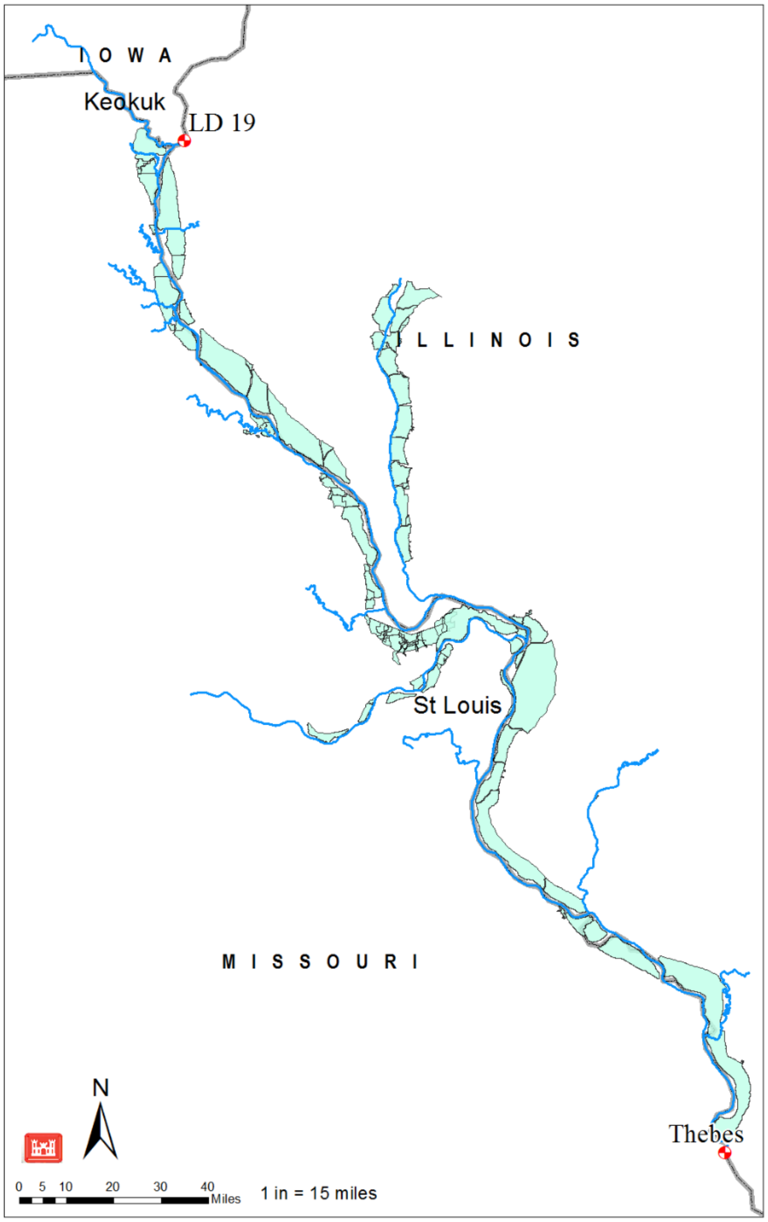
UPPER MISSISSIPPI RIVER
FLOOD RISK MANAGEMENT
EXISTING CONDITIONS HYDRAULIC MODEL
DOCUMENTATION REPORT



Final

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EXECUTIVE SUMMARY

The Upper Mississippi River System (UMRS) watershed has experienced more frequent flood events with increasing damages and threats to human life. The US Army Corps of Engineers (USACE) utilizes the risk framework to assess, communicate, and manage risk. In the last five years, the USACE Levee Safety Inspections, Levee Assessments and Levee Screenings have identified a number of flood risk factors and considerations that warrants the collective re-evaluation of Flood Risk Management (FRM) strategy. An updated hydraulic model was needed to serve as the tool for understanding how the river has changed over time (redistribution of flood risk) while using modeling software that is common to water resources professionals (HEC-RAS). USACE Levee Safety funding was provided to develop and calibrate a FRM hydraulic model for the UMRS main stem river segment from Keokuk, IA through Thebes, IL.

This initial model segment is the first of four potential UMRS model segments. The river segment from Keokuk to Thebes was prioritized for Levee Safety funding because the majority of the floodplain in this reach is excluded by levees. In addition there have been numerous changes and updated survey information which has resulted in numerous discussions about managing future flood risk.

National Levee Database (NLD) levee surveys were completed in 2007/2008 and 2016 for U.S. Army Corps of Engineers (USACE) Rock Island District and 2007/2011/2017 for USACE St. Louis District. The use of the NLD data in this model does not alter the congressionally authorized elevation for individual levee systems or constitute retroactive USACE Section 408 approval of the altered levee.

An updated existing conditions hydraulic model for the UMR is an essential tool to understanding the flood risks that currently exist to the river communities and is a critical first step for the development of systemic flood risk management (FRM) strategy. This new existing conditions model is a tool that can lead to better and more consistent flood risk management. The hydraulic model will improve flood preparation and response, real time river forecasting and real time inundation mapping. The need and applications for a UMR FRM hydraulic model is supported by neighboring states, local communities, and non-governmental organizations (NGOs).

The need for a common tool is supported by a diverse stakeholder group and will serve as a catalyst for development of a more collaborative and holistic FRM strategy for the region. USACE Levee Safety funding was provided to develop the model in collaboration with state/federal technical experts and with regular input from stakeholders. It is envisioned that many of the stakeholders will utilize this model for their own applications and analyses as they pertain to FRM. Potential uses and applications of the HEC-RAS model could include: flood risk management analyses (structural/non-structural), state flood plain management, levee sponsor Section 408 levee alteration studies, and flood response operations.

FEMA acknowledges that the UMR model cannot be used to produce an update or replacement of 2004 UMRSFFS study and FEMA's regulatory products in its current state. The UMR Hydraulic Model has the best available information and will be available for public use. As a result, additional coordination between the flood plain managers at the local, state and federal levels is recommended before using the UMR Hydraulic model for project permitting (i.e. no-rise) purposes.

The development of the UMR FRM hydraulic model was a collaborative effort by federal and state agencies, facilitated by USACE Rock Island and St. Louis Districts covering 320 river miles from Mississippi River Lock and Dam 19 at Keokuk, Iowa (River Mile 364) to Thebes, Illinois (River Mile 44)

using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software version 5.0.3. The UMR FRM hydraulic model leveraged the ongoing Corps Water Management System (CWMS) water control focused modelling effort by using the CWMS model as a base model. The UMR FRM hydraulic model differs from the CWMS model by consisting of more detailed features, additional cross sections, and representing the entire floodplain bluff to bluff.

HEC-RAS is widely used by hydraulic engineers with state and federal agencies and by architect/engineering consultants making it the preferred tool for flood risk management analysis, planning, and decision making. There was no previous model of the UMR that was developed with software that is widely used and accepted as HEC-RAS. The major updates to this model include higher resolution terrain data, inclusion of bridges, 2D flow areas, and updated levee survey data. The model underwent rigorous technical review to ensure accuracy and reliability.

The model geometry was developed using the best available LiDAR (Light Detection and Ranging) terrain data and bathymetry data. USACE LiDAR and bathymetry data were supplemented with state LiDAR data and the United States Geological Survey (USGS) Upper Midwest Environmental Sciences Center (UMESC) topobathy (topography + bathymetry) dataset for the UMR. The calibrated existing conditions model uses one set of parameters that are representative of four flood events (2008, 2013, 2014 and 2017). The existing levee elevations represent the sum of all activities (flood fighting, repairs, dredge material placement, approved and unapproved alterations) that have occurred over time. The goal of this model is to provide a common tool using the best available data and software that can reasonably recreate a range of events that have occurred or may occur in the future to assess flood risk management strategies.

The model contains a single geometry file representing the levees at the existing condition as determined by the most recent NLD survey. There are a handful of systems that were not included in the NLD survey because they were not federally constructed or not in the PL 84-99 Program. The Topobathy terrain dataset was used to determine the levee profile for these systems.

The UMR FRM hydraulic model will help provide consistent and reliable answers on potential impacts caused by changes in the river. It will replace multiple models currently in use, leading to better and more consistent flood risk management. The HEC-RAS model will run unsteady flow hydrographs and will provide a base condition to efficiently evaluate proposed changes and resulting changes in flood risk.

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Introduction

Objective

The objective of the Upper Mississippi River (UMR) Flood Risk Management (FRM) hydraulic model is to serve as a tool to assist the U.S. Army Corps of Engineers (USACE) and other federal and state agencies in UMR system flood risk management and Section 408 alteration requests. The hydraulic model was developed and calibrated with existing levee elevations based on the most recent National Levee Database (NLD) survey information. A limited number of levees were not in the PL84-99 system and therefore did not have NLD survey information. For these levees, the most up-to-date terrain data were used to determine existing levee elevations. Refer to Appendix A-1 for overview maps of the model extents.

Background

Floodplain management decisions for the UMR are in part based on information obtained from hydraulic model results. Most of the hydraulic models that have been previously developed for the mainstem Mississippi River are limited in geographic extent to the immediate study area. Although this approach has its benefits, it does not allow a regional approach for FRM decision making. This new UMR FRM hydraulic model is an improvement over previous pool based models because of the large geographic extent and continuity across multiple navigation dams.

Federal/State Agency Coordination

Multiple web meetings and conference calls were held between USACE and the stakeholders which included federal and state agencies. Federal and state technical team members included Iowa, Illinois, Missouri, Minnesota, and Wisconsin Department of Natural Resources (DNR); Federal Emergency Management Agency (FEMA); United States Geological Survey (USGS); and National Weather Service (NWS) North Central River Forecast Center (NCRFC).

Non-Governmental Organization (NGO) Coordination

Multiple web meetings and conference calls were held between the U.S. Army Corps of Engineers and the NGO stakeholders. NGO stakeholders included UMRBA; UMIMRA and consultant Klingner and Associates; Neighbors of the Mississippi River and consultant Crawford, Murphy, Tilly; American Rivers; and National Wildlife Foundation.

User Guide

Model Availability and Use

This model is available by request to federal, state, local agencies, and nongovernmental organizations (NGOs) along with their engineering consultants. Model users should consult with the appropriate state/local/federal floodplain managers before using this model for regulatory purposes. This is a complex hydraulic model. As a result, experienced and qualified hydraulic engineers with advanced HEC-RAS training should use this model ensuring appropriate model inputs and accurate model results. This report and appendices are not intended to be a substitute for the HEC-RAS User's Manual, HEC-RAS Applications Guide, or formal HEC-RAS training and experience.

Ecological analyses regarding water velocities, water depths, where water goes in the floodplain and how long it stays in the floodplain may be possible with this UMR FRM hydraulic model. A trained and experienced HEC-RAS hydraulic modeler should be consulted to determine whether the model is appropriate for the intended ecological analyses.

As stated above, this model has been developed as a flood risk management tool and is not currently designed or calibrated for sediment transport, water quality, steady state flow modeling, or river training structure analysis. It also was not specifically developed to recreate the 2004 Upper Mississippi River Flow Frequency Study (UMRFFS) or update floodway limits. This model is a good starting point and will provide the base condition for the aforementioned modeling efforts, but it would require appropriate changes and updates by an experienced HEC-RAS hydraulic modeler. This model cannot directly replace the previous flow frequency study as there are significant differences between the modeling software used for the two studies. Please refer to the "Previous Studies/Models" section of this report for more information.

It is anticipated that the requesting organizations may use this model for a variety of applications and changes to the model may be desired. The hydraulic model was developed and calibrated as a regional model therefore USACE recommends maintaining the model in its entirety. However, one common practice may be to reduce this regional model to a reach of the river that encompasses the specific area of interest. When the model is parsed in this way, an experienced HEC-RAS modeler will need to define the appropriate upstream and downstream boundary locations and conditions.

Another application may be to explore alternative actions and "what if" scenarios by modifying the existing conditions model and compare them to the "no action" alternative. These scenarios often involve modifying structures in the channel or floodplain (islands, closing dikes, levees, etc.). For these model runs, an HEC-RAS hydraulic modeler will need to make a copy of the model geometry and then incorporate the changes into the model geometry to create the alternative scenario. It is not technically correct to remove any regulatory structures from the model and analyze that altered model as the "without project" condition.

Model Updates

Periodic updates to the Upper Mississippi River (UMR) FRM hydraulic model may require a separate source of funding depending on the magnitude and scope of the model changes. USACE will periodically evaluate the model to determine when it needs updating. The potential need to update the model may require significant changes in system hydrology or topography. Users of the model who believe it requires an update as a result of improved data or new construction should contact the USACE Rock Island District Corporate Communications Office at 309-794-4200.

Previous Studies/Models

There have been numerous hydraulic models developed for portions of the UMR mainstem, but as stated above, most of these models were developed for a specific geographical reach of the river and for a specific study. Many of these models were for internal USACE projects, such as dam break analysis, and have not been made available to stakeholders. These models were not used to create the UMR FRM hydraulic model, as many of them were created using different software versions and older terrain data.

Major tributaries to the Mississippi River were included in the UMR FRM model. The minimum geographic extents of the tributaries included in this model are from each tributary's confluence with the Mississippi River upstream to its first flow gage. Some of these tributaries had models that were previously developed and for this effort were combined with the newly developed Mississippi River mainstem model. For the other tributaries that had no previous models, new approximate models were created. The approximate models used the most up-to-date terrain data for the cross sections, but used approximate channel data due to the lack of available hydrographic data.

In 2004, USACE completed the UMRSFFS which updated the discharge frequency relationships and water surface profiles for the Mississippi River System upstream of Cairo, Illinois. The model used for the UMRSFFS was developed using the UNET software in the late 1990's. UNET does not have a user-friendly graphical user interface and therefore was not able to be used by a wide range of people. The UNET model incorporated elevation data from a photogrammetry-based Digital Terrain Model (DTM) and best available digital bathymetric data both of which are substantially coarser and less complete than the currently available LiDAR-based DEM and bathymetric datasets.

Also, the interaction between the river and levee areas was limited to user defined upstream and downstream overtopping/breach locations points using simplified linear routing. The UNET model was suitable, and the state of the art tool at the time, for determining the flow frequency profiles but due to some of the limitations of the software, the UNET model used for the UMRSFFS was less capable for detailed floodplain analysis when compared to the current capabilities of HEC-RAS. The scope of work for this UMR FRM hydraulic model does not include an update or comparison to the 2004 UMRSFFS. The UMRSFFS was a multi-year study to update the hydrology of the river system, while the UMR FRM hydraulic model is a tool intended for floodplain/flood risk management.

Geographic Coverage

The UMR FRM hydraulic model extends from the tailwater of Lock and Dam 19 at Keokuk, Iowa (River Mile 364) to Thebes, Illinois (River Mile 44). This covers 320 river miles, includes 7 navigation dams, and encompasses parts of two USACE districts (Rock Island and St. Louis). The two districts worked in conjunction to ensure the development of a continuous model that can be used for a number of applications in this geographic region. The major tributaries (gaged streams) to the Mississippi River are modeled as separate reaches from the tributary's confluence with the Mississippi River upstream to the first USGS flow gage. Minor tributaries are input as lateral inflows. The model extends bluff to bluff to include all leveed areas and storage areas in the model geometry.

Flood History

The Mississippi River has experienced numerous major flooding events throughout the last century. Some of the most significant floods in the modeled reach (Keokuk, IA to Thebes, IL) in the recent past occurred in 1993, 2008, 2013, 2014, 2017. The magnitude and frequency of these spring snow melt and summer rainfall induced flood events indicate that flood risk is a major concern for numerous cities, towns, and agricultural areas within the Mississippi River floodplain.

HEC-RAS Model Development

HEC-RAS Version 5.0.3 2D Modeling Computer Program

HEC-RAS is a hydraulic modeling program developed by the USACE Hydrologic Engineering Center (HEC) (Reference 1). The UMR FRM hydraulic model combines 1D and 2D elements into a single unsteady flow model. The 1D elements of the model include the river channels, overbank areas between the levees, levees which are represented by lateral structures and non-leveed storage areas. The leveed areas are modeled as 2D flow areas which is beneficial in the analysis of any levee overtopping or breach events.

Methodology

Model development consisted of building the model geometry, inputting the inflow data, and defining the boundary conditions resulting in model simulations that reflects the current conditions of the river and provides the most representative water surface information with minimal error. The geometry was developed by using both HEC-RAS and HEC-GeoRAS. HEC-GeoRAS is a group of ArcGIS tools that process geospatial data to be used with HEC-RAS (Reference 2). Many features in the model geometry were first processed in HEC-GeoRAS and subsequently imported into HEC-RAS. The geometry was then further developed in HEC-RAS. The features that were developed in HEC-GeoRAS include river centerline, cross sections, inline structures, bridges, lateral structures, flow paths, storage areas, storage area connections and ineffective flow areas. 2D flow areas and breaklines within 2D areas were developed with the HEC-RAS Geometry Editor.

The modeled reach of the UMR extends into the Rock Island and St. Louis Districts of USACE. Each district developed the model for the reach of the Mississippi River that was geographically covered by their district. Rock Island District developed the model from Keokuk, IA to Lock and Dam 22 and St. Louis District developed the model from the tailwater of Lock and Dam 22 to Thebes, IL. After each district performed the preliminary calibration, the two models were combined into one continuous model. Once it was combined, the final calibration and analyses were performed.

The naming conventions for different model geometry features were kept consistent for each type of feature. For example, all river reaches were named with the same convention. Table 1 lists the different types of features and naming convention used for each.

Table 1 HEC-RAS Model geometry naming conventions

Feature Type	Naming Convention
River Names	River Name w/o “River” (e.g. Mississippi)
Reach Names	Tributary Name “_” Tributary Name (e.g., Salt_Cuivre)
Junction Names	Tributary Name/Initials “_” Mainstem Name/Initials (e.g., BM_MS, North_Miss)
Storage Areas/2D Flow Area Names	Common Levee Name or Combination of River Name, River Station and Side of River (e.g., SouthRiver, MI120R2)
SA/2D Area Connection Names	Upstream Storage Area Name “_” Downstream Storage Area Name (e.g., Big5_MI45L1)

Datum Information

The horizontal projection for the UMR FRM hydraulic model is Albers Equal Area Conic. The geographic coordinate system is North American Datum (NAD) 1983 and the linear unit is U.S. feet. The vertical datum for the model is the North American Vertical Datum (NAVD) of 1988. The linear unit is U.S. feet.

All model inputs that were originally referenced to Mean Sea Level (MSL) 1912 or National Geodetic Vertical Datum (NGVD) of 1929 were converted to NAVD 88. Appendix B lists conversions by river mile through the model reach. USACE Rock Island and St. Louis Districts developed the vertical datum conversion factors differently for their respective reaches of the UMR FRM hydraulic model. The two districts' processes are described below.

For USACE Rock Island District, the conversion factors from NGVD 29 to NAVD 88 were determined from the computer software program Corpscon or were developed from surveys at specific gage locations. Corpscon was developed by the former U.S. Army Topographic Engineering Center which is now the Army Geospatial Center. The vertical accuracy of the Corpscon conversions between NGVD 29 and NAVD 88 is 2 cm (one sigma) (Reference 3). For model inputs that were originally referenced to MSL 12, historic conversions were used to convert the values to NGVD 29 from which the Corpscon conversions were used to further convert to NAVD 88.

For USACE St. Louis District, surveying contractors performed Vertical Control Surveys for the St. Louis District's River Gages in compliance with the ER 1110-2-8160, Policies for Referencing Project Elevation Grades to Nationwide Vertical Datums (Reference 4) and the accompanying EM 1110-2-6056, Standards and Procedures for Referencing Project Evaluation Grades to Nationwide Vertical Datums (Reference 5). The goal was the Height Modernization of the District's gages, Bench Marks (BM) & Reference Marks (RM) with all reasonable efforts being made to provide a direct correlation between current North American Vertical Datum of 1988 (NAVD 88) elevations to the historic Mean Sea Level (MSL) gage elevations derived from National Geodetic Vertical Datum of 1929 (NGVD 29).

The surveys were performed utilizing industry standard methodology to achieve a local relative accuracy of 2 cm and an absolute accuracy of 0.25 ft relative to the National Spatial Reference System (NSRS). Surveyors were required to establish/recover both horizontal and vertical positions, for a minimum of three (3) monuments at each gage location. Collections of NOAA's National Geodetic Survey (NGS) Online Positioning User Service – Database (OPUS-DB) points for inclusion into the NSRS were conducted for one 4.5 hour static session with a fixed height rod. All differential leveling was required to conform to USACE 3rd Order survey standards outlined in the EM. This implies double-run level loop closure tolerances of NTE $0.05 \cdot \sqrt{M}$ ft, where M is in miles. For level lines greater than one (1) mile, more precise procedures were to be considered, such as three-wire leveling or digital leveling. Surveyors were also required to locate and use any existing NGS or USGS monuments within a 1/2 mile radius of each gage, if not initially provided, to establish a direct correlation between published NGVD29 and NAVD88 Vertical datum.

Throughout the geographic range of the model, the conversions from NGVD 29 to NAVD 88 ranged from -0.674 to -0.002 feet. Conversions from MSL 12 to NAVD 88 ranged from -0.682 to -0.561 feet throughout the model. Because the datum conversions vary by USACE District the error potentials will also vary accordingly.

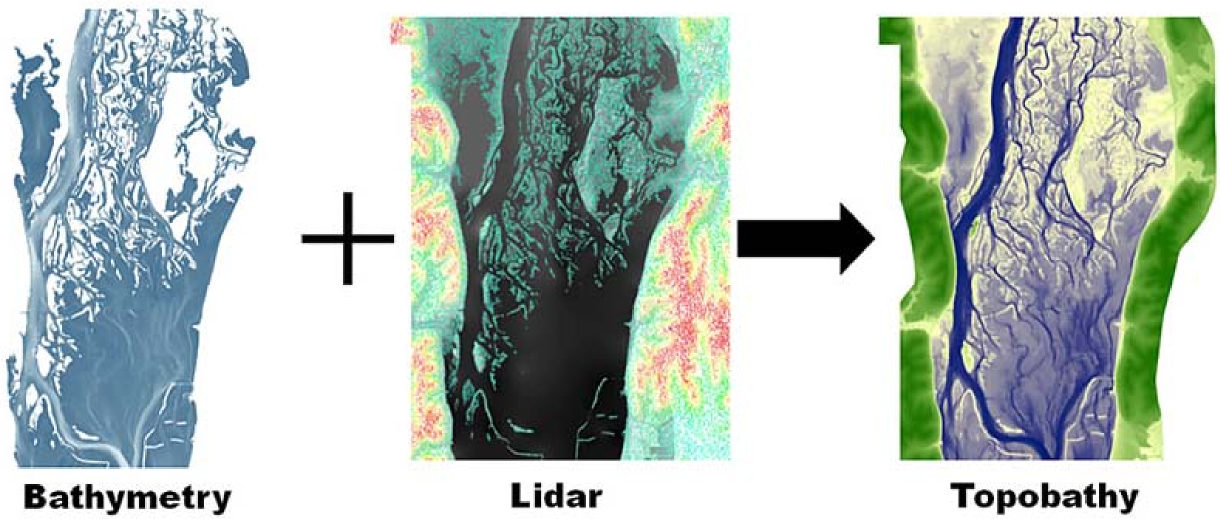
Model Geometry

<u>Cross sections</u>

The HEC-RAS model cross section locations are generally consistent with the locations used in the 2004 Upper Mississippi River Flow Frequency Study (UMRFFS) and are spaced every quarter mile to half mile. The cross sections extend from bluff to bluff across the river valley or to the limits defined by storage/2D areas. Cross sections were added to or revised in the model upstream and downstream of any inline structures or bridges and whenever additional cross sections were deemed necessary during the calibration process.

<u>Terrain and Bathymetry Data</u>

The geometry cross sections were updated with the best available LiDAR (Light Detection and Ranging) terrain data and bathymetry data. USACE LiDAR and bathymetry data were supplemented with state LiDAR data and the United States Geological Survey (USGS) Upper Midwest Environmental Sciences Center (UMESC) topobathy (topography + bathymetry) dataset for the UMR (Figure 1). The topobathy dataset was developed with a vertical datum of NAVD 88 and a horizontal datum of NAD 83 Universal Transverse Mercator (UTM) Zone 15. The dataset went through a horizontal transformation to convert it to Albers Equal Area Conic before being used in model development.



<u>Figure 1 Topobathy dataset development (Reference 6)</u>

This topobathy dataset combines LiDAR elevation data and bathymetry data into one dataset to create a seamless elevation surface (Reference 6). The LiDAR elevation data that were inputs to the topobathy dataset were collected by the USACE Upper Mississippi River Restoration (UMRR) Long Term Resource Monitoring (LTRM) from 2008-2011. These data were collected bluff to bluff with a 1 meter horizontal resolution.

The bathymetry data that were inputs to the topobathy dataset were collected either directly by USACE personnel or through USACE UMRR funding from 1999-2008, 2010, and 2015. These data were collected with single beam and multibeam echosounders and were interpolated to produce a DEM at a 2 meter horizontal resolution. The LiDAR data was resampled at a 2 meter resolution and combined with the bathymetry surface to create the final 2 meter resolution topobathy dataset. Table 2 lists the data sources and collection dates for the topobathy datasets.

Table 2 Data Sources and Collection Dates for Topobathy Dataset

Location	LiDAR Source	LiDAR Collection Dates	Bathymetry Source	Bathymetry Collection Dates
Pool 20	USACE UMRR	2/14/2008 - 2/15/2008	USACE UMRR	1999-2008, 2010
Pool 21	USACE UMRR	2/14/2008 - 2/15/2008	USACE UMRR	1998-1999
Pool 22	USACE UMRR	2/10/08, 2/13/08 to 2/15/08	USACE UMRR	1999-2007, 2009-2010
Pool 24	USACE UMRR	2/10/08 and 2/13/08	USACE UMRR	2006-2008, 2010
Pool 25	USACE UMRR	3/23/11, 12/08/11, 12/11/11	USACE UMRR	2006-2007, 2010
Pool 26	USACE UMRR	11/13/08 - 11/18/08, 12/08/11, 12/11/11, 3/16/11, 3/17/11, 3/25/11	USACE UMRR	2015 (main channel), older contours and breaklines were used but no dates provided
Open River North	USACE UMRR	12/17/09, 2/14/11, 2/15/11, 3/16/11, 12/7/11, 12/8/11, 12/12/11, 12/28/11	USACE UMRR	2001, 2002, 2007, 2008, 2010
Open River South	USACE UMRR	12/16/09, 12/17/09, 12/28/11	USACE UMRR	2001, 2002, 2008, 2010
ILWW Alton Reach	USACE UMRR	3/16/11, 3/17/11, 12/10/11, 12/11/11	USACE UMRR	2007

Supplementary LiDAR data were needed to produce tributary HEC-RAS models as the UMRR LTRM LiDAR did not extend up the tributaries past the Mississippi River bluff. The supplementary LiDAR data were downloaded from state agencies and were 1 meter in horizontal resolution.

Bank Stations

Bank stations are defined to identify the three conveyance zones within the channel cross section. The definition and location of cross section bank stations is typically dependent upon modeler experience and preference. For the UMR FRM model, bank stations were initially set either based on inspection of geometry and terrain breaks, or the extents of the estimated 2-year discharge level. The bank stations were confirmed, or in some cases revised, when Manning's roughness values were added with the inspection of land use areas. Further modification of bank stations occurred during model calibration and the technical review of the HEC-RAS model.

Manning Roughness Coefficients

Manning roughness coefficients are included in the model geometry differently for the 1D and 2D elements of the model. For the 1D elements of the model, the Manning roughness coefficients vary horizontally to include different n-values for the channel and the overbank areas (Figure 2). Given the uncertainty in determining these values, they are used as calibration parameters during the calibration process. For the 2D elements of the model, the Manning roughness coefficients were determined directly from the National Land Cover Database (NLCD) 2011 Land Cover file (2011 Edition, amended 2014) (Reference 7). Table 3 correlates the land cover ID and description with the Manning roughness coefficient used in the UMR FRM hydraulic model. Two guidance documents (*Technical Manual for Levees, MMC* (Reference 8) and *HEC-RAS 2D Modeling User's Manual* (Reference 9)) were used to estimate the initial Manning roughness values. These values were further refined during the model development and calibration.

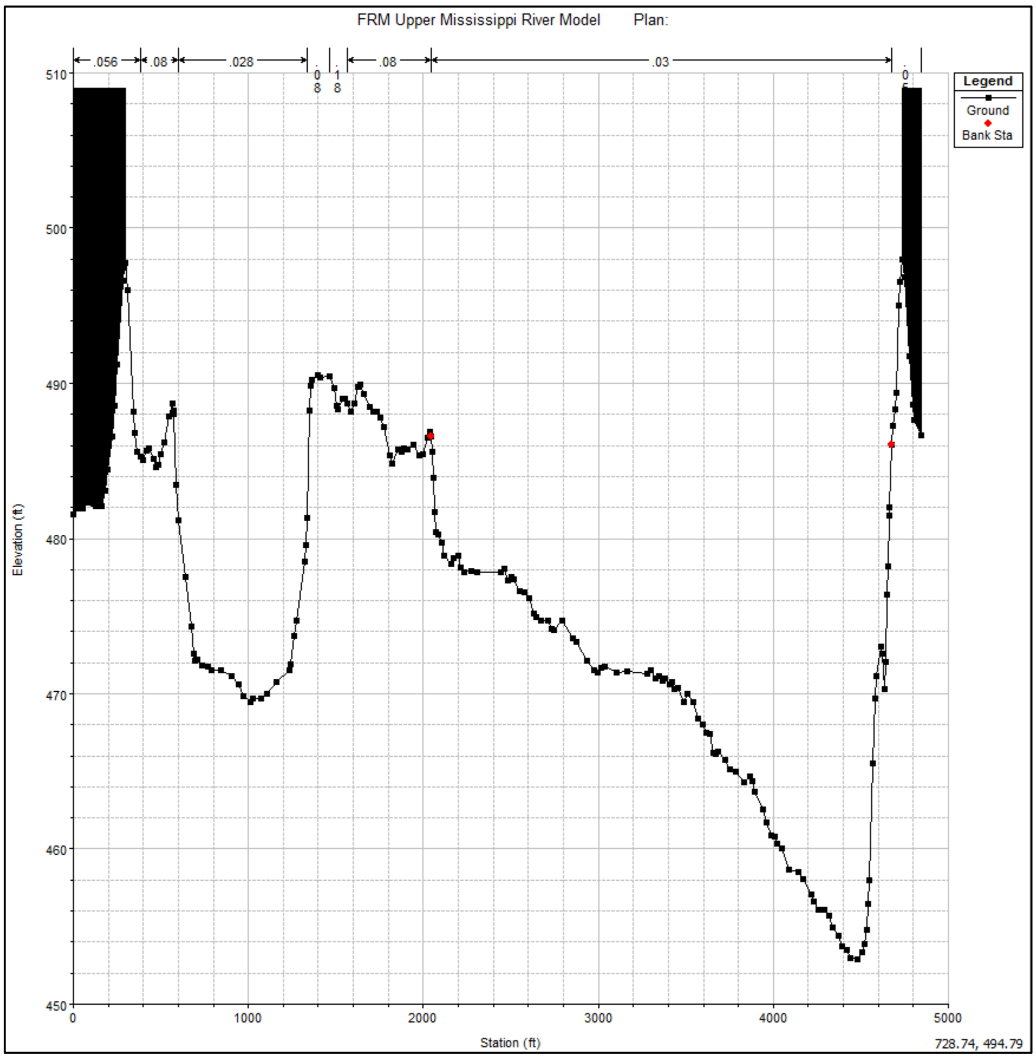


Figure 2 Example Cross Section from HEC-RAS
with Manning Roughness Coefficients displayed along top of cross section

Table 3 Manning's Roughness Coefficients used in the UMR FRM Hydraulic Model based on National Land Cover Database

Land Cover ID	Land Cover Description	Manning's "n"
NA	Main Channel	0.03
11	Open Water/Side Channels	0.028-0.035
21-24	Developed	0.035-0.09
31	Barren Land	0.03
41-43	Forests	0.13-0.19
52	Shrub/Scrub	0.1
71, 81, 82	Agricultural	0.055-0.07
90	Woody Wetlands	0.08-0.13
95	Emergent Herbaceous Wetlands	0.07

Ineffective Flow Areas

In HEC-RAS, ineffective flow areas are defined as areas of a cross section that will contain water that is not actively being conveyed. The boundary of these areas are defined by the cross section stationing and the maximum elevation of the ineffective portion of the flow area. The use of ineffective flow areas is highly dependent on the experience of the modeler, their interpretation of the geometry and the corresponding stream conveyance. This means that there is not a single, established standard for their use in a given cross section. Therefore, the collaborative efforts of several modelers on the UMR FRM hydraulic model team determined the placement of ineffective flow areas in this HEC-RAS model. The model technical reviews also resulted in several revisions to the ineffective flow areas, based on the highly experienced technical reviewers that were involved in the process.

Inline Structures

Inline structures, which included navigation dams, bridges, and training structures, are included in the UMR FRM hydraulic model and are discussed in detail in the subsequent sections.

Bridges

All bridges on the mainstem Mississippi River were included in the HEC-RAS model. Bridge geometries were determined from the best available as-builts or design drawings. These geometries were supplemented with Mobile LiDAR laser scanner data that was acquired by Seaside Engineering and Surveying, LLC (SEAS) in 2013 for all bridges from RM 364 to 300. The critical bridge information needed for HEC-RAS includes high and low chord elevations of the bridge deck, pier width, and pier spacing. When bridges were comprised of one or more vertical curves, the geometry data for the bridge decks were approximated as multiple straight line segments for input into HEC-RAS. The available bridge plans and as-builts differed in their clarity and completeness. For some bridges, the required geometry information was explicitly stated in the plans. For others, certain geometric values had to be measured from the plans using the provided scale. Table 4 lists the bridges included in the geometry for the UMR FRM hydraulic model. The low chord elevation listed in Table 4 represents the low chord over the main channel used in the HEC-RAS model.

Table 4 Bridges included in UMR FRM hydraulic model geometry

River Mile	Bridge Name(s)	Type	Low Chord Elevation (ft, NAVD88)
364	Keokuk Railroad Bridge	Railroad	505.74
363.9	Keokuk Highway Bridge/ U.S. Highway 136	Vehicle	506.83
328	Quincy Railroad Bridge (Burlington Northern)	Railroad	488.33
327.2	Quincy Bayview Bridge (U.S. Highway 24 westbound)	Vehicle	494.97
327	Quincy Memorial Highway Bridge (U.S. Highway 24 eastbound)	Vehicle	482.24
309.9	Hannibal Railroad Drawbridge	Railroad	479.82
309.5	Hannibal (Mark Twain) Highway Bridge (Interstate 72 / U.S. Highway 36)	Vehicle	511.5
283.2	Louisiana (Champ Clark) Highway Bridge (U.S. Highway 54)	Vehicle	477.96
282.1	Louisiana Railroad Bridge	Railroad	480
202.3	New Clark Hwy Bridge (U.S. Highway 67)	Vehicle	436.3
190.8	I-270 Dual Hwy Bridge (New Chain of Rocks Bridge)	Vehicle	449.3
190.5	Chain of Rocks Canal Bridge	Pedestrian / Bicycle	448
183.3	Merchants RR Bridge	Railroad	450
182.5	McKinley Hwy and RR Bridge	Vehicle / Bicycle	456
181.2	I-70 Hwy Bridge (Stan Musial Veterans Memorial Bridge)	Vehicle	464
180.2	Martin Luther King Bridge	Vehicle	478.3
180.0	Eads Hwy and RR Bridge	Vehicle / Pedestrian/ Metrolink	478
179.1	Poplar Street Bridge (I-55 / I-64 / U.S. Highway 40)	Vehicle	477
178.9	Douglas MacArthur RR Bridge	Railroad	460
168.8	Jefferson Barracks Hwy Bridge (I-255 / U.S. Highway 50)	Vehicle	417
109.9	Chester Hwy Bridge	Vehicle	400
51.6	Cape Girardeau Hwy Bridge (Bill Emerson Memorial Bridge)	Vehicle	370
43.7	Thebes RR Bridge	Railroad	400

Navigation Dams/Inline Structures

The navigation dams on the Mississippi River were included in the model geometry. The navigation dams are internal boundary conditions within the UMR model. The geometric properties of each dam was derived from pertinent data in the USACE water control manuals and supplemented by USACE design drawings. The operational controls used as boundary conditions in the UMR model were developed form the operational guidance provided in the USACE water control manuals. For the flood events simulated in the UMR model, the navigation dam gates are typically at open river conditions, with the gates raised to their full open position The gates of the navigation dams are controlled by the HEC-RAS Navigation Dams option which automatically raises and lowers the dam gates to maintain the regulatory pool elevations during model simulation. This allows the model to run a wide range of flow values without the user having to adjust any of the navigation dam parameters. Table 5 lists the lock and dams/inline structures included in the model geometry with the associated river mile.

Table 5 Lock and Dams included in UMR FRM hydraulic model geometry

River Mile	Lock and Dam / Inline Structure Name
343.2	Lock and Dam 20
324.9	Lock and Dam 21
301.2	Lock and Dam 22
273.4	Lock and Dam 24
241.5	Lock and Dam 25
200.6	Mel Price Locks and Dam
190.31	Chain of Rocks/Dam 27

River Training Structures

UMR river training structures, including wing dams, were initially constructed in the late 1800's and early 1900's. They were constructed as part of the effort to transition from the 4 foot navigational channel authorization to the 6 foot navigational channel authorization. With a few exceptions, wing dams ceased to be constructed on the pooled portions of the UMR as the lock and dams were constructed in the 1930's per the 9 foot channel authorization.

A training structure analysis was conducted to assess the long term effect of wing dams on channel geometry. This analysis examined three different representative transects, each located directly over a wing dam in each pool for Pools 20-22. Pools 20-22 were used in this analysis as these pools had Seaside Engineering and Surveying, LLC (SEAS) multibeam echo sounder data that was acquired directly over the top of the wing dams. SEAS did not acquire any data downstream of River Mile 300, therefore no analysis was performed for the other pools in the UMR hydraulic model. The criteria considered in determining the transect locations was that the wing dams in that location were not substantially scoured. Most of the wing dams in these three pools were constructed more than 80 years ago and are degraded below their design elevation due to erosion or ice damage. A small percentage of them have been repaired as funding was made available to reduce localized dredging issues.

Topobathy data, multibeam echo sounder data, and wing dam design information at the three representative transects were plotted along with the nearest UMR HEC-RAS model cross section. The transect / cross section data and plan view locations are shown in Figures 3 – 8.

The topobathy dataset was used in producing the HEC-RAS model cross sections. It was developed mainly from single beam echosounder data in which it was difficult to acquire information over the top of the wing dam due to boat draft and coarse resolution of single beam data associated with channel surveys. Therefore the topobathy dataset doesn't necessarily capture the crest of the wing dams but it does do a reasonable job capturing the general elevation of the bed near wing dams.

The multibeam echo sounder data was acquired in 2014 through a USACE contract with SEAS for RM 364 through RM 300. This data is not part of the topobathy dataset since the topobathy dataset is based on bathymetric data acquired prior to 2014.

The wing dam design information was obtained from an in-house (USACE Rock Island District) wing dam database.

A comparison of the available data, shown in Figures 3 – 8, indicates the following:

1) The wing dams have generally degraded as seen by comparing the multibeam echo sounder data to the wing dam design information;
2) While there are differences, the topobathy dataset is similar to the more detailed multibeam echo sounder data;
3) The HEC-RAS cross sections, which are not located at wing dams, are not significantly different from the topobathy data or the multibeam echo sounder data at the wing dams.

HEC-RAS model cross sections are located every quarter mile to half mile. Between two cross sections, there may be a single wing dam, an entire wing dam field, or no wing dams. Multiple HEC-RAS cross sections would need to be developed at each structure location to model a wing dam in detail. Modeling wing dams with this level of detail is beyond the scope of this project as this model was developed for high flow scenarios to compare the effects of FRM alternatives. In these extreme flows, the wing dams will be highly submerged and have little effect on the hydraulics of the river. The model was not intended to reproduce small-scale, near-field effects the wing dams may have on local water surface profiles. Modifications to this model for evaluating low flows in which the river training structures could influence the water surface profiles will be dependent on the intended purpose and scope of the low flow simulations. For the pooled portions of the UMR model (LD19 to Mel Price Dam), the river has adapted to the presence of the wing dams and this is reflected in the channel geometry. Therefore, the wing dams were not explicitly included in the model geometry for this reach.

For the open river portion of the model (downstream of Mel Price Locks and Dam) the river training structures were modeled as permanent ineffective flow areas in each cross section where flow is affected by the existence of dikes, chevrons, and other structure geometries. The effective width of the training structures was computed utilizing the structures present within the control volume of each cross section. Assumed expansion and contraction ratios of 1:4 and 1:1, respectively, were applied using GIS software to generate the ineffective area within the control volume. This area was then divided by the length of the control volume to determine the effective width of the structures within that control volume. A similar approach was utilized to compute effective elevation, using dike elevation without vertical expansion or contraction ratios. These computed values were then spatially tied to the cross sections to determine starting and ending stations for the permanent ineffective areas within the HEC-RAS model.

Figure 3 Wing Dam comparison plot at RM 354.1. HEC-RAS cross section and topobathy do not perfectly match as they were taken from slightly different cross section locations.

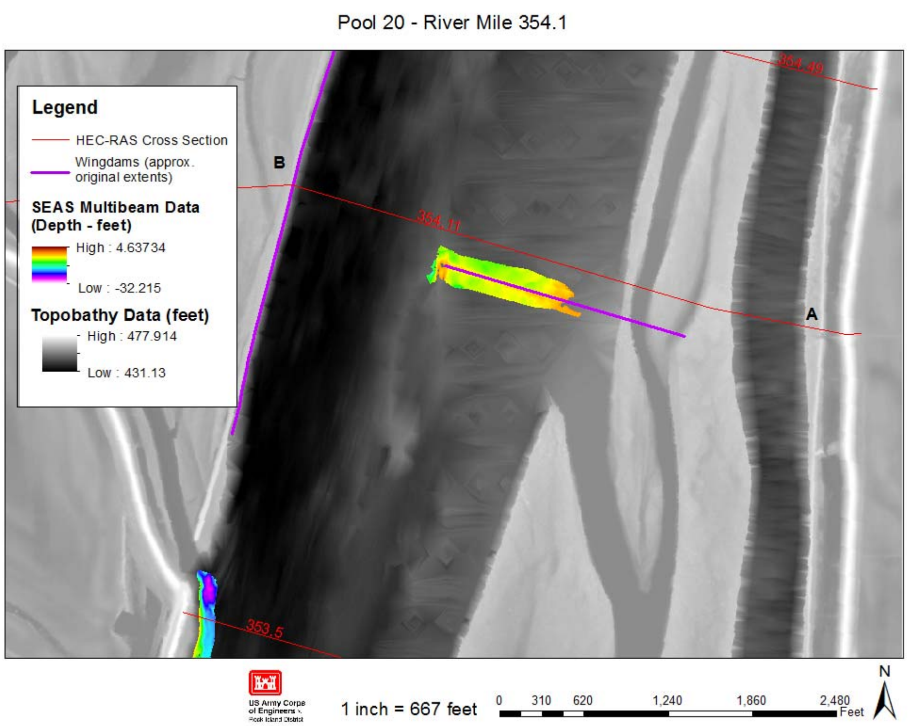


Figure 4 Plan view of Wing Dam at RM 354.1

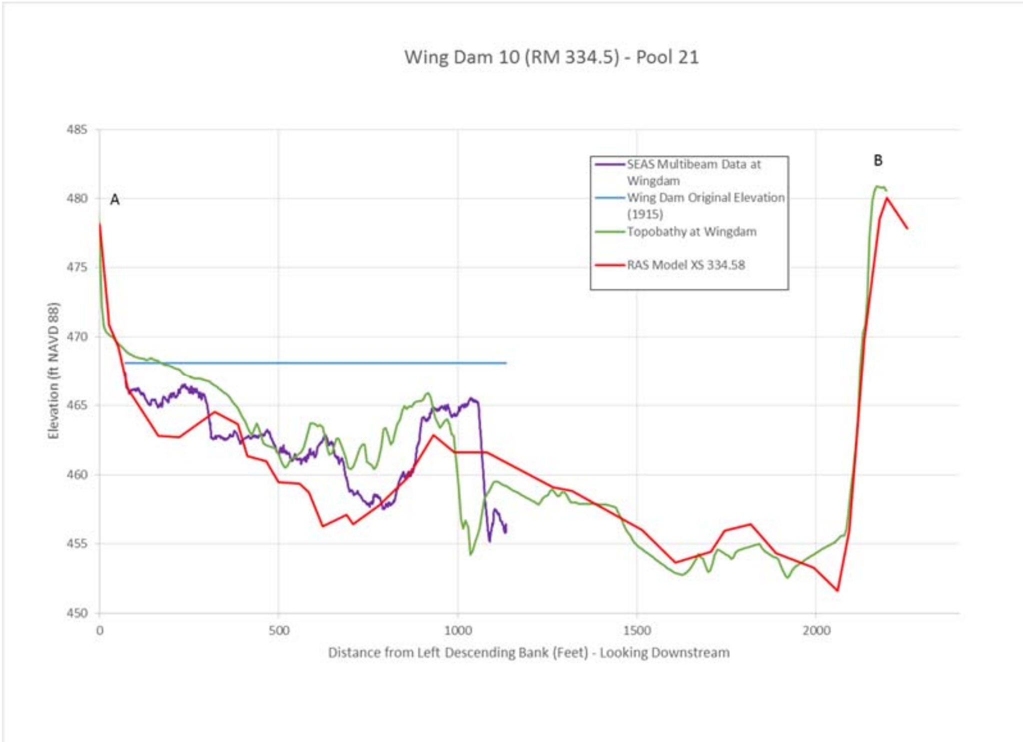


Figure 5 Wing Dam comparison plot at RM 334.5

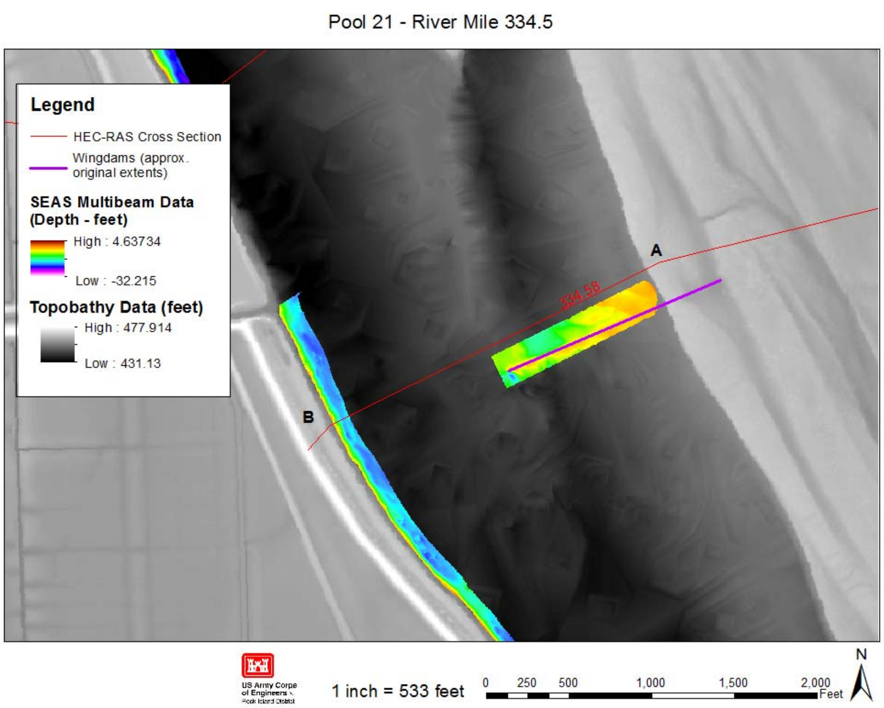


Figure 6 Plan view of Wing Dam at RM 334.5

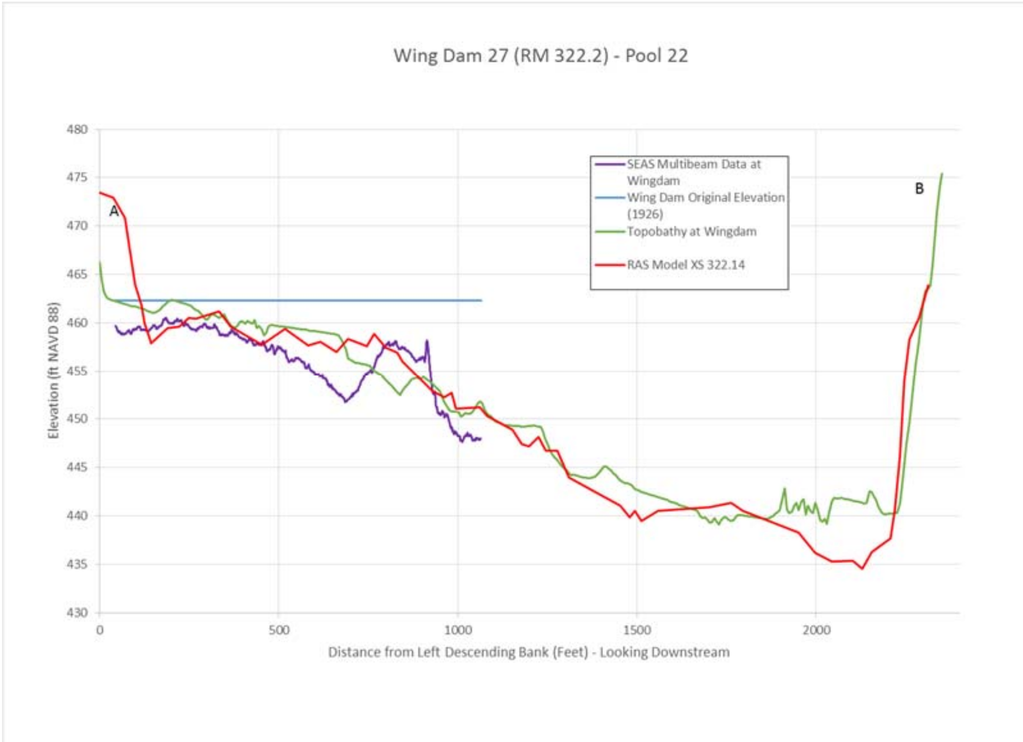


Figure 7 Wing Dam comparison plot at RM 322.2

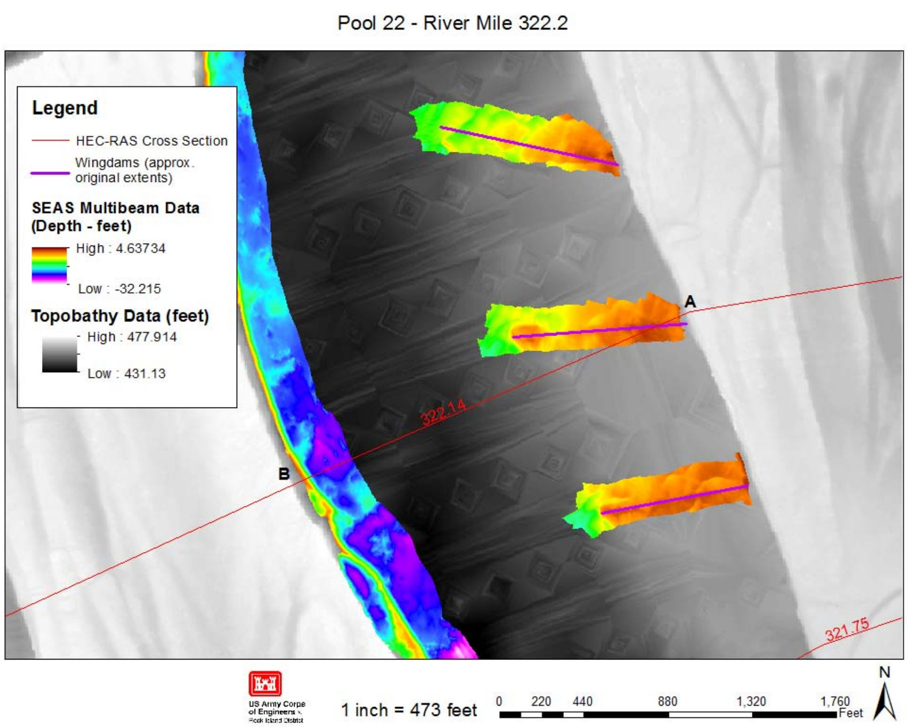


Figure 8 Plan view of Wing Dam at RM 322.2

Storage Areas/2D Flow Areas

HEC-RAS 2D modeling was used for areas behind levees. The 2D flow areas are each comprised of a mesh in which computations occur at each cell and cell face during the model run. This representation allows the model to more accurately represent the dynamic conveyance and spatially varied water surface in the leveed area as compared to the 1D model which defines each storage area purely by an elevation-storage relationship and allows only a single water surface elevation throughout. 1D storage areas were used in the model to represent minor tributaries and overbank areas that are directly connected to the mainstem river and not behind levees. The 2D meshes include breaklines where needed. Breaklines are used to delineate hydraulically significant structures (e.g. raised road grades or railroad grades) that will affect the flow of water through the 2D mesh. The cell sizes in the 2D flow areas were increased to reduce model run time. As a result some of the topographic features within the flow areas may be lost. The user should carefully evaluate the use of any inundation mapping for the leveed areas based on local knowledge. The UMR FRM hydraulic model uses the Diffusion Wave equation to calculate flow in all of the 2D flow areas. The Diffusion Wave equation was used instead of the Full Momentum (Saint Venant) equation because the flow in the 2D areas in this model is driven almost exclusively by gravity and friction. The Full Momentum equation takes into account the acceleration of the flow, but in the UMR FRM hydraulic model, accounting for acceleration does not provide noticeable improvements in model results and greatly increases computational run time.

Levees/Lateral Structures

National Levee Database (NLD) levee surveys were completed in 2007/2008 and 2016 for USACE Rock Island District and 2007/2011/2017 for USACE St. Louis District. The 2016 NLD survey in Rock Island focused on the mainstem levees along the Mississippi. The NLD elevation for the tieback levees are based on the 2007/2008 data in Rock Island District. For St. Louis District the tieback elevations are based on the 2007/2011 NLD survey data. The latest available NLD elevation data was applied to the lateral structures that represent levees in the HEC-RAS model and represents the existing levee elevations. The use of the NLD data in this model does not alter the congressionally authorized elevation for individual levee systems or constitute retroactive USACE approval of the altered levee by bypassing the formal Section 408 process. A limited number of levees were not in the PL84-99 system and therefore did not have NLD survey information. For these levees, the Topobathy terrain data were used to determine existing levee elevations. Closure structures were included in the levee elevations to prevent model simulations from overtopping at known closure locations. The existing levee elevations were used in the model development and model calibration to best align with the conditions of the calibration event. The existing levee elevations were exported from the NLD in the spring of 2017.

Lateral structures were used in HEC-RAS to allow flow to pass between a river reach and a 2D flow area or between a river reach and a storage area. Storage area connections were used to allow flow to pass between storage areas/2D flow areas. Lateral structures that represent levees primarily used the surveyed existing (NLD) levee elevations. For non-federal levees that are not in the PL84-99 system and did not have NLD data, terrain data were used to determine the levee elevations. Appendix F shows the locations of the levees that are not in the PL84-99 system and for which terrain data were used to determine the elevations. For this hydraulic model, all levees are represented as lateral structures, but not all lateral structures are levees. Non-levee lateral structures represent embankments (roads/railroads) or zero-height weirs. The elevations for these lateral structures were derived from the underlying terrain data. Zero-height weirs are the same elevation as natural ground and are used to transfer flow between geometry elements.

The lateral structures were originally developed in HEC-GeoRAS to obtain georeferenced elevations and then were subsequently imported into the HEC-RAS model. Lateral weir coefficients follow the guidance in the HEC-RAS 2D User Manual for range of acceptable weir coefficients. Weir coefficients for zero-height weirs range from 0.2-0.5 while weir coefficients for elevated embankments range from 0.5-2.0 depending on the height of the embankment (Reference 9).

Tributaries

All major tributaries (gaged streams) were included as separate routing reaches explicitly in the UMR FRM HEC-RAS model and have lateral structure connections when appropriate. Tributary models extend from the confluence of the Mississippi River upstream to the first USGS flow gage. The tributaries were included in the model to route flow from the tributary's most downstream flow gage, to include the effects of flow accumulation, timing and volume, to its confluence with the Mississippi River. Two types of tributary models were incorporated into the UMR hydraulic model. USACE leveraged previously developed HEC-RAS models that were used as a part of other studies and projects which include Corps Water Management System (CWMS) models. However, several tributary models were not available and needed to be developed within the budget and time constraints of the UMR hydraulic model. As a result approximate models were developed for these locations and that process is described below. Table 6 lists the tributaries that are included in the UMR hydraulic model.

Previously developed HEC-RAS tributary models were appended to the UMR FRM hydraulic model with minimal changes to the tributary reach. Bridges from previously developed tributary models are included in the UMR Hydraulic model with no additional effort to verify or update the bridge geometry. These models were developed using the best available data at the time of the study or project. However the tributary models were not re-calibrated as part of the scope of the UMR FRM hydraulic model.

Approximate HEC-RAS models were developed for the remaining gaged tributaries that did not have any previously developed HEC-RAS models. The terrain data used to develop each approximate tributary model floodplain geometry were 1 meter resolution LiDAR data. Some of the LiDAR data were acquired at a time of year when tributary flows were low, so some of the channel geometry was captured along with the floodplain geometry. Some of the tributaries did not have any bathymetric data, so the channel geometry that was not delineated by LiDAR had to be approximated. The tributaries that had associated HEC-2 models used the channel geometry from the HEC-2 models for the updated HEC-RAS models. For the tributaries that did not have an HEC-2 model, the channel geometries were estimated as trapezoids whose cross sectional areas were approximately equal to the channel areas denoted on the tributary's bridge plans.

Bridges for the approximate tributary models were developed from bridge plans or, if bridge plans were unavailable, from bridge information from previous HEC-2 models. Many of the bridge plans and HEC-2 models were over 20 years old, so bridge piers and high chord elevations were checked against recent aerial imagery and LiDAR. Adjustments were made to the HEC-RAS bridge data if imagery or LiDAR indicated significant changes since the development of the bridge plans or HEC-2 models

All confluences between rivers are modeled as junctions. The computation mode used at most junctions was the Force - Equal Water Surface Elevations. The Energy Balance computation mode was used for two junctions within the Fabius River reaches where the computation of slope across the junctions was necessary for stability.

Table 6 Tributaries of the UMR that are explicitly included in the FRM hydraulic model.
Models with asterisk (*) are approximate models.

Tributaries to the Mississippi River		River Mile	Drainage area @ mouth (sq mi)
State	**Tributary and Gage Location**		
IA	Des Moines River at Keosauqua, IA	361.3	14,500
MO	Fox River at Wayland, MO*	353.6	500
IL	Bear Creek near Marcelline, IL*	341.0	400
MO	Wyaconda River above Canton, MO*	337.3	458
MO	N. Fabius River near Ewing, MO*	323.0	1,570
MO	M. Fabius River near Ewing, MO*	323.0	
MO	S. Fabius River near Taylor, MO*	323.0	
MO	North River at Palmyra, MO*	321.1	400
MO	Salt River (Louisiana)	284.4	3,500
MO	Cuivre River*	236.4	1,300
IL	Illinois River (Grafton)	218.0	29,300
MO/KS	Missouri River (St. Louis)	195.5	526,000
MO	Meramec River	160.7	4,400
IL	Kaskaskia River (Chester)	117.4	7,200
IL	Big Muddy River	75.6	2,900

Ungaged Inflows

Many Upper Mississippi River tributaries have significant ungaged inflows. To determine the appropriate approximate inflow, the NWS North Central River Forecast Center (NCRFC) and Lower Mississippi River Forecast Center (LMRFC) provided ungaged discharge estimates for each of the modeled flood events for each of the subbasins within the modeled reach. These ungaged inflow hydrographs were inserted into the model as lateral inflows at the location for which each was developed. Ungaged inflows as provided by the NWS-River Forecast Centers (RFC) are lumped based on larger HUC watersheds and not inserted into the hydraulic model at the physical location of every tributary. The RFC model routes the flows from these lumped watersheds to an outlet location on the main stem Mississippi River. These flows are added to the model at the NWS outlet location through the use of a lateral inflow boundary condition.

HEC-RAS has an ungaged computation method that is able to develop ungaged inflow estimates. Experiences have indicated this method can result in model instabilities, hydrograph timing issues, and longer simulation times. The team determined that the NWS RFC discharge estimates would be utilized for the model.

HEC-RAS Model Calibration

All inflow hydrographs for the calibration events reflect observed data from USACE or USGS streamflow gages. The model was calibrated to observed stage and flow hydrographs throughout the entire model runtime to include high and medium stages and flows. The model peak stages were calibrated to the peaks of the observed stage hydrographs. A request for high water mark data was sent to Levee and Drainage Districts and to County Emergency Management Agencies (Appendix E). A limited number of high water mark data was received, and 15 of them corresponded to flood events that were used for model calibration. Three high water marks were provided by Great River Habitat Alliance and were surveyed by Pickett, Ray

& Silver, Inc. All three points were from the same location and corresponded to the flood events of 2008, 2014, and 2017. The high water marks are located approximately 3 miles from the Mississippi River behind a railroad embankment (Figure 9). The other 12 high water marks were provided by the Neighbors of the Mississippi and were surveyed by Crawford, Murphy & Tilly, Inc. These high water marks are at a variety of locations in Missouri and correspond to the flood events of 2008, 2013, and 2017 (Figure 10). The high water marks that were provided that are geographically located in the 1D portion of the HEC-RAS model are included in Appendix C-2 – Model Calibration Profile Plots. The high water marks that occurred in the 2D portion of the model are not included as the profile plots only display the mainstem river elevation and not the 2D area water surface elevation. All the high water marks are included in Appendix C-3 – Model Calibration Statistics. Due to the lack of available high water mark data, available gage data was used almost exclusively for model calibration and the water surface elevations for the leveed areas were unable to be calibrated. As a result, the water surface elevations in the leveed areas will not have the same accuracy as the channel profiles.

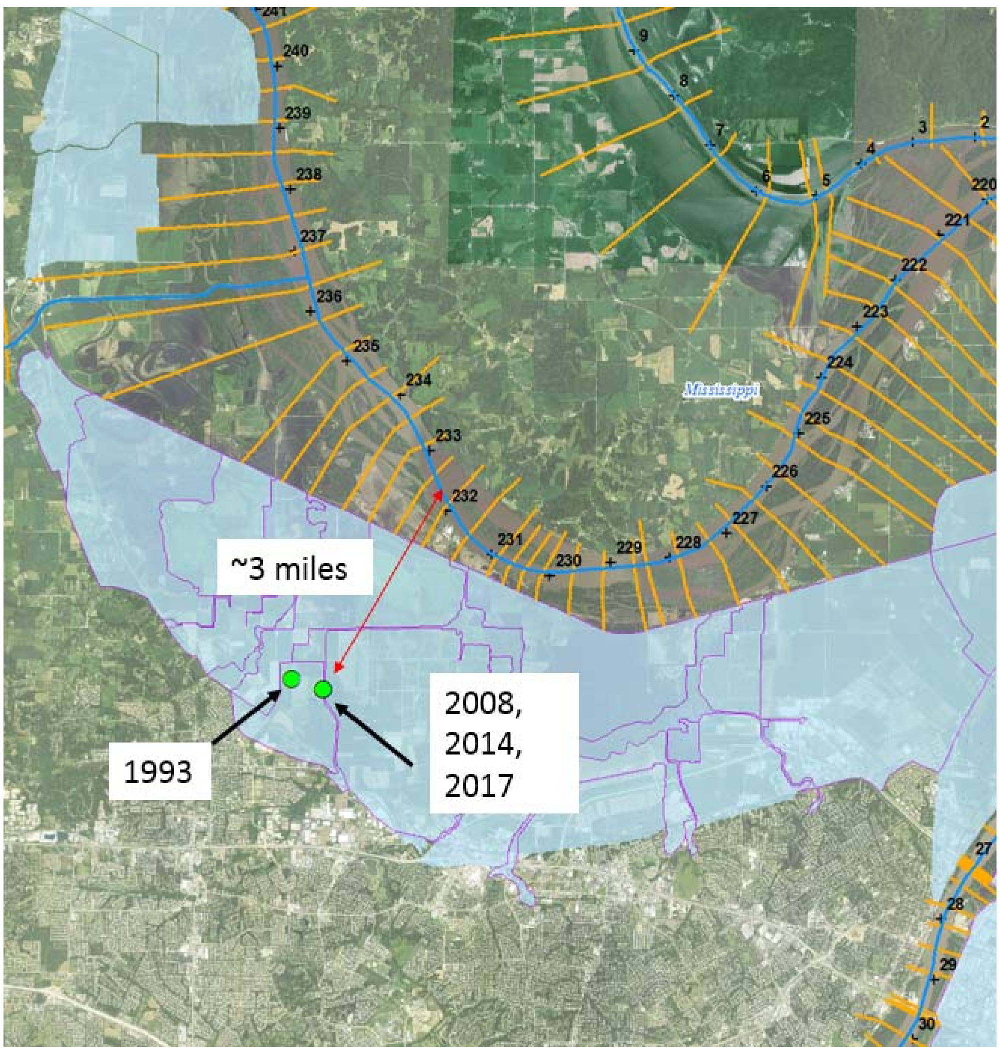


Figure 9 Location of 3 High Water Marks surveyed by Pickett, Ray & Silver, Inc.

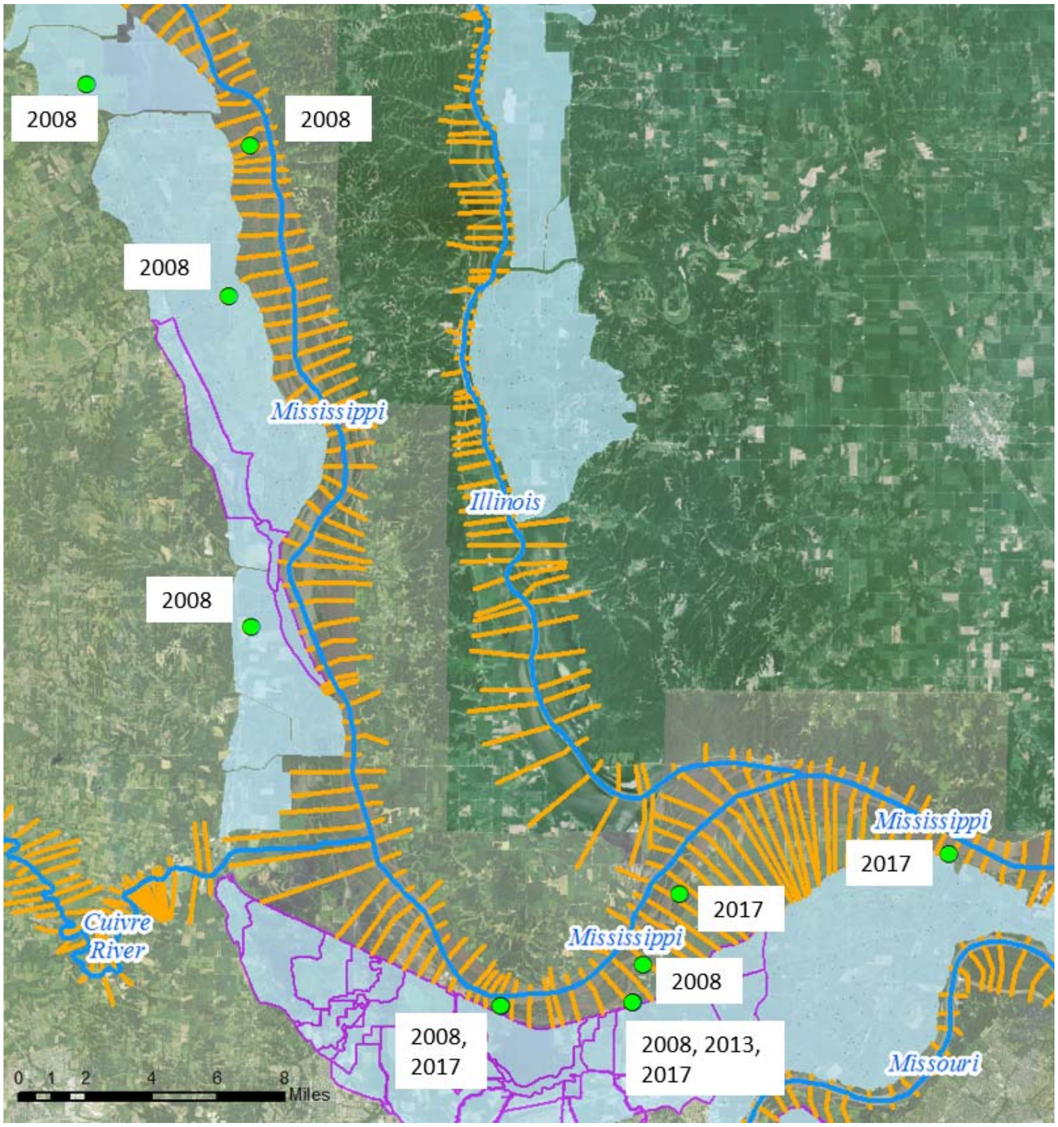


Figure 10 Location of 12 High Water Marks surveyed by Crawford, Murphy & Tilly, Inc.

The model was developed using the best available data. The datasets span a period of time that may not reflect the exact conditions for specific flood events. For example, the available topobathy datasets may not exactly represent the conditions during the 2017 event. Model performance through the calibration process is intended to provide a model that reasonably replicates historic events and serves as the best available tool to discuss systemic performance to develop a regional flood risk management strategy. The long term stage trends and normal stage-flow variations were not analyzed. Throughout this reach, the geomorphology of the Mississippi River is relatively stable throughout high and low flow events. It is expected that this model and its associated Manning roughness values and flow roughness factors will be applicable and produce reasonable model results for a range of flow events as observed and into the future. This reach of the Mississippi River will most likely experience seasonal roughness variations and if this model is to be used to analyze winter floods, it may need to be re-calibrated with seasonal roughness variations included.

Model Uncertainty

The datasets used to develop the model all contain uncertainty and errors within the data. As a result the parameters used for calibration will reflect the compilation of the uncertainties from the input datasets. For example, the observed USGS flow hydrographs use rating curves that are developed from measured flows. These measured flows include relatively few measurements during high flow events. Therefore, there is higher uncertainty in the observed flow hydrographs near the peak flows than during normal flow conditions.

Another known uncertainty in the input data is the National Weather Service (NWS) ungaged inflow data. While this inflow data represents the best available data and is more reliable than alternative methods (drainage area ratio, HEC-RAS ungaged computation method), the NWS ungaged inflow data are estimates and therefore contain some uncertainty.

The topobathy dataset also includes uncertainty in the vertical accuracy from the original LiDAR and bathymetry data. The LiDAR metadata reports an uncertainty of up to 7.3 inches while the bathymetry data includes uncertainty on the order 0.5 feet.

Calibration

Calibration Events

The UMR FRM hydraulic model was calibrated to four specific historic events and was not calibrated to a flow associated with a specific return interval (e.g. 100-yr flood). A comparison of this model with the 2004 UMRFFS is outside the scope of this project. The historic events that were chosen were events that flooded the overbank areas and loaded the levees.

The computational time step for the calibration runs was 5 minutes/15 minutes and the time step for the 2D flow areas was also 5 minutes/15 minutes. The historic events selected for calibration are the flood events of 2008, 2013, 2014, and 2017. Table 7 contains a summary of information regarding the peak discharge, date the peak discharge occurred, and estimated Annual Chance Exceedance (ACE) probability for the event at the location specified based on the information contained in the 2004 UMRFFS.

Table 7 Historic flood events used for model calibration

Calibration Events	Peak Flow (cfs) – LD 20 (est ACE)	Peak Flow Date – LD 20	Peak Flow (cfs) – Thebes, IL (est ACE)	Peak Flow Date – Thebes, IL
2008	565,850 (<0.002)	18 June 2008	717,000 (~0.1)	3 July 2008
2013	392,360 (~0.01)	21 April 2013	723,000 (~0.1)	27 April 2013
2014	400,400 (~0.01)	8 July 2014	539,000 (~0.5)	14 July 2014
2017	240,560 (~0.2)	3May 2017	917,000--(~0.013)	6 May 2017

Boundary Conditions- Calibration

The upstream boundary condition for the mainstem Mississippi River at Lock and Dam 19 at Keokuk, IA (RM 364) is a flow hydrograph of observed data for the respective flood event. A flow hydrograph is also used as the upstream boundary condition for all of the gaged tributaries. The downstream boundary condition on the mainstem Mississippi River at Thebes, IL (RM 44) is a stage hydrograph of the recorded data.

Boundary Conditions – Additional Rating Curve

The model files contain an additional downstream rating curve at Thebes, IL. The additional downstream boundary is a discharge-elevation rating curve, to account for the varying discharge values observed for future simulations that are not based on observed events. The rating curve for the Thebes gage was developed by the U.S. Geological Survey, and it had a maximum discharge value of 1,200,000 cubic feet per second. In order to evaluate hypothetical storms of greater magnitude, the rating curve was extrapolated to 2,000,000 cfs. The rating curve was tested and adjusted for flows greater than a scaled 1993 gaged inflows event.

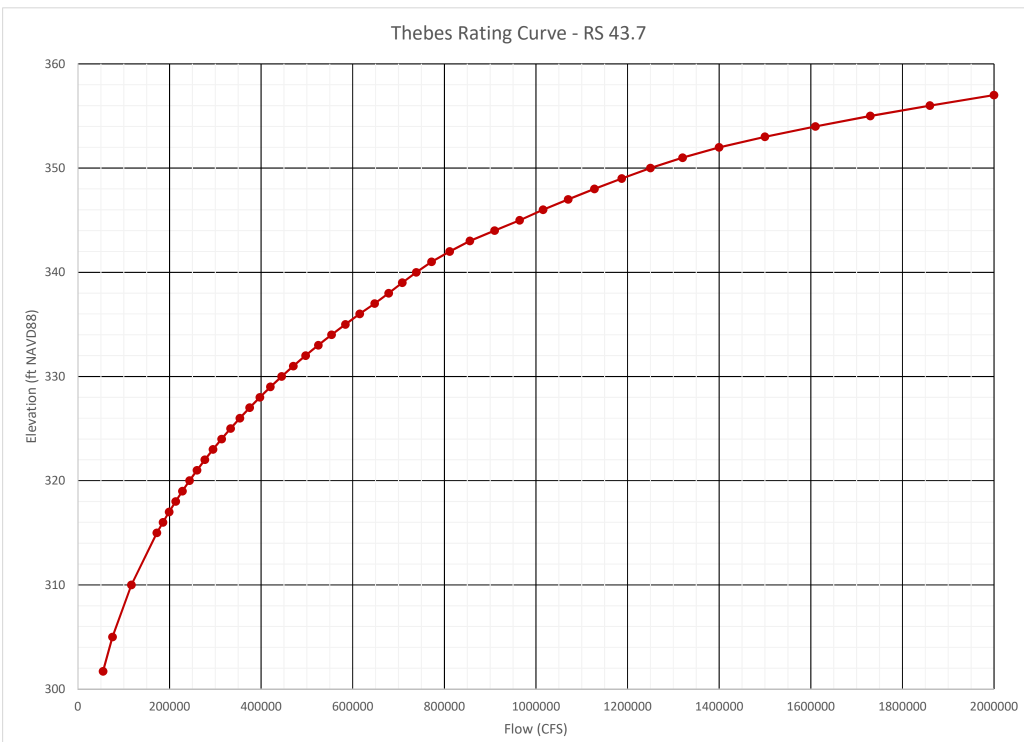


Figure 11 Rating curve used for the downstream boundary condition at Thebes, IL for the model application runs.

Breach Analysis Parameters

Initially for all calibration events, levees that overtopped were assumed not to breach. After the initial calibration, breach data was to be added to the model to improve calibration results and to conduct a sensitivity analysis. Unfortunately, the necessary data (breach date, width, and depth) were only available for the Rock Island District for the 2008 event which was the only event levees breached in the Rock Island District. Therefore, breach data were included for the 2008 event in the Rock Island portion of the model. The mainstem portions of the levees in Rock Island are generally constructed of sand resulting in full loss of section as a result of overtopping.

However, for the St. Louis District portion of the model, for events that exceeded the top of levees, the breach data was not recorded in the detail needed for inclusion in the model. St. Louis District had information on the general locations of the breaches which were lumped into other damage areas such as wave wash and erosion. The data does not specifically identify the key information (breach timing, width, and depth) which prevented the breaches from being accurately included in the model. The levee systems in MVS are generally constructed of clay materials. For many systems that required repairs the systems were completely overtopped during the event, breaches did not erode the full levee section, breaches occurred after the system was overtopped, or the system was intentionally breached to dewater the area after the river receded. Ultimately, breaches in the St. Louis District reach were not modeled for any event since the observed downstream hydrographs did not show significant flow and stage reductions and the model could be calibrated sufficiently well without including these breaches.

Calibration Method

Model calibration focused primarily on stage reproduction at the gage locations along the Mississippi River reaches. Improvement to stage reproduction were mainly achieved through adjustments to roughness values. Manning's roughness values were based on the suggested values shown in Table 3 and distributed horizontally across each cross section based on National Land Cover Data using HEC-GeoRAS. General adjustments to Manning's roughness values provided the first level of adjustment. Flow-Roughness values, which provides adjustment to model roughness specified by flow ranges, provided the second level of adjustment. Tables of Flow-Roughness factors were added to the model geometry to extend between each stage gage location. These factors were used to refine the stage calibration. The range of flow roughness factors varies from 0.6 to 1.2 on the mainstem Mississippi and the Illinois River. On the Kaskaskia River, the flow roughness range varies from 0.8-1.3. The flow roughness were applied on the Illinois and Kaskaskia to assist in the calibration of the mainstem Mississippi.

Calibration Measurement

In addition to evaluating the hydrographs, a second method involving evaluating statistics was developed to support model calibration. Model calibration was measured by using three different goodness-of-fit statistical measures: coefficient of determination (R^2), root mean squared error (RMSE), and mean absolute error (MAE). These statistics were calculated at every location in the model for which observed water surface elevations are available. These statistics were used in conjunction with the modeled and observed hydrographs to perform model calibration. The hydrographs helped determine if the model was matching the timing and peak of the hydrograph while the statistics display an overall goodness-of-fit. The statistics were used primarily as a relative measure of model performance by tracking the improvement in the statistics from one calibration run to the next. The statistics were not intended to be used as a standalone measure to conclude that the model had become calibrated.

The coefficient of determination (R^2) is the proportion of the variance in the observed water surface elevations that is explained by the model. R^2 ranges from 0 to 1 with a value of 1 representing a model that perfectly reproduces the observed values.

$$R^2 = \left\{\frac{1}{n} * \sum_{i=1}^{n} \frac{(x_i - \bar{x}) * ((y_i - \bar{y})}{\sigma_x * \sigma_y}\right\}^2 , \tag{1}$$

where N is the number of observations, x_i is the observed WSEL value for observation i, $\bar{x}$ is the mean observed WSEL value, y_i is the modeled WSEL value for observation i, $\bar{y}$ is the mean modeled WSEL value, σ_x is the standard deviation of the observed WSELs, and σ_y is the standard deviation of the modeled WSELs.

The RMSE is a measure representing the sample standard deviation of the differences between the observed and modeled water surface elevation. An RMSE close to 0 represents a model with low standard deviation.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - y_i)^2} \tag{2}$$

The MAE is a measure representing how close the modeled water surface elevations match the observed water surface elevations. An MAE close to 0 represents a model that closely matches the observations.

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |x_i - y_i| \tag{3}$$

After the statistics were calculated, the manning roughness and/or flow roughness parameters were adjusted, the model was re-run, and the statistics were re-calculated to see if the model calibration improved. This became an iterative process and was repeated until the model was fully calibrated.

Calibration Plots

Profile plots and hydrographs were created to display the results of calibration and are included in Appendices C-1 and C-2. These plots were created with the open-source software R using the package ggplot2. Note a few hydrographs are missing because the observed hydrograph is not available. The existing levee elevations on the profile plots were associated to river miles to display properly on the graph. This association was completed in ArcGIS. These elevations were smoothed with a running average for display purposes only. No smoothing was used for the elevations in the HEC-RAS model. In a few areas of the modeled reach, there are multiple levees associated with a particular river mile for either the right or left descending bank. For these areas, only the most riverward levee was plotted on the profile graph unless the landward levee was a federal levee and higher in elevation. This was done to provide clarity in the profile plots. High water mark data that were provided by others were included on the profile plots if they were geographically located in the 1D portion of the HEC-RAS model. If the high water marks were located in the 2D areas of the model, these data are provided in Appendix C-3 – Model Calibration Statistics. For the high water marks that are displayed on the profile plots, the gage peak stages are plotted at the same river mile as a gage, whereas the surveyed high water marks do not occur at gage locations. The profile plots in Appendix C-2 include symbols and abbreviations to reduce text on the plots. Table 8 describes the symbols and abbreviations used in the profile plots.

Table 8 Symbols and Abbreviations used in Appendix C-2

Symbol/Abbreviation	Description
●	High Water Mark – Color corresponds to flood event
#	Levee is Non-Federal Segment – Terrain Data
*	Levee is Non-Federal Segment - NLD

Appendix C-1 displays hydrographs and references River Stations as determined by the HEC-RAS model centerline and stationing for each gage location. The HEC-RAS model stationing may be slightly different than the river mile for the gage as shown on navigation charts or other websites that display the gage location in river miles. These sources show the river mile of the gage location as associated with the navigation sailing line. Appendix C-2 displays profile plots and references River Miles above Ohio River. Therefore, the gage locations on these appendices match the associated River Mile for each gage.

Calibration Results

The calibration statistical measures were calculated at each gage that had observed water surface elevation data. The final calibration statistics for the 2008, 2013, 2014, and 2017 events are displayed in Appendix C-3.

Sensitivity and Uncertainty

USACE Engineer Regulation ER 1105-2-101 (Reference 10) states "No project or action that is proposed, evaluated, adopted, and implemented, can completely eliminate or mitigate flood risks. Further, the information used to estimate flood risk, formulate and evaluate plans, and determine the results of the analyses is uncertain." The scope of work and funding for this project does not include a sensitivity and uncertainty analysis of key inputs, parameters, and model results for the UMR FRM hydraulic model. Uncertainties exist in natural environment systems due to many factors which may include (but are not limited to): variability in the time of year in which flood events occur, discharge contributions from ungaged portions of the river, the ability of instruments to accurately measure discharge during flood events (Reference 11), and assumptions that are made to fill in missing data such as levee breach initiation, timing, and final dimensions.

The model was developed and calibrated using deterministic methods to establish a single set (average) of parameters (Manning's "n", weir coefficients, junction computation mode etc.) and inputs (LIDAR, bathymetry, regulating structures, dam operations, inflow hydrographs, etc.). The model is well suited for use in discussing and developing planning level alternatives for FRM strategies. However, additional effort will be needed in the future to evaluate and assess statistical performance, resiliency, and long-term risk in accordance with USACE regulations and guidance which require the use of HEC-FDA (Flood Damage Assessment).

USACE EM 1110-2-1619 (Reference 12) defines the procedure for determining the uncertainties of the performance of Flood-Damage Reduction plans, discharge-probability function and stage discharge function. Many factors can result in stage uncertainty and may include: cross section data, debris and obstructions, bed form and sediment transport, backwater effects, survey error and measurement error. Additional functions may need to be evaluated depending on the scope and extent of follow-on studies.

1993 Gaged Inflow Event

In addition to the 2008, 2013, 2014, and 2017 events, which were utilized during model calibration, a 1993 gaged inflows event was also developed and modeled. The 1993 gaged inflows event was added because of the size and magnitude of the event. The 1993 event was a large flood throughout the system and is a useful pattern event to scale up and down to evaluate a range of loading conditions for Regional FRM planning efforts. NWS-NCRFC ungaged inflow estimates are not available for the 1993 event. The term 1993 gaged inflows is used because recreating the 1993 event is outside this scope of work due to the challenges and complexities presented during the event due to flood fighting and levee breaches. As a result, there was no effort or emphasis to recreate the observed 1993 event, only to use the observed flows from the 1993 event.

Table 9 below lists all the geometry files, unsteady flow files, and plan files contained in the existing conditions model.

Table 9 Geometry, Unsteady Flow, and Plan Files used in the UMR FRM Hydraulic Model

Geometry Files	Unsteady Flow Files	Plan Files
UMR Geometry 2D	2013 Event	1993 Inflows 2D-THEBES RC
	2014 Event	2008 Event 2D
	2017 Event	2013 Event 2D
	2008 Event	2014 Event 2D
	1993 Inflows-THEBES RC	2017 Event 2D
Notes: RC is Rating Curve.		

HEC-RAS Model Applications

Section 408 System Performance Analysis

Discussions and scoping for this model initiated in 2014 as multiple drainage and levee districts were evaluating the feasibility of altering their levee systems, which would require USACE approval through the 33 USC 408 (Section 408) program. USACE guidance was in development that describes the process and risk assessments needed to comply with Engineering Circular EC 1165-2-216 "Policy and Procedural Guidance for Processing Requests to Alter US Army Corps of Engineers Civil Works Projects Pursuant to 33 USC 408". As a result of the Section 408 process and guidance, discussions with state, federal and NGO stakeholders were initiated that would ultimately align the support and develop the scope of work for a UMR FRM hydraulic model that could serve as the starting point for follow-on studies and Section 408 alteration requests by Drainage and Levee Districts. Non-federal levee system alterations are required to follow applicable state floodplain regulations and are exempt from the Section 408 requirements. Appendix F of EC 1165-2-216 outlines the procedures required to complete the Hydrologic and Hydraulic System Performance Analysis. It is envisioned this existing conditions model will serve as a starting point for future Section 408 System Performance Analysis.

Quality Control

The review plan was developed in accordance with the requirements of EC 1165-2-214. Participation from states/federal/NGO's was incorporated into the review process. The following section describes the reviews. In general comments were made on the location of ineffective flow areas, selection of Manning's "n" values, orientation and location of cross sections, report language and content, and clarity of figures and appendices.

USACE DQC Reviews

District Quality Control Reviews were performed at 75% and 95% model completion by engineers in St. Paul (MVS) and Omaha (NWO). The 75% review consisted of reviewing the calibrated model using the existing levee condition.

State/Federal Technical Team Review

In addition to participating on the multiple coordination webinars the state/federal technical team was presented the opportunity to review the model on multiple occasions throughout model development. Each agency was responsible for using their own funding to perform the reviews. Two reviews were performed which occurred immediately after the USACE 75% and concurrent with the 97.5% DQC reviews.

FEMA Region's 5 and 7 provided comments on the model and report as a part of the 97.5% review. FEMA's comments help identify some of the key differences in model assumptions and methods between the UMR Hydraulic Model and FEMA modeling standards for detailed flood insurance studies. Should funding become available in the future for either agency, the following items will need to be coordinated. In general due to the scope, size, and model run time the topics below were beyond the purview of this phase of the model development.

FEMA acknowledges that the UMR model cannot be used to produce an update or replacement of 2004 UMRSFFS study and FEMA's regulatory products in its current state. The UMR Hydraulic Model has the best available information and will be available for public use. As a result, additional coordination between the flood plain managers at the local, state and federal levels is recommended before using the UMR Hydraulic model for project permitting (i.e. no-rise) purposes.

The mesh size and breaklines for 2D flow areas will require additional refinement to reflect local drainage features which affect water movement within the leveed area. Additional high water mark information, calibration of the 2D flow areas and use of the Full Momentum equations may also be required for detailed flood insurance studies.

Some of the lateral structures in the model are not the structures designed for flood protection (roads/railroads). FEMA does not model non-levee embankments as levees (lateral weirs) in the analyses to produce FEMA's regulatory products.

USACE Modeling, Mapping and Consequences (MMC) Production Center ATR Review

The USACE MMC is responsible for providing modeling, mapping, and consequence support for all of USACE. The MMC maintains a virtual production team that produces hydrologic and hydraulic models that are used for risk based assessments for the Corps Water Management System (CWMS) along with the Dam and Levee Safety Programs. MMC has been responsible for establishing many model development standards and have served as reviewers for H&H model reviews throughout USACE.

USACE MMC reviewed the model and report immediately following the USACE 95% DQC review (97.5% review) was complete which was concurrent with the state/federal technical team review.

Summary

It is the responsibility of the non-federal sponsor to complete the Section 408 alteration request and receive USACE approval prior to making physical changes to the levee. Discussions and scoping for this model initiated in 2014 as multiple drainage and levee districts were evaluating the feasibility of altering their levee systems which would require USACE approval through the 33 USC 408 (Section 408 program). USACE guidance was in development that describes the process and risk assessments needed to comply with Engineering Circular EC 1165-2-216 "Policy and Procedural Guidance for Processing Requests to Later US Army Corps of Engineers Civil Works Projects Pursuant to 33 USC 408". As a result of the Section 408 process and guidance, discussions with state, federal and NGO stakeholders was initiated that would ultimately align the support to develop the scope of work for the UMR FRM hydraulic model that could serve as the starting point for follow-on studies and Section 408 alteration requests by Drainage and Levee Districts.

This river segment from Keokuk to Thebes was prioritized for Levee Safety funding because the majority of the floodplain in this reach is excluded by levees. In addition there have been numerous changes and updated survey information which has resulted in numerous discussions about the current and future performance and predictability of the system.

The calibrated existing conditions model was developed using the best available NLD data and uses one set of parameters that are representative of four flood events (2008, 2013, 2014 and 2017). The goal of this tool is to provide a common model using the best available data and software that can reasonably recreate a range of events that have occurred or may occur in the future to assess system performance and flood risk management strategies.

The use of the NLD data in this model does not alter the congressionally authorized elevation for individual levee systems or constitute retroactive USACE approval of the altered levee by bypassing the formal Section 408 process. If the non-federally constructed system is not included in the PL84-99 system, then terrain data was used for the existing levee condition. The existing levee condition represents the sum of all activities (flood fighting, repairs, dredge material placement, approved and unapproved alterations) that have occurred over time. Model simulations and water surface profiles were developed for five flood events (1993, 2008, 2013, 2014 and 2017). Maximum water surface elevations are represented in Table 10.

This existing conditions hydraulic model is a tool to more accurately evaluate and communicate impacts as a result of changes to the system that have occurred or will be proposed in future Section 408 alteration requests. The hydraulic model will improve flood preparation and response, real time river forecasting and real time inundation mapping. The need and applications for a UMR FRM hydraulic model is strongly supported by neighboring states, local communities, and non-governmental organizations (NGOs).

Table 10 Model Run Peak Elevations at Gage Locations (ft, NAVD88)

River Mile	Gage Name	Flood Stage (in elevation)*	1993	2008	2013	2014	2017
364.2	LD 19 Tailwater	493.27	504.93	504.59	499.51	501.61	493.25
352.9	Gregory Landing, MO	487.12	499.92	499.40	495.32	497.01	489.48
343.25	LD 20 Pool	N/A	495.97	495.67	491.41	492.73	485.19
343.2	LD 20 Tailwater	481.88	495.51	495.17	490.82	492.00	484.75
335.7	La Grange, MO	481.95	492.81	492.00	487.91	488.68	481.76
327	Quincy, IL	474.89	489.80	488.64	484.89	485.19	478.14
324.95	LD 21 Pool	N/A	488.87	487.66	484.04	484.28	477.17
324.9	LD 21 Tailwater	474.14	487.86	486.77	483.45	483.53	476.56
309	Hannibal, MO	464.85	479.07	478.11	475.65	475.47	469.72
301.25	LD 22 Pool	N/A	475.83	474.86	472.44	472.23	465.52
301.2	LD 22 Tailwater	461.53	474.97	474.14	471.86	471.66	465.05
282.9	Louisiana, MO	452.03	465.28	464.37	461.89	461.70	456.39
273.5	LD 24 Pool	N/A	459.52	458.86	457.03	456.91	452.21
273.2	LD 24 Tailwater	446.57	459.10	458.54	456.72	456.61	451.73
260.3	Mosier Landing, IL	440.54	452.25	451.88	450.55	450.46	446.21
241.5	LD 25 Pool	N/A	445.59	444.17	441.88	441.53	438.77
241.2	LD 25 Tailwater	432.47	445.26	443.83	441.35	440.94	438.40
203	Alton, IL	420.66	437.62	428.39	427.07	422.42	430.60
201.1	Mel Price LD Pool	N/A	437.59	427.79	426.45	421.51	430.31
200.5	Mel Price LD Tailwater	416.48	437.30	427.30	425.95	420.83	430.11
194.16	Locks 27 Pool	N/A	435.80	424.85	423.42	481.04	428.92
190.28	Chain of Rocks	N/A	432.74	421.64	420.21	414.66	426.26
185.1	Locks 27 Tailwater	N/A	430.77	419.33	417.62	412.20	424.07
179.6	St. Louis, MO	409.57	427.29	416.91	415.34	410.51	421.74
176.8	Engineers Depot	N/A	425.63	415.46	413.95	409.19	420.31
168.7	Jefferson Barracks	N/A	421.82	412.20	410.83	406.10	417.34
135.5	Brickeys	383.38	403.11	394.65	393.71	388.43	400.17
125.5	Little Rock Landing	N/A	396.93	388.77	388.06	382.29	394.43
109.9	Chester, IL	367.75	387.70	379.53	379.25	372.71	385.61
94.1	Red Rock Landing, MO	359.38	379.82	371.83	371.55	364.65	377.66
81.9	Grand Tower, IL	349.44	372.39	364.31	364.02	357.28	370.26
66.3	Moccasin Springs, MO	341.33	362.33	355.03	354.83	347.79	360.13
52	Cape Girardeau, MO	336.36	353.38	346.31	346.19	338.71	350.51
43.7	Thebes, IL	332.79	346.78	340.65	340.66	333.34	342.82

*Source of flood stage from either the National Weather Service or USACE.

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Appendices

Appendix A-1 – Model Extent Map
Appendix A-2 – Model Map with Inflows
Appendix B – Datum Conversions
Appendix C-1 – Model Calibration Hydrographs
Appendix C-2 – Model Calibration Profile Plots
Appendix C-3 – Model Calibration Statistics
Appendix C-4 – Summary of Gage Data (Maximum Elevations) and High Water Marks
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Appendix D-1 – High Water Data Correspondence
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Appendix E – Maps of Non-NLD Leveed Areas