Lower Missouri River 2D Hydraulic Modeling

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Abstract

The Missouri River experienced historic flooding in 1993, 2011 and again in 2019. The Lower Missouri River Comprehensive Flood Protection Study is an opportune time for FEMA Region 7 and the USACE Omaha and Kansas City Districts to collaborate in the development of new engineering data to support floodplain management, reduce flood risk, and improve resiliency across multiple States.

The Lower Missouri River study area is from Gavin's Point Dam down to the confluence with the Mississippi river. A total of approximately 811 river miles, 7600 square miles of floodplain, 358 levee systems, 60 bridge crossings, 52 counties, and 5 states are impacted by this study.

A key component of this study is the collaboration of subject matter working groups comprised of experts within the USACE, FEMA, and Stantec to develop and validate approaches to accomplish three primary objectives:

1. Successfully establish a framework for FEMA and USACE collaboration towards analyzing flood risk from very large river systems that impacts multiple States.
2. Provide a consistent product in a baseline platform ready for future customized enhancements by both agencies to support individual needs.
3. Produce flood risk data in support of FEMA's Future of Flood Risk Dataset initiative.

USACE will provide an updated flow frequency analysis that uses a Monte Carlo analysis. Stantec is producing a detailed 2D HEC-RAS model. The study includes compilation of LiDAR into a seamless dataset, incorporation of hydrographic survey data of the river channel, compilation of survey data of bridges, leveraging flow frequency data produced by the USACE, performing stream gage analysis, performing rain-on-grid analysis and hydrograph routing of major contributing tributaries, producing 2D HEC-RAS with-levee model, and production of flood risk data.

Introduction

Previous hydrologic and hydraulic study of the Lower Missouri River reach was completed in year 2003. Since then, this river reach has experienced several large events, including three larger than 1% annual chance of exceedance. In response, USACE initiated a new flow frequency study of this river reach. In the wake of these events, FEMA Region 7, USACE Omaha District and USACE Kansas City district realized that an updated hydraulic model of this reach is crucial for identifying future flood risk and mitigating those flood risks. FEMA and USACE are collaborating to produce a single hydraulic model that can be instrumental in meeting the needs of both agencies. The model is expected to inform flood risk communication, flood risk reduction activities, mitigation planning and other future needs of FEMA, USACE and potentially other stakeholders.

As a collaborative effort of multi-federal agencies, FEMA and USACE entered into an interagency agreement to collect stream bathymetric data, share lidar terrain data, acquire bridge and culvert survey data, produce model calibration data, share flood risk reduction infrastructure related data and other data to support the analysis. Stantec's role as FEMA contractor involves:

- Terrain data development: Collect terrain raster dataset, and bathymetric and hydrographic data from multiple sources, mosaic into a single digital elevation model (DEM).
- Survey data development: Survey railroad bridge crossings the main stem Missouri River, select bridges that are hydraulically significant within the Missouri River overbanks, collect and compile bridge as-built drawings.
- Hydrology data development: Develop a methodology for hydrograph development for the frequency events. Create hydrographs for main stem Missouri River and major tributaries for analyzed frequency events.
- Hydraulic data development: Produce calibrated Base Model Geometry covering the project area. Run select frequency events on a calibrated Base Model Geometry to estimate water-surface elevations along the model reach at these frequency events.
- Flood risk products: Produce velocity, depth and water surface elevation grids for the analyzed events to aid flood risk communication.

The primary objective of the project is to develop a calibrated 2D HEC-RAS model, The calibrated model geometry will be used as a Base Model Geometry to estimate 10%, 4%,2%, 1%, 0.2% and 1% + annual chance event water surface elevations along the modeled reach of the Missouri River. The model is also expected to serve as a base 2D model for US Army Corps of Engineers' stage frequency analysis and for future enhancements to analyze what if scenarios and FEMA's future modeling needs.

Due to the multiple purposes the model is expected to serve, complex hydrologic and hydraulic nature of the system under evaluation and a need for the model to be easily enhanced and upgradable for future needs, a full 2D unsteady state modeling approach is used. In addition, a full 2D unsteady state approach is a prudent approach for FEMA Future Flood Risk Data development and flood risk reduction activities.

Terrain Data

Stantec acquired available lidar terrain data from multiple sources in multiple formats. All the data sources met the QL2 data quality or better and priority was given to 2019 post flood and newer data. Stantec used ArcGIS Desktop 10.8.1 and ArcPro 2.8 to process and mosaic data. Majority of the data were obtained from USGS 3DEP national map and state repositories in DEM format. Channel bathymetric data was obtained as hydrographic cross-section survey point dataset. Stantec's terrain processing involved:

- Ensure all the data uses consistent vertical and horizontal reference datum
- Ensure all the data has consistent resolution
- Inspect and fill 'no data' gaps in the DEM
- Applied an approach to produce a representative raster of a stream channel with meanders using the hydrographic cross-section survey point data
- Develop an approach to fill data gap between bathymetric and terrestrial terrain data
- Project the data to the assigned projection for the study
- Mosaic the rasters into a seamless dataset for each model domain area

Structure Data

Majority of bridge and culvert structure data are obtained from each state department of transportation in the form of as-built drawings. Railroad bridge data were surveyed using terrestrial lidar scan. Modeling approach of the structures in the overbank of the Missouri River will be dependent on their hydraulic significance. These structures will be surveyed, field measured or ignored depending on their hydraulic significance to the model results.

Levee information will be obtained from USACE's National Levee Database (NLD). Crest elevation and dimensions of non-levee features, such as roads and railroads, will be extracted from the lidar terrain.

This study focuses on events rarer than 10% annual chance of exceedance events. River structures built for stream channelization for navigation and habitat restoration purpose will not be included in the model. Sensitivity analyses demonstrated that the Missouri River hydraulics is not sensitive to these structures in the rare events.

Modeling Approach

The study reach will be divided into multiple domains to keep the models manageable from the size and runtime considerations on a personal computer. The project reach will be divided into six domains. Model domains are divided at strategically selected locations to support model calibration and ensure model tie-in. Figure 1 below shows the general overview of the project reach and model domains.

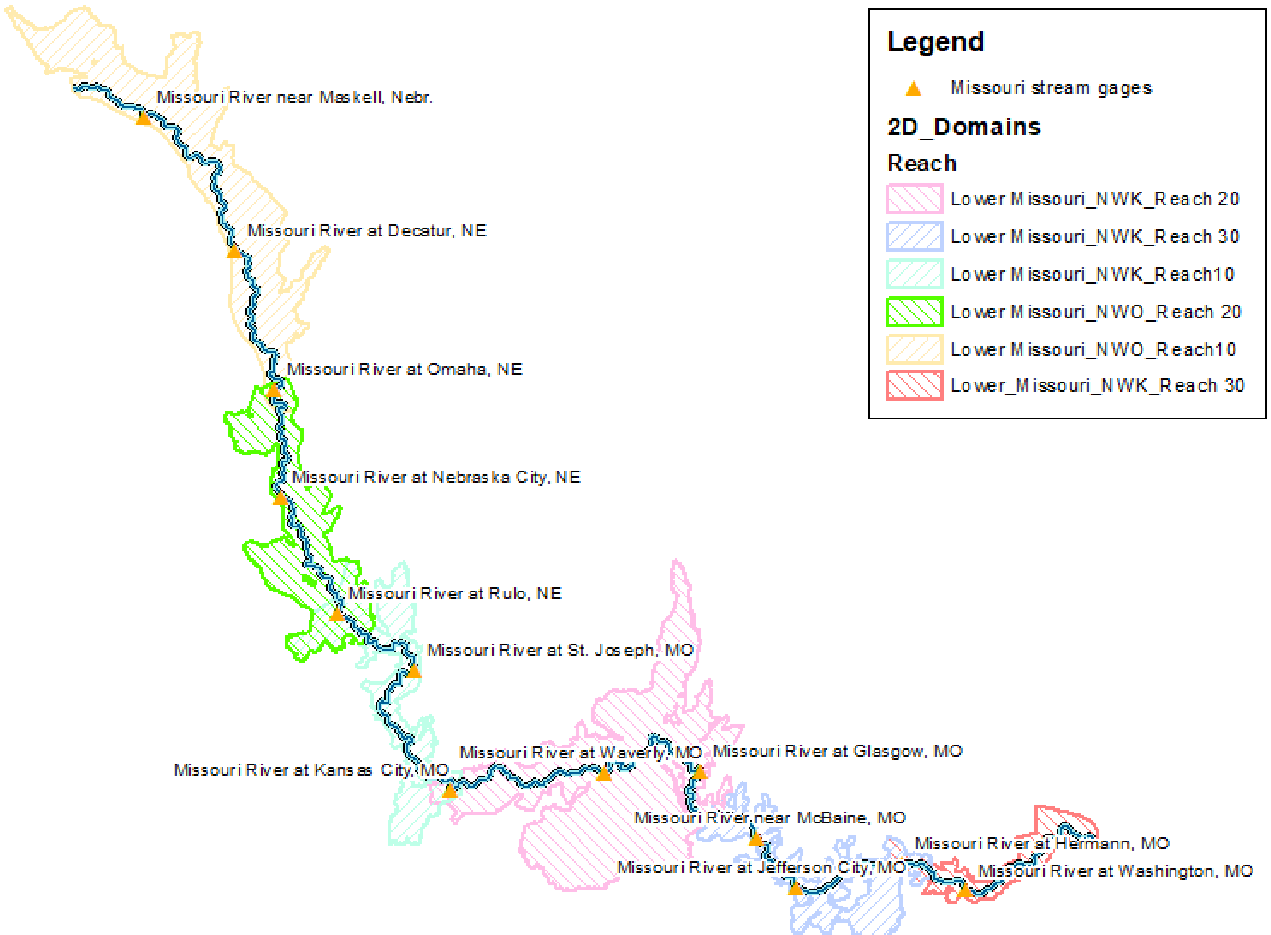

Figure 1 Model domains

Hydrologic Data Development

Each model domain will have an inflow boundary in the form of inflow hydrograph at the upstream main stem Missouri River. Lateral inflows from tributaries along the modeled reach will also be added. Figure 2 below shows the schematic of hydraulic model setup of a model domain.

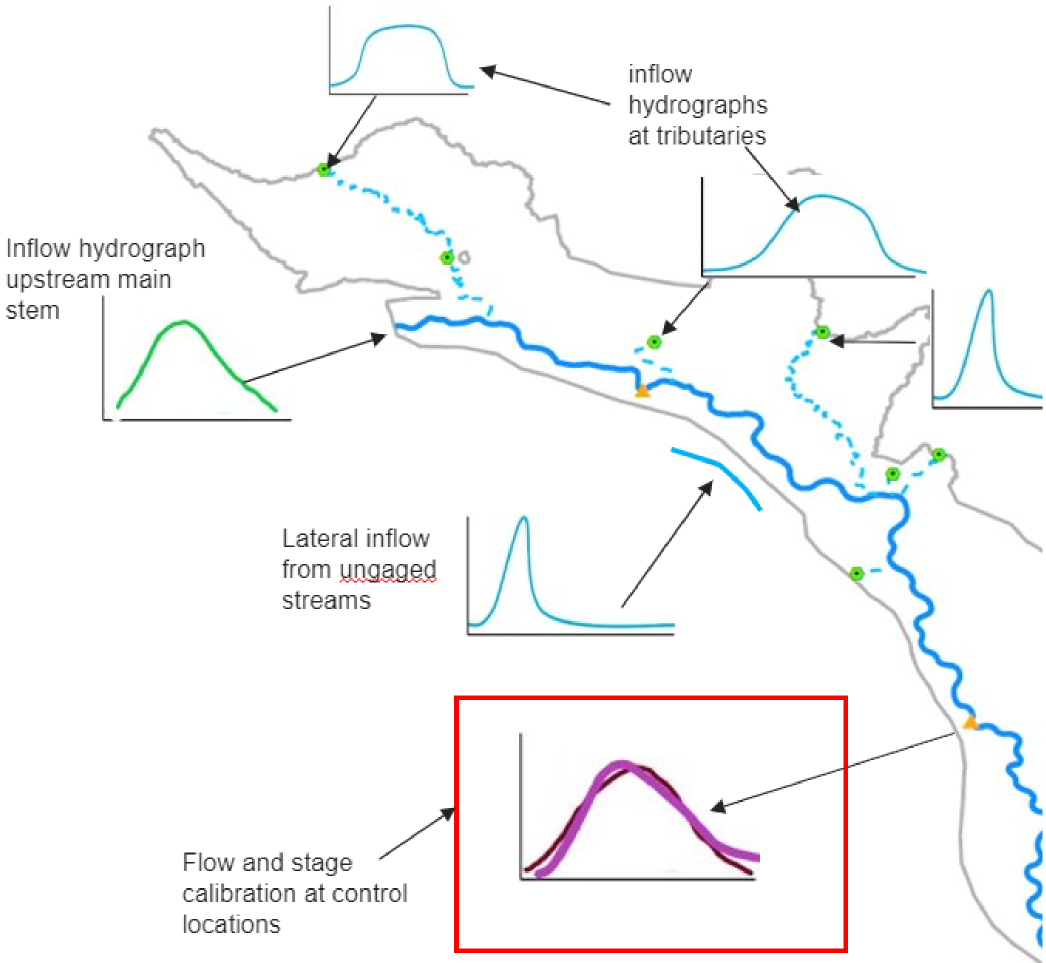

Figure 2. Hydraulic model setup

Hydrologic data development task involved generating hydrograph input data for the unsteady state 2D HEC-RAS hydraulic analysis. To improve confidence in the model results, the model will be calibrated to two observed events. The calibrated model will then be used for frequency event analyses.

Observed Events

The events for the observed events analyses were selected from the recent events so the current topographic and hydrographic data matches the topography of the events selected. In coordination with USACE Kansas City and Omaha districts, the project team evaluated events from 2011 to 2021 to select two observed events.

Hydrologic data required for the observed events analyses were obtained from the USGS. The USGS National Water Information System: Web Interface was used to collect the flow data and stage data. Instantaneous streamflow and stage data at the stream gages of interest along the main stem Missouri River and tributaries were processed using the R statistical software (R Core Team, 2022) to produce the data in DSS file format. Hydrograph input development for tributaries depended on whether the tributary is gaged.

Gaged Tributaries: For gaged tributaries hydrographs were produced from the gage data. Extent of the tributary timeseries were dependent on timing of flooding in the mainstem Missouri River.

Ungaged Tributaries: Inflow hydrographs for ungaged tributaries will be estimated using volume balance between points of interest within Missouri River reach. Inflow from ungaged contributing drainage areas will only be considered in cases where a significant inflow volume is not accounted from inflow from the gaged streams and main stem Missouri River. The missing volume will be distributed proportionately based on drainage area of ungaged tributaries. Though the inflow for observed events analyses is generally based on the observed hydrographs, where inflow from ungagged tributaries is necessary, ungaged tributary inflow will be developed based on methodology used for developing synthetic event hydrographs.

Frequency Events

Stantec will develop synthetic hydrographs for 6 frequency events, 10%, 4%, 2%, 1%, 0.2% and 1%+ annual chance event. The 1%+ annual chance event represents a degree of statistical uncertainty in the estimates approximately equivalent to 1 standard deviation upper confidence band of the 1% annual chance event. Hydrographs are developed using scaling approach. The factors evaluated in developing synthetic hydrographs are:

- Hydrograph peaks and volume
- Hydrograph duration
- Hydrograph timing

Hydrograph Development Methodology

Synthetic hydrographs development for frequency events used three sets of information:

- Peak flow frequency
- Volume-duration frequency
- Average Hydrograph Shape

For the main stem Missouri River, the peak flow frequency information will be obtained from USACE flow frequency analysis, peak flow frequency for the tributaries were calculated using the USACE Risk Management Center's RMC-BestFit software. Tributary peak flow frequency analyses were performed using the Log-Pearson Type III (LP3) distribution for consistency with

Bulletin 17C. A distribution fitting analysis was performed to verify the goodness-of-fit of the LP3 distribution. A Bayesian estimation analysis was carried out using the default options, with custom output frequency ordinates: 0.8, 0.5, 0.2, 0.1, 0.05, 0.04, 0.02, 0.01, 0.005, and 0.002 percent annual chance of exceedance (i.e., 1.25-, 2-, 5-, 10-, 20-, 25-, 50-, 100-, 200-, and 500-year return periods). The posterior mode curve was selected for use in the synthetic hydrograph development process. For the ungaged contributing drainage areas peaks will be estimated using regional regression equations.

Volume-duration frequency analyses for the main stem Missouri River streamflow gages and the corresponding tributaries were performed using the USACE Risk Management Center's RMC-BestFit software. Daily average streamflow data was used for the volume-duration frequency analysis. Volumes were represented as average streamflow for 1-, 3-, 7-, 14-, 30-, 60-, and 90-day windows.

Average hydrograph shapes were calculated for each streamflow gage (both main stem Missouri River and corresponding tributaries) using the following procedure:

1. For each water year, identify the annual maximum daily average flow,
2. Extract the 91-day hydrograph centered on the annual maxima (i.e., peak is at day 46),
3. Rank each water year by the magnitude of the annual maxima,
4. Isolate the 33% largest floods (i.e., "upper tercile" or "tercile 3") in the gage record,
5. Scale each 91-day hydrograph by the corresponding peak flow, and
6. Calculate the average across each ordinate to create the 91-day average hydrograph.

The duration of the average hydrographs was defined as 91 days for consistency between the tributary hydrographs and those for the main stem Missouri River. Additionally, the 91-day duration was selected to encompass the onset and retreat of flooding for gages with large contributing drainage areas that experience persistent flooding, most notably the main stem Missouri River gages. The method for scaling the average hydrographs allows for the specification of shorter or longer durations as needed.

Average hydrographs were defined using only the floods that exceed the 67th percentile (i.e., the 33% largest floods on record) to isolate only those floods that exceed the empirical 2-year return period. These floods have a clearly defined hydrograph shape and are more representative of the magnitude of flooding relevant to this project.

The approach used for synthetic hydrograph development is adopted from a tool developed by the Water Resources Engineering & Management Support Group of the U.S. Bureau of Reclamation Technical Service Center. This tool was developed in Python and translated to R for workflow consistency. Verification and validation of the translation was completed in partnership with Reclamation. The tool can scale the hydrograph by peak, by volume or by peak and volume simultaneously. To preserve the inherent relationship between peak and volume, for this project the tool scales hydrographs by peaks & volumes simultaneously.

Hydrograph Duration: Hydrograph duration for tributaries is estimated based on the drainage area and the latitude of the most downstream tributary gage location. Data analysis of the observed events and their duration demonstrated correlation between flood duration and the drainage area, and food duration and the relative location of the basin. Data demonstrated northern tributaries tend to have longer duration. Based on this analysis a relationship between the drainage area, latitude of the gage location and flood duration is developed. This project will use tributary event duration based on this relationship to develop synthetic hydrographs for the tributaries.

Hydrograph timing: Timing of the tributary inflow is an unknown in case of synthetic events. Therefore, hydrograph timing is not a variable used in the hydrograph development. However, travel time of the hydrograph is critical for hydraulic analysis. Hydrograph timing will be evaluated in the hydraulic modeling. USACE's existing 1D model results and the calibration event model results will be used as a guide to validate the tributary hydrograph routing of the synthetic events. Timing of hydrograph input at the tributaries will be determined based on the response hydrograph at the downstream Missouri River gage. Tributary inflow timing will be adjusted to produce a desired response hydrograph at the downstream Missouri River gages.

Coincident Frequency Considerations: A flood event in Missouri can be caused by multiple combinations of events of different sizes at upstream Missouri River and its tributaries. To account for this variability between event size in the main stem Missouri River and the tributaries, a methodology to estimate coincident frequency events at the tributaries based on the probability of coincident flows was developed. Stantec adopted an approach developed by National Cooperative Highway Research Program Project (NCHRP) 15-36. In the publication "Estimating Joint Probabilities of Design Coincident Flows at Stream Confluences, March 2013" NCHRP presents a set of relationships for joint probability at stream confluence and coincident frequencies at each confluent stream. Stantec analyzed coincident flows at each gaged Missouri River tributaries and used methodology from NCHRP 15-36 to develop a relationship at each gaged tributary confluence to estimate a coincident tributary flow for a given frequency flow at Missouri River. The analysis also estimated the upper and the lower bound of the coincident frequency flow represented by 95 percent confidence band of the joint probability based coincident frequency event at the tributary. Hydraulic analysis will use the tributary inflow hydrographs established by the coincident frequency analysis. The tributary inflow size and timing will be adjusted to produce the target main stem response hydrograph. The maximum and minimum tributary inflow will be guided by the frequencies bound by the 95% confidence band.

In some reaches where volume balance is not achieved from the main stem Missouri River and gaged tributaries, contribution form ungagged tributaries may need to be considered. The reaches where inflow from ungaged tributaries is necessary, hydrographs for these tributaries will be developed using approach described in previous sections.

Hydraulic Model

Hydraulic Analyses will be performed using 2D unsteady state analysis approach. USACE HEC-RAS version 6.3.1 is used for the modeling purpose. Project area is divided into six model domains. Domain breaks were selected focusing on minimizing number of models while keeping the domains small, so the model execution and updates are possible in a personal computer.

2D Mesh Development

High resolution mesh can slow the runtime so the base mesh size of 500ft **x** 500ft will be used. Mesh refinement regions will be used to better define topography of the domain by the mesh. Base mesh size in the refinement regions and breaklines will be 200 ft **x** 200 ft. Stream centerlines, levees, transportation lines, and population centers are some of the features used for breaklines and refinement regions. Mesh refinement will involve mesh alignment to represent streams, both Missouri River and tributaries and high points in the terrain. Mesh size used along the main stem will be between 100-200 ft so the number of 2D cells across the main channel is about 6-10 cells. Number of cells across tributaries will be dependent on tributary size.

All the bridges across the main Stem Missouri River main channel will be included in the model. The bridges in Missouri overbank areas will be included only if they are hydraulically significant. Bridges across the modeled tributaries will not be included in the model. Adding tributary bridges that are hydraulically significant from hydraulic routing consideration will be determined on a case-by-case basis.

Levees will be included in the model. The NLD will be used to identify the location and alignment of the levees. Levee crest elevations in the NLD will be used when available, otherwise, the crest elevation will be extracted from the LiDAR DEM. If a levee overtops, the levee is assumed to stay in place. All levees will be modeled as 2D connections to allow for levee breach analysis as a potential future enhancement.

Boundary Conditions

Inflow boundary conditions will be applied as shown in the Figure 2. An observed gage data or the synthetic hydrograph will be used as an upstream inflow boundary for each model domain depending on the analysis being performed. Hydraulic model output from upstream reach will not be used as a downstream model inflow.

Stantec ran several tests to determine model's sensitivity to downstream boundary conditions. Tests show that the downstream boundary affect model result stages up-to approximately 7 miles from the model boundary. Therefore, the model domains are extended approximately 10 miles downstream from the model's most downstream point of interest. This approach is suitable for developing Base Model Geometry so it can be used for scenarios when downstream boundary is known as well as when it is not known. Normal depth boundary will be used for all the models. Downstream boundary normal depth slope will be determined by the downstream model domain energy grade.

Domain boundary tie in is achieved if the model results at the domain's control location is within the tolerances set by the calibration targets. Control locations are the most upstream and downstream calibration location of the model domain.

Model Calibration

Calibration will be performed to obtain reasonable agreement with observed hydrographs and observed stage for observed events analyses. For frequency event analyses, calibration will be performed to achieve agreement with synthetic hydrographs developed at calibration locations (target hydrographs).

Observed event calibration: Goal of the calibration is to produce a Base Model Geometry for hydraulic analysis of scoped frequency events. Model calibration will involve adjustments to model geometric parameters to achieve reasonable basin response and realistic stage estimates for all the analyzed events.

Calibration will be performed on two observed events. A relatively small flood event and a large flood event from Spring – Fall of 2018 and 2019 were selected for calibration. Hydrologic calibration will involve volume balance prior to HEC RAS analysis. Inflow volume contribution from main steam and tributaries will be evaluated by hydrograph addition. Additional volume from ungagged tributaries, where necessary, will be developed using the volume balance approach outlined in previous sections.

Model calibration will involve model geometric parameters adjustment to simultaneously achieve target hydrograph and target stage.

Frequency Event calibration: The Base Model Geometry from observed event runs will be used for analyzing frequency events. Calibration of frequency events will involve minimal geometric adjustments, calibration process for frequency event runs will primarily involve adjustment to the tributary inflows.

Hydrologic calibration for frequency event will also involve volume balance prior to HEC RAS analysis. Inflow volume contribution from main steam and coincident flow from tributaries will be evaluated by hydrograph addition. Additional inflow from ungagged tributaries, where necessary, will be added using hydrographs developed using the approach outlined in previous sections.

Model calibration will involve matching modeled hydrograph response with synthetic hydrographs produced at the calibration locations at Missouri River.

Calibration Location: Calibration locations are selected based on calibration data availability and its reliability, data availability at the gage locations and additional data available from USACE/USGS. Models will be calibrated evaluating model response at the Missouri River gages where calibration data is available. In some instances due to data limitation and other factors, a calibration location might only be suitable for flow calibration but not for stage calibration and vice-versa. In such situation, modeling team will, provide engineering justification/recommendation and coordinate with FEMA region and USACE for appropriate path forward.

Calibration Target: The calibration target at a given location will be determined based on reliability of available calibration data. Model estimated water surface elevation and response hydrograph will be evaluated across HEC RAS 2D reference line representing Missouri River cross sections and compared with the observed rating curve or stage hydrograph and observed flow hydrographs at calibration location.

This study will focus on overall hydrograph shape of the model basin response, hydrograph peak, hydrograph volume. Nash-Sutcliffe efficiency coefficient will be evaluated to measure achieved calibration. Though, the calibration target at a given location can vary based on data reliability. Target is to achieve less than 1% error in volume balance, peak flow within 5% of target peak. Overall hydrograph calibration is considered achieved when Nash-Sutcliffe efficiency coefficient is 0.8

The model estimates within one standard deviation of gage estimate are a reasonable model prediction per the standardized FEMA's hydrology calibration approach. For this study, flow estimates are based on USACE's flow frequency analysis and volume estimates are based on volume- duration frequency estimates. Where necessary, due to unreliability of calibration data, project team will use one standard deviation of the peak estimates and one standard deviation of volume estimate as a calibration target.

Test runs revealed that the modeled water surface elevation can vary significantly across a cross section in a 2D model. Thus, model average stage across a HEC RAS 2D reference line can be significantly impacted by stage of the overbank flows. Therefore, while comparing model results with USGS data, aligning the approach of estimating flow and stage across a 2D reference line with an approach used in generating the target rating curve or stage hydrograph is vital in achieving a proper model calibration. It is likely targeted calibration may not be met for all flow ranges. Modeling team will evaluate the reason for discrepancy higher than the tolerance. Then document the calibration process and justify why calibration is not achieved within the tolerance.

When High Water Mark (HWM) data is available the model results will be compared with HWM. For FEMA RiskMAP projects stage/ elevations tie in tolerance is generally 0.5 feet. Model results are reasonable where the discrepancy between model results and HWM is +- 0.5 ft. This tolerance will be evaluated at the maximum water surface elevation.

For observed events simulations hydraulic/stage calibration will be based on the observed stage hydrograph. Models' hydrologic response will be compared to the observed hydrographs at the calibration locations. Calibration target may need to be adjusted due to uncertainty in calibration data available for levee breaches and other factors. Focus will be on matching the model rating curve with the target rating curve in such instances.

For frequency event analysis, a USGS rating curve at the calibration locations will be used as a calibration target. Models' hydrologic response will be compared to the synthetic hydrographs at the calibration locations.

Calibration Parameter: Model calibration will be mostly performed and completed in observed events analyses. Calibration will primarily involve adjustments to Manning's roughness coefficients. However, adjustments to 2D mesh alignment and mesh resolution, adjustments to break lines, including levee alignments and crests elevations, and bridge modeling approaches in 2D will be used to achieve calibration.

Levee breaches are common at high flows along Missouri River but, in many instances information on breach initiation time, breach progression and final size are not known. Breach initiation, breach size and breach progression will also be used as calibration parameters. Breach flow weir coefficient for levees and other embankment overtopping will also be adjusted to achieve model calibration.

Objective of this calibration is to produce a Base Model Geometry ready for hydraulic analysis of scoped frequency events and other future modeling needs. Any adjustment to the geometry to calibrate levee breaches and other geometry changes only applicable for a specific calibration event will be removed and reverted to original conditions to produce a Base Model Geometry.

Frequency event model calibration will not involve modifications to the Base Model Geometry other than minor adjustments to manning's n to address variability in manning's roughness based on flood depth.

Frequency events calibration parameters are primarily synthetic hydrograph inflow at the tributaries. Calibration process will involve inflow hydrograph size and timing adjustments to make the model response hydrograph reasonably match the target synthetic hydrograph and target rating curve at the calibration locations. Synthetic hydrographs produced at select locations at Missouri River will be used as a target for flow calibrations.

The Base Model Geometry will be used for analyzing frequency events. These events will assume all the levees and levee like features do not fail for all the events analyzed. If any embankments are overtopped, weir flow coefficient of discharges will also be adjusted.

Conclusion

This study will produce a calibrated HEC RAS 2D Base Model Geometry that can be easily enhanced for future modeling needs. The model will utilize the new flow frequency analysis by the USACE combined with the Base Model Geometry created for the Lower Missouri River reach from Yankton, SD to St. Louis, MO. The Base Model Geometry will be divided into six domains with model tie-ins at the most downstream and most upstream Missouri River gage within the model domain.

The model outputs will include water surface elevations, depth raster, velocity raster of the simulated observed event and the six flood frequency events FEMA uses in flood risk studies. This model can be modified for analyzing additional flood frequency events for Future of Flood Risk Data development and future what-if scenarios.