MISSISSIPPI RIVER MODEL

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INTRODUCTION

Project Background: The Great Mississippi River Flood of 2011 was the catalyst behind the creation of detailed, unsteady flow, hydraulic models of the Mississippi River and Tributaries (MR&T). The MR&T system was tested to new levels during the 2011 event, and the hydraulic models provide a means of evaluating the system performance. The Memphis, Vicksburg, and New Orleans Districts of the Corps of Engineers worked in parallel to create separate models of their systems. The 2011 Post-Flood Assessment and the National System Performance Evaluation were two studies that utilized the first iteration of these hydraulic models. A limited timeline to complete those two projects did not allow for a detailed calibration to a wide range of flows, and the scope of the studies only concerned relative differences to the 2011 event. For the Mississippi River Flow Line and Geomorphology Study, a more detailed calibration of the models was necessary. Each district collected more data and updated its individual models in order to resolve major issues unique to their locations and calibrate to a range of flows before attempting to combine them into one model. This report provides a brief description of the background of the development of the Memphis District model, examples of novel methodologies and assumptions involved in calibrating this large, one-dimensional HEC-RAS model, and some of the methodologies and results from the coupled one-dimensional and two-dimensional HEC-RAS model.

Model Background: The Memphis District portion of the HEC-RAS model originated from the Ohio River Community Model (ORCM). A Mini-Model version of the ORCM was used during the 2011 Flood by the National Weather Service (NWS) with the aid of the Hydrologic Engineering Center (HEC) in an attempt to forecast river stages and the activation of the Bird's Point-New Madrid Floodway (BPNM). The Mini-Model had upstream extents of Chester, Illinois on the Mississippi River and Smithland, Kentucky on the Ohio River. The downstream boundary was Caruthersville, Missouri which is located approximately 110 river miles downstream of the confluence of the Mississippi and Ohio Rivers. The "Mini-Model" was updated significantly by the Memphis District and extended downstream to Vicksburg, Mississippi to include the major tributaries that either contribute significant flow or experience a considerable backwater effect during high flood events. Inflows due to precipitation within the Memphis District model limits were estimated using NWS hydrologic models and further routed by the Memphis District hydraulic model.

Two-dimensional RAS models of the BPNM and the confluence of the Arkansas, White, and Mississippi Rivers were constructed for this effort due to the complexity of those sites. These models were calibrated and refined using the most advanced features available in RAS. RAS2D was being developed during the initial calibration and not all the current software features were available as the work progressed.

DATA

Flow and Stage Data: An unsteady HEC-RAS model is based on a series of assumptions to represent open channel flow in one-dimension, upstream to downstream. It is a robust and flexible model, but like all models it is limited to the accuracy of the input data in addition to its one-dimensionality. The best, most accurate data reasonably obtainable was used for the model development.

For the external and internal boundaries of the Memphis District, flow and stage data needed to be obtained from the United States Geological Survey (USGS), the St. Louis District, the Lakes and Rivers Division, the Little Rock District, the Memphis District, the Vicksburg District, and the NWS. The NWS computes data in Coordinated Universal Time (UTC) while many of the district offices report in their respective time zones, typically Central Standard Time (CST). This data was compiled, converted, and stored in databases using HEC-DSS in both UTC and CST. By switching the databases, the model has the capability of reading data in either UTC or CST.

The vertical datum used for the model is the North American Vertical Datum of 1988 (NAVD88). Many of the gage zeros have been tied to the NAVD88 datum by surveying– that conversion was applied directly to obtain elevation in NAVD88. Other gages have not been surveyed and Corpscon6 software was used to convert the gage zero in the National Geodetic Vertical Datum of 1929 (NGVD29) to NAVD88.

Many points within the model with a significant contribution of flow are monitored by gages by either the USACE or the USGS. Most are real-time stage gages, and flow measurements are taken periodically to develop the stage-flow relationship, but some are merely staff gages read daily. Because the 2011 flood produced some of the highest stages in recent decades, the number of flow measurements at these high stages for available for comparison was limited, which contributed to uncertainty in the model. All stage and flow data was checked to permit accurate calibration.

GIS Data: GIS data was necessary for the creation of the hydraulic model. The HEC Geo-RAS tools for ArcGIS were used to translate the vector and raster data into an HEC-RAS geometry. The projection and datum for the terrain model were USGS Albers Equal Area and NAVD88 (ft), respectively. The terrain model associated with the Memphis District geometry was created from sets of bathymetric data and Laser Imaging, Detection and Ranging (LIDAR) or Digital Elevation Model (DEM) datasets obtained during different years. The use of data obtained in various years was unavoidable due to the model boundaries extending into other districts. However, all the data for the terrain model were obtained no earlier than 2001

Post-2001 Flood surveys and After-Action Reports (AAR) were used to help determine final breach sizes or areas of overtopping and to gain a general knowledge of the flood history. Levees and floodwalls in the National Levee Database (NLD) essential to calibration were included in the model.

METHODOLOGY AND ASSUMPTIONS

General Assumptions: HEC-RAS is a one-dimensional modeling software that has the capability to model split flows, to calculate water surface profiles for gradually varied flows, and to model a single stream reach or a full network of interconnecting channels. It has the ability to model subcritical, supercritical, and mixed-flow profiles. The basic computation routine solves the one-dimension energy equation, taking into consideration energy losses due to channel and overbank friction in the longitudinal direction, and expansion and contraction losses at bridges, culverts, and natural constrictions. HEC-RAS neglects variables such as density and temperature. Because RAS is a one-dimensional model, all input must be assignable to a longitudinal coordinate. The modeling of large, elaborate river systems in one-dimension involves mathematical assumptions, requiring creative use of RAS features to approximate the three-dimensional hydraulics that exist in the field.

As the initial calibration was underway, a two-dimensional modeling capability in HEC-RAS was under development (HEC-RAS 5.0 Beta). Therefore, complex sites such as BPNM and the confluence of the Arkansas, White, and Mississippi Rivers were developed in HEC-RAS 5.0 Beta to obtain a more realistic model. HEC-RAS 5.0 Beta contains a 2-D finite-volume model that solves either the full 2-D Saint Venant equations or the 2-D Diffusion Wave equations. The software has the ability to perform combined 1-D Rivers and Storage areas with 2-D Flow Areas. The combined 1-D/2-D computations are performed together on a time step by time step basis, making the connections from 1-D areas to 2-D Flow Areas more accurate than modeling them separately. The grids for the 2-D areas created are discretized, and an elevation-volume relationship is computed for each cell based on the underlying terrain and bathymetry. The effort to refine and calibrate these 2-D areas was limited, partly because the software was only in a Beta version during the time of the initial calibration. However, the major limitation in the software for this initial calibration was that only one Manning N-value could be assigned to the cells at one site. Once the model was set up and stable, there were few variables available to change to calibrate the 2-D areas. The general expectation was that the application of a RAS 2-D model at a complex site would be more accurate than a 1-D model, regardless of the limitations of the 2-D feature available then. The areas modeled in 2-D were delineated in such a way to represent overbank flow – which is in better agreement with the single Manning's N-value limitation of the software.

In addition to the theoretical assumptions of the software code, assumptions are inherent in the input data before the model is ever created. Regarding the use of surveys from multiple years, the general assumption was that the overall volume for the system has not changed significantly in the past 10 years. Local differences in geometry from the use of older data were not quantified but were rectified by weighting the calibration of the model to the more recent events. The typical error of the published flow data for calibration is considered to range from plus or minus 2 to 8 percent, or more. . The USGS publishes the results of flow measurements taken and estimated accuracy. That accuracy is based on a number of variables such as weather conditions, turbidity, and temperature. Overall, the published flow data was considered the most accurate available.

Methodology for Calibration (1-D): Gaining an understanding how the flow data and geometric data functions in the model for a variety of flood events is a daunting task. Correcting

flow data or modifying the geometric data was considered part of the calibration process. Determining the locations and elevations of lateral structures and corresponding weir coefficients, the storage area volumes and layouts, ineffective flow areas, levee points, and Manning's N-values were the other key tasks in calibrating the Memphis District model.

After the quality check on the published flow data, the calibration to a range of flows began initially by changing Manning's N-values, working upstream to downstream. The 2002, 2008, and 2011 events were the target events used to calibrate the model. Although the 2011 event was the most recent and highest event, 2008 was used for calibration of some of the areas of great complexity. For example, in 2011 there were four major breaches between Cairo and Caruthersville (three of the breaches were intentional, for operation of the BPNM floodway). The unintentional breach was not a breach of a project levee. Since none of those four breaches occurred during the 2008 event ,the 2008 event was used to help isolate variables unique to the cross section geometry. In general, comprehensive data from 2002 to 2011 was used to determine elevation trends for the different levels of flow, with emphasis on the more recent events. Modifying the Manning's N-values was an iterative process conducted by analyzing the trends of flow versus the difference between computed elevations and observed elevations (residuals).

Because of the complex nature of the Mississippi River, adoption of a single Manning's N-value representing the channel for all levels of flow was not prudent. A 0.03 value for the channel was the initial trial Manning's N-value. The initial value was changed on cross sections considered local to a particular gage to obtain a close approximation to in-channel flows. These modified values were then varied with flow by a series of multipliers. For example, if the model residuals were showing that computed elevations were too low for flow ranges of 200,000 to 300,000 cfs, a multiplier greater than 1.0 was used on the Manning's N-values for a series of cross sections delineated for a particular gage during that flow range. This process is tedious, and an automated roughness feature within HEC-RAS was used to help determine reasonable multipliers to correct a high or low trend at the various flow rates.

The Automated Roughness Calibration feature within HEC-RAS was used as a guide for the lower flows. It was used as a time saving feature and not used exclusively in all locations. The automated roughness feature determines the trends of the residuals with flow rates and iteratively determines the multiplier needed to minimize the difference between the computed and observed elevations. The output of this feature was a series of multipliers for the different reaches for the range of flows. This data was adjusted by the modeler to provide smoother transitions. After the in-channel flows at the gages were reasonably calibrated, calibration to higher, out-of-bank flows began. The automated roughness feature did not work as well for higher flows as the geometric features, breaches, and hydrodynamics become more complex, but Manning's N-values were still varied at higher flow rates by the modeler. At higher flow rates, more effort was necessary to represent the conveyance in the cross sections. This became apparent as the computed elevations began to slip in time and peak too late. To represent the conveyance in a given cross section, the cross section had to be delineated horizontally by Manning's n values and schematic changes to the model were necessary.

The larger geometric or schematic changes to the model as a part of the calibration process generally were related to storage areas and lateral structures within the MR&T levee system that

represented breaches that occurred or areas where large overbanks existed in the original cross sections. Storage areas within the MR&T levee system were only used if an obvious high elevation restriction existed. Most of these areas are partially bound by spur levees jutting out almost perpendicular to the path of overbank flow. In the majority of circumstances, water backs up into these areas and does not actively convey downstream; therefore, storage areas were deemed appropriate. The profiles of the lateral structures that control the flow of water into the storage areas were often cut from elevations with little difference in elevation on either side of the structure. The weir coefficients were set to low values (0.1 to 0.7 typically). These lower values not only best represent the flow into or out of these areas, but also tend to be more numerically stable. Ideally, a stage-stage boundary condition between the cross sections and the storage areas would best represent the flow into or out of the storage areas for a range of events, but this capability was not available in HEC-RAS at that time. Other areas of large overbank distance that could not be delineated by obvious elevation restrictions were represented using other tools and methods available in the HEC-RAS interface.

When a long, flat overbank distance (this can be many miles for the Mississippi River) is present in a cross section, issues can arise when attempting to calibrate the model temporally and spatially. When water begins to flood the overbanks, the one-dimensional assumptions in HEC-RAS are not realistic. Specifically, when the computed water levels exceed elevations of the overbanks, RAS assumes that all the water in the overbanks is at an equal elevation to that of the river. In actuality, the water surface elevations near the levees are not the same as that for the channel. A drop in the calculated water surface can be seen as water levels begin to exceed elevation in the flat overbanks of the cross sections, due to the generally flat overbanks. For overbanks with side channels or more depth in the overbanks, too much increase in elevation is seen as these areas begin to compute as conveyance in the model. In some cases, water in the overbanks is essentially stored until water levels in the river drop – at which point that volume begins to return to the channel. These areas were handled with ineffective area points. There are other cases where the water in the overbanks does convey, but slowly. If these areas are treated as strictly ineffective areas, the model will compute too much storage. This subtracts too much volume on the rising side of the hydrograph and returns the overestimated volume on the falling side of the hydrograph. These areas instead were delineated horizontally with associated Manning's N- values. Large Manning's N-values such as 0.2 or 0.3 were used at the fringes of the cross sections to reduce the conveyance of this volume downstream. N-values this high are not listed in any hydraulic textbook strictly for describing roughness, but the complex hydrodynamics actually taking place cannot be modeled otherwise in a one-dimensional model. The energy losses occurring transversely and vertically have to be accounted for, in addition to the standard longitudinal losses, to obtain the correct timing of calculated elevations at the main stem gages. Using these high Manning's N-values, as well as varying the Manning's N-value with flow rates, most of the events could be calibrated satisfactorily. For cases of unusually high flow or events that had a long duration at levels which caused water to oscillate in and out of channel, additional levee points and ineffective areas were necessary for the model to compute accurate elevations without significantly delaying the timing of the peaks. Due to the one-dimensionality of HEC-RAS, the superelevation of the water surface cannot be modeled; however, the conveyances within the cross sections were reasonably modified to compute a close approximation to the observed elevations near the time they occurred. Much effort was spent attempting to calibrate to the events temporally and spatially, but in a one-dimensional model of this magnitude trade-offs have to be made. Aerial photography and the terrain model helped

tremendously in determining how to handle the overbank conveyances. Figures 1 and 2 show prime examples of overbank flow during the 2011 flood and a few of the different methods used by the Memphis District for modeling.

Figure 1 is aerial photography obtained during the 2011 flood. At the top right corner of the photograph a breach occurred in a spur levee. A storage area was used to model the volume shortcutting the Mississippi River. On the right descending bank, a large area is inundated and labeled Storage. This area is partially bound by a levee on the upstream side that did not fail during the flood. Water tends to back up into this area rather than convey in a downstream direction. The bottom right corner of the photograph shows overbank flow modeled with cross sections. The overbank area was considered to be low conveyance instead of storage, as it was not confined by high ground. The sections extended across the overbank approximately 3 to 4 miles. The profile for section A-A in Figure 1 is shown in Figure 2.

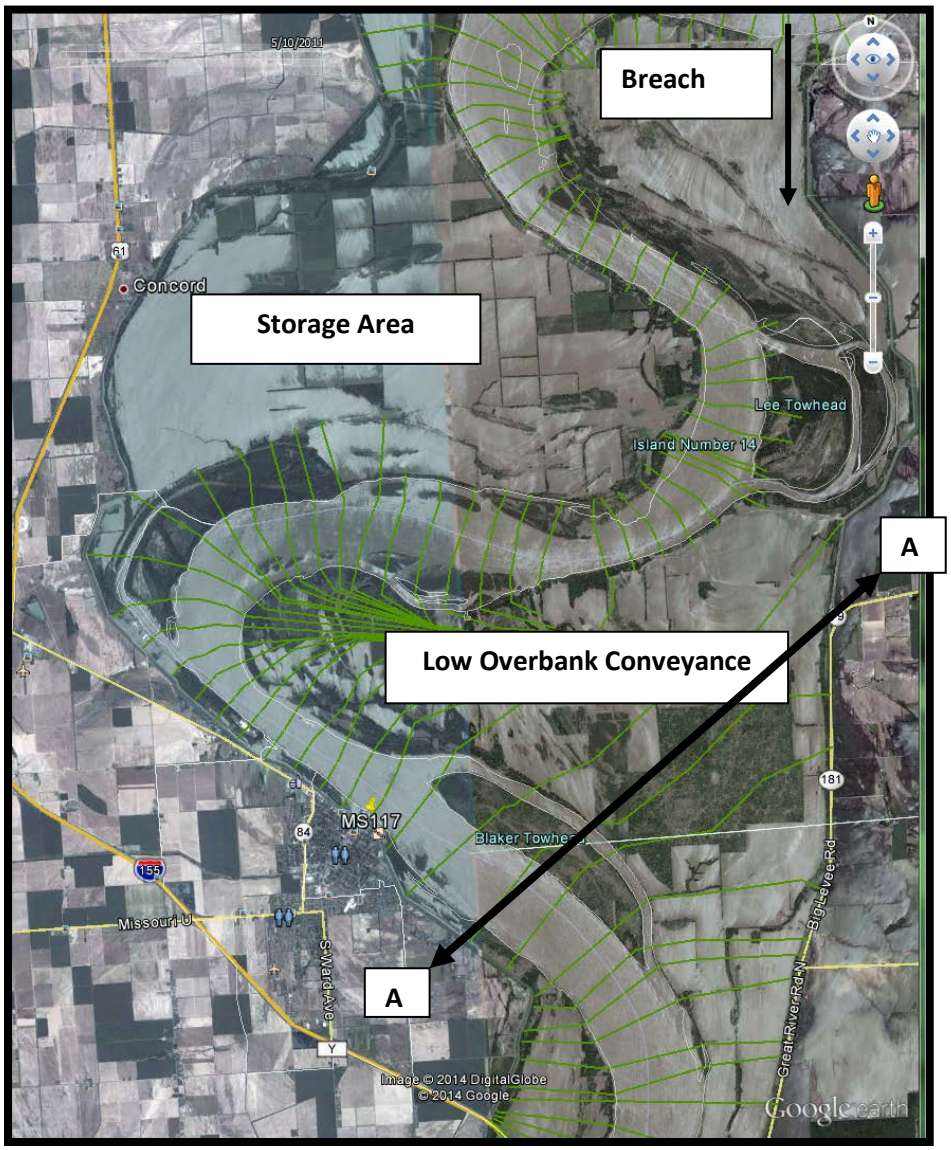

Figure 1 Photograph of Overbank Flow, May 2011

Figure 2 shows the profile for section A-A. The bars across the top indicate the Manning's N-value, as well as its conveyance delineation along the stationing of the profile. The two channels had clearly identifiable banks and were assigned N-values of 0.032. The overbank between the two channels was assigned an N-value of 0.11. The left side of the profile corresponds to the large overbank that has water which conveys downstream slowly. The Manning's N-value there was raised to a 0.17 in order to allow little conveyance downstream. From the plan view in Figure 1, it is clear that the flow in the overbank for this area was not stored, rather it moves slowly through the overbanks downstream. Also in Figure 2, a levee point is present at approximately 22,000 feet from the left overbank. However, this point does not represent a real levee; instead, the point limits flow from being computed in the first 22,000 feet of the cross section until that point is overtopped. Use of such levee points helps to transition the model transversely to fully out of bank flow.

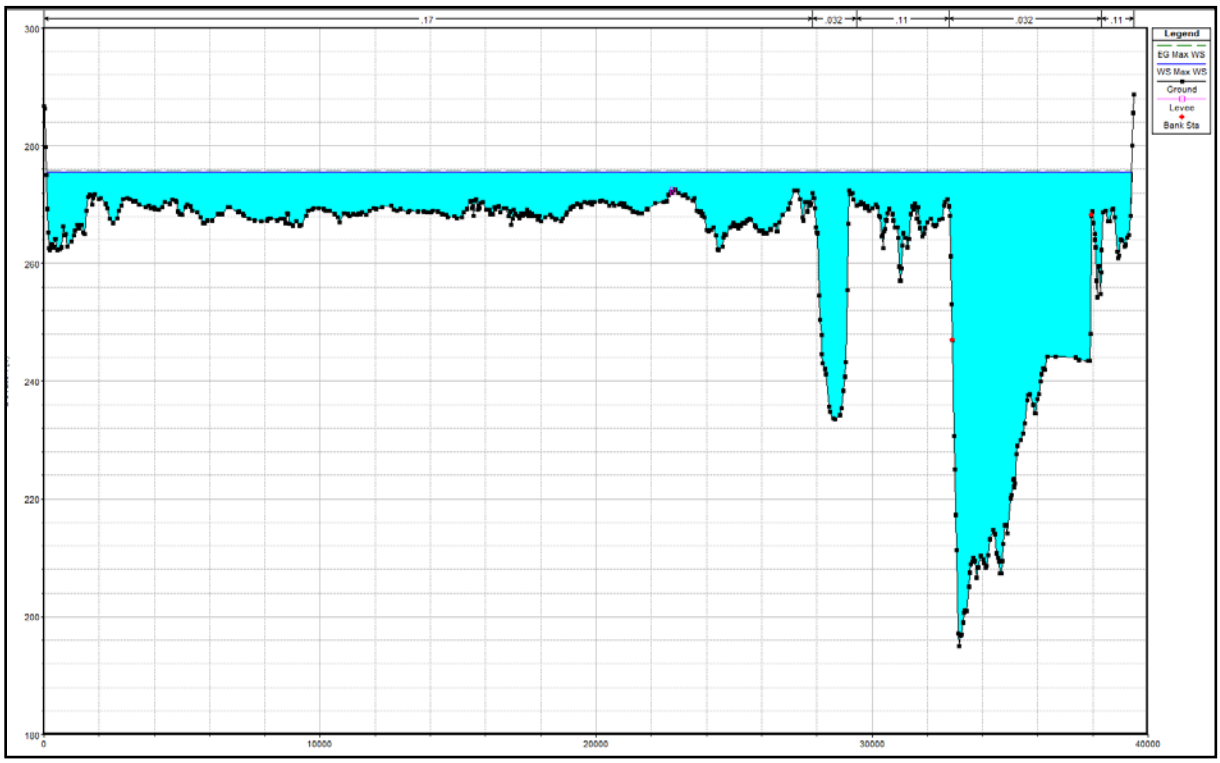

Figure 2 Section A-A – Example of Low Conveyance Overbank Flow

RESULTS AND CONCLUSIONS

Calibration Results: The calibration of the Memphis District hydraulic model focused on the 2002, 2008, and 2011 events primarily, but continuous data from 2002 through 2011 was run through the model as well. In general, gages that recorded hourly stage data were used for a detailed calibration analysis, but intermediate gages with daily data, high water marks, or staff gages with intermittent data were also used for refinement of the model. Table 1 shows results for each of the 3 primary events, and Table 2 shows results from the 10 year simulation from 2002 to 2008. In Table 1, results are listed for locations along the Mississippi River from Chester, Illinois downstream to Arkansas City, Arkansas. For each event and location, the accuracy of the model is described by listing the percent of calculated stages within 0.5 and 1.0 feet of the observed data and the average error. Also, the difference in peak elevations between calculated and observed stages is listed. For all three events the general tendency is for the model to more accurate at the upstream end than at the downstream end. Average errors and differences at peaks are less than 2.0 feet and typically less than 1.0 feet.

Table 1 Memphis District Calibration Results for 2002, 2008, and 2011

	2002 Event				2008 Event				2011 Event			
Gage	% within 0.5 ft	% within 1.0 ft	Average Error	Difference at Peak	% within 0.5 ft	% within 1.0 ft	Average Error	Difference at Peak	% within 0.5 ft	% within 1.0 ft	Average Error	Difference at Peak
Chester	82%	99%	0.29	0.32	81%	94%	0.32	-0.1	77%	99%	0.35	0.03
Red Rock	52%	93%	0.50	-0.05	63%	88%	0.49	-0.2	46%	86%	0.56	0.04
GrandTower	76%	88%	0.41	-1.25	70%	93%	0.39	0.45	73%	98%	0.39	-0.01
Moccasin Springs	22%	77%	0.81	-1.21	37%	50%	1.30	0.7	N/A	N/A	N/A	N/A
Cape Girardeau	54%	93%	0.52	-1	57%	92%	0.53	0.19	65%	99%	0.37	-0.08
Thebes	32%	82%	0.68	-1	74%	92%	0.39	-0.04	75%	96%	0.35	-0.22
Commerce	42%	85%	0.62	-1.05	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Price Landing	26%	75%	0.73	-0.05	51%	88%	0.56	-0.42	60%	91%	0.43	0.37
Thompson Landing	56%	81%	0.57	-0.29	54%	83%	0.62	-0.95	N/A	N/A	N/A	N/A
Bird's Point	61%	89%	0.49	-0.68	47%	78%	0.66	-0.56	60%	84%	0.49	-0.32
Smithland	39%	65%	0.90	0.03	30%	59%	1.03	0.01	34%	56%	1.05	-0.99
Paducah	38%	66%	0.86	0.09	38%	56%	1.06	0.22	32%	61%	1.00	-0.46
Metropolis	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	34%	61%	0.97	0.31
Grand Chain	43%	64%	1.25	0.03	28%	42%	1.84	0.19	44%	69%	0.76	0.02
Cairo	58%	88%	0.52	-0.37	31%	56%	0.97	0.07	38%	71%	0.68	0
Hickman	30%	68%	0.81	-0.96	58%	87%	0.52	-0.32	60%	87%	0.48	-0.62
New Madrid	49%	84%	0.61	-0.83	58%	90%	0.50	-0.23	51%	84%	0.60	0.36
Tiptonville	53%	86%	0.57	-1.03	51%	83%	0.60	-0.46	60%	81%	0.55	1.01
Caruthersville	59%	91%	0.48	-1.1	65%	92%	0.47	-0.67	64%	90%	0.48	0.06
Osceola	59%	80%	0.61	-0.55	58%	81%	0.57	-0.11	34%	74%	0.76	0.14
Memphis	24%	54%	0.96	-0.55	50%	84%	0.59	-0.34	54%	78%	0.65	0.08
Helena	24%	54%	1.06	-0.57	41%	72%	0.81	-0.74	40%	69%	0.89	0.01
Montgomery Point	N/A	N/A	N/A	N/A	21%	38%	1.63	0.19	15%	35%	1.64	-0.64
Arkansas City	32%	60%	1.10	0.91	25%	51%	1.30	1.19	20%	44%	1.18	0.13

In Table 2, results are listed for locations along the Mississippi River from Chester, Illinois downstream to Arkansas City, Arkansas. The percentage of the availability of observed data for the 2002-2011 simulation period is listed. For each event and location, the accuracy of the model is described by listing the percent of calculated stages within 0.5 and 1.0 feet of the observed data and the average error. For the continuous simulation, the general tendency is for the model to more accurate at the upstream end than at the downstream end. Average errors are less than 2.0 feet and typically less than 1.0 feet.

Table 2 Memphis District Calibration Results – 2002-2011 Continuous Simulation

	2002 - 2011 Hourly Simulation			
Gage	Percentage of Observed Data Available	% within 0.5 ft	% within 1.0 ft	Average Error
Chester	100%	83%	98%	0.31
Red Rock	64%	69%	93%	0.47
GrandTower	89%	75%	95%	0.39
Moccasin Springs	69%	59%	84%	0.71
Cape Girardeau	100%	74%	95%	0.44
Thebes	97%	61%	89%	0.48
Commerce	60%	54%	80%	0.85
Price Landing	98%	51%	83%	0.57
Thompson Landing	74%	51%	77%	0.48
Bird's Point	97%	47%	75%	0.58
Smithland	98%	39%	64%	0.97
Paducah	100%	41%	68%	0.94
Metropolis	23%	66%	87%	0.32
Grand Chain	99%	39%	60%	1.24
Cairo	100%	36%	61%	0.77
Hickman	100%	56%	84%	0.58
New Madrid	100%	60%	89%	0.54
Tiptonville	98%	56%	85%	0.56
Caruthersville	100%	63%	91%	0.47
Osceola	96%	60%	86%	0.61
Memphis	78%	52%	81%	0.69
Helena	83%	41%	74%	0.87
Montgomery Point	72%	19%	34%	1.09
Arkansas City	83%	33%	61%	1.13

REFERENCES

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