RESULTS OF A TWO-DIMENSIONAL HYDRODYNAMIC AND SEDIMENT-TRANSPORT MODEL OF THE CONSTRUCTION AND OPERATION OF THE OLMSTED LOCKS AND DAM, OHIO RIVER

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INTRODUCTION

The Olmsted Locks and Dam hydrodynamic and sediment-transport model was developed by the U.S. Geological Survey (USGS) in cooperation with the U.S. Army Corps of Engineers, (USACE) Louisville District to evaluate the environmental effect of the construction and subsequent operation of the Olmsted Locks and Dam on the lower Ohio River. The Olmsted Locks and Dam will replace Locks and Dam 52 and 53 and be the final high-lift dam structure on the Ohio River. The modeling project was conducted in two phases; the first modeling phase focused on simulating the dam construction sequence while the second modeling phase focused on long-term effects of the fully operational locks and dam.

The Olmsted Locks and Dam model was developed to predict the change in sediment-transport patterns around the endangered orange-footed pearly mussel (*Plethobasus cooperianus*) induced by the construction and subsequent operation of the Olmsted Locks and Dam. There is evidence that indicates the orange-footed pearly mussels in the beds located in the lower Ohio River near the Olmsted Locks and Dam are reproducing, so any changes to the mussel habitat could threaten the survival of the species (U.S. Fish and Wildlife Service, 1993).

This paper describes the development and results of the Olmsted Locks and Dam hydrodynamic and sediment-transport model developed on the lower Ohio River (Locks and Dam 53 to Ohio River Mile 974.5). The field data and methodology used to develop and calibrate the models are also described herein.

MODELING APPROACH

The Olmsted Locks and Dam hydrodynamic and sediment-transport model was developed for a section of the lower Ohio River (Locks and Dam 53 to Ohio River Mile 974.5; fig.1). Floodplains were included in the model in order to accurately simulate high-flow conditions, which were thought at the onset of the project to induce the most significant habitat changes. The calibrated model was used to simulate sediment transport patterns for hydraulic conditions ranging from 1,100,000 cubic feet per second (ft^3/s) to 88,000 ft^3/s under a wide range of backwater and free-flowing conditions.

A Resource Management Associates–2 (RMA-2, version 4.53)[1] two-dimensional hydrodynamic model for the reach was calibrated to a middle-flow hydraulic survey (350,000 ft^3/s) and verified

[1] Any use of trade, product or firm names in this paper is for descriptive purposes only and does not imply endorsement by the U.S. Government.

with data collected during a low- and a high-flow hydraulic survey (72,500 ft^3/s and 770,000 ft^3/s, respectively). The calibration and validation process included matching water-surface elevations at the construction site and velocity profiles at 15 cross sections throughout the study reach. The sediment-transport aspect of the project was simulated with the Waterways Experiment Station's (WES) Sed2D model (version 4.52). The purpose of the construction modeling phase of the Olmsted sediment-transport simulation was to estimate the effect the phased in-the-wet construction sequence of the Olmsted Locks and Dam would have on sediment-transport patterns in the study reach and particularly over the mussel beds beginning approximately 2 miles downstream from the dam. The purpose of the operational modeling phase of the sediment-transport simulation was to evaluate the long-term effects of the fully operational Olmsted Locks and Dam would have on sediment-transport patterns in the reach and over the mussel beds.

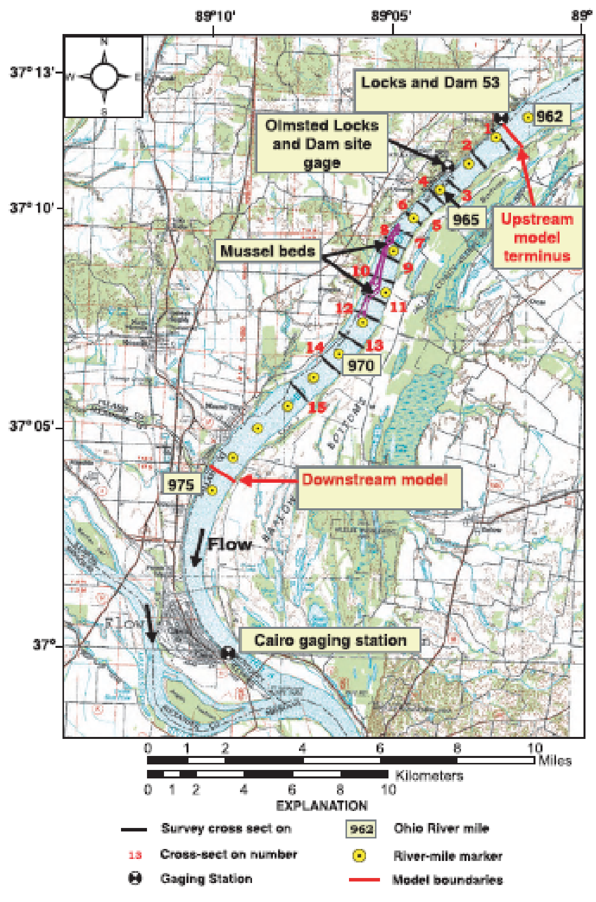

Figure 1 Location of the study area on the Ohio River, near Olmsted, Illinois.

A baseline scenario that included only the completed lock section was run concurrently with both the phased-construction and fully operational scenarios for the 9-year simulation period to compare to the sediment transport patterns induced by the dam construction and subsequent operation.

Hydrograph Development: Stepped annual hydrographs were used as input to drive the steady-state simulations. Representations of actual hydrographs from the USGS gaging station on the Ohio River at Locks and Dam 53 (03612500) were used instead of synthetic hydrographs in order to include the Mississippi River backwater conditions, which are common on the lower Ohio River.

The phased construction process was estimated to take 6 years to complete; therefore, the steady-state sediment-transport model simulated six annual stepped hydrographs. The hydrographs used were representative of conditions in 1996 (a typical annual hydrograph for the reach) and 1997 (a year of extreme high- and low-flow periods).

The fully operational locks and dam were simulated for 3 years, beginning at the end of the modeled 6-year construction phase, by three annual stepped hydrographs. In contrast to the hydrographs in the construction phase model, the hydrographs in operational phase modeling were representative of the hydrograph patterns that occur on a regular basis. The hydrographs used to model the 3-year operational phase were representative of data collected in 1985, 1986, and 1973 on the lower Ohio River.

HYDRODYNAMIC MODEL DEVELOPMENT AND CALIBRATION

At least two data sets are required to calibrate and validate a numerical model. The general procedure used to calibrate and validate the RMA-2 hydrodynamic model was to collect field data (bathymetry, roughness, etc.), which allowed the development of the computational mesh. The model then was calibrated to the water-surface elevations and velocities observed in the field for the initial mid-flow condition (350,000 ft^3/s). Both the low- and high-flow conditions were then 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 these additional flow conditions.

Field Data Collection and Interpretation: Water-surface elevations, channel bathymetry, and detailed water-velocity measurements were collected at the three different flow conditions. Water-surface elevations were measured at the Olmsted construction site and tailwater of Locks and Dam 53 concurrent with all three hydraulic surveys. Detailed water-velocity measurements and channel-bathymetry data were collected with an acoustic Doppler current profiler (ADCP) at 15 cross sections spaced from 2,000 feet to 5,000 feet (ft) apart during each of the hydraulic surveys.

Bathymetry data also were collected from a moving boat. The horizontal position of the boat was measured by use of a differential GPS (DGPS) receiver. Starting in 1993, bathymetric surveys were conducted annually by the USACE St. Louis District using a phased-array echo sounder. The phased-array system produced an extremely dense data set for a majority of the study reach. The raw bathymetry data were processed onto a 40 ft by 40 ft grid to make the file size more manageable, yet still provide high-resolution representation of the channel topography. The floodplains were digitized from USGS 7.5-minute quadrangle topographic maps with 5-ft contour intervals.

Calibration and Validation Results: Data from the mid-flow hydraulic survey were used to calibrate the model, and data from the low- and high-flow surveys were used to validate the model. The calibration and validation process consisted of comparing the simulated water-surface elevations (at the water-surface elevation stations) and 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 most accurately simulated both the surveyed water-surface elevations and velocity profiles. A summary of the water-surface elevation calibration results is presented in Table 1.

Table 1 Summary of water-surface elevation calibration and validation for the Olmsted Locks and Dam study reach near Olmsted, Illinois.

	Olmsted Locks and Dam site		
Discharge (cubic feet per second)	Field water-surface elevation (feet above sea level)	Model water-surface elevation (feet above seal level)	Difference[1] (feet)
75,000	286.84	287.06	-0.22
350,000	305.94	306.00	-.06
750,000	322.34	322.10	.24

[1] Differences are determined by subtracting model from field data

The simulated-velocity magnitudes and distributions compared well with the field measurements. The shape of the field- and model-velocity distributions compared very well; on average, the differences in velocity magnitudes were within 0.25 feet per second (ft/s). The model also accurately reproduced the velocity directions, especially in areas of reverse flow experienced along the Kentucky bank just downstream from Locks and Dam 53 and in the shadow of the Olmsted cofferdam (fig. 2). Continuity also was checked throughout the model to ensure that mass was being conserved. The model conserved mass within +/- 0.7% throughout the reach under the low-, mid- and high-flow conditions.

Upon completion of the calibration and validation process, the proposed Olmsted Locks and Dam structures were added to the model without the ability to compare the model results with field data. The alternative to field data was to compare the numerical model to results from a physical model developed by the USACE Waterways Experiment Station in Vicksburg, MS. The flow fields for the numerical and physical models were consistent for a range of flow conditions.

SEDIMENT-TRANSPORT MODEL DEVELOPMENT AND RESULTS

Simulated velocities and water levels from the hydrodynamic simulations were used with the Waterways Experiment Station's (WES) Sed2D model and information on bed-material characteristics to simulate the effects of the Olmsted Locks and Dam on sediment deposition and erosion in the study reach.

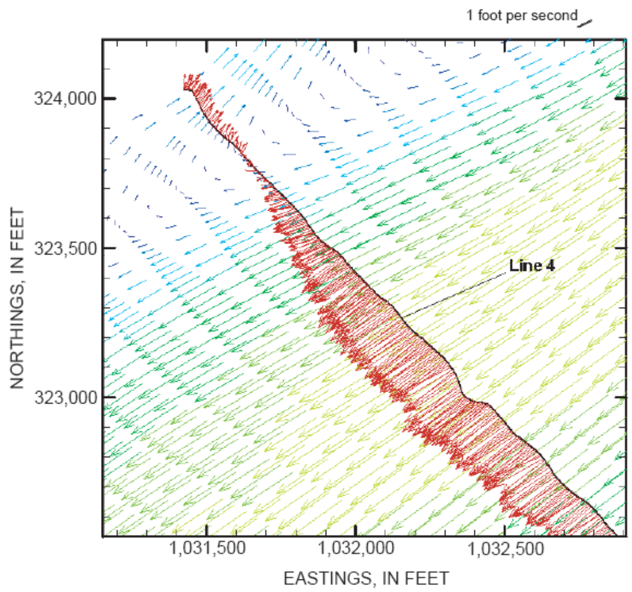

Figure 2 ADCP-measured and simulated low-flow velocity vectors at a cross-section in the Olmsted Locks and Dam study reach near Olmsted, Illinois (red arrows represent field data, multi-colored arrows represent model data)

Sediment-Transport Model Development: The following sections provide a discussion of the input data required to solve the governing equations of the Sed2D model as well as a brief explanation of the methods used to develop the input parameters.

Bed Material: The USACE St. Louis District collected bed-material data in the study reach on June 30, 1993 and February 13, 1994. These data were processed into a percent-finer format and geographically positioned to evaluate the composition of the bed material throughout the study reach. A summary of the D_{50} for all bed-material data collected in four cross sections over the mussel beds is illustrated in Figure 3 along with the position of each sample in the cross section. The data reveal that the mussel bed (located along the right bank) is primarily composed of gravel (average grain size around 10 millimeters (mm)), and the main channel is primarily composed of sand.

Selection of Representative Grain Size: The Sed2D model (version 4.52) currently (2003) considers only a single, effective grain size during each simulation. By entering the mussel-bed grain size (10 mm) into the Hydraulic Engineering Circular-18 (HEC-18) (Richardson and Davis, 2001) equation for critical velocity, it was estimated that the mussel bed would not scour at any of the hydraulic conditions being modeled; therefore, the representative grain size for the reach was determined by inspection of the D_{50} in the other areas of the reach. The field data shown in Figure 3 indicate that, aside from the mussel beds, the average grain size of the material comprising the channel bed is around 0.6 mm. A grain size of 0.6 mm was determined to be the most representative of the reach assuming that no scour of the mussel beds would occur for the hydraulic conditions being modeled.

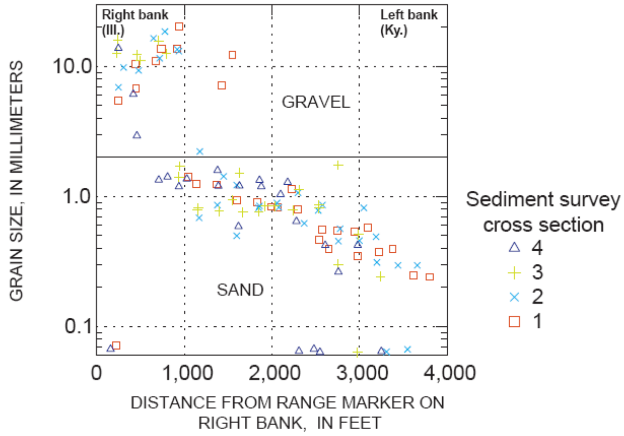

Figure 3 Summary of the bed-material D_{50} for sediment samples collected at four cross sections located around the mussel beds in the Olmsted Locks and Dam study reach near Olmsted, Ill.

Sediment-Inflow Concentration: The sediment-inflow boundary conditions for the annual hydrographs were established by a rating curve developed by Sed2D model runs. The various hydrograph steps were modeled with no sediment supply to the study reach to allow the river to reach equilibrium conditions. The equilibrium-sediment concentration for each step was used to build the bed-material inflow-rating curve. The absence of grain-size distributions for the suspended-sediment concentrations collected in the field and the inability of Sed2D to model multiple grain sizes prevented the use of empirical bed-load equations.

SEDIMENT-TRANSPORT MODEL RESULTS:

The results of the Olmsted modeling project are summarized according to the two modeling phases. The construction phase modeling will focus on results of the 6-year dam construction simulation and the operational phase modeling will focus on the long-term results of the 3-year fully operational locks and dam simulation.

Construction Phase Model - Sediment Transport: The cumulative difference in bed change between the baseline and construction phases at the end of the six annual hydrographs is shown in Figure 4. The amount and downstream extent of deposition caused by the dam construction progressively increases from year 1 through year 6. The initial concerns by U.S. Fish and Wildlife Service and USACE were that high-flow conditions would have the most effect on sediment-transport patterns in the study reach; however, the most significant bed change occurred during the low-flow period at the end of year 5 in which the wicket gates were closed and the flow of the river passed through the tainter gates (fig. 5). The maximum cumulative deposition on the mussel beds was approximately 1.5 ft, which occurred at the end of year 6. The greatest areas of deposition are shown to develop at the upstream section of the mussel beds as well as near the downstream end of the mussel beds, along the edge of the area where scour was prevented.

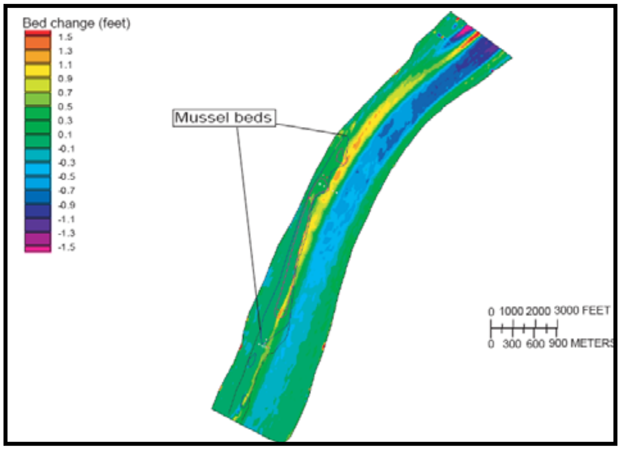

Figure 4 Difference in bed change between baseline and construction simulations after year 6 in the Olmsted Locks and Dam study reach near Olmsted, Illinois.

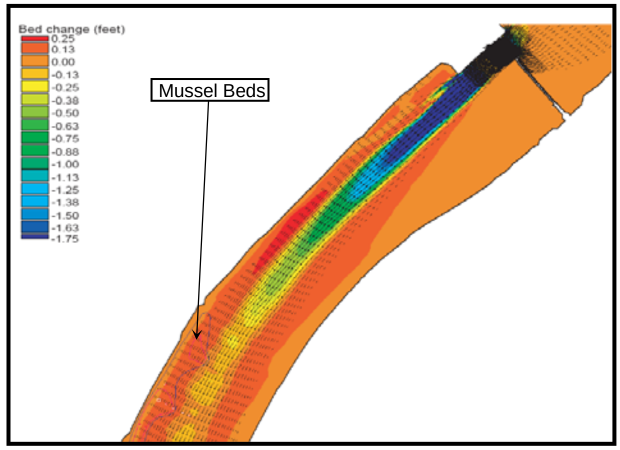

Figure 5. Difference in bed change between baseline and construction simulations after year 5, superimposed with hydraulics for a low-flow model simulation of Olmsted Locks and Dam.

Aside from these two sections, the majority of the mussel-bed area is expected to have little or no bed change that can be associated with the dam construction process over the 6-year simulation. Most areas of the mussel beds indicated less than 0.5 ft of bed change between the baseline and construction phases during the six annual hydrographs

Operational Phase Model - Sediment Transport: The cumulative difference in bed change between the baseline and operational dam scenarios at the end of the three annual hydrographs is shown in figure 6.

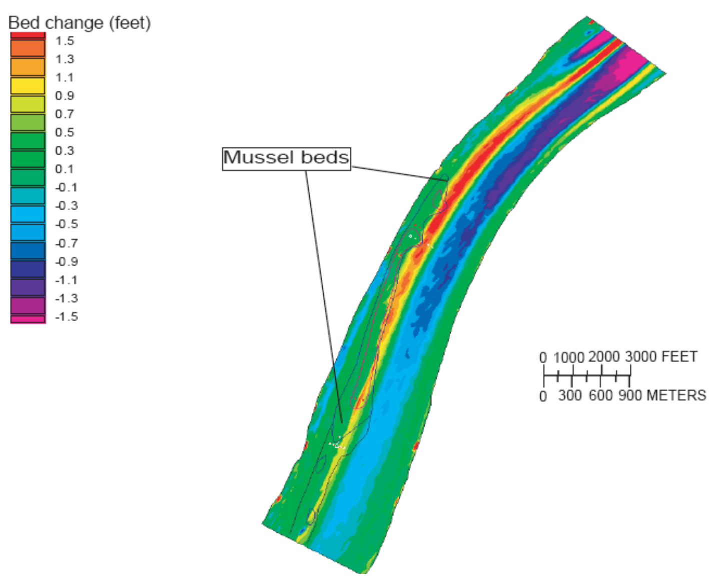

Figure 6 Difference in bed change between baseline and fully operational locks and dam simulation after year 9 in the Olmsted Locks and Dam study reach near Olmsted, Illinois.

The depth and downstream extent of scour and deposition caused by the dam operation progressively increases from year 7 through year 9. Although the depth of deposition continued to increase around the mussel beds in the operational phase modeling, the lateral migration of the deposition toward the mussel beds is limited. The spatial distribution of the depositional areas at the end of year 9 (fig. 6) is nearly identical to the spatial distribution simulated through year 6 in the construction phase model (fig. 4). As in the construction phase model, the most appreciable bed change during the operation phase model occurred during the low-flow periods when the wicket gates were closed and the flow of the river passed through the tainter gates. The maximum cumulative deposition on the mussel beds is approximately 2 ft occurring at the end of year 9.

SUMMARY AND CONCLUSIONS

The Olmsted Locks and Dam sediment-transport model was developed by the USGS incooperation with the USACE Louisville District to evaluate the environmental effect of the construction and subsequent operation of the Olmsted Locks and Dam on the lower Ohio River. Simulation of the phased Olmsted Locks and Dam construction and subsequent 3-year operation period resulted in a maximum additional deposition of approximately 2 feet when compared to the bed change simulated with baseline conditions. The areas of highest deposition are in the upstream section of the mussel beds and in the small area near the downstream extent of the beds. Aside from these two sections, the majority of the mussel bed area had minimal bed change that can be associated with the dam construction and (or) operation over the 9-year simulation. Most areas of the mussel beds had less than 0.5 ft of cumulative bed change between the baseline and construction phases during the nine annual hydrographs. Inspection of the scour and deposition patterns caused by the dam construction revealed a large scoured area in the channel downstream from the navigable pass and tainter gates (as a result of the flow contraction in those regions) and a section of high deposition located along the right descending (Illinois) bank, downstream from the tainter gates. The hydrodynamic changes are most prominent during low-flow conditions when the entire river flow passes through the tainter gates. The most appreciable increase in bed change between the baseline- and construction-phase conditions occurred during year-5 of the simulation because of an unusually extended low-flow period in which the entire flow for nearly 6 months passed through the tainter gates, which greatly altered the hydrodynamics of the river. The bed change over the 9-year Olmsted Locks and Dam simulation reveals a continuous downstream progression, deepening of the regions of scour in the main channel, and deposition along the right bank with limited lateral migration toward the more densely populated mussel-bed areas.

REFERENCES

Richardson, E.V., and Davis, S.R., 2001, Evaluating Scour at Bridges:Washington, DC, Federal Highway Admin., Hydraulic Engineering Circular No.18 FHWA-NHI-01-001, 378 p.

U.S. Fish and Wildlife Service, 1993, Supplemental biological opinion for the proposed Olmsted Locks and Dam, Ballard County, Kentucky: Cookeville, Tenn., 15 p.