of HEC-RAS (such as in a GIS program) would be the preferred approach.

Incorporating terrain data from existing models or other sources, such as channel bathymetry where the LiDAR surface includes standing water in areas not covered by bathymetric survey, may be necessary if the standing water would significantly affect the channel capacity and/or potential project assessment.

It is expected that existing shapefiles, rasters, and as-builts will be used for the development of new models. High-priority streams and hydraulically significant structures will require more detailed inputs;

therefore, the modeling and data collection teams should work closely to locate any available background data for them.

4.3. Hydraulic Parameter Development

This section documents the standard procedures that will be used to address hydraulic parameter development during the development of RBFS hydraulic models. This section will document data sources that should be examined for potential existing data and potential upgrades to existing data for hydraulic parameters. This section was inspired from the items outlined in Section 2.0 – 'Hydraulic Analysis' of the *USACE Minimum Standards*.

4.3.1. Level of Detail

This section identifies the full information that would be needed for a high level of detail RBFS model. Where a lower level of detail model is appropriate, engineering judgment will be used to determine what aspects of the SOP may be relaxed, while still meeting the minimum standards required for the desired funding source.

4.3.2. General Considerations

The modeler is expected to document key decisions made when developing the model, including but not limited to justification of selected modeling methods (e.g., 1D, 2D, steady-state, unsteady state), computation options, and hydraulic parameters.

In general, the default method for new studies will be 2D unsteady. In cases where recent 1D models are available and include sufficient detail, the 1D methodology will be maintained and models will be scaled up or updated as needed to meet the objectives of the RBFS. Existing 1D models may be extended and combined with new 2D models, as necessary.

In addition to historical calibration and/or validation events, all riverine models shall include multiple frequencies to comply with FEMA and USACE hydraulic modeling requirements. These will typically include the 0.2%, 1%, 2%, 4%, 10%, 20%, and 50% AEP events. The events modeled may vary based on the funding sources for potential projects within a model extent. Each storm scenario must have separate plan and flow files when performing unsteady flow analyses.

To facilitate the comparison of pre-project to post-project conditions for a potential project, it is imperative that the only changes in the model geometry between the pre-project and post-project models represent actual proposed changes due to the project. The engineer should strive to keep the 1D cross sections, 2D mesh centers, roughness values, boundary conditions, and other modeled features identical unless those items are directly affected by the proposed project configuration. Where possible, the base conditions model should have an appropriate level of detail to support development of potential projects without modification of the base conditions model.

4.3.3. Manning's Roughness Coefficients

Riverine studies will primarily use the NLCD 2019 dataset for land use. When selecting Manning's roughness coefficients, modelers should refer to the NLCD dataset, aerial imagery, and various reference materials on Manning's n values. The *HEC-RAS Reference Manual* provides Manning's n values for the most common types of channels beginning on page 3-14 (summarized here in **Table 4-2**). The Reference Manual also lists various other resources for methods of selecting Manning's n values. The *HEC-RAS 2D User's Manual* also provides example Manning's n values for various NLCD Land Cover Types, as shown in the table below. These represent typical ranges; values outside of these ranges may

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be selected based on supplemental data or engineering judgment and should be justified and documented.

Models within the coastal region will benefit from the Coastal Change Analysis Program (C-CAP) land cover data from NOAA, which has more detailed classifications in coastal areas, especially for coastal wetlands, compared to NLCD. C-CAP-based data have a different set of coded land cover values. The same values in the two datasets can refer to different land cover types. To avoid mistakes, the NLCD dataset should be converted to an unsigned integer and the Sea Level Affecting Marshes Model (SLAMM)/C-CAP codes should have 100 added, prior to merging the datasets. **Table 4-3** lists the SLAMM/C-CAP land use codes (original and +100), n value ranges, and descriptions. Only the coastal-related values that will be used in the RBFS models are included in the table.

Building footprint polygons may be used to update the land classification in some areas for Medium Detail and High Detail models. Buildings can be given a code of 1, which is not used by NLCD and will not interfere with the SLAMM/C-CAP + 100 codes. An initial roughness of 10 can be used for buildings; this value will obstruct active flow, while still allowing water to fill the cell and provide storage volume. The Texas Water Development Board has building footprint datasets associated with Regional Flood Planning Groups.

- TWDB Building Footprints Dataset - https://twdb-flood-planning-resources-twdb.hub.arcgis.com/pages/buildings-nov2021

Table 4-2. NLCD Land Cover Codes, n Values, and Descriptions

NLCD Value	n Value Range	Description
11	0.025 - 0.05	**Open Water** - areas of open water, generally with less than 25% cover of vegetation or soil. This is for natural streams on mild to moderate slopes–
21	0.03 - 0.05	**Developed, Open Space** - areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.

Table 4-2. NLCD Land Cover Codes, n Values, and Descriptions *(continued)*

NLCD Value	n Value Range	Description
22	0.06 - 0.12	**Developed, Low Intensity** - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units–
23	0.08 - 0.16	**Developed, Medium Intensity** - areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units–
24	0.12 - 0.20	**Developed High Intensity** - highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.–
31	0.023 - 0.030	**Barren Land (Rock/–and/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover–

41	0.10 - 0.20	**Deciduous Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change–
42	0.08 - 0.16	**Evergreen Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage–
43	0.08 - 0.20	**Mixed Forest** - areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover–
52	0.07 - 0.16	**Shrub/Scrub** - areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.–
71	0.025 - 0.05	**Grassland/Herbaceous** - areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.–
81	0.025 - 0.05	**Pasture/Hay** - areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.–
82	0.020 - 0.05	**Cultivated Crops** - areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.–
90	0.045 - 0.15	**Woody Wetlands** - areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water–
95	0.05 - 0.085	**Emergent Herbaceous Wetlands** - areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

Table 4-3. SLAMM/CCAP Land Cover Codes, n Values, and Descriptions

SLAMM/ C-CAP Value	+100 Value	n Value Range	Description
5	105	0.07	Inland Fresh Marsh (SLAMM)
8	108	0.05	Regularly Flooded Marsh (SLAMM)
5	105	0.07	Inland Fresh Marsh (SLAMM)

Table 4-3 SLAMM/CCAP Land Cover Codes, n Values, and Descriptions *(continued)*

SLAMM/ C-CAP Value	+100 Value	n Value Range	Description
8	108	0.05	Regularly Flooded Marsh (SLAMM)
10	110	0.035	Estuarine Beach (SLAMM)
11	111	0.04	Tidal Flat (SLAMM)
15	115	0.025	Inland Open Water (SLAMM)
17	117	0.025	Estuarine Open Water (SLAMM)
6	106	0.13	Tidal Fresh Marsh (SLAMM)
12	112	0.03	Ocean Beach (SLAMM)
13	113	0.04	Ocean Flat (SLAMM)
14	114	0.06	Rocky Intertidal (SLAMM)

18	118	0.025	Tidal Creek (SLAMM)
19	119	0.025	Open Ocean (SLAMM)
23	123	0.1	Tidal Swamp (SLAMM)
43	143	0.03	Unconsolidated Shore (C-CAP)
44	144	0.025	Open Water (C-CAP)

Manning's n values for the landcover classes shown on **Table 4-3** were determined based on Bunya et. al. 2010 and Arcadis 2013 for use in the Texas Coastal Resiliency Master Plan modeling. Similar values are recommended for use in the RBFS models.

Careful conversion and merging of the land cover data is important to ending up with a consistent dataset that matches the original sources. Because the coordinate systems and source grid sizes differ, it is recommended that the conversion and merging be done in GIS and carefully checked to confirm that the end result matches the source data. Specifically, use the ArcMap "Resample" tool or equivalent to convert coordinate systems, snap the dataset to (0,0) in the project coordinate system, and up-sample to a 10'x10' grid. All these processes can be performed in the same GIS operation using environment variables.

As discussed in the *HEC-RAS 2D User's Manual*, the values in **Table 4-2** are for appreciable depths of flow and are not meant for shallow overland flow. Shallow overland flow Manning's n values are generally much higher due to the relative roughness compared to the flow depth. Higher Manning's n values may be applied to shallow overland flow areas using roughness modification areas in a 2D model. In addition, roughness values for 1D channels typically include some of the head loss associated with sinuosity that is implicitly handled within a 2D model. As a result, channel roughness values in a 2D model can be lower than the roughness for the same channel in a 1D model to achieve the same total head loss.

HEC-RAS 2D currently applies a single roughness value at the center of the cell face to the entire cell face. Along a 2D channel centerline, the roughness values from the NLCD will not be representative of channel roughness values and may be much too high. Roughness modification regions along all channel centerlines will be required to ensure that HEC-RAS uses realistic roughness values for 2D channels. There are two ways of adding modification polygons in HEC-RAS. One is with a Classification Polygon that is part of the Land Cover dataset. The second is with Calibration Regions, which are part of the geometry. If Classification Polygons are to be used, new land use codes will be needed in the list so that the channel roughness can be calibrated separately from the overland roughness value. Because HEC-RAS only includes codes that are present in the land classification dataset, a template file with all desired land use codes may need to be added to the land classification dataset. This will allow calibration of the channel roughness separate from the general land use codes that have the same roughness. These additional codes should be coordinated between adjacent models to facilitate potential merging of models at a later date. If Calibration Regions are to be used, they can be added directly in the HEC-RAS geometry.

4.3.4. HEC-RAS 1D Geometry

Per the *USACE Minimum Standards*, horizontal and vertical variations in Manning's n values should be used with discretion. If horizontal variations are used, particularly in the overbank regions, care should be taken to minimize the number of n value regions (i.e., modelers should not add a unique n value region for a sidewalk or a single row of trees). Manning's n value regions should represent general changes in vegetation, development, land use, etc. Specifically, the NLCD land use roughness values used for a 2D model should not be used directly to create roughness regions on an NLCD-cover grid cell size basis but, if necessary, should be used to develop larger roughness regions that can be applied to the model and represent large sections of the channel or overbank.

4.3.5.HEC-RAS 2D Geometry

Manning's n datasets for 2D models should be created in RAS Mapper using the "Create New Land Cover Layer" tool. The modeler should ensure that the appropriate classifications are assigned. Refer to Chapter 2 of the *HEC-RAS User's Manual* for guidance on creating the Land Cover layer. The initial pre-calibration roughness values assigned to each NLCD grid code are given in **Section 3**, while reasonable n value ranges for each code are provided in **Table 4-2**.

HEC-RAS versions 6.0 and newer allow the user to assign Manning's n and percent impervious values to a "Land Cover vs Roughness Table" within RAS Mapper. Modelers should assign their default Manning's n values to the Land Cover layer using this table. Refer to Chapter 2 of the *HEC-RAS User's Manual* for guidance on this step. Percent impervious values are not required unless the modeler intends to use the precipitation and infiltration features within HEC-RAS.

Previous versions of RAS Mapper allowed users to manually override land cover regions using the "Override Regions" layer. HEC-RAS version 6.0 has further expanded on this concept and now requires additional steps to adjust n values in the 2D domain, as described in Chapter 2 of the *HEC-RAS User's Manual*. The primary tools used to override Manning's roughness values within a 2D domain are summarized below.

Classification Polygons – Users can define polygons that will override the polygons already delineated in the Land Use layer. This should typically be applied in all main channel areas of a river system but may also be appropriate in cases where land use has significantly changed since the development of the NLCD 2019 dataset.

Manning's n Calibration Regions – This layer can be used to associate a specific Manning's n value for a particular geometry file. This can be used when calibrating models by raising or lowering channel n values for different reaches or for evaluating different mitigation alternatives.

4.3.6.Cross Sections (1D Geometries Only)

If 1D modeling is to be utilized, the basic data requirements for 1D models, as described in Chapter 3 of the *HEC-RAS Reference Manual*, should be included. This includes, but is not limited to stream centerlines, channel bank lines or points, flowpaths, and cross sections. Use of RAS Mapper to create/edit certain geometry features is beneficial because of the capability of RAS Mapper to automatically compute and extract the hydraulic properties for a hydraulic element (e.g., reach lengths from flowpaths, cross section stationing, etc.). Refer to the *HEC-RAS Mapper User's Manual* for more details on these features.

General Cross Section Placement

For modeling efforts using existing 1D models, cross section placement should be evaluated to ensure compliance with RBFS standards. Cross sections should be placed perpendicular to flow path centerlines and spaced in accordance with **Table 4-4**, per the *USACE Minimum Standards*. Note that additional cross sections may be required to reasonably model different alternatives for future scenarios. Engineering judgment should be used for larger rivers when determining appropriate cross section spacing (for example, cross section spacing at no more than 80% of average floodplain width).

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Table 4-4. Suggested Cross Section Spacing

Channel Bed Slope	Suggested Cross Section Spacing
10 feet or less per river mile	1,000 to 1,500 feet
Greater than 10 feet per river mile	500 to 1,000 feet

Cross sections should contain all possible flow scenarios. Where it is not feasible to contain all flows within 1D cross sections, other modeling approaches, such as 2D modeling or combined 1D/2D modeling, should be considered. The use of interpolated cross sections in the final model is not acceptable. Any interpolated cross sections placed during the development of the model should be georeferenced and elevation data for the cross section should be extracted from the terrain.

Cross Section Property Tables

When performing a 1D Unsteady Flow Analysis, modelers should evaluate the hydraulic property tables under the "HTab Parameters" button in the Geometric Data Editor (see **Figure 4-1**). The engineer should ensure that the selected increment and number of points are large enough to encompass the full range of stages that may be incurred during unsteady flow simulations at all cross sections (within the limit of 500 points), but that the increment is not so large that the resulting tables are not detailed enough to reasonably depict changes in area, conveyance, and storage with respect to water surface elevation.

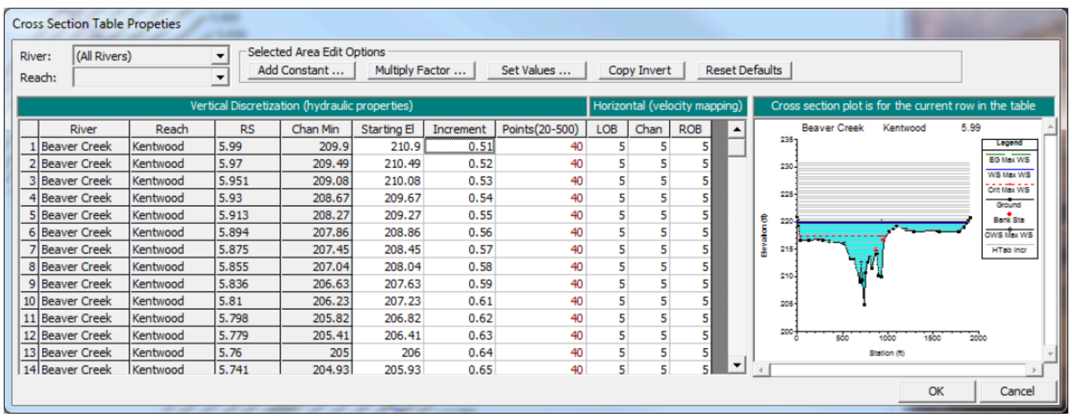

Figure 4-1. HTab Parameters Editor

Cross Section Placement at 1D Structures

Where models include 1D Structures, bounding cross sections should follow the standard recommended layout described in Chapter 5 of the *HEC-RAS Reference Manual* (see **Figure 4-2**). The chapter also describes in detail the methods for determining proper expansion/contraction coefficients and ineffective flow placement for bridges, culverts, and inline structures.

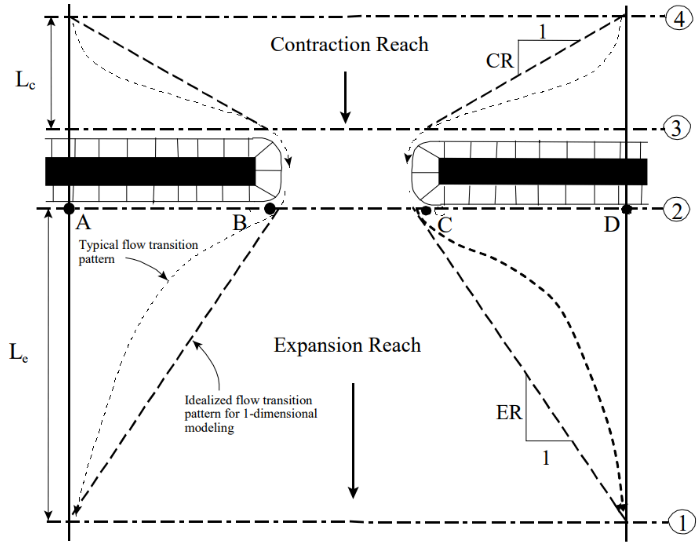

Figure 4-2. HEC-RAS Recommended Cross Sections around a Bridge

In addition to proper cross section placement at 1D structures, ineffective flow area placement is critical for proper modeling of structures. Cross sections 1 and 4 in the diagram above are typically considered to be fully effective in conveying flow. Cross sections 2 and 3 will have ineffective flow areas on either side of the structure opening to represent the constriction of effective flow area until the flow overtops the structure. For medium and low level of detail models, the structure should be included as a bridge, with the deck along the road centerline representing the embankment obstruction. A description of the approximation should be included in the bridge coding.

Hydraulic Structure Property Tables

Stability in 1D unsteady models is heavily dependent on the user properly defining hydraulic structure property tables. Upon initial test runs of the model, the default values for the HTab parameters (for cross sections, as well as within the Bridge and Culvert or Storage Area Connection editors) should be refined to create smooth, representative curves. Modelers can view the resulting internal boundary curves for each structure under the "Stage and Flow Hydrographs" option to help identify potential parameter adjustments (see **Figure 4-3**). In a 1D/2D model, the maximum WSEL may be higher than the top of the cross section or structure. The HTab Maximum Headwater value should be set higher than the highest likely headwater value. Any warning messages about extrapolation above cross section tables should be addressed by adjusting the HTab parameters for the cross section or structure.

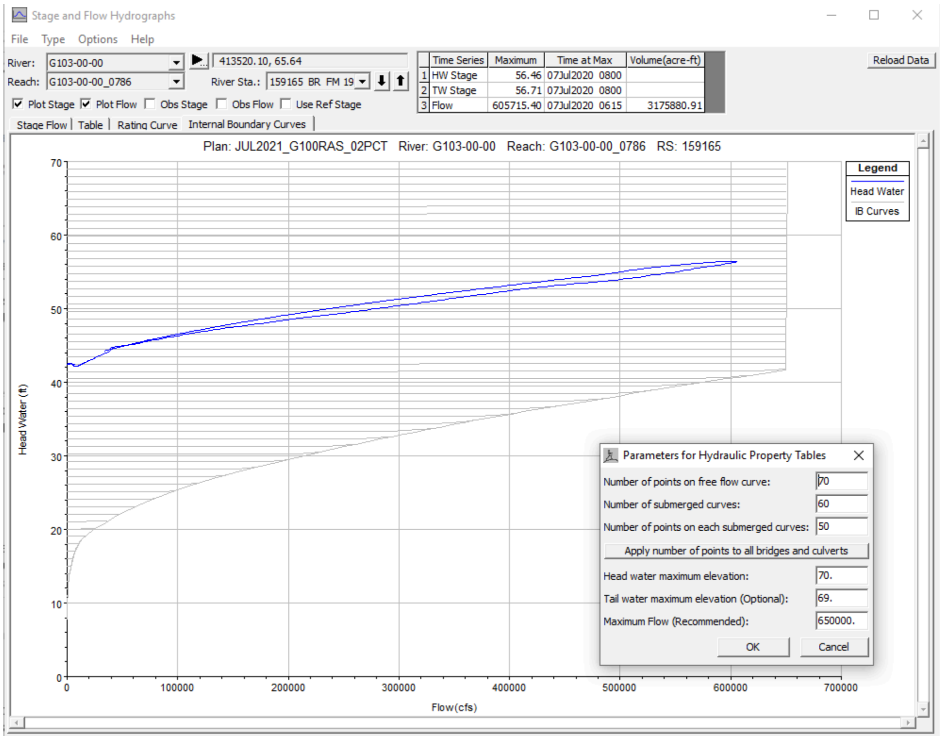

Figure 4-3. HEC-RAS Bridge Rating Curve Graph

General 1D Modeling Practice

Other 1D HEC-RAS modeling features (e.g., overbank flowpath lengths, bank station placement, placement of ineffective flow and obstruction regions) should follow general good modeling practices as described in the HEC-RAS manual.

4.3.7.2D Geometry Features

2D Flow Areas

In general, the number of separate 2D flow areas should be minimized to allow for seamless interaction of flow within the model, with one 2D area being ideal. Connecting multiple 2D areas with internal connections (such as weirs) leads to head losses that may not be representative of actual conditions. In cases where multiple 2D areas are warranted, the modeler should make a conscious effort to delineate the boundaries along high points where either minimal or no flow interaction is expected, or where traditional weir flow, possibly combined with flow through culverts, is likely to occur and can reasonably be represented by a 2D connection. The HEC-RAS software may struggle to successfully generate the mesh if the model boundary contains an excessive number of vertices or sharp bends. Therefore, the modeler should consider simplifying the boundary using the points filter within HEC-RAS or in ArcGIS prior to importing it into HEC-RAS.

1D/2D Connections

While a fully 2D approach is recommended, if an existing 1D/2D model is being used, 1D/2D connections will be required. Lateral structures should be placed along the 1D reach to connect to the 2D mesh. Lateral structures should be georeferenced and should follow the ridge or high point between the channel and overbank. If the weir equation is used for a lateral structure, the weir coefficient should be selected based on typical overland flow coefficients.

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In some areas, a 1D reach may be connected directly to a 2D area either upstream or downstream. These connections should be placed in areas where the flow and stage are highly one-dimensional and uniform across the cross section. If not, the 1D cross section will not be able to compute a similar flow/stage as the 2D areas if the area is more 2D in nature, since the 1D model has one stage, while the 2D can have a gradient on the stage. The 1D cross section and 2D boundary should be placed along the same line, and the roughness values along the cross section and 2D should match, so that the conveyance matches well between the 1D and 2D areas. Cross sections with multiple low flow channels may cause instabilities if the channels are not hydraulically connected in the 2D.

2D Computational Mesh

Multiple factors must be addressed when selecting the standard cell size for a model's computational mesh. In general, the number of cells for a mesh should not exceed 1 million. Cells should be as large as possible while still capturing the characteristics of the terrain and flow patterns to minimize run times. As described in the sections below, refinements and smaller cells can be used in certain areas, as needed, while keeping in mind that smaller cells require smaller time steps for the entire model.

When developing the base computational mesh, the modeler should keep in mind that a single WSEL is computed in the center of each cell. In flatter areas where the WSEL is not changing very rapidly, larger cells are appropriate. If the slope of the water surface and/or velocity are varying more rapidly, smaller cell sizes are warranted.

Near the riverine area of interest, it is anticipated that base cell sizes will be between 100' x 100' and 300' x 300', depending on the size of the model, the steepness of the terrain, and other parameters. This range may be narrowed based on information gained by modeling teams as pilot studies are completed. Areas away from the key streams can be represented by coarser mesh sizes to reduce model run times. Additional guidance on the mesh size selection in the coastal regions is provided in the **Section 5**. For example, it is expected that very large models in the coastal region which include multiple watersheds may need to be developed with coarser mesh sizes to be efficient.

While a smaller mesh can provide better convergence, it also will increase the computational time. The "Mesh Refinement Region" tool in HEC-RAS can be used to increase the mesh density, as necessary. Mesh size should be adjusted relative to the water surface slopes in a given area. Where there are flat or slowly changing topographic features, larger cells can be used. Conversely, steeper water slopes will require smaller grid sizes to capture the rapidly changing water surface.

Mesh Refinement

In many cases, the standard grid placement of cell centers will produce cell faces that allow unwanted "leakage" or flow transfer across high points in the terrain that would realistically not allow water to pass. Breaklines and refinement regions should be used to ensure the model is correctly representing the real-life conditions of the study area.

Ideally, 2D models developed for the RBFS will have the mesh designed such that re-creating the entire mesh (possibly even with a different mesh size) does not adversely affect the model. However, because HEC-RAS does not provide complete control over the order of enforcement for breaklines, mesh refinement regions, and 2D connections, a thorough review of the mesh will be necessary in the event that a mesh must be re-created. Manual adjustment of mesh centers should be minimized in order to maximize mesh size flexibility, both for the alternatives analysis phase of this project and for future users of the models who may need to truncate, extend, or regenerate the mesh. As discussed in the

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sections below, placement and selection of properties for breaklines, 2D connections, and refinement regions will be critical in minimizing the need for manual cell adjustments.

Breaklines

At a minimum, breaklines should be placed at levees, railroads, raised roadways, or any ridges that would realistically obstruct flow, but are not wide enough to be captured by the base grid and are within an area that experiences concentrated flow (see **Figure 4-4**). Once breaklines are placed and enforced, they should be checked to ensure no cell faces are failing to snap correctly and causing unwanted leakage. Results should be checked for multiple storm scenarios to identify situations where flow leakage is occurring.

Figure 4-4. Breakline Enforcement along a Narrow Ridge to Prevent Flow Leakage

If hydraulic structures exist (e.g., culverts, low water crossings, etc.) that allow water to pass through high areas, they should be incorporated into the model. See **Section 4.6** for more details on placement and modeling of hydraulic structures.

The HEC-RAS mesh generation routine does not always result in mesh faces that follow breaklines or refinement region edges, especially where breaklines intersect or are close to each other. Adjustments to breakline alignments and cell sizes can result in better cell placement without requiring manual cell adjustments. In the following example, breakline enforcement at the intersection did not result in proper cell alignment (see left image, **Figure 4-5**). Upon splitting one of the breaklines and shifting the vertices away from the intersection, HEC-RAS breakline enforcement resulted in better cell face alignment (see right image, **Figure 4-5**).

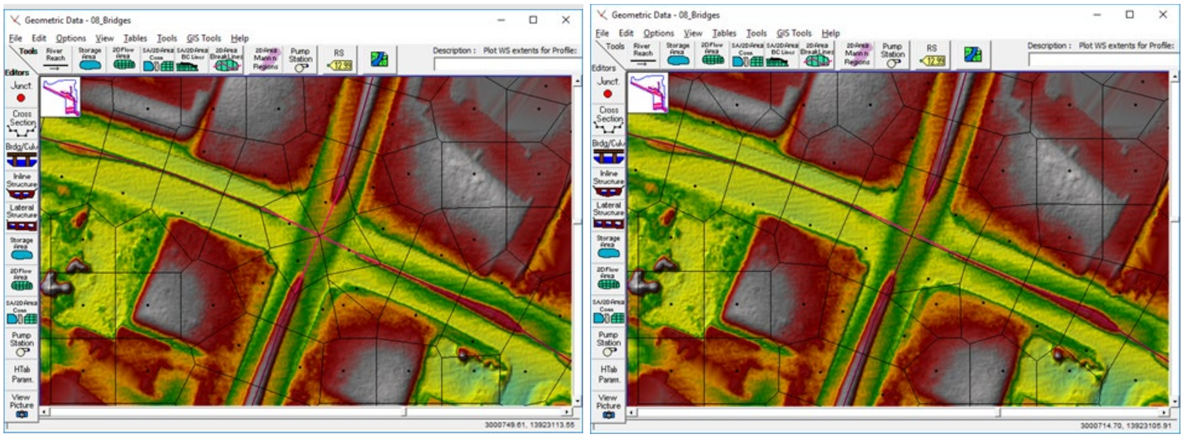
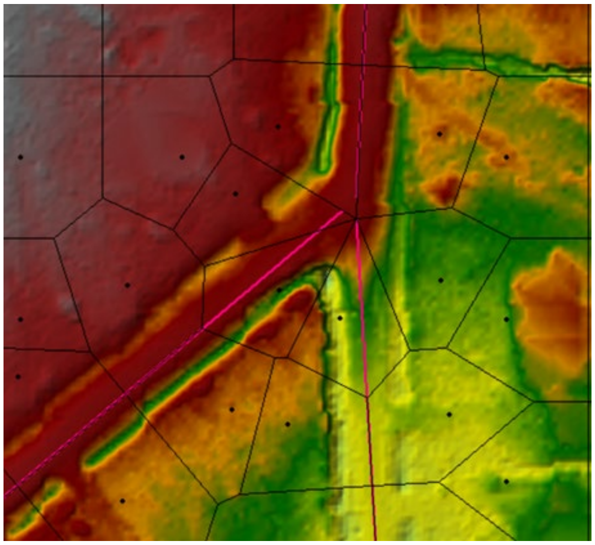


Figure 4-5. Splitting Breaklines to Align Cell Faces

A similar approach of splitting breaklines can be used for acute intersections, but additional steps typically need to be taken. The enforcement issues can be resolved by moving breakline endpoints further away from the intersection or by creating segments of breaklines near the intersection with smaller cell spacing (see **Figure 4-6**).



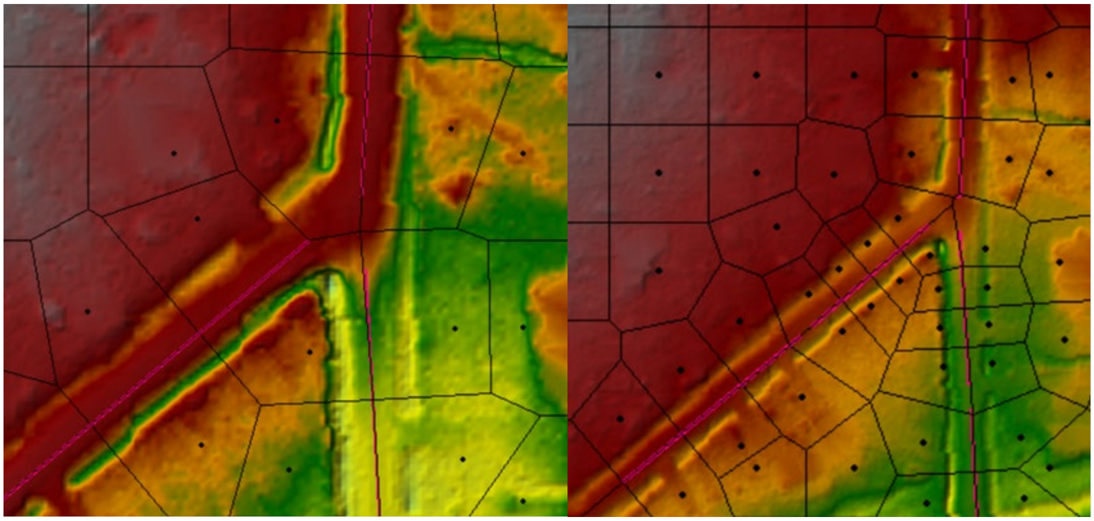


Figure 4-6. Breakline Placement to Align Cell Faces

RAS Mapper allows for the specification of multiple parameters for each breakline.

- **Near Spacing:** specifies the cell size along the breakline.
- **Near Repeats:** optional field that allows user to repeat the near spacing cell size a certain number of times on either side of a breakline.
- **Far Spacing:** optional field that controls the transition zone, where the cells double in size, starting with the near spacing cell size and doubling the size of each subsequent row of cells until the cell size reaches the far spacing cell size (defaults to nominal cell size if left blank). This helps to limit dramatic cell size differentials between the near spacing and nominal cell sizes and is most useful when the refinement region or breakline cell spacing is smaller than the nominal cell size.

In the example below, the nominal mesh size is 100 feet and each breakline has a Near Spacing value of 50 feet. Each breakline has varying values for Near Repeats and Far Spacing, as specified in **Figure 4-7**. The Far Spacing in the example is too large, as it results in cells larger than the base cell size for the 2D area. This is not a preferred solution but is included to demonstrate what Far Spacing does.

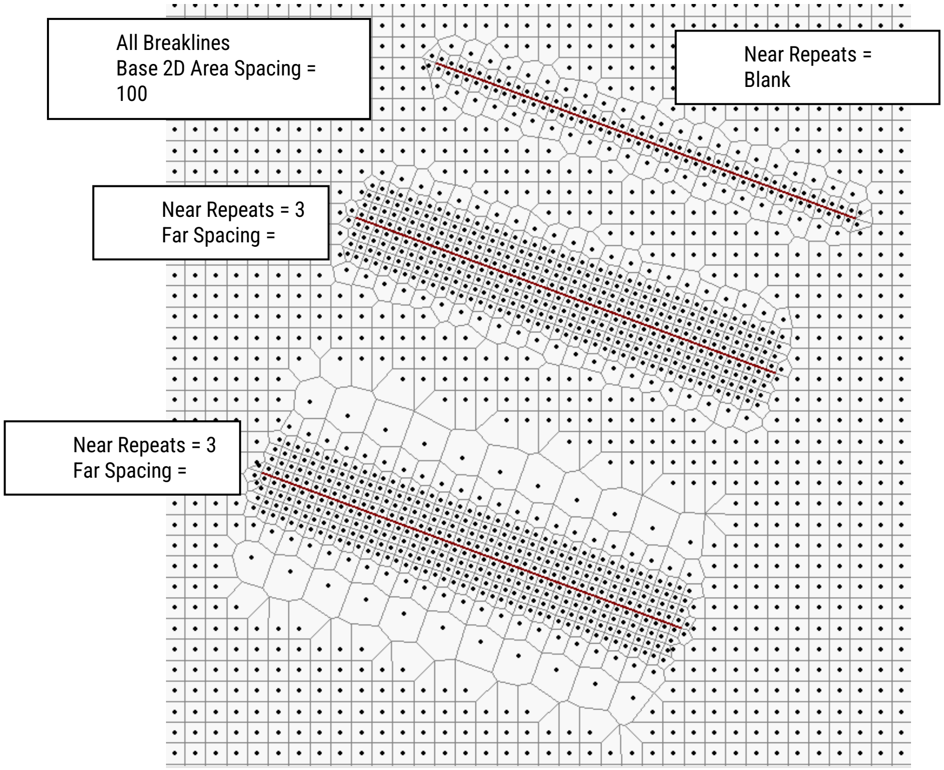


Figure 4-7. Near Repeats and Far Spacing for Breaklines

Additionally, the modeler has the option to select "Enforce a 1 Cell Protection Radius" for each breakline. This option protects the cells immediately around the breakline from being deleted or moved due to enforcement of later breaklines nearby. The following screenshot is an example of this (see **Figure 4-8**).

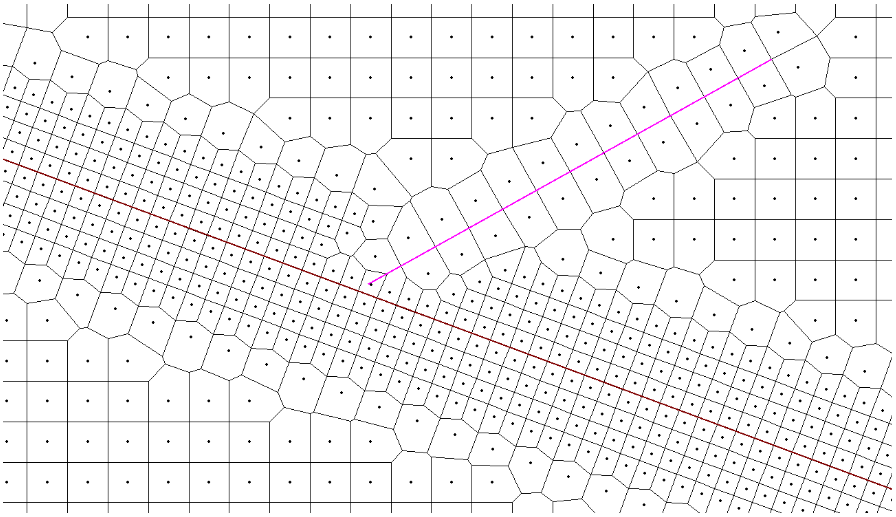


Figure 4-8. Enforcing a 1 Cell Protection Radius around a Breakline (Red Breakline Preceded Pink Breakline in Model Development)

Refinement Regions

Refinement regions allow different sections of a 2D mesh to have different base mesh sizes, as shown in **Figure 4-9**. The interior of the refinement area is given a cell spacing (like the 2D area) and the bounding polyline is given a point spacing (like a breakline). More details on mesh refinement regions can be found in Chapter 3 of the *HEC-RAS 2D Modeling User's Manual*.

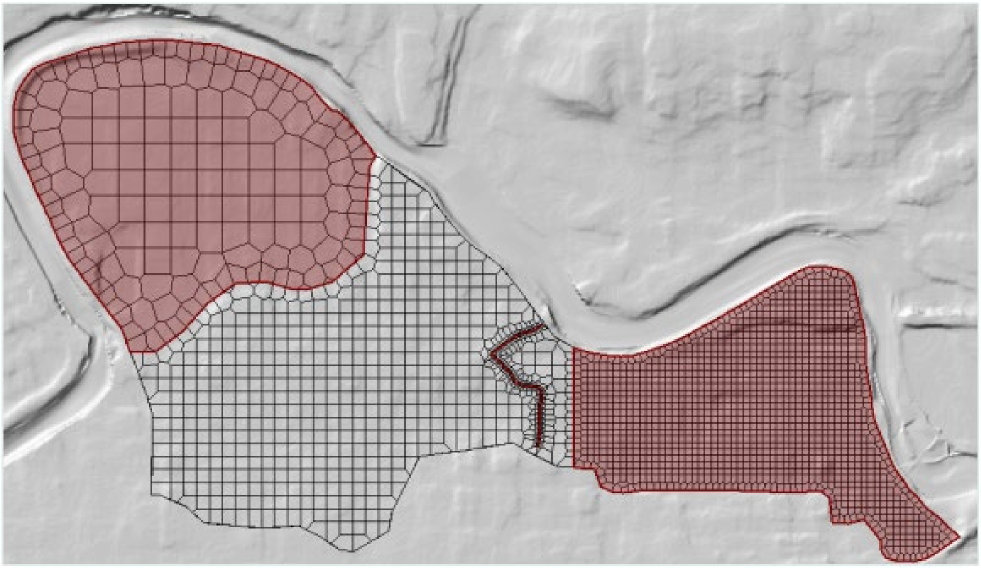


Figure 4-9. Refinement Regions to Change Cell Spacing

Similar to breaklines, it is also possible to specify Near Repeats, Far Spacing, and 1 Cell Protection Radius protection for each individual refinement area. The parameter called "Perimeter Spacing" is similar to Near Spacing for breaklines and indicates the cell size immediately along the refinement region perimeter. The cell spacing X and Y fields specify the cell size within the region (note that Cell Spacing Y has not yet been implemented in HEC-RAS).

Cell Alignment Along Streams

Refinement regions can also be used to define mesh characteristics along channels modeled within the 2D region. Because cell faces act like cross sections, model stability and accuracy are increased when cell faces are properly aligned with the direction of flow. Using a refinement region along the channel banks and having proper cell size specification will result in cells oriented properly. In the example below, the refinement region cells are set to 100', which aligns with the general channel width of 100' (see **Figure 4-10**). Breaklines can also be placed along channel banks to ensure that cell faces snap to high points along the banks to prevent flow from prematurely leaving the main channel. All channels that will have flows assigned along them from HEC-HMS should have refinement regions or otherwise have cell faces aligned to be generally perpendicular to flow along the channel centerline.

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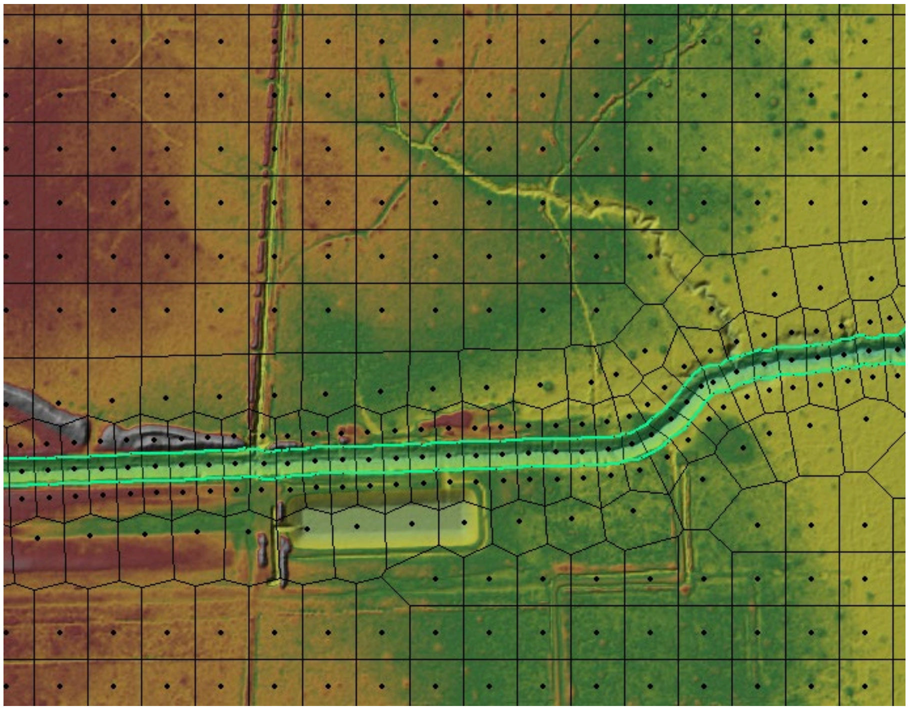

Figure 4-10. Cell Alignment Along Streams

Common Mesh Issues
Chapter 3 of the *HEC-RAS 2D Modeling User's Manual* identifies multiple possible issues that can result from the automated mesh generation tool in the "Potential Mesh Generation Problems" section.

Upon running model scenarios, adding the "Courant" or "Velocity" results map layers in RAS Mapper can be useful in identifying individual cells or specific areas where cell orientation may not be adequate. These result layers can also help identify problem areas that may be increasing model run time or adding to the overall model error.

4.4. Hydraulic Model Inflows

This section documents the SOP that will be used to apply hydrologic inflows during the development of RBFS hydraulic models. This section was inspired from the items outlined in Section 2.0 – 'Hydraulic Analysis' of the *USACE Minimum Standards*.

4.4.1. Level of Detail

This SOP identifies the full information that would be needed for a high level of detail RBFS model. Where a lower level of detail is appropriate, engineering judgment will be used to determine what aspects of the SOP may be relaxed while still meeting the minimum standards required for the desired funding source.

4.4.2. General Considerations

In most cases, inflow hydrographs to be used in the hydraulic models will be developed during the hydrologic phase of the RBFS studies. In cases where flows from previous studies are being leveraged, clear documentation should be provided on the data source.

4.4.3.HEC-RAS Flow File

Because the models in the RBFS will use only unsteady flow, an unsteady flow file will be required for each hypothetical storm event and each calibration event (see **Figure 4-11**). The inflows used will primarily come from the hydrologic portion of the study for the basin. The flow files must also include boundary conditions, as discussed in **Section 4.4.4** and **Section 4.5**. All input flow and boundary conditions should refer to a DSS file. Modelers should refer to HEC-RAS manuals for details on developing unsteady flow file data.

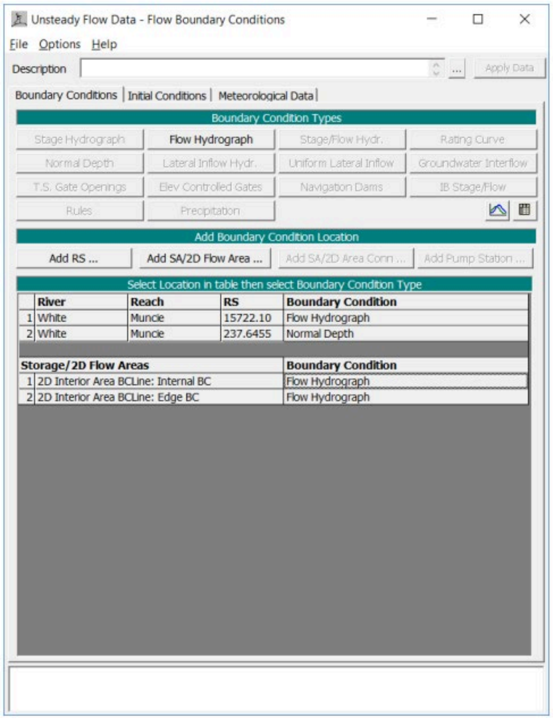

Figure 4-11. HEC-RAS Unsteady Flow Editor

4.4.4.2D Inflows

Internal Boundary Conditions – Internal boundary condition (BC) lines should be used to apply Internal Flow Hydrographs within the 2D domain (see **Figure 4-12**). DSS files and flow hydrographs are linked to the BC lines within the Unsteady Flow editor. BC lines are recommended to be drawn along the stream centerline at the downstream end of each subbasin. It is recommended that the length of the BC line is approximately 10% of the Length to Centroid (L_{ca}), covering at least four cells. BC line names should be unique and should reference the subbasin flow hydrograph being applied at that location. Modelers should ensure that all inflows from HEC-HMS have been imported and that no flows are being added more than once. In addition, the time of concentration calculations for hydrology and unsteady boundary condition placement for hydraulics should be coordinated to minimize the likelihood of significant double-counting of attenuation via routing of flow within a subbasin.

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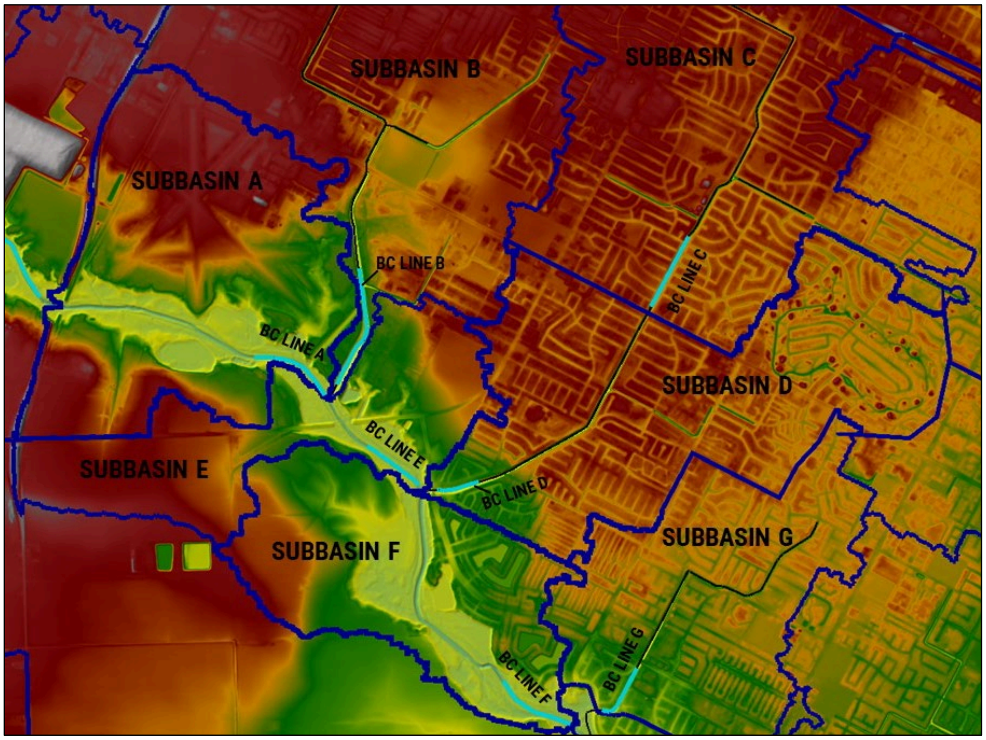

Figure 4-12. Applying Subbasin Flow to Internal Boundary Conditions

External Boundary Conditions – External BC lines should be used when applying flows coming from external sources (e.g., adjacent basin study overflows, upstream inflows if stream is truncated, etc.). In these cases, the BC line is drawn perpendicular to the direction of flow as opposed to parallel (see **Figure 4-13**). The line should be long enough to sufficiently cover the anticipated floodplain width, as flows are distributed across the cells touched by the line. Flow entering from an external BC is generally applied first to the lowest cells. The user must supply an energy grade slope that is used to determine the depth of flow and where the flow is applied horizontally; this should generally be the channel slope in the area.

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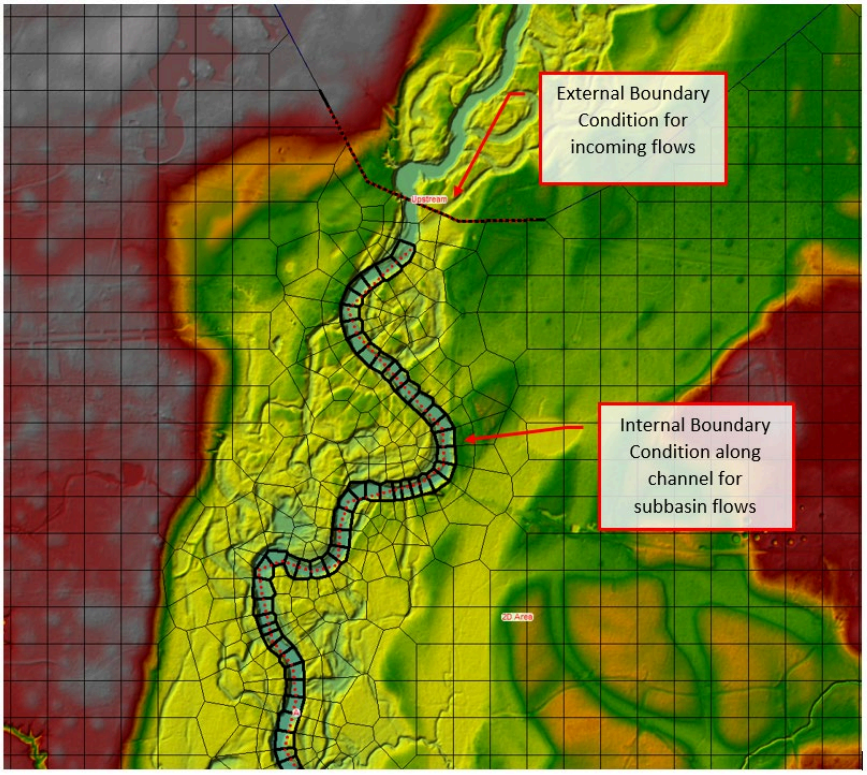

Figure 4-13. Applying Internal and External Boundary Conditions to a 2D Mesh

Rainfall
Rain-on-mesh models will generally not be an acceptable modeling format for Medium and High Detail riverine models, as specified in the FMIP, work plan, or the 25% Submittal. some Similarly, auxiliary ROM models may be developed by the modeling teams to support calibration processes and select preliminary modeling parameters. In these cases, rainfall may be added as a uniform hyetograph for the entire 2D domain or as a gridded hyetograph. While gridded ROM rainfall is not anticipated to be used within HEC-RAS, if it is appropriate for a given model, a gridded hypothetical or elliptical rainfall raster would need to be developed outside of the available HEC tools. More guidelines on the development of rainfall depth time series and grids are provided in **Section 3**.

4.4.5.1D Inflows
If 1D geometries are being utilized, subbasin delineation and general flow trends should be used to identify how inflows should be applied.

Lateral Inflow Hydrographs – Lateral inflow hydrographs should be used when flow is entering at a specific point along the stream. They should be used to represent tributary inflows into the stream being modeled. The lateral inflow hydrograph should be associated with the cross section just upstream of where the flow is intended to come in, so that the change in flow will take place at the next cross section downstream of the inflow hydrograph location.

Uniform Lateral Inflow Hydrographs – Uniform lateral inflow hydrographs should be used when flows are to be distributed along a portion of the river reach between two user-specified cross sections. These can be used to represent subbasin flows entering the channel.

Flow Hydrographs – If a basin model is truncated to model only a portion of a stream, a flow hydrograph should be applied at the upstream-most cross section to represent the incoming flows from the portion of the stream not being modeled.

4.4.6. Initial Conditions

Initial conditions should be developed that provide consistent initial water surface elevations and flows. Surges in flow into or out of a system and spikes in flow or WSE at the start of the model run should be avoided.

The default options for the initial conditions may not generate consistent initial WSELs and flows. A 1D/2D warm up or 2D Initial Conditions Time and Ramp Up option can be used to run a warmup period for the model based on the initial conditions by running a series of time steps with constant inflow. This warmup period will usually provide a model starting condition that has WSELs that are consistent with the unsteady flow equations used in the modeling. Initial water surfaces within a 2D area may also be set by initial condition points. If these methods are not satisfactory, a restart file can be used to develop initial conditions. This may be required for more complex situations, such as variable initial conditions and base water surface elevation and flow in a reservoir, rather than a single-value flat initial water surface.

Streams with very small baseflow may lead to instabilities during the beginning of simulations, particularly where wind forces will also be applied. Modelers should keep this in mind and balance reasonable baseflow with model stability. Increasing baseflow to a fraction of the 1-year flow is a potential solution to instabilities at the beginning of simulations.

4.5. External Boundary Conditions

This section documents the standard procedures that will be used to address the selection of external boundary conditions during the development of RBFS hydraulic models. This section describes high level considerations related to coastal influences and guidelines related to the type and location of boundary conditions.

4.5.1. Coastal Boundary Conditions

The first consideration toward the selection of the optimum boundary conditions should be the assessment of potential coastal influences in the study area. The delineation of the exact extents of the coastal influence for the various modeling scenarios is detailed in **Section 5.1** If there is a coastal zone within or directly adjacent to the model domain, then the coastal conditions should be reflected by the boundary conditions. Coastal influences should be taken into consideration whether the model is assessing riverine-only or coastal/compound flooding.

For coastal and compound models, the coastal boundary conditions will include a water level time series that corresponds to a historical tropical storm event or a different time series that has been derived via the joint risk analysis. Water level gages and USACE coastal study models are expected to be the primary sources for the selection of the most appropriate time series for each modeled scenario. The appropriate location of the coastal boundary conditions line, along with the tidal time series are detailed in **Section 5.6**. In some cases, the modeling team may choose to split a certain coastal area into multiple models and develop some upstream models that are not influenced by coastal conditions. This decision will need to be justified by a bigger picture discussion about the purpose of each model and the evaluation of riverine, coastal, and compound flooding.

For riverine models that outfall to a coastal zone, it is recommended that a local tide gage be used to define the boundary conditions as a constant tailwater elevation. All events can be paired with the mean higher high water (MHHW) elevation or a higher elevation derived via analysis of the tide gage records. The modeling teams can discuss different tailwater elevations in their FMIPs, work plans, or 25% submittals. Considerations for sea level rise and other future conditions in the coastal zone are discussed in **Section 5.4**

4.5.2. External Boundary Condition Type

The types of external boundary conditions that may be encountered in the modeling phase are normal depth, stage/flow hydrographs, rating curves, and constant water surface elevations. Some brief considerations for the application of each boundary type are described below.

Normal Depth

Normal depth will be the preferred downstream boundary condition for riverine models that do not outfall to a zone controlled by tidal effects. Initial estimates of the normal depth slope may match the terrain's slope in the vicinity of the outfall. Additionally, auxiliary ROM and other existing models may also inform the selection of the initial normal depth. Normal depth should not be used in zones controlled by tidal effects and should only be used where riverine flooding controls.

The final normal depth slope may be further refined during the hydraulic calibration process. In many cases, it will be preferred that the surface runoff or stream outfall boundaries are split into multiple sections to account for differences in terrain elevations, slopes, and land cover types. In these cases, different normal depth slopes may be used for each boundary line.

It should be noted that when the downstream boundary of the model is at a confluence with a larger stream, then normal depth may not be the preferred boundary condition; instead, stage hydrographs, rating curves, or constant elevation boundary conditions should be considered.

Time-Varying Stage/Flow Hydrograph

Time-varying stage and/or flow hydrographs are expected to be used in the following cases:

- The boundary coincides with the location of a stream or tidal gage
- The boundary is located within the extent of an existing model (i.e., this model is a tributary along a longer river)
- The boundary is located within the coastal zone and time series are used to represent the stream level during a historical event
- The boundary is located within the coastal zone and a constant elevation time series is used to represent the MHHW tidal boundary
- The boundary is placed at the inflow/outflow location of a reservoir

In general, flow hydrographs are more appropriate for upstream boundary conditions and stage hydrographs are more appropriate for downstream boundary conditions.

Rating Curve

Rating curves can be an appropriate type of downstream boundary condition for locations near stream gages or locations that have been modeled by a reliable existing model. If the quality or reliability of the rating curve is not guaranteed, then the modeler may choose to use different boundary conditions, such as normal depth, and compare the modeling result to the rating curve.

4.5.3. Boundary Line Placement

Stream Inlets/Outlets and Surface Runoff

Potential projects should be located sufficiently far from the boundaries (upstream or downstream) of a model such that minor changes to the boundary conditions (e.g., normal depth slope, timing of stage/flow hydrographs, etc.) do not result in significant changes to the WSEL or flow at the proposed project location.

Boundary conditions should be placed at the inlet and outlet of every stream and at the model boundaries to allow the flow to enter and exit the model. Initial BC lines can be placed at the location of every stream that can be identified via terrain or aerial examination, and that is described in the FEMA FIS and/or other engineering reports. Additionally, a preliminary ROM model should be developed to help identify the location and number of boundary condition lines. Modelers can run the ROM model with a uniform hyetograph that corresponds to a historical storm event or a simplified hyetograph representing the 500-year NOAA Atlas 14 rainfall intensities. Flow vectors throughout the entire duration of the simulation and depth maps at the end of the simulation can be used to identify locations where river or surface runoff flow is "trapped" at the edge of the model. This exercise will help identify areas where the boundary has not been placed at a correct location (i.e., along ridges) and needs to be refined by adding an internal breakline to allow flow (e.g., across a culvert) that is otherwise blocked in the terrain. The boundary condition lines may need to be reevaluated when the final HEC-RAS models are under development, potentially at the 25% or 50% stage of production. In general, it will be beneficial to use the same geometry for all modeled AEP events so that the boundary conditions can be set to accommodate the most extreme events.

Stream or surface runoff outflow at every location can be represented by a single or multiple boundary condition lines. The modeling teams may choose to use multiple boundary condition lines if there is determined to be a benefit in assigning different boundary conditions to each line. For example, it may be beneficial to split the downstream boundary conditions for a single stream into different lines for the main channel and the overbank areas and assign different normal depth slopes to each segment.

In cases where streams discharge to tidally influenced bays or the Gulf of Mexico, downstream boundary conditions should be placed to account for coastal influences as described in **Section 5.6**. The full range of possible coastal surge elevations and stream discharges that are expected to be modeled should be accounted for in the boundary condition placement so that one boundary condition type and location can be included for all model simulations. NOAA Atlas 14 discharges and 500-year storm surge from the USACE Coastal Texas Study (plus sea level rise) should be considered for upper ranges of storm surge elevation and stream discharge respectively.

Gages

If the model extents do not cover the entire watershed, the most appropriate location to place inflow or outflow boundaries may be at the location of a stream gage with a long and reliable period of record. For downstream boundaries of hypothetical simulations, it is recommended that the rating curve of the gage is used as the boundary condition. For upstream boundaries of hypothetical simulations, modeling teams may choose to consider the results of the statistical hydrology at the gage in combination with the results of the HEC-HMS model. For upstream or downstream boundaries of historical simulations, the recorded stage hydrograph at the gage will be used. However, it should be noted that in many cases it will be more appropriate to include the gage rating curve within the model domain, as then the gage data can be used to perform hydraulic calibration.

Availability of Reliable Results from Previous Studies near the Boundaries
If the model area is adjacent to or overlaps with an existing model with results of acceptable quality, as discussed in **Section 4.1** the outputs of the existing model can be considered during the development of the boundary conditions. This requires that the existing model has been reviewed in detail and has been modified, if necessary, to be compatible with the new models. If these conditions are met, then upstream boundaries can be represented by inflow hydrographs and downstream boundaries can be represented by stage hydrographs or rating curves.

Reservoirs
If a designated modeling team decides that a reservoir near the study area does not need to be included in the model, then the model boundary can be set at the inflow or outflow location of the reservoir. In this case, reservoir regulations or the results of the RMC-RFA can be used to assign the appropriate hydrograph at that location. Detailed descriptions on the hydrologic analysis and the hydraulic setup for reservoirs are provided in **Section 3.10**, respectively.

4.6. Hydraulic Features – Bridges/Culverts/Dams/Levees/Reservoirs
This section documents the standard procedures that will be used to address hydraulic structure parameter development during the development of RBFS hydraulic models. This section will outline data sources that should be examined for existing data and potential upgrades to existing data for hydraulic structures, including bridges, culverts, levees, dams, and reservoirs within the watershed. This section was inspired from the items outlined in Section 1.2 – 'Initial Data Collection for Baseline Hydrology' and Section 1.3 – 'Preliminary Frequency Flow Analysis' of the *USACE Minimum Standards*.

4.6.1. Level of Detail
This section identifies the full information that would be needed for a high level of detail RBFS model. Where a lower level of detail is appropriate, engineering judgment will be used to determine what aspects of the SOP may be relaxed, while still meeting the minimum standards required for the desired funding source.

4.6.2. General Considerations
Modeling teams should evaluate the structures contained within any existing models for inclusion in the RBFS models. The various existing modeling sources that should be considered are referenced in **Section 4.1** and **Section 4.2**. It is expected that all structures included in an existing model will be included in the RBFS model if the structure is included correctly in the existing model. Similarly, if a structure in an existing model is not represented accurately but can be refined with moderate effort, then it will also be included in the RBFS model. If a structure in an existing model is clearly not adequately represented, it will be treated as if it were not present in the existing model and included or excluded based on the same criteria as a previously un-modeled structure.

Inclusion or Exclusion of Structures – All locations known to contain hydraulic structures along a modeled stream reach within the detailed study area should be included in the RBFS model as either 2D connections, 1D bridges/culverts, 1D inline structures, or, in some cases, lateral structures connected to a 1D channel. The purpose is to include any structures downstream of a location where flow is applied in the model. The structures can be included with or without full structure detail, as described below. Structures within the 2D area but upstream of HEC-HMS inflows are, by definition, outside of the detailed study area and need not be included in the model explicitly. In a 1D model, all structures along the reach should be included, as there will be flow applied throughout the entire 1D reach. Structures adjacent to the main stem that cross tributaries or structures near the upstream end of a HEC-HMS

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inflow line may be necessary to include with low level of detail if the terrain would otherwise prevent that storage from being recognized in the model. Minor structures, such as culverts at the end of a roadside ditch that empties into a channel or driveway culverts, may be excluded based on the engineering judgment of the modeler and general level of detail in the model. For structures in the preliminary ROM model, additional structures away from the main channel reach may be modeled using mesh modifications (e.g., breaklines, v-notches), rather than by adding 2D Connections.

Structure Modeled Level of Detail – The amount of detail included in the model for a structure will depend on the level of hydraulic impacts expected from the structure, the importance of the structure to the assessment of potential projects, and the priority level of the stream where the structure is located. High impact structures will generally be included with more detail than low impact structures. The impact classification of a structure will be based on the size of the structure opening, the depth of flow from the channel bottom required to overtop the structure, the presence of other structures upstream of the structure that are near or below the overtopping elevation, the upstream drainage area, and the volume of flow that would be impounded below the overtopping elevation. Structures that are anticipated to result in structural flooding upstream in high frequency storms (e.g., 4% AEP or smaller) should be considered high impact.

Examples of low hydraulic impact structures would include:

1. Low water crossings, where most flow passes over the structure and any hydraulic impacts are limited to areas immediately adjacent to the structure with limited upstream storage effects.
2. Structures that have substantially elevated bridge decks and embankments that do not encroach into the floodplain (so that the hydraulic impact is solely due to piers and contraction/expansion losses would be minimal and/or addressed well by the rest of the 2D domain, or so that a 1D model would not be expected to see substantial head loss).

A high-impact structure that is not near a proposed project or along a high-priority stream may be modeled with a lower level of detail (i.e., based on field visits, aerial photography, and/or LiDAR to estimate structure sizes, rather than relying on as-builts or survey) if the engineering judgment of the modeler indicates that it is unlikely to affect the expected project benefits and/or impacts in a proposed project area.

The engineering judgment and quantitative assessment used to determine whether a structure is high or low impact and the desired level of model detail are recommended to be documented in an internal logbook, including a description of comparisons with similar structures on other streams or any sensitivity testing that is done.

Structures near potential projects may need to be modeled with high levels of detail, even if they have low hydraulic impacts, to meet funding guideline criteria.

Rain-On-Mesh Upland Structures – To accommodate rain-on-mesh models, mesh development should be such that water is not impounded behind linear structures (such as where the LiDAR runs along the roadway deck) or other structures or ridges where an opening is not present in the LiDAR and a breakline follows the ridge. V-notches or other simplified methods that allow water to flow across the ridge may be used within these upland areas. In downstream areas with concentrated flow downstream of a HEC-HMS inflow boundary line, or where proposed projects are to be assessed, 2D connections should be used as described above. If a ROM model is primarily to be used for screening and preliminary analysis, the level of structure detail will generally be lower than for the final project model.

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Sources for Structure Detail – Structure details can be obtained from several sources, including:

1. Existing models that contain some structure data.
2. Texas Department of Transportation (TxDOT) maintained bridges and culverts included in a TxDOT database.
3. As-built drawings, field visits, or aerial surveys that identify general structure dimensions.
4. Raw LiDAR LAS points that may be useful in some situations to identify pier locations and sizes and potentially estimate deck thickness.
5. Field reconnaissance data with culvert dimensions, approximate bridge deck thickness, or other information for a structure.
6. Field survey for structures expected to be associated with a proposed project that do not have sufficient available structure data and for which the expected structure impact is critical (note that field survey is not anticipated to be a significant part of this study).
7. Bathymetric data In a 2D model, add a SA/2D connection with the weir extracted from the terrain the same way as for a 1D model, described above. The 2D connection should be set to use the 2D equations (unless there is a significant vertical drop across the structure, in which case the weir equations should be used).
8. In either 1D or 2D models, if the structure is a bridge or culvert where the road surface has not been removed from the terrain, the approximate width of the culvert or bridge opening should be cut into the shape of the weir. While it is not necessary to modify the terrain in this case, see **Section 4.2.3** for examples of using vector modification options in HEC-RAS version 6.0 and later.

If the structure is a bridge with the deck substantially above the expected water level, the terrain typically will not include the bridge deck. In this case, simply include the terrain elevation as the bridge weir, use the 2D equations for the analysis, if applicable, and note the approximate elevation of the bridge deck in the structure description. Terrain modification or modifications to the weir geometry could be used to add piers if their effects are expected to be significant to the model. The structure description in the HEC-RAS model will discuss why the structure is considered low impact.

4.6.3. Bridge/Culvert Geometry

Structure detail should be confirmed and documented based on available data sources. Structures imported from existing models should be checked against aerial photos, LiDAR, or other data sources to confirm that the structure sizes and openings are well represented in the model. Where available, as-built drawings, field visits, or survey may also be used to document a structure's representation in the model. Detail confirmation, including data sources referenced, are recommended to be noted in an internal model logbook.

HEC-RAS 1D Geometry

Within a 1D HEC-RAS model, a structure's geometry shall include the placement of appropriate upstream and downstream cross sections and ineffective flow areas, following the placement guidance in the *HEC-RAS User's Manual*. The choice of bridge modeling methods (e.g., energy only, pressure/weir, etc.) shall be made based on engineering judgment for each structure and are recommended to be documented in an internal model logbook.

HEC-RAS 2D Geometry

Within a 2D HEC-RAS model, a structure shall be added as a SA/2D Connection, with the high point of the structure (i.e., road, levee, or dam) enforced in the mesh to prevent flow leakage across the

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structure. HEC-RAS version 6.0 guidelines should be followed to include structure information within the 2D domain for both bridges and culverts.

HEC-RAS Bridges
The following are general guidelines for modeling bridges in HEC-RAS.

Bridge Deck Elevation – The bridge deck elevation should represent the highest point along the bridge deck, including solid rails or other vertical extensions that will substantially resist flow where present. The LiDAR point cloud may be able to provide bridge deck information where the terrain DEM follows the channel centerline.

Bridge Low Chord – The bridge low chord should represent the lowest horizontal member of the bridge spanning the channel. If the maximum WSEL is at or higher than the bridge low chord elevation, the bridge low chord elevation will be vital to estimating total bridge capacity. Survey or as-built drawings would be required for such a bridge near a proposed project. Field measurements of bridge deck thickness combined with LiDAR estimates of the bridge deck top elevation may be sufficient for bridges farther from a proposed project area.

Twin-Span Bridges – For a twin-span bridge, if the distance between the spans is less than each span width, the modeler should use a single, wider span for the bridge in HEC-RAS, with the total modeled deck width being the distance from the upstream edge of the upstream span to the downstream edge of the downstream span. For wider spacing, use two separate bridge spans.

SA/2D Connection Length – In HEC-RAS 2D, limit the SA/2D connection length for a bridge to the larger of the bridge opening width or the expected cell spacing along the channel, and include each opening of a structure with multiple openings as a separate SA/2D connection. HEC-RAS 2D computes one family of curves for a SA/2D connection and calculates the flow through each cell face within that connection, based on fractions of those curves through each cell face, so care should be taken that the flow through each opening will be representative. Modeling each opening separately provides the finest level of control. If a potential project may include increasing the opening width, extend the 2D connection to encompass the potential project's full opening width.

Bridge Approaches – Bridge approaches can be modeled within a SA/2D connection or simply with cell faces along the high point. If the bridge approach is modeled in a SA/2D connection, proposed improvements changing the roadway proposed grade line can be made via a connection weir, rather than with terrain modification. This may result in simpler proposed conditions modeling. If a solid rail is present down the road centerline or if there is a vertical drop across the embankment that may cause stability problems, a SA/2D connection with a weir may be more appropriate than modeling with a breakline.

Ensure that there are breaklines and/or SA/2D connections along the road high point (generally the roadway centerline) and that there is no leakage below the deck besides the bridge/culvert opening. SA/2D connections should be drawn from left to right looking downstream. This will prevent HEC-RAS from producing an error if the direction of culvert barrel centerlines, drawn from upstream to downstream, do not agree with the direction of the connection lines.

HTab Parameters and Curves – The engineer should review the bridge modeling approach, HTab parameters, and HTab curves based on HEC guidance. Specifically, HTab curves should extend above the highest expected headwater (but not significantly higher) and tailwater elevations and should be

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reviewed for sharp changes or reversals that may result in model instability. The HTab curves should be reviewed to confirm that there are no inappropriate kinks, and that the lowest values have sufficient detail. Increasing the number of free flow points (max 499 as of HEC-RAS 6.1 and 6.2) may help improve the detail.

Ineffective Flow Areas – For a 1D model, the engineer should also review ineffective flow areas around structures, following HEC guidance.

HEC-RAS Culverts

The following are general guidelines for modeling culverts in HEC-RAS.

In a 2D model, both ends of the culvert should be within cells that have sufficient volume to supply the culvert with flow. Small cells (by area) or cells with small volumes will require small computational time steps for a stable model. Culvert volume is not included in the calculations for a 2D model. Where needed to improve model stability, the terrain can be modified to cut out the culvert width from the embankment, thereby adding the culvert volume to the upstream/downstream cells. For long culverts where the terrain exhibits an extended break in the channel, a SA/2D connection with a culvert or terrain modification will be preferable to using v-notches or other mesh face manipulation in the upland area.

During the West Region pilot study, it was observed that culvert instabilities were common during joint probability coastal events, particularly during high surge and low rainfall events. In some cases, culverts were replaced with bridges, with an opening that approximated the culvert. If persistent culvert instabilities are encountered, engineers should keep alternative options in mind to model the culvert and use discretion when making these adjustments. Several alternative options include: bridges with approximate opening, 2D weirs, v-notch breaklines, or terrain modifications.

4.6.4. Modeling Dams and Levees

Dams and levees can be modeled in multiple ways depending on their locations, opening structures, and model type (i.e., 1D, 1D/2D, or full 2D). While a dam is usually inline and a levee is usually offline, adjacent to the channel, both involve assigning the weir elevation and including any low flow structures using the same HEC-RAS elements. The dam or levee modeling method is categorized based on the type of HEC-RAS element used to model the structure.

Information on levees may be obtained from the National Levee Database and information on dams may be obtained from the National Inventory of Dams. Other sources of information may include data from counties, municipalities, survey, or the latest LiDAR terrain. In the case of recently built levees, construction plans may be used; in their absence, a survey may be recommended to gather data on the top of the levee and its extents.

While it is possible to model a dam or levee within a 2D area using breaklines and terrain modifications to enforce the dam or levee crest, this approach is not recommended for the RBFS, as it does not allow for breaching, inclusion of modeler notes, or the use of the weir equation to model overtopping and does not provide a stage or flow output in the model. All dams and levees should be modeled using HEC-RAS structures.

4.6.5. Levee Modeling Methods

The levee, lateral structure, inline structure, SA/2D connection, and breakline features in HEC-RAS, along with 1D storage area or 2D area connections may be used to simulate levees, channel berms, or major roads within the watershed. Three general methods for modeling levees are presented below. The methods cover cases where the levee is sufficiently high and overtopping is not a concern, as well as where there is overtopping potential.

Single-Reach 1D Model, Levee Point in Cross Section – In 1D models where overtopping of the levee is not a concern, the levee is sufficiently higher than the maximum WSEL, and no breach analysis is anticipated or breaching flow would be limited to the area immediately behind the levee with no flow paths away from the levee, a levee point may be defined by enabling the levee option in the cross section with a corresponding location with respect to the main channel and entering an elevation representing the actual levee elevation. Even though the terrain may pick up the shape of the existing levee, defining levees within the model will force the model to contain the flow on the channel side of the levee. The following figure shows the levee in a 1D cross section (see **Figure 4-14**). This option is very limited in its usefulness and is not likely to be applied within a RBFS model.

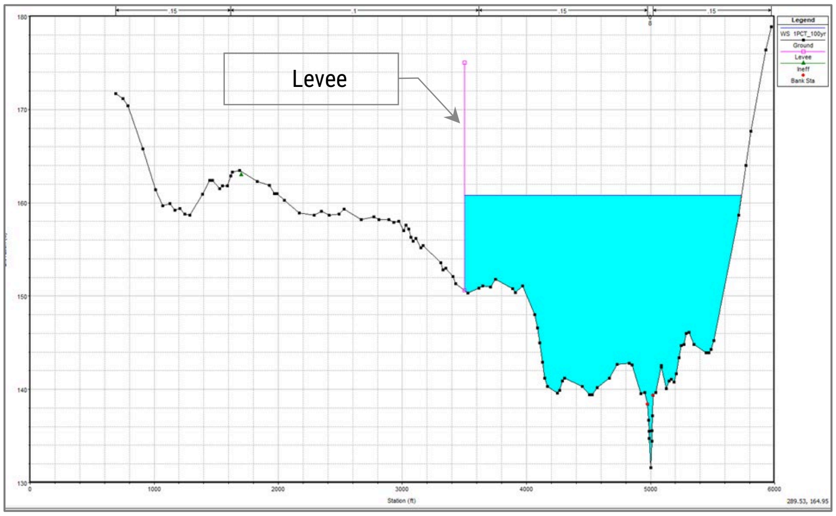

Figure 4-14. Levee in a 1D Model

1D Lateral Structure – In 1D models where the maximum WSEL may overtop the levee in some or all locations and/or where any overtopping or breaching flow would proceed downstream either along the channel or away from the channel, the levee point option, described above, will not provide an accurate representation of conveyance behind the levee. For instance, in an overtopping scenario, the 1D point option ignores the levee and uses the entire cross section for conveyance. This is unlikely to be an accurate representation of flow patterns, since the levee still impacts conveyance and often the area behind a levee will primarily serve as storage, with little or no active flow. In these cases, the levee can be better represented by a lateral structure. The landward side of the levee can be modeled either as a 1D storage area representing overland ponding with no flow path, another 1D channel reach to allow flow away from the levee, or a 2D area representing ponding and potential flow away from the levee. The lateral structure can function as a weir and can include other hydraulic conveyance features such as gates, culverts, diversion rating curves, and an outlet time series. A 1D storage area is defined in terms of elevation-volume data, while a 2D area has storage determined based on the terrain. The possible connections are described below.

- **1D Lateral Structure to 1D Channel Connection:** In this case, there is another channel on the landward side of the lateral structure (i.e., levee) that receives flow when the levee is overtopped. The channel is defined as a separate reach with cross sections. The backwater effects from the connected channel serve as the downstream boundary condition for the lateral structure. HEC-RAS uses standard unsteady flow equations in this scenario.

- **1D Laterals Structure to Storage Area Connection:** In this case, there is a storage area on the landward side of the lateral structure (i.e., levee connects) to the which flow is connected. An elevation-volume curve is added to the storage area and serves as the downstream boundary condition for the lateral structure. HEC-RAS uses level pool routing to evaluate the flow exchange between the main channel and the storage area.
- **1D Lateral Structure to 2D Flow Area Connection:** In this case, the lateral structure connects to a 2D flow area on the landward side. The WSEL in the 2D grid serves as the downstream boundary condition for the lateral structure. HEC-RAS uses 2D equations to evaluate the flow exchange between the lateral structure and the 2D flow area.

SA/2D Connection – A SA/2D connection allows connections between two 2D areas, between a storage area and a 2D area, or internal to a 2D area. The weir elevation for a levee can be extracted from the terrain but should be reviewed and adjusted to follow the certified levee elevation if the connection centerline drifts or if the terrain does not fully capture the levee top elevation. Openings in the levee where certified flood gates will be installed during a flooding event should be modeled as if they are properly closed (except possibly during a breach analysis). For a 2D connection, the user has the option of selecting the normal 2D equations or the weir equation. The weir equation should be used if there is a drop in water elevation across the structure.

4.6.6.Dam Modeling Methods

Dams are usually inline features along the channel. In some rare cases, a dam may be located offline from a main stem, in which case it is likely an inline feature of a tributary or possibly pumped storage. Three methods for modeling dams are presented below.

1D Inline Structure – In a 1D model or a 1D/2D model, an inline dam is defined using the inline structure tool. The inline structure tool has various hydraulic conveyance options to define flow across the dam structure. These options include weirs/spillways, gates, culverts, outlet rating curves, and a specified outlet time series. The reservoir upstream of the dam may be defined either using standard model cross sections representing the reservoir cross section using a 1D storage area connected to the upstream end of a reach, one or two cross sections upstream of the inline structure to define the volume-elevation relationship, or a 2D area connected to the upstream end of the reach.

- **1D Channel Reservoir:** The reservoir is represented by a series of cross sections. The flow hydrographs into the reservoir pool can be added as upstream boundary conditions. The dam is modeled as an inline structure connecting the upstream and downstream cross sections. HEC-RAS used standard 1D unsteady equations in this case.
- **1D Storage Area Reservoir:** The reservoir is added as single storage area, which is connected to the upstream and downstream river reaches. An elevation-volume curve is added to the storage area and the storage area will receive flow from the upstream reach or inflow directly into the reservoir. The dam is modeled as an inline structure and the flow is routed using the level pool routing method.
- **2D Flow Area Reservoir:** The reservoir is modeled as a single 2D area encompassing the reservoir extents. The 2D area will connect to the upstream and downstream river reaches. Flow hydrographs into the reservoir are added as 2D area boundary conditions or flow coming in from the upstream reach. The dam is modeled as an inline structure connecting the reservoir 2D area and the downstream river reach cross sections and uses 2D equations to route flow.

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1D Lateral Structure – The methods for modeling offline dams in 1D are similar to methods for modeling levees using lateral structures in 1D models, as described in Section 4.6.5 – 'Levee Modeling Methods.'

SA/2D Connection – In a full 2D model, a SA/2D connection can be used to model a dam, similar to the way a levee in a 2D area is modeled, as described in **Section 4.6.6**. The flow across the dam and through its outflow structures can be modeled via the weir/spillway, gate, culvert, diversion rating curve, and specified time series options.

4.6.7.Dam and Levee Breach Modeling Methods

Dam or levee breaches are modeled within HEC-RAS using the breach editor for inline structures, lateral structures, or SA/2D features (for 2D models). The breach editor in HEC-RAS is identical for all three types of structures. To perform a breach analysis, the breach characteristics need to be determined for the structure, as these will determine the shape and peak of the flow hydrograph leaving the dam. Many factors can contribute to the progression of a breach including soil characteristics, structural or geotechnical failures, piping, erosion, overtopping, etc. The user may choose from one of three options to define a dam breach: User Entered Data, Simplified Physical Breaching, or Physical Breaching (DLBreach). A breach analysis is not required for hypothetical runs. The team can consider choosing a calibration event that includes a breach. However, if a breach occurred during a calibration event, it must be modeled. Additionally, a breach analysis may be performed if there is documentation and guidance from local entities, USACE, or GLO that supports the need for this analysis, and it is included in the baseline model scope of work.

User Entered Data – In the User Entered Data option, the user is required to input all data manually, including the breach size and location, development time, progression, and failure mode (i.e., overtopping or piping). A 1998 publication by Tony L. Wahl of the U.S. Bureau of Reclamation entitled "Prediction of Embankment Dam Breach"Parameters" documents procedures to predict dam breach based on study of historical dam breaches. The *HEC-RAS User's Manual* recommends using this publication. Regression equations have been developed by several researchers to predict peak outflow and time based on parameters such as dam height, reservoir storage, embankment geometry, etc.

Simplified Physical Breaching – In the second option, Simplified Physical Breaching, HEC-RAS will compute the breach based on "Velocity vs Downcutting Rate" and "Velocity vs Widening Rate" curves provided by the user within the parameters of the overall breach geometry, also specified by the user.

Physical Breaching – The third option, Physical Breaching, will compute the breach based on the dam type and configuration, soil properties, flood levels, and other input parameters. Additional information on estimating the breach parameters is available in the "Using HEC-RAS for Dam Break Studies" manual, dated August 2014, as well as in Section 14 – 'Advanced Features for Unsteady Flow Routing,' of the latest *HEC-RAS User's Manual*.

While the reservoir storage, inflows, and breach characteristics are important for analysis of a dam breach scenario, the downstream reaches are equally essential to evaluation of the after-effects of a breach. The reaches downstream of the dam need to be modeled such that the cross-section extents or 2D areas cover the anticipated flood extents. Tributary flows affect the flow hydrograph shape, and peak flow, and offer storage for the flood wave after the breach, so any major tributaries should be included in the model. Levees may be present downstream of a reservoir to protect certain high-risk areas. These levees can be modeled using the levee feature or lateral structures. Finally, high velocities associated with dam breaches may require smaller time steps and different cell sizes or 1D cross section spacing than would be required for a non-breach model.

Similar considerations should be made for areas on the landward side of a levee that breaches, as the flow velocity will be high, and the configuration of the landside system can affect the inundation area resulting from a breach.

4.7. Low Detail Rain-on-Mesh Hydraulic Modeling

Low Detail modeling is intended to provide a consistent basis for flood risk evaluation across each region. This level of modeling can be used to defined baseline flood risk in low-risk or low-priority watersheds, and as an interim tool for higher detailed models as mentioned in **Section 1.1.1** and described in **Section 3.2**. Low Detail hydraulic models produced as part of the GLO RBFS will be comparable to existing FEMA and TWDB BLE models.

1D and 2D BLE models are available throughout the state of Texas and can be used as a base for Low Detail model development as part of the GLO RBFS. To view the status of BLE models, visit the TWDB BLE Status Viewer at:

- TWDB BLE Sta–us Viewer - https://www.twdb.texas.gov/flood/mapping/ble-status-viewer.html

In general, 1D BLE models are not recommended for use in the GLO RBFS. The Central Region upgraded an existing 1D BLE model during their pilot study and although it was successfully upgraded, the study team found that the level of effort was not appreciably different from developing a new model from scratch. If a study team elects to utilize a 1D BLE model in their study, the following items should be considered:

- 1D BLE models should be used for streams that are low-risk or low-priority, where an approximate representation of a stream's hydraulic characteristics is adequate.
- 1D BLE models are challenging to upgrade, so they are best suited for streams that will not be upgraded during later phases of this study or where mitigation alternatives are not anticipated.

Existing 2D BLE models, where available, will satisfy the purposes of the Low Detail hydrologic and hydraulic model with a few minor adjustments. If a BLE model does not use spatial infiltration because of a limitation in the version of HEC-RAS used at the time of the BLE study, then the model version should be updated to HEC-RAS v6.1 or newer, and spatial infiltration should be set up to reduce the number of assumptions.

To have a better understanding of the modeling decisions and efforts made in creating the BLE data, refer to the following guidelines and standards. The appropriate guidance to utilize will depend on whether the entity who completed the work was FEMA or TWDB. Guidance for Flood Risk Analysis and Mapping – Base Level Engineering (BLE) Analysis and Mapping is available using the link below.

- FEMA BLE Modeling Guidance - https://www.fema.gov/sites/default/files/2020-02/Base_Level_Engineering_Guidance_Feb_2018.pdf

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4.7.1. Low Detail Model Expectations

Low Detail models are not limited to BLE models, but BLEs currently are the most common and readily available source of low-level detail modeling in Texas. A low-level detail model typically accomplishes the following goals.

- Modeling is large scale—typically, BLE is produced on a HUC-8 watershed or is county-wide.
- Modeling is approximate—no survey or structures are incorporated.
- Modeling can be upgraded—all data used to produce the model is readily available to be used to replicate results and add detail as needed.
- Model has been validated and can be utilized to represent the watershed as a whole—this provides the opportunity to utilize overall results as a downstream boundary condition or upstream contributing area to a neighboring watershed.

Due to the approximation of Low Detail models, there are inherent limitations that should be considered, particularly when considering planning or mitigation opportunities.

- Low level detail is not considered a regulatory product; it can, however, be used as "best available" data in some regions where available data is insufficient.
- Low level detail models are only as accurate as the assumptions made based on the data available at production. In most cases, major modeling assumptions cannot be verified within the limits of a low detail model. These include, but are not limited to, assumptions made for dam operation, diversion structures or split flows, levee levels of protection, channel roughness and widths, and conveyance capabilities of drainage structures.
- Existing 1D low level detail models use separate models for each stream and are not connected on a watershed-wide basis. These models should be combined into a single, comprehensive model as applicable.
- Existing 1D low level detail models are steady state models and should at a minimum be upgraded to unsteady state modeling.

4.7.2. Low Detail Model Standards

The purpose of this section is to provide an overview of the typical standards used to create BLE models. The standards listed here can be utilized for generating new Low Detail models, as may be the case in areas where only 1D BLE is available or where 2D BLE is not yet readily available for use or incorporation. Additional detail is given to the 2D model generation.

1D Low Detail Standards

This section describes the standards that FEMA and TWDB used to develop 1D BLE models.

Centerline Development

Centerline generation for 1D BLE models are created from 10ft terrain DEMs. These unaltered terrains are processed to begin centerline creation after a threshold of contributing drainage area is achieved. For FEMA standards, BLE models are created for centerlines that meet the following criteria:

- 0.9 sq. mi. contributing drainage area limits
- 0.5 sq. mi. contributing drainage area limits within populated areas
- Cover all effective mapping
- Cover all FEMA Coordinated Needs Management Strategy streams

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Cross Section Layout

Cross section layout practices should follow appropriate guidance provided by HEC-RAS, as well as additional recommendations listed within the SOP. For typical BLE studies, the following special considerations are made:

- Cross section spacing for tributaries or other typical streams with small to moderate drainage areas should be kept to approximately 500ft spacing
- Cross section spacing for mainstems or streams with large drainage areas should be approximately 1,000ft
- For major roadways or crossings that cause floodplain constriction or gaps, cross sections are added to the upstream and downstream bounding limits
- For dams, cross sections are placed on the upstream and downstream bounding faces, and one cross section is placed over the top of the dam
- Changes to spacing based on meandering stream geometries is expected

Roughness Coefficients

NLCD provides the land cover that is utilized to create appropriate roughness coefficients for varied Manning's n values for each cross section. Smoother n values are applied to spaces between bank stations for channels.

Bank Stations

Bank stations are adjusted as necessary and, as a general approach, are kept under the 100-year WSEL, unless the channel capacity would indicate otherwise.

Downstream Boundary Conditions

The default approach for downstream boundary conditions is normal depth or stage hydrograph as applicable to the overall study.

Ineffective Areas

Ineffective areas are typically considered a more detailed effort; for low level detail modeling, the use of ineffective areas is minimized. Ineffective areas are incorporated as needed and are typically used to address crossing profiles or areas of excessive conveyance based on cross section geometry.

2D Low Detail Standards

This section describes low level detail standards for 2D BLE models.

Mesh Development

The watershed boundary is used to establish the mesh area. It is recommended that the mesh boundary is buffered a set distance from the model watershed limits to identify any potential flow interactions between neighboring watersheds. The typical mesh size is 200ft x 200ft for a 10ft cell size terrain DEM. This cell size can be adjusted as necessary to achieve reasonable model run times while maintaining accuracy. Like Medium and High Detail 2D models, modelers should aim to create a mesh that regenerates without cell errors.

Breaklines

In addition to considering the stream centerlines as breaklines, topographic features that should be accounted for with breaklines include:

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- Major Roadways – Include all roadways that cross streams or impact flow due to higher elevation than surrounding at-grade elevation.
- Railroads – Incorporate all railroads that would impact flow.
- Irrigation Canals – Irrigation canals can act as bermed channels and should be incorporated, as they impact stream flow and are not storm water conveyance.
- Levees – Levee breaklines should be included on accredited and non-accredited levee systems.

Hydraulic Structures

2D Low Detail models should include only significant structures whose inclusion/exclusion is determined to substantially alter the response of the watershed. For these "critical" hydraulic features, the modeler can use a v-notched or u-notched breakline to approximate the structure. Where possible, dams should be modeled with SA/2D connections which can provide a better representation of the structure using an outlet rating curve or detailed information on the dam's outlet characteristics.

Roughness Coefficients

As with 1D low level detail models, roughness coefficients are pulled from the NLCD. Overbank n values are applied to all overbank areas. Stream centerlines are buffered an appropriate distance based on characteristics of the watershed and incorporated as the channel n value layer. The typical channel n value used for this layer is 0.045, but this can vary within HEC-RAS recommended values. Natural channel n values typically range from 0.025 to 0.06, depending on channel size and vegetation.

Simulation Time Step

Time steps for Low Detail models are set higher initially to reduce model run times for efficient model adjustments and are refined as model changes are minimized. A larger time step can reduce overall computation run times. Final time steps can be 30 seconds to 1 minute. This refinement in time steps is to stabilize Courant values, with a goal to be under 5 for diffusion wave conditions or under 3 for full momentum conditions. Achieving these values and full model stability may not be possible in all scenarios, and engineering judgment should be applied.

Calibration and Validation

For Low Detail models, validation is primarily incorporated via gage analysis and adjusting hydrologic parameters. Additional adjustments in hydraulics can include adjusting Manning's n values within the recommended ranges. Stage comparisons to gages or HWMs can be included where there is available data; however, the accuracy of a Low Detail model is lower than for a more detailed model. Additional Guidance on hydraulic calibration and validation can be found in **Section 4.8**.

4.8. Hydraulic Calibration

This section documents the standard procedures for calibration and validation of hydraulic models. A 1D/2D, 2D-only, or 1D HEC-RAS model will be developed for streams based on available data and stream priority level. HEC-RAS models should be calibrated with observed data, where available.

The hydraulic model calibration process follows the hydrologic (i.e., HEC-HMS) model calibration process in general; however, some adjustment of hydrologic parameters (i.e., calibrated hydrologic parameters in HEC-HMS) may be necessary to optimize the calibration of HEC-RAS models. The flows from the HEC-HMS model are input into the HEC-RAS model for each selected storm event for calibration of hydraulic parameters within the HEC-RAS model.

4.8.1. Storm Event Selection

The storm event selection process is described in detail in **Section 3**.

4.8.2. Data Collection and Processing

Observed hydrologic and hydraulic data is needed to calibrate and validate model results for the selected storm events. The observed data should be gathered and organized to make it useable for the calibration and validation processes. Engineering judgment should be used to evaluate which data sources are more reliable and should be given priority in the calibration process. The observed data collection items and data organization process is described below.

1. Surveyed high water mark data: Acquire available surveyed HWMs from counties, municipalities, and drainage districts to compare with the model-computed peak water surface elevations. HWMs that have not been surveyed should not be used, except in specific cases where they may provide valuable information and there is a lack of observed data.
2. Aerial and field photographs: Acquire aerial and field photographs of the flooding during the selected storm events. Compare the model-computed flood levels, floodplain extents, and surface ponding with those shown in the photographs. Use landmarks and physical features along the floodplain boundaries in the photographs and compare them with the floodplain boundary in the model. Where possible, the time of the photograph should be confirmed so that the floodplain extent at the same time from the model can be compared.
3. Rainfall data: Refer to **Section 3**.
4. Observed stream flow and stage data: Refer to **Section 3**.
5. Reservoir operation data: Refer to **Section 3.10**.
6. Dam and/or levee breaching data: Acquire information during a calibration event.
7. Contemporaneous watershed characteristics: Refer to **Section 3.6**.

4.8.3. HEC-RAS Model Preparation

The HEC-RAS model for the watershed should be updated with flow data for each of the selected historical storm events from the calibrated HEC-HMS model. If gridded precipitation or flow is being used, the models should be updated accordingly. If a reservoir is located within the watershed, the reservoir storage and operation data should be updated in the model accordingly. Observed data may be added to a HEC-RAS model to allow comparisons within the model. All observed data is added within the Unsteady Flow editor, which has options for comparisons to 1D cross section locations, 2D reference points, 2D reference lines, and boundary condition lines. After a model has been run, when the results for a location with observed data are shown, the observed data can be viewed alongside the model results.

For a calibration event, it is important to have model geometry, terrain, and land use data that represent the conditions during the selected historical storm events. It is possible that some roads, reservoirs, detention basins, or developments had not been constructed at the time of the historical storm events; these features should be removed from the model geometry, terrain, or land use files. It is also possible, in some rare cases, that features were removed after a particular storm event and should be added to the geometry, terrain, and land use files to reflect contemporaneous watershed conditions. Engineering judgment should be used to assess whether the model geometry should be adapted to each historical event by determining if the changes to geometry would be expected to have a measurable effect on the model output and calibration.

For calibration events that involve dam or levee breaches, the actual breaching information should be included in the model setup.

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4.8.4. HEC-RAS Model Calibration

Model calibration is performed by adjusting the parameters within HEC-RAS models to best match the model-computed flow and stage hydrographs, peak flow, and peak stage data with observed data, surveyed high water marks, and aerial and field photographs. The overall model calibration process includes hydrologic model calibration, as discussed in **Section 3**, and hydraulic model calibration, as discussed herein. There is some overlap between these calibration steps, as the hydrologic calibration includes some changes that can affect timing and peak stage results.

In addition to the steps for hydrologic calibration, the following adjustments to improve the hydraulic calibration may be used.

1. Adjustment of Manning's roughness values

    a. Adjust roughness values in 1D and 2D areas to better represent the watershed at the time of the storm event(s). Seasonal vegetation and land use at the time of the storm event(s) may impact roughness values.
    b. Adjust roughness values upstream of the gage location to match the model stage hydrograph peak timing and shape (i.e., attenuation) with observed data.
    c. Adjust roughness values in the vicinity of gage locations to match the model peak stage with observed data.

2. Adjustments to bridge and culvert data to better represent head losses

    a. Adjust bridge ineffective flow area extents and elevations.
    b. Change bridge modeling approach, which varies depending on the flow conditions through the bridge/culvert. Refer to the latest *HEC-RAS User's Manua*l for guidance.
    c. For bridges with multiple openings, adjust conveyance zones to better represent the distribution of flow between the openings.
    d. Adjust weir data for roadway deck (i.e., maximum submergence ratio and weir crest shape).
    e. For culverts, adjust the entrance and exit loss coefficients and solution criteria (i.e., inlet vs outlet control).
    f. Adjust contraction and expansion coefficients in the vicinity of the bridge.

3. Other adjustments

    a. Further refinement of the 2D mesh may be necessary in specific overland flooding scenarios or ponding areas where complex flow is observed.
    b. Breaklines and blocked obstructions may be adjusted to better represent correct lake surface area and lake water levels during the time of the event.
    c. Adjustments to lateral structure connections between model elements may be needed. Adjustments include number of data points, elevations, and weir coefficients.
    d. Boundary conditions configuration may be adjusted, as needed.
    e. Review of dam or levee operation information, pump operation information, and breach data may be necessary to assess whether there is a potential that the source data or its application to the model may be incorrect.

Modelers should utilize the above techniques to obtain a best match between model and observed data in terms of flow hydrograph volume, peak, and timing and stage hydrograph shape, peak, and timing. Modelers should compare the peak water surface elevations, flooding extent, and surface ponding with

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surveyed HWMs and aerial and field photographs to ensure the results are reasonable. Example comparisons between model and observed data for flow and stage are presented in **Figure 4-15** and **Figure 4-16**.

Model parameters should be adjusted within reasonable limits and should not exceed reasonable limits just to achieve a better match. Hydrologic parameters may need further adjustment while performing hydraulic calibration to optimize the overall hydrologic and hydraulic calibration. Refer to **Section 3.6** for adjustment of hydrologic parameters.

Evaluation of Calibration Quality

Engineering judgment and statistical metrics should be used to evaluate the quality of calibration. Engineering judgment involves the following:

- Understanding the sensitivity of parameters, discrepancies in observed rainfall and gage data, and limitations of the model in determining the best possible calibration.
- Evaluating model performance based on visual and numerical comparisons. Visual comparisons include flow and stage hydrograph shape (i.e., rising and falling limbs), hydrograph peak, peak timing, etc. (see **Figure 4-15** and **Figure 4-16**). Numerical comparisons include differences in flow hydrograph volumes, as well as flow and stage hydrograph peaks.

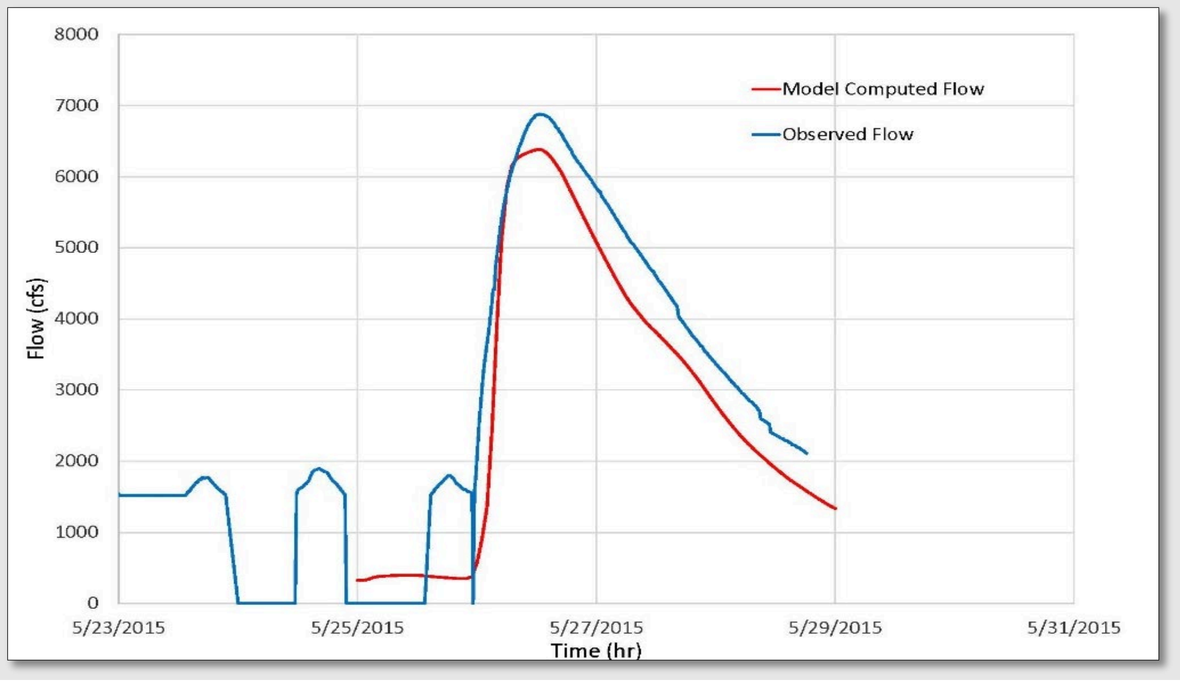

Figure 4-15. Example Model vs Observed Flow Hydrograph at a Gage Location

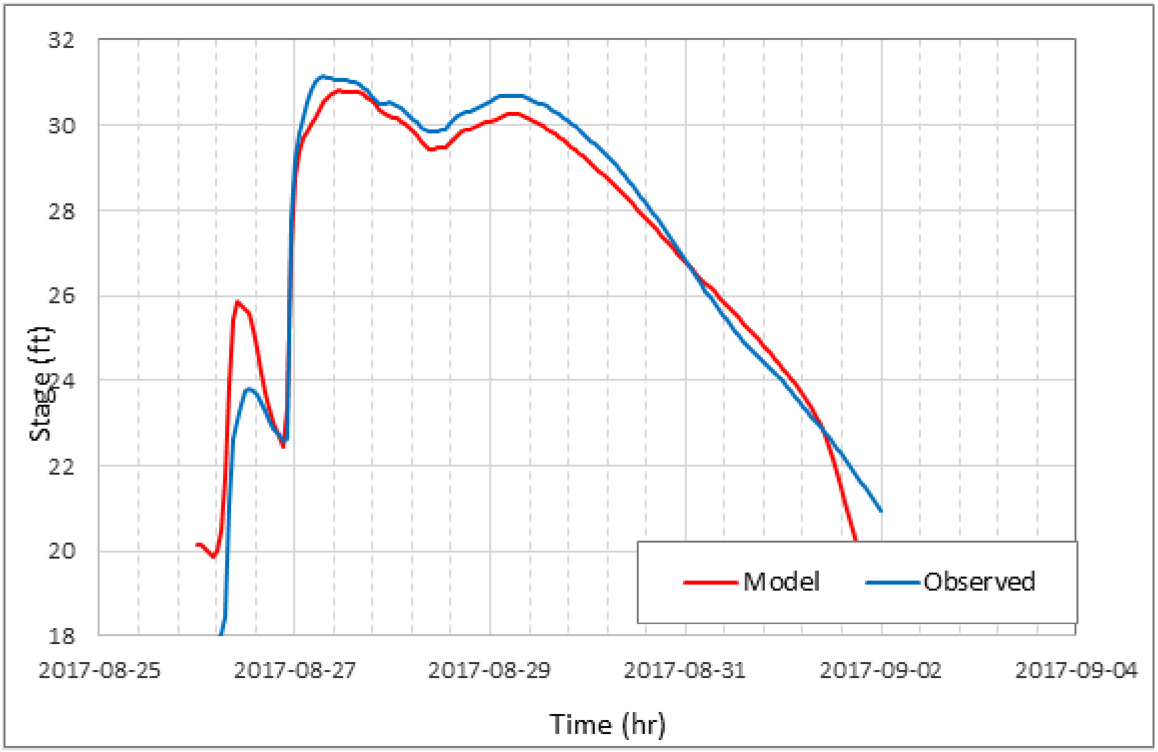

Figure 4-16. Example Model vs. Observed Stage Hydrograph at a Gage Location

Quantitative Methods – Quantitative methods for evaluating hydrologic model performance are presented in **Section 3**. For a hydraulic model, there is no standard for statistical assessment of calibration quality similar to the Nash-Sutcliffe method for hydrology. Quantitative measures for evaluating hydraulic models are described below and should be included in the model report. These are not true statistical comparisons with a statistical measure of goodness of fit, but they can be used to provide an understanding of the model's usefulness for the assessment of a given potential project. Numerical comparisons that may be helpful in assessing the calibration quality include Mean Error, Mean Absolute Error (MAE), and Root Mean Square Error (RMSE). Each of these can be applied to either a set of HWMs across the model or to individual gage time series of stage data. They all provide information on the general goodness of fit, but none is inherently better than another.

- **Mean Error:** Mean Error simply adds up the differences between observed and modeled values. A value away from zero indicates that the model is either biased high or low, in general; however, a zero value may be the result of high values being offset by other low values.
- **Mean Absolute Error:** By taking the absolute value, MAE measures how close the two values are to each other and does not allow highs to offset lows. MAE weights all errors equally. A lower number is generally better.
- **Root Mean Square Error:** RMSE gives extra weight to large errors in a dataset. A higher number indicates that there are more places where the two data sets differ substantially.

Other quantitative measures include calculating the percentage of observations within a given WSEL of the observed HWM.

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4.8.5. HEC-RAS Model Validation

The HEC-RAS model is validated by running the validation storm events with the calibrated hydraulic parameters using flows from validated HEC-HMS model. Modeling teams should compare the HEC-RAS model flows and stage with observed data to ensure calibrated parameters yield reliable results. The teams should also perform the same visual and numerical comparisons and statistical analysis as were performed for the calibration models to evaluate validation quality. Engineering judgment should be used to assess whether the validation is successful and modeling teams should document the comparison of model results to observed data for the validation event. Once a model is considered calibrated and validated, the final model parameter values should be documented for use in frequency storm events.

4.8.6. Final Hydraulic Parameter Development

Some parameters including roughness, entrance and exit loss coefficients, elevations and extents of ineffective flow areas, and extent of multiple opening conveyance zones may be averaged over calibration events and average values may be used in frequency storm event models. Other adjustments, such as contraction and expansion coefficients, bridge and culvert modeling approaches, grid refinement, lateral structure adjustments, etc. may have to be finalized based on engineering judgment. It is recommended that only one geometry file be developed for all storm frequencies.

4.8.7. Documentation

The following documentation should be prepared for all storm events.

1. Flow hydrograph comparison graphs: HEC-RAS model vs observed data (see **Figure 4-15**).
2. Stage hydrograph comparison graphs: HEC-RAS model vs observed data (see **Figure 4-16**).
3. Peak flow, hydrograph volume, and time to peak comparison tables: HEC-RAS model vs observed data, including percent difference.
4. Peak stage and time to peak stage comparison tables: HEC-RAS model vs observed data.
5. Table of calibrated hydraulic parameters for each storm event and final calibrated parameters. These parameters include roughness values, entrance and exit loss coefficients, contraction and expansion coefficients, and bridge and culvert modeling approach.
6. Explanation of deviations between model output and observed data.
7. Documentation of quantitative analysis and model performance.

4.9. Hydraulic Sensitivity and Uncertainty

This section documents methodologies that can be considered to address hydraulic sensitivity analysis during the development RBFS hydraulic models. These methodologies cover the range of parameters that may be examined in 1D and 2D hydraulic models. In general, hydraulic sensitivity analyses should be performed as early as possible, so that later steps (including calibration) can benefit from any improvements or decisions made during sensitivity analysis.

For the RBFS, *sensitivity* will be used to refer to how the model responds to numerical or program options that do not have direct physical meaning, while *uncertainty* will be used to refer to how the model results are affected by uncertainties in the physical parameters that underly the model. In general, some sensitivity analyses will be performed for all models, while uncertainty analyses will be reserved for High Detail models and may be performed at a later date when assessing how certain the modeler is of benefits of a particular proposed project.

4.9.1. Level of Detail

This SOP identifies a rigorous approach to sensitivity and uncertainty analyses, including several components that may be deemed unnecessary, even for High Detail studies. Engineering judgment should be used to determine what aspects of the SOP may be relaxed while still meeting the minimum standards required for the desired funding source. For each project, the modeling team will discuss with USACE and will make a recommendation on the components of the sensitivity and uncertainty analyses to be performed. In some cases, a detailed sensitivity or uncertainty analysis may be postponed until the next phase, when the proposed conditions analysis will be performed.

4.9.2. General Considerations

Model sensitivity analysis provides an understanding of which model features are critical in the modeling process. This is achieved through performing multiple model runs, while modifying parameters to evaluate the processes and values within the models that make the most impact to the results. This step will also allow for a better understanding of where the modeling teams should focus efforts to ascertain that model parameters and modeling methods are accurate.

4.9.3. Numerical Sensitivity Analyses

Numerical sensitivity involves adjusting the parameters that impact and affect the mathematical and numerical processing of the solution within the hydraulic program. For a full 2D model, many of the numerical sensitivity analyses can be assessed prior to adding structures to the model, which may reduce the model run time during the sensitivity testing. Specifically, addressing the mesh size and time step early can result in a shorter run time for all later analyses.

Mesh Size and Complexity

An appropriate mesh size should be selected to capture the detail of the terrain, such as ridge lines or slow changes in topography, while minimizing model run time. Understanding that once breaklines, 2D connections, and other features are added to a model, changing the base cell size can cause issues, it is advisable to test the sensitivity of the base mesh to various cell sizes and establish a base cell size very early in the process, prior to adding structures and performing substantial breakline development. Different mesh sizes should be tested to make certain of a convergence for a solution. The mesh size should be as large as possible while maintaining reasonable accuracy. See **Section 4.3** for a full discussion of mesh size selection.

Full Momentum (Shallow Water Equations) vs Diffusion Wave

Two-dimensional unsteady flow routing sensitivity may be examined by testing the full momentum equations, also known as Shallow Water Equations (SWE), to determine if these are more appropriate than the default Diffusion Wave method. There are two variations to the SWE that may be tested: the original SWE with a Eulerian-Lagrangian approach and the stricter SWE with a Eulerian approach. If the three methods produce significantly different results, one of the SWE methods may be more appropriate for the model than the diffusion wave method. Any model that includes wind forces will need to use one of the two SWE equation methods. A shorter time step will likely need to be used to run the SWE equations in a stable manner.

Computational Time Step

Selecting the computational time step should occur through an iterative process of changing the time step size and comparing the model result accuracy, stability, mass balance error, and model run time. The Courant-Friedrichs-Lewy condition is one measure of stability that should be kept lower than 5 for diffusion wave conditions or under three for full momentum conditions in a full 2D model. See **Section 5.6.** for further discussion of computational time step and cell size in coastal regions.

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Theta Weighting Factor
The default value for theta in HEC-RAS is 1.0, which provides stability to the model but potentially reduces accuracy when compared to lower values of theta. Once the model has been developed and is working, the user may consider adjusting the theta value towards 0.6. During this adjustment, the results from models with different theta values can be compared. If there is a change in results and the model remains stable, the lower value for theta may be used, as it provides a greater accuracy in the numerical solutions.

Model Tolerances
Model calculation tolerance values can be examined once the model is stable to determine if a smaller tolerance, which would achieve greater model accuracy, will impact results significantly without generating undue run times or instability. This concept includes a number of computational options, such as:

- 2D area preprocessor tolerances, such as the "Cell Volume Filter Tolerance" in the 2D Flow Area editor
- 1D and 1D/2D unsteady flow options, such as the lateral structure flow stability factor
- 2D flow options, such as theta and the WSE and flow tolerances, as well as number of cores
- 1D/2D options, such as iterations between 1D and 2D
- 1D mixed flow options in the "Computation Options and Tolerances" editor.

Testing model tolerances is not mandatory but can be performed if the modeler and the reviewer believe it can add value.

Documentation
Hydraulic sensitivity analyses involve many interim model runs. It is not anticipated that all these runs will be submitted as formal documentation; however, vendors may choose to submit some interim models (or other documentation) regarding items that result in significant changes to the model, in addition to the items specified below. Sensitivity documentation will be part of the Final Hydraulic Products provided for this study. Documentation may include:

- Comparison plots showing results of parameter range sensitivity investigations
- Log of model changes during sensitivity analyses (optional, for internal purposes only)
- Spreadsheet results and tracking of parameter adjustments (optional)
- Discussion of any changes from initial parameters and reasoning for adjustments
- Final parameter spreadsheet and model

4.9.4. Physical Parameter Uncertainty
Because physical parameters are part of the calibration process and are adjusted to develop a calibrated model, physical parameter uncertainty analysis will not be performed for most models. If physical parameters are varied during calibration, these results can provide some insight into how sensitive the model would be to changes in those parameters. A discussion of the observed sensitivity may be helpful to future modelers, but it is not a required deliverable.

Assessment of physical parameter uncertainty involves adjusting the hydraulic parameters and geometric properties of the model to determine impacts to the model results. This provides a reasonable range of parameter values that are appropriate for the particular model and demonstrates the potential range of results. Several physical parameters that can be included in an uncertainty

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analysis are described below. Specifics on how to perform an uncertainty analysis are included in **Section 4.9.5**.

Boundary Conditions

Boundary conditions (i.e., flow hydrographs upstream and stage hydrographs downstream) may be assessed for a reasonable range of values, including values associated with larger events. A multiplier can be added to a flow hydrograph to result in a peak flow that is higher than the maximum expected value based on a review of existing modeling events.

For downstream stage-time boundaries, the modelers may perform a comparison between a normal depth and a stage-time boundary condition to assess whether a normal depth condition is appropriate for the model. Simplifying the downstream boundary condition to remove a stage-time curve is preferred if the results are reasonable and the boundary is far from any potential project.

Normal depth downstream boundary conditions should be assessed for a range of slopes somewhat above and below the typical channel slope at the downstream boundary of the project.

Manning's n Values

Manning's n values are typically estimated based on physical data about the stream and floodplain; other times, Manning's n values are calibrated to align with flow velocities based on a limited number of storm events. Either way, Manning's n values are not exact and require some sensitivity testing. Modeling teams should estimate a realistic range of values that the Manning's n could fall within for their streams. For example, if a modeler estimated a channel condition for a stream as, "clean, winding, some pools and shoals," HEC-RAS would supply an average Manning's n value of 0.04, whereas a realistic range for the n value might be 0.033 to 0.045. The modeler would then run the lower Manning's n value and the higher Manning's n value in the range to evaluate the model's sensitivity to the range of potential n values.

Weir Spillway Coefficients

Lateral weir or spillway coefficients can have significant impacts on the results of a model simulation, because they control the amount of water entering or leaving the main stream system. These coefficients can vary greatly for lateral structures, depending upon structure angle to the main flow, the velocity of the main flow, and other factors. The default weir or spillway coefficient values are typically used; however, the sensitivity of these coefficients may also be evaluated through the range of reasonable spillway coefficient values. The *HEC-RAS User's Manual* provides a wide range of values that are appropriate for specific weirs and spillways and should be referenced for appropriate weir coefficients. In general, sensitivity testing for the weir spillway coefficients will be considered optional.

Bridge and Culvert Parameters

In general, bridge and culvert parameters normally only affect the locally computed WSELs just upstream and downstream of the structure. The effect that a bridge or culvert structure will have on the water surface is much greater in flat streams than in steep streams, because a small increase in WSEL can back upstream for a long distance if the river is flat. However, the sensitivity of the WSELs around a bridge or culvert can be very important to localized flooding. Bridge and culvert hydraulic parameters may, therefore, also be evaluated to test their sensitivities. Parameters to test the range of acceptable values (as reported in the *HEC-RAS User's Manual*) include roadway deck weir coefficients, maximum submergence, culvert entrance loss coefficients, bridge modeling approaches, and pier shape drag coefficients. If these items are assessed and varied as part of the calibration process, no additional sensitivity testing is recommended. In general, sensitivity testing for the bridge and culvert parameters will be considered optional.

Expansion/Contraction Coefficients
Expansion and contraction coefficients are 1D features primarily used in steady flow models. For unsteady models, they are typically not included since the unsteady calculations include consideration for changes in flow area between cross sections. If expansion and contraction coefficients are used in a model, they could be added as part of the calibration process, and the sensitivity of the model to coefficient variations could have been considered during the calibration process. No additional sensitivity testing is recommended.

Ineffective Flow Areas and Blocked Obstructions
Portions of 1D cross sections are often defined with (a) ineffective flow areas representing portions of the cross section that have storage, but no conveyance, or (b) blocked obstructions, representing portions of the cross section where the terrain is not representative for either storage or conveyance calculations. Ineffective flow areas are often used around a structure to represent contraction and expansion of flow as it approaches and leaves the structure opening. Since the elevation and placement of ineffective flow areas are based on physical conditions of contraction and expansion, the model's sensitivity to variations in their placement is less important than ensuring that the placement is representative of the actual flow conditions around the structure. Similarly, blocked obstructions are also based on the physical conditions at a cross section, making model sensitivity to variations in their placement less important. As a result, the placement and elevations of ineffective flow areas and blocked obstructions should not be varied as part of a model's sensitivity analysis.

Flow Rates
For planning studies, examining a range of flow rates provides an effective process to understand the sensitivity of the model to changes in channel capacity and future flow increase. Because the models are executed under unsteady flow conditions, they will be executed using a wide range of observed events and several storms of varying return frequencies. The models will also be executed in future phases for future land use conditions. As a result, further variation of flow rates as part of a sensitivity analysis is not recommended.

4.9.5. Model and Results Uncertainty Analysis Methodology

Although the sensitivity analysis, model calibration, and validation steps described in related sections in this SOP are important parts of addressing model uncertainty and reliability and increasing decision makers' confidence in a model, a well-calibrated and validated model still may or may not be adequate to provide insights and support decisions regarding flood prediction and protection strategies. Decision makers also need to know the reliability of the predictions determined by the numerical model. Therefore, certain quantitative measures may be needed to improve reliability; this is typically accomplished through an uncertainty analysis.

Uncertainty analyses are an optional task that may be included for some high-impact projects where model development uncertainties could have a significant impact on the effectiveness and benefits of a potential project but are not expected to be included for most RBFS models. An uncertainty analysis may include one or more of the features described below, as specified within the work plan or FMIP for each RBFS model. When an uncertainty analysis is performed, it should be performed using the final, calibrated models.

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The major steps and approach for an uncertainty analysis can be adopted from the "Models Performance Assessment Metrics and Uncertainty Analysis" guidance developed by USACE and the Louisiana Coastal Protection and Restoration Authority (Messelhe et al. 2013). The goal of the uncertainty analysis, sources of uncertainty, analysis approach and steps, and detailed methodology are described below. It is noted that the methodology described herein is very rigorous and will not be required to be followed for all studies. For example, models with low-to-moderate level of detail or detailed models with small validation errors are not expected to require this level of uncertainty analysis. The modeling teams will have the flexibility to quantify or assess uncertainty using different methods determined through discussions with USACE. An initial recommendation about the requirements of the uncertainty analysis for each project will be provided in the FMIP, work plan or 25% submittal, but the modeling teams and USACE may choose to deviate from these recommendations at a later stage.

Goals of Uncertainty Analysis

The goals for the presented uncertainty analysis are to:

- Establish the confidence bounds in a numerical model's predictions and assess the model's ability to predict the impacts on flood modeling and other, related purposes
- Identify weak areas or elements of high uncertainty in the model that limits the model's predictions and its overall use
- Provide insights and recommendations to reduce such uncertainties

Sources of Uncertainty

Uncertainty can be caused by, but not be limited to, the following factors:

- Outdated, insufficient, inaccurate, or unrepresentative input data
- Poor or incomplete knowledge of the pertinent physical processes represented in the predictive model
- Approximations and assumptions in the numerical scheme and model
- Imperfect characterization of numerical and physical parameters in the formulations utilized in the model

Uncertainty from data sources is addressed in **Section 4.2**. To alleviate uncertainty in the physical and numerical processes, if there are other existing models using different modeling processes and numerical schemes, then a comparison can be made between the newly developed model and other types of models to (1) help overcome and understand the limitations and constraints of any approximations and numerical assumptions, and (2) provide valuable insight into the impact of these approximations and assumptions on capturing the spatial and temporal patterns of the pertinent physical processes studied. Comparisons of new 2D models to existing 1D models may provide some confirmation that the 2D processes used in HEC-RAS are suitable.

General Outline of the Uncertainty Analysis Approach

HEC-RAS has undergone benchmark testing against both physical test cases and other hydrodynamic models, as described on the HEC website. However, further such comparisons are beyond the scope of this project. Thus, the focus of the uncertainty analysis for this project will be on the characterization of numerical and physical parameters, and especially in the uncertainties in the model parameters. As such, the presented uncertainty analysis approach is as follows:

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- Determine a set of performance measures that are critical and can serve as proxies for the project objectives.
- Establish the key model parameters that affect the selected performance measures and a range for each key parameter.
- Identify and analyze the impact of uncertainties on the selected performance measures in specifying the key parameters.

The steps outlined below can be considered to determine uncertainties of the key model parameters influencing the performance measures and are adopted from Lall et al. (2002):

- **Step 1:** Determine the performance measures most appropriate as proxies for the project objectives. These can be measures such as shoaling and/or erosion in the river channel, change of flow velocity, change of flooding to nearby communities, or any others that are agreed upon by the project team.
- **Step 2:** Identify the model outputs that impact the performance measures identified in Step 1. These outputs could include velocity, stage, flow, sediment load, or other outputs.
- **Step 3:** Perform a sensitivity analysis to determine which model parameters or functional relationships influence the model outputs identified in Step 2. Modeling teams should refer to **Section 4.9** for this step, which should result in a set of independent parameters. Modeling teams should focus on the parameters that have the most impact on the model outputs identified in Step 2 to minimize the number of numerical simulations needed to complete the uncertainty analysis.
- **Step 4:** For each parameter selected in Step 3, modeling teams should identify a range that the parameter is likely to fall within. This range reflects the degree of uncertainty associated with each parameter.
- **Step 5:** Design an array of numerical simulations based on combination of values assigned to the parameters identified in Steps 3 and 4 to reflect the specified parameter uncertainties. The combinations of parameter values should produce the widest possible range in the model outputs and performance measures identified in Steps 1 and 2.
- **Step 6:** Based on the results of Step 5, the modeling team would construct empirical probability distributions for each of the selected performance measures to assess the impact of model uncertainties on the prediction of performance measures and evaluate whether and how such uncertainties can affect the selection of a specific flood control strategy or else determine whether this strategy is or is not feasible.

Selection of Performance Measures

The technical team, study planners, and managers should work together to select the performance measures. The possible set of performance measures could include:

- Change in flooding (flood depth) or inundation areas of nearby communities
- Change in velocities in the river channel
- Property and structure damages

These performance measures are directly related to critical, relevant model parameters that control the model outputs used to calculate the performance measures. However, the impact of these model parameters on the model outputs and, subsequently, on the performance measures, is uncertain. Thus, this analysis is performed to quantify the uncertainty bounds of the performance measures as propagated through the model parameters.

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Critical Model Outputs

Modeling teams should identify critical model outputs for each of the performance measures and the possible impact of these outputs on the performance measures. An example list of model outputs that could possibly influence the performance measures is shown in **Table 4-5**. Some or all of these parameters are spatially variable. Therefore, ranges for the parameters should be established for each spatial zone or region.

Table 4-5. Example of Key Model Parameters Affecting the Model Output and Performance Measures

Output	Parameter with Uncertainty
Stage	Bed roughness
Velocity	Bed roughness
	Turbulence model parameters

Note: **Table 4-5** is an example list; the final list will be identified by the modeling teams. In the model calibration and uncertainty analysis section of the Final Hydraulics Report, the modeling teams should provide a description of each of these parameters, how a typical value has been assigned, and how a range has been established. An example of the uncertainty range of the key model parameters that influence the model outputs could be: low, medium low, base, medium high, and high, where the "base" value refers to the value that was identified during model calibration to produce the best comparison with available field observations.

Methods

An approach to construct a cumulative distribution function (CDF) for the uncertainty analysis is described below.

Design Uncertainty Analysis Realizations – A simulation experiment composed of multiple model simulations is referred to herein as a "realization." Realizations are based on sampling from the key model parameter values in the range of values. Values assigned to the key model parameters should be selected so that the various combinations produce the widest possible range in the model output predictions.

Construct Cumulative Distribution Functions – A CDF is calculated from the results of the uncertainty realizations to determine the probability that a given parameter will not exceed a certain parameter value. However, CDF analyses can provide important information aside from probabilities of exceedance. For instance, the width of each CDF curve provides a measure of the effect of model-induced uncertainties on the model's ability to predict a specific value, like flooding area, and can be used to provide that value (in this case, the flooding area) within a desired confidence range (e.g., 5%-95%, 25%-75%, etc.). A CDF curve also be used to determine the median value corresponding to 50% probability of exceedance.

One important concern of decision makers is the ability of the model to show a discernible benefit of a potential project (i.e., whether the project benefit would be masked or shadowed by uncertainties). This type of uncertainty analysis can address this and similar questions. An ideal case can be seen in **Figure 4-17a**, where the 25%-75% confidence bound for a hypothetical parameter of interest under pre-project conditions (gray) is completely separate from the confidence bound under post-project conditions (black). This is an ideal case where the benefit of a potential project is clearly not masked by model uncertainty. In **Figure 4-17b**, the confidence bounds of the pre-project and post-project model responses overlap. In this case, the benefit of the potential project is masked by the model uncertainty.

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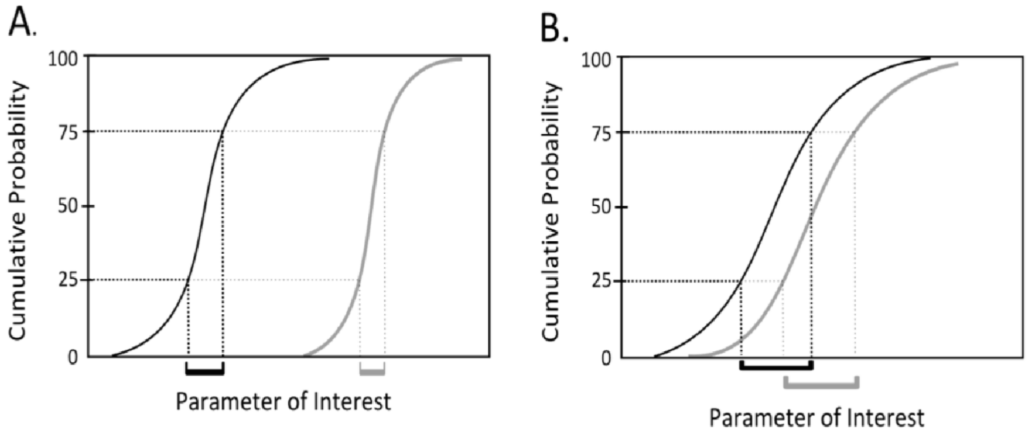

Figure 4-17. Cumulative Probability Function (CDF) for a Hypothetical Parameter of Interest under Pre-Project (gray) and Post-Project (black) Conditions

One alternative, or perhaps a simpler indicator of the ability of numerical models to assess the impact of a proposed response strategy, is to determine the median of the distribution of the base (i.e., pre-project) case and cases with projects. It would be of value to identify if the median value of the "with-project" cases fall outside the CDF curve of the base condition, which would imply that the model prediction of the impact of a project is not masked by uncertainties. If the CDF curves of the "with-project" and base cases exhibit excessive overlap, that would imply that the impact of a specific project or strategy is minor or that the model is unable to provide a discernible prediction of project impact when compared to the base case.

4.10. Hydraulic Results Comparisons and Evaluation

This section documents the standard procedures that will be used when evaluating the results for the RBFS hydraulic models.

4.10.1. Previously Completed Studies

If applicable, hydraulic modeling results should be compared to effective FEMA floodplain boundaries and any published WSEL values to validate newly identified flood risk. Major discrepancies between new and previous studies should be investigated and justified, as needed. Examples of reasons causing differences may include, but are not limited to:

- Date of previous study
- Quality and date of terrain data
- Changes in land use, infrastructure, or land development
- Changes in model methodology (1D vs 2D)
- Errors not previously identified in previous studies
- Discrepancies identified in flow frequency comparisons the carry over to hydraulic models (see **Section 3**)

Maps illustrating the resulting inundation boundaries are required as a part of the hydraulics submittal package (see example provided in **Figure 4-18**). If effective floodplain mapping boundaries are available, areas of major change should be highlighted and discussed. Tables and flood profile plots may also be prepared to show differences in WSELs between old and new studies.

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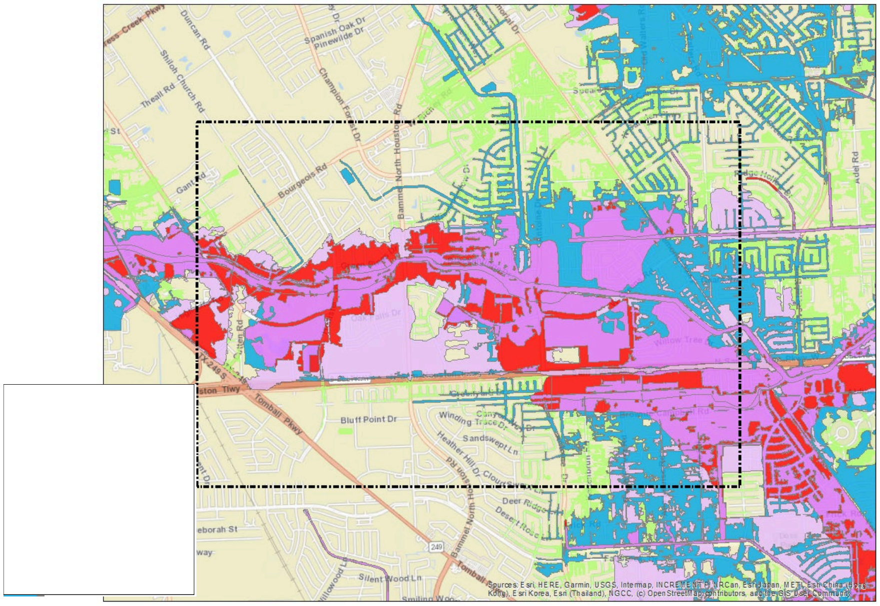

Figure 4-18. Example Inundation Comparison Map

4.10.2. Differences Between RBFS Model Results and Prior Models

Modeling teams will be required to investigate any significant differences (e.g., WSEL changes in the 1% AEP event greater than 1.0 foot or floodplain width changes greater than +/-50%) between the SOPs and any existing hydraulic models that are revealed during the comparison to previously completed studies. All modeling teams will submit a report chapter describing their findings. The report chapter should include discussions on the strengths and weaknesses of each hydraulic analysis performed, as well as justification for significant deviations from the effective, published WSELs or those shown in previously completed studies.

4.10.3. Calibration and Validation

Section 4.8 discusses the steps to be taken when calibrating and validating the hydraulic model, as well as the documentation to be prepared demonstrating calibration and validation.

4.10.4. Adjacent or Overlapping New Models

In cases where separate, new studies are being performed in areas that are either adjacent to or overlapping with one another, modeling teams should evaluate the results at common locations to ensure reasonably smooth transitions between the studies. Per FEMA's "Guidance for Flood Risk Analysis and Mapping – Contiguous Community Matching" document, dated December 2020, WSEL differences between studies on a continuous stream should be within 0.5 feet of one another.

4.10.5. Model Limitations

An understanding of the limitations of a model is important to assess the usefulness of a model for a specific purpose. The modeler should address model limitations in a report section. One example of a model limitation would be a listing of structures that have assumed opening information, as opposed to using as-built or survey data. Another example would be limitations to available bathymetric data. The modeler should consider all aspects of the model that may limit a model's future usability.

4.11. Final Hydraulic Products

Individual components of the final hydraulic files will be developed and reviewed over the course of the modeling process. This section describes the final hydraulic submittal products for the RBFS hydraulic models. Section 2: Submittal and Review Processes and associated QC checklists provide a detailed outline of items required for each interim submittal.

The final report should document all assumptions and decisions made during the modeling process, as well as all backup data used, so that the results may be reproducible by future modelers. Section 2: Submittal and Review Process of the SOP outlines the data that should be included in the final submittal packages, as well as a recommended outline for the report and an example folder structure.

4.11.1. Hydraulic Models and Calculations

The final hydraulics submittal should include all calculations, assumptions, results, and any other relevant documentation necessary to fulfill the USACE interim submittals described above.

HEC-RAS model data and all reference data should be assembled in the standard submittal folder structure and should follow all naming conventions. Model files should be properly linked to projection, land use, and terrain files within the folder structure. Final model folders should be cleared of all previous geometry iterations, calibration plans, extraneous flow files, and output files. Note that the model folder name should include the version number with which the model was executed.

The hydrologic model and associated files (e.g., DSS) should be contained locally within the model folder so that it may be used by future modelers. The model should be cleaned of all extraneous files not directly relevant to the final simulations.

HEC-RAS model files and elements should use clear naming conventions that account for the limitations to length of model names and element names, such as the following:

- **Model Code** – A three-digit code, such as "Oso" that can be used with all model elements to prevent duplication of element names in case two adjacent models need to be merged at some point in the future. The vendors should have a master list of these three-digit codes that can be referenced and updated when creating a new code for a new model.
- **2D Area** – "Oso1" for Perimeter 1 of area "Oso" (16 character maximum).
- **Internal 2D/2D Connections** – Oso1_IC001, representing the associated 2D area and unique Internal Connection ("IC") identifier; (16 character maximum).
- **External 2D/2D Connections** – Oso1_Oso2_EC001, representing unique External Connection ("EC") identifier between separate 2D areas (Oso1 and Oso2); (16 character maximum).
- **Internal Boundary (IB) Conditions** – Oso1_SUB1_IB01, representing flows from "Subbasin 1" being input in 2D Area Oso1. If Subbasin 1 flows are split between BC lines using multipliers, IB"##" can be used to uniquely identify each BC line. The subbasin name identifiers should follow the hydrology naming convention; (32 character maximum).
- **External Boundary (EB) Conditions** – Oso1_XXXX_EB01, where external flow (XXXX being its unique description) is being applied to Oso1 or flow is allowed to leave Oso1; (32 character maximum).

4.11.2. Spatial Data

Spatial data submitted are expected to align with the USACE Minimum Standards interim submittal requirements. At the completion of the modeling work, the following results files should be provided:

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- Inundation boundaries for all AEP events modeled
- Depth rasters for all AEP events modeled
- Water surface elevation rasters for all AEP events modeled

Final models and resulting shapefiles should also include enough detail for a community to pursue FEMA Flood Insurance Rate Map updates, should they choose to. Exceptions may be allowable where a community expresses no interest in updating FEMA maps within their community.

4.11.3. Results Mapping

This section documents the required results mapping for Riverine study areas. Only the 1% AEP will be universally required to be mapped. Flood maps for other hypothetical and historical events may also be developed as necessary. Mapping for Coastal and Transition areas is covered in **Section 5.9**. Hydraulic results for selected modeled scenarios will be output directly from RAS Mapper with minimal to no additional manual refinements. Raw rasters and shapefiles from RAS Mapper may include disjointed, localized areas of inundation that could obscure model results. The engineer should use discretion when determining if these areas warrant manual clean up. For each simulated event (i.e., frequency and historical events), modeling teams should produce depth grid rasters and inundation boundary shapefiles and provide these in a standalone database. Depth grids should be created at resolutions that balance grid resolutions with file sizes. The following events are expected to be mapped for each study area:

For each simulated event, modeling teams should consider developing the inundation exhibits described below for high risk or high priority areas within each study area. These exhibits should display the depth grid, inundation boundary, and other relevant data. The exhibits should be at a scale that balances visible detail with the number of exhibits. Modeling teams should also consider including the data listed below on each exhibit.

1. Background Data
    a. Counties
    b. Cities
    c. Roadways
    d. Bridges

2. Model Data
    a. Cross section extents
    b. 2D area extents
    c. Inflow and outflow hydrograph locations
    d. Subbasin boundaries

3. Flood Risk Data
    a. Depth grid raster
    b. Inundation boundary
    c. Inundated structures(optional)
    d. Point shapefile classified by inundation depth
    e. Coastal zone of influence

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4.12. References

- USACE Minimum Standards for Baseline and Future without Project Hydrologic, Hydraulic, and Coastal Analysis, December 2020
- HEC-RAS User's Manual (version 6.0), May 2021 (the latest version should be referenced)
- HEC-RAS Hydraulic Reference Manual (version 6.0), May 2021
- HEC-RAS 2D Modeling User's Manual (version 6.0), May 2021
- HEC-RAS Mapper User's Manual (version 6.0), December 2020
- Models Performance Assessment Metrics and Uncertainty Analysis, Messelhe et al., December 2013
- Lall, U., Phillips, D.L., Reckhow, K.H., & Loucks, D.P. (2002). Quantifying and communicating model uncertainty for decision making in the everglades. Report of the Comprehensive Everglades Restoration Plan's Model Uncertainty Workshop, US Army Corps of Engineers and South Florida Water Management District, West Palm Beach, FL.
- Bunya, S.; Dietrich, J.C.; Westerink, J.J.; Ebersole, B.A.; Smith, J.M.; Atkinson, J.H.; Jensen, R.; Resio, D.T.; Luettich, R.A.; Dawson, C.; et al. A High-Resolution Coupled Riverine Flow, Tide, Wind, Wind Wave, and Storm Surge Model for Southern Louisiana and Mississippi. Part I: Model Development and Validation. *Mon. Wea. Rev.* **2010**, *138*, 345–377.
- ARCADIS U.S. Inc. *ADCIRC Based Storm Surge Analysis of Sea Level Rise in the Corpus Christi Bay Area*; The Nature Conservancy, 2013.

5. Coastal and Compound Flooding

This section is intended to provide a structure and standard processes for baseline flood model development during Phase 3 of the GLO River Basin Flood Studies project for basins influenced by coastal and/or compound flooding effects. In general, this section builds on and support the previous sections addressing hydrologic and hydraulic modeling considerations. As with the rest of this SOP, this section will encourage consistency of modeling approach and application between the four study regions. This SOP covers hydrologic and hydraulic model setup for coastal influenced areas and shares common elements with the *USACE Minimum Standards* document.

Previous versions of the coastal SOP (this section) were used during the execution of pilot studies during Phase 2 of the study. The SOP has now been updated to include QC checklists, model submittal and review processes established with the USACE (Section 2, Submittal and Review Process), and model prioritization criteria that were used in the development of Phase 3 work plans / FMIPs. During Phase 3, further updates to include processes for consequence analysis and alternatives analysis are anticipated.

Table 3-1 and **Table 4-1** summarizes how the specified level of detail might affect the application of specific components of the SOP. Refer to **Section 1.1** for an overview of the level of detail concept.

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Table 5-1. Breakdown of Coastal Analysis Components by Study Level of Detail

Section	Coastal Analysis Components	Study Level of Detail		
		Low	Medium	High
5.1	Coastal Influence Extent	Utilizes existing studies to identify preliminary extents of coastal / compound flooding under existing conditions (i.e., No Sea Level Rise)	Utilizes existing studies to identify preliminary extents of coastal / compound flooding under existing conditions (i.e., No Sea Level Rise)	Utilizes existing studies to identify preliminary extents of coastal / compound flooding under future conditions (i.e., Consider Sea Level Rise)
5.2	Existing Flood Studies in Coastal Influenced Areas	Leverage existing coastal models input and output, and downstream boundary conditions.	Same as low detail.	Same as low detail with consideration of sea level rise and future conditions as reflected in CTXCS, S2G, and TX CRMP.
5.3	Coincident Storm and Joint Hazard Methodology	Surge and rainfall pairings via Villarini and Zhao (2021) where dependence structure exists, otherwise alternative methodology. Excludes assessment of lag between rainfall and surge.	Surge and rainfall pairings via Villarini and Zhao (2021) where dependence structure exists, otherwise alternative methodology. Excludes assessment of lag between rainfall and surge.	Surge and rainfall pairings via Villarini and Zhao (2021) where dependence structure exists, otherwise alternative methodology. Incudes assessment of lag between rainfall and surge.

Table 5 1. Breakdown of Coastal Analysis Components by Study Level of Detail *(continued)*

Revised Section	Coastal Analysis Components	Study Level of Detail		
		Low	Medium	High
5.4	Future Conditions Considerations and Analyses	No future conditions analysis.	No future conditions analysis.	Consider future land use and sea level changes. Future land use changes considered. Consider future mitigation and dredging projects as well.
5.5	Hydrology Model Setup in Coastal Influenced Areas	HMS Inflows from Contributing Riverine Basins. TC events per Coincident Storm and Joint Hazard Methodology.	HMS Inflows from Contributing Riverine Basins. TC events per Coincident Storm and Joint Hazard Methodology.	HMS Inflows from Contributing Riverine Basins. TC events per Coincident Storm and Joint Hazard Methodology.
5.6	Hydraulic Model Setup in Coastal Influenced Areas	See **Section 4**.	See **Section 4**.	See **Section 4**.

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Section	Coastal Analysis Components	Study Level of Detail		
		Low	Medium	High
5.7	Model Calibration and Validation	Minimal or no calibration, but simulation of historical storms required for sensitivity analyses.	Calibration with a surge dominated event and rainfall dominated event.	Calibration with a surge dominated event, a rainfall dominated event, and a compound flooding event. Additional events for validation.
5.8	Coastal Influence Model Sensitivity and Uncertainty	Minimal or no sensitivity analyses. No uncertainty analyses.	Sensitivity analyses including wind. Uncertainty associated with placement of inland, adjacent, and downstream boundaries. Downstream boundary condition uncertainty assessed through rainfall-surge pairings and lag effects.	Sensitivity analyses including wind. Uncertainty associated with placement of inland, adjacent, and downstream boundaries. Downstream boundary condition uncertainty assessed through rainfall-surge pairings and lag effects.
5.9.1	Coastal Flood Risk Mapping, Depth Grid Rasters	Historical events, TC AEPs (10, 50, 100, and 500)	Historical events, TC AEPs (10, 50, 100, and 500)	Historical events, TC AEPs (10, 50, 100, and 500)
5.9.2	Coastal Flood Risk Mapping, Map Book	1% Events only	1% Events only	1% Events only

5.1. Coastal Influence Extents

Planning for modeling of coastal floods requires an initial estimate of the extent of coastal and compound flooding. A preliminary coastal flood boundary allows the modeler to increase model resolution to incorporate natural or artificial features that affect flow movement. Three sources of coastal flood extents for the Texas coast were used for this analysis:

- USACE Coastal Texas Study (CTXCS) Advanced Circulation (ADCIRC) model domain.
- FEMA 0.2% AEP coastal limit of inundation.
- NOAA Maximum of the Maximum Envelope of High Water (MOM) based on the Sea, Lake, and Overland Surges for Hurricanes (SLOSH) hurricane modeling.

Figure 5-1 through **Figure 5-3** show the extents of the three sources, overlapped with the four GLO study regions. These figures show that the CTXCS ADCIRC model domain extends furthest inland. NOAA's maximum of maximums (MOM) data, which identifies an envelope of inundation limits from several Category 5 hurricanes, extends beyond FEMA's 0.2% AEP flood area but does not exceed the CTXCS model domain. Of note, coastal flooding extents may vary from those shown on **Figure 5-1** through **Figure 5-3** depending on geographic features and the modeling approach implemented in each region. The SOP includes these extents for planning purposes only. The figures reference the GLO Flood Model Development Plan (FMDP) regions.

For the purpose of defining the limits of each coastal model, coastal influence extents will be assessed further within the program with consideration of additional studies including USACE Sabine-to-

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Galveston (S2G) study and CTXCS results, as appropriate. Estimated relative sea level change will be evaluated and appropriately addressed in each watershed-specific plan.

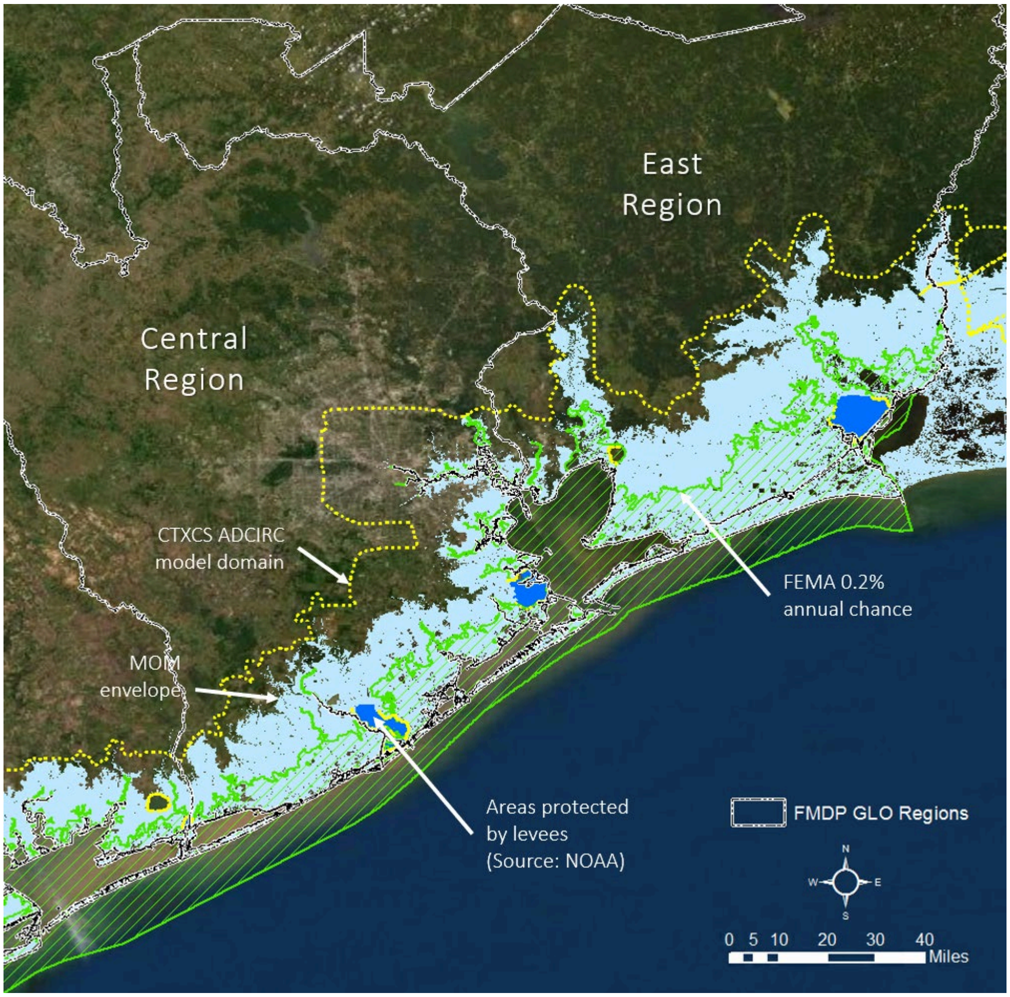

Figure 5-1: Approximate Coastal Flooding Extents in East and Central GLO Regions Note Flood Extents do not Consider Estimated Relative Sea Level Change

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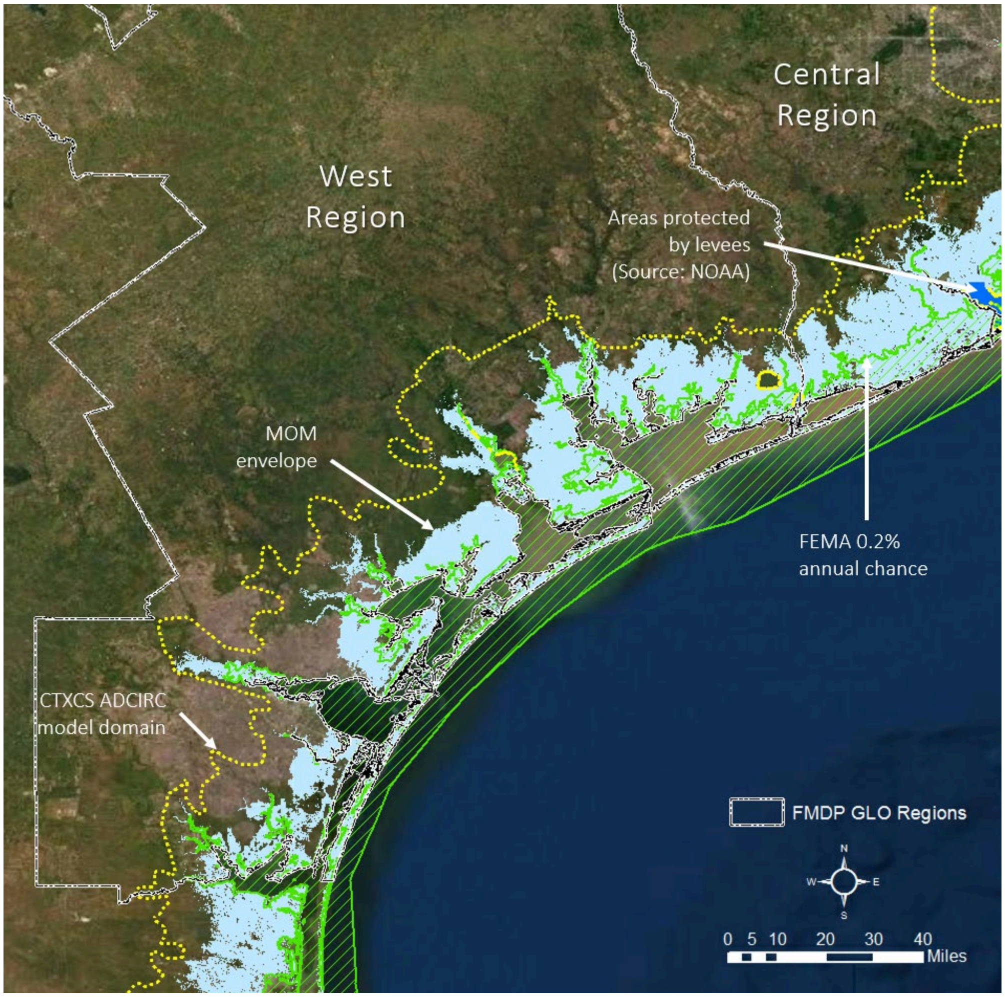

Figure 5-2: Approximate Coastal Flooding Extents in West GLO Region
Note Flood Extents do not Consider Estimated Relative Sea Level Change

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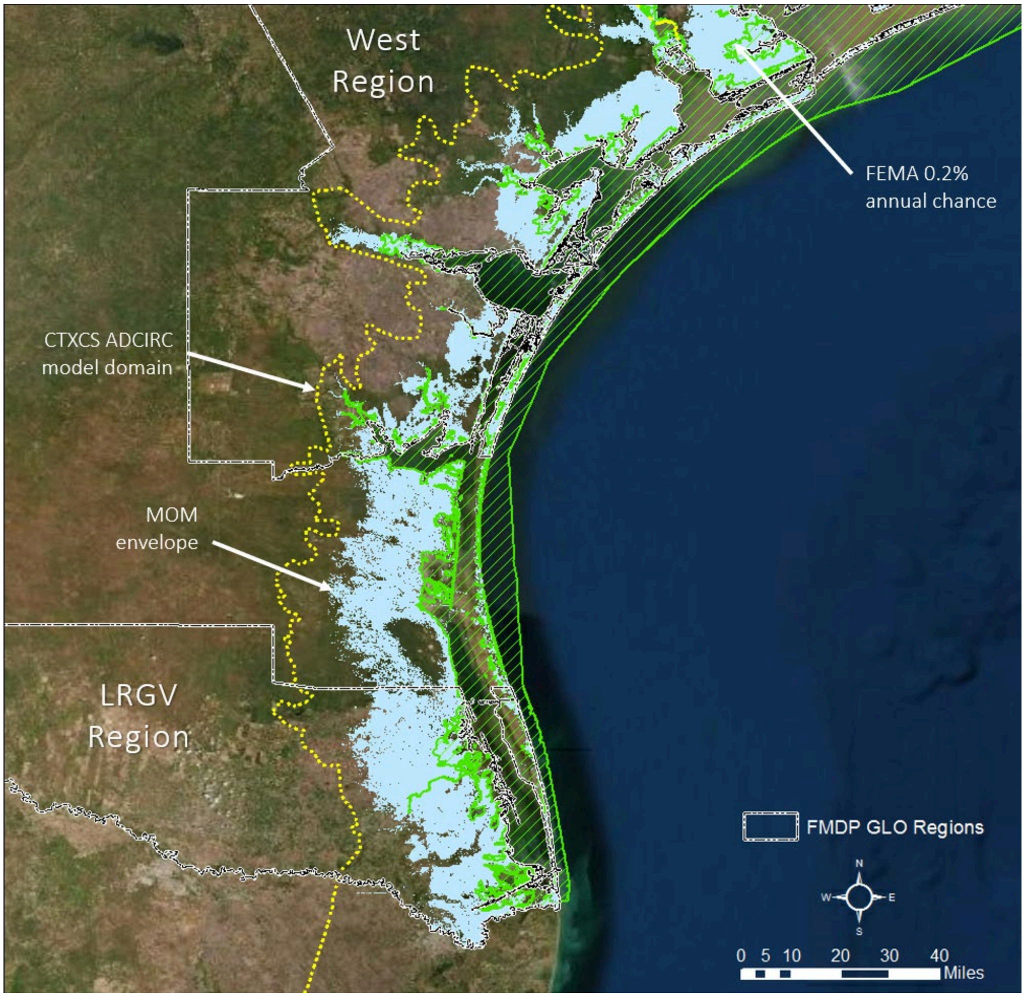

Figure 5-3: Approximate Coastal Flooding Extents in Lower Rio Grande Valley (LRGV) GLO Region Note Flood Extents do not Consider Estimated Relative Sea Level Change

5.2. Existing Flood Studies in Coastal Influenced Areas

Existing studies are summarized below, organized by coastal flood risk studies and compound flood risk studies. Additional information on each study, including the applicability of each study to each GLO region and a topical overview of each study considering coastal, compound flooding numerical modeling, joint rainfall/surge analysis, and future conditions analysis, is included in **Appendix B**.

5.2.1. Existing Coastal Studies

Several large-scale coastal flood risk studies have been completed for coastal Texas by FEMA and USACE. The major coastal studies include:

- **FEMA 2011:** FEMA Region VI Risk Mapping, Analysis and Planning (Risk MAP) study using 2008 conditions.
- **S2G2015:** USACE feasibility study for flood risk management on the Sabine-to-Galveston portion of the Texas coast (Melby et al. 2015b).
- **CTXCS2018:** USACE feasibility study for flood risk management of Coastal Texas (Massey et al. 2018 and Nadal-Caraballo et al. 2018).

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- **2019 Texas Coastal Resiliency Master Plan Technical Report:** Technical report for the GLO master plan for coastal resiliency projects along the Texas coast (GLO 2019).
- **2023 Texas Coastal Resiliency Master Plan Technical Report:** Technical report for the GLO master plan for coastal resiliency projects along the Texas coast (GLO 2023).
- **CTXCS2020:** USACE feasibility study for flood risk management of Coastal Texas (Melby et al. 2020 and Melby et al. 2021a). Note that the topography and bathymetry used in the ADCIRC mesh and the Steady-State Spectral Wave (STWAVE) grids were the same as were used in the TX2008 ADCIRC mesh for the entire Texas coast and in the Gulf of Mexico.
- **S2G2021:** Sabine Pass to Galveston Bay Pre-Construction, Engineering and Design project (Melby et al. 2021b). Note that LiDAR data were collected during 2018 by TWDB and processed to construct a bare earth DEM for the area (the DEM was transformed into Texas South Central State Plane [feet] coordinate system and NAVD88 Geoid12B).

The ADCIRC model meshes for the FEMA Risk MAP study, the Sabine-to-Galveston study, and the CTXCS share the same extent within Texas (**Figure 5-1**).

FEMA 2011

The FEMA 2011 study applied the Joint Probability Method of Optimum Sampling (JPM-OS) methodology to characterize the probabilistic nature of coastal tropical storms and associated responses that include storm wind and pressure fields, waves, and surge. It also used the revised Atlantic hurricane database (HURDAT2) of historical tropical storm climatology to define a joint probability model of hurricane parameters. The sampling yielded 446 synthetic tropical storms with 223 for Texas North and 223 for Texas South. According to the USACE assessment (Melby et al. 2020b), the FEMA 2011 study:

- Applied uncoupled surge and wave modeling for the coastal modeling of Texas and Louisiana that resulted in a discontinuity in the statistical response of the 1% annual chance exceedance surge and wave height near the Texas-Louisiana border.
- Applied limited parameter sampling for JPM-OS and limited response surface that resulted in poor parameter space resolution.
- Did not well represent the bed elevation near the Coastal Storm Risk Management (CSRM) area including portions of Galveston Island and Bolivar Peninsula or specifically approximately 19 miles of western Galveston Island shoreline, from San Luis Pass to the western end of the seawall and 26 miles of western Bolivar Peninsula, from Fort Travis to High Island.
- Applied a risk assessment of CSRM that was primarily based on the 100-year average recurrence interval water level.
- Did not include wave impacts, detailed wave analysis in the vicinity of CSRM, and multi-variate probability analysis of hazard. More recent modeling studies like the CTXCS2020 (Melby et al. 2020) and S2G2021 study (Melby et al. 2021, Stehno et al. 2021a, and Stehno et al. 2021b) provided better model fidelity near CSRM project features and improved JPMOS parameter sampling.

S2G2015 (Melby et al. 2015)

Melby et al. (2021) noted that (a) the S2G2015 study mostly applied the FEMA 2011 modeling procedure, so this study has similar limitations as the FEMA 2011 study; (b) S2G2015 used updated surge and wave modeling software and consistent technologies from Louisiana to Texas to re-model storms that have primary influence in the Sabine region near the Texas-Louisiana border; and (c) based its risk assessment of CSRM primarily on 100-year average recurrence interval water level.

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Melby et al. (2021) opined that although the S2G2015 risk assessment analysis was improved compared to FEMA 2011, its wave impacts, detailed wave analysis in the vicinity of CSRM, and multi-variate probability analysis of hazard are still limited compared to more recent studies.

CTXCS2018 (Massey et al. 2018)
Melby et al. (2021) concluded that (a) the CTXCS2018 modeling provided significant improvements over the FEMA 2011 and S2G2015 studies in both the storm characterization through the JPM-OS and the regional storm surge and wave modeling, and (b) the CTXCS2018 resolved the limitations of the FEMA 2011 and S2G2015 studies, as its wave modeling is continuous and of consistent quality throughout the region.

2019 Texas Coastal Resiliency Master Plan Technical Report (GLO 2019)
The 2019 Texas Coastal Resiliency Master Plan (CRMP) Technical Report documents the numerical modeling performed for the 2019 Texas CRMP, an update to the 2017 Texas CRMP. The technical study team used the SLAMM model with 1 m (3.3ft) global mean sea level (GMSL) rise and compared SLAMM outputs from year 2100 with the 2001 output generated by the Gulf Coast Prairie Land Conservation Cooperative to identify areas vulnerable to future sea level rise.

- Gulf Coast Prairie Land Conservation Cooperative SLAMM Outputs – https://lccnetwork.org/lcc/gulf-coast-prairie

The SLAMM model predicted future land cover combined with USGS predicted land cover for 2100 and its outputs provided the ADCIRC model friction parameters that are representative of future conditions. The ADCIRC and Simulating Waves Nearshore (SWAN) modeling applied a GMSL scenario of 3.3 ft for the year 2100. After considering the 660 synthetic tropical storms in USACE (2018), the CRMP study selected six Category 2 hurricanes for 14 ADCIRC+SWAN model simulations—six present-day conditions, six 2100 conditions, and two future conditions with resiliency projects—to assess the combined impact of the GMSL and future topography and land cover. SWAN+ADCIRC model results provided the inundation depths imported into FEMA's Hazus program for a Level 2 Hazus flood analysis.

2023 Texas CRMP Technical Report (GLO 2023)
The 2023 Texas CRMP Technical Report is in development and will document the numerical modeling performed for the 2023 Texas CRMP, an update to the 2019 Texas CRMP. The intent of the modeling effort is to further understand and quantify the future impacts of relative sea level rise and storm surge events, comparing a no-action scenario (i.e., no additional coastal resiliency projects implemented beyond current conditions) and a future with-project scenario (i.e., includes implementation of some coastal resiliency projects). Additional datasets were also developed showing the changes or vulnerabilities relative to time due to gradual (e.g., relative sea level rise) and episodic (e.g., storm surge) coastal changes. The technical study applied SLAMM for two new GMSL rise scenarios, 0.5 m (1.6 ft) and 1.5 m (4.9 ft), in addition to the 1.0 m (3.3 ft) GMSL rise scenario from the 2019 CRMP.

SLAMM provided the future topographic surface that was used to update the FEMA (2011) ADCIRC mesh. SLAMM predicted future land cover combined with the USGS predicted land cover for 2100 and its outputs provided the ADCIRC model friction parameters that are representative of future conditions. The ADCIRC and SWAN modeling applied the same three GMSL scenarios as the SLAMM analysis for the year 2100. Considering the 660 synthetic tropical storms in USACE (2018), the study added 13 additional synthetic storm scenarios to the six storms from the 2019 CRMP study for 19 storms across current, future (year 2100), and future with-project scenarios. These results will be used as inputs for additional Level 2 Hazus flood analyses. This study is currently underway and expected to be complete by mid-2022, with datasets from early portions of the study currently available by request.

CTXCS2020 (Melby et al. 2020)
CTXCS2020 is a feasibility study that describes coastal storm water level (i.e., surge, tide, relative sea level rise) and wave hazard and beach morphology modeling to evaluate the impacts of several flood mitigation alternatives on the Texas Gulf coast. The study presents a joint probabilistic model of historical hurricane parameters that includes frequent, low-intensity storms to very infrequent, intense storms. The joint probability model describes the continuous spatial and temporal hazard and facilitated development of a suite of 660 synthetic tropical storms that characterize the coastal storm flood hazard for Texas. Further sub-sampling developed a suite of 170 synthetic tropical storms that essentially capture the flood hazard for Galveston and the Galveston Bay region. The Planetary Boundary Layer (PBL) model provided wind and pressure fields for the 660 tropical synthetic storms.

Melby et al. (2020) developed new model meshes for with- and without-project scenarios using very high-resolution land and sub-aqueous surveys. Together with S2G2020, the study provides the highest resolution regional surge and wave modeling done to-date for the region. Historical storms provided the data for Coastal Storm Modeling System (CSTORM) model validation. CSTORM modeling also included simulation of 170 synthetic tropical storms with two relative sea level change (RSLC) scenarios for with- and without-project meshes. The two RSLC scenarios are (a) SLC0 that corresponds to a historical sea level change rate, and (b) SLC1 that corresponds to a high rate. The morphological modeling applied a third RSLC rate.

Computation of hazard curves for the CSTORM output over the study region quantified flood hazard exposure of the flood mitigation alternatives. Computed AEPs ranged from 100% to 0.01147nálisis147r stillwater levels (SWL) and wave height (H_{m0}). Model results also included wave period (T_p) and mean wave direction associated with H_{m0}. Melby et al. (2020) used the Cross-Shore (CSHORE) beach morphology model to evaluate cross-shore sediment transport during significant storm events. Stochastic assessment of the beach morphology applied an embedded CSHORE model in a time-dependent Monte Carlo sampling scheme within the larger StormSim stochastic modeling system.

S2G2021 (Melby et al. 2021b, Stehno et al. 2021, and Stehno et al. 2021)
The Final Integrated Feasibility Report – Environmental Impact Statement (USACE 2017), identifies several Sabine Pass to Galveston Bay Project CSRM formulated measures that consist of reducing risks of tropical SWL impacts. These measures include construction of the new CSRM system in Orange County and increasing the level of risk reduction and resiliency of the existing Port Arthur and Vicinity and Freeport and Vicinity Hurricane Flood Protection systems.

S2G2020 consist of three Pre-construction, Engineering, and Design studies that describe the methods used to analyze coastal SWL and wave hazards of the entire CSRM systems for Jefferson, Brazoria, and Orange counties. The studies used hydrodynamic and wave modeling (ADCIRC and STWAVE) and stochastic simulations to quantify coastal SWL, wave loading, and wave and SWL overtopping. Melby et al. (2021b) presents a joint probabilistic model of historical hurricane parameters that includes frequent, low-intensity storms to very infrequent, intense storms. The joint probability model describes the continuous spatial and temporal hazards and facilitated development of a suite of 195 synthetic tropical storms that effectively capture the flood hazard for the region from Freeport to the Texas-Louisiana border. The PBL model provided wind and pressure fields for the 195 tropical synthetic storms.

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Like the CTXCS2020 study, Melby et al. (2021b) developed new model meshes for with- and without-project scenarios using very high-resolution land and sub-aqueous surveys to provide high resolution regional surge and wave modeling for the region. Historical storms provided the data for CSTORM model validation before CSTORM modeling of the 195 synthetic tropical storms.

Stehno et al. (2021a; 2021b) describe the coastal storm water level and wave hazards for the Port Arthur CSRM and Orange County CSRM studies, respectively. These studies applied the 195 synthetic tropical storms with three RSLC scenarios for with- and without-project meshes. The RSLC scenarios correspond to three specific periods in the future:

1. SLC0 with a Geoid offset of 1.52 ft and an associated “Low” RSLC projection of 0.17 ft for project completion in 2027.
2. SLC1 with a Geoid offset of 2.93 ft and an associated “Intermediate” RSLC projection of 1.58 ft for the end of a 50-year service lifecycle in 2077.
3. SLC2 with a Geoid offset of 4.73 ft and an associated “Intermediate” RSLC projection of 3.38 ft for the end of a 100-year service lifecycle in 2127; for all practical purposes this scenario is equivalent to a “High” RSLC projection for the end of a 50-year service life in 2077.

Computations of hazard curves for the CSTORM output near the structures quantified flood hazard exposure of the project features. The computed AEPs ranged 100% to 0.01% for peak SWL and H_{m0} but the study reports only provide AEPs between 0.2% and 0.001% in tables. Model results also included the T_p and mean wave direction associated with H_{m0}.

5.2.2. Existing Compound Flooding Studies

Several joint rainfall/discharge and surge flooding studies have been completed for coastal Texas. Their geographic scope and modeling methodologies are presented below.

A Copula-Based Bayesian Network for Modeling Compound Flood Hazard from Riverine and Coastal Interactions at the Catchment Scale: An Application to the Houston Ship Channel, Texas (Couasnon et al. 2018)

For this paper, the authors built a Bayesian Network based on Gaussian copulas to generate the equivalent of 500 years of daily stochastic boundary conditions for a coastal watershed in Southeast Texas. In doing so, they overcome many of the limitations of conventional univariate approaches and are able to probabilistically represent compound floods caused by riverine and coastal interactions. They model the resulting water levels using a 1D steady-state hydraulic model and find that flood stages in the catchment are strongly affected by backwater effects from tributary inflows and downstream water levels. By comparing their results against a bathtub modeling approach, they show that simplifying the multivariate dependence between flood drivers can lead to an underestimation of flood impacts, highlighting that accounting for multivariate dependence is critical for the accurate representation of flood risk in coastal catchments prone to compound events.

Applying a Bayesian network based on Gaussian copulas to model the hydraulic boundary conditions for hurricane flood risk analysis in a coastal watershed (Sebastian A. et al. 2017)

This paper describes a method to stochastically simulate a large number of combinations of peak storm surge and cumulative precipitation to determine the hydraulic boundary conditions for a low-lying coastal watershed draining into a semi-enclosed tidal bay. The method is computationally efficient and takes into consideration five tropical cyclone characteristics at landfall: windspeed, angle of approach,

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landfall location, radius of maximum winds, and forward speed. A precipitation gage network and tidal gage data were used, along with observations from over 300 tropical cyclones in the Gulf of Mexico. A Non-parametric Bayesian Network was built to generate 100,000 synthetic storm events and is used as input to an empirical wind set-up model to simulate storm surge within Galveston Bay and at the downstream boundary of the watershed. Based on the results, probable combinations of cumulative precipitation and peak storm surge for the watershed during hurricane conditions are determined. These boundary conditions can be easily incorporated into a coastal riverine model to determine flood risk in the watershed.

Compound flooding in Houston-Galveston Bay during Hurricane Harvey (Valle-Levinson, A. et al. 2020)

This paper analyzes the environmental conditions during Hurricane Harvey as they related to compound flooding. Winds and rainfall interacted to produce atypical storm surges along the coast and estuaries of Texas and compound flooding in the Houston region. Data from the NOAA's Center for Operational Oceanographic Products and Services provided information on water levels in this region. The highest water levels, 3 m (9.8 ft) above predicted, occurred from August 27th to 29th at Buffalo Bayou in the uppermost reaches of the Galveston-Trinity-Tabbs-Burnet Bay system. The peak surge occurred on Aug 29th because of the triple punch of a) the ocean wind stress and corresponding surge, plus the rainfall-related land-derived discharge from b) Buffalo Bayou and then from c) the San Jacinto River. Winds from the ocean persisted during that 3-day period and drove onshore water transport. This transport, together with anomalously high mean sea levels and the coastline modifications in the upper bay system, delayed the seaward motion of the land-derived discharge. Numerical model simulations that turned forcings on and off, highlighted the importance of the two river pulses in causing the widespread flooding. The simulations also underscored the influence of the interaction between land-derived discharge and ocean-derived surge along different parts of the Houston-Galveston Bay system.

Lower Clear Creek and Dickinson Bayou Flood Mitigation Plan (FNI 2021a and FNI 2021b)

League City contracted with Freese and Nichols, Inc. (FNI) to perform a study with support from multiple planning partners, including Pape-Dawson Engineers, Inc. (PDI) and RPS Group (RPS), to identify areas of concern in the Lower Clear Creek and Dickinson Bayou watersheds and evaluate the effects of conceptual flood reduction alternatives. FNI (2021b) performed hydrologic analysis over the 35 square mile study area using HEC-HMS v4.3. The historical data at Galveston County tributaries of Mary's Creek, Chigger Creek, and Cowart Creek from Hurricane Harvey in 2017 and Tax Day storm in 2015 provided data for the Lower Clear Creek hydrologic and hydraulic models calibration. PDI and RPS performed additional calibration efforts for the main stems of Lower Clear Creek and Dickinson Bayou, respectively.

FNI and RPS used the models to simulate existing and future conditions flood events with AEPs of 50% (2-year), 20% (5-year), 10% (10-year), 4% (25-year), 2% (50-year), 1% (100-year), and 0.2% (500-year). Hydrologic and hydraulic modeling of Hurricanes Harvey (2017), Ike (2008), and Allison (2001) included the combination of rainfall and storm surge flooding.

Lower Sabine Riverine Flooding Analyses (Parola et al. 2019)

In this study, a 2D HEC-RAS model was used to route flows from the Ruliff, TX stream gage to Sabine Lake. The hypothetical balanced frequency flow hydrographs were developed at the USGS Ruliff, TX stream gage based on the annual peak flow frequency analysis at this location and utilized as the upstream boundary condition for the HEC-RAS model. To account for the effect of coastal storm surge, the observed water level from the 2016, 2017 (Hurricane Harvey), and 2008 (Hurricane Ike) flood events at NOAA Gauge 8770475 at Port Arthur were selected as downstream boundary conditions. A

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hypothetical weir and storage area with infinite storage capacity were used at the eastern boundary downstream of Orange, TX to simulate the flood attenuation and inundation during high flow events.

Cow Bayou Hydrologic and Hydraulic Analysis (Mosser et al. 2020; Ross and Mrse 2020)
Mosser et al. (2020) developed an updated rainfall-runoff model of the Cow Bayou watershed in HEC-HMS. The model was calibrated using three historic storms: October 2006, Hurricane Harvey in 2017, and Tropical Storm Imelda in 2019. After calibration, frequency storms were applied to the model to calculate frequency flows that were used as the upstream boundary condition for the 1D/2D HEC-RAS model developed by Ross and Mrse (2020) to determine what impacts flood flows from Cow Bayou have on the proposed gate structure and pump station. A stage hydrograph output from the Lower Sabine HEC-RAS model (Parola et al. 2019) was utilized for the calibration and validation.

Lower Neches Riverine Flooding Analyses (Mosser et al. 2019)
The overall approach for this study is similar to the Cow Bayou Hydrologic and Hydraulic Analysis. An existing USACE HEC-HMS rainfall-runoff model, developed for the 2014 Neches Basin CWMS Implementation, was updated for the Neches River basin above the Salt Water Barrier. The model was calibrated and used to calculate frequency flows at the lower end of the Neches River near the Salt Water Barrier. The results of the HEC-HMS model were compared with the statistical results from the RiverWare modeling efforts in the same study and were adopted for use as the upstream for the 2D HEC-RAS model between the Salt Water Barrier and Sabine Lake. The model also takes into consideration the effect of coastal storm surge by simulating the total water level from NOAA Gauge 8770475 at Port Arthur as the downstream boundary.

Coupled Induced Riverine Flow-Storm Surge Modeling (Loveland et al. 2021)
To evaluate risks associated with compound flooding of new CSRM mitigation projects along the Texas coast, the authors modified the existing ADCIRC model (Melby et al. 2021) of the Port Arthur-Orange, Texas region including the Lower Neches and Sabine River watersheds to account for river inflows from the Neches and Sabine rivers under different flood regimes. The riverine flow boundaries were extracted from an existing HEC-RAS model (Mosser et al. 2019 and Parola et al. 2019). Four storms were investigated in this study: Hurricane Rita, Hurricane Ike, March 2016, and Hurricane Harvey.

Using Multivariate Statistical Modeling to Assess Compound Flooding Effects in Sabine Lake (Santos et al. 2021)
Santos et al. (2021) evaluated the dependence between rainfall-induced river discharge and storm surge processes and assessed potential compound flooding effects in Sabine Lake using the copula-based statistical model. The main streams flowing to Sabine Lake (Sabine and Neches rivers) were combined to represent the total inflow. Water elevation data from NOAA tide gages located in and around Sabine Lake were used to account for coastal water levels. The framework implemented in this study can be used for other locations as a preliminary assessment to assess possible compounding effects and help inform and guide the potential for further modeling study.

Joint Probability Analysis of High River Discharge and Storm Surge (Jane et al. 2021)
Like the study performed by Santos et al. (2021), the dependence between high river discharge and storm surge in the Sabine River Basin (i.e., Cow Bayou and Adams Bayou) and at two locations along the Brazos River was assessed using the copula (i.e., statistical) analysis in this study. According to the methodology adopted in the study, compound flooding is more associated with the Sabine Basin region than the Brazos Basin.

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5.2.3. Data Processing and Incorporation of Existing Flood Studies

According to Melby et al. (2020b), "the CTXCS modeling will provide a strong foundation for doing with-project regional modeling, detailed wave modeling in the vicinity of the CSRM, multivariate probability analysis of the hazard, and accurate estimation of CSRM response and related flood risk". It is anticipated that each of the four GLO regions will leverage significant pieces of the modeled input and output including bathymetry, Manning's roughness coefficients, and water level hydrographs as downstream boundary conditions from both CTXCS and S2G models.

A data gap analysis will be performed to identify available bathymetric data sources beyond those mentioned in **Section 4.2** and **Appendix B.** Since the project scope includes AEPs up to 0.2%, inundation extents from the FEMA coastal 0.2% AEP will inform placement of the coastal area HEC-RAS model domain perimeter. However, inland HEC-RAS model domain extents should also consider other sources to ensure relative sea level rise and other future conditions considerations can be properly represented.

The Coincident Storm and Joint Hazard Methodology section that follows was based on a review of methods and data from previously conducted compound flood studies.

The GLO Texas CRMP 2023 update that is currently in development is applying NOAA's low-intermediate, intermediate, and high-intermediate scenarios in its evaluation of sea level rise impacts on the Texas Coast. For consistency with that coastwide study, many of the recommendations discussed in **Section 5.3** are based on the Texas CRMP.

5.3. Coincident Storm and Joint Hazard Methodology

To assess the importance of coastal compound flooding due to interactions between rainfall and storm surge, a bivariate copula analysis will be conducted on all watersheds (i.e., High, Medium, and Low Detail) where coastal compound flooding is deemed relevant. The methodology to conduct a bivariate copula analysis is summarized in **Figure 5-4** (green rectangle) and detailed guidance is provided in Villarini and Zhao (2021), included in **Appendix B**

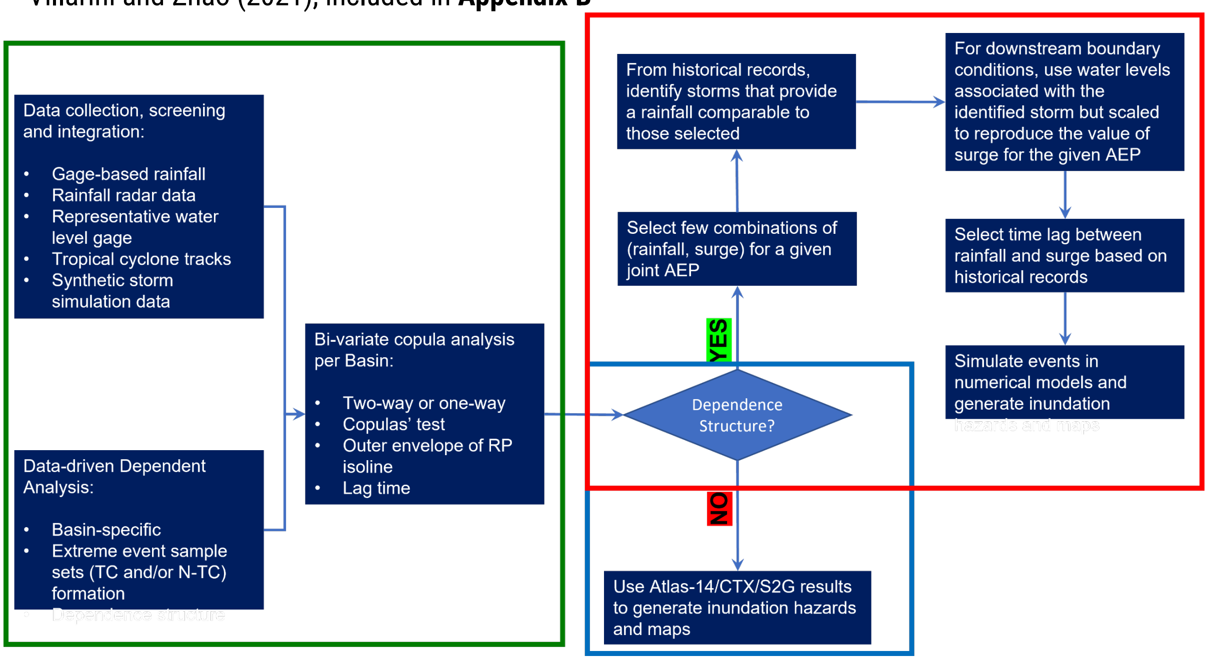

Figure 5-4. Flow Chart with Main Steps for Dependence Analysis

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As shown in **Figure 5-4**, if there is a lack of significant dependence between rainfall and surge, joint inundation hazards and maps will be created by combining Atlas 14 rainfall with the appropriate coastal surge from the USACE Sabine-to-Galveston study, CTXCS study, or similar. The same approach will be followed for the alternatives analysis.

If significant dependence is found, the results of the bivariate copula analysis will be used to develop "design" storms based on historical events. These storms will then be simulated in the calibrated and validated numerical models for each watershed to develop inundation hazards and maps (red rectangle in **Figure 5-4**). The same approach will be followed for alternatives analysis. Detailed guidance on selection and development of the "design" storms can be found in Villarini and Zhao (2021).

A coast-wide Extended JPM-OS analysis will be conducted by the USACE Galveston District as a separate study. GLO, USACE, and vendors will discuss and develop guidance in the future as to how the Extended JPM-OS analysis results can be incorporated in the alternative analysis if the results are available prior to the project alternative analysis.

5.4. Future Conditions Considerations and Analysis

Future conditions could be developed to evaluate flood hazards over community planning horizons and the design life of proposed mitigation projects. In the coastal zone, future conditions may involve sea level rise effects, future development / land use changes, or regional mitigation / dredging projects. Each of these conditions are discussed further in the sections below.

5.4.1. Sea Level Rise

Sea level rise projections and applications that could be leveraged to evaluate flood hazards are summarized below.

Global Mean Sea Level Change

Predictions of sea level rise have been released by numerous entities, as summarized in publications by USACE and NOAA (USACE 2019 and NOAA 2017). The predictions are based on global climate models that commonly report GMSL change predictions. The range of GMSL by 2100 from most of these studies approaches approximately 2.5 meters. Many variables control the GMSL change; however, one of the key components that leads to the higher GMSL projections is the rate of ice sheet melt in Antarctica and Greenland (NOAA 2017).

Table 5-2 correlates the GMSL predictions by 2100 to the low, intermediate, and high projections published by the USACE and NOAA. Because each agency has assigned different GMSL projections to their classification of low, intermediate, and high there are differences in the sea level rise projections from each agency. NOAA has further subclassified the intermediate scenario into low-intermediate, intermediate, and high-intermediate scenarios.

Table 5-2. Correlation between USACE and NOAA Low, Intermediate, and High Sea Level Rise Projections and GMSL Projections by the Year 2100 in Meters (USACE 2019 and NOAA 2017)

	USACE			NOAA				
GMSL 2100 (m)	0.2	0.5	1.5	0.3	0.5	1.0	1.5	2.0

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	Low	Intermediate	High	Low	Low-Intermediate	Intermediate	High-Intermediate	High

NOAA's projections assume a more rapid loss of ice sheets around Antarctica and Greenland for their intermediate and high projections. The NOAA high projection is at the upper end of GMSL projections that have been published in the literature. NOAA has also published an extreme scenario that is based on 2.5 meters of GMSL by 2100, the upper limit of what has been predicted by global climate modeling research.

Both the USACE and NOAA low projections are based on a historical rate of sea level rise, assuming that the historical rate will continue into the future. Therefore, they are in close agreement, with NOAA being adjusted slightly higher based on recent sea level observations from satellite imagery (NOAA 2017).

The GLO's Texas CRMP 2023 update that is currently in development is applying NOAA's low-intermediate, intermediate, and high-intermediate scenarios in its evaluation of sea level rise impacts on the Texas coast. For consistency with that coastwide study, many of the recommendations discussed in this section are based on the Texas CRMP.

Local Sea Level Projections / Tide Gages

The GMSL predictions from the global climate change models are translated to local sea level rise projections that account for local circulation patterns and vertical land movements (e.g., subsidence). To adjust these global scenarios to local projections, the GLO's 2019 Texas CRMP developed representative sea level projection curves for four regions of the state. For the middle and lower portions of the coast, the data is in point location format. However, in the upper coast region, including Galveston Bay, spatially variable sea level curve data is available (GLO 2019). These curves are available for the NOAA low-intermediate, intermediate, and high-intermediate scenarios at 10-year intervals through 2100.

To determine USACE sea level rise projections or to compare the GLO Texas CRMP sea level rise curve data, a representative tide gage station should be selected nearest to the location or project of interest. Gages with at least 40 years of observations should be prioritized (USACE 2020). As part of the CTXCS study, the Galveston Pier 21, Rockport, and Port Isabel gages were selected to represent each portion of the Texas coast (USACE 2020). Melby et al. (2021b) describe the application of NOAA gages and USACE Sea Level Change calculator (USACE 2021) in establishing the RSLC scenarios for the Freeport and Sabine region. Both the USACE and NOAA projections can be viewed for various tide gages in Texas via the Sea Level Change Curve Calculator website (USACE 2021).

5.4.2.Sea Level Rise Applications

During this study, sea level rise could be applied to evaluate direct tidal flooding of coastal communities (i.e., "sunny day flooding"); to evaluate the impact of sea level rise on coastal drainage systems (i.e., combined sea level rise and precipitation); or to evaluate proposed mitigation strategies such as levees, floodwalls, or floodproofing / elevating assets. Sea level rise could also be applied in the evaluation of joint precipitation and storm surge in coastal watersheds, but only on a limited basis. In watersheds where federal projects are under consideration, sea level rise applications should be coordinated with USACE. Determining which sea level projection to apply depends upon the application, as discussed further below.

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Direct Tidal Flooding at Coastal Communities
When evaluating direct tidal flooding of coastal communities, a tidal datum such as MHHW could be combined with sea level projections to inform future tidal vulnerabilities and hazards. Sea level projections from the GLO's 2019 Texas CRMP (i.e., NOAA low- intermediate, intermediate, and high-intermediate) aligned with the planning horizon of the community should be applied (GLO 2019). The sea level rise projections will be in mean sea level (MSL) datum; therefore, local adjustments to MHHW will be needed using the nearest representative tide gage or NOAA's Vertical Datum Transformations (VDATUM) tool.

Coastal Drainage Systems
Similarly, coastal drainage systems or outfalls are often designed to account for a MHHW boundary condition. To evaluate the effects of higher future tides on the drainage capacity of these systems, sea level projections from the GLO's 2019 Texas CRMP (i.e., NOAA low-intermediate, intermediate, and high-intermediate) aligned with the planning horizon of the community could be applied (GLO 2019). The sea level rise projections will be in MSL datum; therefore, local adjustments to MHHW will be needed using the nearest representative tide gage or NOAA's VDATUM tool.

USACE Mitigation Strategies
When evaluating mitigation strategies that could become future projects studied, constructed, or maintained by the USACE, it is recommended by USACE to apply the USACE low, intermediate, and high projections over the expected life of the asset. USACE policy documents that there is a possibility of any scenario playing out over the planning or design life, and that, therefore, a range of scenarios should be considered (USACE 2019).

Because these mitigation projects typically involve storm surge hazard reduction techniques, the USACE CTXCS2020 (Melby et al. 2020) and S2G2021 (Melby et al. 2021) data will be the best sources of information for this evaluation, since these results incorporate nonlinearities associated with storm surge and sea level rise. Storm surge probabilities for the year 2085 USACE high sea level projection is available throughout the study area (USACE 2020).

Additionally, the GLO's Texas CRMP is evaluating storm surge plus NOAA's low-intermediate, intermediate, and high-intermediate sea level projections in 2100 along the Texas Coast. These model evaluations are based on a subset of 30 storms from the 660 synthetic storms included in the USACE CTXCS2020 study (GLO 2019). These simulations are also being coupled with SLAMM to evaluate changes in coastal features (such as wetlands) that are expected with sea level rise. These simulation results could also be reviewed in the development of mitigation strategies.

Joint Precipitation and Storm Surge in Coastal Watersheds
When evaluating coincident storm surge and precipitation in coastal watersheds, joint AEPs will be developed as described in **Section 5.3** above. The storm surge events that will be recommended from the joint AEP analysis for modeling will be based on historical storm surge events. However, linear addition of sea level rise projections to the historical storm surge events should be avoided due to the nonlinearity of storm surge and sea level rise in Texas bays and estuaries (USACE 2020). Therefore, the application of sea level rise to the joint risk analysis is expected to be limited.

5.4.3. Future Land Use and Land Cover

Future land use and land cover data could be applied coincident with relative sea level rise projections described in the previous section where appropriate land use and land cover data are available. Identifying future hazards in advance allows for the most efficient and equitable mitigation.

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The USGS and 2019 GLO Texas CRMP future conditions data described below could be used to identify vulnerabilities for communities that are not readily apparent from historical and existing conditions studies. However, it should be noted that underlying assumptions need to be consistent between RSLC assumptions included in coastal influenced model setup and future land use and land cover data, in order to leverage existing data (e.g., consistent sea level rise assumptions driving land cover projections).

USGS & EPA Land Use / Land Cover Data

Future patterns of development are challenging to develop in a comprehensive manner, as many factors play into these future patterns, including ecology, climate, and socioeconomics. Many projections are based on historical trends, but the most robust models incorporate both historical trends and science-based data that could alter those historical patterns.

The primary source of future development and land change data is the USGS LULC projections. This dataset attempts to incorporate all of these concepts along with multiple climate projection scenarios to give an array of datasets on the topic. The projections extend through the year 2100 and serve as a foundational data source for this consideration. This dataset also incorporates land use changes not directly associated with development patterns, as these other changes in land type are based more so on changing climate patterns and relative sea level rise. This dataset could be reviewed for use in assigning changes in friction values based on changes in land use for future conditions model simulations. Differences in resolution between the land cover data and the model should be kept in mind and may require interpolation. It should also be noted that the EPA's ICLUS dataset is available. This dataset could also be reviewed and considered in model applications.

CRMP Future Land Type Changes

Another land type change dataset of a much higher resolution was developed for the GLO's Texas CRMP using SLAMM (GLO 2019). This analysis looked at land type changes along the Texas coast through the year 2100 based on RSLC rates, incorporating Texas focused subsidence data as a further enhancement. Additionally, this analysis incorporated available shoreline erosion data into the land change model. However, the model does have limitations for beach and dune system changes, so these shoreline types are not well predicted into the future. In the simulation of future conditions, the Texas CRMP future land types could be reviewed to determine any changes in land type that may influence the friction values assigned for future conditions modeling. Differences in resolution between the land cover data and the model should be kept in mind and may require interpolation.

5.4.4. Future Mitigation / Dredging Projects

In addition to the USGS and CRMP data, there are also planned regional mitigation and dredging projects that should be considered for future conditions analysis. Layouts and elevations of regional levee / floodwalls systems or the bathymetry from dredging studies could be assigned to future conditions models that overlap with these future projects. For identified future projects, data requests should be coordinated with the implementing agencies. Inclusion of planned projects will be determined by standardized criteria established by GLO in consultation with USACE.

5.5. Hydrology Model Setup in Coastal Influenced Areas

This section of the SOP and **Section 5.6** are intended to document additional model considerations beyond those identified in **Section 3** and **Section 4** when developing HEC-RAS models in coastal influenced areas. The Coastal Influence Extents section (**Section 5.1**) defines initial coastal influenced areas extents, although the extents will be assessed and may be refined as the program matures.

Traditional rainfall runoff / routing methods and parameters may not produce accurate results for portions of coastal influenced models with the following characteristics:

- “Flat” topography
- Tidal influence
- Shallow groundwater tables
- Marsh vegetation, soils, and channel networks

Additionally, flow exchange across subwatersheds may occur during rainfall events. For coastal influenced areas, runoff / routing methods and parameters should be carefully selected to best characterize these complex features, heavily relying on observed data for calibration and validation. During the pilot studies, methods and parameters that produce the most accurate results for complex, tidally influenced areas along the Texas coast were evaluated. Through those efforts, it was determined that rain on mesh (ROM) applications are preferred in coastal influenced areas.

Rainfall-runoff modeling for non-TC events will follow the procedures outlined in **Section 3.2** and **Section 4** in accordance with the modeling level of detail. For TC-events, the methods outlined in **Section 5.3** shall be used.

5.6. Hydraulic Model Setup in Coastal Influenced Areas

The setup and application of HEC-RAS v6.3 models in coastal influenced areas should follow SOPs described in **Section 4**, as well as the additional considerations documented within this section. HEC-RAS models should be setup with a coastal water surface elevation boundary condition and upland inflow boundary conditions where applicable, as well as designed to apply Rain-on-Mesh, either through one-way coupling with HEC-HMS or directly though HEC-RAS, as described above. Specific HEC-RAS model considerations for coastal-influenced areas are listed in the sections below.

5.6.1. Model Version

Consistent with **Section 4.1.2**, new models will be developed in HEC-RAS v6.3 or the latest final version of HEC-RAS available at model initiation. Updated models should also be migrated to HEC-RAS v6.3 because of its expanded capabilities relevant for current or future applications in the coastal influence areas, including wind, spatially varying precipitation, spatially varying stage boundary conditions, hydraulic structures in the 2D domain, and improved computational efficiency compared to earlier versions of HEC-RAS.

5.6.2. 1D / 2D Model Domains

Consistent with **Section 4.1**, new models will include only 2D domains. Updated models will need to be evaluated to determine if 1D segments/channels should be converted to 2D. To simulate multi-directional flows expected in coastal influenced areas, 2D domains are preferred.

1D segments/channels could be suitable, particularly in inland reaches of coastal influence areas where longitudinal riverine processes are dominant. When 1D segments/channels are used, they will be simulated with unsteady flow. 1D Finite Volume Method (FVM) is preferred (see the Wind Field application section, below). Care should be taken to validate 1D FVM results, as large volume errors can occur.

5.6.3. 2D Flow Areas

Consistent with **Section 4.3.7**, the number of separate 2D flow areas should be minimized to allow for seamless interaction of flow within the model, with one 2D area being ideal.

Internal connections, such as weirs between flow areas, do not preserve momentum and lead to errors in tidal and surge propagation. If 2D subareas are used, the weirs should be located along land features where weir flow is likely to occur (e.g., levees or raised roadways), where possible. Otherwise, for other coastal connections that are in the marshes or waterbodies, a small weir coefficient (e.g., < 1) should be used.

Per the USACE Minimum Standards: "If 2-D modeling is required, contractors are encouraged to minimize the number of 2-D flow areas to avoid internal weirs, as they do not conserve momentum, and thereby may cause error in resolving tidal and surge propagation dynamics."

5.6.4. 2D Computational Mesh

See **Section 4.3.7** for guidance on mesh refinement, breaklines, refinement regions, and cell alignment along waterbodies.

5.6.5. Terrain Model

Per the *USACE Minimum Standards*: "Coastal watersheds often lack a single, defining stream that drains the watershed. Instead, small coastal watersheds often include multiple streams that run relatively parallel to each other before discharging into the ocean or bay. Some of these rivers and bayous may experience frequent interbasin flow transfers, which a two-dimensional model can simulate well, if the terrain is accurate for both overland and bathymetric surfaces. As such, the development of a terrain model must replicate this drainage pattern."

5.6.6. Bathymetry

Sources of bathymetry for coastal model setup include the CTXCS2020 and S2G2021 model data, NOAA navigational surveys, NOAA Digital Coast, and USACE surveys in navigational channels. A data gap analysis will be performed to identify additional bathymetric data sources. Future bathymetry from proposed projects may also be considered for future conditions simulations as discussed in the Future Conditions section (**Section 5.4**).

5.6.7. Structures

It is expected that coastal structures will not be available from regional scale ADCIRC models or from FEMA effective flood model studies. Therefore, as-builts for coastal structures should be obtained from TxDOT or local public works departments to assign coastal structures to HEC-RAS 2D models.

5.6.8. Model Formulation

Dynamic wave solver (i.e., full momentum equations) should be used in 2D flow areas that have coastal influenced waterbodies or waterways.

Though the *USACE Minimum Standards* state, "the contractor shall also perform sensitivity analysis utilizing full momentum and diffusive equation solvers to resolve 2-D flow hydraulics in the coastally influenced region, and determine if there is a significant difference between model results," a dynamic wave solver is recommended in all cases. The *HEC-RAS 2D Modeling User's Manual* (USACE 2021) indicates, "If you are modeling a bay, estuary, or river that is tidally influenced, then you have to use the full momentum based equation set. The propagation of waves (tidal cycle) cannot be modeled with the diffusion wave equations."

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5.6.9. Wind Fields

As described in the Coincident Storm and Joint Risk Methodology section, wind forcing is considered optional in the HEC-RAS model setup for production simulations (i.e., those events simulated to support Flood Risk Mapping). If wind forcings are applied in HEC-RAS models, methods to create suitable wind fields will be explored and defined for each basin. If importing wind field data from existing models (i.e., ADCIRC), modelers should note that winds are not applied in the same manner across modeling platforms and should take steps to ensure wind data is imported correctly into HEC-RAS.

Model sensitivity to wind forcing will be explored as part of model calibration and validation. Simulation of historical events with and without wind forcing should be included in model calibration and validation efforts to understand the importance of wind fields in each area and to inform the HEC-RAS model setup for production simulations. If wind forcing is considered in model calibration/validation, "best reanalysis" winds should be used. To evaluate the effect of wind product selection, simulations should also be performed using PBL winds and compared with "best reanalysis" results.

Note that models that will include wind forcing should account for the following:

- The dynamic wave solver must be used to apply wind stresses
- In 1D areas, wind stresses can only be applied if the 1D FVM option is selected

5.6.10. Manning's n

See **Section 4.3.3** for reference. Additional information from CTXCS2020, SGS2021, and the 2023 Texas CRMP may be leveraged to select suitable Manning's n values in coastal influenced areas.

5.6.11. Computational Stability Factors

The adaptive time step feature may be used to modify the time step during prolonged periods of high or low velocities while maintaining the limit on Courant numbers.

HEC-RAS v6.3 has a direct solver and iterative solver options. Generally, the direct solver is more stable but slower than the iterative solver. The direct solver may be appropriate during the model setup, but the iterative option is generally better for production runs.

5.6.12. Steady / Unsteady Modeling Approach

Per the *USACE Minimum Standards*: "The contractor shall also consider applying an unsteady modeling approach to characterize hydraulics in the coastal region, especially in regions with flat topography."

5.6.13. Inland Boundary

See **Section 4.4** and **Section 4.5**. The boundary between coastal influenced model extent and model domains for inland areas (i.e., riverine models) will need to extend inland beyond the expected coastal flood extents (e.g., ADCIRC outputs) and compound flood effected areas to accommodate other considerations (e.g., backwater effects). When applicable, open boundaries should be located at surface water (i.e., stage or discharge) gage locations to provide model boundary conditions and observational datasets to assess model performance during calibration and validation.

Per the *USACE Minimum Standards*: "The upstream limits of each coastal HEC-RAS model should be determined at the kickoff meeting. The contractor should determine several reasonable possible upstream limits of the coastal HEC-RAS modeling based on engineering judgment and the HEC-RAS River Analysis System 2D Modeling User's Manual Chapter 6: Steady vs. Unsteady Flow and 1D vs. 2D Modeling for discussion at the kickoff meeting."

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5.6.14. Coastal Boundary

See **Section 4.5**. Boundaries should be placed to leverage coastal model outputs (see the Existing Studies **Section 5.2.2**, above) as well as gage measurements to aid in model calibration and validation.

Boundary placement should consider wave effects, such that the wave radiation stresses are minimized within the coastal influence model extents (e.g., place the boundary far enough inland that large-scale storm surge model simulations applied at the boundary capture wave effects). HEC-RAS v6.3 does not include wave setup or radiation effects. Similarly, boundary placement should consider that large-scale storm surge model simulations (e.g., USACE's CTXCS2020 and S2G2021 studies) do not include rainfall and stream flows, and thus may underestimate elevations if the boundary placement is too far inland.

It is generally recommended to set the coastal boundary outside the area of interest, so unique modeling approaches that increase stability may be implemented without impacting results near the area of interest.

5.6.15. Adjacent Watersheds

Due to storm surge propagation across the coastal plain (i.e., interbasin transfer), model setup needs to factor in adjacent watersheds to ensure consistent assumptions, analysis, and outputs.

Consistency will be necessary at model boundaries between coastal influenced models to account for the possibility of interbasin transfer that may need to be considered as part of the model setup (e.g., combining adjacent models for future applications).

Per the *USACE Minimum Standards*: "Interbasin transfer is also probable at the low-lying boundaries of the larger drainages near the coast in low frequency scenarios. Overall contract watershed boundaries have been delineated so that basin interflow will likely occur between coastal watersheds within the contract but will not likely occur at the borders of the contracted model boundaries. Therefore, while each major drainage should be modeled separately, an additional 2-dimensional coastal HEC-RAS model with all reaches in the contracted model area will be needed to appropriately route the low frequency scenarios."

5.7. Model Calibration and Validation

See **Sections 3.6** and **4.8**.

For HEC-RAS models should be calibrated and validated to tropical and non-tropical storms. Selected calibration and validation storm events should represent varying conditions including consideration of coastal conditions (e.g., high storm surge, low rainfall; low storm surge, high rainfall).

ADCIRC coastal storm surge models have been calibrated and validated for several storms for studies of coastal Texas (Melby et al. 2020) and of the Texas coastline from Sabine Pass to Galveston Bay (Melby et al. 2021). In addition to observational data from discrete locations and aerial photography, HEC-RAS results in coastal influenced areas should be compared to ADCIRC model results during the calibration and validation process.

Simulation of historical events with and without wind forcing should be included in model calibration and validation efforts to understand the importance of wind fields in each area and to inform the HEC-RAS model setup for production simulations.

Per the *USACE Minimum Standards*: "The contractor shall identify a list of historical storms which will be used to calibrate and validate coastal RAS models. These historical storms will include a range of events which caused compound flooding, surge-dominated flooding, and rainfall-runoff-dominated flooding. The Coastal RAS models shall be calibrated and validated against observed historical datasets, including, but not limited to, water level and discharge time series, HWMs, and aerial imageries."

5.8. Coastal Influenced Models Sensitivity Testing and Uncertainty Analysis

5.8.1. Sensitivity Analysis

As discussed in **Section 4.9,** sensitivity testing is an important aspect of model calibration and validations efforts. It is also key to optimizing model resolution and processing time, given the large number of simulations associated with coastally influenced areas. Sensitivity testing for numerical and physical parameters in coastal areas should consider the following:

- Considerations listed in the Coincident Storm and Joint Risk Methodology section.
- Sensitivity tests as appropriate for any models that include 1D/2D model setup when leveraging existing 1D/2D models.
- Sensitivity tests may be completed for 2D flow area setup (i.e., mesh size and complexity) to assess tide propagation and/or run times.
- During model calibration and validation, the effects of wind forcing may be tested for a given basin. Note that the storms simulated to develop annual exceedance probabilities (see the Coincident Storm and Joint Risk Methodology section 5.3) will not include wind forcing.
- Computational stability factors including time step.
- Uncertainties associated with boundary conditions for inland and adjacent watersheds.
- Additional uncertainty tests when identified as necessary in the 25% report.

5.8.2.Uncertainty Analysis

For all models not designated as "high-detail" as described in **Section 1.1**, uncertainty analyses as described in **Section 4.9** are anticipated to be beyond the scope of baseline modeling efforts. However, specific sources of uncertainty in flood depths and inundation will be considered for coastal influence areas, namely uncertainties in placement and refinement of downstream boundaries (i.e., coastal) and uncertainties associated with boundary conditions for inland and adjacent watersheds. For coastal boundaries, sensitivity testing conducted as part of the model calibration and validation process will generally determine the best placement and orientation of the downstream boundary. Therefore, the primary source of uncertainty with compound flooding will originate from the various surge and rainfall pairings. The methodology outlined in **Appendix B**, which calls for simulation of a most likely surge-rainfall pairing, surge dominated pairing, and a rainfall dominated paring to elucidate uncertainty in compound flooding for a given AEP. Additionally, simulation of lag effects between peak rainfall and peak surge will only be considered for high level of detail models, although the bivariate methods outline in **Appendix B** will provide the data sets necessary to evaluate the uncertainties in flood depth and timing due to lag effects.

5.9. Coastal Flood Risk Mapping

To support flood risk mapping, it is expected that three events per each joint AEP will be mapped in addition to the Atlas 14 rainfall-only event: the "most likely" design event, a rainfall-dominated event, and a surge-dominated event. These events will be based on the RBFS vendors' professional judgement,

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with justification documented in the report. The final WSE raster, depth raster, and inundation will reflect the maximum WSE of the three events and Atlas 14 event. A high-level comparison of the events will also be documented in the report using a profile plot and/or rasters of the three events. This high-level comparison can be used to support alternatives analysis during Phase 4. Mapping of the transition zone is not necessary.

Flood risk mapping for coastal influenced models will be done consistent with the guidelines in **Section 4.11** unless otherwise noted. The two primary outputs are described below.

5.9.1.Depth Grid Raster

For each simulated event, frequency and historical, the contractor should produce depth grid rasters, inundation boundary shapefiles, and delineation of the compound flood zone and provide these in a standalone database. The following AEPs are expected to be mapped for each study area in addition to the rainfall-only Atlas 14 events:

1. AEPs. For TC, depth grid rasters for the most likely, surge dominated, and rainfall dominated will be produced (3 simulations per AEP). A combined raster for each AEP will also be produced that represents the maximum of the three TC events and the corresponding Atlas 14 event. It is expected that TC events will produce higher inundation depths than non-TC events; therefore, non-TC AEP events will typically not be modeled..
   a. 10-year
   b. 50-year
   c. 100-year
   d. 500-year
2. All Historical Events from model calibration and validation

5.9.2.Map Book

Map books will be consistent with the approach defined in **Section 4.11**.

5.10. Final Coastal Products

Final coastal and compound flood work products are described in **Section 2**. Data will be organized consistent with the structure described in **Section 4.11**.

5.11. References

- Couasnon, A. et al. 2018. A Copula-Based Bayesian Network for Modeling Compound Flood Hazard from Riverine and Coastal Interactions at the Catchment Scale: An Application to the Houston Ship Channel, Texas. Water 2018, 10(9), 1190; https://doi.org/10.3390/w10091190
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Appendix A – Summary of Existing Coastal and Compound Flood Studies

Study Name	Study Description	Lead Agency/ Entity	Study Area by GLO Region				Elements within the Study			
			East	Central	West	Valley	Coastal Storm Surge (e.g., ADCIRC)	Coastal Influence Model Setup (e.g., HEC-RAS)	Coincident Storm and Joint Risk Methodology	Future Conditions Analysis
FEMA 2011	Applied, uncoupled surge and wave modeling and different technologies for the coastal modeling of Texas and Louisiana that produced a discontinuity in statistical response of the 1% AEP surge and wave height near the TX-LA border. Applied limited parameter sampling for JPM-OS. The study did not include wave impacts, detailed wave analysis in the vicinity of CSRM, or multi-variate probability analysis of hazard.	FEMA	X	X	X	X	X			
S2G2015	The study has similar limitations as the FEMA 2011 study but used updated surge and wave modeling software and consistent technologies from Louisiana to Texas to remodel storms that have primary influence in the Sabine region near the TX-LA border.	USACE	X	X			X			
CTXCS2018	The study provided significant improvements over the FEMA 2011 and S2G2015 studies in both the storm characterization through the JPM-OS and the regional storm surge and wave modeling. It resolved the limitations of the FEMA 2011 and S2G2015 studies, as its wave modeling is both continuous and of consistent quality throughout the region.	USACE	X	X	X	X	X			
CTXCS2020	The study's joint probability model describes the continuous spatial and temporal hazard and facilitated development of a suite of 660 synthetic tropical storms that characterize the coastal storm flood hazard for Texas. Further sub-sampling developed a suite of 170 synthetic tropical storms that essentially capture the flood hazard for Galveston and the Galveston Bay region. The study provides the highest resolution regional surge and wave modeling done to-date for the region.	USACE	X	X			X			X
S2G2020	The study identifies several S2G Project CSRM formulated measures that consist of reducing risks of tropical SWL impacts. These measures include construction of the new Orange 3 CSRM system in Orange County and increasing the level of risk reduction and resiliency of the existing Port Arthur and Vicinity and Freeport and Vicinity Hurricane Flood Protection systems. The study applied a joint probability model that describes the continuous spatial and temporal hazard and facilitated development of a suite of 195 synthetic tropical storms that effectively capture the flood hazard for the region from Freeport to the TX-LA border.	USACE	X	X			X			X

Study Name	Study Description	Lead Agency/ Entity	Study Area by GLO Region				Elements within the Study			
			East	Central	West	Valley	Coastal Storm Surge (e.g., ADCIRC)	Coastal Influence Model Setup (e.g., HEC-RAS)	Coincident Storm and Joint Risk Methodology	Future Conditions Analysis
Lower Clear Creek and Dickinson Bayou Flood Mitigation Plan	The study applied HEC-HMS v4.3 to develop input upstream and inflow hydrographs to the HEC-RAS v5.0.7 model. The FNI (2021b) study applied the Basin Development Factor methodology—a process locally introduced as part of the MAAPnext effort lead by the Harris County Flood Control District—to perform a consistent hydrologic analysis over the approximately 35-square-mile study area. In both the Lower Clear Creek and Dickinson Bayou HEC-RAS models, the main stems and tributaries are modeled as 1D channels defined from the 2018 LiDAR data and the adjacent floodplains are modeled as 2D domains developed from the 2018 LiDAR data. Simulations of historical hurricanes include Harvey (2017), Ike (2008), and Allison (2001). Model simulations for these events characterize compound flooding in the watershed with coincident rainfall. Processed, measured rainfall data provided HEC-HMS model input rainfall and measured Galveston Bay water level provided the HEC-RAS model downstream boundary water level condition.	Freese and Nichols, Inc.		X			X	X	X	
2019 Texas Coastal Resiliency Master Plan Technical Report	The 2019 Texas Coastal Resiliency Master Plan is the second installment of a statewide plan to "protect and promote a vibrant and resilient Texas coast that supports and sustains a strong economy and healthy environment for all who live, work, play or otherwise benefit from the natural resources and infrastructure along the Texas coast." The Texas CRMP included gulf beach erosion and dune degradation; bay shoreline erosion; existing and future coastal storm surge damage; and coastal flood damage among eight priority issues of concern on risks and threats to the coastal communities and industries. The plan's technical study applied SLAMM to estimate future habitat changes, the SWAN wave model coupled with ADCIRC with a 3.3-ft global mean sea level rise to estimate storm surge inundation areas, and FEMA's Hazus model to estimate potential losses in current, future without projects, and future with project conditions. The plan recommends 123 Tier 1 resiliency projects in coastal Texas at a cumulative cost of $5.4 billion.	GLO	X	X	X	X	X			X
Lower Sabine Riverine Flooding Analyses (Parola et al. 2019)	In this study, a 2D HEC-RAS model was used to route flows from Ruliff, TX to Sabine Lake. The hypothetical, balanced frequency flow hydrographs were developed at the USGS Ruliff, TX stream gage based on the annual peak flow frequency analysis at this location and were utilized as the upstream boundary condition for the RAS model. To account for the effect of coastal storm surge, the observed water level from the 2016, 2017, and 2008 flood events at NOAA Gage 8770475 at Port Arthur were selected as downstream boundary conditions. A hypothetical weir and storage area (with infinite storage capacity) were used at the eastern boundary downstream of Orange, TX to simulate the flood attenuation and inundation during high flow events.	USACE	X					X		

Study Name	Study Description	Lead Agency/ Entity	Study Area by GLO Region				Elements within the Study			
			East	Central	West	Valley	Coastal Storm Surge (e.g., ADCIRC)	Coastal Influence Model Setup (e.g., HEC-RAS)	Coincident Storm and Joint Risk Methodology	Future Conditions Analysis
Cow Bayou Hydrologic and Hydraulic Analysis (Mosser et al. 2020; Ross and Mrse 2020)	Mosser et al. (2020) developed a new rainfall-runoff model for the Cow Bayou watershed in HEC-HMS. The model was calibrated using three historical storms: October 2006, Hurricane Harvey in 2017, and Tropical Storm Imelda in 2019. After calibration, frequency storms were applied to the model to calculate frequency flows that were used as the upstream boundary condition for the 1D/2D HEC-RAS model developed by Ross and Mrse (2020) to determine what impacts flood flows from Cow Bayou would have on the proposed gate structure and pump station. A stage hydrograph output from the Lower Sabine HEC-RAS model (Parola et al., 2019) was utilized for the calibration and validation.	USACE	X					X		
Lower Neches Riverine Flooding Analyses (Mosser et al. 2019)	The overall approach for this study is similar to the Cow Bayou Hydrologic and Hydraulic Analysis. An existing USACE HEC-HMS rainfall-runoff model, developed for the 2014 Neches Basin Corps Water Management System Implementation, was updated for the Neches River basin above the Salt Water Barrier. The model was calibrated and used to calculate frequency flows at the lower end of the Neches River near the Salt Water Barrier. The results of the HEC-HMS model were compared with the statistical results from the RiverWare modeling efforts in the same study and were adopted for use as the upstream boundary condition for the 2D HEC-RAS model between the Salt Water Barrier and Sabine Lake. The model also takes into consideration the effect of coastal storm surge by simulating the total water level from NOAA Gage 8770475 at Port Arthur as the downstream boundary.	USACE	X					X		
Coupled Induced Riverine Flow-Storm Surge Modeling (Dawson and Kiaghadi 2019)	To evaluate risks associated with compound flooding of new CSRM mitigation projects along the Texas coast, the authors modified the existing ADCIRC model (Melby et al., 2019) of the Port Arthur-Orange, Texas region, including the lower Neches and Sabine River watersheds, to account for river inflows from the Neches and Sabine Rivers under different flood regimes. The riverine flow boundaries were extracted from an existing HEC-RAS model (Mosser et al., 2019, Parola et al., 2019). Four storms were investigated in this study: Hurricane Rita, Hurricane Ike, March 2016, and Hurricane Harvey.	USACE	X					X		
Using Multivariate Statistical Modelling to Assess Compound Flooding Effects in Sabine Lake (Santos and Wahl 2019)	Santos and Wahl (2019) evaluated the dependence between rainfall-induced river discharge and storm surge processes and assessed potential compounding effects in Sabine Lake, TX using the copula-based statistical model. The main streams flowing to Sabine Lake (Sabine and Neches rivers) were combined to represent the total inflow. Water elevation data from NOAA tide gages located in and around Sabine Lake were used to account for coastal water levels. The framework implemented in this study can be used for other locations as a preliminary assessment to assess possible compounding effects and help inform and guide the potential for further modeling study.	USACE	X						X	

Study Name	Study Description	Lead Agency/ Entity	Study Area by GLO Region				Elements within the Study			
			East	Central	West	Valley	Coastal Storm Surge (e.g., ADCIRC)	Coastal Influence Model Setup (e.g., HEC-RAS)	Coincident Storm and Joint Risk Methodology	Future Conditions Analysis
Joint probability analysis of high river discharge and storm surge (Jane et al. 2021)	Similar to the study performed by Santos and Wahl (2019), the dependence between high river discharge and storm surge in the Sabine River Basin (Cow Bayou and Adams Bayou) and at two locations along the Brazos River was assessed using the copula (i.e., statistical) analysis in this study. According to the methodology adopted in the study, compound flooding is more associated with the Sabine Basin region than the Brazos Basin.	USACE	X	X					X	

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Appendix B – Compound Flooding Risk Evaluation Using a Bivariate Analysis (Villarini and Zhao 2021)

As a way to evaluate the risk due to the compound flooding from precipitation and storm surge, a bivariate analysis is proposed to determine the role of compound events at desired AEPs. A road map is included in Figure 1. The compound events include both tropical cyclones (TC) and non-tropical cyclones (N-TC). The bivariate analysis integrates four critical steps, to be conducted for each basin of interest.

1. Data collection
2. Dependence structure evaluation
3. Assessment of joint probability of compound events
4. Creation of design events

1.1 Data Collection and Review (Box 1)

To complete the bivariate analysis, observed precipitation, water levels, and extreme events information are required. The following sections describe datasets that are potentially useful for the analysis. However, depending on the use and availability of data in each basin, it may not be necessary to collect or use them all. The overall purpose of this section is to provide observed time series of rainfall intensities and water levels that have overlapping time period for the dependence analysis for TCs and N-TCs, respectively.

Radar-Based Precipitation

Stage IV QPE products over the continental United States provide gridded rainfall fields at hourly resolution and ~4-km spatial resolution (Lin and Mitchell 2005). The radar-based precipitation data are available from 2002 to the present. The Analysis of Period of Record for Calibration (AORC) dataset is a new product released in October 2021 and represents a source of meteorological variables for calibrating the National Water Model (NWM) (Kitzmiller et al., 2018). The AORC precipitation dataset is available on a ~4 km grid cell at an hourly time scale covering the period from 1979 to the near present. To form the dataset used in the evaluation of the dependence structure and joint probability assessment, the basin-averaged precipitation is computed from the gridded rainfall fields.

Gage-based Precipitation

Precipitation gage data are available from NOAA, TWDB, and local drainage and flood control districts as described in the **Section 3**. They can be used to potentially supplement rainfall data before the availability of radar-based precipitation (i.e., pre-2002) or be used independently, as long as a single gage or a set of gages is confirmed to be sufficient for representing the basin precipitation condition spatially (e.g., basin-averaged precipitation) and temporally (e.g., hourly). The annual maximum time series (AMT) of precipitation in the NOAA Atlas 14 study (Volume 11, Version 2.0: Texas) is also considered as a gage-based dataset. The Atlas 14 study practiced screening nearby stations (i.e., within 3-5 miles of target location) and merging the records to increase record length. Therefore, the published annual maximum series extraction at relevant station within the study area can be a source of extreme event sample sets. Precautions for use include: 1) being careful in relaying the data to basin-averaged precipitation, 2) distinguishing TC events from N-TC events, and 3) understanding the disadvantage of AMT in comparison to the peaks-over-threshold (POT) dataset. Gage-based data and radar-based data may be collectively or individually used to identify extreme events.

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Modeled PRISM Precipitation

PRISM datasets provide the time series of daily total precipitation estimated using a method called climatologically aided interpolation. Two versions of daily data are available (D1/D2), which covers the period from 1981 to present. The latest version, D2 daily dataset, incorporates not only precipitation gage data but also radar-based data in central and eastern US for the period of 2002-present. The PRISM dataset, especially the data prior 2002 is worth collecting for extending the length of data record.

Water Levels

Water levels from the Tides and Currents database by NOAA, at multiple gages within the study basin (e.g., the final selection will be determined by the proximity of the gages to the outlet and by the representativeness of the tide gage of downstream conditions) are to be collected and reviewed. Analyses should be based on gage that has a sufficiently long (ideally 30 years) data record and can represent the basin downstream condition; if the records are short, the analyses will be affected by sampling size, and uncertainties need be documented through a Monte Carlo approach to reflect the sampling errors associated with the estimated parameters.

- NOAA Tides and Currents - https://tidesandcurrents.noaa.gov/

The measured time series is detrended with a nonlinear polynomial or smoother (e.g., loess, cubic splines) to remove long-term sea level rise. Tidal signals are removed by subtracting tidal prediction from the detrended time series. The remaining surge residual also known as non-tidal residual (NTR) will be used in the further statistical analyses.

Tropical Cyclone Database

HURDAT2 database by the National Hurricane Center summarizes TCs impacting the United States. The recorded TCs are used in the analysis to distinguish TCs from N-TCs. An extreme event identified from above collected dataset will be defined as a TC even if recorded in the HURDAT2 database and will be included in the statistical analysis sample set if the storm track is in the proximity of 5 decimal degrees (~500km) to the study area.

- National Hurricane Center - https://www.nhc.noaa.gov/data/

Synthetic Storm Simulations in Coastal Texas Study (CTX2019)

Peak surges from synthetic storm and annual exceedance probability curves at save points along coastal Texas are available. This dataset could potentially provide water level boundary condition at the HEC-RAS downstream open boundary and/or marginal distribution of storm surge when conditioning on surge if a designed event is defined as a synthetic storm combined with a predicted rainfall intensity at a desired return period. This dataset will also be a critical part if a probabilistic TC rainfall generator is developed for Texas. The synthetic rainfall and simulated storm surge can be paired for surge/rainfall bivariate analysis. More information is referred to in Section "Probabilistic Rainfall Generator (Box 5)."

2.1 Dependence Structure Evaluation (Box 2)

The section is to evaluate the dependence of extreme NTRs and precipitation pairs in the basin of interest. To identify the compound events, the peak-over-threshold approach will be applied to NTR time series (e.g., surge conditioned) and precipitation time series (i.e., precipitation conditioned), respectively; then the peaks of precipitation and water levels within a ±3-day window of the POT events are selected accordingly. The window size of three days is large enough to capture maxima close to the occurrences of POT events but also small enough to minimize the possibility of picking inconsistent

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events. Both the POT threshold and window size proposed here are initial recommendation. A final decision on the threshold and the window to identify independent events will be made after analyzing the data and checking the goodness-of-fit of the Generalized Pareto Distribution (GPD). The outcomes are two sets of compound events: storm surge conditioned, and precipitation conditioned.

Due to the nature of the compound hazard, once POTs have been identified, the following analyses will be performed for TC and N-TC events separately. To classify a compound event as associated with a TC, the HURDAT2 database will be used to determine if the center of circulation of the storm passed within a certain distance from the tide gage during the observed POT event. Based on the literature (see Khouakhi et al. [2017] and references therein), a starting radius of 5 decimal degrees will be applied (~500 km, e.g., Khouakhi et al. [2017]), but smaller radii will also be considered to avoid the potential inclusion of non-TC rainfall if deemed necessary after having analyzed the data.

In each of the TC or N-TC compound events group, for the surge-conditioned and rainfall-conditioned event sets, the Kendall's tau (τ) coefficient and significance level are computed to quantify the significance of the dependence. The joint probability will be estimated using copula modeling if the estimated value of Kendall's tau is larger than 0.3 and/or its p-value is smaller than 0.05. Otherwise, the two variables are treated as independent.

Based on preliminary results for both Texas and Louisiana, we do not expect that N-TC events will exhibit significant dependence between rainfall and surge. If this is confirmed during the analyses, then rainfall and surge can be treated as independent random variables and no bivariate modeling is needed. On the other hand, if the independence assumption is not justified, then a bivariate modeling is required as described above.

3.1 Joint Probability Analysis

Joint Probability Analysis using Copula Modeling (Box 3)

If the joint dependence structure is confirmed, the joint probability analysis is conducted using copula modeling. A copula is a multivariate probability distribution with uniform marginal distributions. Various copulas are tested, and the final selection should be based on the Akaike Information Criterion (AIC) or a similar criterion. Once the copula is determined, the joint AEP will be determined using the copula and the marginal distribution of the conditioning and conditioned variable. Take the TC compound event set as the example, for event sets conditioning on surge and on precipitation the marginal distribution for the conditioning variable is fit to the GPD; the marginal distribution for the corresponding variable is fit to an appropriate bounded or unbounded distribution, e.g., logistic distribution; the joint AEP is determined by copula modeling. The ultimate joint AEP of precipitation and storm surge will combine the joint AEP when conditioning on surge and the joint AEP when conditioning on precipitation using the outer envelope of two AEP isolines. Eight AEPs will be considered (i.e., 50%, 20%, 10%, 4%, 2%, 1%, 0.5%, 0.2%).

If the impacts of one conditioning variable on compounding flood are justified as negligible, the two-way joint probability analysis may be simplified as one-way joint probability analysis, for instance, only the surge-conditioned joint probability analysis is carried forward.

With AEP combinations of precipitation and storm surge determined, the lag time between the peak precipitation intensity, and the peak storm surge will also be examined. To develop the expected lag for the watershed of interest, the time lag between peak storm surge, and peak precipitation intensity for all events included in the statistical analysis will be computed. If the data set is too small or if no parametric distribution satisfactorily fit the data, a bootstrap technique should be applied to increase the sample size of the lag time distribution to provide confidence intervals with the mean expected lag time values. The lag times can then be used by the modeling teams to offset the peak storm surge of the storm surge time series and the peak precipitation intensity of the precipitation events for each AEP combination of interest. This sensitivity analysis should be performed only on the most likely design event for each AEP.

Joint Probability Analysis w/ Assumption of Independence (Box 4)

If the independence structure is confirmed, for instance, N-TC events will most likely exhibit little dependence, rainfall and surge will be treated as independent random variables and no bivariate modeling is needed. However, the mean lag time between the peak precipitation intensity and the peak storm surge will still need to be determined as described in the last paragraph of previous section.

Joint Probability analysis w/ Probabilistic Rainfall Generator (Box 5)

It is possible to develop a probabilistic TC rainfall generator (Villarini et al. 2021). If developed, synthetic rainfall fields may be generated with equal probability for each synthetic storm in the Texas synthetic storm suite. This will lead to an ample dataset of surge-precipitation pairs, which are used in the joint probability analysis with the copula modeling. The improved surge-precipitation dataset can embrace the aleatory uncertainties in rainfall intensity and spatial distribution during possible TCs and improve the joint probability estimation of surge and precipitation. However, this is optional depending on schedule, budget, and scope of work.

4.1 Design Events and Inundation Maps

The outcomes of these analyses will include combinations of precipitation and storm surge as design events for the modeling and mapping of flood hazards in coastal watersheds. For each AEP, a minimum of three points needs to be selected to sample a range of possible rainfall/NTR combinations on the given AEP isoline. To develop spatially variable precipitation, a disaggregation method is required. To accomplish this, the basin-averaged precipitation for each historical event included in the analysis will be reviewed to identify an event with a precipitation comparable to the AEP of interest. If there are no historical events from the statistical analysis with comparable precipitation, or if more than one storm is needed, the precipitation for historical events can be scaled up or down across the entire precipitation field to match the basin-averaged precipitation corresponding to the AEP precipitation event of interest. The spatial and temporal variation of the historical event can then be applied in the modeling efforts as observed from the precipitation data. Similarly, a time series will be developed for the AEP peak surge values of interest. The time series of storm surge of the selected events included in the statistical analysis will be aligned based on the corresponding peak storm surge. A normalized storm surge time series will then be developed based on averaging the storm surge at each time interval. The resulting normalized storm surge time series can then be applied with any AEP peak storm surge value of interest. The expected lag times (i.e., computed as the difference between the time of the surge POT event and the maximum accumulated precipitation within a given time window of, say ±3 days) are applied between the peak precipitation intensity and the peak storm surge.

For all design events at a given AEP, HEC-HMS and HEC-RAS are performed to create the set of inundation maps for further flood hazard mapping and risk analysis. There will be two sets of design events for a given AEP (i.e., TC and N-TC). The inundation map should reflect the maximum extent among the different simulations available for each AEP (i.e., joint events, sensitivity to lag, TC vs. N-TC).

5.1 Limitations and Caveats

In performing the analyses, consideration should also be given to the strengths and weaknesses of this approach as documented in **Table 1**. The use of this approach for design storms should be handled with care and recognizing that there are large uncertainties associated with these analyses, especially when dealing with short samples and small AEPs.

Table1. Summary of the Strengths and Weaknesses of the Bivariate Modeling Approach

Strengths	Weaknesses
Straightforward to implement and can be tailored to individual basins	There can be discontinuities (e.g., inundation maps and flood frequency) among neighboring basins if extended beyond a single basin.
Based on observations	Affected by small sample sizes. This would lead to an underestimation of the upper tail of the storm surge and rainfall distributions.
It can capture the relative likelihood of events along an isoline	The simplified (i.e., one-way conditioning) bivariate modeling can underestimate the magnitude of the possible design events.
It could incorporate the results of the USACE's studies for storm surge (CSTORM/StormSim for CTXCS, S2G) in the simplified bivariate modeling (i.e., one-way conditioning)	There is no information about rainfall from USACE's studies (CSTORM/StormSim for CTXCS, S2G) that is available.
It allows the generation of rainfall fields with high spatial and temporal resolution and the corresponding downstream surge boundary condition based on historical events	It suffers from the many pitfalls of event-based approaches that can misrepresent inundation level associated with the annual exceedance probabilities.

6.1 References

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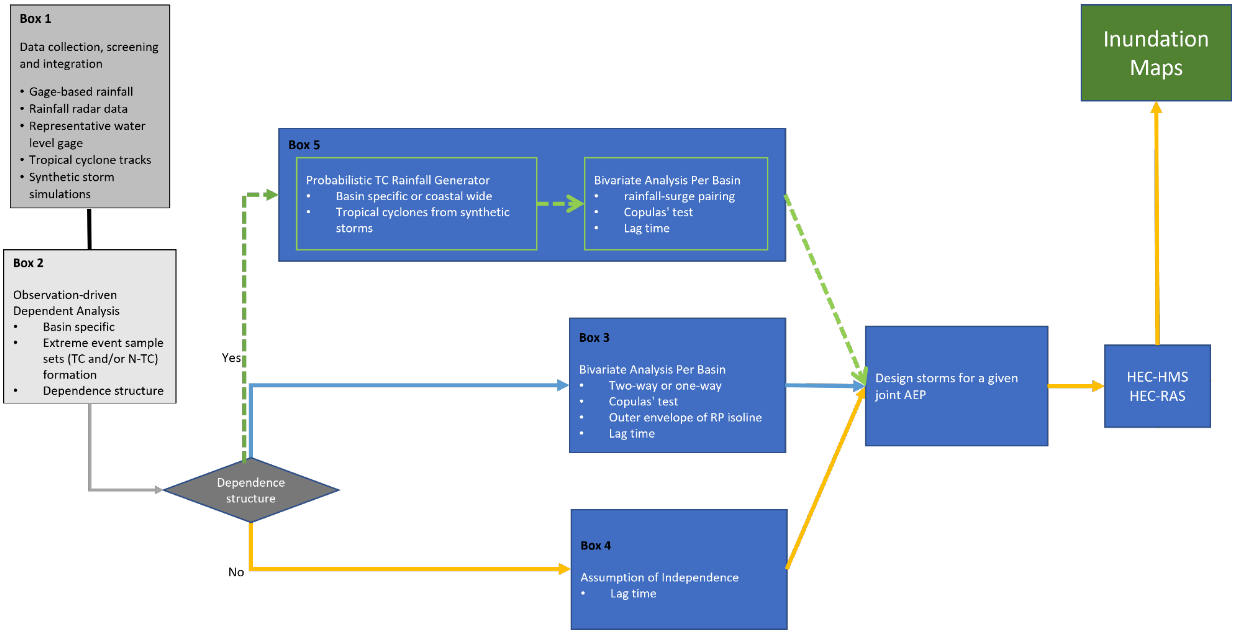

Figure 1. Compound Flooding Risk Evaluation Using a Bivariate Analysis