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Navigation Systems Research Program

Hydraulic Modeling of Lock Approaches

S. Keith Martin, Mario J. Sanchez, and Carlos B. Bislip-Morales

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Under Project 405392, "FY14 Martin-Hydraulic Modeling of Lock Approaches"

Abstract

The following report presents the initial phase of research under the Navigation Systems Research Program work unit Modeling Lock Approaches. The objective was to provide an effective method of computing current magnitudes and directions at lock approaches for open river conditions. The meshes were developed using the Surface-water Modeling System. The two-dimensional, depth-averaged numerical flow solver Adaptive Hydraulics was used to run the simulations. Eighty-seven of the 131 U.S. Army Corps of Engineers (USACE)-maintained lock and dam projects were modeled during this research effort, which represent the structures with the highest priority in each of the 12 USACE districts located in the Mississippi Valley. Models were developed using a wide range of sources for data that included USACE districts, design memoranda, the U.S. Geological Survey, and water control manuals.

Contents

Abstract ii

Figures and Tables iv

Preface v

Unit Conversion Factors vi

1 Introduction 1

Background 1
Objective 1
Approach 1

2 Model Development Methods 4

Model description 4
Mesh development 5
Boundary conditions 7
Model validation 9

3 Modeling Results 10

4 Summary 13

References 14

Appendix A: List of Completed Lock Models and Mesh Examples 15

Report Documentation Page

Figures and Tables

Figures

Figure 1-1. Lock and dam structure locations in the Mississippi Valley Region. 2
Figure 2-1. Shape file for Mississippi River Lock and Dam No. 4. 5
Figure 2-2. Drawing from water control manual for Lock and Dam No. 4. 6
Figure 2-3. Available bathymetric data for Mississippi River Lock and Dam No. 7. 7
Figure 2-4. Available bathymetric data for Mississippi River Lock and Dam No. 4. 8
Figure 2-5. Bathymetric data for Mississippi River Lock and Dam No. 10. 8
Figure 3-1. Computational mesh for Mississippi River Lock and Dam No. 10. 11
Figure 3-2. Computed velocity vectors for Mississippi River Lock and Dam No. 10.......................... 11
Figure A-1. Lock and Dam No. 7 – Mississippi River. 18
Figure A-2. Lock and Dam No. 21 – Mississippi River. 18
Figure A-3. McAlpine Lock and Dam – Ohio River. 19
Figure A-4. Morgantown Lock and Dam – Monongahela River. 19
Figure A-5. Opekiska Lock and Dam – Monongahela River. 20
Figure A-6. Greenup Lock and Dam – Ohio River. 20
Figure A-7. Terry Lock and Dam – Arkansas River. 21
Figure A-8. Oliver Lock and Dam – Black Warrior River. 21

Tables

Table 3-1. Number of structures modeled, by river. 10
Table A-1. Mississippi Valley models developed to date. 15

Preface

This study was conducted for the U.S. Army Corps of Engineers under Project Number 405392, “FY 14 Martin-Hydraulic Modeling of Lock Approaches.” This study was conducted as part of the Navigation Systems Research Program (NavSys) under the direction of Charles E. Wiggins, Program Manager. The model validation was conducted during the period of October 2011 through May 2014 as part of the NavSys work unit Hydraulic Modeling of Lock Approaches.

The work was performed by the Navigation Branch (HNN) of the Navigation Division (HN), U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time the work was completed, Howard Park was acting Branch Chief, CEERD-HNN; Dr. J. S. Pettway was Division Chief, CEERD-HN; and W. Jeff Lillycrop was the Technical Director for Navigation. Director of ERDC-CHL was José E. Sánchez.

At the time of publication of this report, COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director of ERDC.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1,609.347	meters
square feet	0.09290304	square meters

1 Introduction

Background

Barge tow accidents in the vicinity of lock approaches are often attributed to a tow operator not being aware of the flow conditions in lock approaches. Accidents usually occur when river flows render adverse or unexpected navigation conditions. Accidents are costly to the towing industry due to project closures and to the government due to structural repair requirements, and in extreme cases can lead to loss of life. In one incident at Dam 2 on the Arkansas River, a barge accident blocked five of the eight gates, effectively closing the structure. The costs attributed to the closure were estimated at $5M per day (Hite et al. 2006).

Accident frequency might be reduced if tow boat pilots are provided hydraulic information (e.g., velocity magnitude and direction, difference from typical conditions) at lock approaches. Reduction of incidents will not only improve safety to project and tow personnel, it will also reduce the government and industry costs by minimizing the number of unscheduled outages.

Objective

The objective of the research presented in this report was to develop an efficient method of computing the current magnitudes and directions within lock approaches for a variety of flow conditions and spillway gate opening configurations. This report presents the initial phase of the research in which computational models were developed for open river conditions.

Approach

This study focuses on the development of a computational modeling method to simulate flow conditions in lock approaches for structures maintained by the United States Army Corps of Engineers (USACE) in the Mississippi Valley (Figure 1-1). Simulation results were validated using field and/or physical model data. The numerical modeling code chosen for this task was Adaptive Hydraulics (AdH).

Figure 1-1. Lock and dam structure locations in the Mississippi Valley Region.

The computational models were developed using project conditions that included discharges, stage, gate operations, bathymetry, design memorandums, and as-built drawings.

The scope for the initial phase of this study was to model all the navigation locks maintained by the USACE. A team of U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulic Laboratory (CHL), engineers and scientists was tasked with the modeling effort, which encompassed more than 130 locks in 13 river systems, including the Mississippi, Ohio, and Tennessee Rivers. This task required the collaboration of multiple entities such as the ERDC, U.S. Coast Guard, and 12 USACE districts where the navigation locks were located. Modeling efforts were divided by river systems, and priority schedules were selected by gathering feedback from the districts and local traffic in the areas of study. A low priority was given to a structure due to system geometry associated with the water depth in the lock approach. In these cases, the water is sufficiently deep such that hydrodynamic effects of gate operation on the tow are negligible when compared to other factors, such as wind forcing. Several lock and dam structures on the Tennessee River were given low priority due to the depth of water in the approach and in the vicinity of the dam. High priority was given to structures with frequent barge traffic or a high frequency of structure allisions.

2 Model Development Methods

Model description

Two-dimensional (2D) computational models were used to simulate open river conditions at most of the Federally maintained lock and dam structures in the Mississippi Valley region. All of the structures in the region are represented in Figure 1-1. Structures were not modeled where little or no data existed with respect to bathymetry in the vicinity of the structure as well as boundary data: upstream discharge and downstream tailwater (water surface elevation). The numerical modeling code chosen for this task was AdH.

AdH is a finite element modeling code that is capable of simulating three-dimensional (3D) Navier Stokes equations, 2D and 3D shallow water equations, and groundwater equations. AdH can be used in a serial or multiprocessor mode on personal computers, UNIX, Silicon Graphics, and CRAY operating systems. The uniqueness of AdH is its ability to dynamically refine the domain mesh by splitting elements in areas where more resolution is needed at certain times due to changes in the flow or transport conditions and then remove the added resolution when no longer needed. 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. This code is being developed at ERDC's CHL and has been used for a wide variety of applications including flow and sediment transport in complex sections of the Mississippi River, tidal conditions in southern California, and flow field changes caused by vessel traffic in the Houston Ship Channel.

For this study, the 2D shallow water module of AdH was used for all simulations. This tool solves for depth and depth-averaged velocity[1]. Due to the sheer number of the structures to be modeled, model simulations were run by a team of ERDC engineers and scientists. The simulations were run either on a desktop PC or one of ERDC's high-performance computers[2].

[1] More details of the 2D shallow water module of AdH and its computational philosophy can be found at http://adh.usace.army.mil.

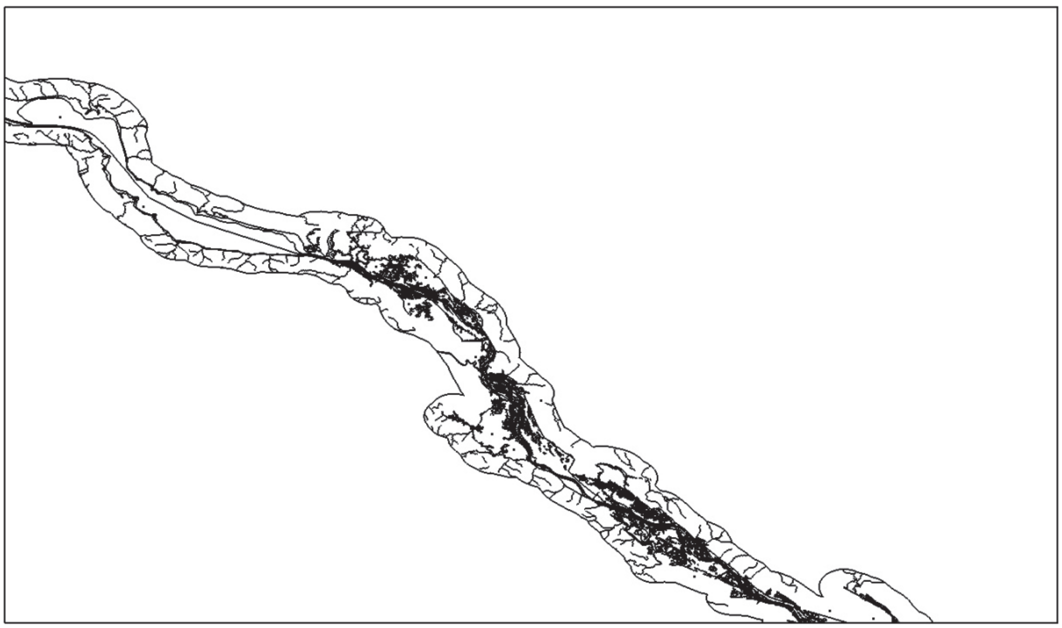
[2] For more information on ERDC's high performance computing, see http://www.erdc.hpc.mil.

Mesh development

The computational meshes were developed using the Surface-water Modeling System (SMS), a graphical user interface for increasing the modeling productivity for a variety of USACE numerical models, including AdH.

The starting point for all the meshes in this study was a shape file that contained outlines of the structures, banklines, channel center lines, and other information necessary for developing a mesh for a numerical model (Figure 2-1). In most cases, the shape file was obtained from the USACE inland navigation website (http://inland.agc.army.mil/enc/echarts/IENCShapeFileRequest.cfm). However, this website did not contain shape files for all of the structures of interest. In those cases, the shape file or drawing was obtained directly from the USACE district responsible for the structure in question.

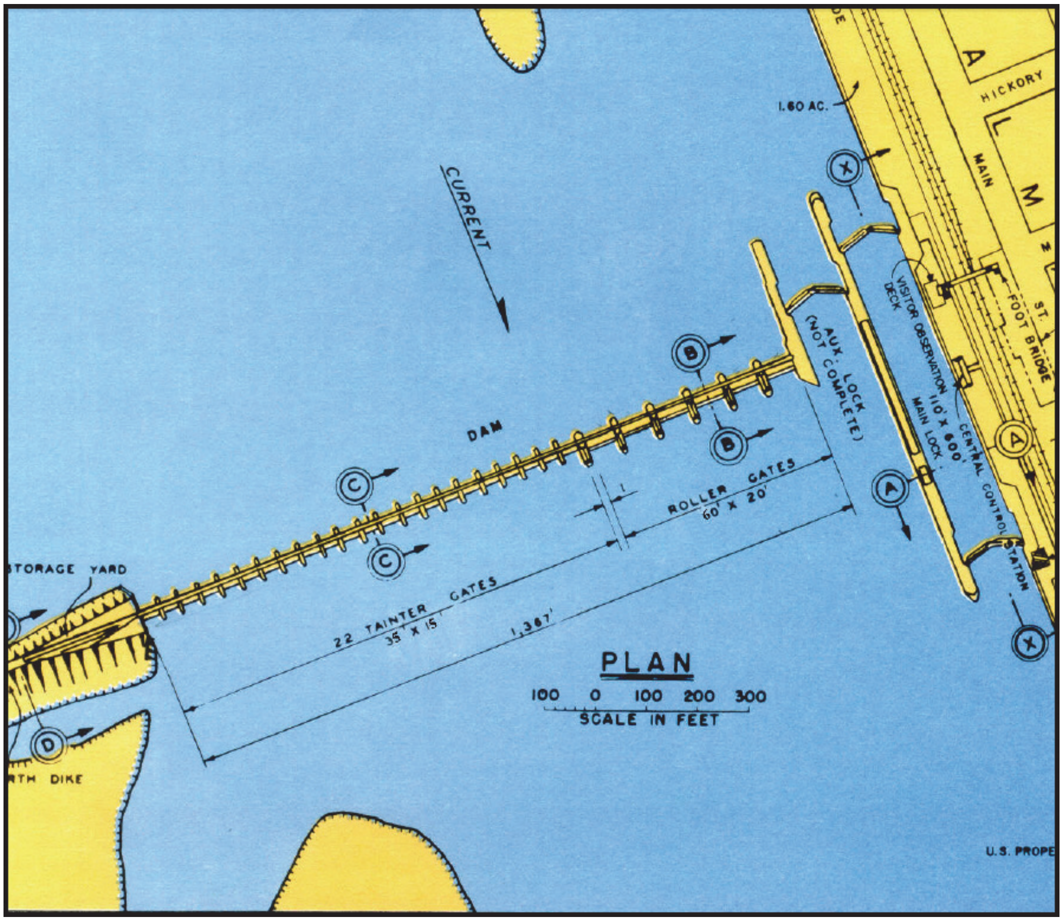
Figure 2-1. Shape file for Mississippi River Lock and Dam No. 4.



Additional information about the structures was obtained from the design memoranda of the projects, as well as from reports detailing the first inspection of the structures following construction. In several cases the inspection report was especially important as modifications were made to the design of the structure during construction. One such common modification was that the guidewall design changed from a solid wall to one on pilings in which water was allowed to flow through and/or under the wall.

In some instances, the structure's lock or water control manual also provided information regarding the size of spillway gate openings, pier sizes in the dam structure, total dam structure length, and sill elevations (Figure 2-2). Sill elevations and spillway gate type information were also obtained from the manual.

Figure 2-2. Drawing from water control manual for Lock and Dam No. 4.



Bathymetric data was obtained from USACE districts. The amount of coverage varied by structure. In some cases, data existed above and below the lock and dam and the navigation channel leading up to the structure as shown in Figure 2-3 for Lock and Dam No. 7 on the Mississippi River. Note that the density of the data identifies it as multibeam data. In other instances, there were gaps in the data. For example, Mississippi River Lock and Dam No. 4 had a gap in the navigation channel (Figure 2-4). In the case of Lock and Dam No. 10 on the Mississippi River, there was a large gap in the multibeam data for the navigation channel, and some of the data below the structure were acoustic Doppler current profiler (ADCP) data (Figure 2-5). These gaps were generally handled through interpolation. In most cases, very little, if any, data existed outside of the navigation channel, most of which were obtained from USACE districts. Bathymetry in these cases was generated through extrapolation. In general, extrapolation techniques used the elevations from the edge of the navigation channel survey as a starting point.

Boundary conditions

Boundary conditions were developed for the validation of the lock models using discharge data upstream of the structure and water level data downstream of the structure. These data were obtained from several sources that included the design memorandum of the structure, water control manuals, and USACE and U.S. Geological Survey (USGS) gages.

Discharge data were obtained for open river conditions. *Open river* indicates all spillway gates are open and the flow moves through the structure unhindered by any factors other than friction and the geometric shape of the gate piers. Sources for this data include water control manuals, other documents such as USGS discharge reports, and USGS streamflow gages.

Figure 2-3. Available bathymetric data for Mississippi River Lock and Dam No. 7.

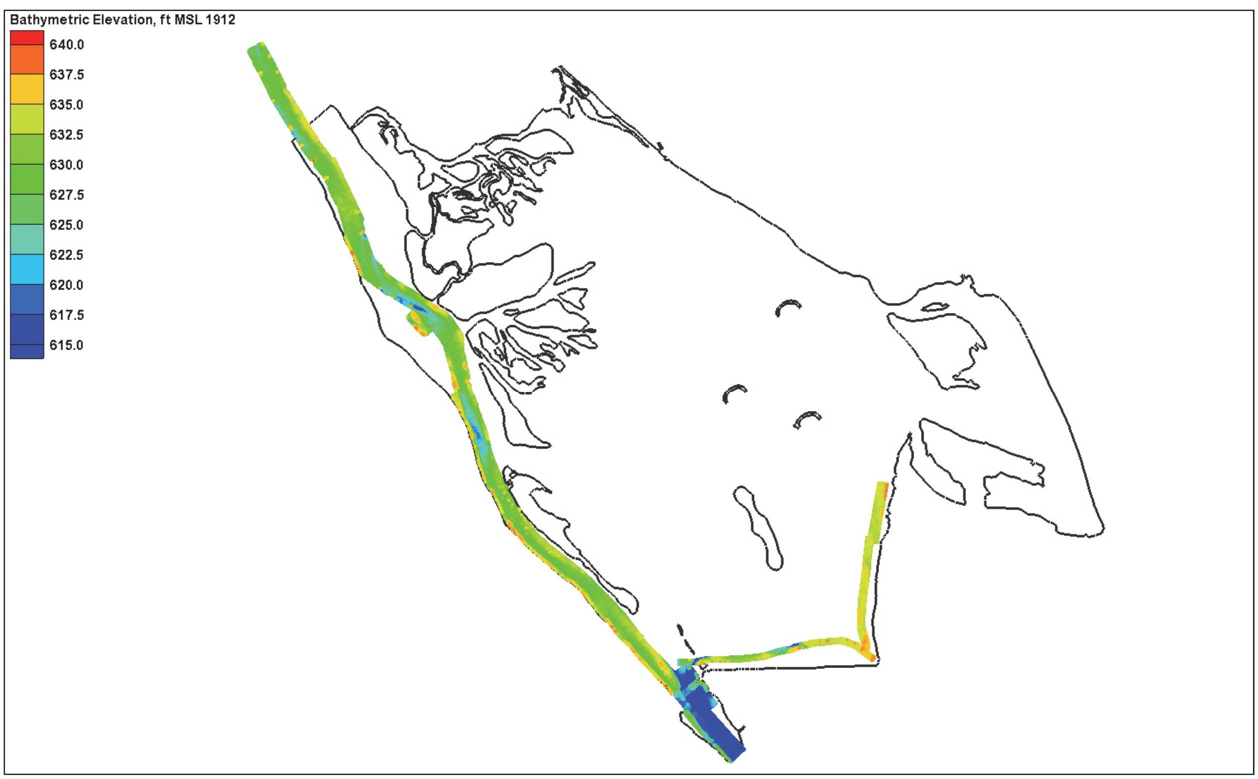


Figure 2-4. Available bathymetric data for Mississippi River Lock and Dam No. 4.

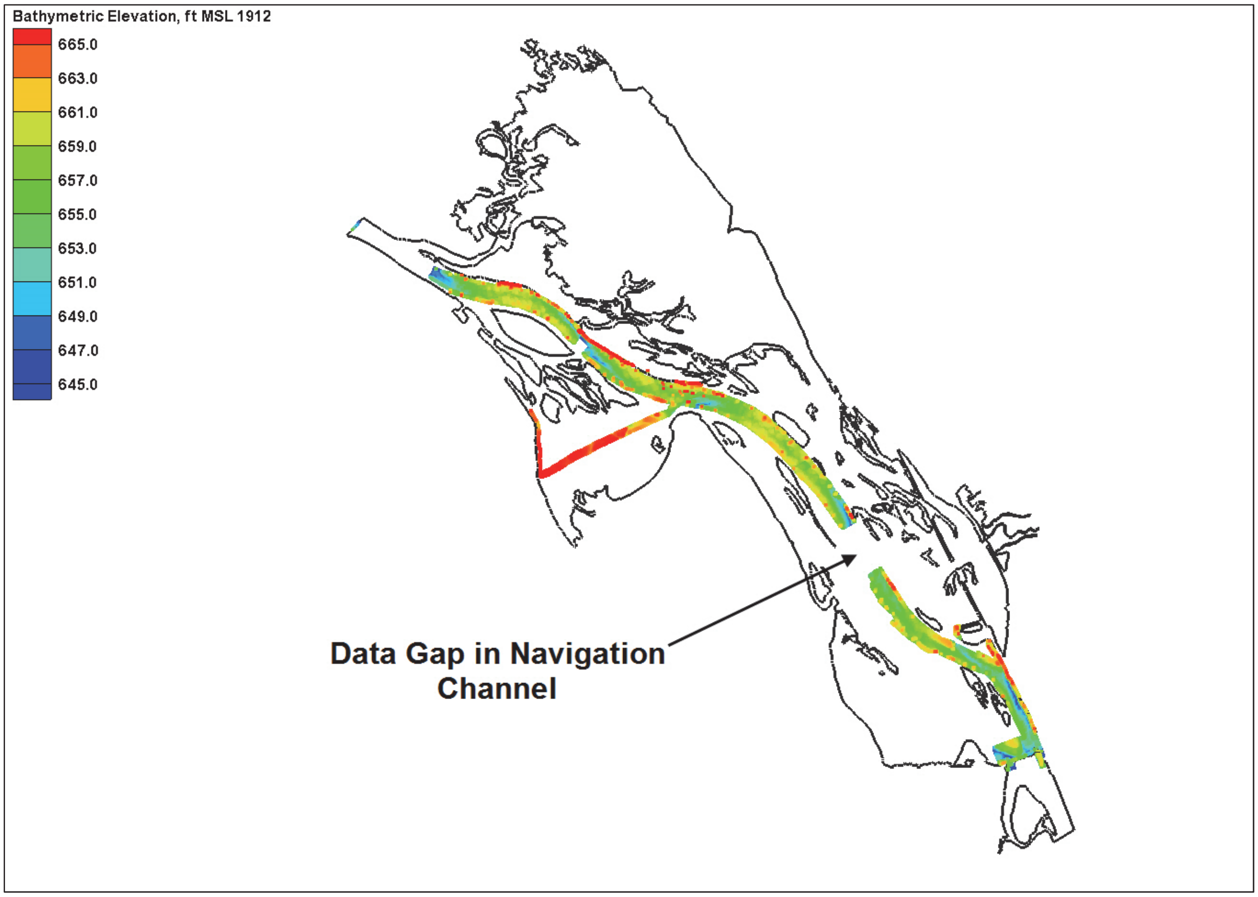
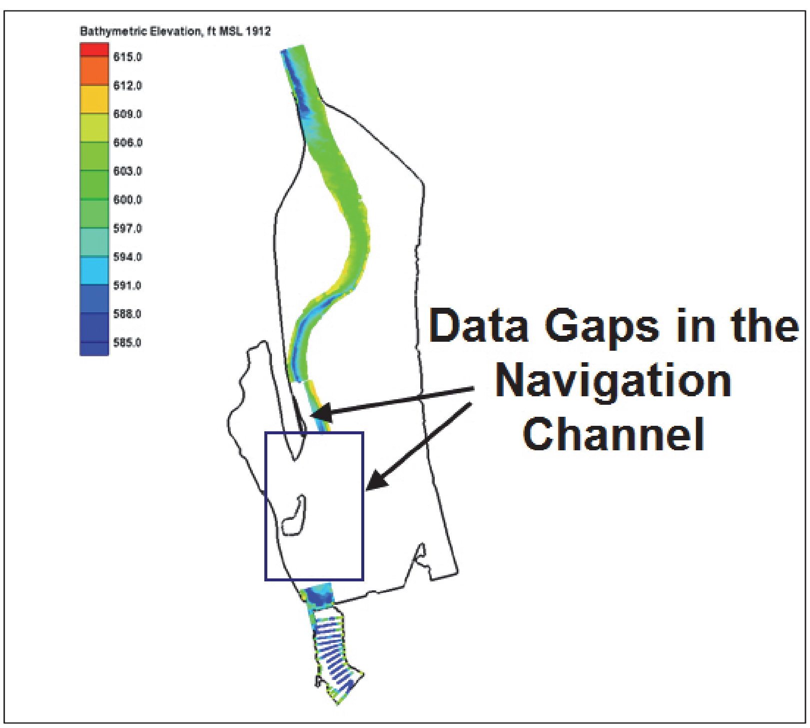


Figure 2-5. Bathymetric data for Mississippi River Lock and Dam No. 10.



Tailwater conditions for the models were obtained from USGS and USACE gages. Typically, these gages measured the lower pool elevation of the structure that was used if the model included the lower pool. If the model ended at the structure, the upper pool elevation was used as the tailwater condition for the model.

Model validation

A 2D numerical model for Montgomery Lock and Dam on the Ohio River was validated in a previous research effort (Bislip and Stockstill 2013). Experiments were conducted to assess the ability of the AdH code to compute flow conditions at navigation lock approaches. The model was able to reproduce flow distribution, velocity magnitudes, and directions on rather simple bed geometry configurations. At the time of the study, the model could not accurately predict flow patterns around guard wall cells, especially with submerged weirs in the approach. These effects are attributed to both the mild-slope and hydrostatic-pressure assumptions within the numerical code.

The remaining models in the present study produced reasonable comparisons to the upper pool elevation for each structure during open river conditions. However, a rigorous validation similar to the one completed for Montgomery Lock and Dam has not been performed for the remaining structure models. This task should be performed as needed for structures with a history of frequent impact events.

3 Modeling Results

Computational flow models have been developed for navigation approach conditions for 87 of the 131 USACE-maintained Lock and Dam projects in the Mississippi Valley. Table 3-1 presents a summary of lock models, completed by river system.

Table 3-1. Number of structures modeled, by river.

Lock Structures Modeled	River System
1 of 8	Allegheny
12 of 14	Arkansas
3 of 4	Black Warrior
1 of 3	Cumberland
7 of 7	Illinois
3 of 3	Kanawha
24 of 29	Mississippi
6 of 10	Monongahela
17 of 19	Ohio
5 of 5	Red River
1 of 1	Savannah
5 of 12	Tennessee – Tombigbee
1 of 8	Tennessee
1 of 1	Tombigbee

The models are archived on a server and will be made available to USACE at large in the future. Each lock structure has its own directory on the server. The directory contains all files necessary for running the model, including the boundary condition file, the mesh file, and the hotstart file. The directory also contains a fact sheet describing the model files, the data used to construct them, and the datums used. Example output files associated with the model run files are also in the directory. A full list of models completed to date is provided in Appendix A in addition to several examples of model coverage of a lock approach.

An example of model results is shown for Mississippi River Lock and Dam No. 10 in Figures 3-1 and 3-2.

Figure 3-1. Computational mesh for Mississippi River Lock and Dam No. 10.

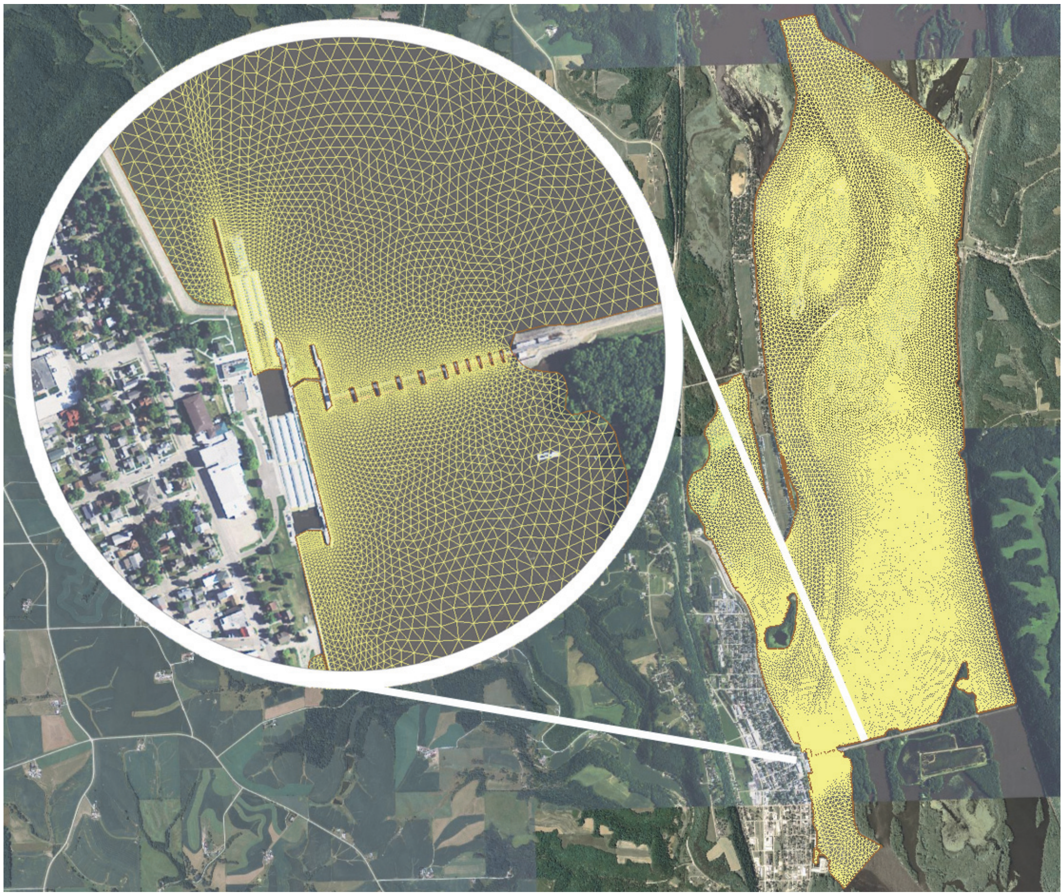
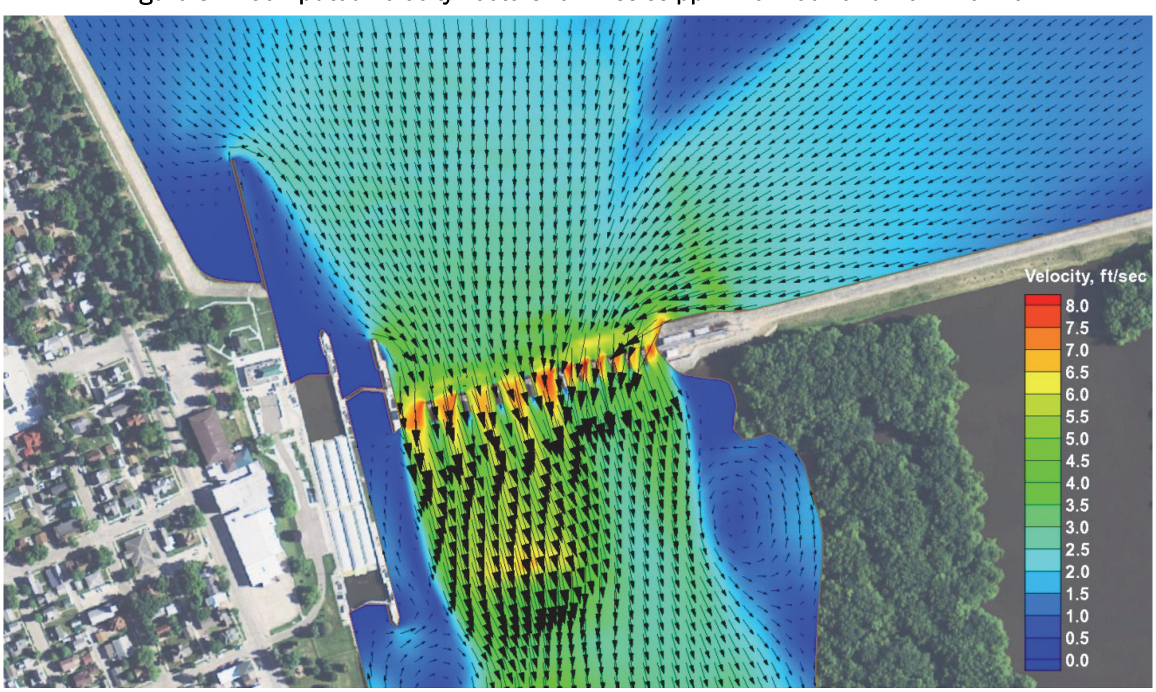


Figure 3-2. Computed velocity vectors for Mississippi River Lock and Dam No. 10.



To date, only a few structures deemed important by USACE districts have not been modeled as part of this study. The remaining structures in the Mississippi Valley region without a computational model were deemed low priority for the following reasons:

- operation of the structure may have been turned over to a state or private agency
- lack of data – bathymetric and boundary condition
- system geometry.

System geometry is associated with the water depth in the lock approach. In this case, the water is sufficiently deep such that hydrodynamic effects of gate operation on the tow are negligible when compared to other factors such as wind forcing.

4 Summary

The objective of the research presented in this report was to develop an efficient method of computing the current magnitudes and directions within lock approaches for a variety of flow conditions and spillway gate opening configurations. This report presents the initial phase of the research in which computational models were developed for open river conditions. Providing this information to tow operators is anticipated to enhance their ability to safely navigate the approach to the structure.

Computational flow models have been developed for navigation approach conditions for 87 of the 131 USACE-maintained lock and dam projects in the Mississippi Valley. The models were developed with data from a variety of sources including USACE districts, USGS, design memoranda, and water control manuals. These models represent the highest priority structures for each USACE district. The existing models were run with open river conditions where river discharge was such that all spillway gates were completely open.

The remaining structures were not modeled due to meeting at least one of three possible criteria. First, the structure may no longer be under the control of USACE. Second, the structure may have been given low priority by the USACE district where it resides. Finally, system geometry concerns related to water depth may have resulted in a low priority.

In future work, the computational model simulations will be performed for a variety of flow conditions and spillway gate opening configurations for each structure.

References

Bislip-Morales, C. B., and R. L. Stockstill 2013. *Validation of modeling flow approaching navigation locks*. ERDC/CHL TR-13-9. Vicksburg, MS: U.S Army Engineer Research and Development Center.

Hite, J. E., J. E. Clausner, and D. N. McComas, ed. 2006. *Navigation lock and dam inspection and emergency repairs workshop summary*. ERDC/CHL SR-06-2. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Appendix A: List of Completed Lock Models and Mesh Examples

Table A-1 lists all the lock and dam structures that have been modeled as part of this study.

Table A-1. Mississippi Valley models developed to date.

Project Name	River System	District
Lock and Dam 2	Allegheny	LRP
Lock and Dam 4 –Emmett Sanders	Arkansas	SWL
Lock and Dam 5 – Maynard	Arkansas	SWL
Lock and Dam 6 – Terry	Arkansas	SWL
Lock and Dam 7 – Murray	Arkansas	SWL
Lock and Dam 8 – Toad Suck Ferry	Arkansas	SWL
Lock and Dam 9 – Ormund	Arkansas	SWL
Lock and Dam 10 – Dardanelle	Arkansas	SWL
Lock and Dam 12 – Ozark	Arkansas	SWL
Lock and Dam 13 – Trimble	Arkansas	SWL
Lock and Dam 14 – Mayo	Arkansas	SWT
Lock and Dam 15 – Kerr	Arkansas	SWT
Lock and Dam 18 – Newt Graham	Arkansas	SWT
Bankhead Lock and Dam	Black Warrior	SAM
Holt Lock and Dam	Black Warrior	SAM
Oliver Lock and Dam	Black Warrior	SAM
Cheatham Lock and Dam	Cumberland	LRN
Brandon Road Lock and Dam	Illinois	LRC
Dresden Lock and Dam	Illinois	MVR
Lagrange Lock and Dam	Illinois	MVR
Lockport Lock and Dam	Illinois	LRC
Marseilles Lock and Dam	Illinois	MVR
Peoria Lock and Dam	Illinois	MVR
Starved Rock Lock and Dam	Illinois	MVR
London Lock and Dam	Kanawha	LRH
Marmet Lock and Dam	Kanawha	LRH
Winfield Lock and Dam	Kanawha	LRH
Lock and Dam 2	Mississippi	MVP

Project Name	River System	District
Lock and Dam 3	Mississippi	MVP
Lock and Dam 4	Mississippi	MVP
Lock and Dam 5	Mississippi	MVP
Lock and Dam 6	Mississippi	MVP
Lock and Dam 7	Mississippi	MVP
Lock and Dam 8	Mississippi	MVP
Lock and Dam 9	Mississippi	MVP
Lock and Dam 10	Mississippi	MVP
Lock and Dam 11	Mississippi	MVR
Lock and Dam 12	Mississippi	MVR
Lock and Dam 13	Mississippi	MVR
Lock and Dam 14	Mississippi	MVR
Lock and Dam 15	Mississippi	MVR
Lock and Dam 16	Mississippi	MVR
Lock and Dam 17	Mississippi	MVR
Lock and Dam 18	Mississippi	MVR
Lock and Dam 19	Mississippi	MVR
Lock and Dam 20	Mississippi	MVR
Lock and Dam 21	Mississippi	MVR
Lock and Dam 22	Mississippi	MVR
Lock and Dam 24	Mississippi	MVS
Lock and Dam 25	Mississippi	MVS
L ock and Dam 26 – Mel Price	Mississippi	MVS
Monongahela L&D 2 – Braddock	Monongahela	LRP
Monongahela L&D 3 – Elizabeth	Monongahela	LRP
Monongahela L&D 4 – Charleroi	Monongahela	LRP
Morgantown Lock and Dam	Monongahela	LRP
Opekiska Lock and Dam	Monongahela	LRP
Point Marion Lock and Dam	Monongahela	LRP
Belleville Lock and Dam	Ohio	LRH
Cannelton Lock and Dam	Ohio	LRL
Capt Anthony Meldahl L&D	Ohio	LRH
Dashields Lock and Dam	Ohio	LRP
Emsworth Lock and Dam	Ohio	LRP
Greenup Lock and Dam	Ohio	LRH
Hannibal Lock and Dam	Ohio	LRP

Project Name	River System	District
JT Meyers Lock and Dam	Ohio	LRL
Markland Lock and Dam	Ohio	LRL
McAlpine Lock and Dam	Ohio	LRL
Montgomery Lock and Dam	Ohio	LRP
New Cumberland Lock and Dam	Ohio	LRP
Pike Island Lock and Dam	Ohio	LRP
Racine Lock and Dam	Ohio	LRH
RC Byrd Lock and Dam	Ohio	LRL
Smithland Lock and Dam	Ohio	LRL
Willow Island Lock and Dam	Ohio	LRH
Red River Lock and Dam 1	Red River	MVK
Red River Lock and Dam 2	Red River	MVK
Red River Lock and Dam 3	Red River	MVK
Red River Lock and Dam 3	Red River	MVK
Red River Lock and Dam 5	Red River	MVK
New Savannah Bluff Lock and Dam	Savannah	SAS
Demopolis Lock and Dam	Tombigbee	SAM
Aberdeen Lock and Dam	Tennessee-Tombigbee	SAM
Glover-Wilkins Lock and Dam	Tennessee-Tombigbee	SAM
Montgomery Lock and Dam (Lock E)	Tennessee-Tombigbee	SAM
Rankin Lock and Dam	Tennessee-Tombigbee	SAM
Tom Bevill Lock and Dam	Tennessee-Tombigbee	SAM
Watts Bar Lock and Dam	Tennessee	LRN

The following Figures, A-1 through A-8, are presented as examples of the models developed for this study. Rivers represented include the Mississippi, the Ohio, the Monongahela, the Illinois, the Arkansas, and the Black Warrior.

Figure A-1. Lock and Dam No. 7 – Mississippi River.

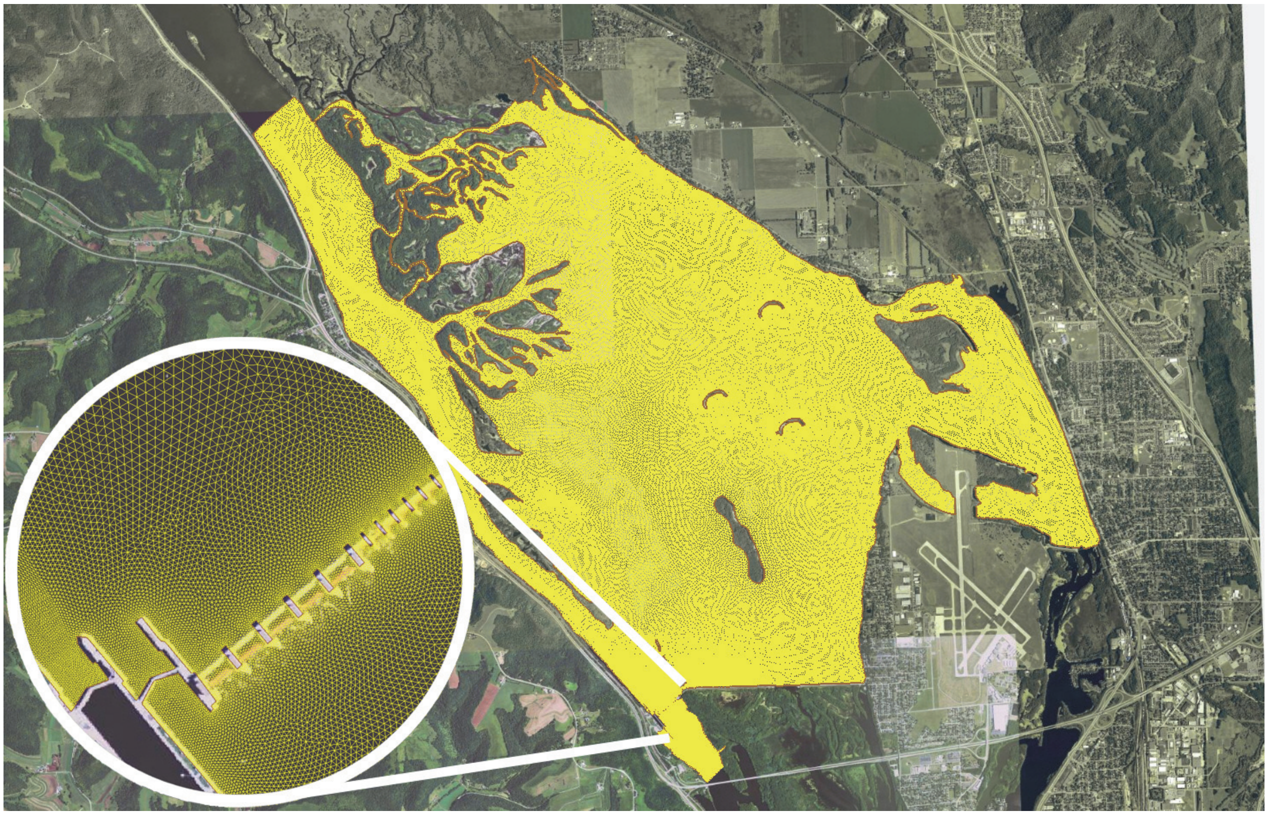


Figure A-2. Lock and Dam No. 21 – Mississippi River.

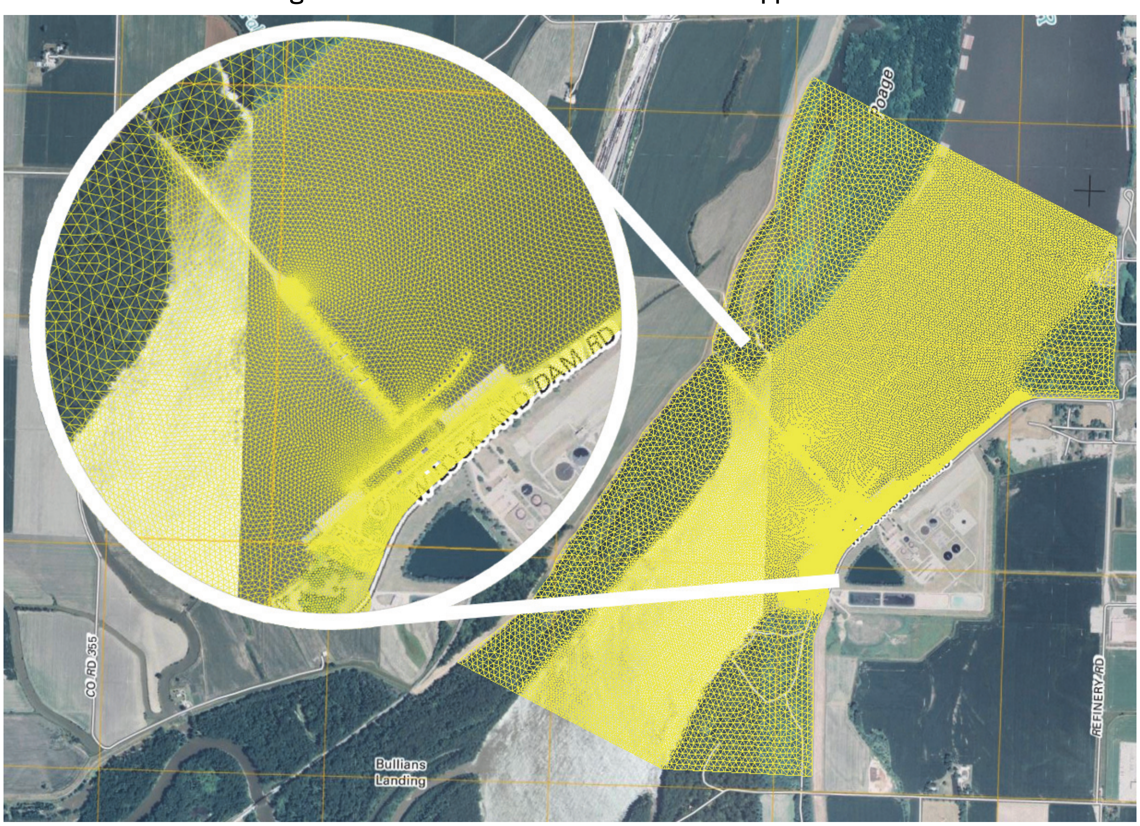


Figure A-3. McAlpine Lock and Dam – Ohio River.

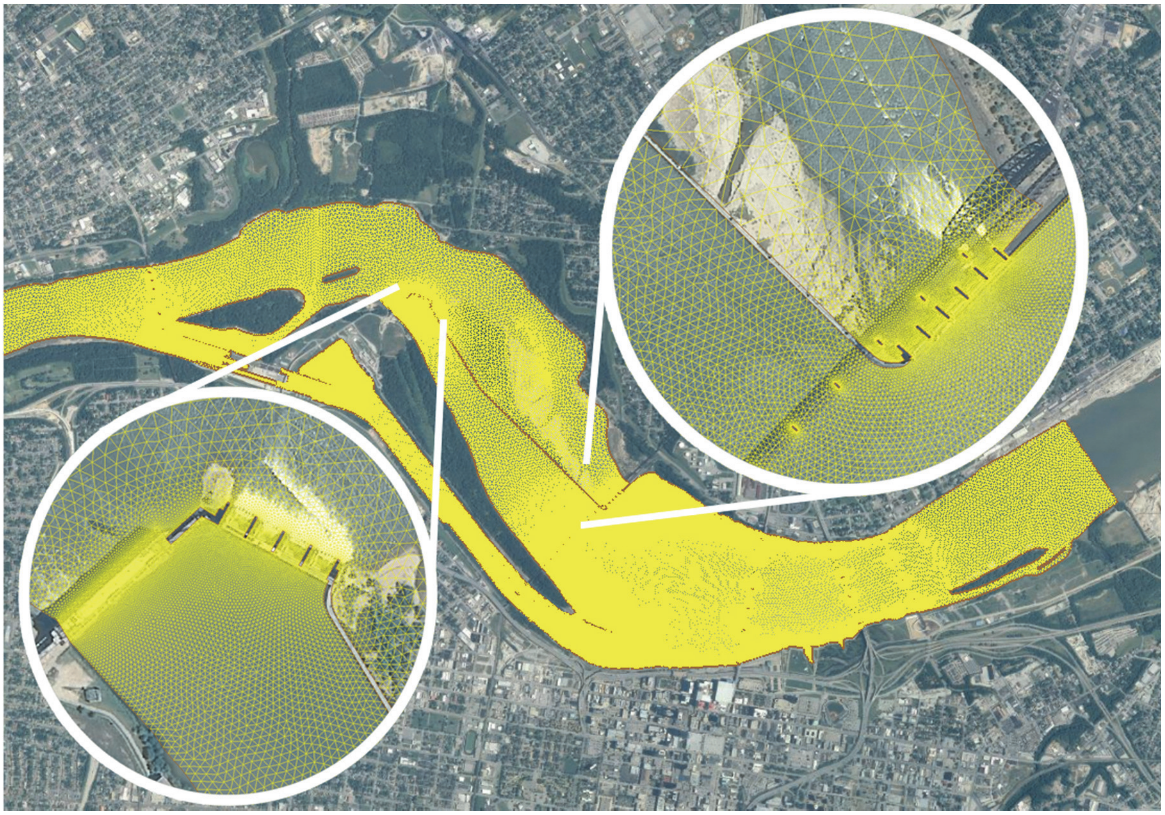


Figure A-4. Morgantown Lock and Dam – Monongahela River.

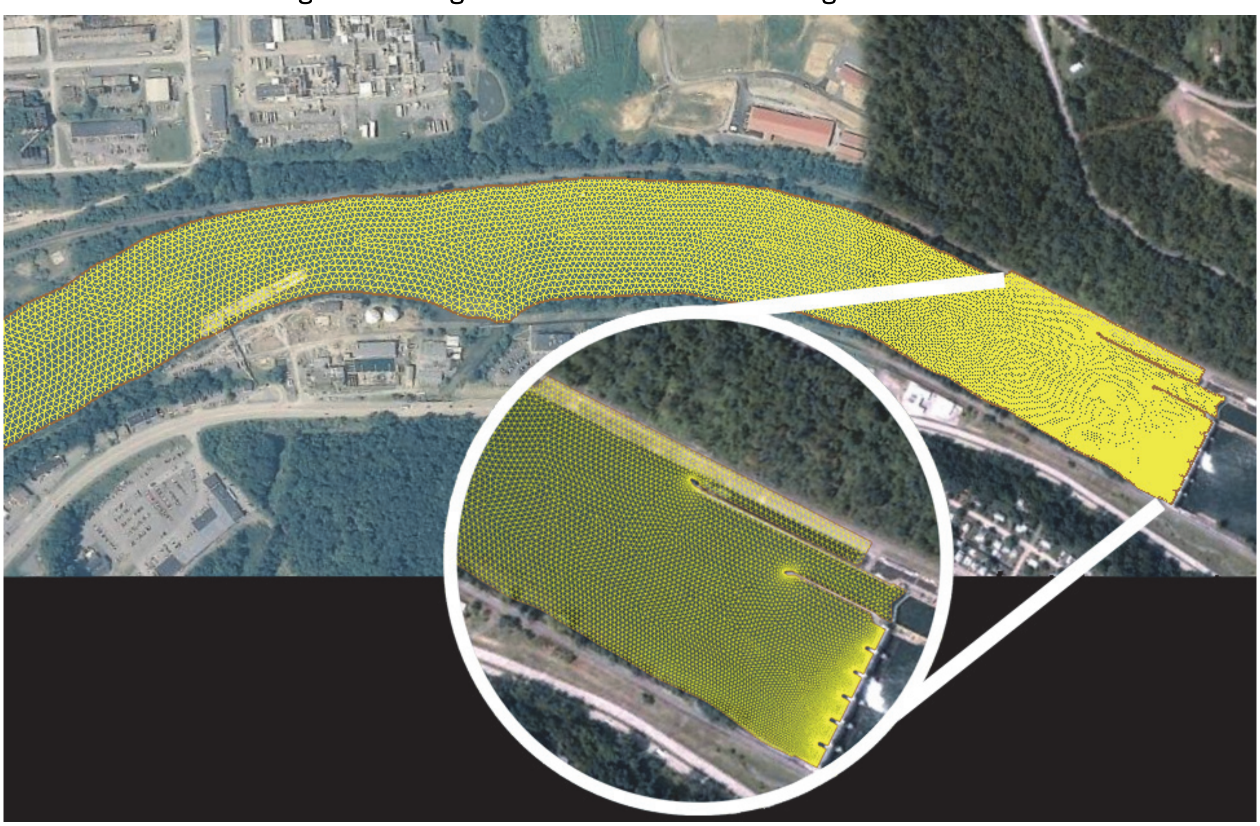


Figure A-5. Opekiska Lock and Dam – Monongahela River.

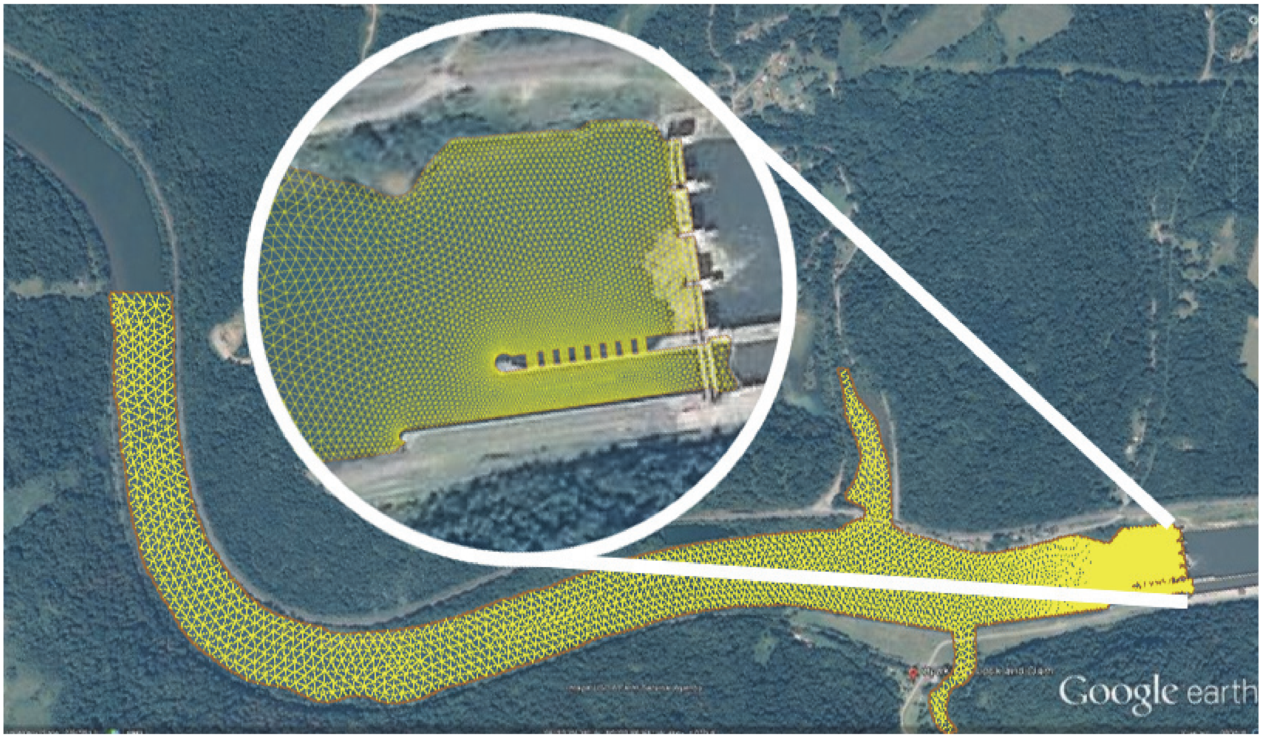


Figure A-6. Greenup Lock and Dam – Ohio River.

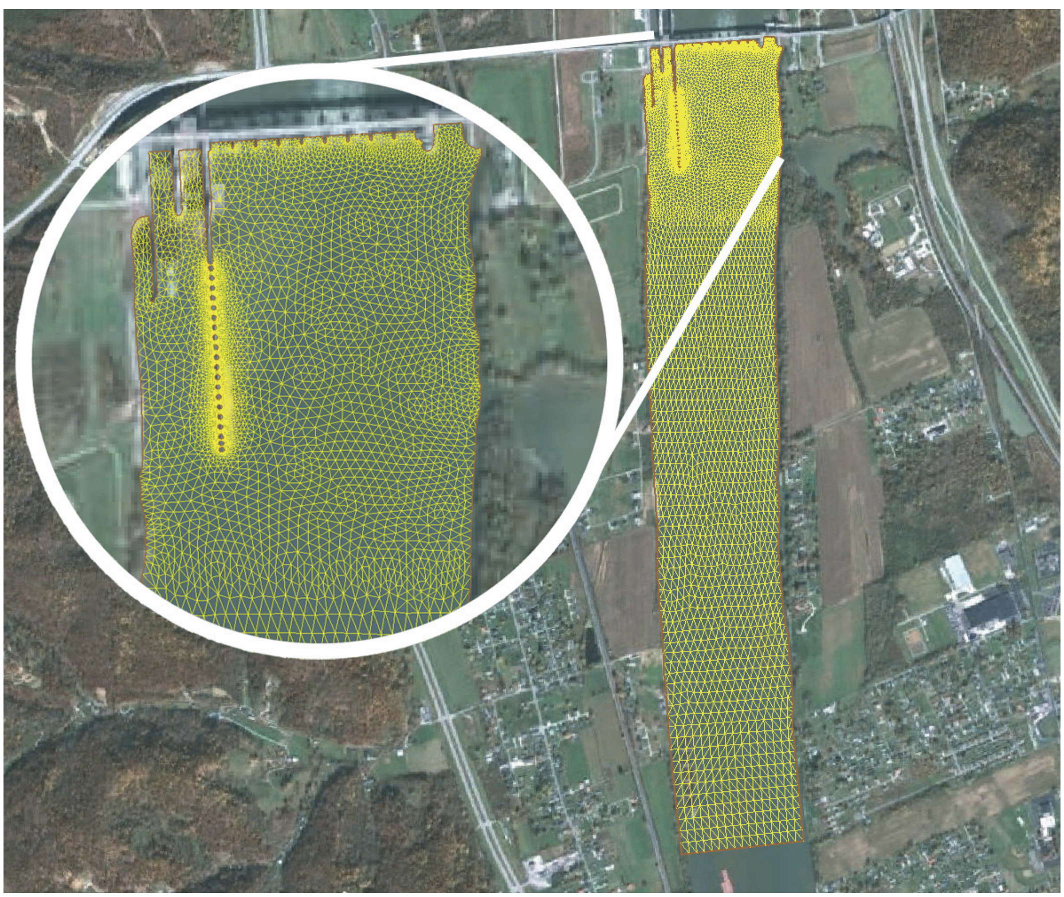


Figure A-7. Terry Lock and Dam – Arkansas River.

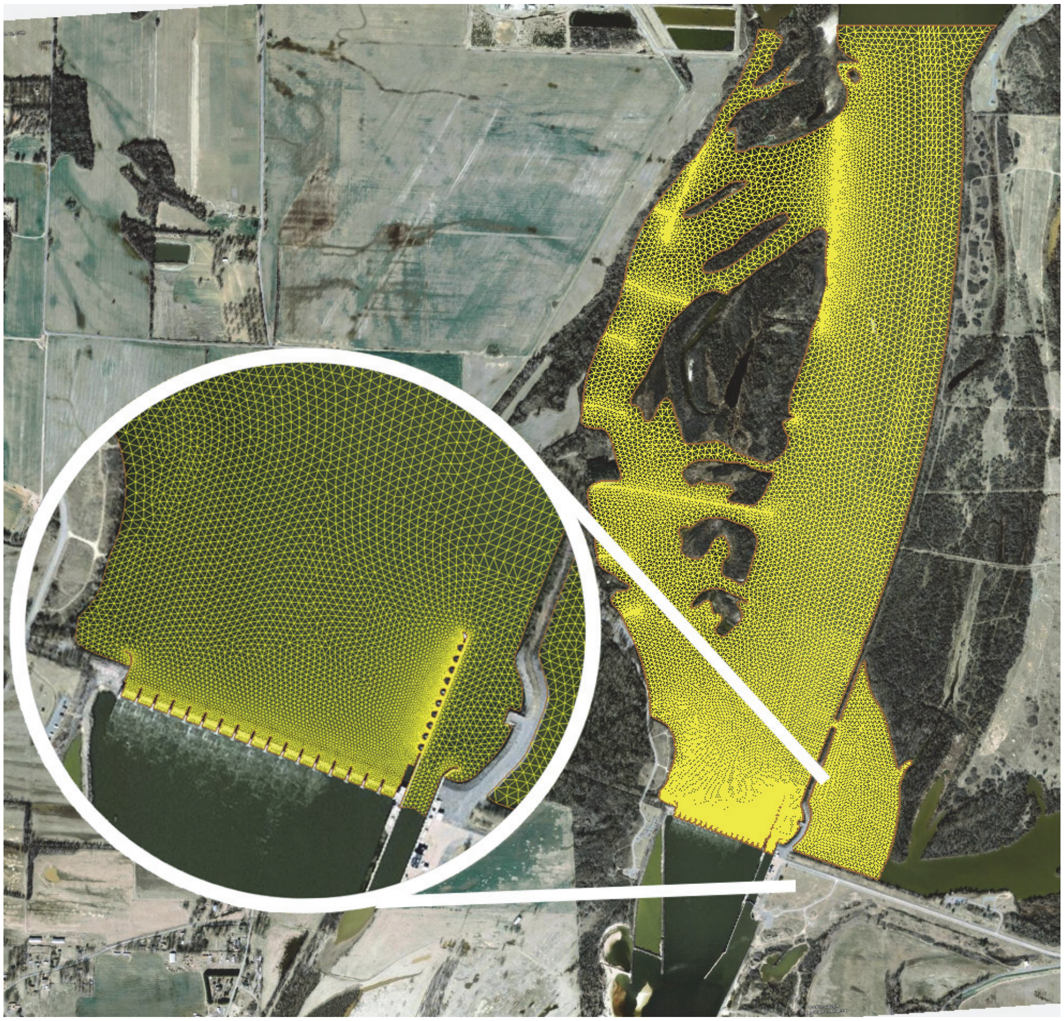
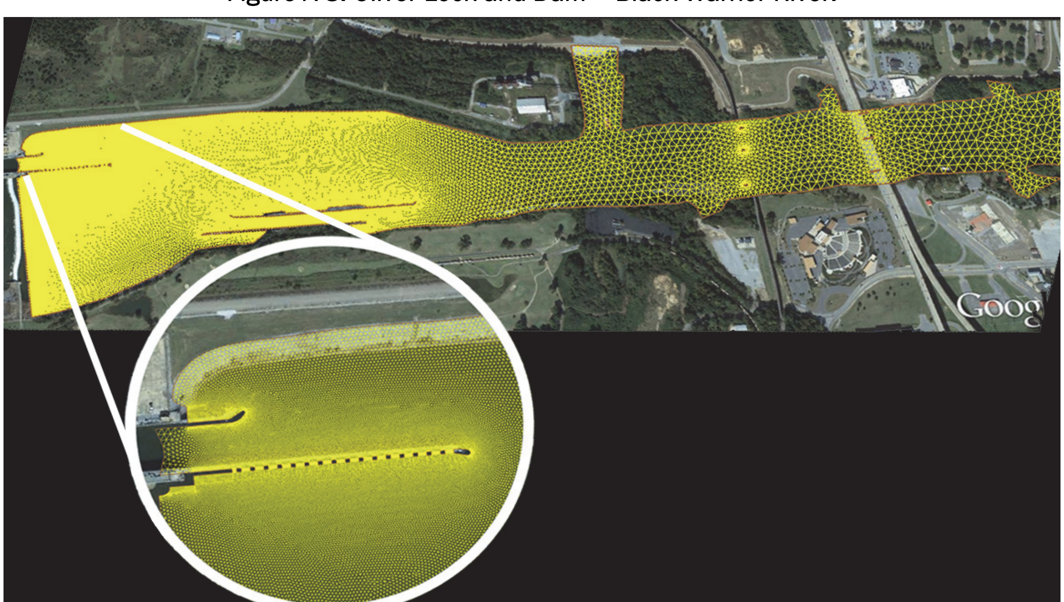


Figure A-8. Oliver Lock and Dam – Black Warrior River.



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14. ABSTRACT

The following report presents the initial phase of research under the Navigation Systems Research Program work unit Modeling Lock Approaches. The objective was to provide an effective method of computing current magnitudes and directions at lock approaches for open river conditions. The meshes were developed using the Surface-water Modeling System. The two-dimensional, depth-averaged numerical flow solver Adaptive Hydraulics was used to run the simulations. Eighty-seven of the one hundred thirty-one U.S. Army Corps of Engineers (USACE)-maintained lock and dam projects were modeled during this research effort, which represent the structures with the highest priority in each of the twelve USACE districts located in the Mississippi Valley. Models were developed using a wide range of sources for data that included USACE districts, design memoranda, the United States Geologic Service, and water control manuals.

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Waterways

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified		28	

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