ERDC/CHL TR-22-4

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Wabash and Ohio River Confluence Hydraulic and Sediment Transport Model Investigation

A Report for US Army Corps of Engineers, Louisville District

Gary Bell, David Abraham, Nate Clifton, and Kenneth H. Lamkin

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Abstract

Avulsions of the Wabash River in 2008 through 2011 at its confluence with the Ohio River resulted in significant shoaling in the Ohio River. This caused a re-alignment of the navigation channel and the need for frequent dredging. A two-dimensional numerical hydrodynamic model, Adaptive Hydraulics (AdH), was developed to simulate base (existing) conditions and then altered to simulate multiple alternative scenarios to address these sediment issues.

The study was conducted in two phases, Phase 1 in 2013 – 2015 and Phase 2 in 2018 – 2020. Field data were collected and consisted of multi-beam bathymetric elevations, bed sediment samples, suspended sediment samples, and discharge and velocity measurements.

The model hydrodynamic and sediment transport computations adequately replicated the water surface slope, flow splits, bed sediment gradations, and suspended sediment concentrations when compared with field data. Thus, it was shown to be dependable as a predictive tool.

The alternative that produced the most desirable results included a combination of three level-crested emergent dikes on Wabash Island and four submerged dikes on the Illinois shore with a level crest from the bank to the tip of the dike. The selected alternative produced an improved sailing line while maintaining authorized channel depths.

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Preface

This study was conducted for and funding provided by the US Army Corps of Engineers, Louisville District. The technical monitor for the Louisville District was Mr. Kenneth Lamkin.

The US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), conducted this study in 2013 through 2020. The study was conducted under the direct supervision of Mr. David P. May, chief, River and Estuarine Engineering Branch, and Dr. Cary A. Talbot, chief, Flood and Storm Protection Division. At the time of publication of this report, Mr. Keith Flowers was the deputy director of CHL, and Dr. Ty V. Wamsley was the director.

COL Teresa A. Schlosser was the commander of ERDC, and the director was Dr. David W. Pittman.

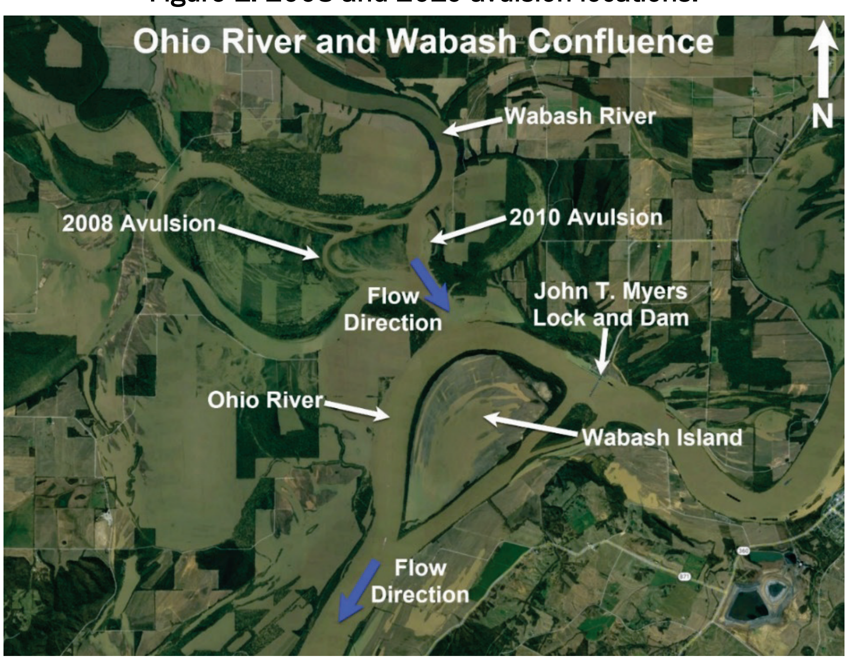
1 Introduction

This report describes the Phase 1 and 2 modeling efforts. It includes the results of several alternative condition simulations as well as the most effective alternative in reducing shoaling and moving sediment through the impacted reach of the Ohio River while at the same time maintaining navigation channel functionality. The site description, study methodology, and results are discussed in subsequent sections.

1.1 Background

The shoal at the mouth the Wabash River caused a re-alignment of the navigation channel in the Ohio River and has recently required constant attention to maintain operational functionality. Prior to 2008, there were five dredging events with the first dating back to 1949. However, since 2008, dredging has been required every year. This recent increase in dredging events is believed to be the result of an avulsion that cut off the lower meander loop of the Wabash River in 2008 and then again in 2010 (Figure 1). Both cutoffs formed after heavy spring and summer rainfall events that occurred between 2008 and 2010. Large amounts of sediment were removed in the avulsion formation process and transported downstream, forming shoals at and downstream of the confluence with the Ohio River.

Figure 1. 2008 and 2010 avulsion locations.



1.2 Objective

The purpose of the study is to assist the US Army Corps of Engineers (USACE), Louisville District, in the investigation of proposed river training structures to help mitigate shoaling in the navigation channel of the Ohio River just downstream of its confluence with the Wabash River. This report describes the details of numerical modeling efforts performed as part of that investigation. The study was conducted in two phases: Phase 1 in 2013 – 2015 and Phase 2 in 2018 – 2020.

The Phase 1 effort resulted in a seven-dike configuration to improve the navigation channel by smoothing the sailing line and maintaining a navigable water depth. The Phase 2 effort was initiated to consider several additional alternatives, including a refinement of the preliminary design determined in the Phase 1 study. The refinements addressed the number, footprint, placement, length, spacing, and elevation of all structures considered.

This report documents the background, modeling, and results for the Phase 1 and Phase 2 portions of the study, with greater emphasis on the Phase 2 portion. The studies were conducted by the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL).

1.3 Approach

A numerical hydrodynamic model was developed to simulate base conditions and then altered to simulate multiple scenarios as possible solutions to these sediment issues. Since the Wabash River is uncontrolled and the USACE has no authority over it, it is essentially unregulated and morphologically unstable. Therefore, longer-term simulations were not attempted since the purpose of this study is to develop river training structures that would improve and maintain the present navigation channel in the Ohio River.

1.4 Site description

The study location is on the Ohio River approximately 5 mi[1] west of Uniontown, KY. The main area of interest is the reach that starts approximately 2 River Miles (RM) directly downstream of the John T. Myers Locks and Dam at the confluence of the two rivers and continues approximately three more miles downstream to the southern tip of Wabash Island. Mitigation with structures can have the greatest impact in this area for improving navigation conditions after the adverse effects of the avulsions on the Wabash River. District personnel were also concerned with possible sedimentation impacts farther downstream, so the model was extended (in Phase 2) approximately 70 RM downstream to the Smithland Locks and Dam, which is the downstream model boundary (Figure 11). The model includes the chute that is southeast of Wabash Island on the Ohio River. It also includes the cut-off bend in the Wabash River, and the two avulsions. The inflow boundary for the Wabash River portion of the model is approximately 4 RM upstream of the 2010 avulsion. The Ohio River inflow boundary is located at the J. T. Myers Locks and Dam complex.

Figure 2 shows pre-cut-off conditions of the convulsed area on the Wabash River immediately upstream of the Wabash and Ohio River confluence. Figure 3 shows the same area post-cut-off conditions along with colored lines showing bank line migration for various years.

[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Figure 2. Pre-cut-off condition (June 2007).

Figure 3. Post-cut-off condition (September 2010).

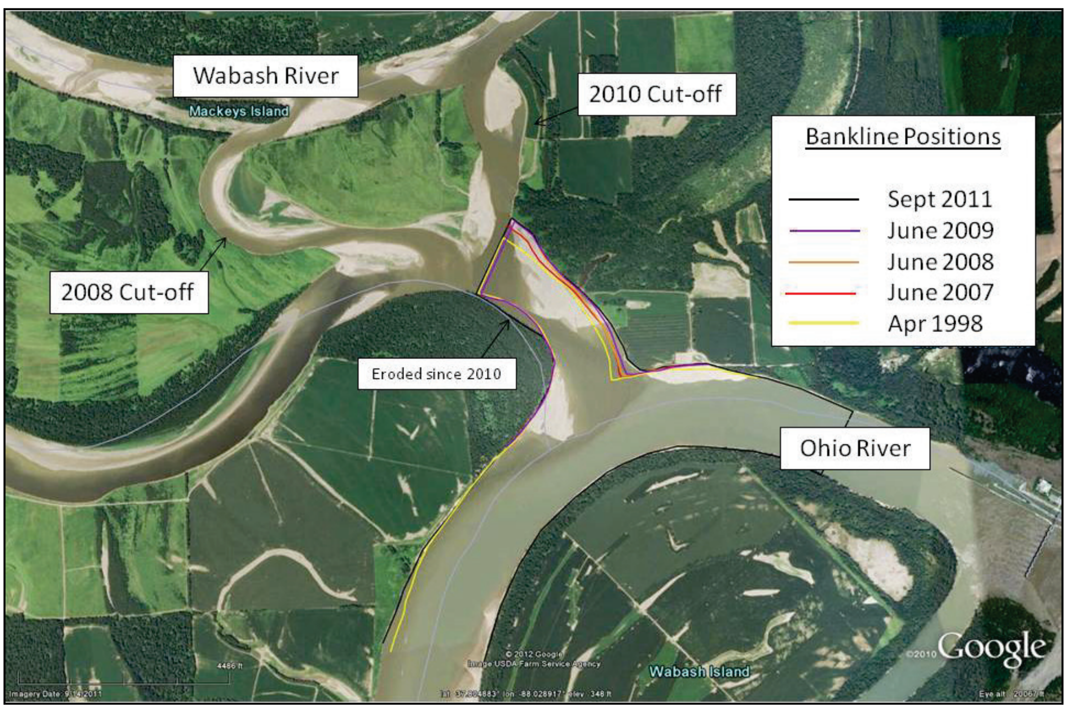
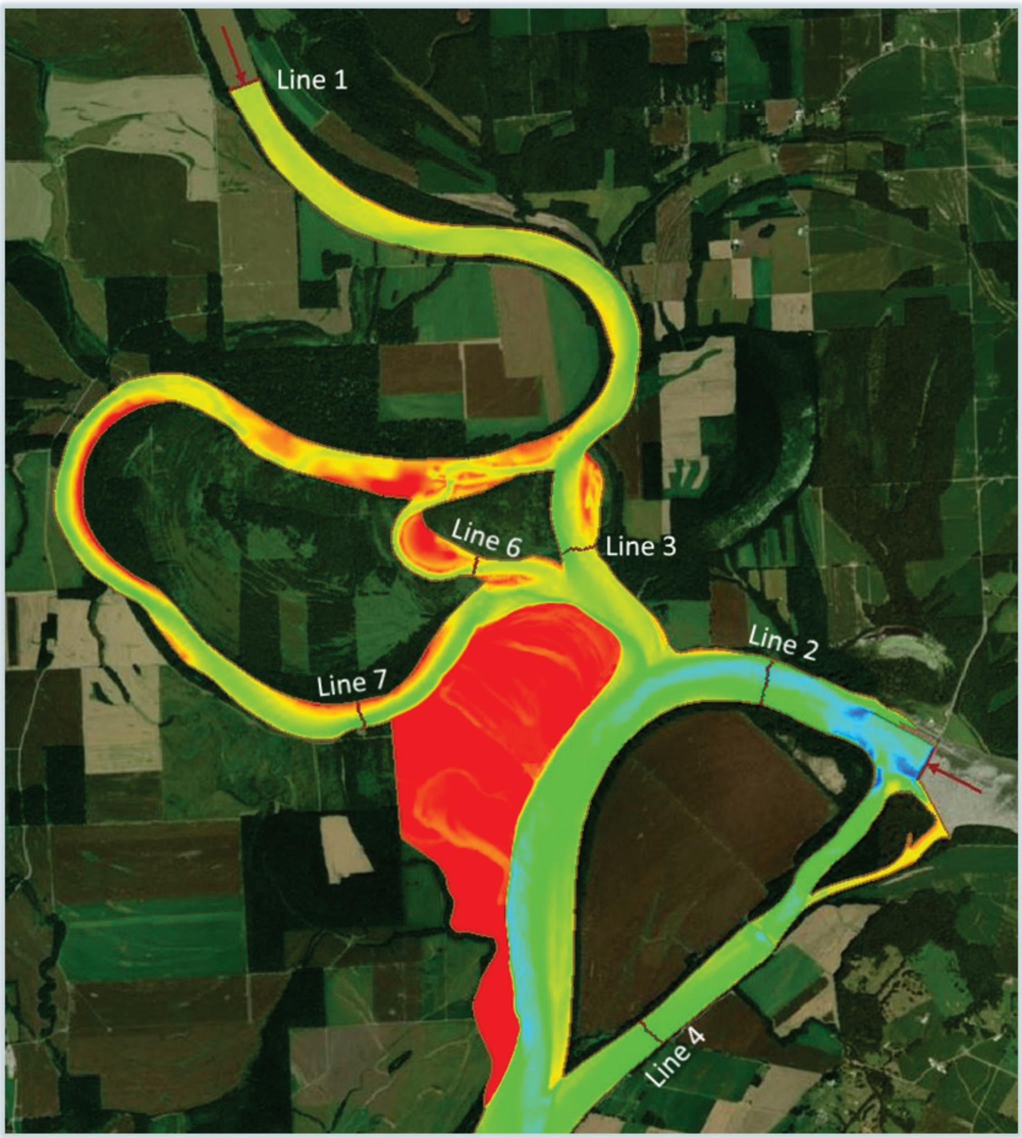


Figure 4 depicts combined data from the Phase 1 and Phase 2 data collection efforts. Most of the in-channel bathymetric survey information shown in this figure was obtained in the Phase 2 collection effort of this study. It shows the bathymetry used in the Phase 2 model for the general area of the confluence of the two rivers and includes LiDAR data for the Wabash-Ohio Floodplain, which is the large, red-contoured area. The colors range from blue areas being deep, navigable waters, to the orange areas being shallow to dry, depending on the flow conditions.

Figure 4. Example of Ohio and Wabash River confluence combined bathymetric surveys (June 2012 and November 2018).



2 Model Development and Calibration

2.1 Numerical model code description

Adaptive Hydraulics (AdH) is the numerical code applied for the simulations in this study. It is a finite element code that can simulate three-dimensional (3D) Navier-Stokes equations, two-dimensional (2D) and 3D shallow water equations, and groundwater equations. It can be used in a serial or multiprocessor mode on personal computers and high-performance computing systems. AdH will refine the domain mesh in areas where more resolution is needed during the simulation due to changes in the flow conditions and then later removed when it is no longer needed to minimize the computational burden. The code also includes automatic time-step adaption. AdH can simulate the transport of conservative constituents, such as dye clouds, as well as sediment transport that is coupled to bed and hydrodynamic changes. The ability of AdH to allow the domain to wet and dry within the floodplain areas as the hydrograph changes is a requirement for shallow floodplain environments with varying flow conditions. This code has been applied to model sediment transport in sections of the Mississippi River, Ohio River, Missouri River; tidal conditions in southern California and San Francisco Bay; vessel traffic in the Houston Ship Channel; and many other sites.

For this study, the AdH 2D shallow water module was utilized to solve water depths/velocities and transport of sediment. The sediment bed interactions are computed through a linkage to SEDLIB (Brown 2012). More details of the 2D shallow water module of AdH and its computational philosophy and equations are available in Savant et al. (2014). The sediment transport modeling (SEDLIB) (Brown 2012) includes computation of bed load and suspended sediment transport. It also accounts for changes in bed composition (changes in grain-size distributions) and bed layer thicknesses (deposition and scour) for multiple grain sizes.

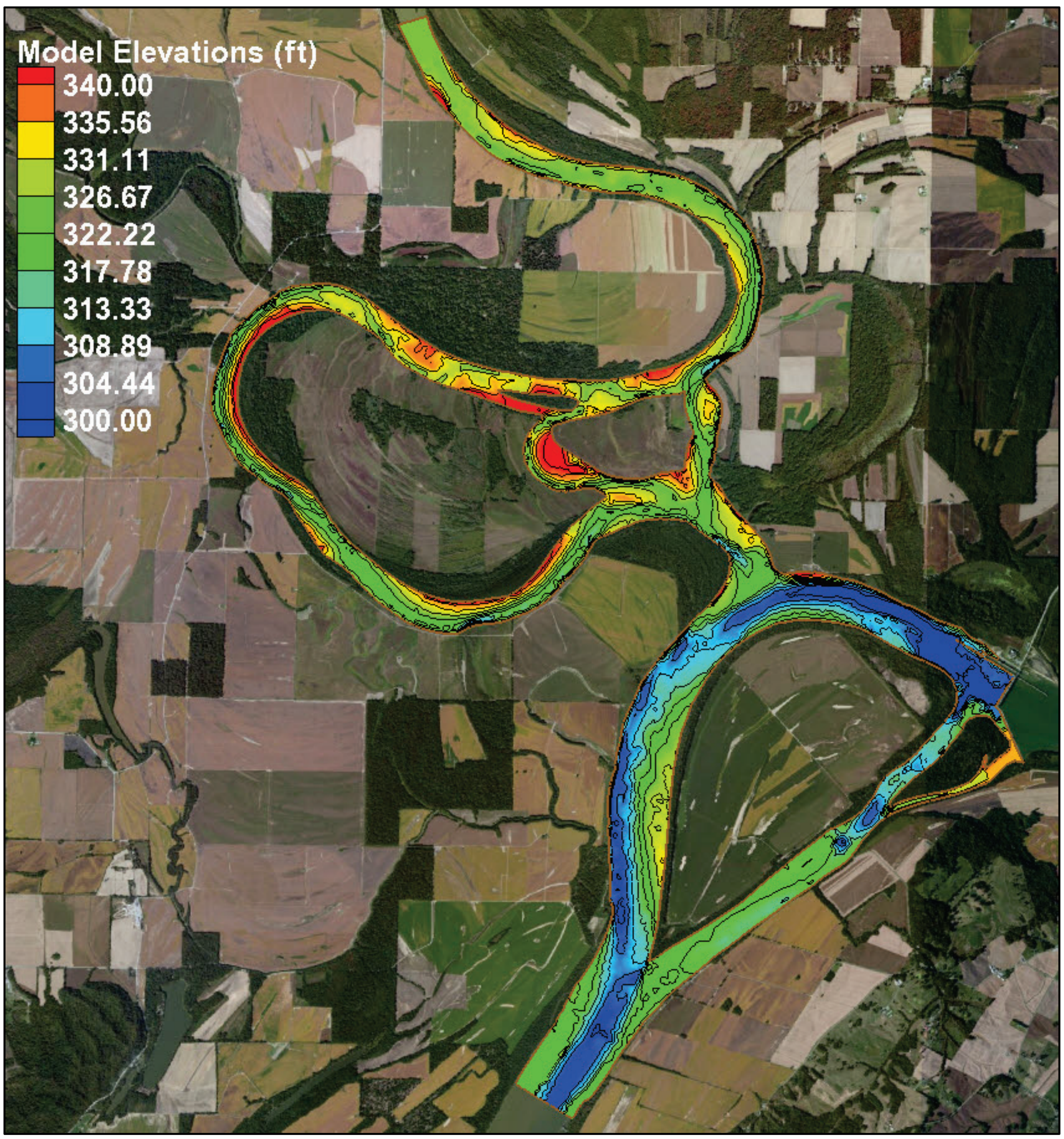
2.2 Model development

This section describes the details of the numerical modeling effort performed on the Ohio River at the confluence with the Wabash River, which was conducted in two phases. The first phase was performed in 2012 and 2013 to determine if some combination of riverine training structures could improve the navigation channel and prevent future shoaling in the Wabash Island reach. A brief description of the Phase 1 effort is provided in the next section.

2.3 Phase 1 model

The model bathymetry for Phase 1 is shown in Figure 5. Louisville District supplied the Ohio River Bathymetry from its January 2012 survey. The Field Data Collection Branch (FDCB) of the ERDC CHL in collaboration with the River and Estuarine Engineering Branch conducted a data collection effort that gathered bathymetric data for the Wabash River and sediment samples throughout the entire model reach.

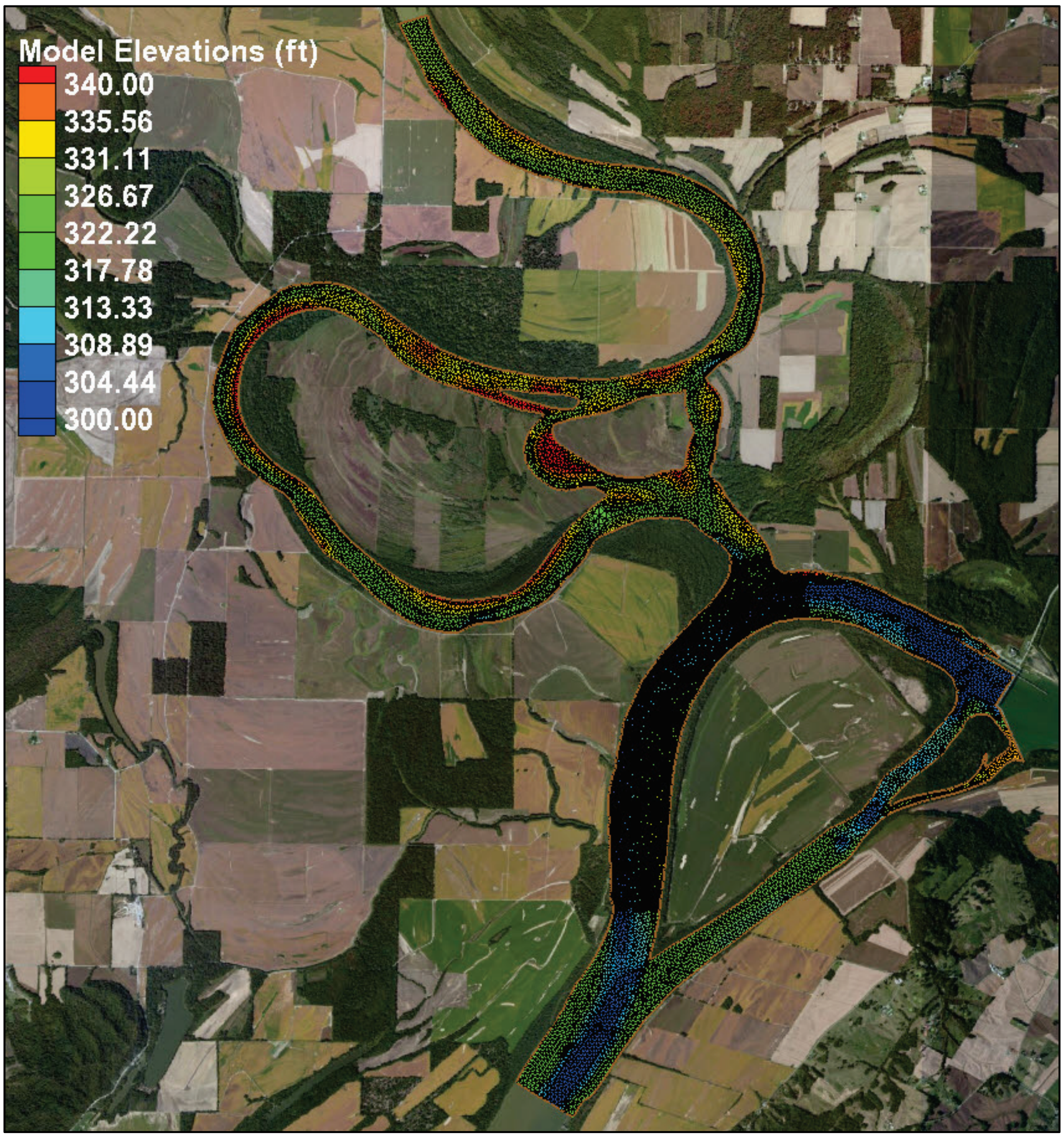
Figure 5. Phase 1 model domain with bathymetric elevations (feet).



The shoaling at the mouth of the Wabash River and farther downstream on the left descending bank of the Ohio River adjoining Wabash Island is demonstrated by the green and yellow contours. These locations with higher bed elevations indicate shallow non-navigable water.

The Phase 1 numerical model mesh, or grid, was designed so various combinations of structures could be tested. The entire mesh for the Phase 1 study is shown in Figure 6.

Figure 6. Phase 1 model domain with elements.



The model contains approximately 13,000 computational nodes and approximately 23,000 elements. The horizontal coordinate system is UTM Zone 15 North, NAD83 in meters. The vertical datum is the "Ohio River" Datum. At J. T. Myers lock and dam, this value is NGVD29 -0.35 ft. (Contact USACE Louisville District for current information on other Ohio River locations.) The flow data consist of mean daily discharge gathered by the US Geological Survey (USGS). The total flow of the Wabash and Ohio Rivers is gaged at USGS gage # 03381700 near Old Shawneetown, IL. This location is approximately 7 mi downstream of the tip of Wabash Island. The total flow from the Wabash River entering the Ohio River at their confluence is the sum of three gages and provides the Wabash River inflow boundary condition. The three gages are Wabash River at New Harmoney, IN (USGS gage# 03378500); Big Creek gage near Wadesville, IN (USGS gage# 03378550); and the Little Wabash near Carmi, IL (USGS gage#03381500). Subtracting the total Wabash flow from the flow at Old Shawneetown provided the inflow value at J. T. Myers Lock and Dam, which is the other inflow boundary to the model. The model water surface slope through the study reach compares well to measured data (Figure 7). The bed sediment gradations produced by the model also compare well to measured bed gradations obtained by field samples (Figure 8). The mesh resolution is illustrated in Figure 6. The resolution was increased in the area of concern and directly downstream where the training structures are proposed. Figure 9 shows a zoomed-in view of the area of concern with the added refinement at the proposed structure locations. This allows for testing of numerous combinations of structures. The most effective configuration was determined to be four structures on the right descending bank (Illinois side of the reach) and three structures on the left descending bank (Wabash Island side of the reach). The modeling effort of the Phase 1 study shows that the seven-dike configuration is effective in maintaining the navigation channel, holding the Illinois bank, and reducing the size of the point bar on Wabash Island. However, these dikes are sloped from the bank to near center channel and therefore could interfere with navigational safety at lower water levels.

In January 2019, a "Value Engineering Workshop" was conducted in Louisville, KY. The purpose of this workshop was to identify alternatives to the Phase 1 design that might be more cost effective, technically sound, and compatible with navigational requirements. The attendees consisted of contract workshop moderators and multidisciplinary USACE team members and Louisville District personnel. A constraint was that there should be a minimum impact on Raliegh Bar downstream of Wabash Island. After many different ideas and alternatives were suggested, four new alternatives were selected for additional testing as part of the Phase 2 modeling effort. Those alternatives are detailed in Chapter 3 of this report.

Figure 7. Phase 1 water surface elevation comparison.

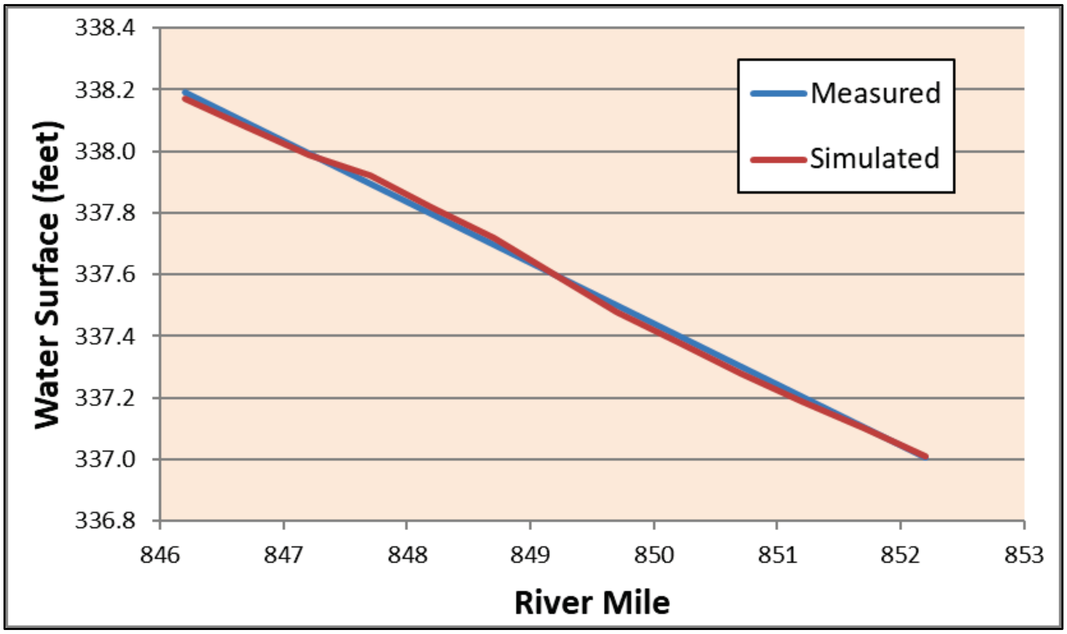


Figure 8. Phase 1 bed gradation comparison on the Ohio River near the mouth of the Wabash River.

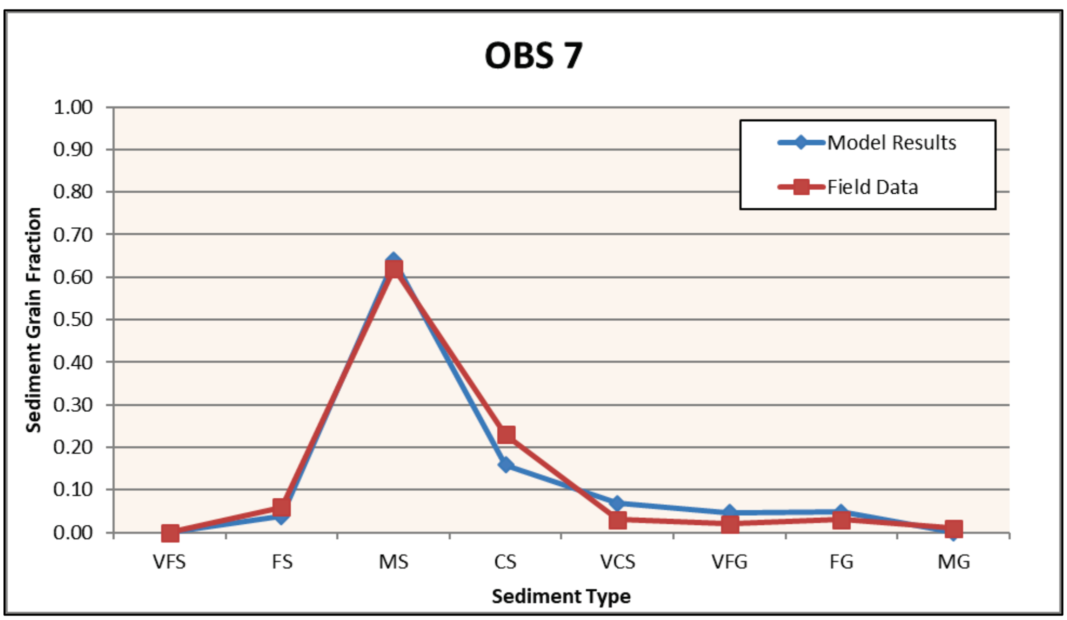
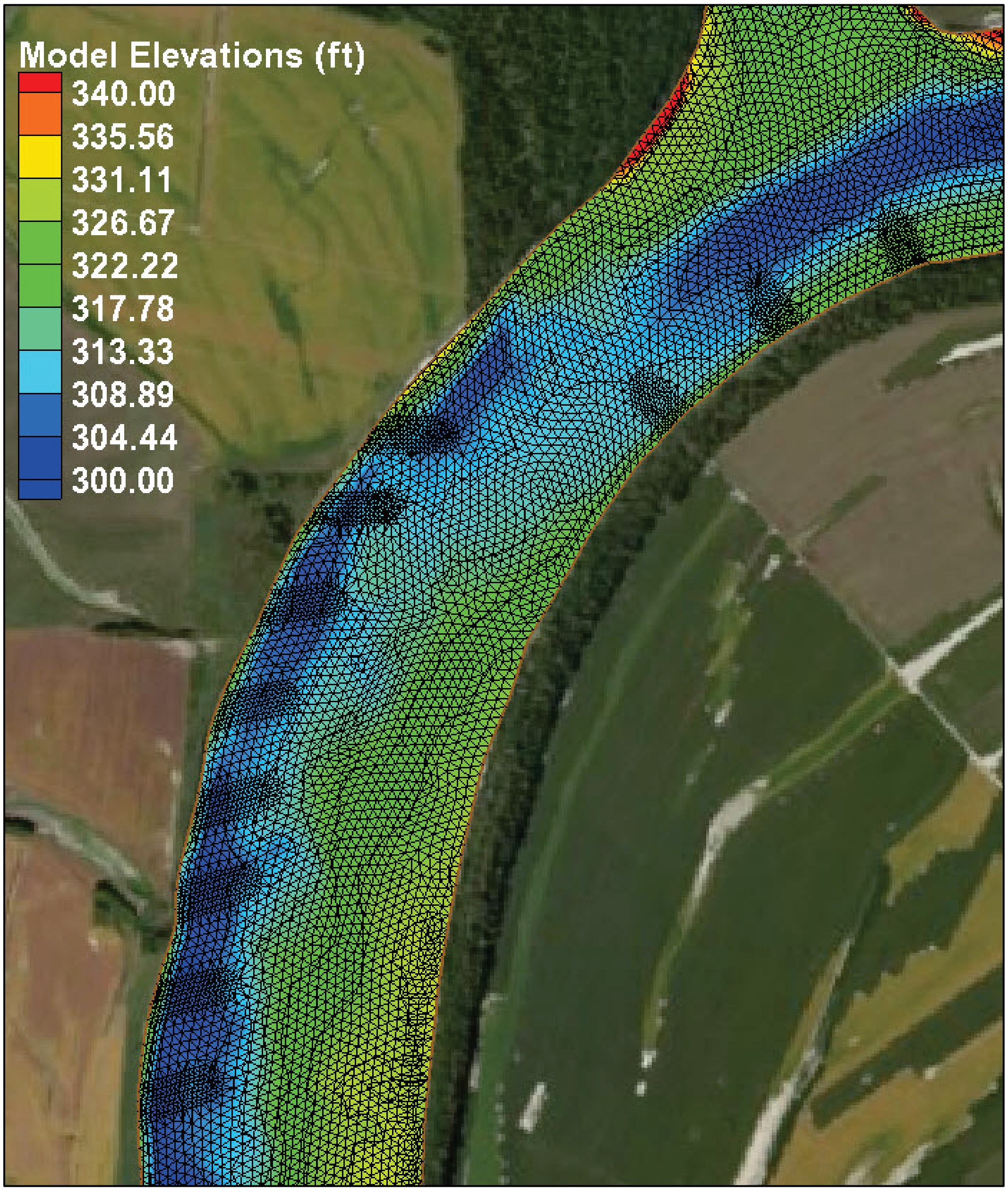


Figure 9. Phase 1 zoomed view of model elements in area of interest.



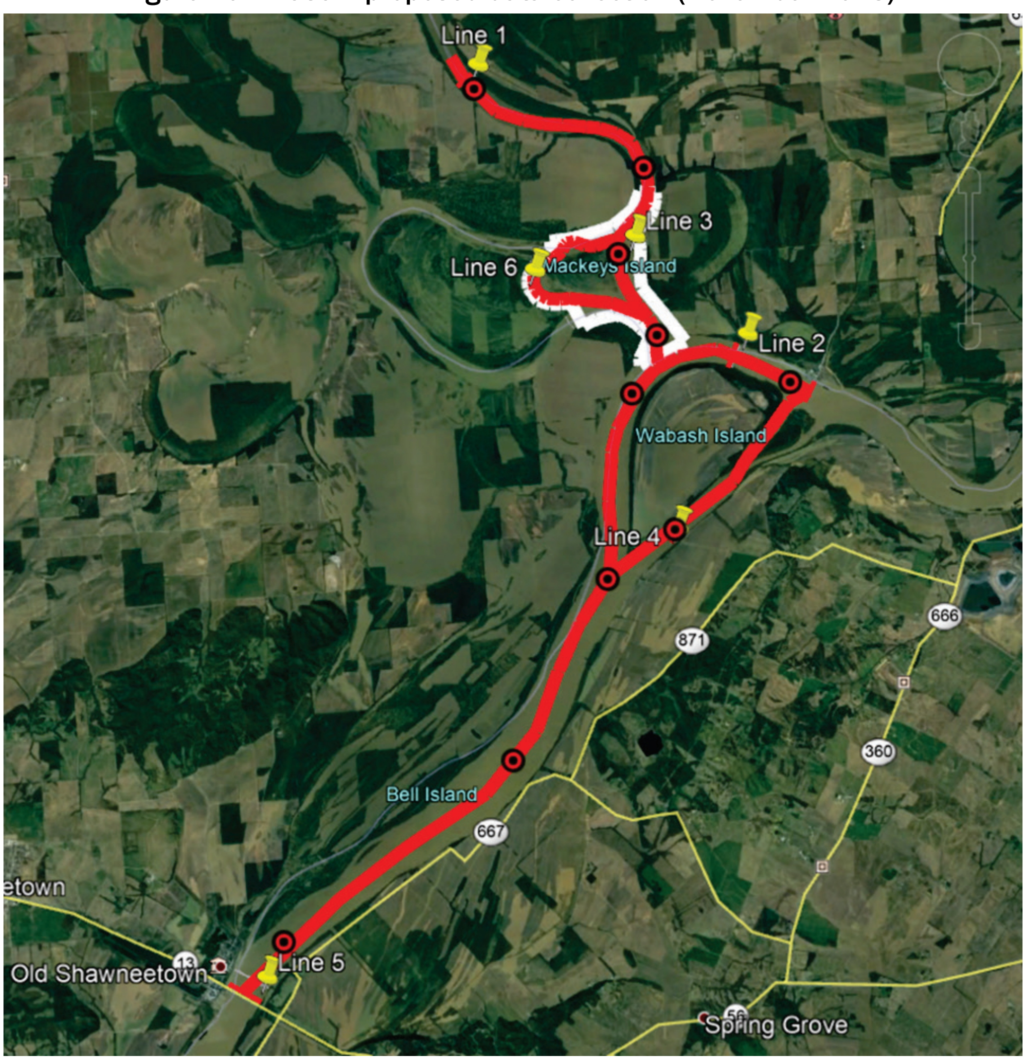
2.4 Phase 2 model

This section describes the Phase 2 modeling effort, including data collection, model development, hydraulic validation, and sediment validation.

2.4.1 Phase 2 data collection

The hydraulic calibration of the Phase 2 model was centered in the vicinity of the confluence of the two rivers and the two avulsions. There were significant changes in the morphology of the entire avulsed area between 2013 and 2018, so a second data collection effort was initiated. That effort was carried out in November 2018. Figure 10 shows the approximate locations of the various data types collected.

Figure 10. Phase 2 proposed data collection (November 2018).



The white line delineates the area of interest for the 2018 effort in the vicinity of the avulsions. The red areas indicate the portions of the rivers where multi-beam bathymetric data were acquired. These measurements captured the changes in bathymetric features from bank to bank that occurred since the Phase 1 data collection. This was possible because of the high flows at the time of the data collection effort. The actual bathymetric elevations can be seen in Figure 27 of this report. The new bathymetric data were used to update the numerical model bathymetry for utilization in the Phase 2 modeling.

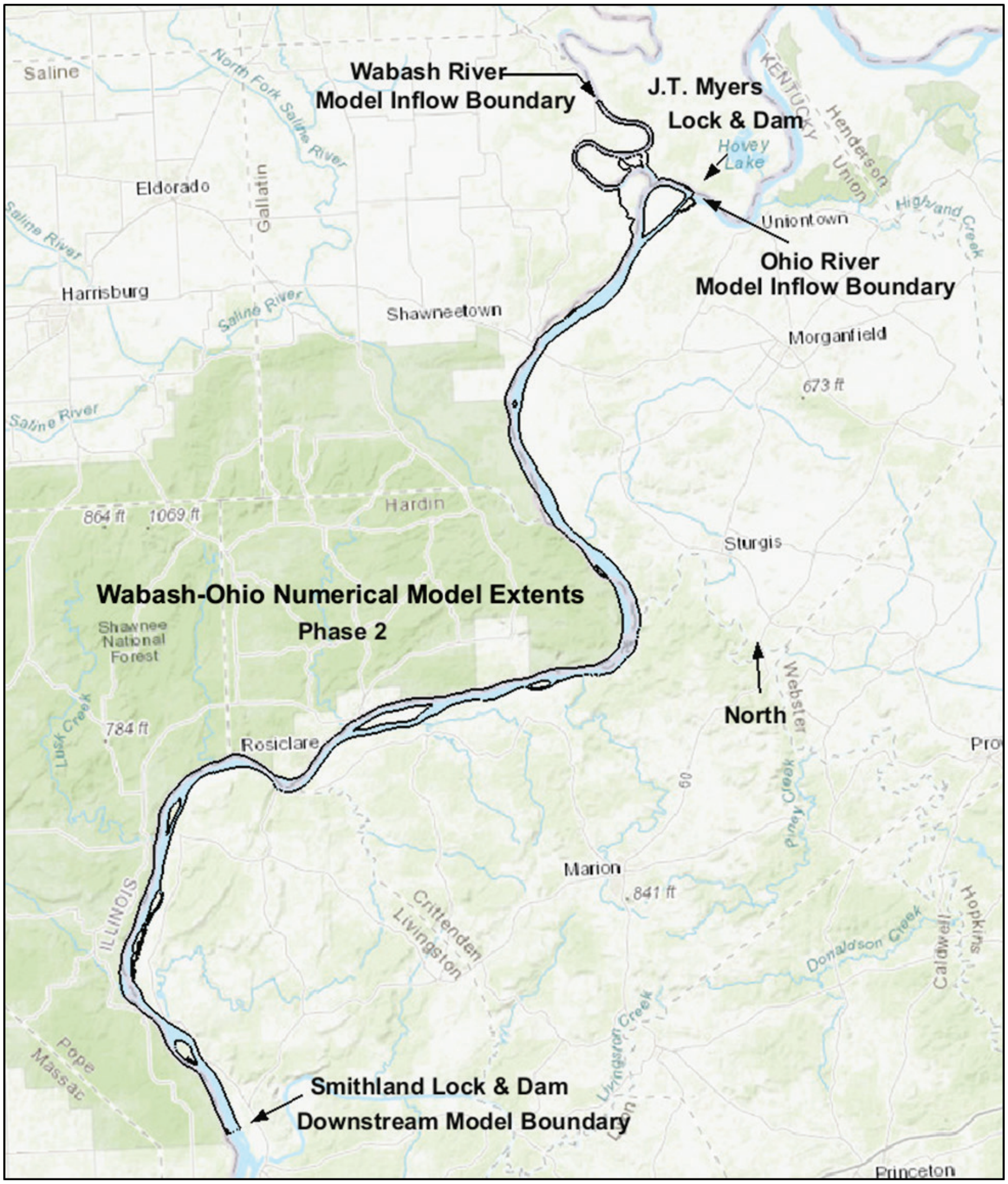
During this time, additional data were collected via acoustic Doppler current profiler (ADCP) and sampling of bed gradations and suspended sediment. The black and red circles in Figure 10 show the locations of bed samples and the “Line #” labels show the cross-section locations of ADCP velocity measurements and suspended sediment samples.

Multi-beam data were not collected downstream of Old Shawneetown Bridge. Channel bathymetric cross section data were provided by the District at approximately 400 ft longitudinal spacing from the Old Shawneetown Bridge to the downstream model boundary at Smithland Locks and Dam.

2.4.2 Phase 2 model and hydraulic validation

The Phase 2 model was created by updating the bathymetry from the Phase 1 model with the model domain extended downstream to Smithland Locks and Dam (Figure 11). The vertical datum is given in Section 2.3. This datum is used in all elevations in the study area of interest.

Figure 11. Extents of the Phase 2 model.



The model was extended to that location to evaluate sediment impacts farther downstream of the model study area. It also provided a reliable downstream boundary condition. The J. T. Myers Locks and Dam is located at RM 846.2, and the Smithland Locks and Dam is located at RM 918.5. The length of the Ohio River portion of the model is approximately 72 RM.

The Phase 2 mesh was modified to provide structure placement at the locations shown in Figure 11. Six positions were considered on the Illinois side of the river, enclosed by the white line. One structure was placed at the mouth of the Wabash, and three structures were placed on Wabash Island, enclosed by the black line. These structure locations show up as dark patches on the banks of the Ohio River shown in Figure 12 because mesh resolution was greatly increased around each structure to capture the necessary bathymetric details. From these 10 locations, different alternative configurations were modeled, not necessarily using all 10 locations.

Figure 12. Phase 2 model: numerical mesh in the study area.

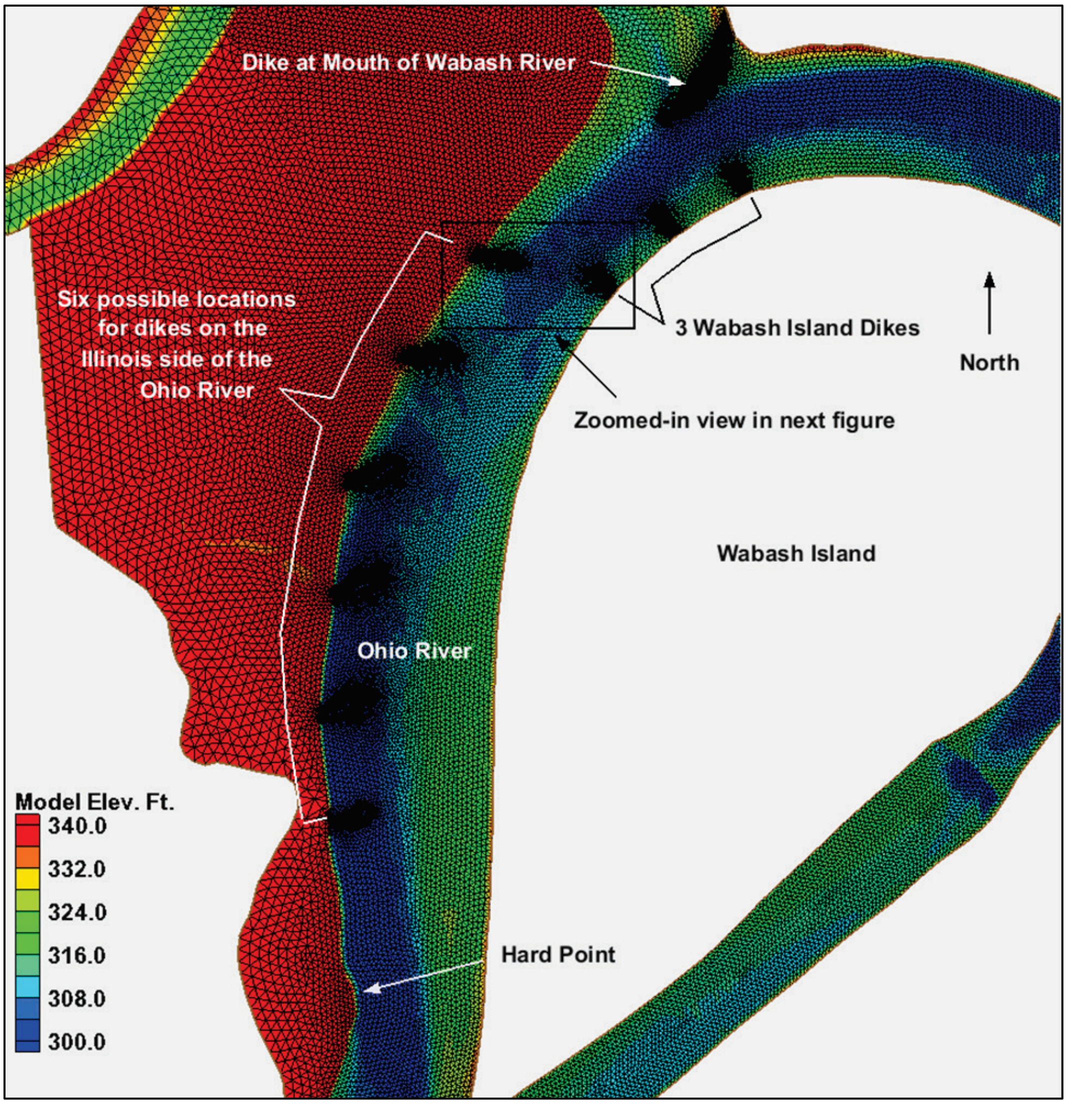
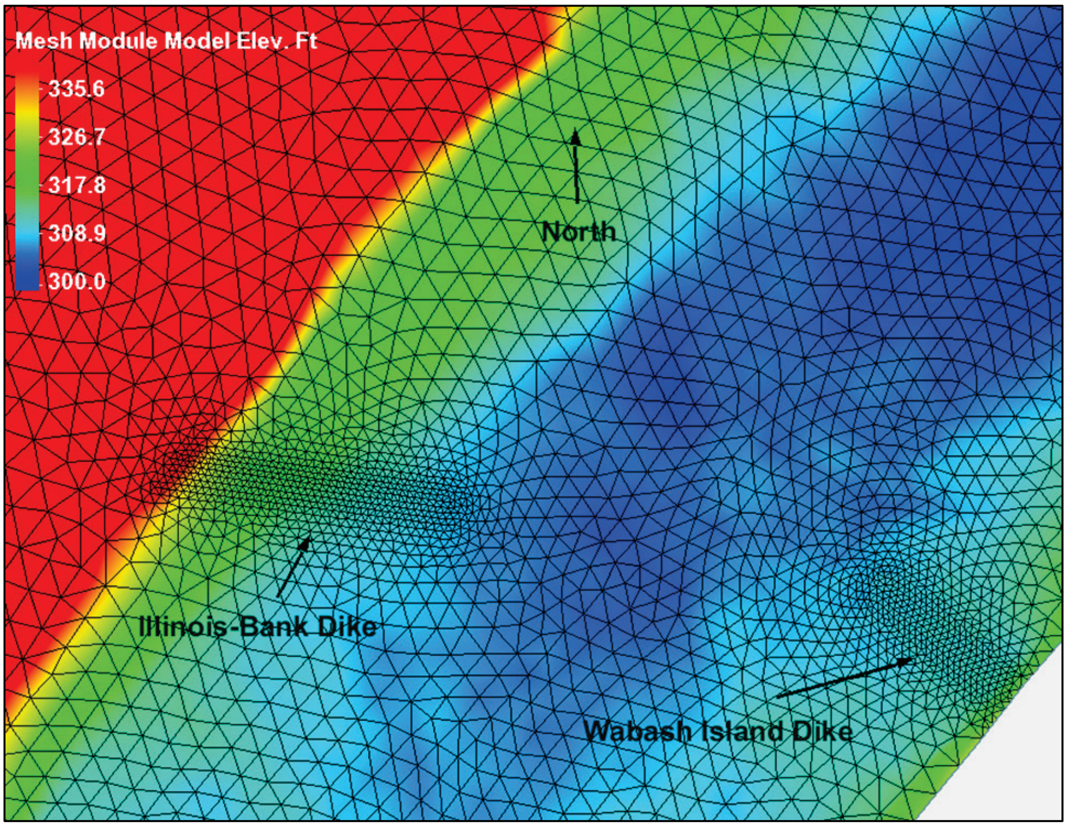


Figure 13 shows a zoomed-in view of two of the potential structure locations. In this figure, the elevations of the nodes in the structure represent the bottom of the river since it is a base condition with no raised structures. It shows the third dike location on the Wabash Island side and the first dike location on the Illinois bank.

Figure 13. Zoomed-in view of two structures.



The entire Phase 2 model consists of approximately 220,000 elements, 116,000 nodes, and 12 different material types. Material types are used to specify resistance to flow. Significant morphological changes occur in the study area between the Phase 1 modeling effort and the Phase 2 modeling effort. In the old Wabash bend and in the avulsed channels, these changes include major channel infilling, migration of sand bars, and major changes in the type and amount of vegetation in and on the banks and bars. To properly represent these changes, more material types were required. Figure 14 shows the revised material-type map, and Table 1 lists the friction type and values used for the Phase 2 model. Values for some of the parameters stayed the same, such as the main channels, but others required updated values due to vegetative changes between the Phase 1 and Phase 2 efforts. Also, some of the vegetated areas were updated with

Unsubmerged Ridged Vegetation (URV) specifications instead of the more familiar Manning's *n* value. URV is used to more accurately define friction impacts of larger vegetation such as shrubs and trees. Three factors are specified as input on URV cards: bed roughness height, average stem diameter, and stem density. Guidance for these values can be found in the AdH user manual (Savant et al. 2014) as well as Bell et al. (2017) and Bell et al. (2018). In this study, values for URV material types 3, 10, and 11 were assigned as shown in Table 2.

Figure 14. Numerical model materials.

Table 1. Manning's *n* and URV values for Phase 2 model materials (2018).

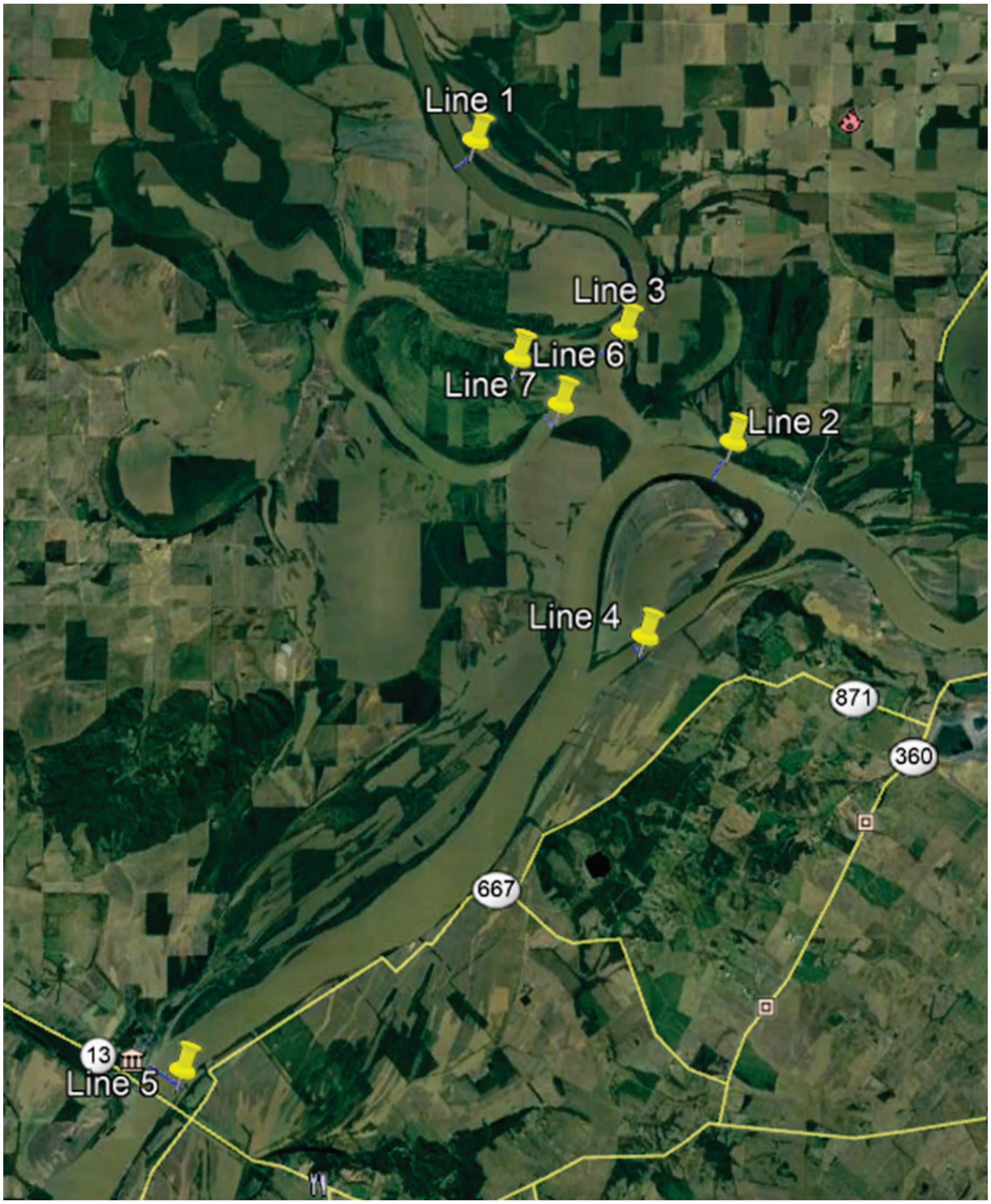
Material Number	Description	Friction *n*-value
1	Old Wabash River Bend Channel and 2010 Avulsion Channel (red)	0.028
2	Sand Bars (light blue)	0.030
3	Vegetated Bars (grey)	URV 3
4	Structure at Mouth of Wabash (orange)	.026
5	Ohio River Channel (gold)	0.024
6	Head Bay for Wabash River (pink)	0.028
7	New Structures (purple)	0.024
8	Rip-Rap Area Just Downstream of Dam (light green)	0.024
9	Vegetated Floodplain between Old Wabash Bend and Ohio River, Also, Rock Sill in Ohio Back Channel (mauve)	.028
10	Forested Area of Floodplain between Old Wabash Bend and Ohio River (dark green)	URV 10
11	Infilled and Vegetated Old Wabash North Bend Channel (dark brown)	URV 11
12	2008 Avulsion Channel (brown)	.024

Table 2. URV card specifications.

URV Number	K (m)	Diameter (m)	Stem Density (number of stems per sq m)
3	0.02	1.5	0.1
10	0.02	1.5	0.1
11	0.02	1.95	0.25

The hydraulic calibration of the Phase 2 model consisted of comparing measured flow splits through the avulsed channels of the Wabash River and main channels of the Ohio River with model output flow values at the same locations. ADCP flow measurements were made at the line numbers indicated in Figure 15 on 6 – 7 November 2018. The yellow pins show the approximate location of each line. Line 5 is just upstream of the Highway 13 (Old Shawneetown) Bridge, or approximately 7.4 mi downstream of the southern tip of Wabash Island.

Figure 15. ADCP flow measurement locations.



The measured flow data were obtained with an ADCP on 6 November 2018 for lines 2 and 4 (Ohio River). Measured ADCP flow data for lines 1, 3, 6, and 7 on the Wabash River and line 5 on the Ohio River were obtained on 7 November 2018.

USGS gages on the Ohio River (03381700, Old Shawneetown IL-KY), and the Wabash River (03378500, New Harmony, IN) show significantly increasing flows during data collection on 6 – 7 November 2018. Increases in flow up to 14,000 cfs in the Ohio River and 3,000 cfs in the Wabash River in a 24 hr period were reported. These rapidly changing flows in combination with the fact that lines 2 and 4 (Ohio River) were taken a day earlier than line 5 (Ohio River) complicated the model validation. The rising backwater of the Ohio River into the avulsed channels of the Wabash River causes a reduction in velocity and increased storage in those channels. This can be seen in the "Measured Discharge" data of Table 3, since the sum of measured flow values for lines 3, 6, and 7 is less than the measured flow at line 1, indicating a decrease in velocity and/or increase in water levels of the avulsed channels. The model hydrograph covers the time period 26 September 2015 to 26 September 2017 while the measured data were obtained in November 2018. There was no way to compare timed measured data to any dynamic simulation.

Table 3. Measured discharges.

			Measured Discharge			Model Results		
	String	Line	Q (cfs)	Q (cms)	%	Q (cfs)	Q(cms)	%
Wabash River	Wabash	1	67737	1918		62684	1775	
	Old Channel	7	808	23	1%	1021	29	2%
	2008 Cutoff	6	5219	148	8%	4407	125	7%
	2010 Cutoff	3	56651	1604	90%	57256	1621	91%
Ohio River	Main Channel	2	175144	4960	63%	174017	4928	62%
	Behind Island	4	103864	2941	37%	105005	2973	38%
	Total Ohio	5	363465	10292		341705	9676	

For all these reasons, a single steady state simulation was used for a verification run; it was named It2_B_DB. The strategy was to use the measured-versus-model flow splits at lines 7, 6, 3, 2, and 4 to infer model predictive capability. These locations are all interior locations whose flow-sum should reflect the flow input at their common boundary along with the rising-Ohio-River backwater effect. When given the same boundary inputs, the model should reproduce a similar percentage of flow through the various channels as was measured. A presumption here is that the flows were measured simultaneously, which, of course, they were not. Therefore, it is a source of uncertainty. The best approximation for the Wabash boundary inflow was the sum of the measured discharge of the three avulsed channel locations, lines 3, 6, and 7, which was 62,639 cfs. For the Ohio River boundary inflow at J. T. Myers Locks and Dam, the best approximation was the sum of the measured discharge of the two channels at lines 2 and 4, which was 278,826 cfs. The downstream boundary elevation at Smithland Locks and Dam for these conditions was

322.88 ft. The steady state simulation mentioned above along with those boundary conditions produced the model results shown in Table 3.

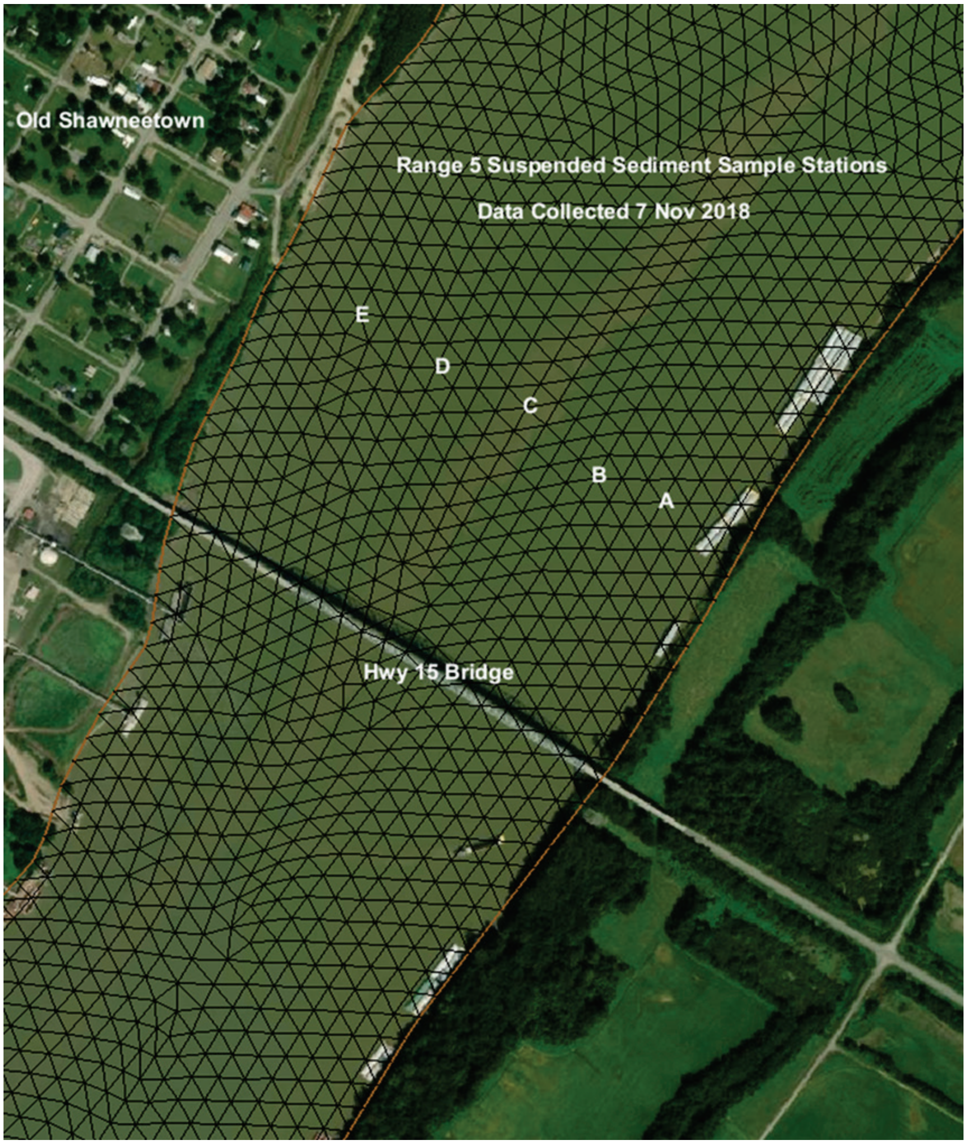
Table 3 shows a comparison of the measured and modeled flow values and percentages of flow at the interior locations (lines 2, 3, 4, 6, and 7). The percent “Measured Discharge” for lines 7, 6, and 3 in the table is derived as the flow at each line divided by the sum of the three lines. Likewise, for the Ohio River, the percent “Measured Discharge” for lines 2 and 4 in the table are derived as the flow at each line divided by the sum of the two lines. The model percent values were determined in the same manner. As seen in the table, the flow split percentages of the model results are very similar to the flow split percentages of the measured data, thus providing confidence in the model’s predictive capability with respect to hydraulics.

2.5 Phase 2 model sediment validation

With flow splits validated, the next important parameter to validate was the sediment transport. This can be done by comparing measured suspended sediment and bed gradations with the model output for these parameters.

The 2018 data collection effort performed by the FDCB measured suspended sediment samples at lines 1, 2, 4, and 5 shown in Figure 15 with a P6 sampler (USGS 2011). Line 5 just upstream of the Old Shawneetown Bridge is shown in the body of this report. The other lines (also referred to as ranges) are given in Appendix B. The five positions for line 5 at which samples were obtained are shown in Figure 16.

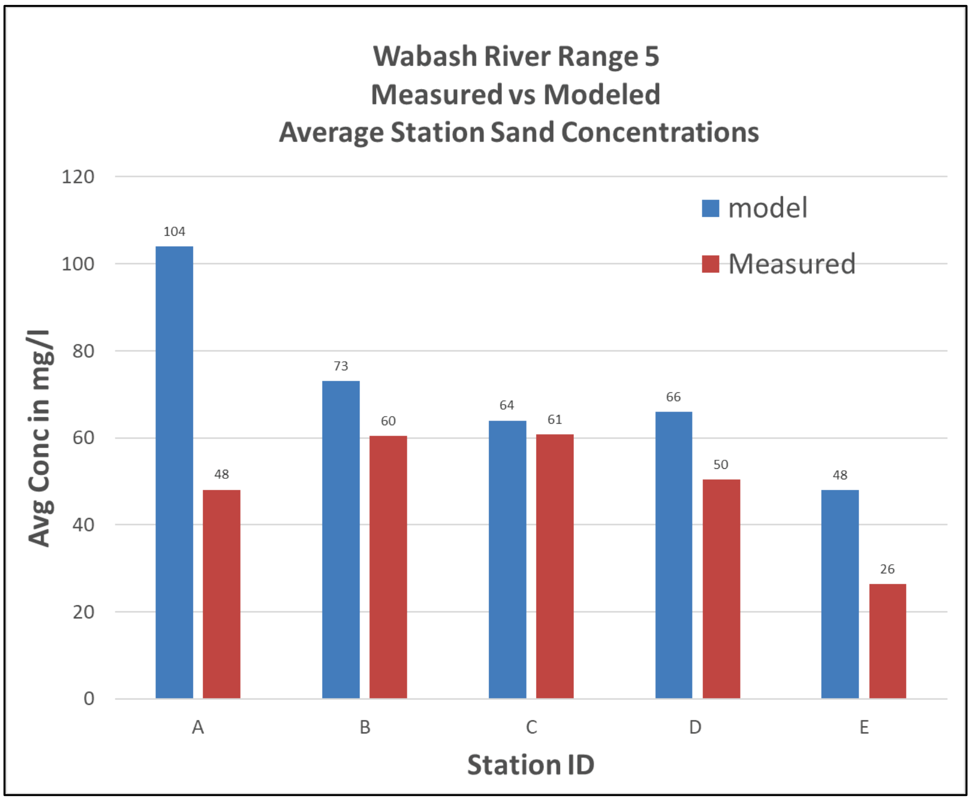
Figure 16. Range 5 suspended sediment sample locations.



Flow is in the downward-left direction. Four to five separate samples were obtained at each station, starting at 3 ft below the surface until just above the bottom. Since the model is depth-averaged, an average value of the samples in the vertical for each station was calculated and compared to the model results.

Suspended sediment samples were taken on 6–7 November 2018. USGS (Old Shawneetown gage) recorded flows ranging from ~284,000 to 416,000 cfs (10,021 to 14,679 cms) from 2 to 8 November 2018 on the Ohio River. Similar conditions in the model hydrograph occurred between 29 April to 5 May 2017 (model days 946–952). Modeled flows in that time period ranged from 279,805 to 416,868 cfs (9,873 to 14,710 cms). This was also a rising limb of the hydrograph following a series of moderately low flows as in the USGS hydrograph. Because of these similarities, days 946 to 952 of the model output were used to compare suspended sediment concentrations. Summed sand concentrations from each nodal location at these times were extracted for the comparison. An average value was computed from day 946 to 952 for each node. Thus, each model value was averaged vertically in space (four to five samples were taken at each station) and over the time interval mentioned. Figure 17 shows the results for Range 5.

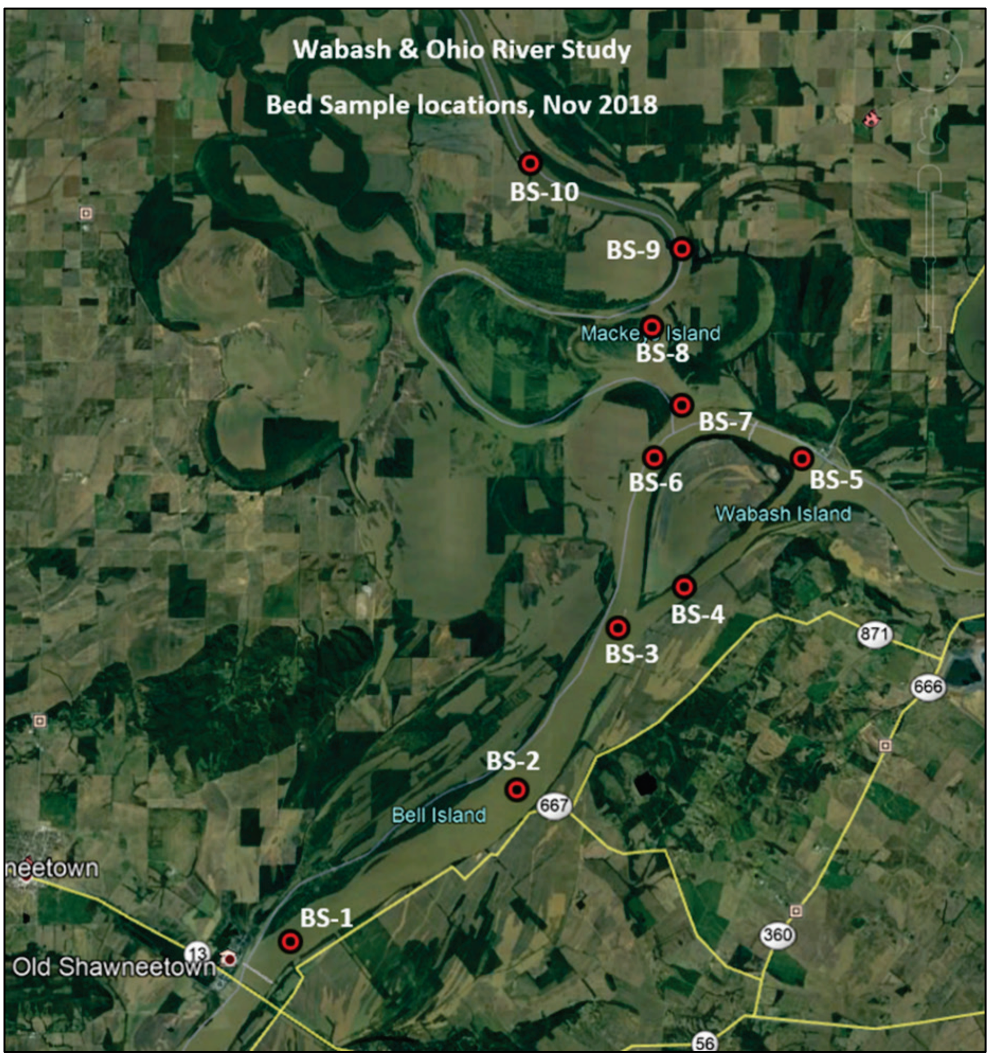
Figure 17. Model vs. measured suspended sediment concentrations.



While the difference between modeled versus measured values for Station A and E are nearly or slightly more than double, the interior values are very close to the measured values. Overall, for the range, the average difference between measured and modeled values is approximately 51%. For sediment transport comparisons in natural rivers, these values are acceptable. For a discussion of the range of variability that can exist within measured samples themselves, see the “Summary and Conclusions” in USGS Professional Paper 1333 (Burkham 1985). Standard sampling errors range from 2.5% up to 70%. Considering this sampling error range, the difference between model and measured values could just be due to the variability of the measured samples as the differences between modeled and measured concentrations fall within the noted range of variability. Errors for the other three ranges shown in Appendix B are all in better agreement with the measured values. Thus, the numerical model results should be considered sufficiently accurate for the purposes of this study, especially in view of the rapidly changing flow conditions during the sediment field measurements.

Comparisons for the other three ranges for which suspended sediment samples were obtained (Ranges 1, 2, and 4) are given in Appendix B. Bed samples were obtained during the November 2018 data collection effort. The locations of each sample are shown in Figure 18 and are noted as BS-XX, where XX represents the measurement location.

Figure 18. Bed samples obtained at time and locations as indicated.



Bed samples provide information about the bed materials (commonly referred to as sediments) that make up the bed of the river. These samples will reveal, for example, whether the bed is composed of sand, silt, clay, gravel, crushed shells, etc., and/or any combination of these. The varying sizes or gradations of the granular material can also be determined from properly collected bed samples. Knowledge of the type of granular material and its gradation is important in sediment transport modeling. There are big differences in how water erodes, transports, and deposits the various types and sizes of sediment. Sediments can vary significantly in terms of shape, density, fall velocity, and electrostatic charges, all of which play important roles in the erosion, transport, and deposition of the sediments.

When simulating sediment transport, the model must account for these processes throughout the model domain. It does this through bed sorting and re-sorting, which can be used as a means of validating whether the sediment transport functions are performing correctly for the given conditions. If the model can reproduce the measured gradations of the bed with reasonable accuracy, then the model can be considered validated with respect to bed-material load processes. Plots of measured versus modeled gradations at a given location provide visual indications of the accuracy of the model in replicating the field data.

Bed samples were taken on 2 November 2018. The hydrograph for the Ohio River on that date recorded 252,189 cfs (7,147 cms), on a rising limb. Similar conditions in the model hydrograph for which output data were written occurred on 20 December 2016 (model day 816) with 226,154 cfs (6,408 cms). This was also a rising limb following a series of moderately low flows.

The measured bed samples were sorted into sediment classes by grain size from very fine sand to medium gravel. The locations shown for comparison with model data were those in the Ohio River main channel, since the study is focused on what will happen in the vicinity of the dike field and downstream, specifically those for the main channel at BS-6, downstream of Wabash Island at BS-3 and Raliegh Bar at BS-2. These are shown in Figure 19 – Figure 21, respectively. The sand sizes in the figures follow the Wentworth scale classification (included as Appendix A) for sediments. The model nodes used for the comparison were no more than 30 ft from the location where the bed sample was taken.

Figure 19. Bed gradation comparison, model vs. measured, at BS-6.

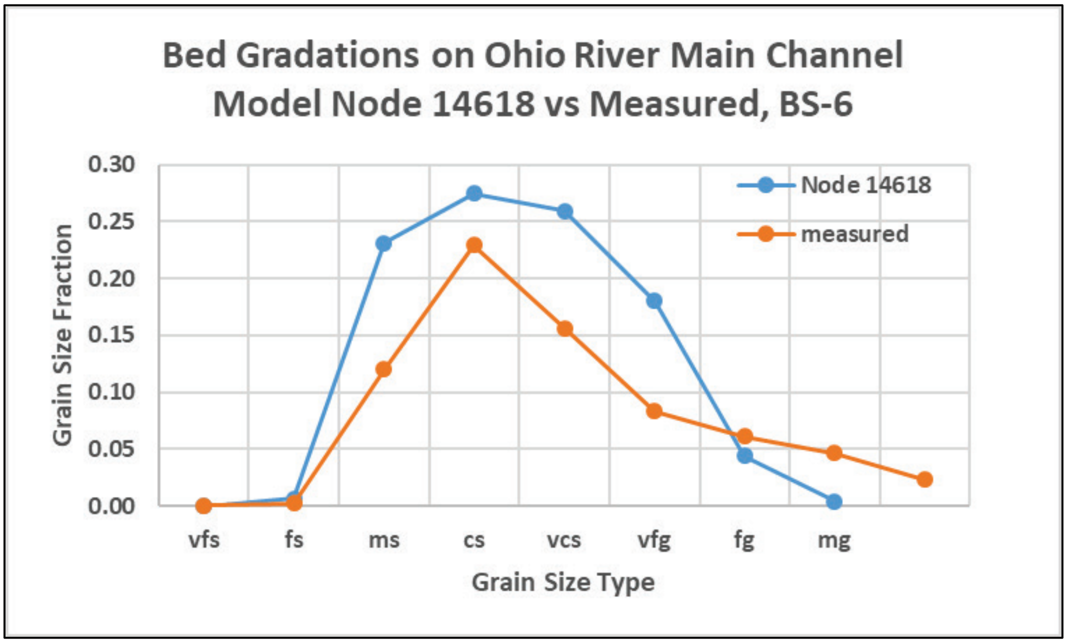


Figure 20. Bed gradation comparison, model vs. measured, at BS-3.

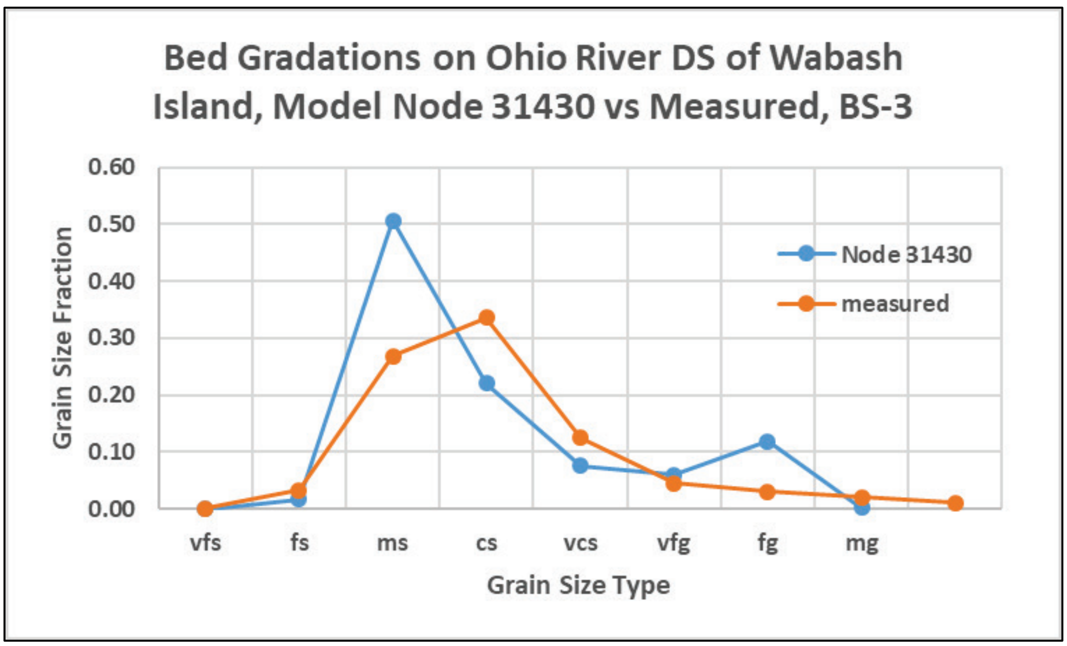
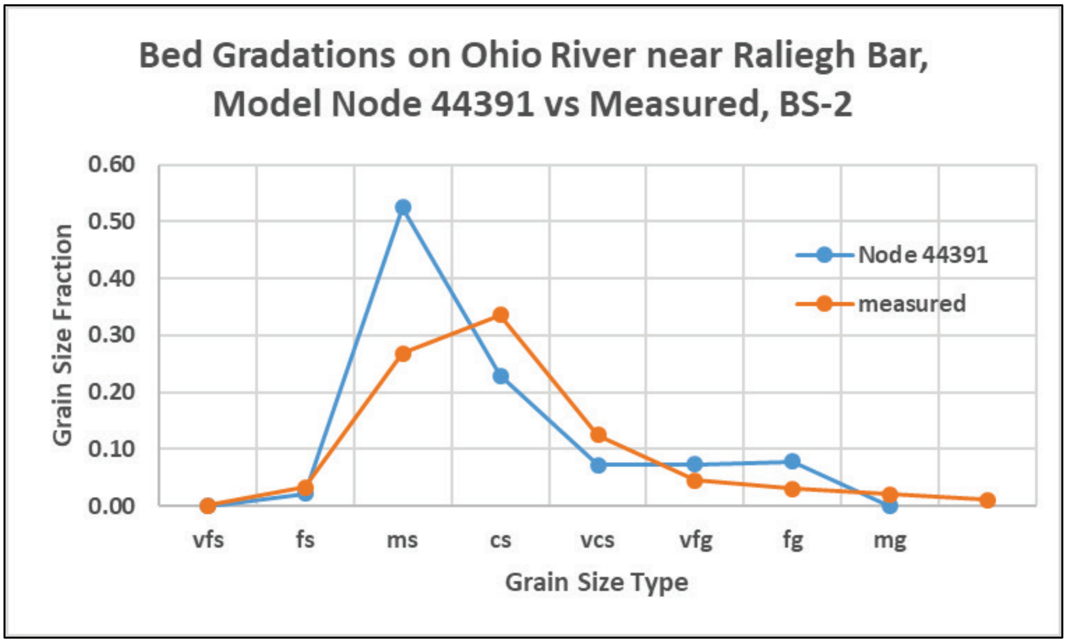


Figure 21. Bed gradation comparison, model vs. measured, at BS-2.



The model bed gradations compare favorably with the measured bed samples, both in terms of size distribution and percentage quantities. The coarser grain sizes are slightly overrepresented in sample BS-6. In the other two samples, only the medium sand shows any meaningful difference with the measured data, and that difference is approximately 25% or less.

Based on the above results, the model adequately replicates the sediment transport observed in the field for the purposes of this study.

3 Phase 2 Model Simulations and Results

3.1 Alternative simulations

As a result of the Value Engineering Workshop mentioned in Section 2.3 of this report, four new alternatives were chosen to be tested with the Phase 2 model. In the discussion that follows, the alternatives are identified by their model run name, for example, “It2_HP.” Those alternatives are the following:

1. Alternative It2_HP, the removal of a bank line, natural (not man-made) “hard point,” is shown in Figure 22. This location on the right descending bank just downstream of the proposed dike fields consists of a harder, less erodible, bank material. Its projection into the flow field was suspected by district personnel of influencing tow traffic by causing a constriction of flow. It was suggested that removing it might provide a more uniform velocity field across the river at that point. Though the dikes are shown in the figure, they have no effect on flow in this simulation because their elevations and friction values are set to that of the channel. The natural hard point elevations were also set to channel elevations. Therefore, the difference between this run and the base condition is only the removed natural hard point.
2. Alternative It2_W3, a 500 ft long dike, was proposed as a viable alternative. Such a structure was not proposed in Phase 1. It would extend across approximately 80% of the width of the Wabash River Mouth. It is shown in Figure 23 with a suggested crest elevation of 337.8 ft. Four level crested dikes on the Illinois bank with crest elevations of 312 ft were included as well.
3. Alternative It2_MD consists of six dikes on the right descending bank, level crested, and at elevation 312 ft. Two dikes are placed on Wabash Island and are sloped downward from the bank to their tip, as noted in Figure 24.
4. Alternative It2_PC330 is a seven-dike plan in the same layout as the Phase 1 “most effective” configuration mentioned (but not shown) in Section 2.3. The major difference is that this alternative has level crests on both sets of weirs (Illinois bank and Wabash Island bank), and the weirs are sized to actual planned construction dimensions. The top of the dikes is held at a constant elevation of 312 ft on the Illinois bank from its intersection with the bank out until its tip in the interior of the river. The dikes on the Wabash Island side of the river are likewise held

at a constant elevation from its intersection with the bank out until its tip in the interior of the river, but at an elevation of 330 ft. These are shown in Figure 25.

Figure 22. Remove hard point, Model Run: It2_HP.

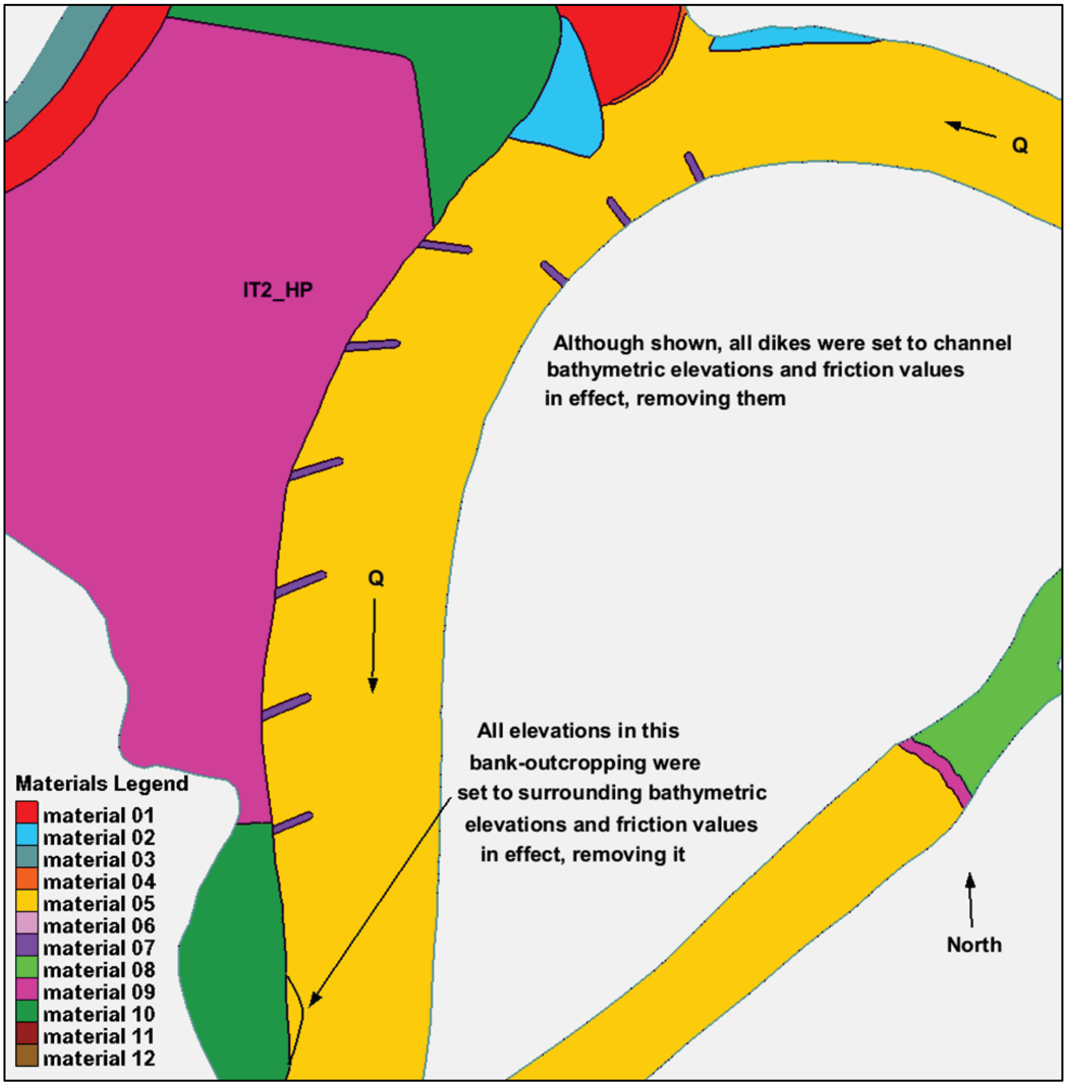


Figure 23. Model Run: IT2_W3.

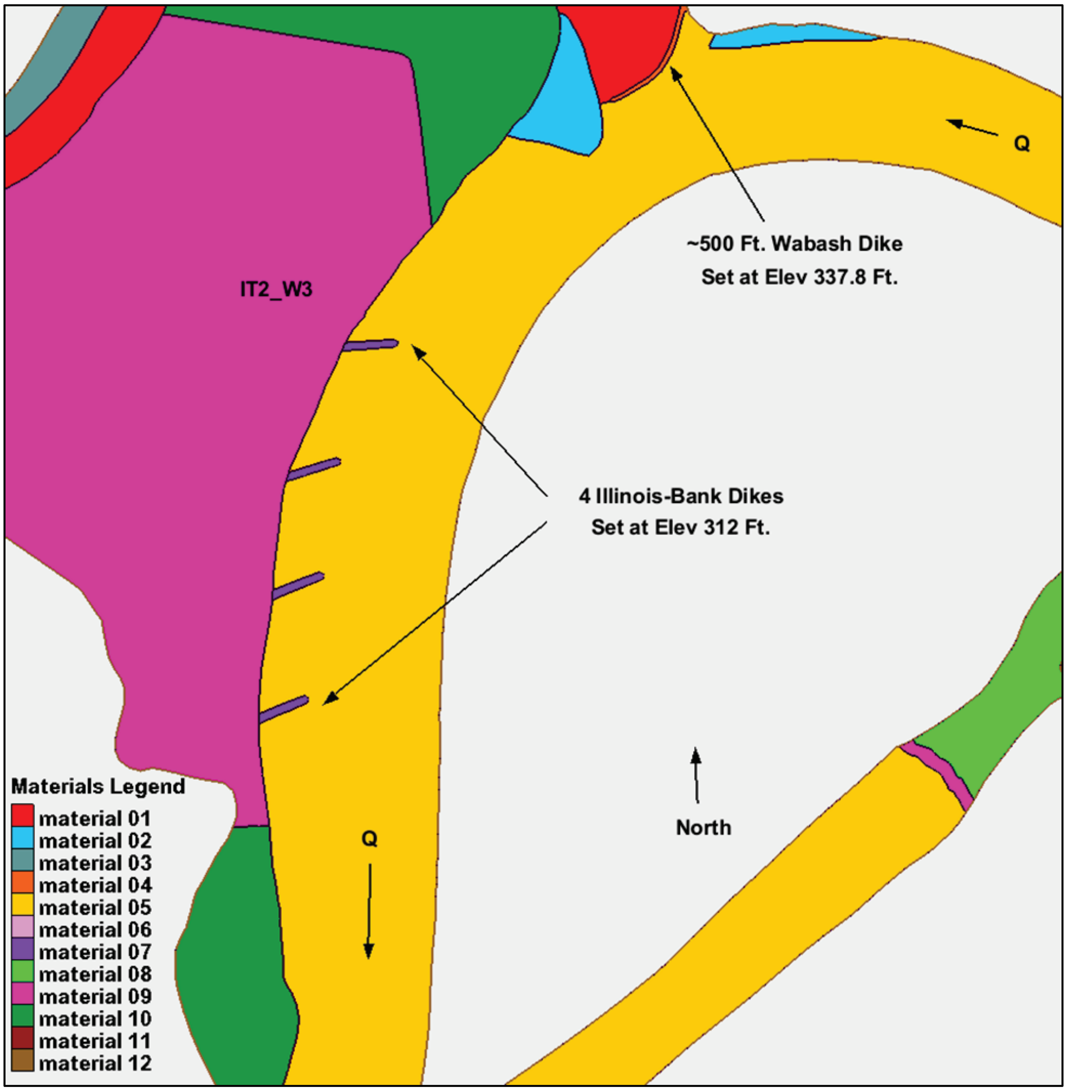


Figure 24. Model Run: It2_MD.

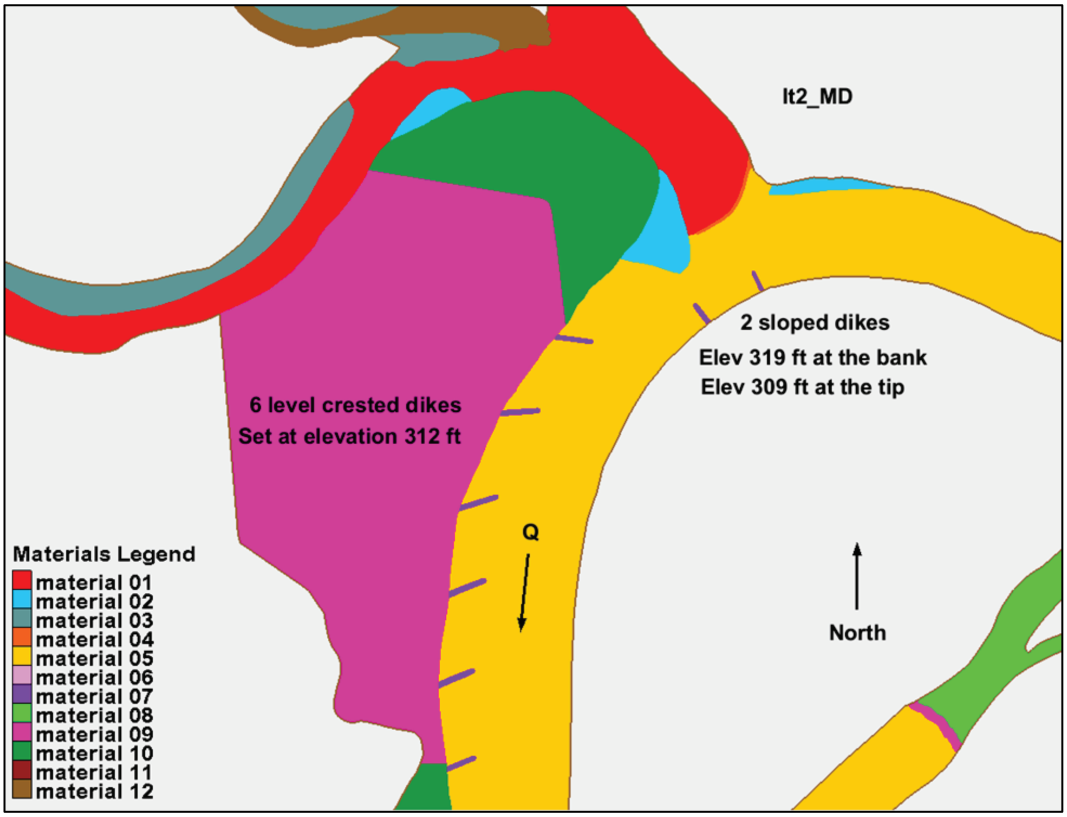
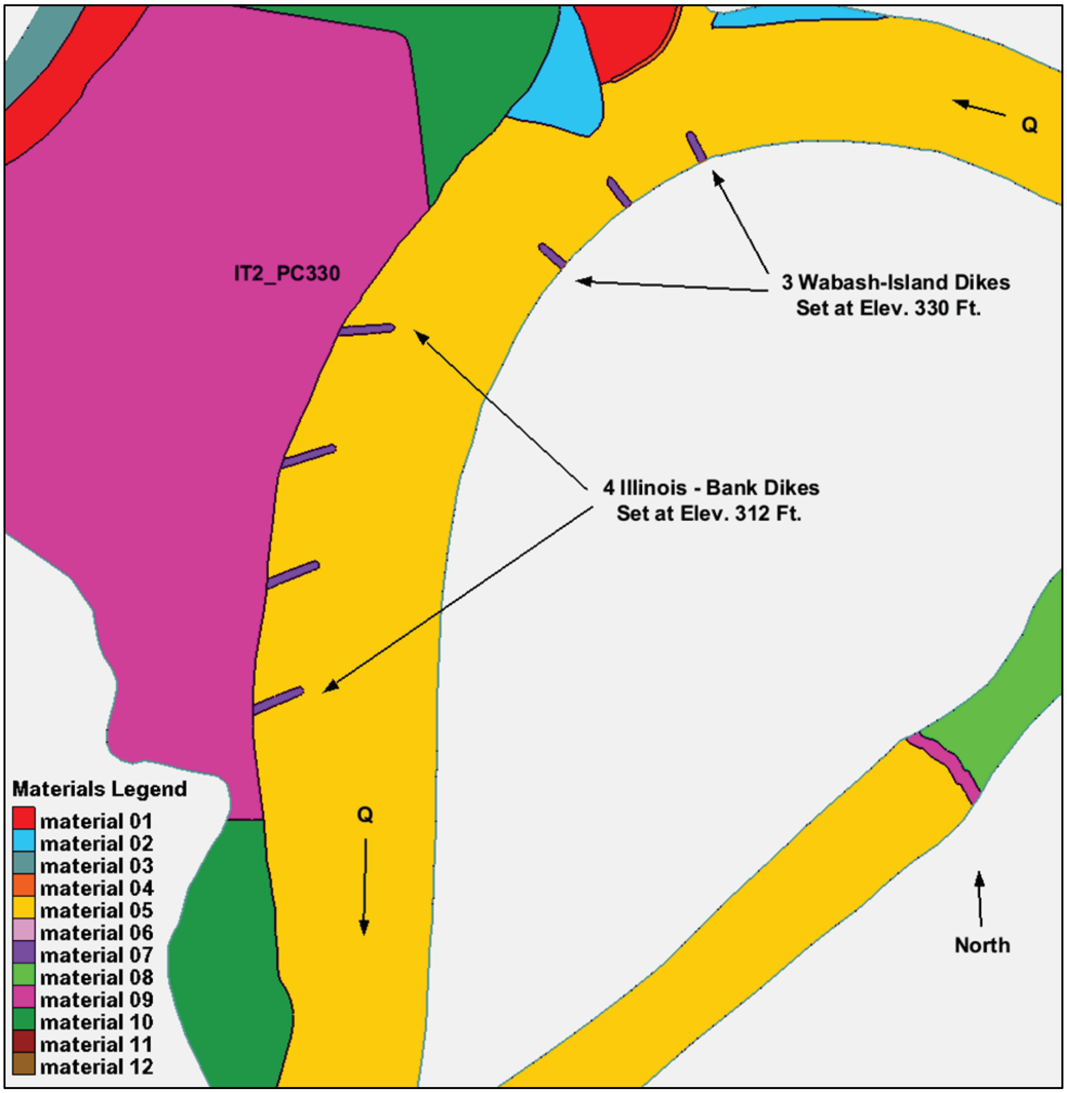


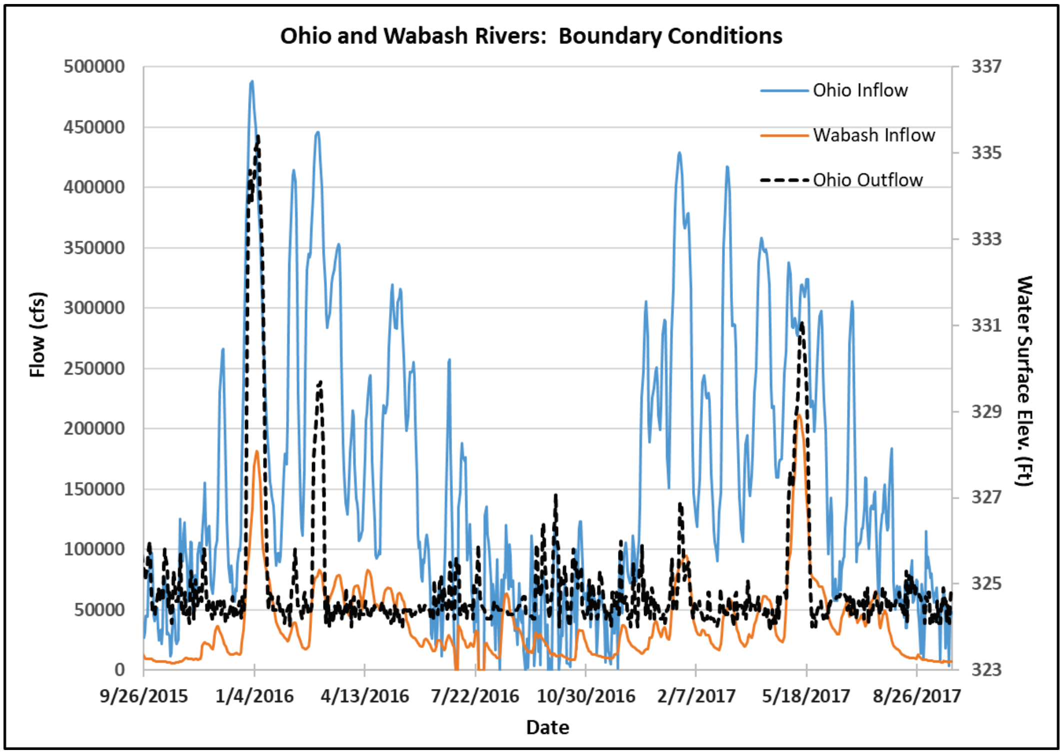
Figure 25. Model Run: It2_PC330.



3.2 Model boundary conditions and simulations

All the above alternative simulations were run using a 2 yr hydrograph from 26 September 2015 to 26 September 2017, as shown in Figure 26.

Figure 26. Model inflow hydrograph from 26 September 2015 to 26 September 2017.

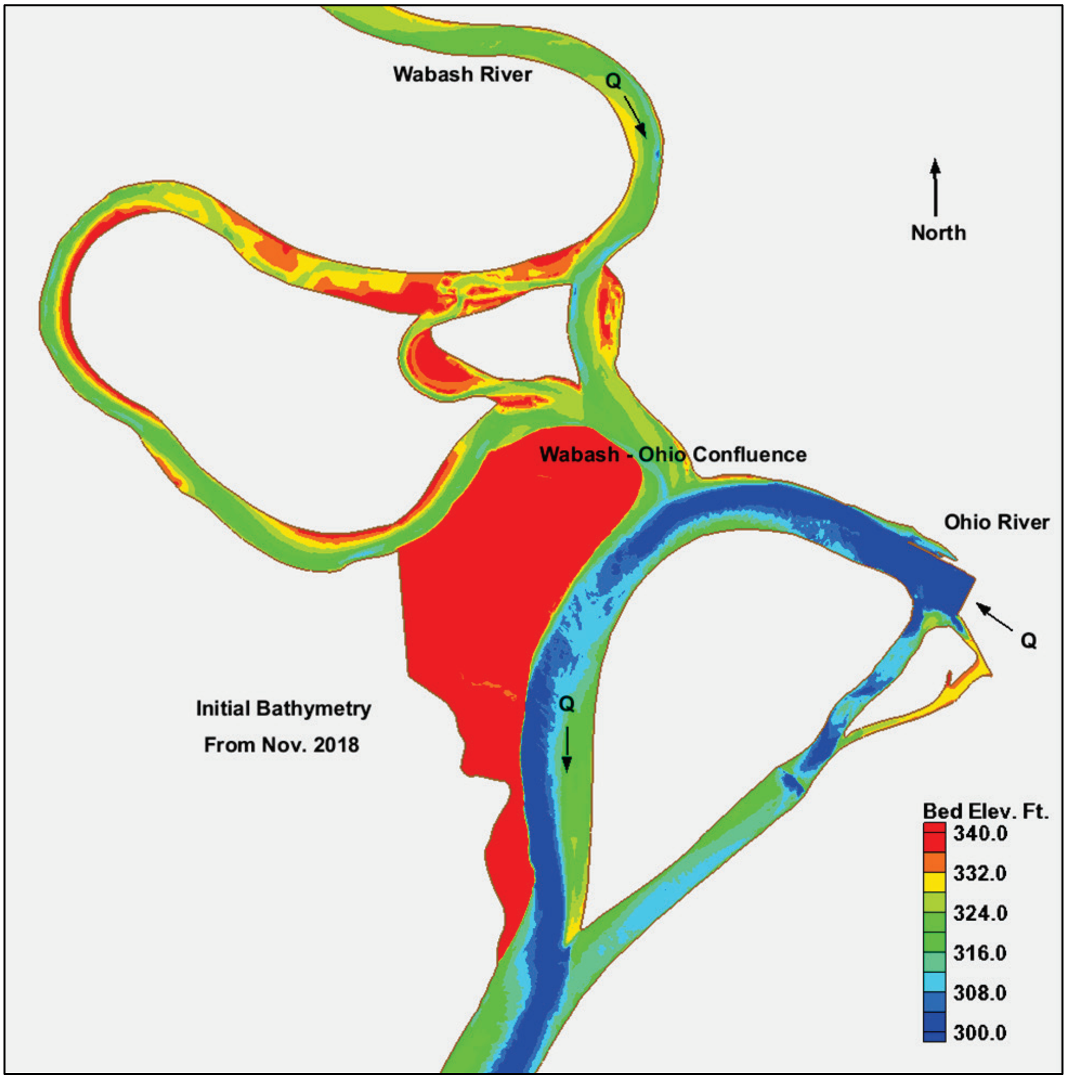


The Ohio River tailwater in Figure 26 is defined by the upper pool gauge records at Smithland Locks and Dam. The minimum pool elevation maintained by Smithland Locks and Dam downstream is elevation 324 ft (Ohio River Datum; see Section 2.3).

The hydrodynamic and sediment base condition model used current information from the November 2018 data collection effort described in Section 2.4.1. The same bathymetry was used as the starting bed configuration for each of the alternative simulations, except for areas where the river training structures (dikes) were added. In the case of the hard point removal simulation, It2_HP, the elevations at that location were lowered to match the elevations of the surrounding riverbed.

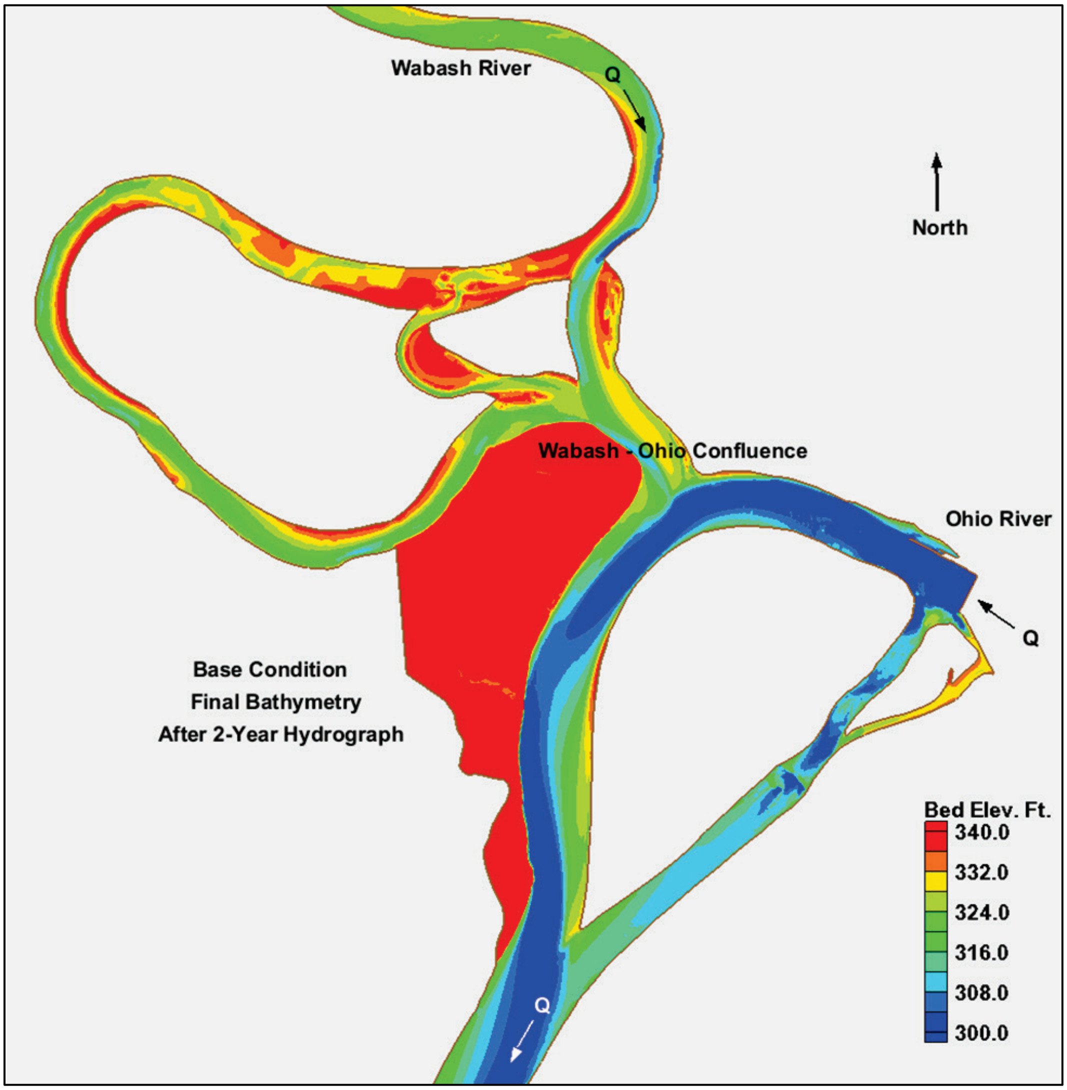
The land surface and bathymetric elevations obtained in November 2018, as mentioned above, were used as the initial elevations for all simulations. These starting elevations are shown in Figure 27.

Figure 27. Initial land and bathymetric elevations.



At any time-step throughout the 2 yr simulations, bed elevations at any inundated model location might be raised or lowered based on the amount of scour or deposition occurring at that time and place. The elevations at the end of the run represent the cumulative change over the 2 yr period. For the Base Run condition (no structural, bed and/or bank modifications made), the final bed elevations are shown in Figure 28. These provide bathymetric values and thus water surface elevations and depths, to compare the Alternatives against after each alternative has also run through the same 2 yr hydrograph.

Figure 28. Final bathymetry at end of 2 yr hydrograph.

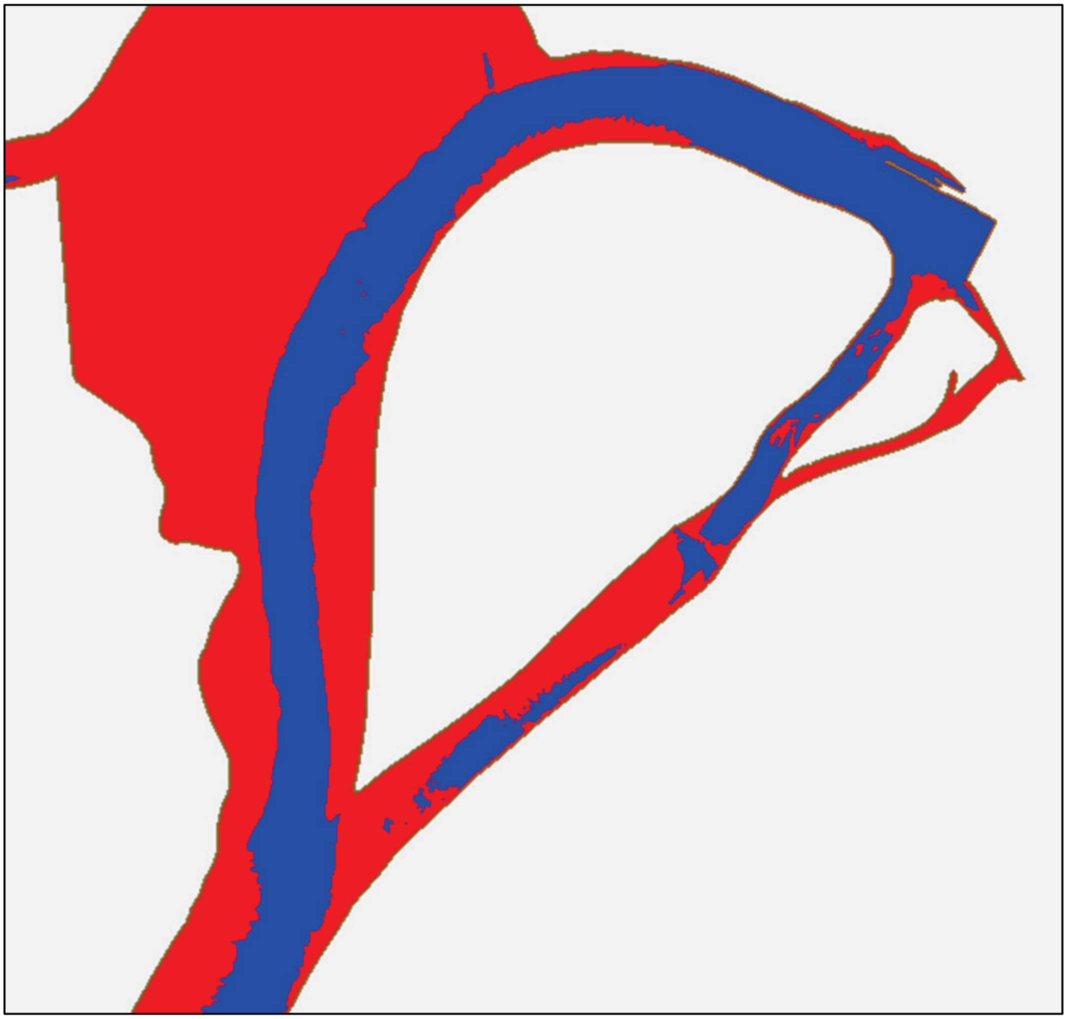


3.3 Model results showing navigable water extents

Because this is a navigation study, it is more important to produce plots that would show where the tows can navigate rather than simply plotting bathymetric changes. The initial base condition bathymetry was used in a special plot that is contoured to show water depths of 12 ft or greater in blue, with everything else shown in red. For a 9 ft draft vessel, this provides a 3 ft clearance over the bottom elevation. So, in the plots that follow, blue shows navigable water with a 3 ft clearance, and red is considered non-navigable.

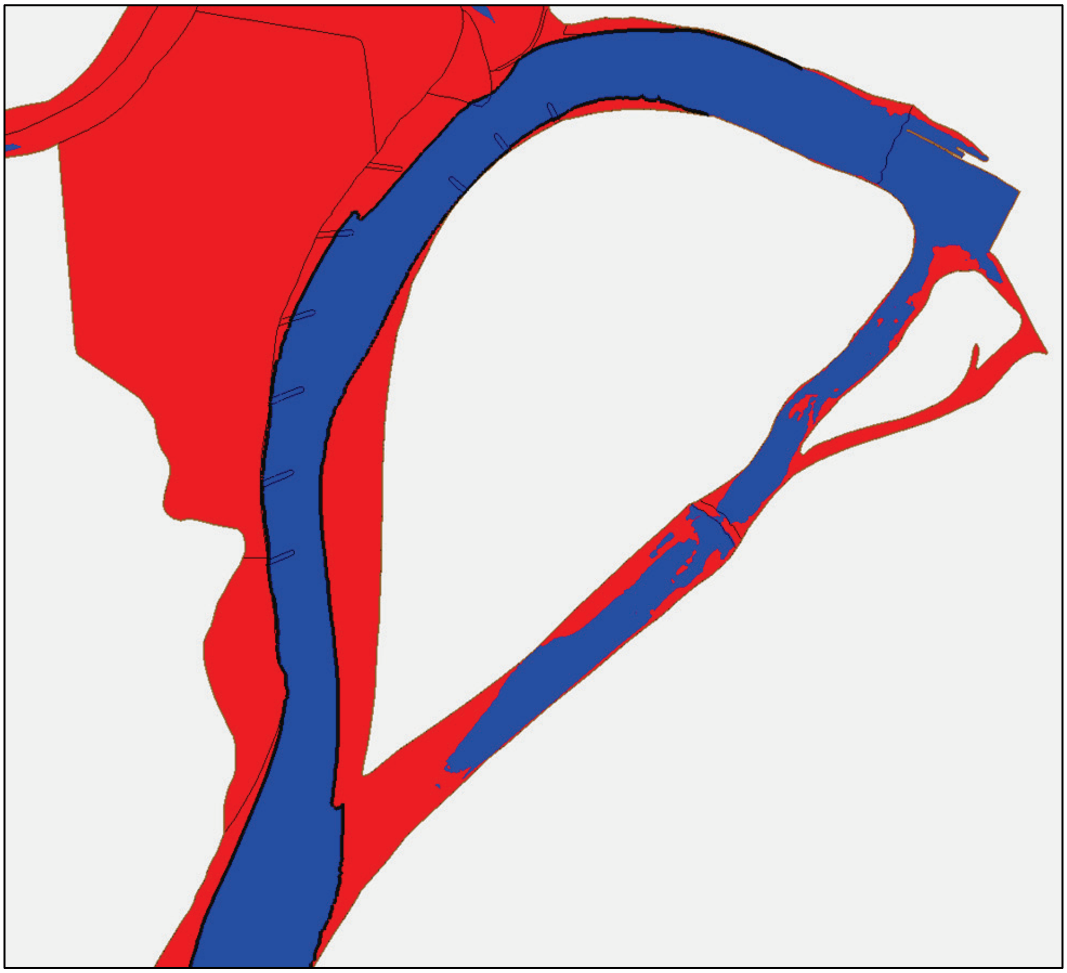
Figure 29 shows the initial, or base, navigable water condition that was used for each of the modeled alternatives. All alternative simulations were started with the same initial bathymetry and the same flow hydrograph of Figure 26, which simulates approximately 2 yr of extremely variable river flows.

Figure 29. Initial, base condition navigable water depth.



For the Base Condition Simulation, the changes in bathymetry at the end of the hydrograph produce navigable water depths as shown in Figure 30. In Figure 30, the black contour lines show the extent of the navigable water after the 2 yr hydrograph. Note: The dark line does not show up well in Figure 30 because it falls directly on the red and blue intersection, which is the navigable water extent at the end of the base condition simulation. That intersection, or black line, is used to visually compare how much more or less navigable water resulted from each of the alternative plans, as compared to the base condition.

Figure 30. Time = final, base condition, navigable water.



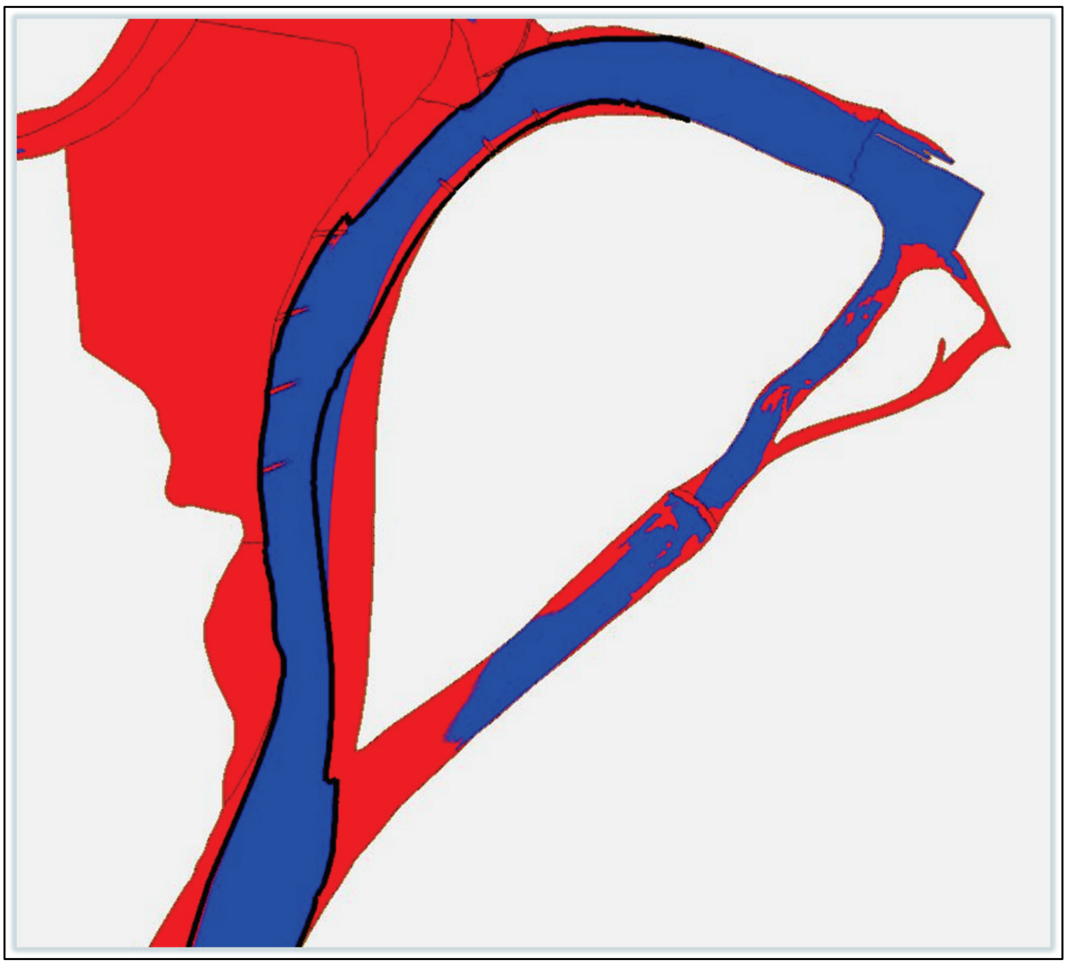
In Figure 30, the structures are outlined to show where they would be, but not raised because it is a base condition. The difference between the initial and final times shows that without any structures or channel maintenance, there is significant loss of navigable depth at the mouth of the Wabash and along the Illinois bank (increase of red area due to deposition) compared to the start of the simulation. This in turn causes erosion (increase of blue area due to scour) along the toe of Wabash Island opposite to the mouth of the Wabash River. The large bar along the west side of Wabash Island (left descending bank of main Ohio River channel) shows very little if any change.

Alternative simulation results

The model results for the final Phase 1 alternative and the above listed Phase 2 alternatives are shown next. Similar to Figure 29 and Figure 30, the dark lines parallel to the Ohio River banks show the navigable water limits from the base condition run at the end of the 2 yr hydrograph. Therefore, any deviation from that line indicates an increase or decrease of navigable water for the set of structure(s) in a given alternative.

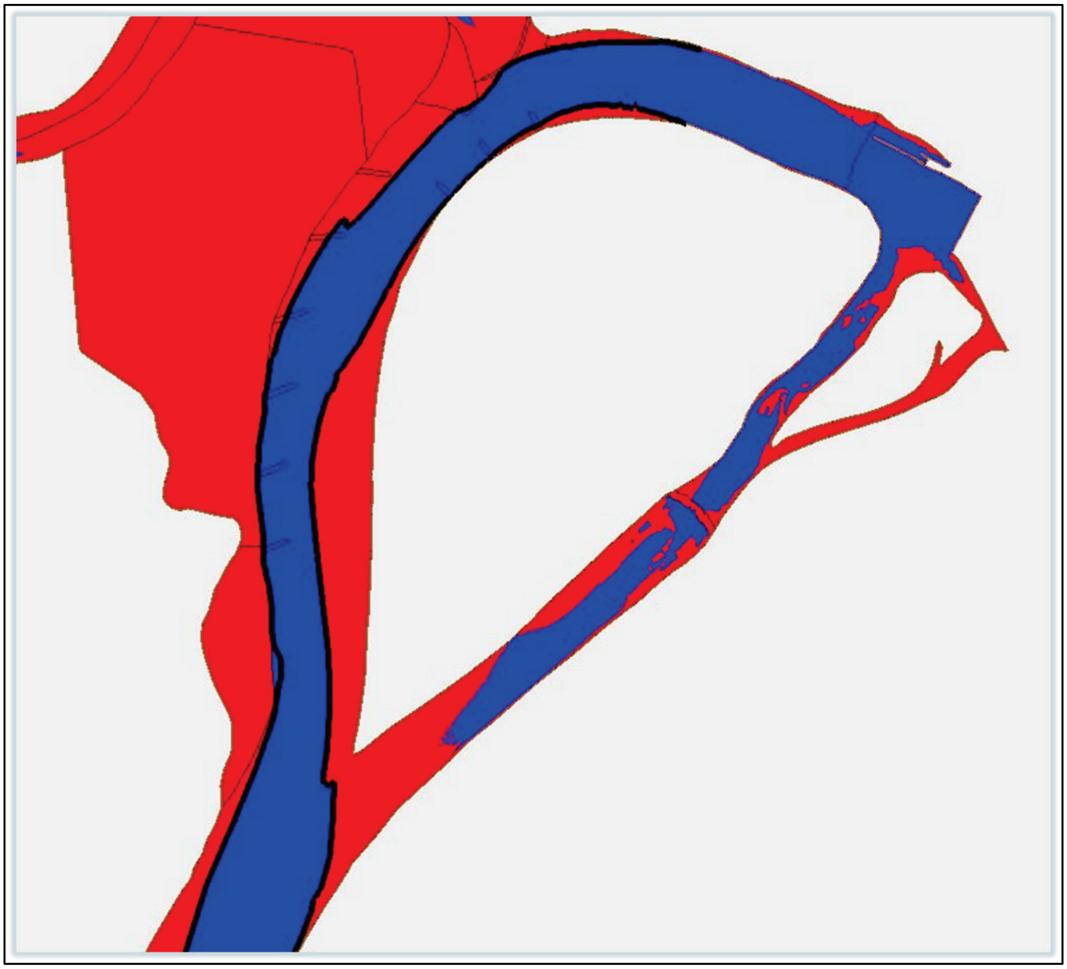
For reference, the final 2012 alternative in Phase 1 is shown first (Figure 31). The dike configuration in that run has three dikes on the Wabash Island and four dikes on the Illinois bank. The dikes are sloped and emergent at lower water levels and would therefore cause navigation hazards at moderate to lower flows. They function well in pushing back the bar on Wabash Island but cause a sharper bend radius for barge traffic since the tows cannot sail very close to the Illinois bank due to the protruding dikes. Safety being paramount, the Phase 1 final alternative was rejected in favor of level crested weirs where the crest elevations are set such that the tows can move over the weirs at low pool.

Figure 31. Phase 1 final 2012 alternative, navigable water.



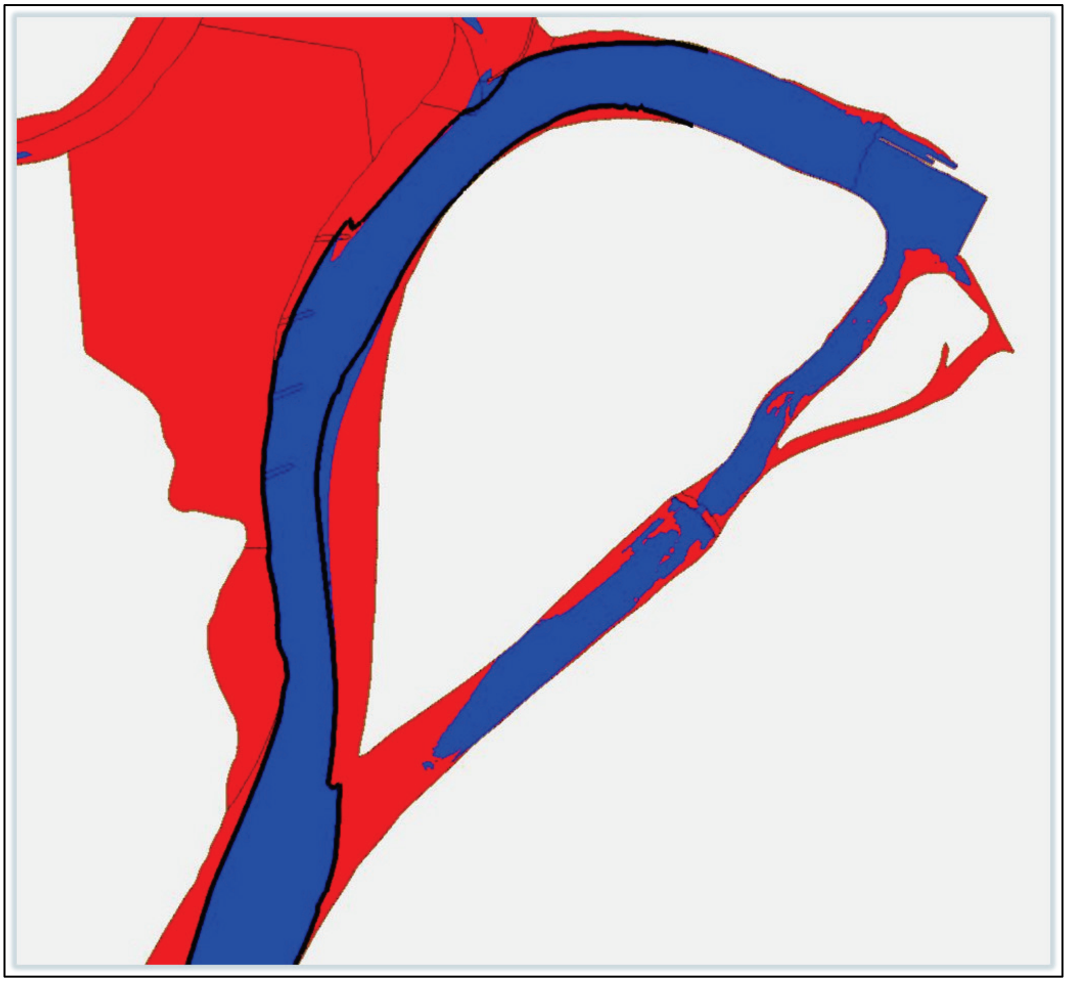
The hard point removal, It2_HD alternative, is shown next. No other changes, such as adding structures, were made for this run. As seen in Figure 32, the removal of the hard point has no effect on improving navigable water anywhere in the channel, except in the area where the bank was excavated to remove it. The alternative was not given further consideration.

Figure 32. Time = Final, hard point removal, navigable water.



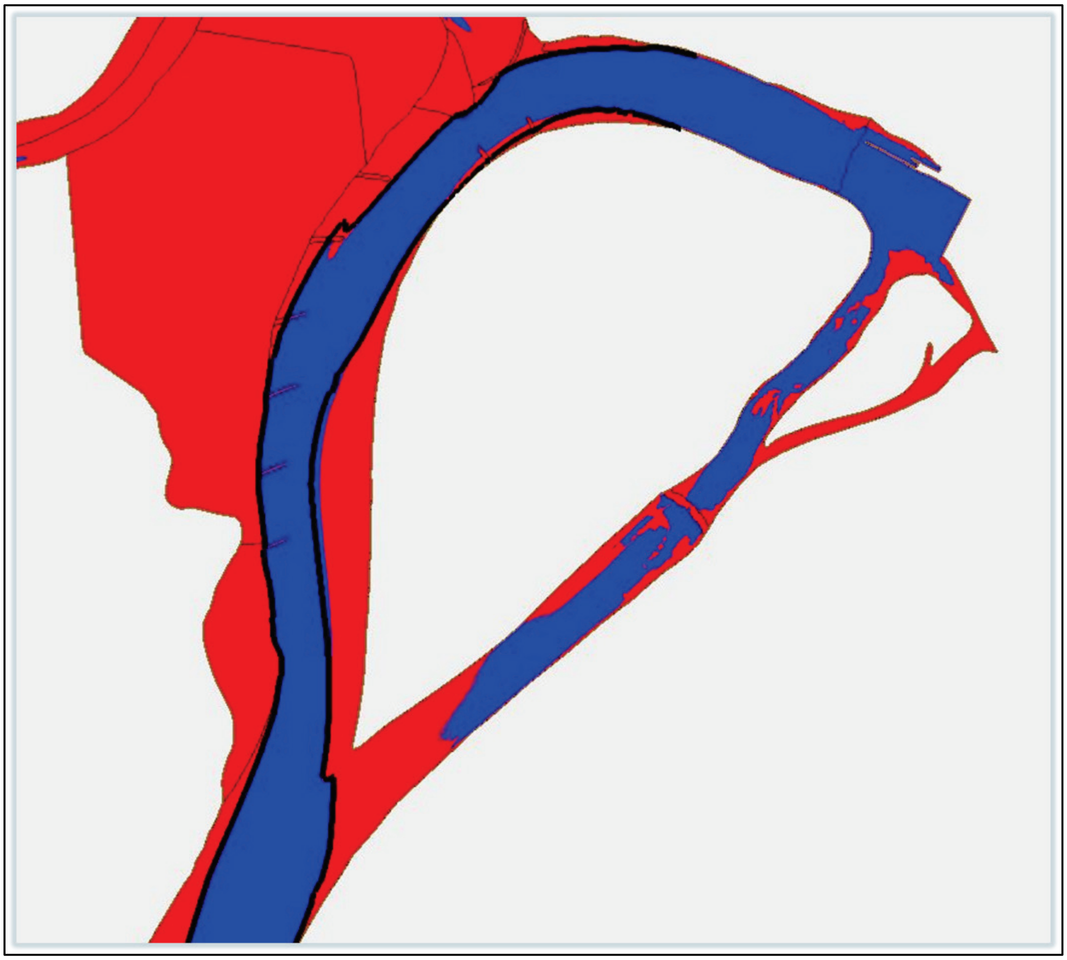
The major feature of the It2_W3 alternative (Figure 33) is the construction of a long and high dike at the mouth of the Wabash River. The results of this simulation indicate an increase of the navigable width of the channel. However, the bar just downstream of the mouth of the Wabash appears to increase in length and width slightly, while opposite it on the north-west side of Wabash Island, the bar is pushed back. The alternative seems viable based on the model output results in Figure 31. However, the length, elevation, and location of the Wabash confluence dike could be problematic. Long-term deposition and high flows could make it very difficult to maintain. Also, should it be flanked on the northeast end, it could quickly unravel, launching large quantities of stone into the main channel. This could cause a serious blockage and realignment of the main channel, both of which would not be advantageous to navigation interests.

Figure 33. Time = Final, Wabash confluence dike, It2_W3, navigable water.



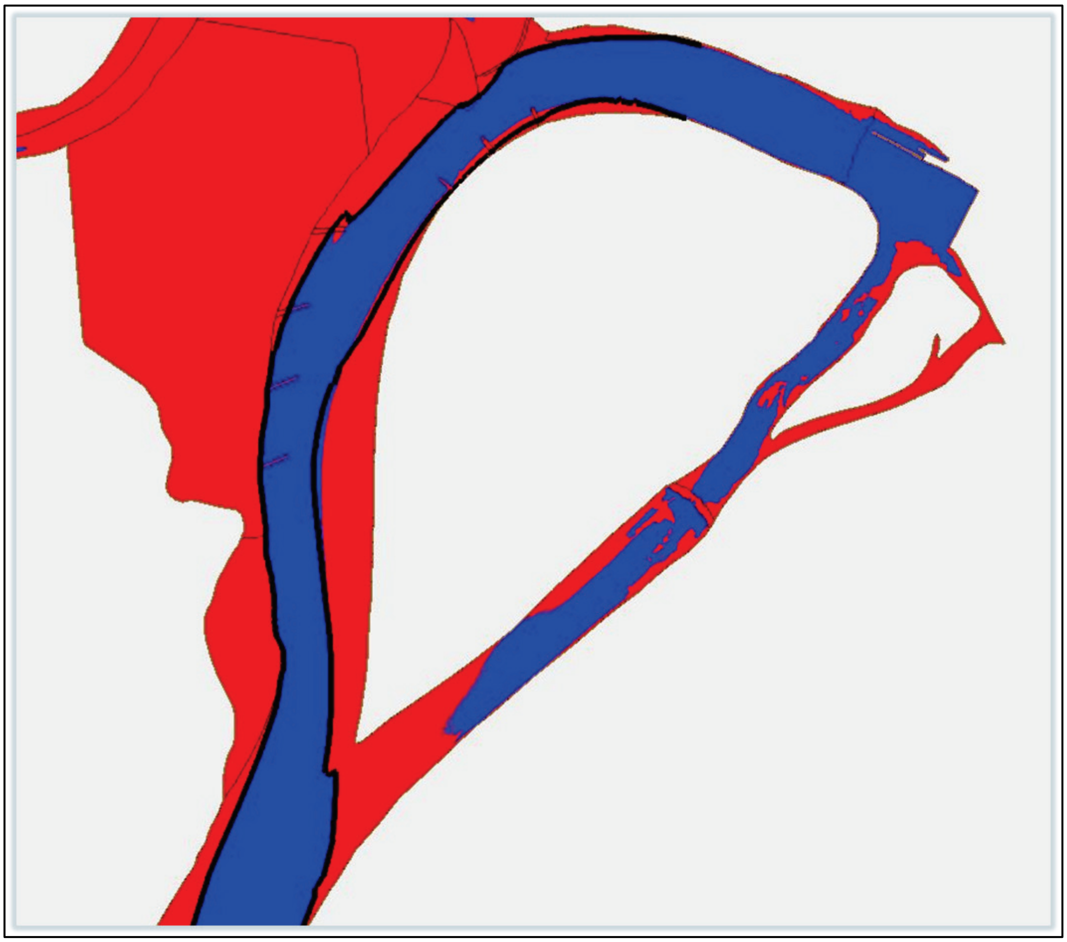
For the It2_MD alternative (Figure 34), there is an increased width of navigable water on the west side of Wabash Island. At the mouth of the Wabash, the additional structure seems to cause a slight widening and lengthening of the bar on the Illinois side, increasing turn radius for the tows at that location. This alternative is viable but requires eight structures.

Figure 34. Time = Final, additional dikes, It2_MD run, navigable water.



For the It2_PC330 alternative shown in Figure 35, there is an increased width of navigable water on the west side of Wabash Island. At the mouth of the Wabash River, the bar on the Illinois side lengthens slightly and is held steady or slightly reduced in width. This alternative is viable and requires seven structures. Because the results are nearly identical to the It2_MD alternative and it requires only seven dikes instead of eight, it was selected as the best alternative.

Figure 35. Time = Final, It2_PC330, seven-dike alternative, navigable water.



4 Summary

The Wabash channel avulsions in 2008 and 2010 that occurred in the bend just upstream of its confluence with the Ohio River resulted in massive sediment transport and deposition in the Ohio River. The ensuing large-scale shoaling caused a re-alignment of the navigation channel in the Ohio River and consistent dredging to maintain operational functionality. This study was initiated to explore various configurations of river training structures that would mitigate the extensive shoaling.

A numerical hydrodynamic model was developed to investigate alternatives to do that. The model was hydraulically validated to measure flow splits in the channels at the confluence of the two rivers. It was also validated for sediment transport using measured suspended and bed-material load grain size distributions. It was found to be adequately validated for the purposes of this study. The model was used to simulate base conditions and then altered to simulate multiple alternatives as possible solutions to the shoaling issues. The simulation was 2 yr in duration using the observed hydrograph for the simulated time period of 26 September 2015 to 26 September 2017.

The results of the base condition simulation as well as the various alternatives are presented in Chapter 3. Although several of the alternatives produce similar results in terms of an improved navigation channel, other considerations that are important are minimizing bend radii, the number and sizes of structures required, and anticipated maintenance requirements. All these factors were considered in determining the most appropriate alternative.

The selected alternative includes a combination of three dikes on Wabash Island and four dikes on the Illinois shore. Those on the Illinois side are level crested at an elevation of 312 ft, and those on the Wabash Island side are also level crested at an elevation of 330 ft. The results indicate shoaling at and just downstream of the mouth of the Wabash River are reduced as compared to the base condition. The bar growth on the west side of Wabash Island shows no growth and/or is slightly reduced in areal extent. An additional benefit of the dikes on the Illinois side of the river is protection from further erosion in this direction while creating a better sailing line for navigation.

Regarding navigation, a separate ship simulation study was conducted by the ERDC CHL Navigation Branch[1]. The navigation study used velocity fields produced in this study and incorporated into the ERDC ship simulator facility to test how the structures might impact the towboats. The results of those simulations indicate favorable outcomes with negligible impacts to tow traffic.

Note that the numerical modeling effort and results discussed in this report indicate that the selected dike configuration will improve and maintain the navigation channel through a wide range of flows. However, it must be remembered that the Wabash River is mostly unregulated. There are few, if any, river training structures and/or dams of any significance throughout its length. Therefore, the normal hydrologic cycle, and occasional extreme events, will continue to cause unpredictable morphological changes in the river, such as the avulsions that occurred in 2008 and 2010 at the confluence with the Ohio River. The present modeling effort cannot and does not address such large-scale morphologic events or their consequences.

[1] Pazan, Kiara I., S. N. Stever, S. K. Martin, and D. D. Abraham. In publication. *Wabash River Dike Field Study – Navigation Impact Assessment.* Vicksburg MS: US Army Engineer Research and Development Center.

References

Bell, G. L., N. D. Clifton, and D. D. Abraham. 2017. *Hydrodynamics in the Morganza Floodway. Report 1: Phase 1 – Model Development and Calibration*. MRG&P Report No. 13. Vicksburg, MS: US Army Engineer Research and Development Center.

Bell, G. L., N. D. Clifton, and D. D. Abraham. 2018. *Hydrodynamics in the Morganza Floodway and Atchafalaya Basin Report 2: Phase 2*. MRG&P Report No. 26. Vicksburg, MS: US Army Engineer Research and Development Center.

Brown, G. L. 2012. "Modification of the Bed Sediment Equations of Spasojevic and Holly (1993) to Account for Variable Porosity, Variable Grain Specific Gravity, and Nonerodable Boundaries." *IIHR Third International Symposium on Shallow Flows*, Iowa City, IA, June 4–6, 2012.

Burkham, D. E. 1985. *An Approach for Appraising the Accuracy of Suspended-sediment Data*. USGS Professional Paper 1333. Alexandria, VA: US Geological Survey.

Savant, G., R. C. Berger, T. O. McAlpin, and C. J. Trahan. 2014. *Three-Dimensional Shallow-Water Adaptive Hydraulics (AdH-SW3) : Hydrodynamic Verification and Validation*. ERDC TR-14-7. Vicksburg, MS: US Army Engineer Research and Development Center.

USGS (US Geological Survey). 2011. *Federal Interagency Sedimentation Project (FISP). Technical Committee Memorandum 2011.01. Subject: US P-6 Point Integrating Suspended-Sediment Sampler, January 2011*. https://water.usgs.gov/fisp/docs/FISP_Tech_Memo_US_P-6.pdf

Wentworth, C. K. 1922. "A Scale of Grade and Class Terms for Clastic Sediments." *The Journal of Geology* 30(5): 377–392. http://www.jstor.org/stable/10.2307/30063207 https://manoa.hawaii.edu/exploringourfluidearth/sites/default/files/M1U5-Table5.5.%20The%20Wentworth%20scale.pdf

Appendix A: Wentworth References

Figure 36 presents the Wentworth scale for grain size classification. Table 4 presents a simplified Wentworth scale.

Figure 36. Wentworth scale for grain size classification.

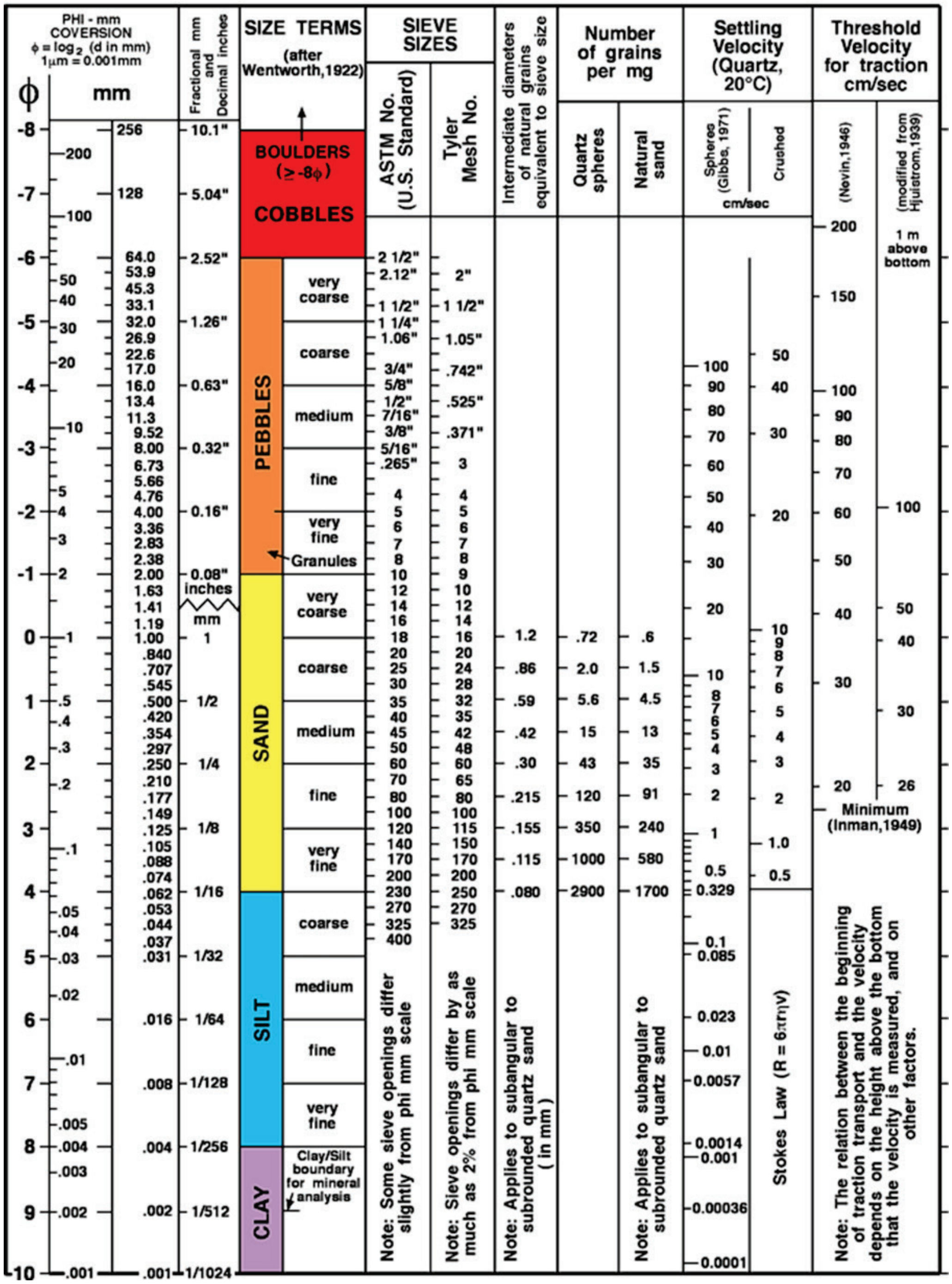


Table 4. Wentworth scale (simplified).

Category	Type	Grain diameter (mm)
Boulder	Boulders	250–100
Gravel	Cobbles	65–250
	Pebbles	4–65
	Granules	2–4
Sand	Very coarse sand	1–2
	Coarse sand	0.5–1
	Medium sand	0.25–0.5
	Fine sand	0.125–0.25
	Very fine sand	0.0625–0.125
Mud	Coarse silt	0.031–0.625
	Medium silt	0.0156–0.031
	Fine silt	0.0078–0.0156
	Very fine silt	0.0039–0.0078
	Clay	<0.0039
	Dust	<0.0005

Appendix B: Suspended Sediment Comparison for Ranges 1, 2, and 4

Figure 37 – Figure 39 present suspended sediment comparison for Ranges 1, 2, and 4.

Figure 37. Suspended sediment comparison Range 1.

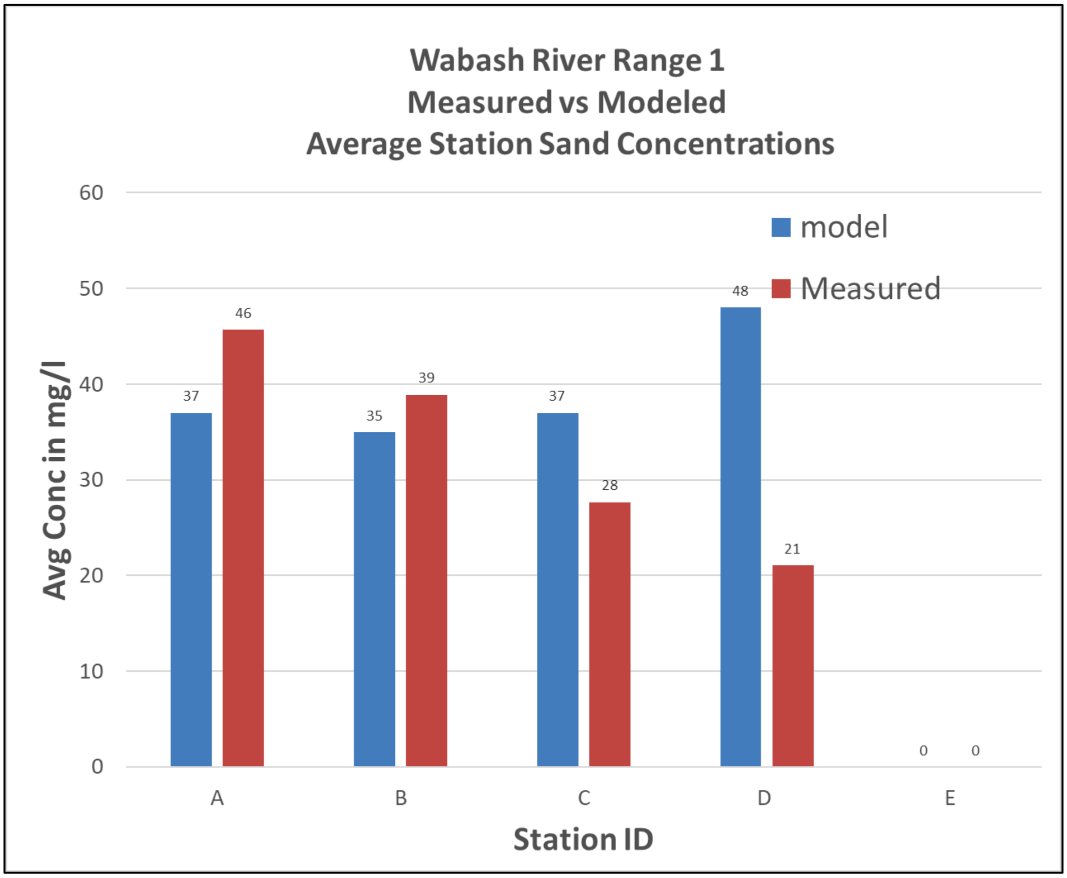


Figure 38. Suspended sediment comparison Range 2.

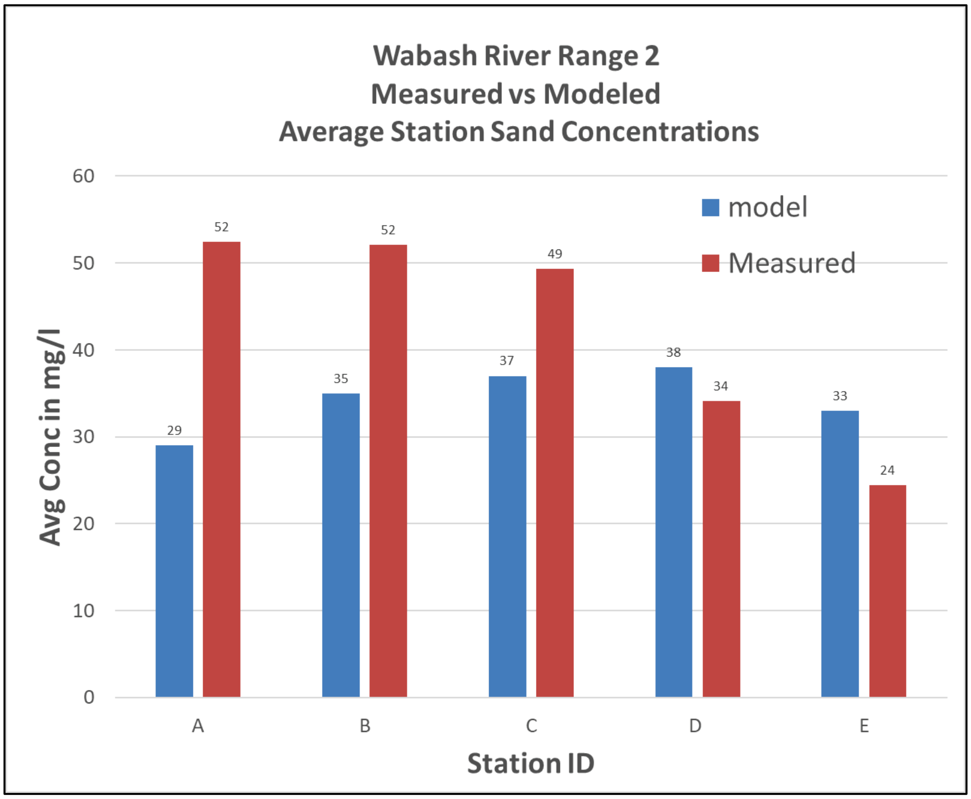
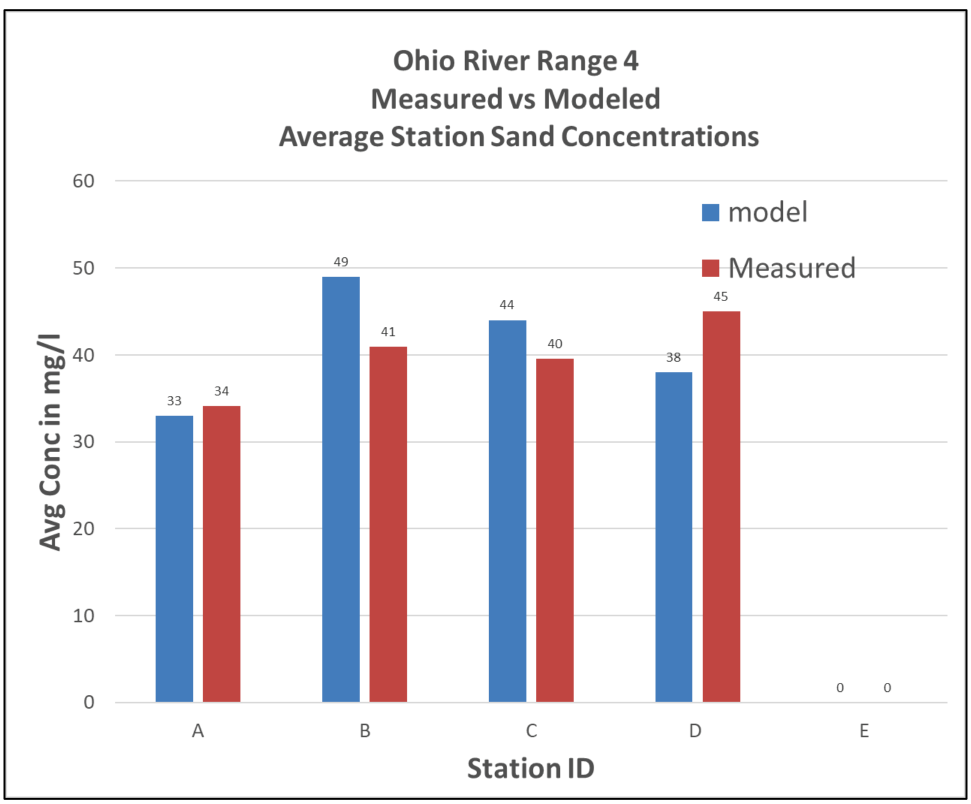


Figure 39. Suspended sediment comparison Range 4.



Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
Square foot (sq ft)	0.09290	Square meter (sq m)
miles (US statute)	1.609	kilometer
Cubic feet per second (cfs)	0.028317	Cubic meters per second (cms)

Acronyms and Abbreviations

2D	Two-dimensional
3D	Three-dimensional
ADCP	Acoustic Doppler current profiler
AdH	Adaptive Hydraulics
CHL	Coastal and Hydraulics Laboratory
ERDC	US Army Engineer Research and Development Center
FDCB	Field Data Collection Branch
RM	River Mile
URV	Unsubmerged Ridged Vegetation
USACE	US Army Corps of Engineers
USGS	US Geological Survey

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14. ABSTRACT
Avulsions of the Wabash River in 2008 through 2011 at its confluence with the Ohio River resulted in significant shoaling in the Ohio River. This caused a re-alignment of the navigation channel and the need for frequent dredging. A two-dimensional numerical hydrodynamic model, Adaptive Hydraulics (AdH), was developed to simulate base (existing) conditions and then altered to simulate multiple alternative scenarios to address these sediment issues.
The study was conducted in two phases, Phase 1 in 2013 – 2015 and Phase 2 in 2018 – 2020. Field data were collected and consisted of multi-beam bathymetric elevations, bed sediment samples, suspended sediment samples, and discharge and velocity measurements.
The model hydrodynamic and sediment transport computations adequately replicated the water surface slope, flow splits, bed sediment gradations, and suspended sediment concentrations when compared with field data. Thus, it was shown to be dependable as a predictive tool.
The alternative that produced the most desirable results included a combination of three level-crested emergent dikes on Wabash Island and four submerged dikes on the Illinois shore with a level crest from the bank to the tip of the dike. The selected alternative produced an improved sailing line while maintaining authorized channel depths.

15. SUBJECT TERMS
Confluence, Hydraulic models, Ohio River, Sedimentation and deposition, Sediment transport, Wabash River

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