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Calibration and Validation of a Two-Dimensional Hydrodynamic Model of the Ohio River, Jefferson County, Kentucky

Water-Resources Investigations Report 01-4091

U.S. Department of the Interior
U.S. Geological Survey

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By Chad R. Wagner *and* David S. Mueller

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Louisville, Kentucky
2001

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CONVERSION FACTORS AND VERTICAL DATUM

CONVERSION FACTORS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
mile (mi)	1.609	kilometer

VERTICAL DATUM

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Elevation, as used in this report, refers to the distance above or below sea level.

Calibration and Validation of a Two-Dimensional Hydrodynamic Model of the Ohio River, Jefferson County, Kentucky

By Chad R. Wagner *and* David S. Mueller

Abstract

The quantification of current patterns is an essential component of a Water Quality Analysis Simulation Program (WASP) application in a riverine environment. The U.S. Geological Survey (USGS) provided a field validated two-dimensional Resource Management Associates-2 (RMA-2) hydrodynamic model capable of quantifying the steady-flow patterns in the Ohio River extending from river mile 590 to 630 for the Ohio River Valley Water Sanitation Commission (ORSANCO) water-quality modeling efforts on that reach. Because of the hydrodynamic complexities induced by McAlpine Locks and Dam (Ohio River mile 607), the model was split into two segments: an upstream reach, which extended from the dam upstream to the upper terminus of the study reach at Ohio River mile 590; and a downstream reach, which extended from the dam downstream to a lower terminus at Ohio River mile 636.

The model was calibrated to a low-flow hydraulic survey (approximately 35,000 cubic feet per second (ft^3/s)) and verified with data collected during a high-flow survey (approximately 390,000 ft^3/s). The model calibration and validation process included matching water-surface elevations at 10 locations and velocity profiles at 30 cross sections throughout the study reach. Based on the calibration and validation results, the model is a representative simulation of the Ohio River steady-flow patterns below discharges of approximately 400,000 ft^3/s.

INTRODUCTION

Combined sewer overflows (CSO's), sanitary sewer overflows (SSO's), nonpoint sources, and storm-water runoff are all sources of wet-weather pollution that contribute to the degradation of our Nation's vital water resources. In situations where more than one of these sources contributes to the impairment of water quality, a holistic approach defining the relative importance of each source's contribution to the problem is the most efficient way to arrive at an economical control plan. In order to determine the relative significance of the various sources of wet-weather pollution on major waterways, an understanding of the local hydrodynamics, pollutant land loading, and pollutant-transport characteristics is essential.

Background

The Ohio River Valley Water Sanitation Commission (ORSANCO) is nearing completion of a national demonstration study to develop a water-quality model that is capable of simulating pollutant concentrations in the river during wet-weather periods and is able to quantify improvements to the water quality resulting from pollution control best-management practices. The initial project was completed on a reach of the Ohio River, which included the Cincinnati/northern Kentucky metropolitan area. The Water Quality Analysis Simulation Program (WASP) was utilized to simulate the water-quality constituent transport and transformation during low-flow periods spanning the recreational-contact period May-September. The flow field required by WASP was simulated by use of a two-dimensional Resource Management Associates-2 (RMA-2) hydrodynamic model.

In order to demonstrate the transferability of this project to other riverfront metropolitan areas, a similar study was initiated in the Louisville, Kentucky, metropolitan area; this study involved both hydrodynamic and water-quality modeling and field data collection. The U.S. Geological Survey (USGS), in cooperation with ORSANCO, developed a field-validated hydrodynamic model to support the water-quality model being developed by a consultant contracted by ORSANCO.

Purpose and Scope

This report describes the calibration and validation of the two-dimensional RMA-2 model to simulate the complex hydrodynamics of a 40-mi study reach of the Ohio River near Louisville, Ky. (Ohio River mile 590 to 630; fig. 1). The field data used to calibrate and validate the model also are described. Because of the hydrodynamic complexities induced by McAlpine Locks and Dam (Ohio River mile 607), the model was split into two segments: an upstream reach, which extended from the dam upstream to the upper terminus of the study reach at Ohio River mile 590; and a downstream reach, which extended from the dam downstream to a lower terminus at Ohio River mile 636.

Floodplains were not included in the model domain because of the project emphasis on low-flow periods spanning the recreational-contact period May-September. The final model was used to simulate the steady-flow patterns of the Ohio River for flows ranging from 6,500 to 197,700 ft^3/s. The lower limit of the simulated flows (6,500 ft^3/s) is consistent with the discharge during a dye-tracing survey done by ORSANCO in September 1999. The upper limit of the range of simulated flows (197,700 ft^3/s) corresponds to the 90-percentile flow during the recreational-contact period based on historical discharge data during 1987–98. Although more historical discharge data are available, ORSANCO and the private consultant chose to use only recent data (1987–98) to determine the 90-percentile flow. The process and methodology used to calibrate and validate the model with field data as well as the results of the model simulations are discussed in this report.

Study Area

The Ohio River study area begins at the northeast corner of Jefferson County, Ky., and extends southwestward through the county and ends 6 river miles downstream from the mouth of the Salt River (fig. 1). The upstream reach is in the McAlpine Locks and Dam pool and the water level is kept at an elevation of approximately 420 ft above sea level during low-flow periods. The downstream reach of the study area is in the tailwater of McAlpine Locks and Dam. The water level at the dam is held at a normal pool level of 383 ft above sea level by the Cannelton Locks and Dam, which is located 150 river miles downstream. The channel has a generally trapezoidal geometry with steep banks rising at slopes greater than 22 percent (0.22 ft/ft). The banks along the upstream reach extend to an approximate elevation of 440 ft, whereas the banks of the downstream reach rise to approximately 420 ft.

The following river characteristics were determined from the data collected during the hydrographic surveys. At a discharge of 36,000 ft^3/s, the average depth of the river thalweg was approximately 30 ft in the upstream reach and 20 ft in the downstream reach. The average width of the river at a discharge of 36,000 ft^3/s was approximately 3,000 ft in the upstream reach and 1,600 ft in the downstream reach. A discharge of 390,000 ft^3/s produced an average depth in the thalweg of approximately 45 ft in both the upstream and downstream reaches. The width of the river at a discharge of 390,000 ft^3/s was approximately 4,000 ft in the upstream reach and 2,500 ft in the downstream reach. The bank and bed material of the study reach varies between cohesive and noncohesive sediment. The bank vegetation predominately consists of small shrubbery and vegetation, void of large trees.

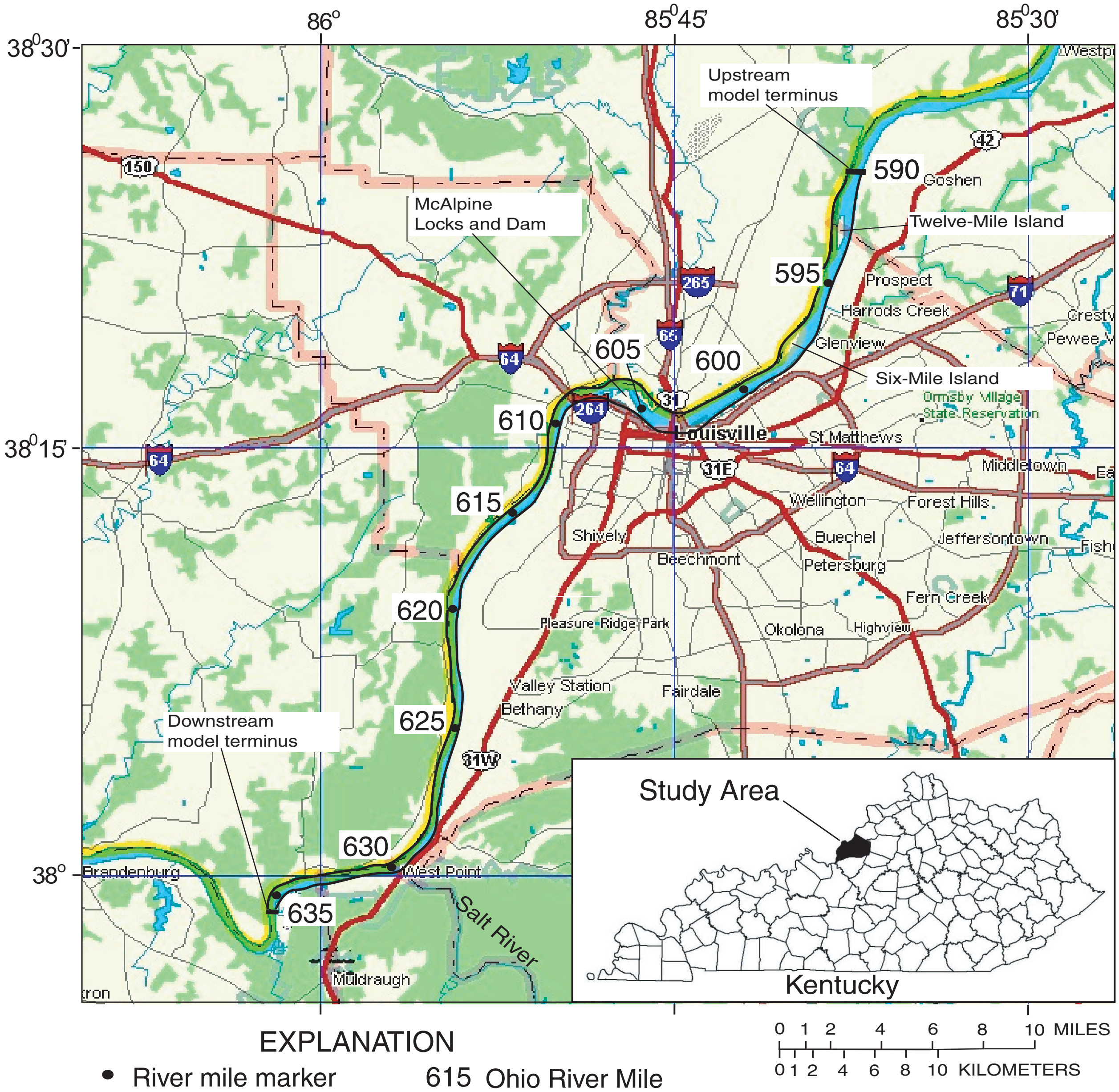


Figure 1. Location of study area near Louisville, Kentucky.

The structures that compose McAlpine Locks and Dam are located on the northwestern side of Louisville, Ky., and extend from Ohio River mile 604.4 to 607.4. The current locks-and-dam configuration (fig. 2) consists of a hydroelectric powerhouse; two lock chambers (one 600 by 110 ft and the other 1,200 by 110 ft in length and width, respectively); nine tainter gates, four near the powerhouse and five just upstream of the Conrail Railroad Bridge; and a fixed weir with a crest at an elevation of 422 ft at the downstream gates, incrementally raised to an elevation of 423 ft at the upper set of gates. An earthen dike was constructed at the upstream end of Shippingport Island to reduce the crosscurrents affecting vessels navigating the lock canal. The shoal area that exists downstream from the upper gates and fixed weir is referred to as the Falls of the Ohio and is an area of archeological importance. To facilitate public use of the fossil beds at the Falls of the Ohio, the U.S. Army Corps of Engineers (COE) has agreed to a 2-month operational period (typically August-October) each year when the fixed weir and upper gates are not used to pass flow, except for extreme hydrological events. Under low flow or when the upper gates of McAlpine Locks and Dam are not in operation, the Falls of the Ohio is an area of slack flow.

MODEL CALIBRATION AND VALIDATION

At least two data sets are required to adequately calibrate and validate a numerical model. The general procedure used to calibrate and validate the RMA-2 model was to first collect field data in order to develop the computational mesh. The model then was calibrated to the water-surface elevations and velocities observed in the field for the initial flow. A second flow condition then was simulated without changing the computational mesh or model parameters, and the simulated water-surface elevations and velocities were compared with those observed in the field for this second flow condition.

Model Description

RMA-2 is a two-dimensional depth-averaged finite-element hydrodynamic numerical model capable of computing water-surface elevations and horizontal-velocity components for subcritical, free-surface flow in two-dimensional flow fields (U.S. Army Corps of Engineers, 1997). The model is designed for problems in which vertical accelerations are negligible, and velocity vectors generally point in the same direction over the entire depth of the water column at any discrete period in time.

Typical applications of the RMA-2 numerical model include calculating water-surface elevations and flow distribution around islands; flow patterns at bridges having one or more relief openings, in contracting and expanding reaches, into and out of off-channel hydropower plants, and at river junctions; circulation and transport in water bodies with wetlands; and water levels and flow patterns in rivers, reservoirs, and estuaries.

One of the predominating operating assumptions in RMA-2 is that acceleration of flow in the vertical direction is negligible. The model is not intended for applications in which vortexes, vibrations, or vertical accelerations are the primary interests; therefore, the simulation of vertically stratified flow fields is beyond the capabilities of RMA-2 (U.S. Army Corps of Engineers, 1997).

Field Data Collection and Interpretation

Water-surface elevations, channel-bathymetry, and detailed water-velocity measurements were collected at two different flow conditions (36,000 and 390,000 ft^3/s) and used in the model for calibration and validation, respectively. Water-surface elevations were measured at 10 locations (4 upstream and 6 downstream) along the study reach concurrent with both hydraulic surveys. Detailed water-velocity measurements and channel-bathymetry data were collected at 30 cross sections (12 upstream and 18 downstream)—spaced approximately 1.5 mi apart—during each of the hydraulic surveys (figs. 3 and 4). A separate data-collection trip from the two hydrographic surveys was used to collect channel-bathymetry data in sufficient detail for the development of a computational mesh.

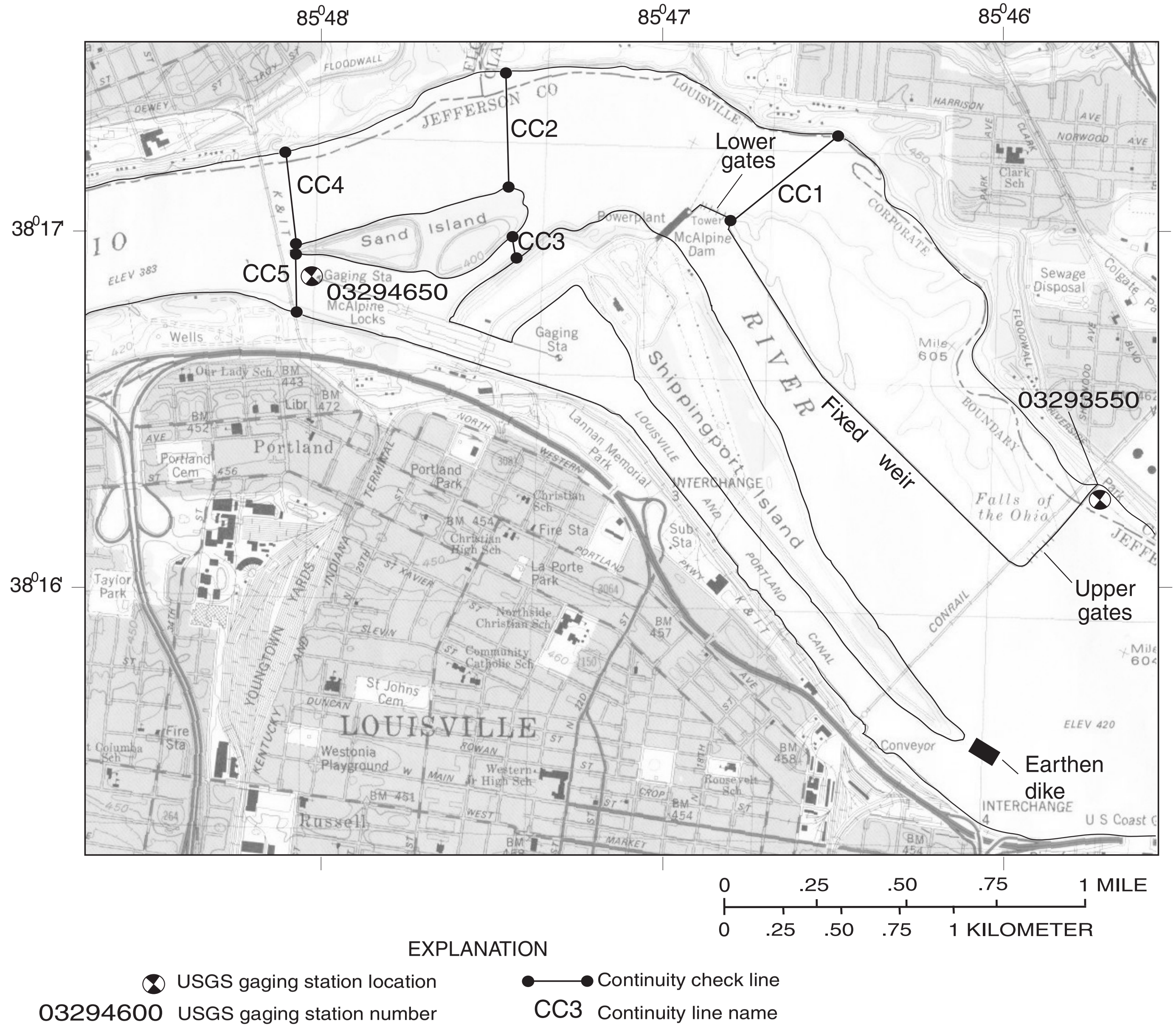


Figure 2. McAlpine Locks and Dam configuration and U.S. Geological Survey (USGS) gaging station locations near Louisville, Kentucky.

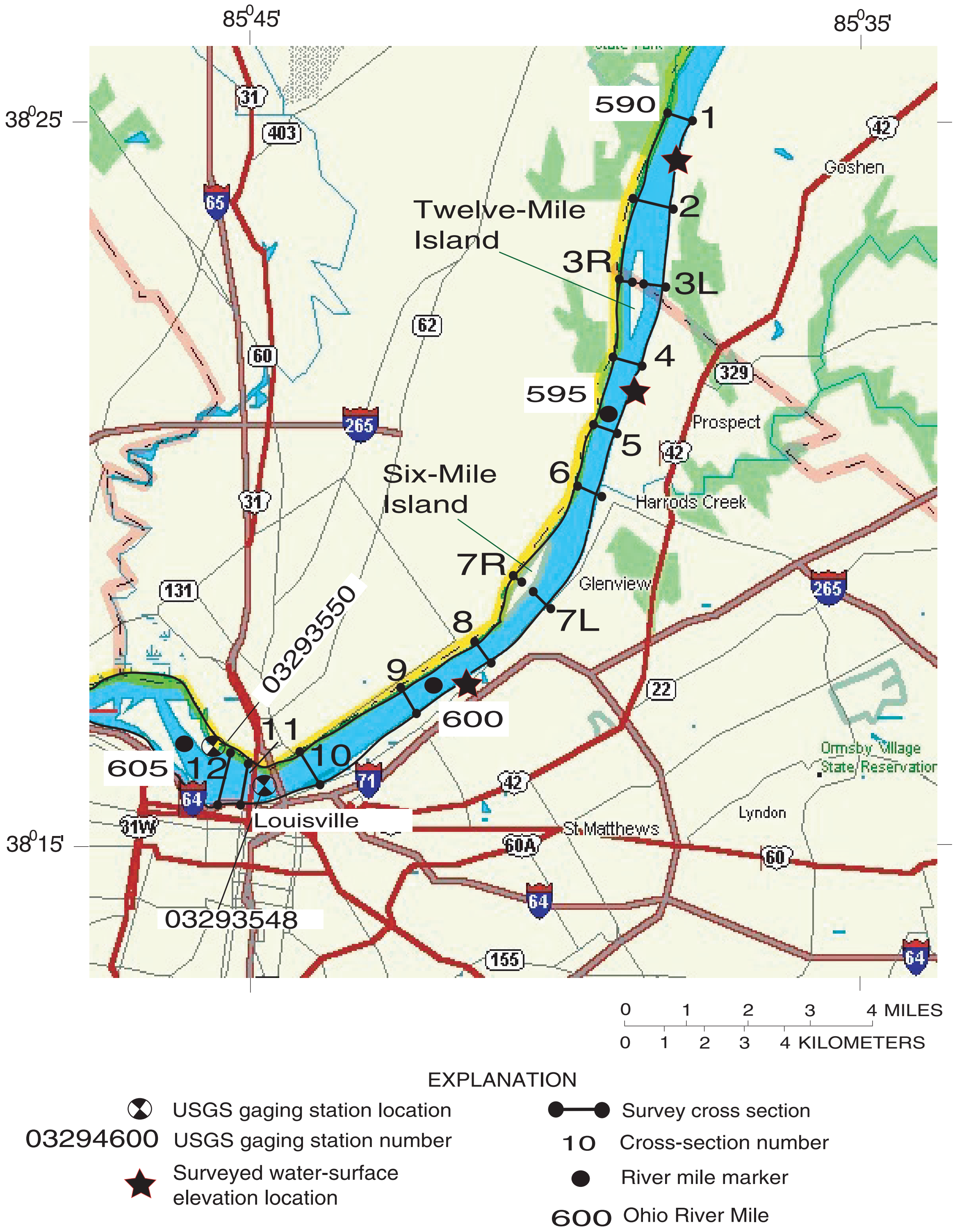


Figure 3. Location of hydrographic-survey cross sections, surveyed water-surface elevation stations, and U.S. Geological Survey (USGS) gaging stations in the upstream study reach near Louisville, Kentucky.

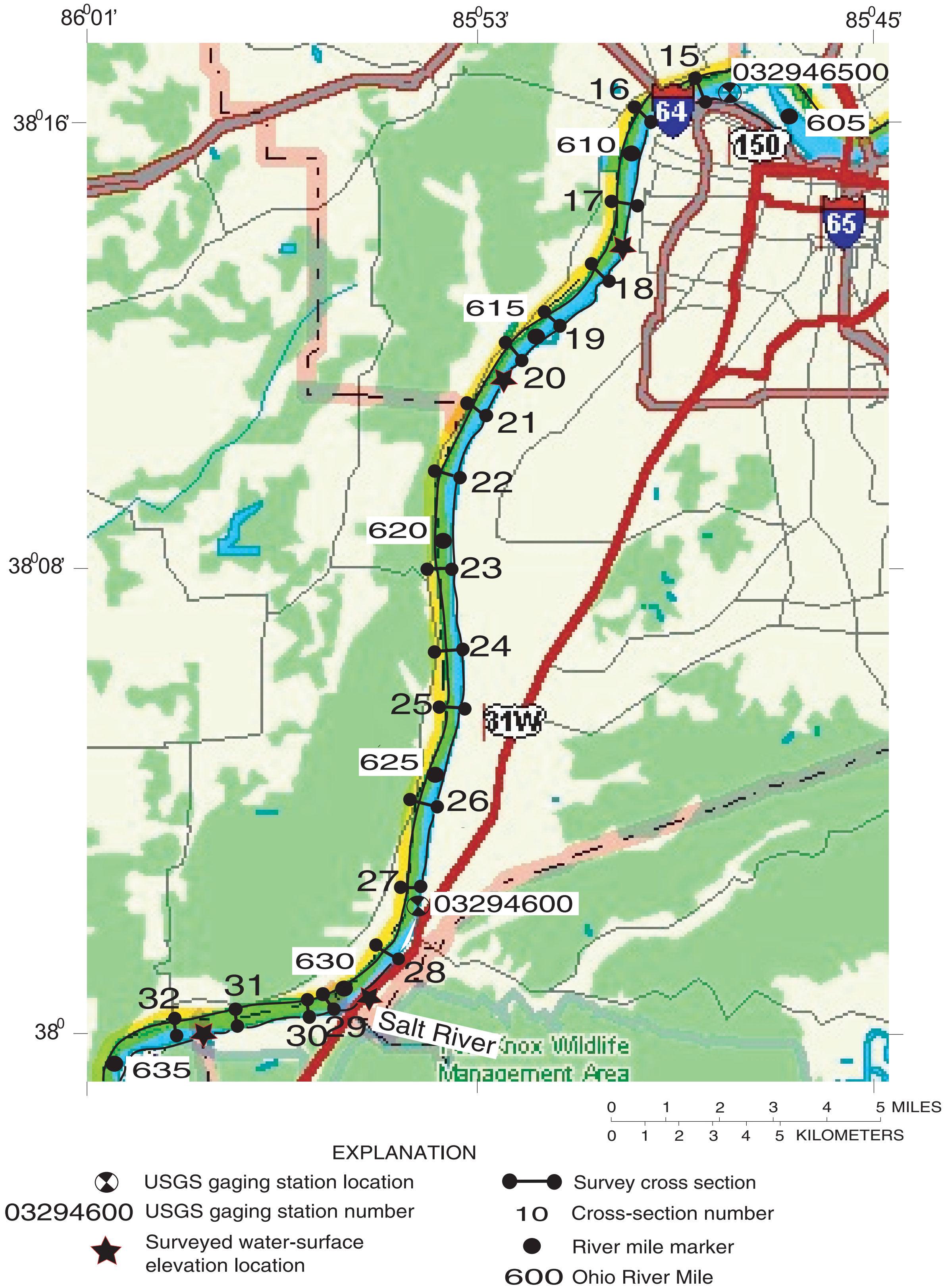


Figure 4. Location of hydrographic-survey cross sections, surveyed water-surface elevation stations, and U.S. Geological Survey (USGS) gaging stations in the downstream study reach near Louisville, Kentucky.

Water-Surface Elevations

Water-surface elevations at the seven locations throughout the reach (figs. 3 and 4) were surveyed with a total station. To document the changes in river stage during a hydraulic survey, the water-surface elevations were surveyed in the morning and then again in the afternoon. The average water-surface elevation was used to determine a water-surface slope corresponding to the average discharge measured during the survey.

The 40-mi study section of the Ohio River includes a total of four USGS stream gages—two each in both the upstream and downstream reaches. Both upstream gages—one located on the Second Street Bridge (number 03293548) and the other at Indiana Pass (number 03293550)—are located near river mile 604 and provided to assist the COE, Louisville District in maintaining the McAlpine Locks and Dam normal pool elevation. The Second Street Bridge gage is located on a pier near the center of the channel about 4,000 ft upstream from McAlpine Locks and Dam; the Indiana Pass gage is located on the Indiana shore about 500 ft downstream from the Second Street Bridge gage (fig. 3). The McAlpine tailwater and Kosmosdale gaging stations (numbers 03294500 and 03294600, respectively) are located within the downstream reach (fig. 4). The McAlpine tailwater gage is located near the Kentucky shore on the downstream end of the lock guide wall (river mile 607). The Kosmosdale gage is located on the Kentucky shore, 19.8 mi downstream from the tailwater gage (river mile 628).

Velocity and Discharge

Water-velocity and discharge data were collected from a moving boat. The horizontal position of the boat was measured using a differentially corrected global positioning system (DGPS) receiver. The DGPS system used receives its differential corrections from a commercial service's communications satellite. The unit is specified by the manufacturer to be accurate to 3.3 ft at two standard deviations; tests and prior use of this unit indicate that typically about 80 percent of the data are within 3.3 ft of the true location.

Recent advances in velocity-measurement technology allow three-dimensional velocities to be collected from a moving boat using an acoustic Doppler current profiler (ADCP) (Oberg and Mueller, 1994; Mueller, 1996). All velocities were measured with an ADCP. The ADCP allows three-dimensional velocities to be measured from approximately 4 ft beneath the water surface to within 6 percent of the depth to the bottom. Established methods were used to estimate the discharge in the unmeasured top and bottom portions of the profile (Simpson and Oltmann, 1991). Cross-sectional average velocities were computed by dividing the measured discharge by the measured cross-sectional area. In addition, depth-averaged velocities were computed for subsections of the flow in each cross section; however, these discrete depth-averaged velocities were computed as an average of the measured velocity and did not account for the velocity in the unmeasured portions of the water column.

In order to compensate for the slight changes in discharge of the river during the survey, all the discharge measurements collected were averaged to produce a flow rate that was representative of the entire survey period. The time necessary to complete a hydraulic survey on each of the simulated sections did not permit both the upstream and downstream reaches to be surveyed on the same day; therefore, minor differences are present in the discharge measurements used to calibrate and validate the upper and lower models.

Bathymetry

Bathymetry data also were collected from a moving boat. The horizontal position of the boat was measured using the DGPS receiver. During the initial low-water survey, a 200-kHz echo sounder was used to measure the channel bathymetry at the 30 predefined cross sections.

The channel bathymetry obtained from the initial bathymetric survey at the 30 velocity-measurement cross sections was compared to the 1963 COE hydrographic survey of the area. The surveyed data points of the 1963 hydrographic survey were digitized along straight cross sections spaced at 1/4-mi intervals and oriented perpendicular to flow. All data points were digitized from paper maps. A triangulated irregular network (TIN) of the 1963 data was generated to extract cross sections from the 1963 data for the 30 locations surveyed for this project. The shapes of the cross sections measured in the downstream reach were similar to cross sections extracted from the 1963 hydrographic-survey data. Differences in elevation were within the errors expected from the survey technologies of 1963 and those used in this survey; therefore, data from the 1963 hydrographic survey were used for the channel bathymetry in the downstream hydrodynamic model. The shape of the cross sections measured in the upstream reach displayed differences from the cross sections extracted from the 1963 hydrographic-survey data; therefore, a second bathymetric survey of the upstream reach was completed with cross sections spaced approximately 1,000 ft apart. The data from the second bathymetry survey was used for the channel bathymetry in the upstream hydrodynamic model.

Bathymetric data surveyed with the echo sounder in the upstream reach did not fall on perfectly straight cross sections because of inconsistencies in the boat course across the river. The internal triangulation routine done by the RMA-2 interface software package—Surface-water Modeling Systems (SMS), version 7.0 (Brigham Young University, 1999)—did not properly interpret the collected bathymetry data, resulting in triangulation within the same cross section and a large portion of the area between two cross sections estimated with only three data points. An example of the raw-data triangulation is presented in figure 5a. The raw data collected along each cross section was mathematically forced onto a straight line and re-triangulated; figure 5b shows the re-triangulation of the section shown in figure 5a. Although forcing the data points onto a straight line does introduce some error, the straight-line cross sections produced a better representation of the upstream channel bathymetry than the unadjusted data.

Upstream River Reach

The simulated upstream reach begins 3 mi upstream of the Jefferson/Oldham County line (Ohio River mile 590) in Kentucky, and extends downstream to McAlpine Locks and Dam (Ohio River mile 607). Two islands are present that add hydraulic complexities to this reach: Twelve-Mile Island located at Ohio River mile 593, and Six-Mile Island located at Ohio River mile 598. The configuration of McAlpine Locks and Dam includes upper and lower sets of tainter gates and a hydropower plant that served as downstream boundary conditions for the model.

Computational-Mesh Configuration

The finite-element network for the upstream river reach consisted of 6,920 elements. The islands and dike were simulated by installing gaps in the mesh because the simulated flows did not overtop these features (figs. 6 and 7). The boundary nodes at the upstream and downstream points of the islands were specified as "stagnation points" (locations of zero velocity). These specifications generally are located in corners of grids or along boundaries with relatively negligible flow velocities and are applied to reduce artificial loss of discharge out of the channel boundaries. The resolution of the grid was increased in the area around McAlpine Locks and Dam in order to reproduce the hydraulic complexities induced by these structures (fig. 8). In order to maintain numerical stability, the sloping banks were truncated at an elevation of 418 ft. Above this elevation, the banks were assumed to be vertical walls.

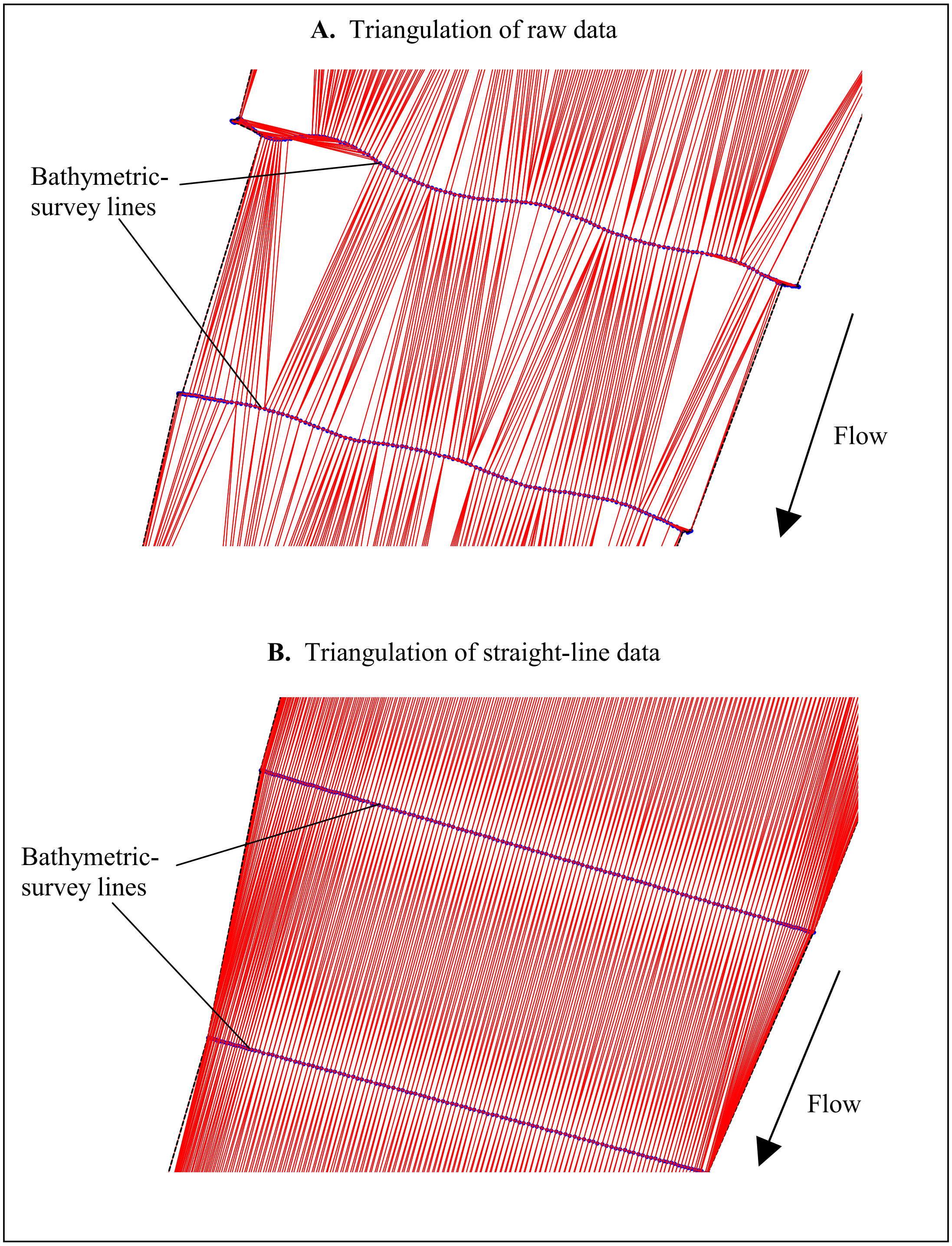


Figure 5. Surface Water Modeling System (SMS) software triangulation of raw and straight-line bathymetry data for a section of the upstream study reach in the Ohio River model simulation near Louisville, Kentucky.

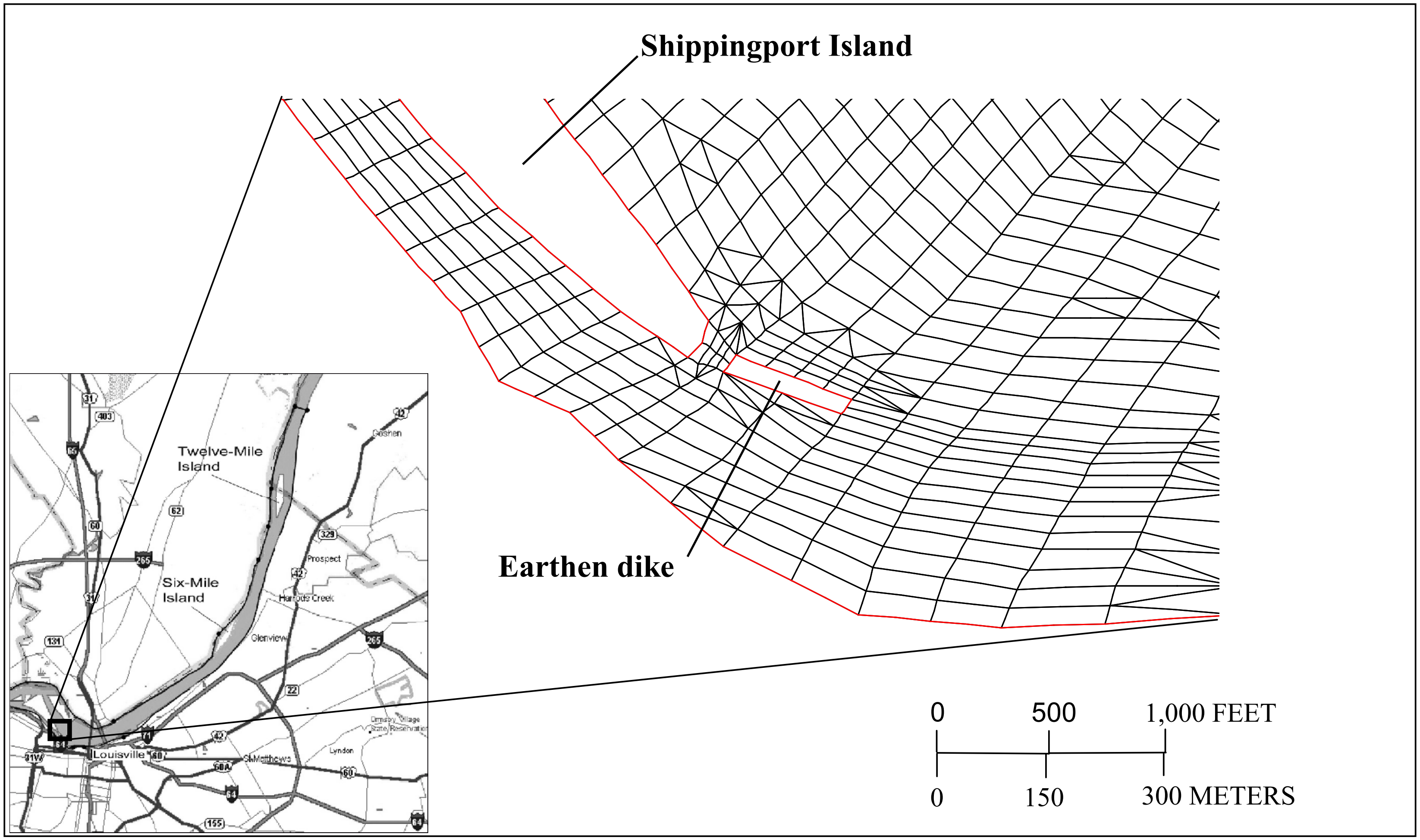


Figure 6. Mesh configuration around the earthen dike adjacent to Louisville, Kentucky, and upstream of McAlpine Locks and Dam in the Ohio River model simulation near Louisville, Kentucky.

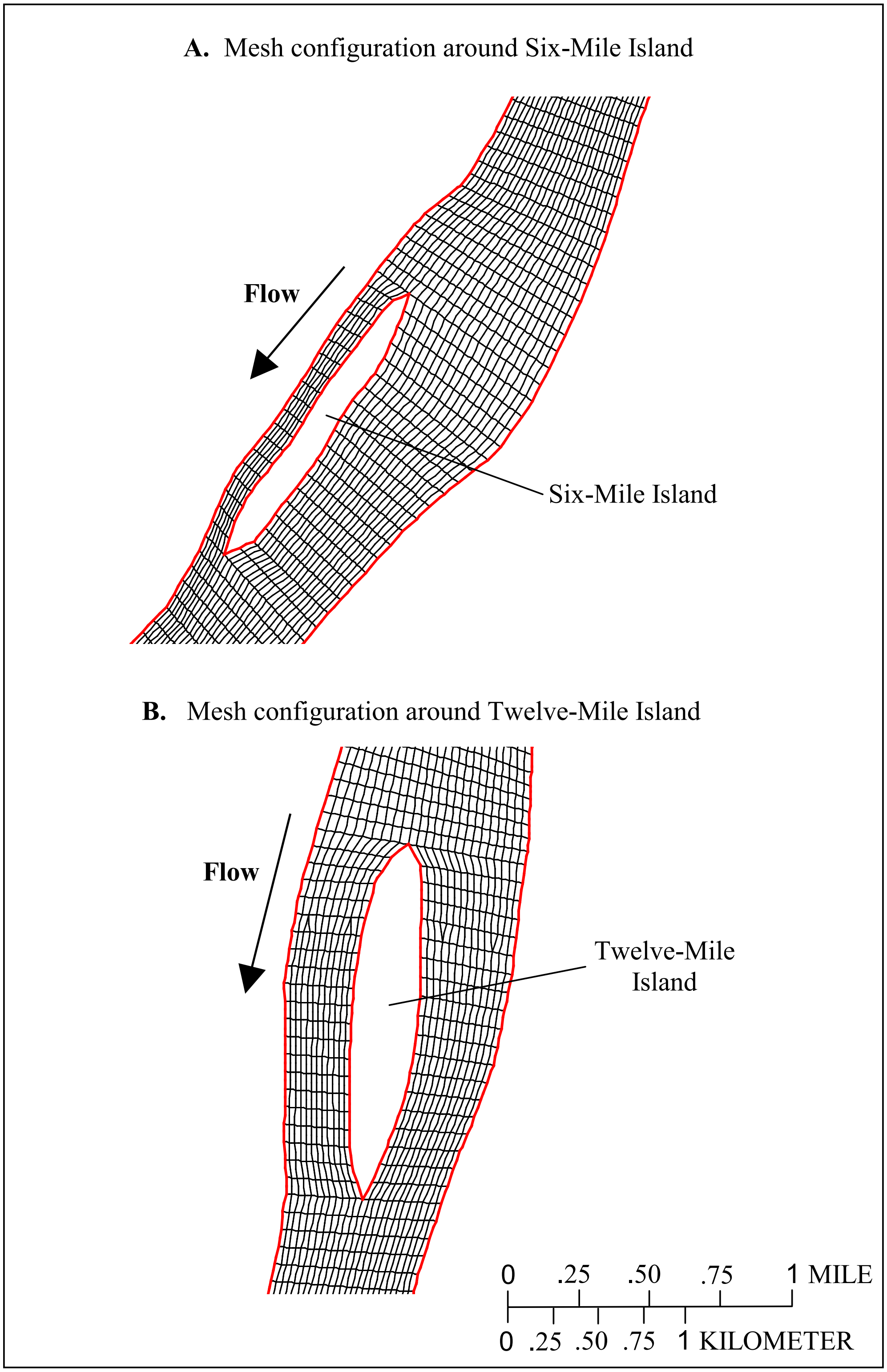


Figure 7. Mesh configurations around Six- and Twelve-Mile Islands in the upstream Ohio River study reach near Louisville, Kentucky.

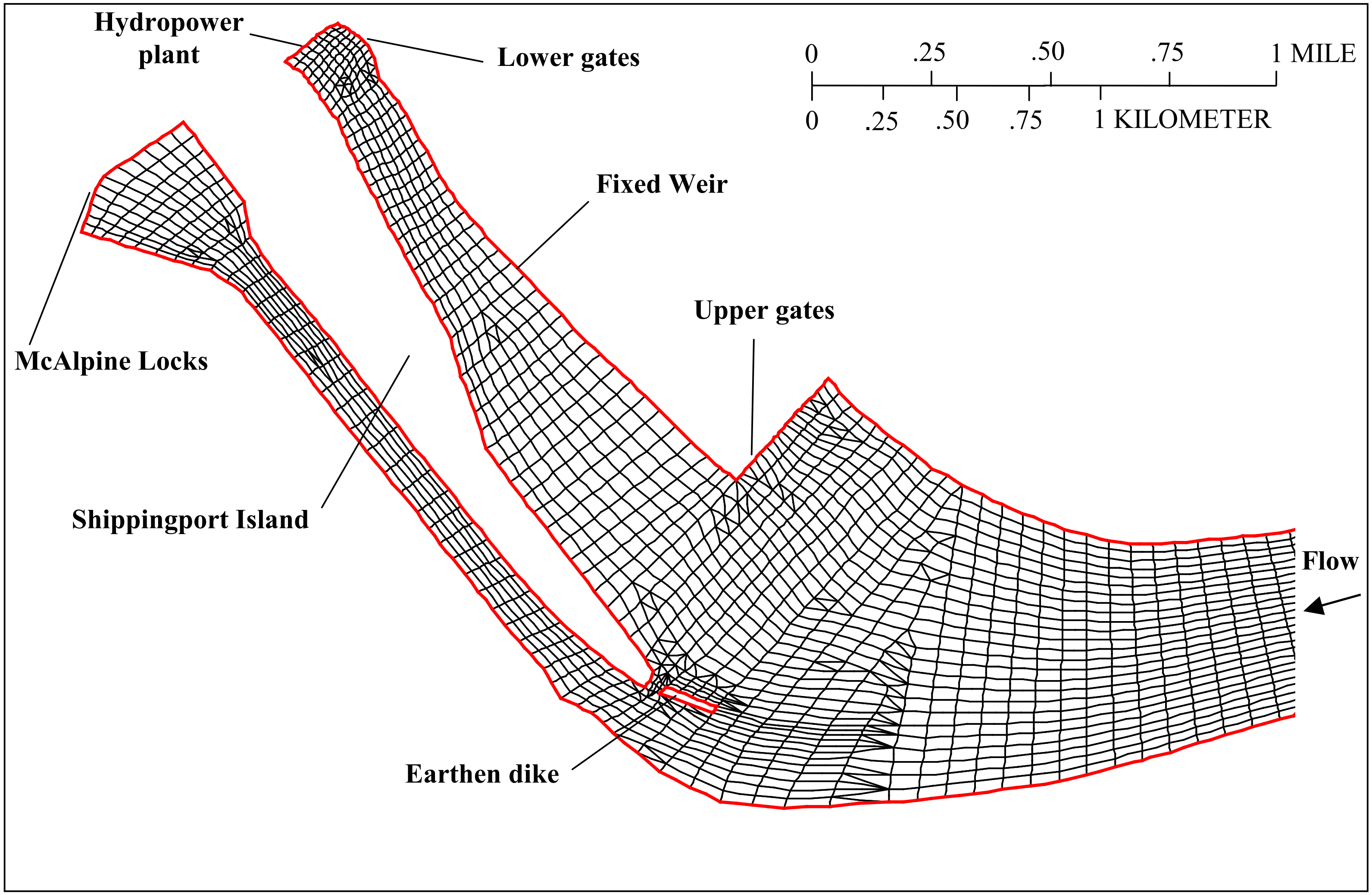


Figure 8. Upstream reach mesh configuration around McAlpine Locks and Dam near Louisville, Kentucky.

Boundary Conditions

Steady-state discharges of 34,000 and 383,000 ft^3/s were used to calibrate and validate the model. These discharges were used as the upstream-boundary condition for the model and the lateral-flow distribution was assumed to be uniform across the inflow boundary for both discharges.

The downstream-boundary condition consisted of outflows through the lower gates and hydropower plant (low-flow only) and a head condition assigned to the upper gates. The lower set of tainter gates carried 14,000 ft^3/s, whereas the hydropower plant passed the remaining 20,000 ft^3/s under the low-flow condition. At 383,000 ft^3/s, the flow is divided between the upper and lower gates, with 126,350 ft^3/s passing through the lower gates and the remaining 256,650 ft^3/s passing through the upper gates. The McAlpine Locks and Dam pool elevations for both discharges were determined from the USGS gaging station records at Indian Pass (number 03293550) and Second Street Bridge (number 03293548). Normal pool elevation (419.6 ft) was used for 34,000 ft^3/s flow, and a pool elevation of 423.9 ft was used for 383,000 ft^3/s flow.

Calibration and Validation Results

Data from the low-flow (34,000 ft^3/s) hydraulic survey were used to calibrate the model, and data from the high-flow (383,000 ft^3/s) survey were used to validate the model. The calibration and validation process consisted of comparing the simulated water-surface elevations at the 4 upstream water-surface-elevation stations and 12 cross-sectional velocity profiles with those surveyed in the field. A Manning's roughness coefficient (n) was assigned to each element and iteratively adjusted until the model adequately simulated the surveyed water-surface elevations and velocity profiles.

Inspection of the velocity profiles collected in the field revealed no-slip conditions along the riverbanks, indicating that the shear stress along the banks is great enough to cause the tangential velocity to approach zero. To simulate this characteristic with RMA-2, the Manning's n value was increased to 0.035 for one row of elements along the outer boundary of the mesh. The calibrated Manning's n in the remainder of the channel was 0.024. This combination produced the best simulation of water-surface elevation (table 1), velocity magnitudes, and lateral-velocity distribution for both low- and high-flow conditions. Matching the high-flow water-surface elevations verified that the area lost by truncating the banks was negligible in the model simulation.

Table 1. Summary of water-surface elevation calibration and validation for the upstream study reach in the Ohio River model simulation near Louisville, Kentucky

	(8/13/98) Low-flow condition			(2/16/00) High-flow condition		
Station	Field water-surface elevation (feet above sea level)	Model water-surface elevation (feet above sea level)	Difference[1]	Field water-surface elevation (feet above sea level)	Model water-surface elevation (feet above sea level)	Difference[1]
Harmony Landing	419.99	419.66	-0.33	427.59	427.68	0.09
Louisville Water Company	419.91	419.64	-.27	426.51	426.46	-.05
Cox's Park Well	419.86	419.62	-.24	425.19	425.04	-.15
Indiana Pass	419.60	419.60	0	423.88	423.90	.02

[1]Differences are determined by subtracting field from model-simulated water-surface elevation.

The simulated velocity magnitudes and distributions compared well with the field measurements. A comparison of the model and field-velocity profiles for cross-section number 5 (13 mi upstream from McAlpine Locks and Dam) is shown in figure 9. The shape of the field- and model-velocity distributions were similar, whereas on average, the velocity magnitudes were within 0.1 ft/s. The average cross-sectional velocities for the 12 cross sections also were compared. The model adequately reproduced the average field velocities (figs. 10 and 11). The model also accurately reproduced the measured-flow distributions around Twelve- and Six-Mile Islands (table 2).

Continuity was checked throughout the downstream model to assure that mass was being conserved. The model conserved mass throughout the reach under high flow, but a 3 percent loss resulted under low flow in the approach to the lower tainter gates and hydropower plant (table 3). A tolerance of +/- 3 percent in mass-conservation discrepancy is typically acceptable for most models (U.S. Army Corps of Engineers, 1997). Algorithms used to import RMA-2 output into the WASP water-quality model can correct for mass-conservation discrepancies.

Downstream River Reach

The simulated reach begins at the McAlpine Locks and Dam (Ohio River mile 607) and extends downstream to Ohio River mile 636, 6 mi downstream from the mouth of the Salt River. This section of the model includes part of the Cannelton Locks and Dam pool, which is held at a normal pool elevation of 383 ft. The two sets of tainter gates, the hydropower plant, a lock wall supported on piles that allows flow beneath the wall, and Sand Island all contribute to the hydraulic complexities of the area located immediately downstream of the McAlpine Locks and Dam.

Computational-Mesh Configuration

The finite-element network for the downstream river reach consisted of 10,803 elements. In order to maintain numerical stability, the sloping banks were truncated at an elevation of 380 ft. Above this elevation, the banks were assumed to be vertical walls.

Sand Island and an unnamed island in the Falls of the Ohio region were simulated by installing gaps in the mesh at the location of these features. The resolution of the grid is increased in the area around Sand Island, the hydropower plant, the lock wall, and both sets of tainter gates to improve simulation of the hydraulic complexities induced by these structures (fig. 12). In order to simulate the passage of flow under the lock wall, an increased Manning's roughness value (n = .50) was assigned to the elements representing the lock wall; this value allowed flow through the elements under a much greater resistance. Stagnation points were created at sharp break points along Sand Island and the mesh boundary in the area of the lower tainter gates to reduce artificial loss of discharge through the boundaries.

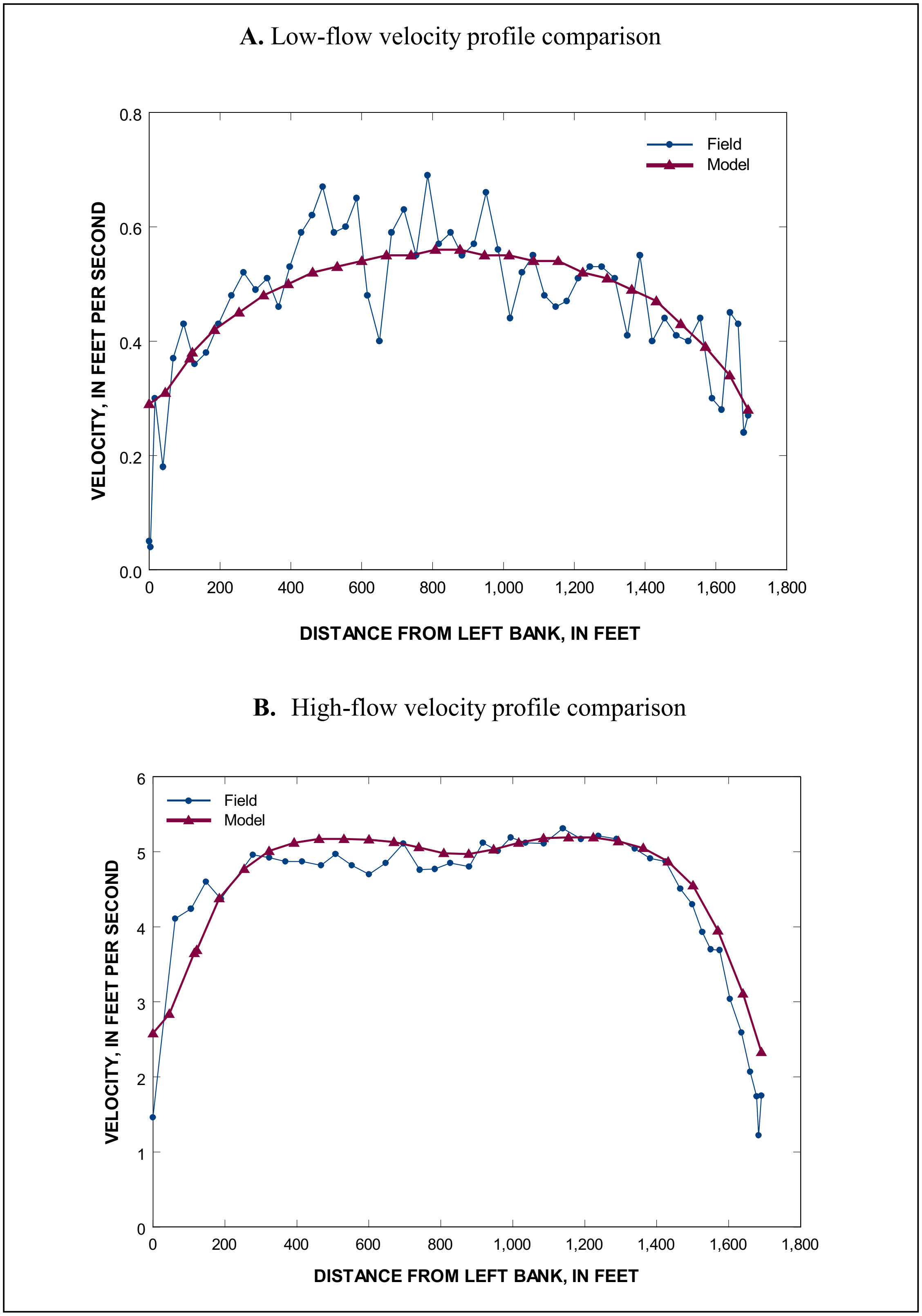


Figure 9. Field-measured and model-simulated velocity profiles for cross-section 5, 13 miles upstream from McAlpine Locks and Dam near Louisville, Kentucky.

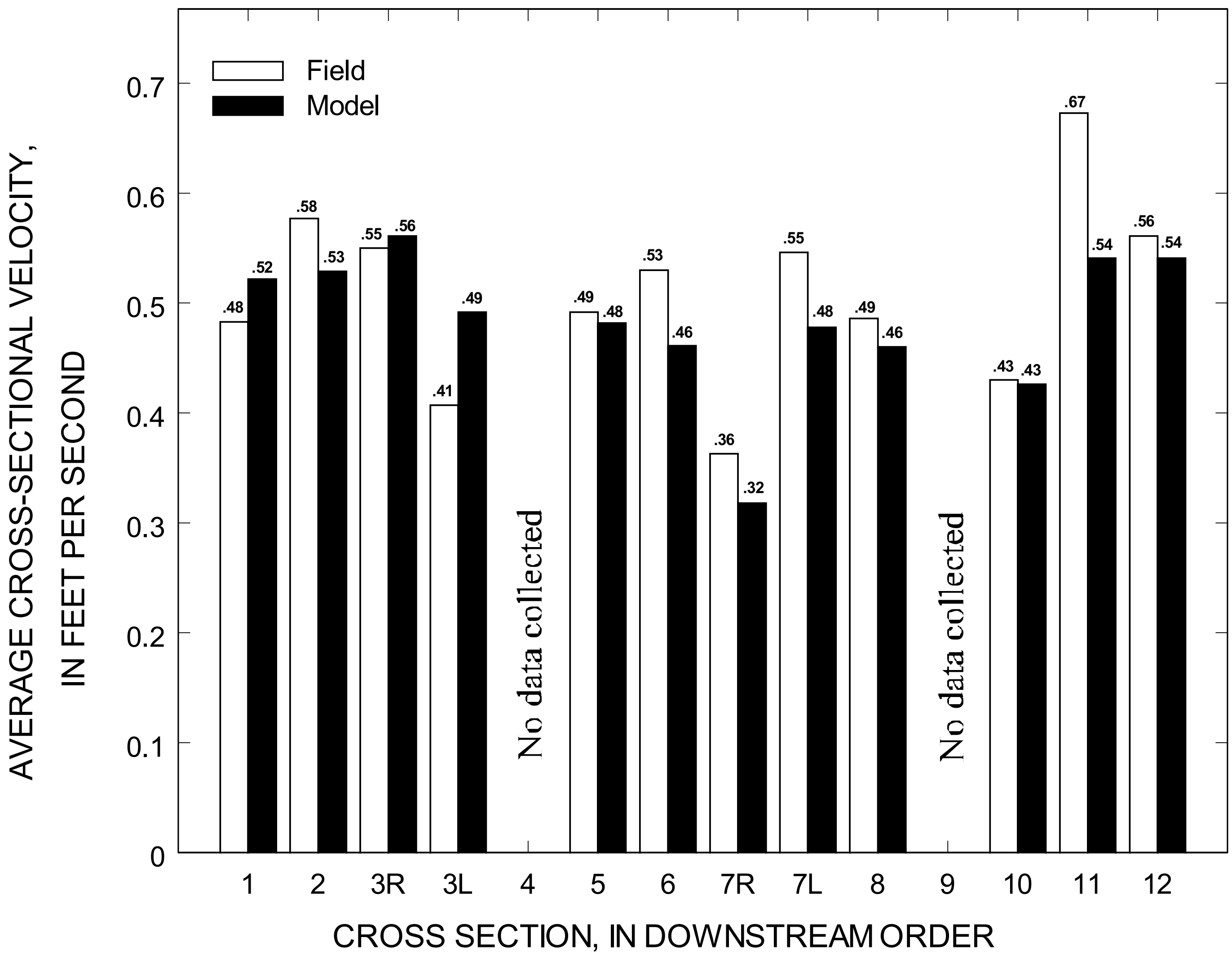


Figure 10. Field-measured and model-simulated low-flow, distance-weighted average cross-sectional velocities in the upstream study reach from the Ohio River model simulation near Louisville, Kentucky.

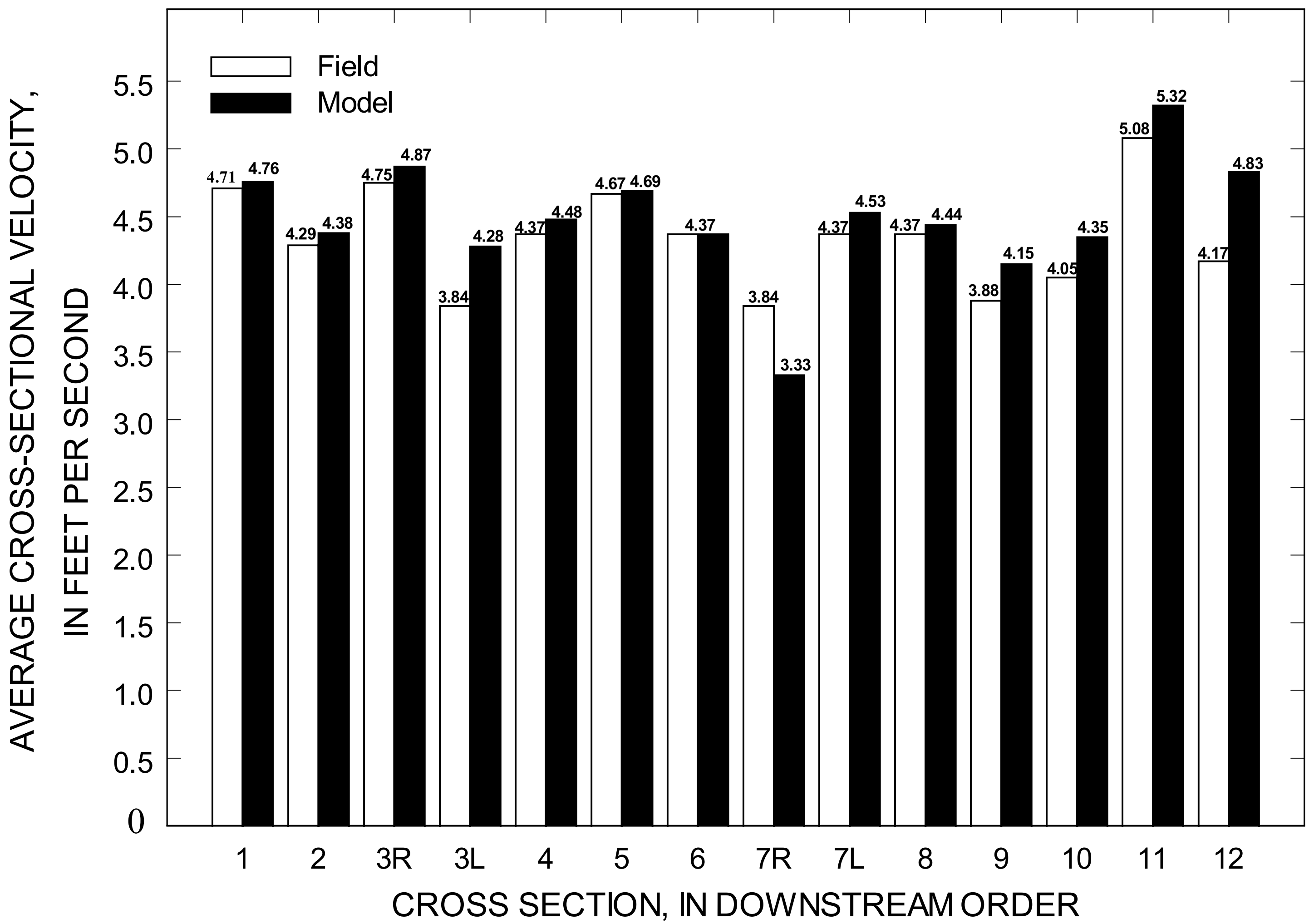


Figure 11. Field-measured and model-simulated high-flow, distance-weighted average cross-sectional velocities in the upstream study reach from the Ohio River model simulation near Louisville, Kentucky.

Table 2. Summary of flow-split calibration and validation for islands in the upstream study reach in the Ohio River model simulation near Louisville, Kentucky

Location	Low flow		High flow	
	Field flow split (percent)	Model flow split (percent)	Field flow split (percent)	Model flow split (percent)
Twelve-Mile Island – Right	53.6	51.7	51.6	49.9
Twelve-Mile Island – Left	46.4	48.3	48.4	49.5
Six-Mile Island – Right	8.9	7.8	11.2	10.0
Six-Mile Island – Left	91.1	92.0	88.8	90.0

Table 3. Summary of continuity checks in the upstream Ohio River model simulation near Louisville, Kentucky

Continuity check line description (fig. 3)	Percent of total discharge	
	Low flow	High flow
Inflow	100	100
Cross section 2	99.5	99.8
Cross section 3R	51.8	50.1
Cross section 3L	48.2	49.5
Cross section 5	100	100
Cross section 7R	8.0	10.2
Cross section 7L	92.0	89.6
Cross section 11	100	99.7
Upper gates	0	66.5
Lower gates	45.2	32.8
Hydropower plant	52.0	0
Total outflow	97.2	99.3

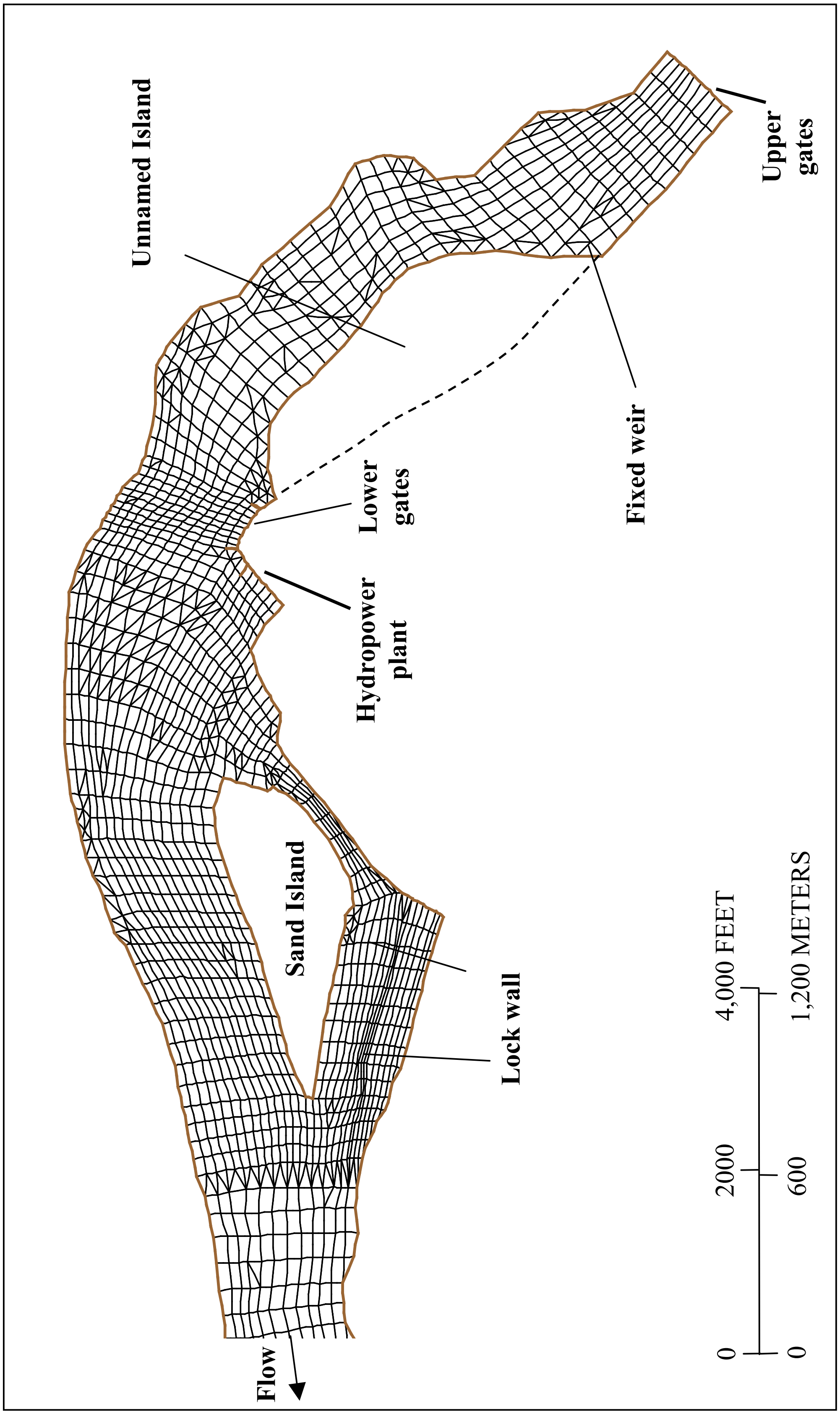


Figure 12. Mesh configuration in the downstream study reach around the tailwater area of McAlpine Locks and Dam near Louisville, Kentucky.

Boundary Conditions

Steady-state discharges of 36,000 and 397,000 ft^3/s were used to calibrate and validate the model, respectively. At 36,000 ft^3/s, the hydropower plant passed 22,000 ft^3/s, whereas the lower gates passed 14,000 ft^3/s. At 397,000 ft^3/s, the inflow is divided between the upper and lower gates, with 266,030 ft^3/s from the upper gates and 130,970 ft^3/s from the lower gates.

The downstream head-boundary conditions for both discharges were determined from stage-discharge relations developed from USGS gaging-station records at the McAlpine tailwater (number 032946500) and Kosmosdale (number 03294600) gages. The relation between stage and discharge was determined by plotting the discharge computed for the McAlpine gage with the stage measured at the McAlpine tailwater and Kosmosdale gaging stations (figs. 13 and 14). A relation between discharge and water-surface slope between the McAlpine tailwater and Kosmosdale gages also was developed (fig. 15). The downstream head-boundary conditions were determined by translating the observed water-surface elevations from the Kosmosdale gage 5 mi downstream to the model boundary by use of the discharge water-surface slope relation. For simulated flows other than those measured for calibration and validation, the stage at Kosmosdale can be determined from a known discharge and the stage-discharge relation and then translated to the downstream end of the model based on the discharge water-surface slope relation (fig. 15). The difference between the McAlpine tailwater rating and the water-surface elevation (simulated by RMA-2 based on the downstream boundary condition estimated from the technique described above) ranges from 0.16 to 0.4 ft (table 4).

Calibration and Validation Results

Similar to the upstream reach, the low-flow (36,000 ft^3/s) hydraulic survey was used to calibrate the model, and the high-flow (397,000 ft^3/s) survey was used to validate the simulation. The calibration and validation process consisted of comparing the simulated water-surface elevations at the 6 downstream water-surface elevation stations and 18 cross-sectional velocity profiles (fig. 4) with those surveyed in the field. A Manning's roughness coefficient (n) was assigned to each element and iteratively adjusted until the model adequately simulated the surveyed water-surface elevations and velocity profiles.

Inspection of the velocity profiles collected in the field revealed no-slip conditions along the riverbanks, which were similar to the upstream reach. To simulate this characteristic with RMA-2, the Manning's n value was increased to 0.035 for one row of elements along the outer boundary of the mesh. The calibrated Manning's n in the remainder of the channel was 0.024. This combination produced the best simulation of water-surface elevation (table 5), velocity magnitude, and lateral-velocity distribution for both low- and high-flow conditions. Matching the high-flow water-surface elevations verified that the area lost by truncating the banks was negligible.

Comparison of the simulated velocity magnitudes and distributions with field measurements showed good agreement for the low-flow simulation but less favorable agreement for the high-flow simulation. Examples of the general agreement between the low-flow simulated velocities and the field measured velocities are shown in figure 16. The maximum difference at low flow was about 0.25 ft/s. For the high-flow condition, the simulated velocities consistently were greater than the measured velocities, despite excellent agreement in the water-surface elevations.

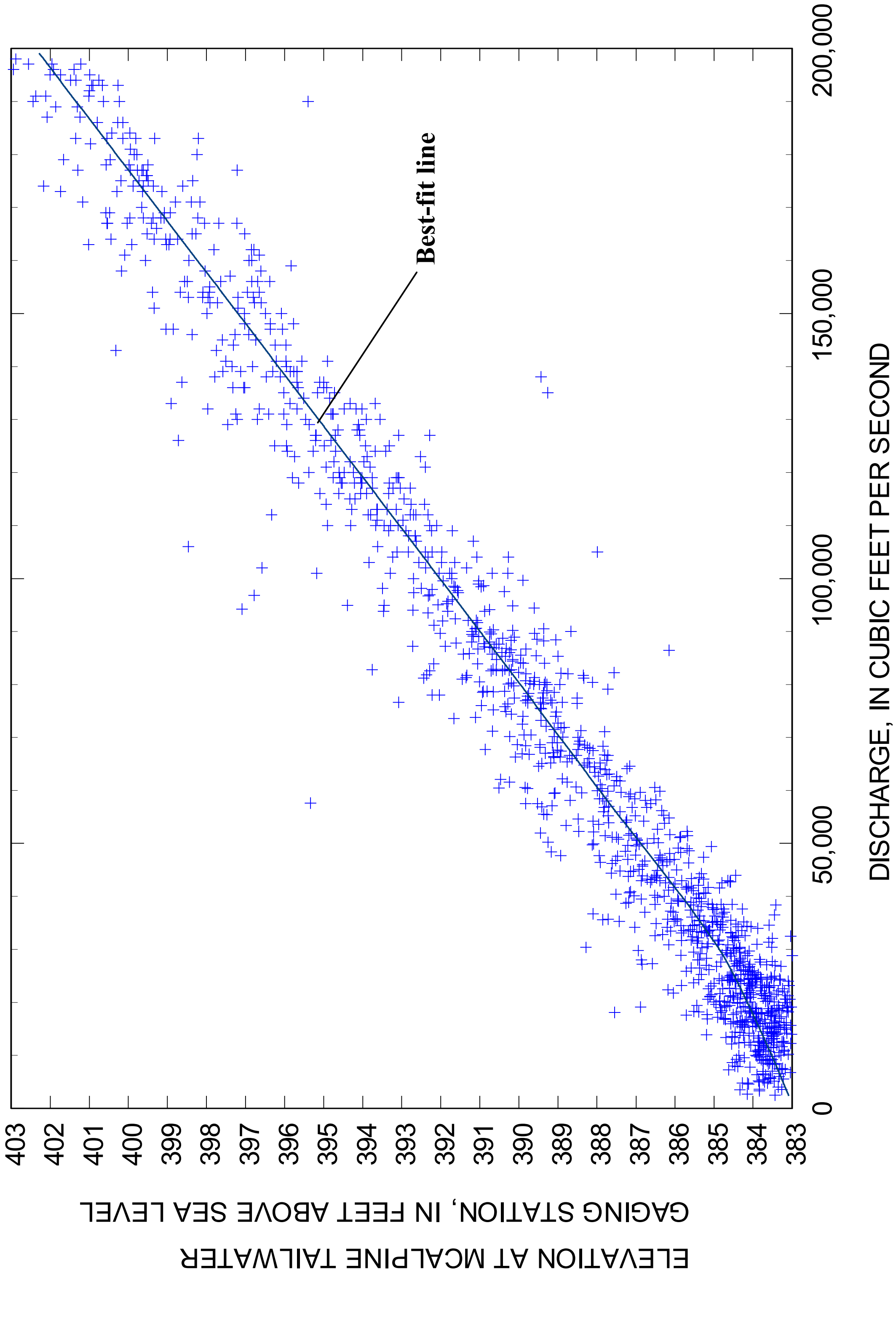


Figure 13. Stage-discharge curve for McAlpine tailwater gaging station near Louisville, Kentucky, 1990-2000.

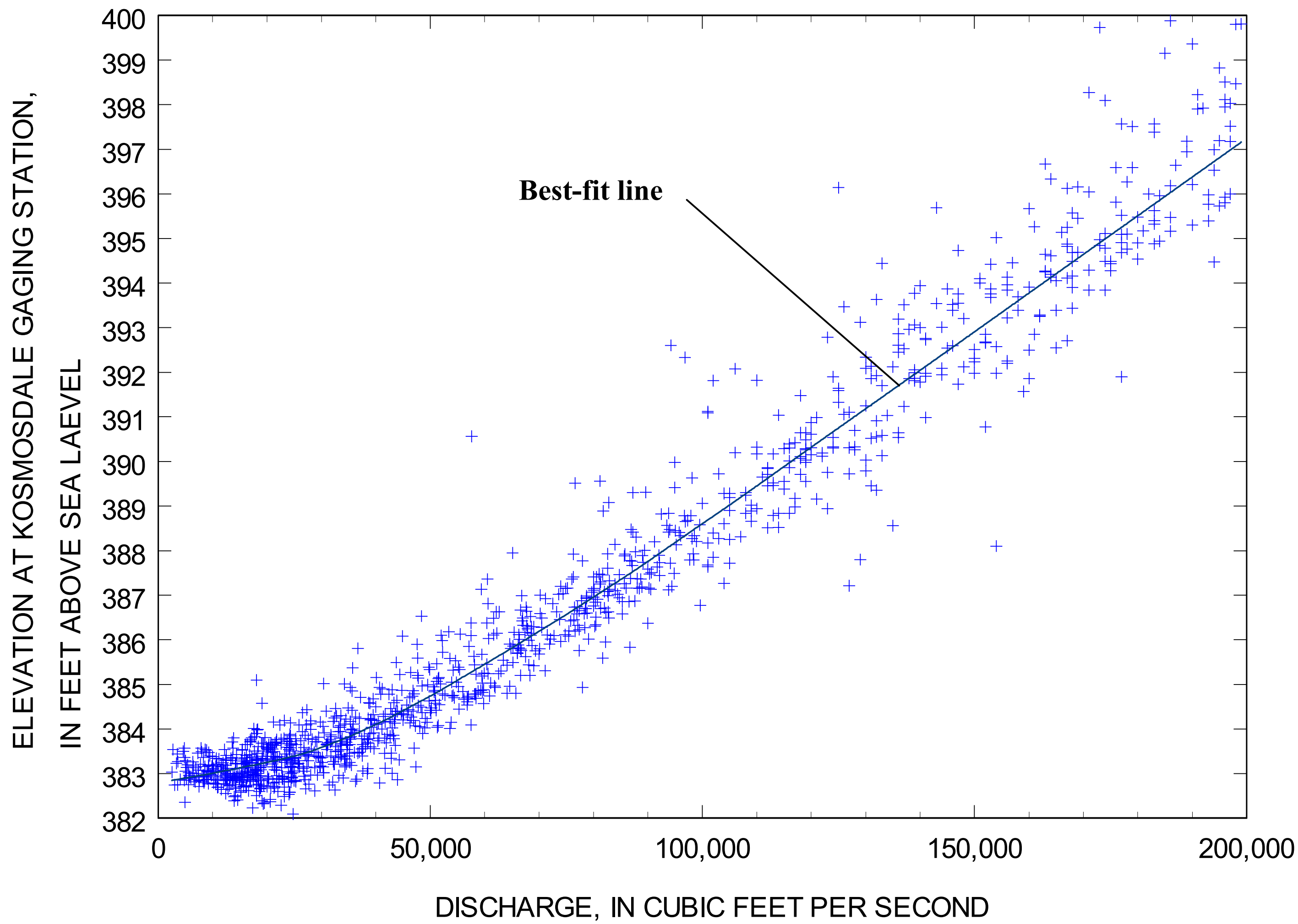


Figure 14. Stage-discharge curve at Kosmosdale gaging station near Louisville, Kentucky, 1995-2000.

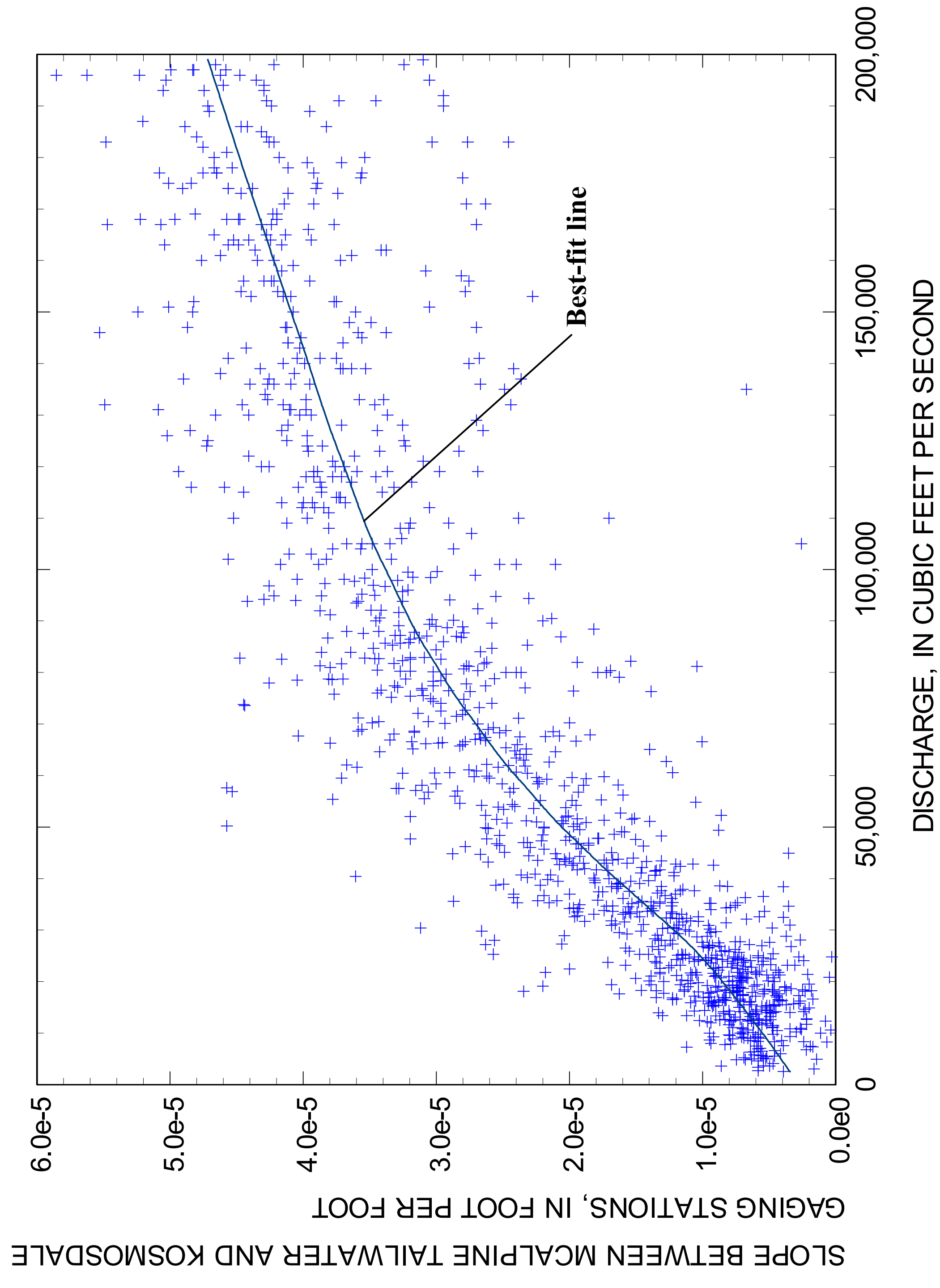


Figure 15. Discharge-slope curve between McAlpine tailwater and Kosmosdale gaging stations near Louisville, Kentucky, 1995-2000.

Table 4. Evaluation of the Resource Management Associates-2 (RMA-2) simulation representation of the Ohio River rating developed for the downstream study reach near Louisville, Kentucky

Downstream discharge (cubic feet per second)	Boundary condition (elevation above sea level)	Rating water-surface elevation, McAlpine tailwater (elevation above sea level)	Model water-surface elevation, McAlpine tailwater (elevation above sea level)
16,000	382.74	383.60	383.22
23,000	382.98	384.20	383.80
43,000	383.86	386.10	385.94
97,000	387.25	391.80	392.23
200,000	395.54	402.60	402.27

Table 5. Summary of water-surface elevation calibration and validation for the downstream study reach in the Ohio River model simulation near Louisville, Kentucky

	(5/19/00) Low-flow condition			(2/17/00) High-flow condition		
Station	Field water-surface elevation (feet above sea level)	Model water-surface elevation (feet above sea level)	Difference[1]	Field water-surface elevation (feet above sea level)	Model water-surface elevation (feet above sea level)	Difference[1]
McAlpine tailwater	385.20	384.90	-0.30	416.18	416.13	-0.05
Shawnee well	384.75	384.50	-.25	415.10	415.21	.11
RR-22 well	384.68	384.20	-.48	413.65	413.83	.18
Kosmosdale	383.85	383.50	-.35	410.10	410.12	.02
West Point	383.54	383.40	-.14	409.70	409.50	-.20

[1]Differences are determined by subtracting field from model-simulated water-surface elevation.

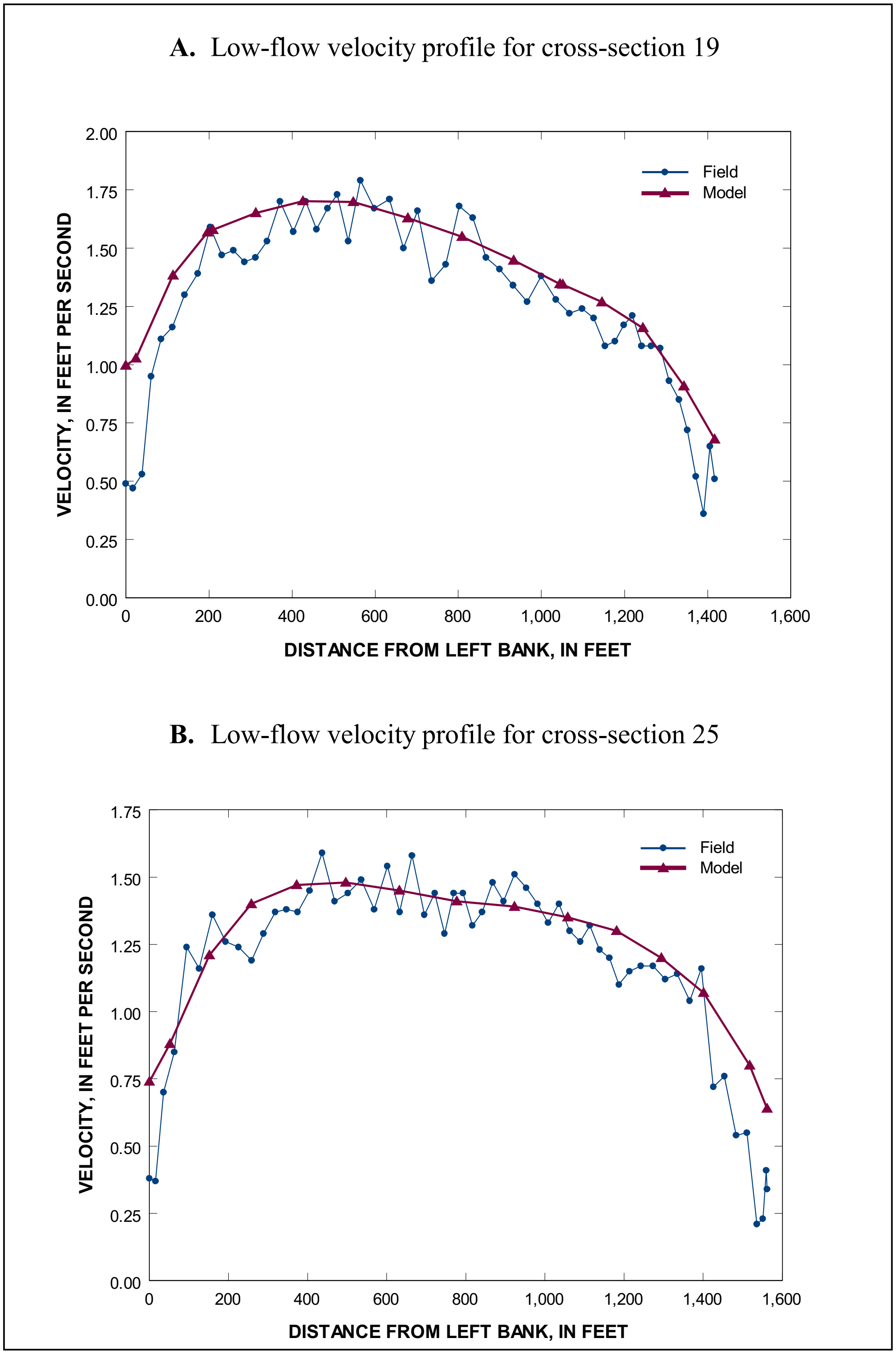
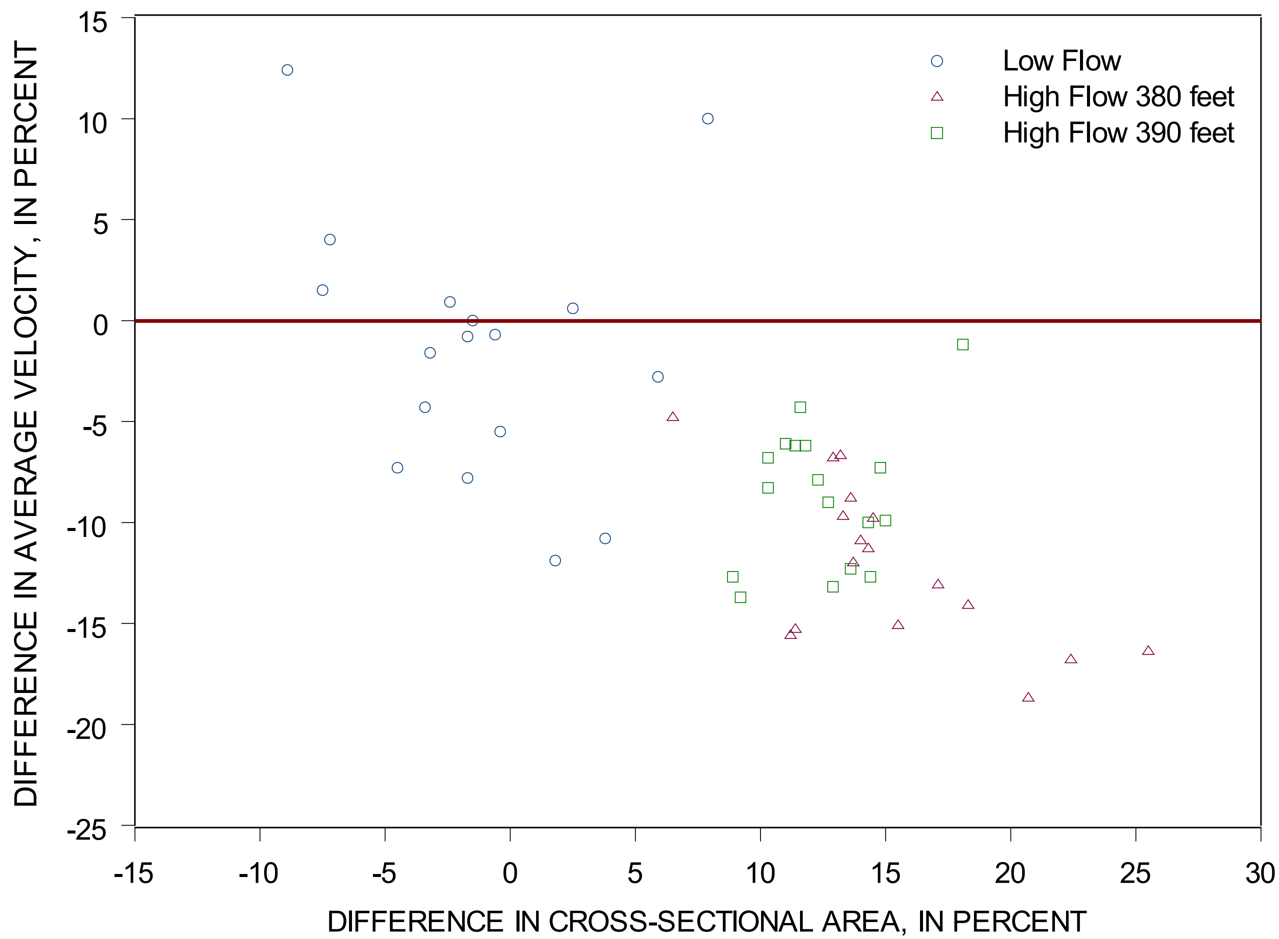


Figure 16. Field-measured and model-simulated low-flow velocity profiles for cross-sections 19 and 25 in the Ohio River model simulation near Louisville, Kentucky.

To identify the cause of the disagreement between the simulated and measured velocities for the high-flow condition, the cross-sectional areas of the model and the field were evaluated. The difference between the magnitudes of the model and field average cross-sectional velocities is correlated closely with differences in cross-sectional area (fig. 17). This difference in areas for the high-flow condition indicates that truncating the channel bathymetry at an elevation of 380 ft may not be acceptable for high flows. Extending the bathymetry to an elevation of 390 ft improved the agreement between field and model velocities but failed to explain all of the error. For low-flow conditions, the errors between the field data and the model are somewhat randomly distributed around zero. The errors for the high-flow condition with banks truncated at an elevation of 380 ft show a linear pattern, while the errors for the high-flow condition with banks truncated at an elevation of 390 ft show a less distinct pattern but still well below zero. The patterns indicated by the high-flow data indicate that something outside the scope of the model may be responsible for the apparent errors. Scouring of the channel bottom occurred during high flow and is partially responsible for the large difference between the model and field cross-sectional areas and average velocities because the model is not able to simulate the scouring of the channel bed (figs. 18 and 19). A comparison of the average cross-sectional velocities for the field and two model meshes are shown in figures 20 and 21.

Although extending the banks to an elevation of 390 ft improved the overall accuracy of the high-flow simulation (3.4 percent in average cross-sectional velocity), the primary reason for the difference between the model and field cross-sectional areas and velocities is that the model has a fixed bed and the river adjusted its cross section in the downstream reach during high flow. To minimize errors of future simulations, the bathymetry was truncated at an elevation of 380 ft for flows less than 200,000 ft^3/s, and bathymetry was truncated at an elevation of 390 ft for flows ranging from 200,000 to 400,000 ft^3/s.

Continuity was checked throughout the model to ensure that mass was being conserved. The location of the continuity-check lines near Sand Island and the Falls of the Ohio is shown in figure 2; mass is conserved around Sand Island and the Falls of the Ohio (table 6). Based on the calibration and validation results, the model is a representative simulation of the Ohio River steady-flow patterns below discharges of approximately 400,000 ft^3/s.



EXPLANATION

High Flow 380 feet - All bathymetry truncated at elevation 380 feet above sea level

High Flow 390 feet - All bathymetry truncated at elevation 390 feet above sea level

Figure 17. Scatter plot of the cross-sectional area and average velocity differences between field measurements and model-simulated results for the 18 downstream Ohio River cross sections near Louisville, Kentucky.

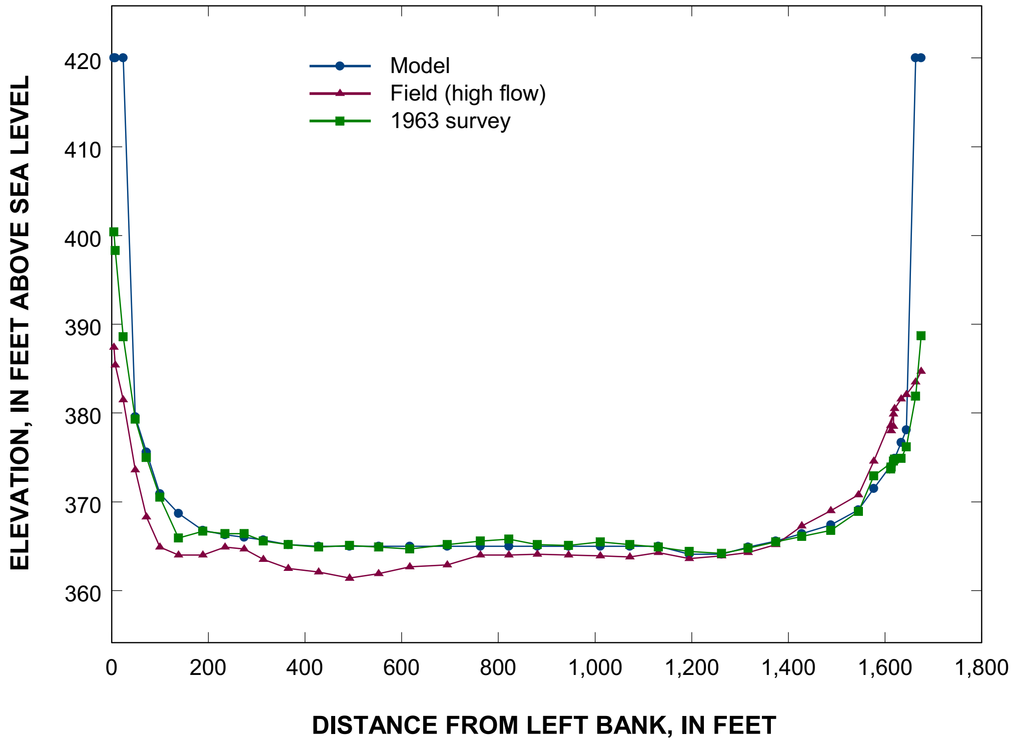


Figure 18. Comparison of cross-section 24 bathymetry in the downstream Ohio River study reach near Louisville, Kentucky.

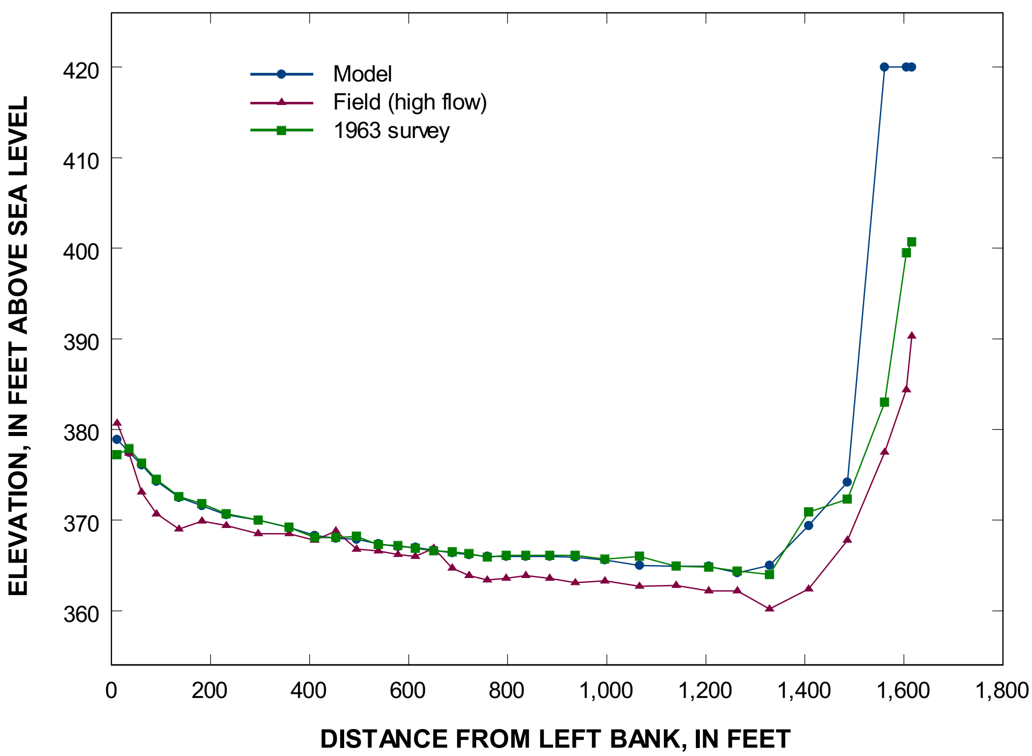


Figure 19. Comparison of cross-section 20 bathymetry in the downstream Ohio River study reach near Louisville, Kentucky.

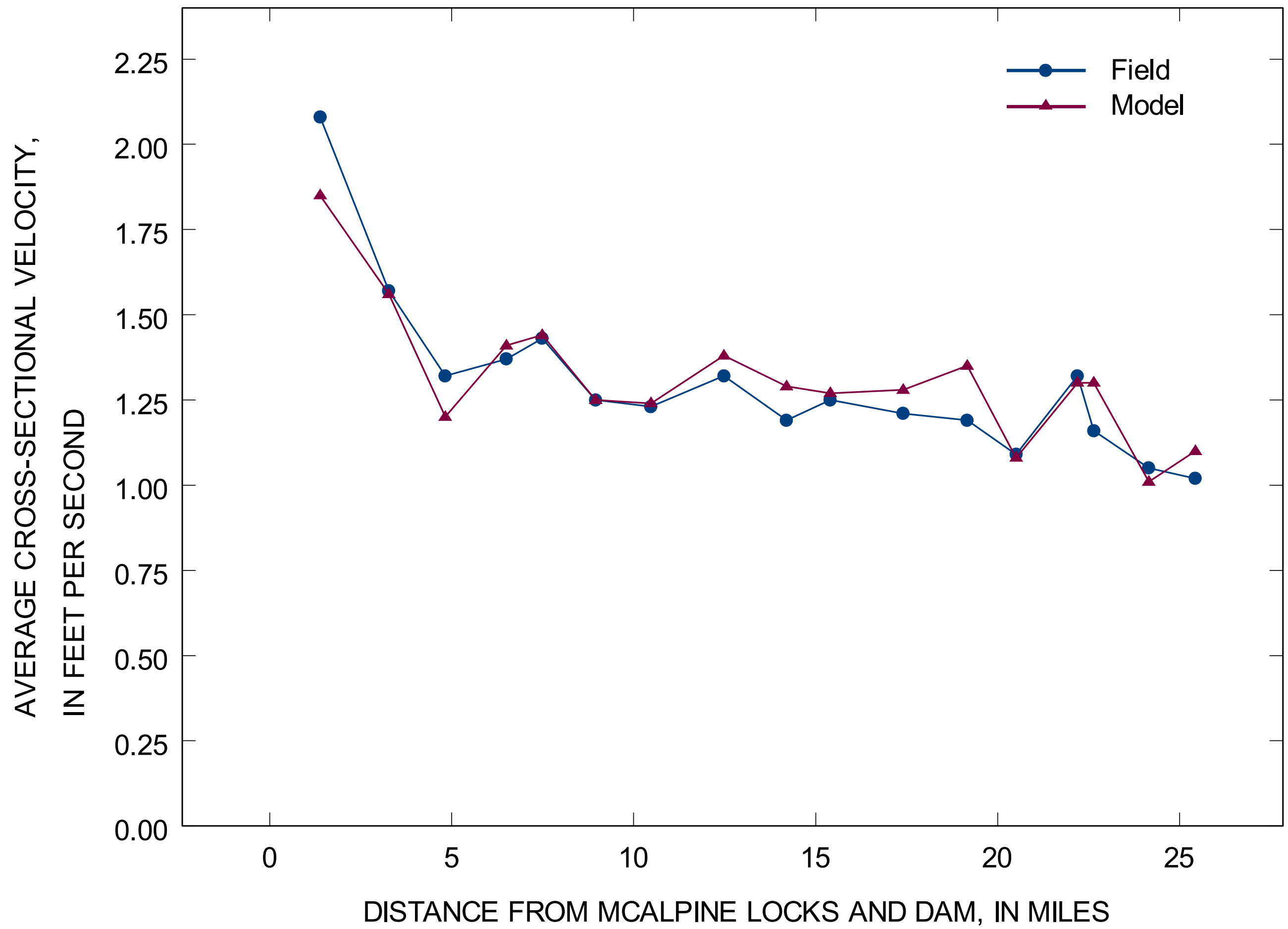
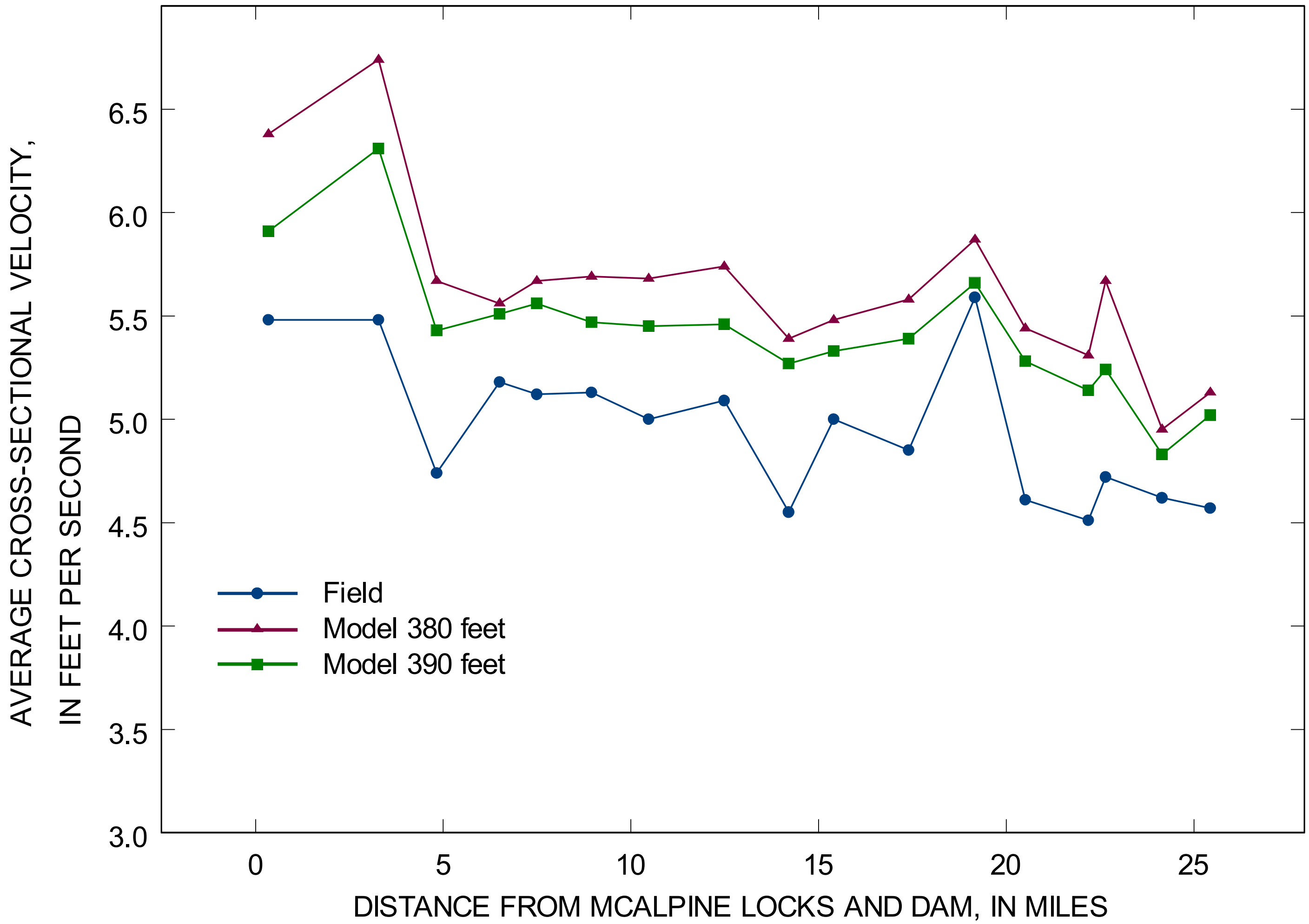


Figure 20. Low-flow distance-weighted average cross-sectional velocity profile for the downstream study reach in the Ohio River model simulation near Louisville, Kentucky.



EXPLANATION

Model 380 feet - All bathymetry truncated at elevation 380 feet above sea level

Model 390 feet - All bathymetry truncated at elevation 390 feet above sea level

Figure 21. High-flow distance-weighted average cross-sectional velocity profile for the downstream study reach in the Ohio River model simulation near Louisville, Kentucky.

Table 6. Summary of continuity checks in the downstream Ohio River model simulation near Louisville, Kentucky

Continuity check line description (figs. 2, 4)	Percent of total discharge	
	Low flow	High flow
Upper gates - inflow	0.0	67.0
Hydropower - inflow	60.4	0
Lower gates - inflow	39.4	33.0
Total inflow	99.8	100.0
CC1	.1	65.6
CC2	84.0	101
CC3	17.6	-.4
CC4	79.4	100.7
CC5	19.2	-.5
Cross section 15	102	98.4
Cross section 22	100	99.9
Outflow	100	100

SUMMARY AND CONCLUSIONS

The determination of current patterns is an essential component of a Water Quality Analysis Simulation Program (WASP) in a riverine environment. The U.S. Geological Survey (USGS), in cooperation with the Ohio River Valley Water Sanitation Commission (ORSANCO), developed a field-validated two-dimensional hydrodynamic model capable of quantifying the steady flow patterns in the reach of the Ohio River extending from Ohio River mile 590 to 630 for the ORSANCO water-quality modeling efforts on that reach. The model was calibrated to a low-flow hydraulic survey (approximately 35,000 cubic feet per second (ft^3/s)) and validated with data collected during a high-flow survey (approximately 390,000 ft^3/s). The model calibration and verification process included matching water-surface elevations at 10 locations and velocity profiles at 30 cross sections in the study reach. The study area was separated into an upper and lower river reach separated at McAlpine Locks and Dam (Ohio River mile 607). A bathymetric survey was conducted on the upstream reach to determine the channel geometry. Data from the Ohio River survey (1963) done by the U.S. Army Corps of Engineers was used to determine bathymetry on the downstream reach. Data collected during the upstream bathymetric survey was mathematically forced onto straight cross-section lines providing a more accurate triangulation of the data in the modeling software package. Bathymetry of both reaches was truncated along the banks to eliminate Resource Management Associates-2 (RMA-2) convergence problems associated with the steeply sloping banks of the Ohio River. The upper reach was truncated at an elevation of 418 ft for both flow conditions, whereas the lower reach was truncated at an elevation of 380 ft for low flows (less than 200,000 ft^3/s) and an elevation of 390 ft for high flows (from 200,000 to 400,000 ft^3/s).

Based on historical discharge data during 1987–98, the 90-percentile flow during this recreational-contact period (May-September) is 197,700 ft^3/s; therefore, only the model with bathymetry truncated at an elevation of 380 ft is needed to simulate these flows.

The model was calibrated and validated by use of water-surface elevations and average cross-sectional velocities to achieve the minimum error for both high- and low-flow conditions. The simulated low-flow water-surface elevations typically were biased between 0.2 and 0.3 ft low, whereas the simulated high-flow water-surface elevations were within 0.1 ft of the field conditions. Simulated average cross-sectional velocities were typically within 0.1 ft/s for low flow and 0.3 ft/s for high flow when compared with field data.

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