Evaluation of Aquatic Habitat on the Middle Missisippi River

Prepared for
U.S. Army Corps of Engineers
St. Louis District
Contract W912P9-10-D-0516
Delivery Order No. 0004

Prepared by
WEST Consultants, Inc.
2601 25th Street SE
Suite 450
Salem, OR 97302

December 2014

TABLE OF CONTENTS

List of Tables

List of Figures

List of Appendices

List of Abbreviations

2-D ....Two-Dimensional
3-D ....Three-Dimensional
ADCP ....Acoustic Doppler Current Profiler
CCHE ....Center for Computational Hydroscience and Engineering
CHeT ....Computational Hydro-engineering Technology
GFM.......................................Government Furnished Material
GIS ....Geographic Information System
GMS.......................................Groundwater Modeling System
LiDAR....................................Light Detection and Ranging
MVS.......................................Mississippi Valley Division, St. Louis District
MMR......................................Middle Mississippi River
NAD.......................................North American Datum
NAVD....................................North American Vertical Datum of 1988
NCCHE..................................National Center for Computational Hydroscience and Engineering
NGVD....................................National Geodetic Vertical Datum of 1929
RM ....River Mile
TIN...Triangular Irregular Network
USACE ..................................U.S. Army Corps of Engineers
UTM ....Universal Transverse Mercator
USGS .....................................U.S. Geological Survey
vx ....Velocity in the x-direction
vy ....Velocity in the y-direction
vz ....Velocity in the z-direction
WEST.....................................WEST Consultants, Inc.

1 Introduction

1.1 Purpose

The St. Louis District (MVS) is in the process of preparing a supplemental environmental impact statement (SEIS) on the Regulating Works Project on the Middle Mississippi River (MMR). The MMR is defined as the reach of the Mississippi River between its confluences with the Missouri and Ohio Rivers. A quantification of aquatic habitat is necessary to understand what currently exists and to forecast what changes will occur through the implementation of the proposed alternatives.

It has been determined through coordination with the environmental partners of the MMR that two of the most defining attributes of aquatic habitat are velocity and depth. The structures used to maintain the navigation channel on the MMR are designed in a way to maximize velocity and depth diversity. The quantification of what habitat is being changed when structures are constructed is difficult due to the complex three dimensional flow and sedimentation patterns, and it is also important to have an understanding of habitat availability for different river stages.

In support of the SEIS, MVS contracted WEST Consultants (WEST) to develop a 3-dimensional (3-D) hydraulic model of the MMR between River Miles (RM) 92.0 and RM 109.9; run the model for three in-channel discharges; and evaluate the model results to quantify the volume of habitat available based on velocity. The selected reach was chosen to serve as a proxy reach to gain an understanding of habitat changes over the entire MMR.

1.2 Authorization

This study was authorized by the U.S. Army Corps of Engineers, St. Louis District (MVS) under contract W912P9-10-0516, Delivery Order Number 0004.

1.3 Study Area Description

The reach for this study is the Middle Mississippi River from RM 92.0 at the downstream end to RM 109.9, which is located near Chester, Illinois, at the upstream end. A map of the study reach is provided in Figure 1-1. An aerial photo of the study reach is provided in Figure 1-2 through Figure 1-5. The study reach includes 15 stone low water weir structures, 155 stone river training structures, seven chevron structures, and three side channels. The three side channels include:

(1) Crain Chute, which diverts from the Mississippi River near RM 105 and returns near RM 103.8.
(2) Liberty Chute, which diverts from the Mississippi River near RM 102.7 and returns near RM 100.7 and at RM 99.7 (lower branch diverted from the main branch at about 0.3 miles upstream of where the main branch confluences with the Mississippi River).
(3) Jones Chute, which diverts from the Mississippi River near RM 98.2 and returns near RM 95.

The Mississippi River within the study reach has an average depth of 32 feet, an average slope of 0.012% (0.6 feet per mile), and an average width of 2,240 feet.

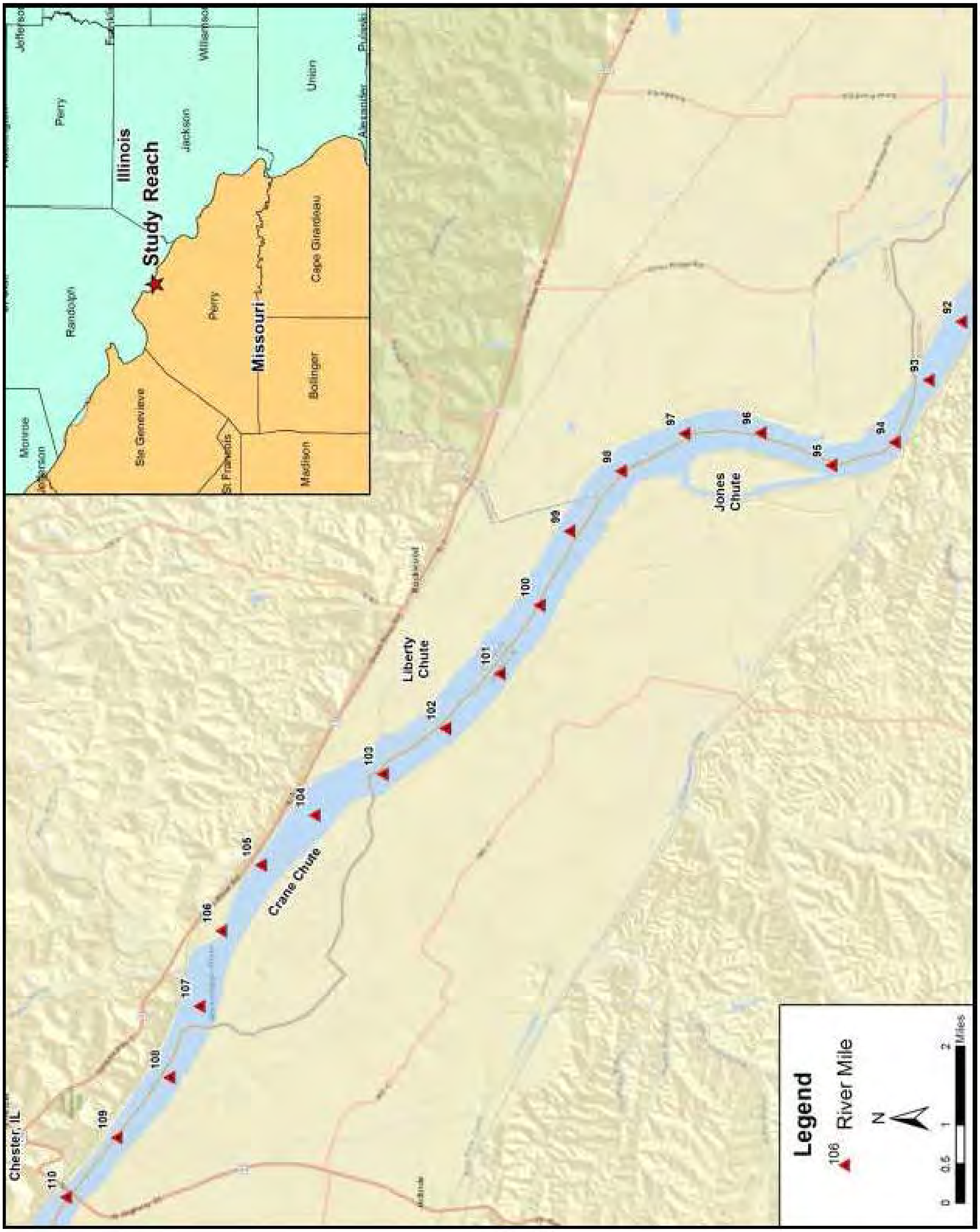


Figure 1-1. Location map

Figure 1-2. Aerial photo of study reach (RM 105 to 110)

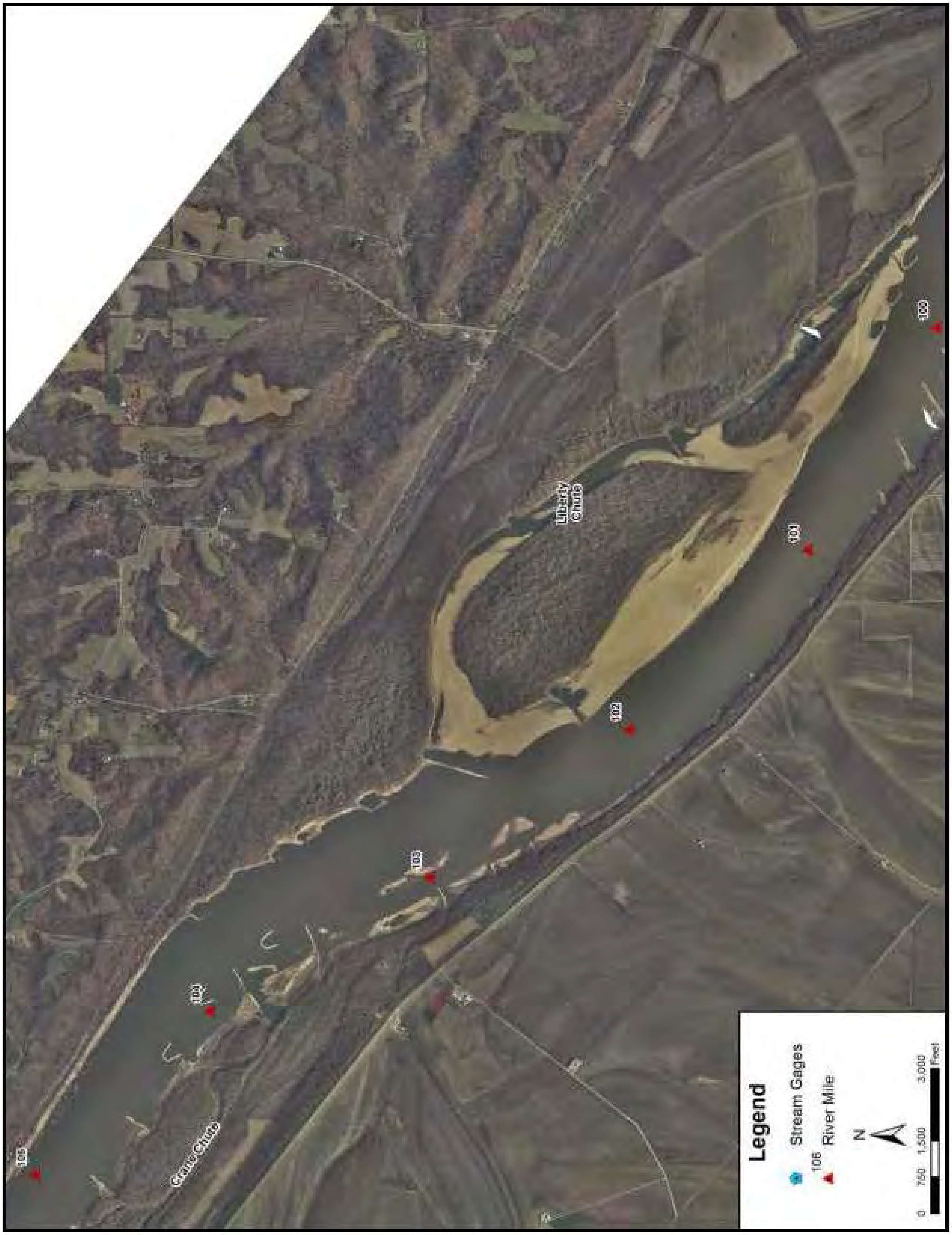


Figure 1-3. Aerial photo of study reach (RM 100 to 105)

Figure 1-4. Aerial photo of study reach (RM 96 to 100)

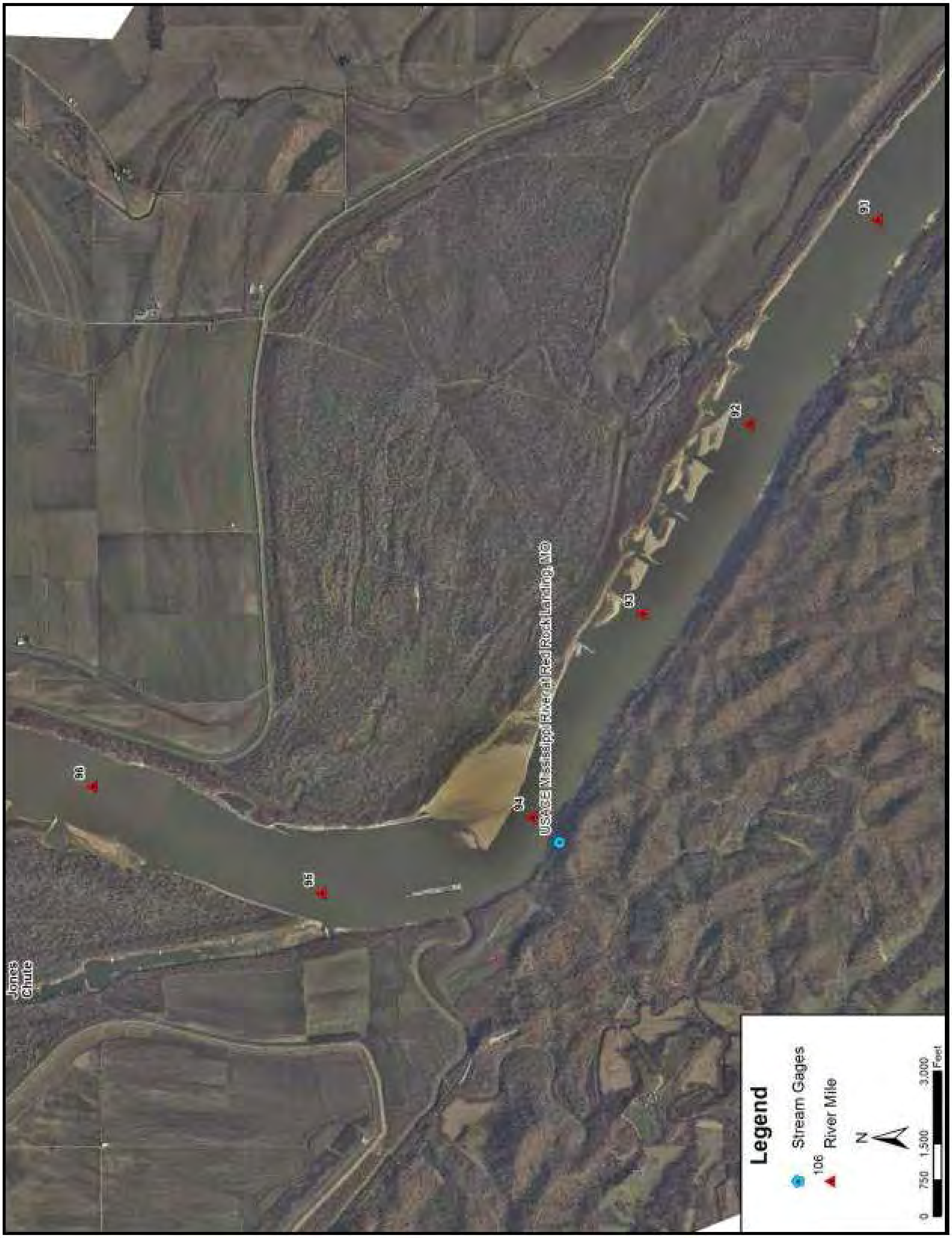


Figure 1-5. Aerial photo of study reach (RM 91 to 96)

1.4 Report Organization

This report is organized into six sections and three appendices. Section 1 provides introductory and background information. Section 2 provides information about the post-processing tools developed as part of this study. Section 3 provides information about the development of a CCHE3D model of a local reach near the upstream end of the study reach. Section 4 provides information about the development of a CCHE3D model of the study reach. Section 5 provides a summary of this study. Section 6 documents the references used in this study. Appendix A includes the User's Guide for the scripts and tools developed for this study. Appendix B includes velocity and reclassification plots of the CCHE3D model results for the study reach. Appendix C includes DVDs of the project files.

1.5 Datums

All geographic and spatial data used in this study except for the CCHE3D models are based on a horizontal datum of the NAD 1983 Missouri State Plane East, a vertical datum of North American Vertical Datum of 1988 (NAVD88), and English units. The CCHE3D only supports metric units, so the models are based on a horizontal datum of NAD 1983 Universal Transverse Mercator, Zone 16, a vertical datum of NAVD88, and metric units.

1.6 Acknowledgements

Don Duncan, P.E., of the USACE, MVS, provided Technical Management for the District, and Edward Brauer, P.E. of the USACE, MVS was the Technical Point of Contact for the District. Chris Bahner, P.E. was the WEST's Project Manager for this study. He also developed the CCHE3D hydraulic models for the study and wrote the majority of this report. Erik McCarthy and Rebeca Yalcin developed the scripts and ArcGIS tools to process the data. Thomas Grindeland, P.E., provided Quality Control\Quality Assurance for this study, and Dr. Walton reviewed the CCHE3D model. Everyone's contributions are gratefully acknowledged.

2 Post-Processing Development

As mentioned in the first chapter, the main purpose of this study is to define the hydraulic model results for quantifying the volume of habitat available based on velocity characteristics. Seven tools were developed to assist in the quantification of habitat volume. A brief discussion of each tool is provided as follow:

(1) ***CCHE3D_Output_TxtFile_Creation.xlsm*** is a Visual Basic (VBA) program in Excel that converts the CCHE3D model results to x-direction (x), y-direction (y), and velocity (v) ASCII files for 1 meter depth increments from the water surface to within about 1 meter of the existing bed elevation (Note: The elevation of each depth layer varies due to the variation in the water surface elevation within the study reach). The velocity determined at each 1 meter increments was estimated using Log-Log interpolation of the CCHE3D model results (Note: Linear interpolation and Power-Index approaches were also considered, but the Log-Log interpolation was utilized since it performed the best out of the three different interpolation approaches). This tool will generate ASCII files with the name of "Depth_#" where the # represents the depth below the water surface elevation.

This tool also creates three additional ASCII files:

(i) CCHE3D.3dm is a 3D mesh file that represents the computation mesh. It consists of a title line of "MESH3D" followed by records to describe the all of the elements in a consecutive order by ID, followed by all of the nodes, also in consecutive order. The elements are described with an "E8H" record that includes the element ID, nodal connectivity ID, and material ID. The nodal connectivity ID involves eight nodes defining the element with the first four nodes defining the base of the element in a counterclockwise direction followed by second four nodes defining the top of the element also in a counterclockwise direction starting in the same corner as the base. The material ID can used to define different regions of the computation mesh. A material ID was set to 1 for all elements. The nodes are described with an "ND" record that includes the node ID, and x-, y-, z-coordinate location. This file can be imported into Aquaveo's Goundwater Modeling Software (GMS). The x- and y-coordinate location in this file are based on a horizontal datum of NAD83 UTM Zone 16 (metric), and the z value is based on a vertical datum of NAVD88.

(ii) Vel_Results.dat is a dataset file of the flow velocity at each of the computational mesh nodes in a format that can be imported into Aquaveo's GMS. It includes information about the total number of nodes and elements, type of data (scalar or vector), name of the dataset, and then the values are listed for each node on separate lines.

(iii) WS_VolCal.txt is an ASCII file that contains the CCHE3D water surface elevation results (x, y, and wsel). The x- and y- coordinate location in this file are based on a horizontal datum of NAD83 UTM

Zone 16 (metric), and the wsel is based on a vertical datum of a vertical datum of NAVD88.

This tool has the option to write the GMS files (CCHE3D.3dm and Vel_Results.dat) for the reach of the computational mesh from an upstream and downstream RM defined by the user. The output files from this tool are written to the same directory as the Excel file.

(2) ***Middle Mississippi River Aquatic Evaluation.tbx (Create Output Workspace)*** is an ArcGIS Version 10.1 Toolbox function that creates the workspace directories for the Classify Velocity Range and Calculate Area tool. This tool only needs to be run once prior to running the Classify Velocity Range and Calculate Area tool.

(3) ***Middle Mississippi River Aquatic Evaluation.tbx (Classify Velocity Range and Calculate Area)*** is an ArcGIS Version 10.1 Toolbox function that classifies velocity data into ranges and calculates associated area within the model extents or a specified area. It converts the x, y, v ASCII files of 1 meter depth increments developed from Tool No.1 as described above to raster files and then classifies them into five velocity zones:

(i) Zone 1 is for velocities between 0 m/s and 0.10 m/s

(ii) Zone 2 is for velocities between 0.11 m/s and 0.25 m/s

(iii) Zone 3 is for velocities between 0.26 m/s and 0.50 m/s

(iv) Zone 4 is for velocities between 0.51 m/s and 1.0 m/s

(v) Zone 5 is for velocities greater than 1.0 m/s

This tool also computes the area of each velocity zone for all of the 1 meter depth layers. Five different output files are generated by this tool as described in the User's Guide (Appendix A). The velocity and classified velocity zone raster files are provided for two horizontal datums: (i) NAD83 UTM Zone 16 (metric), and (ii) NAD 1983 Missouri State Plane East (feet).

(4) ***Middle Mississippi River Aquatic Evaluation.tbx (Create Output Workspace - Volume Difference Tool)*** is an ArcGIS Version 10.1 Toolbox function that creates the workspace directories for the Volume Difference Between Water Surface and Bathymetry tool. This tool only needs to be run once prior to running the Volume Difference Between Water Surface and Bathymetry tool.

(5) ***Middle Mississippi River Aquatic Evaluation.tbx (Volume Difference Between Water Surface and Bathymetry)*** is an ArcGIS Version 10.1 Toolbox function that defines the volume difference between the CCHE3D water surface elevation and a raster file of the bathymetry data. The raster of the bathymetry data must be based on

a horizontal datum of NAD83 UTM Zone 16, a vertical datum of NAVD88, and the metric unit system.

(6) ***Middle Mississippi River Aquatic Evaluation.tbx (Copy Workspace to New Location)*** is an ArcGIS Version 10.1 Toolbox function that can be used to place copies of all the files within one directory to a new workspace location.

(7) ***Volume_Summary.xlsm*** is a VBA program in Excel that extracts the area of classified velocity zones from the DBF files generated from Tool No. 2, and creates a summary table of the area (m^2) and volume (m^3) for each velocity zone per 1 meter depth increments, and the total fractional volume for each velocity zone.

Information about each tool is summarized in Table 2-1. A User's Guide with step-by-step instructions for each tool is provided in Appendix A.

Table 2-1. Summary Information of Scripts and Tools Developed for this Study

Tool No.	Name	Type	Required Input Files	Output	Notes\Comments
1	CCHE3D_TxtFile_Creation.xlsm	Excel_VBA	CCHE3D *.geo,*.fuz,*.flw, and *.flw3d files	x, y, v ASCII files for 1 meter depth increments. The name of the ASCII files will be "Depth_#" where the # represents the depth below the water surface elevation. This tool also creates three additional ASCII files: (i) CCHE3D.3dm, (ii) Vel_Results.dat, and (iii) WS_VolCal.txt.	• It is best to start with a cleaned file (about 112 KB file size). This can be accomplished by clicking "Clear All" button and saving the file. • All CCHE3D files have to be located in the same directory. • Output files will be written to the same directory as the Excel file. • Tool will overwrite TXT files existing within the specified output. • The status bar (lower left side below the worksheet tabs) will show the status of the processing.
2	Middle Mississippi River Aquatic Evaluation.tbx (Create Output Workspace)	ArcGIS Tool	None	Creates workspace directories for Tool No. 3 (Classify Velocity Range and Calculate Area)	• The default directory is C:\MVS\MMR\Velocity. • Tool would need to be edited in ArcGIS if a different default directory is desired. • Tool needs to be run only once prior to running Tool No. 3 (Classify Velocity Range and Calculate Area).
3	Middle Mississippi River Aquatic Evaluation.tbx (Classify Velocity Range and Calculate Area)	ArcGIS Tool	x, y, and v files (Depth_#.txt) generated from Tool No. 1, schema.ini file, and a polygon shapefile of the evaluation extents (optional)	This tool generates five different output files for each 1 meter depth increment: (i) point shapefile of x, y, v data; (ii) TIN file of the x, y, v data, (iii) ArcGIS raster file of the x, y, v data,	• The TIN and raster files generated from this tool will have the same name as the x, y, v ASCII text file generated from Tool No. 1, i.e., "Depth_#.*" where the # represents the depth below the surface elevation. • The name of the DBF files generated from this tool will be"Area_Depth_#.dbf" where the #

Table 2-1. Summary Information of Scripts and Tools Developed for this Study

Tool No.	Name	Type	Required Input Files	Output	Notes\Comments
3 Cont.	Middle Mississippi River Aquatic Evaluation.tbx (Classify Velocity Range and Calculate Area)	ArcGIS Tool	x, y, and v files (Depth_#.txt) generated from Tool No. 1, schema.ini file, and a polygon shapefile of the evaluation extents (optional)	(iv) ArcGIS raster files of the classified velocity zones, and (v) a DBF file containing the area for each velocity zones.	represents the depth below the surface elevation. • It is important that all of the directories specified in the ArcGIS Toolbox input editor exists. • This tool must be run from a local drive and will not replace existing files.
4	Middle Mississippi River Aquatic Evaluation.tbx (Create Output Workspace – Volume Difference Tool)	ArcGIS Tool	None	Creates workspace directories for Tool No. 5 (Volume Difference Between Water Surface and Bathymetry)	• The default directory is C:\MVS\MMR\CutFill. • Tool would need to be edited in ArcGIS if a different default directory is desired. • Tool needs to be run only once prior to running Tool No. 5 (Volume Difference Between Water Surface and Bathymetry)
5	Middle Mississippi River Aquatic Evaluation.tbx (Volume Difference Between Water Surface and Bathymetry)	ArcGIS Tool	WS_VolCal.txt file generated from Tool No. 1 and raster file of the bathymetry data	Raster file of the CCHE3D water surface elevation, and a raster file and DBF file of the Cut\Fill volume computed between the CCHE3D water surface elevation and the specified bathymetric data. Output raster file is based on NAD83 UTM, Zone 16 datum.	• Raster of the bathymetry data must be based on a horizontal datum of NAD83 UTM Zone 16, a vertical datum of NAVD88, and metric unit system. • The name of the DBF output file is "Vol_Change_WS_VolCal.dbf". • It is important that all of the directories specified in the ArcGIS Toolbox input editor exists. • This tool must be run from a local drive and will not replace existing files.

Table 2-1. Summary Information of Scripts and Tools Developed for this Study

Tool No.	Name	Type	Required Input Files	Output	Notes\Comments
6	Middle Mississippi River Aquatic Evaluation.tbx (Copy Workspace to New Location)	ArcGIS Tool	None	Copies files from an existing workspace directory to a new workspace directory	• The tool can be run after running Tools No. 3 (Classify Velocity Range and Calculate Area) and No. 5 (Volume Difference Between Water Surface and Bathymetry) to copy the files generated from the tools to a new location prior to running the tools again for another condition. • The defined new workspace directory has to be a new directory.
7	Volume_Summary.xlsm	Excel_VBA	DBF files generated from Tool No. 3	No output file created from this tool. Area and volume information are summarized in the "Summary" worksheet	• Running the tool will take the user directly to the "Summary" worksheet. • The status bar (lower left side below the worksheet tabs) will show the status of the processing.

3 Hydraulic Model of Local Reach

3.1 Introduction

A 3-D hydraulic model was developed for a short reach near the upstream end of the study reach to obtain a more refined understanding of the computational requirements for the entire 18 mile study reach and for applying the Post-processing tools and scripts developed as part of the study. The local model extends from RM 107.8 at the downstream end to RM 110 at the upstream end (Figure 3-1). Information about the development of the local 3-D hydraulic model is provided in the remainder of this section of the report.

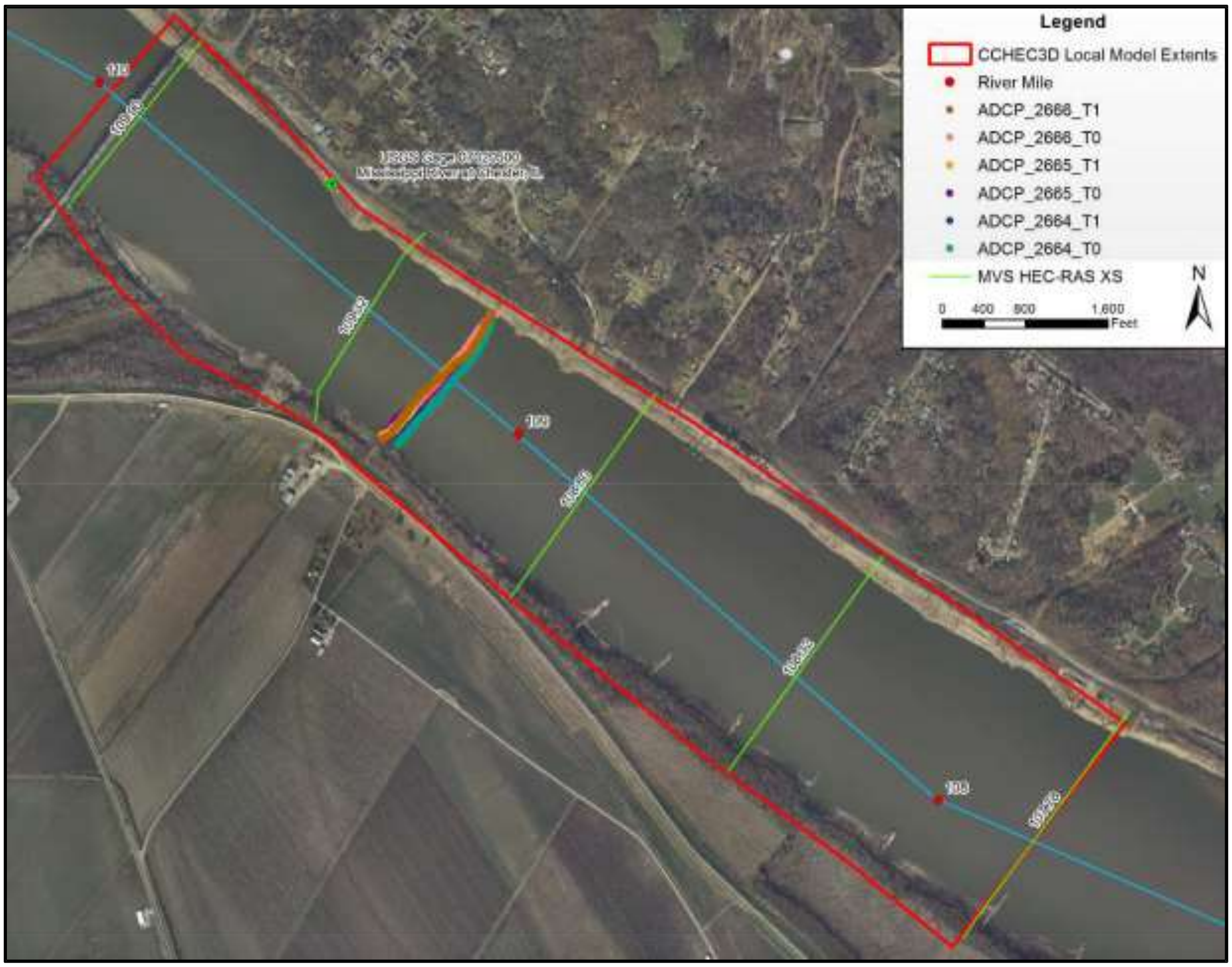


Figure 3-1. Map of local model extents

3.2 Description of Numerical Model

CCHE3D (NCCHE, 2013) is a three dimensional (3-D) numerical model that can simulate free surface turbulent flows with sediment transport, pollutant transport, and water quality analysis capabilities. Full Reynolds equations are solved using the Efficient Element Method, a collocation approach of the finite element method. Several turbulence closure schemes are available for users to select for their applications. The model can be used for both small scale

near field, detailed flows and sediment transport analyses and large-scale engineering applications. The finite element transformation allows the model to be applied to cases with complex natural geometric and topographic domains. Mixed with the finite volume approach, mass conservation is preserved both locally and globally.

The model uses a structured grid to discretize the computational domain, and a partially staggered grid is used for solving the pressure field to eliminate oscillation. Equation systems are solved implicitly with the Strongly Implicit Procedure (SIP) method. Unsteady governing equations are solved for both steady and unsteady flow conditions. A free surface is computed with the free surface kinematic equation. Boussinesq assumptions are used to formulate turbulence stresses, and several turbulence closure schemes are available. A wall function can be applied as boundary conditions for vertical walls as well as for irregular bed surface using a simple slip and partial slip boundary condition. The model has the capability to assess both hydrostatic and dynamic pressures. Dynamic pressure becoming important for pronounced vertical flow acceleration.

The model were developed at the National Center for Computational Hydroscience and Engineering (NCCHE), the University of Mississippi, over the past twenty years. The CCHE3D model has been copy-righted by the NCCHE. Computational Hydro-engineering Technology Inc. (CHeT) has the exclusive right to sub-lease license the model and provide user support and user services.

The NCCHE has developed two graphical user interface software programs for developing models: (1) CCHE-MESH, and (2) CCHE-GUI. CCHE-MESH is a 2-D mesh generator for both structured and unstructured meshes. It allows rapid quality mesh generation from the topography database, topography images or maps, Digital Elevation Model (DEM) data, and GIS shape files. It provides users input and output (I/O) management, algebraic mesh generation, numerical mesh generation, mesh editing, and operations on the topography database. CCHE-MESH generates a geometry file (*.geo) for the computational mesh. The geometry file includes the following information for each of the nodes included in the computational mesh: (1) x-coordinate, (2) y-coordinate, (3) initial water surface elevation, (4) ground elevation, (5) boundary node ID, and (6) hydraulic roughness value (either Manning’s n-value or roughness heights for a 2-D model and roughness heights for a 3-D model).

CCHE-GUI is an integrated software system for file management, simulation management, results visualization, and data reporting for all of the software developed by NCCHE. The CCHE-GUI software is used to create the 3-D mesh and run the CCHE3D software. The 3-D mesh is developed from the 2-D mesh by adding vertical planes as specified by the user in CCHE-GUI. The general steps for developing and running a CCHE3D model is summarized as follows: (1) develop 2-D computational mesh, (2) specify boundary conditions, (3) set the model parameters for 2-D simulation, (4) run the 2-D model using CCHE2D to establish initial flow conditions, (5) create a 3-D mesh by defining the number of vertical layers, (6) set the model parameters for 3-D simulation, and (7) run the model with CCHE3D. It should be noted that the vertical layers are not at the same elevation. The software distributes the vertical layers based on the flow depth at each of the nodes. The default distribution is to utilize a uniform distribution.

The models for this study were developed using the 64-bit version of the latest version of CCHE-MESH and CCHE-GUI software (Version 4.0), and are based on the metric unit system since it is the only unit system supported by the NCCHE software.

3.2.1 Model Development

As previously mentioned, a CCHE3D model was developed for a short reach near the upstream end of the study reach to obtain a more refined understanding of the computational requirements for the entire 18 mile study reach and for applying the Post-processing tools and scripts developed as part of the study. The local model extends from RM 107.8 at the downstream end to RM 110 at the upstream end.

3.2.1.1 Mesh Development

Mesh development for a CCHE3D model involves developing a 2-D mesh using CCHE-MESH software. The CCHE-MESH is also used to define the bed elevation, initial water surface elevation, and roughness characteristics. The final mesh from the CCHE-MESH software is shown in Figure 3-2. The computational mesh extends from the Highway 51 Chester bridge near RM 110 to about 2.2 miles downstream. The computational mesh covers a total area of about 1 mi^2, and it is comprised of 120 x-direction nodes (j nodes in CCHE-MESH), 46 y-direction (i nodes in CCHE-MESH), and 11 vertical layers (k nodes) for a total of 60,720 nodes (5,520 nodes in each of the 2-D layers). There are 5 river training structures existing within the local reach. The average dimension of 2-D grid elements located away from the river training structures is about 25 meters wide by 60 meters long, while near the river training structures they are about a 5 meter square. For the flow discharge of 8,580 m^3/s, the average flow depth within the local reach was 8 meters (maximum depth of 18.5 meters).

The elevation data for the mesh was based on a DEM developed using bathymetry and LiDAR data (USACE, 2012) provided by MVS. The LiDAR data is based on the NAD83 Missouri East (feet) horizontal datum and NAVD88 vertical datum, and was provided as a raster file. The bathymetry data is based on the NAD27 Missouri East (feet) horizontal datum and NGVD29 vertical datum. The bathymetry data was provided by the District as several ASCII files of x, y, and z values. Information about the bathymetry data is summarized in Table 3-1.

The elevation of the bathymetry data was converted to the NAVD88 datum by subtracting 0.537 feet. The files were then converted to a point shapefile using ArcGIS. The point shapefiles were used to create a Triangular Irregular Network (TIN) and then converted to a raster file using ArcGIS. The bathymetry raster file was then combined with the LiDAR raster file using the Mosaic Option in ArcGIS to create the final raster of the DEM for the study reach. For the CCHE3D model, the DEM was converted to the NAD83 Universal Transverse Mercator (UTM), Zone 16 horizontal datum, NAVD88 vertical datum, and metric units.

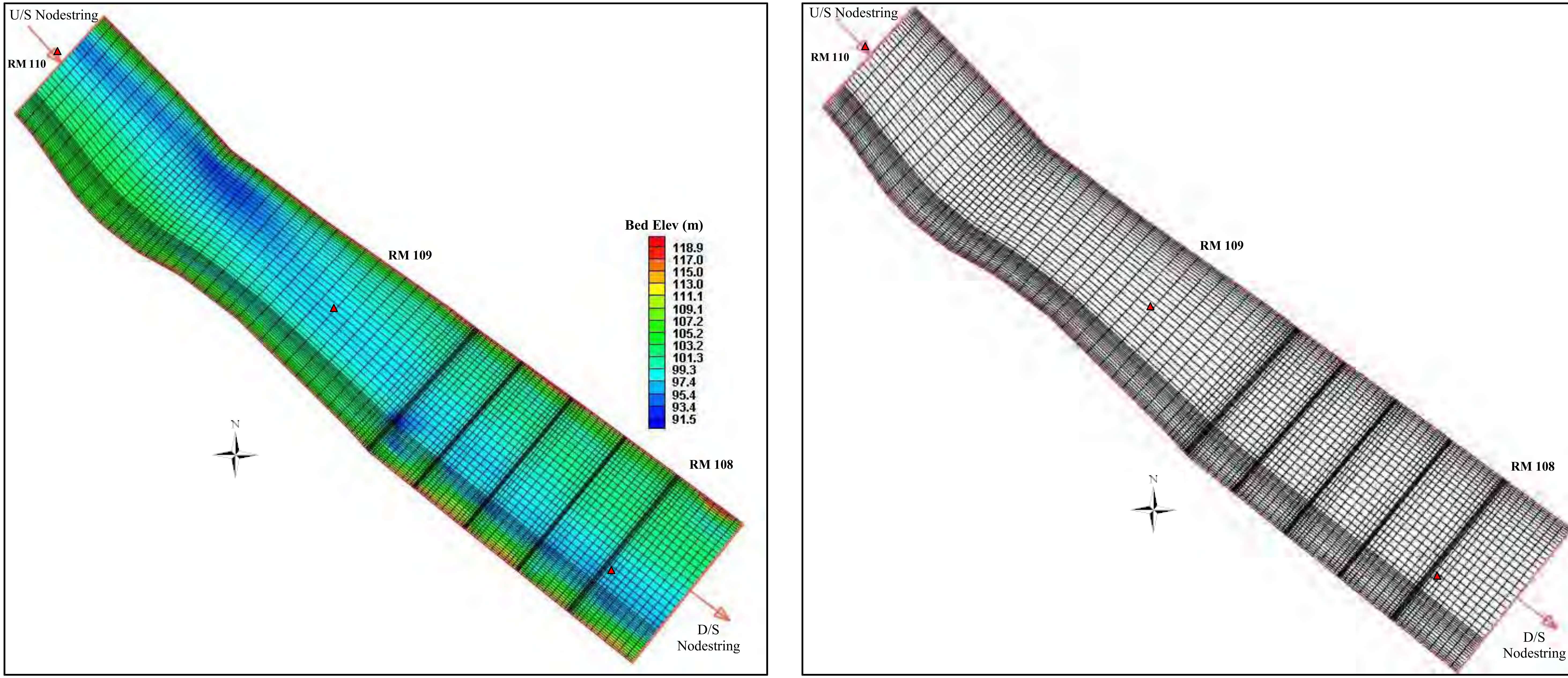


Figure 3-2. Computational mesh for local CCHE3D model

Table 3-1. Summary of Bathymetry Data

Type	Location	Name
Single Beam	Main Channel	094-089D0313.xyz
		098_094D0213.xyz
		100_098D0113.xyz
		105_102C2713.xyz
		107_099C2813.xyz
		112_107C2613.xyz
		098j2807\10_elev.xyz
	Side Channel	CrainsChute_05042011_1x1.xyz
		Jones_chute_04272011_3x3.xyz
		LibertyChute_05042011_3.5x3.5.xyz
	Dredge Survey	105_101g1213_elev.xyz
		102k1711.xyz
Multi Beam Surveys	Main Channel	093e1213_4x4.xyz
		096c1312.txt
		RM96_97_07262012_2x2.xyz
		104c1412.txt
		Weirs_RM97_97pt6_2x2.xyz

3.2.2 Model Boundary Conditions

The hydrodynamic calculation algorithms of CCHE3D require the following boundary and initial conditions: (1) upstream flow boundary condition, (2) downstream elevation boundary condition, and (3) initial water depths and flow velocities. The development of the boundary and initial conditions was accomplished as follows.

3.2.2.1 Boundary Conditions

The CCHE3D model requires defined information at the upstream and downstream boundaries (nodestrings) of the mesh. The upstream and downstream nodestring locations are shown in Figure 3-2. The boundary conditions considered for the local model are summarized in Table 3-2. It should be noted that the local model was only evaluated for the largest in-channel discharge considered for this study, which is the referred to Flow Condition 3 in this report. A total discharge was defined at the upstream boundary, and a water surface elevation was defined at the downstream boundary.

Table 3-2. Boundary Conditions

Flow Condition	Discharge (m^3/s)	D/S Water Surface Elevation (m)
3	8,580	109.92

The water surface elevation at the downstream boundary was obtained from the HEC-RAS model provided by MVS. The provided HEC-RAS model was an unsteady flow model for the Middle Mississippi River reach (from RM 1.39 near Birds Point Gage to RM 180.02 near St. Louis Gage). The model was converted by WEST to a steady flow model that covers the reach from RM 91.83 to RM 114.54. As discussed in Section 3.2.4.1, the HEC-RAS model was calibrated using two streamflow gages. The downstream end of the Local CCHE3D model is at RM 107.78.

3.2.2.2 Initial Water Surface and Flow Velocities

CCHE3D requires that the initial water surface elevation and velocity be defined at all of the mesh nodes. This was accomplished using a two-step process. First, the initial water surface elevations were defined using the HEC-RAS model results. The HEC-RAS model results were exported as a GIS format. HEC-GeoRAS was then utilized to convert the GIS export file to a TIN file of the water surface elevation. The water surface TIN was then converted to a raster using ArcGIS. The water surface raster file and a point file of the computational mesh were then used to define the water surface elevation at each node of the computational mesh. The information was then incorporated into the geometry (*.geo) file of the computational mesh. CCHE2D was then used to define the initial water surface and flow velocities used for the CCHE3D model.

3.2.3 Model Parameters

3.2.3.1 Hydraulic Roughness Heights

Eight material types were used to define the hydraulic roughness within the study reach. The material type boundaries were defined based on topography, aerial photography, and shapefiles of rock revetment and river training structures. The material types are shown in Figure 3-3. Initially, the Manning's n values for each material were estimated using information documented in Chow's *Open-channel Hydraulics* (Chow, 1959) and the HEC-RAS User's Manual (USACE, 2011). The estimated Manning's n values for each material are summarized in Table 3-3.

CCHE3D model requires that the bed roughness be defined using the roughness height, ks, and not Manning's n-values. Per the CCHE3D User's Manual, the following equation (Strickler's Equation) was used to estimate the equivalent roughness height based on the estimated Manning's n values:

$$n = \frac{ks^{1/6}}{A}$$

Where,

ks = equivalent roughness height
n = manning's coefficient
A = empirical constant that is dependent on sediment size, bed form, vegetation and channel morphology. It can vary between 14 and 29. A value of 19, as recommended by NCCHE was used to estimate the equivalent roughness heights provided in Table 3-3. Adopted values in the table are based on the calibration of the CCHE3D model.

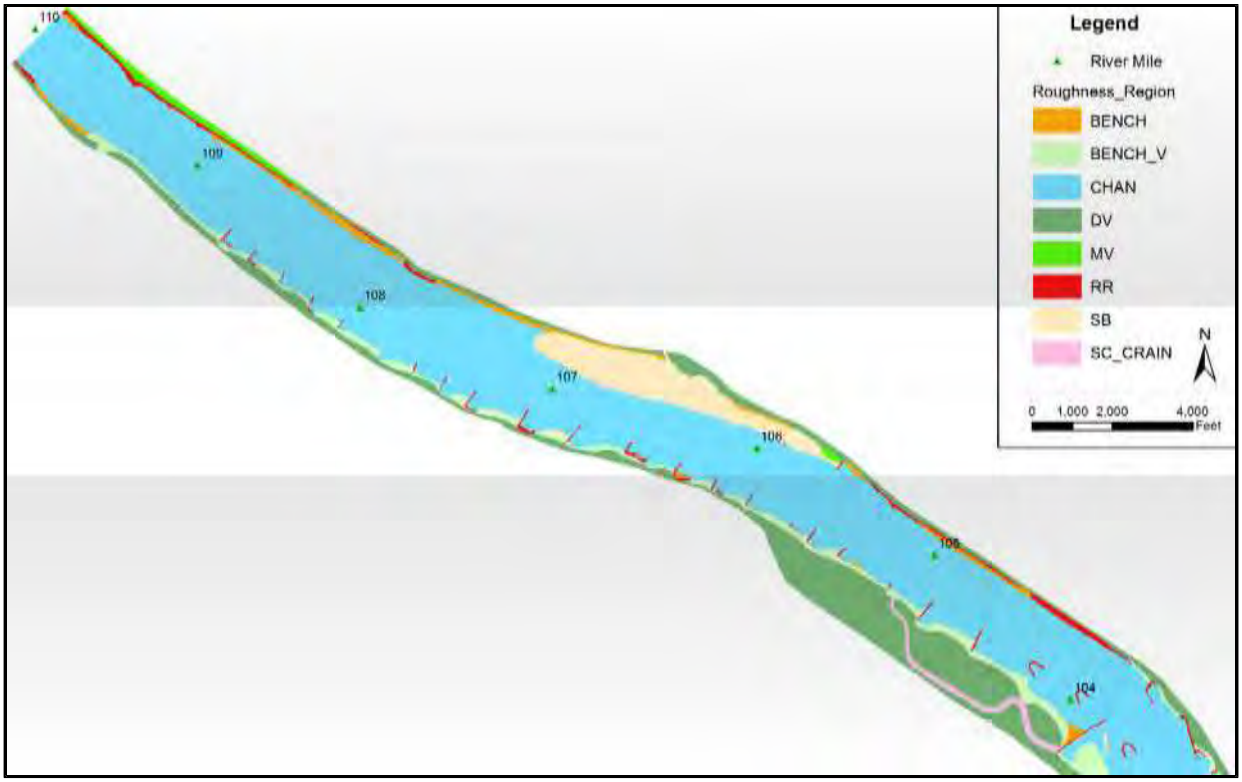


Figure 3-3. Mesh materials

Table 3-3. Roughness Heights for the CCHE3D Material Types

Material	Description	Initial Manning's n Value	Initial Equivalent Roughness Height (m)	Adopted Roughness Height (m)
Bench	Bench area with sand, cobble, and boulders	0.032	0.051	0.193
Bench_V	Bench area with sand, cobble, and vegetation	0.055(1)	1.302	1.302
Chan	Main channel	0.032	0.051	0.086
DV	Overbank area with dense vegetation	0.10	47.046	47.046
MV	Overbank area with moderately dense vegetation	0.050(1)	0.735	0.735
RR	Riprap (D50 of 2 ft and D90 of 3.2 ft)	0.050	0.7626	0.7626
SB	Sand bar within or near main channel	0.032	0.051	n.a.(2)
SC_Crain	Crain chute side channel	0.060	2.195	n.a.(2)

Note:

1. Bench_V was assigned a higher roughness coefficient than MV due to more pronounced irregularities and obstructions.
2. n.a. corresponds to not applicable for local reach model.

3.2.3.2 Eddy Viscosity

Eddy Viscosity represents the turbulence generated in the spreading of momentum that is smaller than can be represented by the grid resolution. CCHE3D has five options for defining eddy viscosity: (1) Mixing Length, (2) K-Esplon, (3) Non-linear K-Esplon, (4) K-Esplon RNG, and (5) K-Omega. Per recommendations from NCCHE, the eddy viscosity is represented in the model using the Mixing Length option with a coefficient of 1.0.

3.2.3.3 Model Parameters

Additional model parameters defined in the CCHE3D model is provided in Table 3-4.

Table 3-4. Model Parameters

Parameter	Value
Pressure Simulation	1st Order Non-hydrostatic
Time (s) Tim	14,400
e Step (s)	0.5
Wall Slippage Coefficient	1.2
Depth to Consider Dry	0.001
Time Iteration Method	Method 1

3.2.4 Model Calibration

The HEC-RAS and CCHE3D models were calibrated to observed conditions. The HEC-RAS model for the study reach was calibrated to three in-channel flows of interest for this study using observed water surface elevations at two streamflow gages existing within the study reach. The CCHE3D Local Reach model was calibrated to the largest of the three in-channel flows of interest for this study using observed water surface elevation at one of the streamflow gages and observed flow velocities measured using an Acoustic Doppler Current Profile (ADCP) device. Information about the calibration of the two models is provided in this section of the report.

3.2.4.1 HEC-RAS

As previously stated, MVS provided an unsteady flow HEC-RAS model of the Middle Mississippi River covering reach from RM 1.39 near Birds Point Gage to RM 180.02 near the St. Louis Gage. The model was converted by WEST to a steady flow model for the reach from RM 91.83 to RM 114.54. The HEC-RAS model was calibrated for three in-channel discharges (3,143.2 m^3/s, 6,031.5 m^3/s, and 8,580.0 m^3/s) and measured water surface elevations at the USGS Gage 07020500, *Mississippi River at Chester, IL* and the USACE's *Mississippi River at Red Rock Landing, MO* gages. The calibration was completed in two steps. For the first step, a model was developed for the reach from the Red Rock Landing gage to the Chester, IL gage. The downstream boundary of this initial model was set to the observed water surface elevations at the Red Rock Landing gage. The Manning's n coefficients in the model were adjusted to match the water surface elevations at the Chester, IL gage. The average Manning's n coefficient was estimated to be 0.035 for the discharge of 3,143.2 m^3/s, 0.033 for the discharge of 6,031.5 m^3/s, and 0.032 for the discharge of 8,580.0 m^3/s. For the second calibration step, additional cross sections were added to the downstream end of the model developed as part of the first step of calibration process. For the second model, normal depth was assumed at the downstream boundary, and the energy slope used for the normal depth computation was adjusted to get the calculated water surface elevation at the Red Rock Landing gage to be within 0.1 m (4 inches) to the observed water surface without causing a change in the water surface elevation at the Chester, IL gage.

The calibration results are summarized in Table 3-5, and shown in Figure 3-4. As shown in Table 3-5, the calibrated HEC-RAS model computes a water surface elevation that exactly matches the observed water surface elevations at the Chester, IL gage and a minor difference in the water surface elevation (0.02 meters or 0.8 inches) at the Red Rock Landing gage.

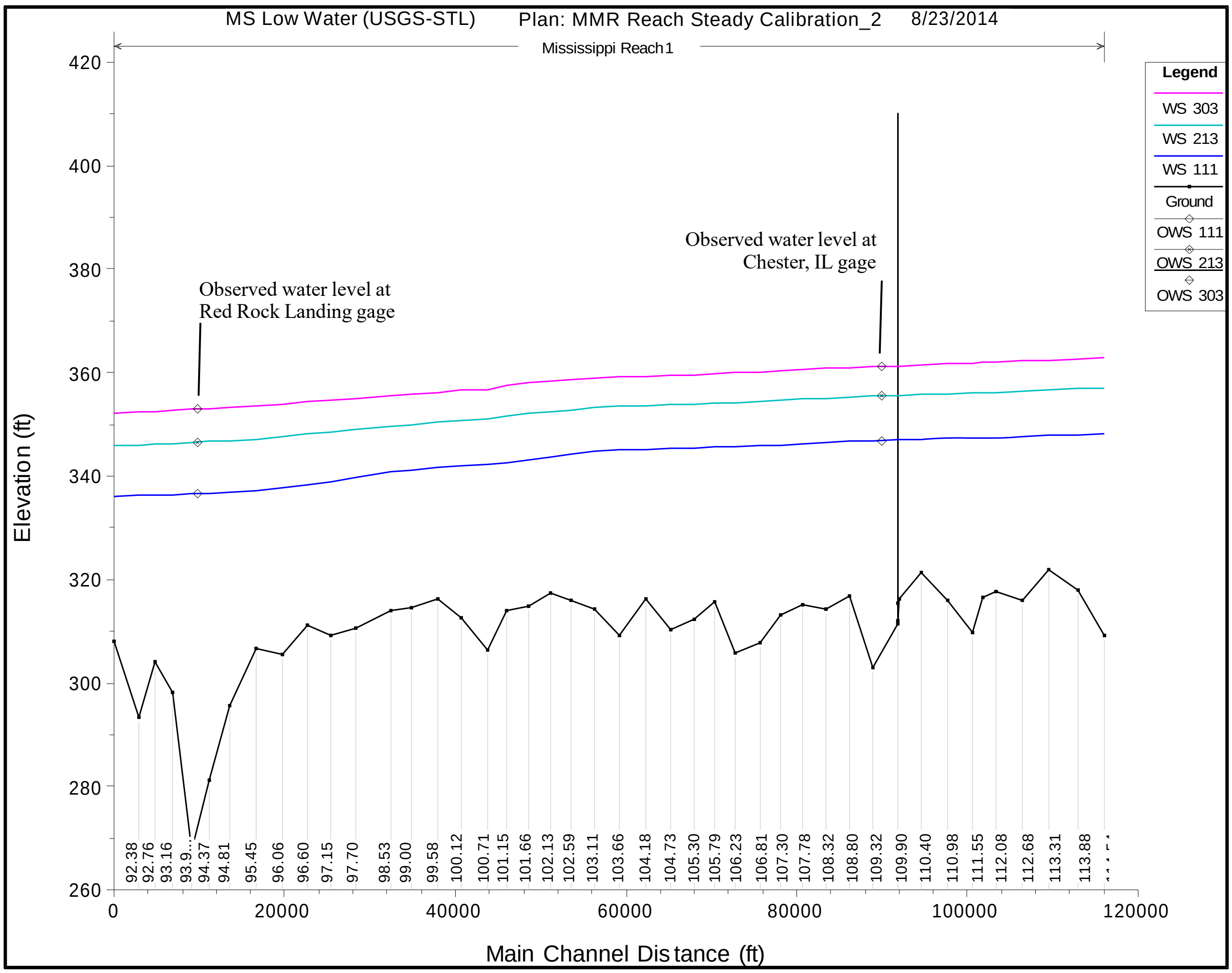


Figure 3-4. HEC-RAS calibration results

Table 3-5. Summary of HEC-RAS Calibration

Gage	Discharge (m^3/s)	Observed (m)	Calculated (m)	Difference (m)
Mississippi at Red Rock Landing	3,143.2	102.57	102.58	0.01
	6,031.5	105.60	105.62	0.02
	8,580.0	107.55	107.57	0.02
Mississippi at Chester, IL	3,143.2	105.72	105.72	0.00
	6,031.5	108.35	108.35	0.00
	8,580.0	110.09	110.09	0.00

Notes:

1. The average Manning's n coefficient was estimated to be 0.035 for the discharge of 3,143.2 m^3/s, 0.033 for the discharge of 6,031.5 m^3/s, and 0.032 for the discharge of 8,580.0 m^3/s.

3.2.4.2 CCHE3D

The CCHE3D Local Reach model was used to analyze the hydrodynamics associated with the largest of the three in-channel flows of interest for this study. Therefore, the calibration was completed only for this discharge. Since CCHE3D requires that the initial water surface elevations and flow velocities be defined with a CCHE2D model, the CCHE2D model was calibrated by adjusting the roughness height so that the calculated average water surface elevation matches the observed water surface elevation at the USGS Chester, IL gage. The calibrated roughness heights are provided in Table 3-3.

ADCP velocity data obtained by the USGS was also used in the calibration of the CCHE3D model. The location of the ADCP measurements are shown in Figure 3-1. A summary of the ADCP data is shown in Table 3-6. The measurements consist of two transects that generally reflect each of the three in-channel flow conditions of interest for this study. The raw data files provided by MVS was converted to text files using WinRiverII developed by Teledyne RD Instruments. The text files were then imported into Excel for comparing with the calculated velocities from CCHE3D model.

Table 3-6. Summary of ADCP Data

File	Date	Transect	Direction	Avg Direction	Discharge (cms)	Avg Q (cms)	Avg Q (cfs)
CHES0310_2664	3/10/2014	000	132.21	131.36	3,057.8	3,146.2	111,107
		001	130.51		3,234.6		
CHES0416_2665	4/16/2014	000	130.65	132.08	6,199.2	6,026.1	212,810
		001	133.51		5,853.0		
CHES0505_2666	5/5/2014	000	128.13	128.15	8,590.6	8,581.2	303,043
		001	128.17		8,571.8		

The CCHE3D model was calibrated by adjusting the roughness height, pressure methodologies, eddy viscosity methods and coefficients, and side wall boundary assumption to minimize the difference between the computed and observed velocity magnitude and direction. The CCHE3D water surface profile with the results from the calibrated HEC-RAS model is shown in Figure 3-5.

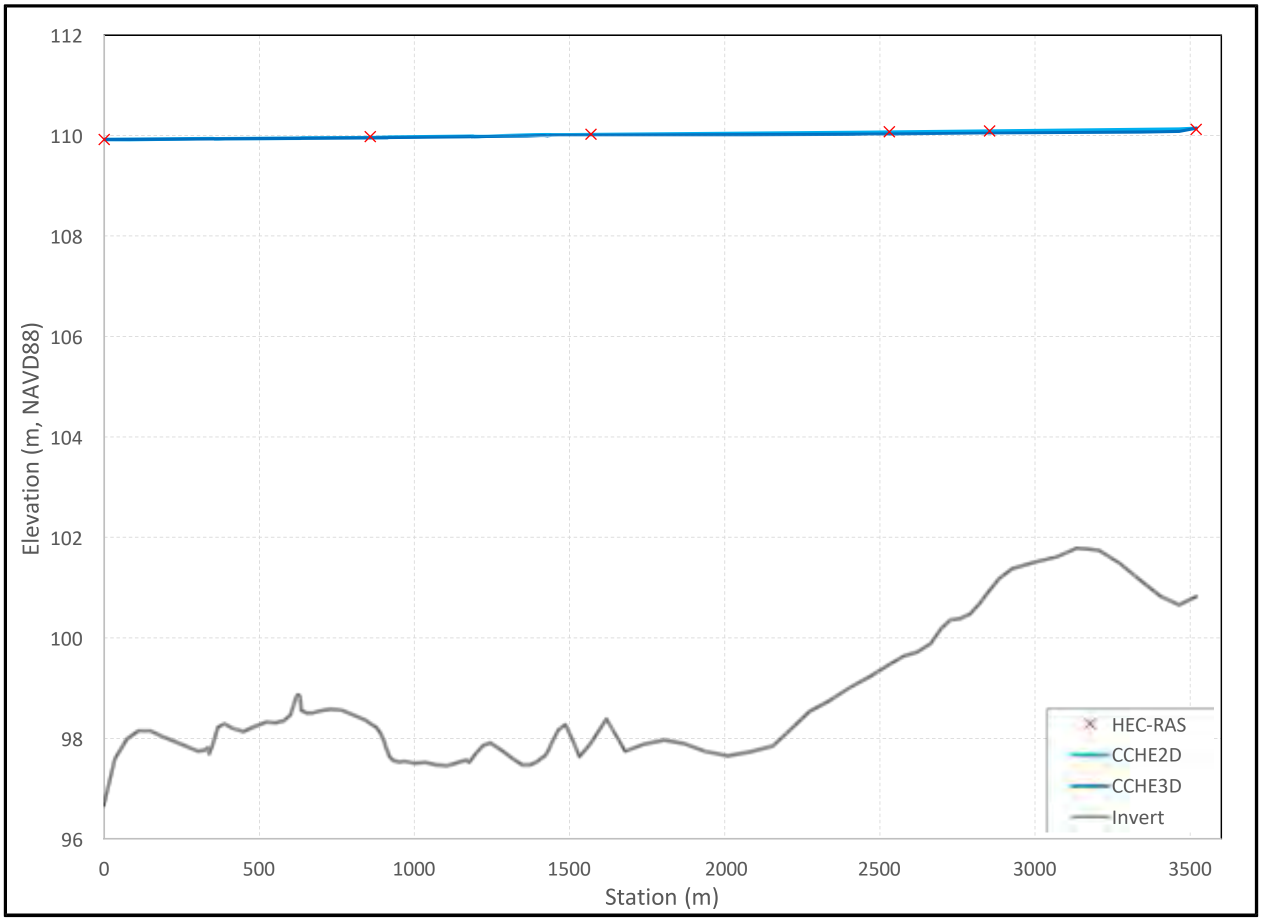


Figure 3-5. CCHE3D water surface elevation calibration results

Additional information related to the calibration model results are provided in Table 3-7 thru Table 3-9. Table 3-7 provides a comparison of computed average cross sectional values to the average cross sectional values at the USGS Chester, IL gage and ADCP locations. As indicated in this table, the CCHE3D model does a good job at representing the average cross sectional conditions.

A comparison of the velocity magnitude and direction at each measured flow depth is provided in Table 3-8 and Table 3-9, respectively. Both of these tables provide the average computed values, average measured values, delta in the values, percentage difference associated with the delta, absolute delta in the values, and the percentage associated with the absolute delta of the values. It should be noted that the percentage of change associated with the minor changes in the velocities are larger relative compared to the changes in the velocity direction due to the velocity being a lot smaller than the velocity direction. A review of the results indicates that the

Table 3-7. Summary of CCHE3D Calibration Results (Cross Sectional Basis)

Item	Observed	Computed	Delta	Percentage Difference
WS at Gage (m)	110.09	110.06	-0.03	-0.03%
Average Velocity (m/s)	1.43	1.42	-0.01	-0.70%
Average Velocity Direction (degrees)	128.2	129.9	1.7	0.94%

Table 3-8. Summary of CCHE3D Calibration Results (Average Ensemble Velocity per Depth)

Depth (m)	Observed Velocity (m/s)	Computed Velocity (m/s)	Delta[(1)]	Percentage Difference	Absolute Delta[(1)]	Percentage Difference for Absolute Delta
1.66	1.57	1.52	-0.06	-3.1	0.11	7.4
2.16	1.55	1.52	-0.03	-1.9	0.09	6.3
2.66	1.55	1.51	-0.04	-2.0	0.11	7.3
3.16	1.55	1.50	-0.04	-2.5	0.11	7.4
3.66	1.51	1.49	-0.02	-0.7	0.11	8.0
4.16	1.50	1.48	-0.02	-0.8	0.11	7.5
4.66	1.48	1.47	-0.01	0.3	0.11	7.9
5.16	1.47	1.46	-0.01	0.6	0.11	8.2
5.66	1.47	1.47	0.00	0.5	0.11	7.5
6.16	1.45	1.45	0.00	1.1	0.13	9.0
6.66	1.44	1.43	-0.01	-0.2	0.13	9.2
7.16	1.42	1.43	0.01	1.2	0.11	8.1
7.66	1.40	1.40	0.00	0.9	0.12	8.8
8.16	1.40	1.43	0.03	3.0	0.11	8.5
8.66	1.41	1.47	0.04	3.8	0.14	10.7
9.16	1.41	1.49	0.09	7.9	0.17	13.1
9.66	1.39	1.48	0.08	8.6	0.17	13.9
10.16	1.38	1.48	0.10	10.0	0.18	14.6
10.66	1.38	1.49	0.11	9.7	0.19	13.8
11.16	1.34	1.52	0.17	13.6	0.17	13.6
11.66	1.12	1.37	0.26	26.3	0.26	26.3
Average			**0.03**	**3.7**	**0.14**	**10.3**

Notes:

1. The Delta provided in the table above is based on the average delta values provided at each ensemble. It might not equate to the difference to the average computed and measured values in the table due to rounding errors.

Table 3-9. Summary of CCHE3D Calibration Results (Average Ensemble Velocity Direction per Depth)

Depth (m)	Observed Velocity Direction (Degrees)	Computed Direction (Degrees)	Delta[1]	Percentage Difference	Absolute Delta[1]	Percentage Difference for Absolute Delta
1.66	129.5	129.7	0.3	0.1	2.5	1.4
2.16	129.4	129.8	0.4	0.2	2.6	1.4
2.66	128.7	129.8	1.1	0.6	3.2	1.8
3.16	129.1	129.8	0.7	0.4	2.7	1.5
3.66	129.4	129.8	0.4	0.2	3.1	1.7
4.16	129.7	129.8	0.1	0.0	3.7	2.1
4.66	130.4	129.8	-0.6	-0.3	3.8	2.1
5.16	130.1	129.8	-0.3	-0.2	4.3	2.4
5.66	130.0	129.9	-0.1	-0.1	4.4	2.5
6.16	129.4	129.9	0.6	0.3	4.6	2.6
6.66	128.9	130.0	1.1	0.6	5.3	3.0
7.16	128.3	130.1	1.8	1.0	5.4	3.1
7.66	129.3	130.1	0.9	0.5	5.1	2.9
8.16	129.9	129.6	-0.3	-0.2	4.5	2.5
8.66	128.4	129.3	0.9	0.5	4.9	2.7
9.16	129.2	129.0	-0.1	-0.1	5.3	2.9
9.66	129.7	129.3	-0.4	-0.2	5.7	3.2
10.16	128.8	130.2	1.4	0.8	5.3	2.9
10.66	129.0	130.7	1.6	0.9	6.7	3.7
11.16	126.6	130.2	3.6	2.0	6.8	3.8
11.66	118.7	131.2	12.5	7.0	12.5	7.0
Average			**1.21**	**0.7**	**4.88**	**2.7**

Notes:

1. The Delta provided in the table above is based on the average delta values provided at each ensemble. It might not equate to the difference to the average computed and measured values in the table due to rounding errors.

CCHE3D does a fairly good job at matching observed conditions with the computed velocity being within ±10% of the observed value. The model slightly underpredicts the velocity in the upper water portion of the column and overpredicts the velocity in the lower portion of the water column with the difference increasing at the depth increases.

Potential causes in the difference between the computed and observed data include: (1) changes in the bathymetry (Figure 3-6), (2) uncertainty in ADCP observations (rating indicates measurements are within ±5 to 8%), (3) difference in spatial locations (ADCP measurements are not at the exact same location as computational mesh nodes), and (4) computational mesh doesn’t capture the detailed bed irregularities within the reach.

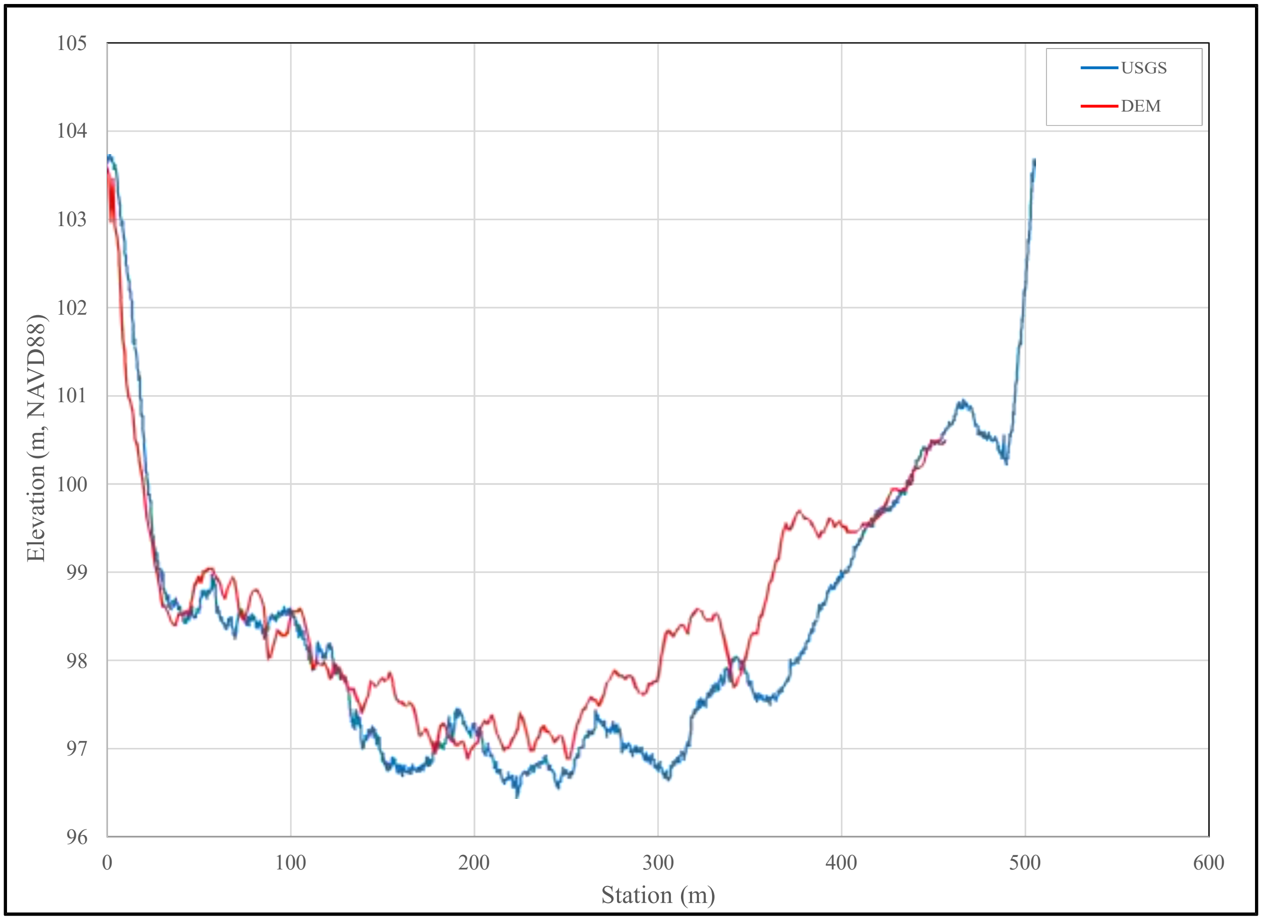


Figure 3-6. Comparison of the cross section for the ADCP CHES0505_2666 measurement

3.2.5 Model Results

The tools and scripts, as discussed in Chapter 2 of this report, were used to evaluate the aquatic habitat relative to velocity. The results of the evaluation are summarized in Table 3-10. The results in the table indicate that majority of the flow velocity within the Local Reach is greater than 1 m/s. For the flow condition considered (8,580 m^3/s), plots of velocity and reclassification of velocity generated from applying the tools are shown in Figure 3-7 through Figure 3-12 (depths of 0, 2, 4, 6, 8, and 10 m). These figures show that the majority of the local model area is comprised of velocities greater than 1.0 m/s with the areas near banks and downstream of the river training structures being comprised of lower flow velocities.

Table 3-10. Summary of Aquatic Habitat Evaluation of Local Model Reach (Flow of 8,580 m^3/s)

	Volume (m^3 per Depth) per Velocity Zone (m^3/s)				
	1	2	3	4	5
Depth (m)	0.0 - 0.10	0.11 - 0.25	0.26 - 0.50	0.51 - 1.0	1.01 - Max
0 – 1	39,325	74,013	117,838	162,888	1,744,255
1 – 2	32,763	78,500	117,713	164,425	1,740,240
2 – 3	27,225	82,538	117,838	163,100	1,734,450
3 – 4	26,213	87,313	116,825	159,875	1,725,850
4 – 5	24,025	84,613	118,213	167,225	1,710,375
5 – 6	23,825	73,313	107,863	199,763	1,679,690
6 – 7	18,438	62,775	88,975	248,013	1,630,465
7 – 8	11,500	56,675	81,175	294,500	1,564,290
8 – 9	12,913	48,725	73,975	421,688	1,393,880
9 – 10	12,400	40,550	72,075	594,863	1,126,465
10 – 11	8,038	35,913	68,338	577,875	850,050
11 – 12	3,050	35,963	56,000	521,538	511,425
12 – 13	1,525	35,100	54,763	595,913	232,775
13 – 14	1,525	22,788	53,125	550,100	144,600
14 – 15	738	7,025	29,563	329,575	87,988
15 – 16	0	63	6,325	125,363	28,400
Total (Percentage of Total)	**243,500 (1%)**	**825,863 (3%)**	**1,280,600 (5%)**	**5,276,700 (21%)**	**17,905,198 (70%)**

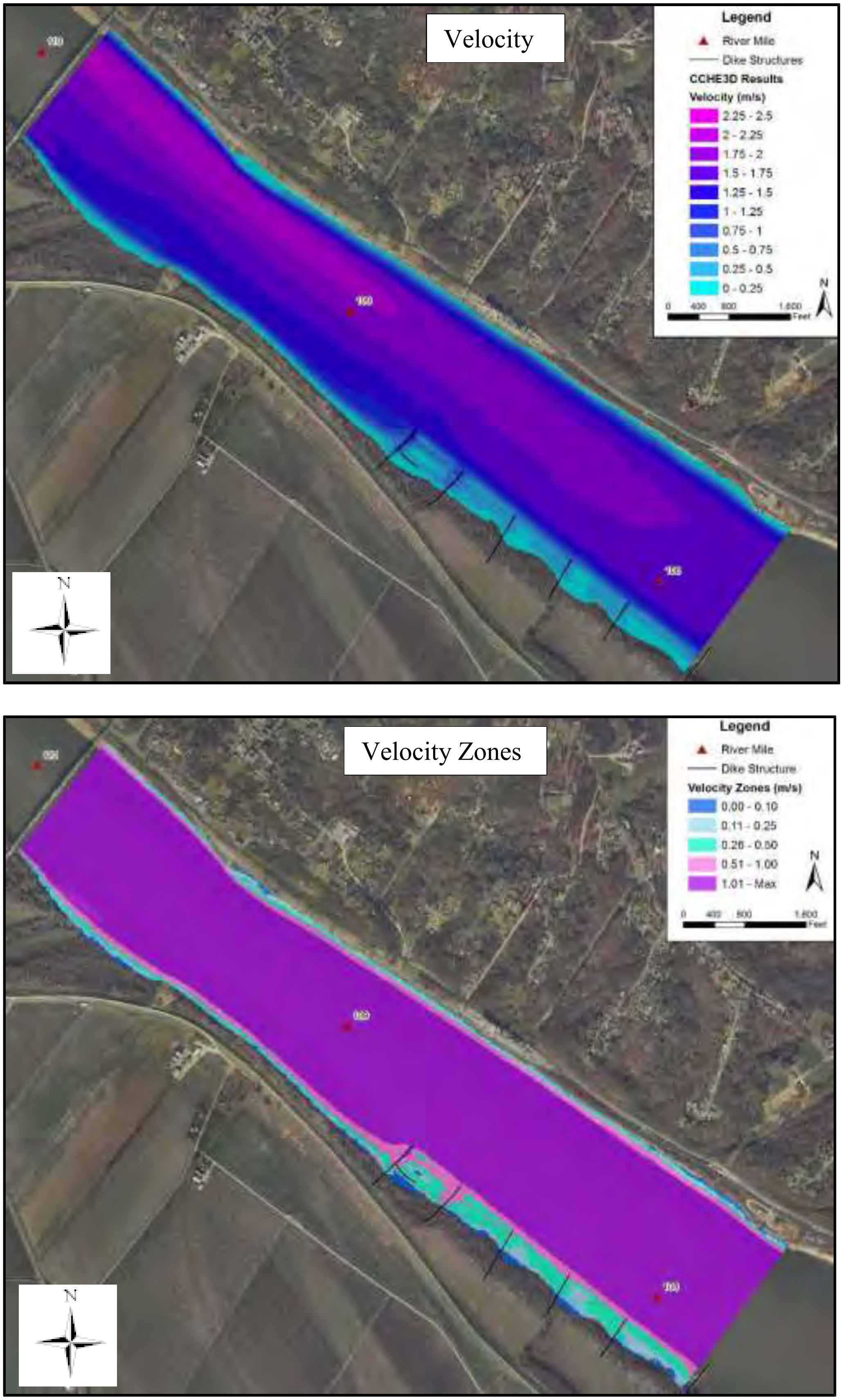
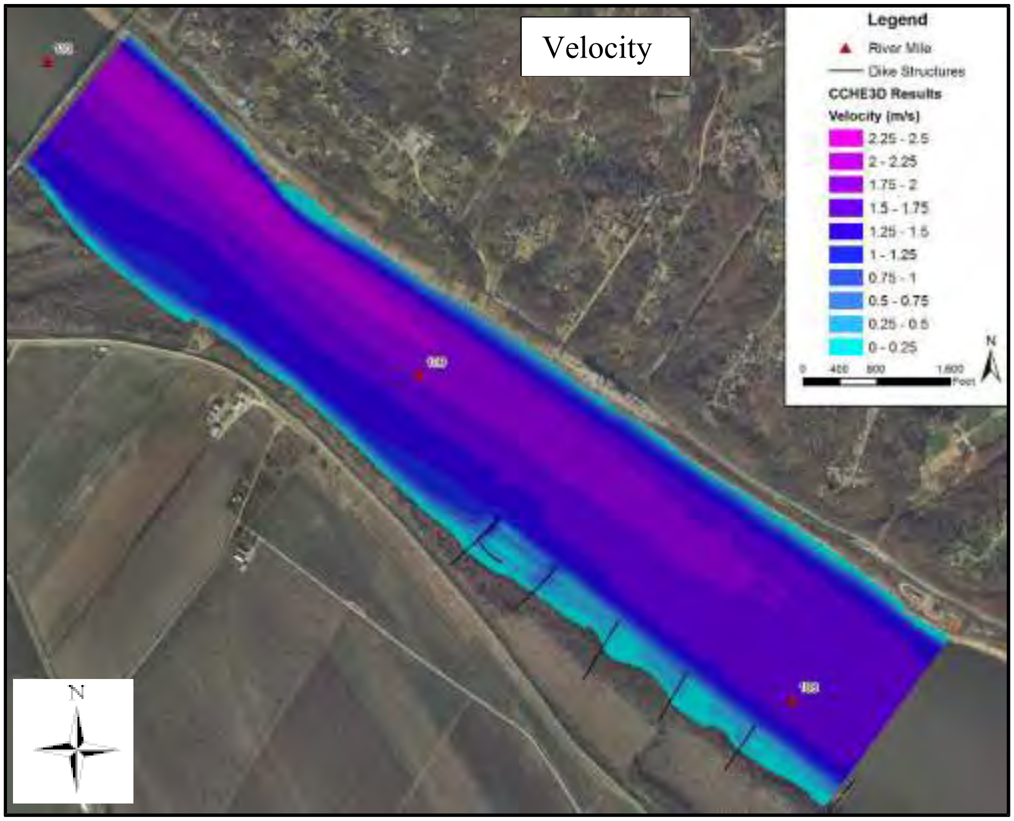


Figure 3-7. CCHE3D velocity results at water surface (flow of 8,580.0 m^3/s)



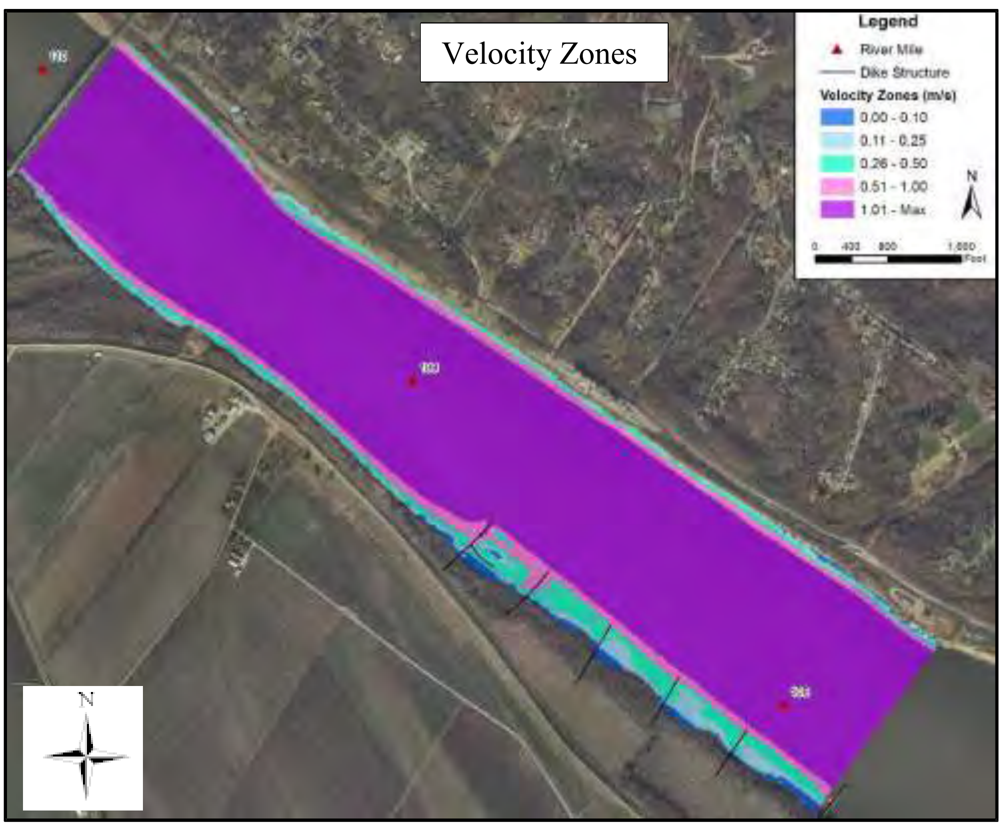


Figure 3-8. CCHE3D velocity results at a depth of 2 m below water surface (flow of 8,580.0 m^3/s)

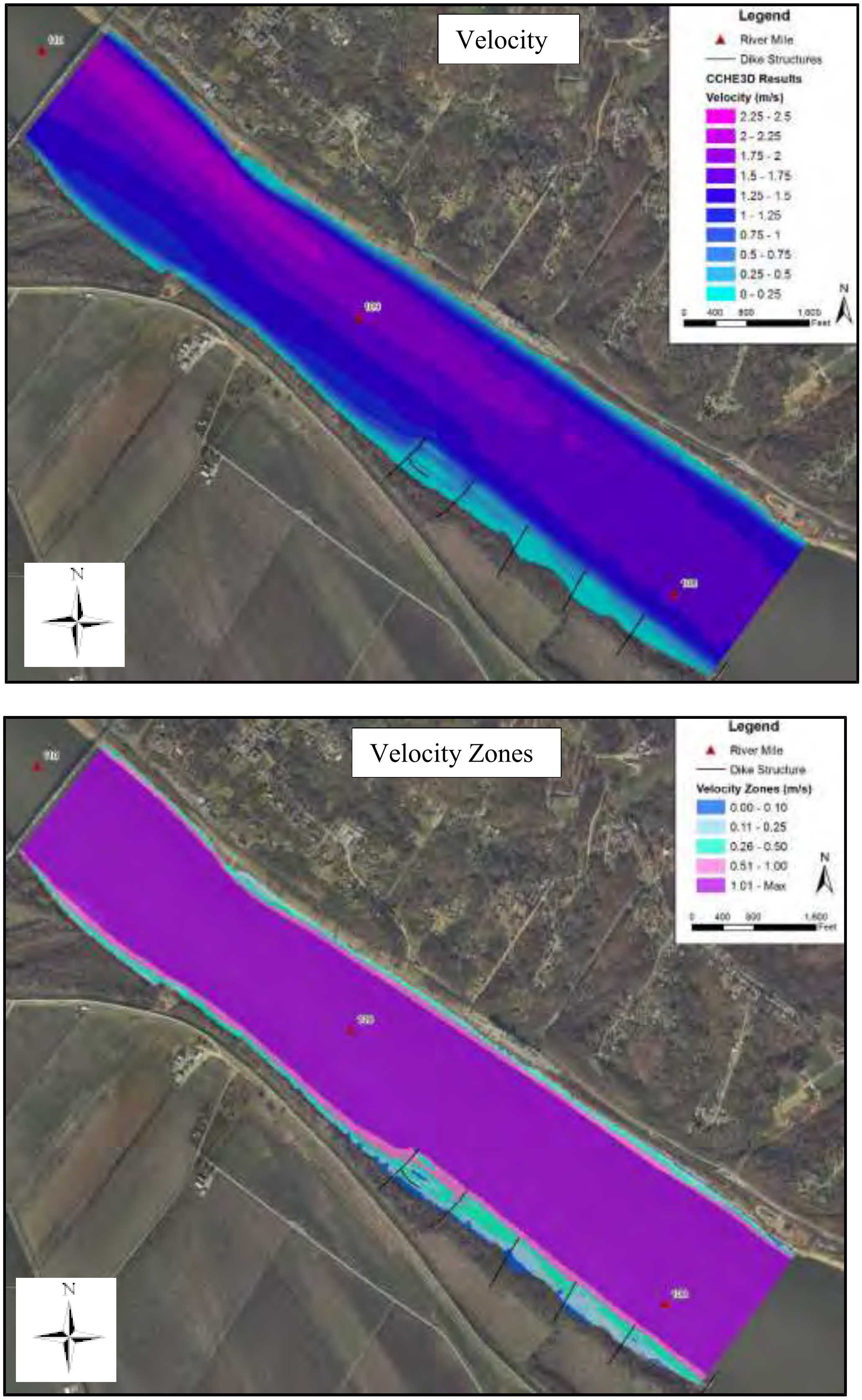
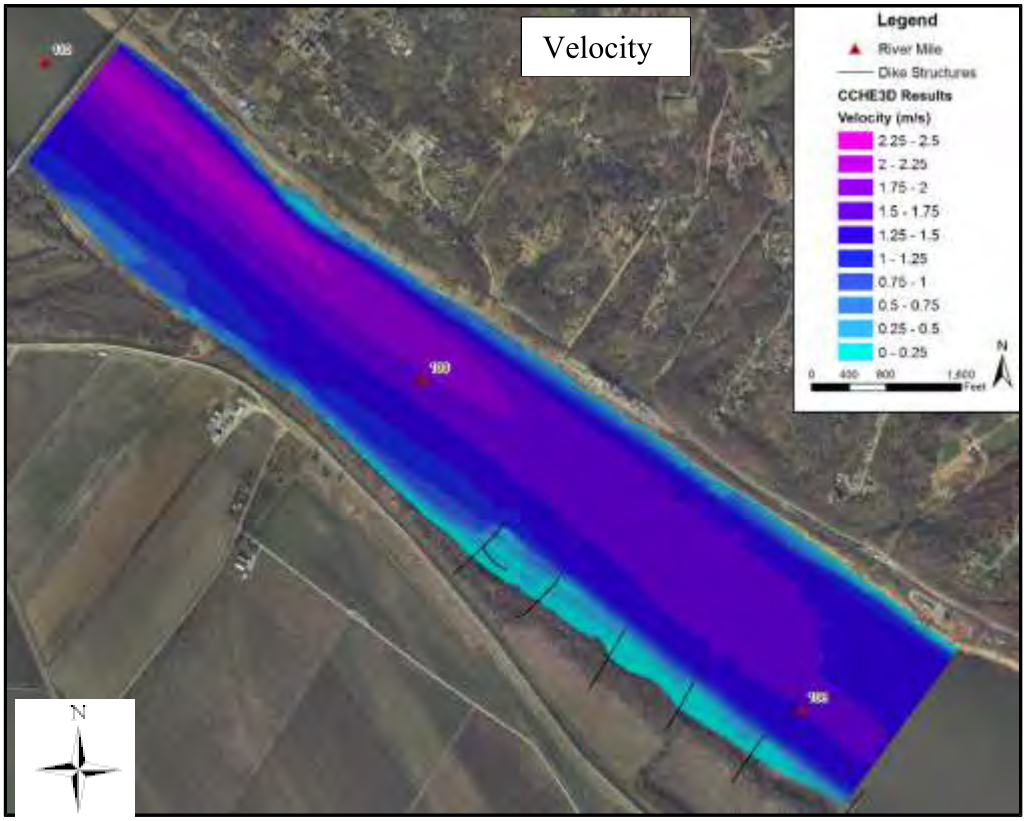


Figure 3-9. CCHE3D velocity results at a depth of 4 m below water surface (flow of 8,580.0 m^3/s)



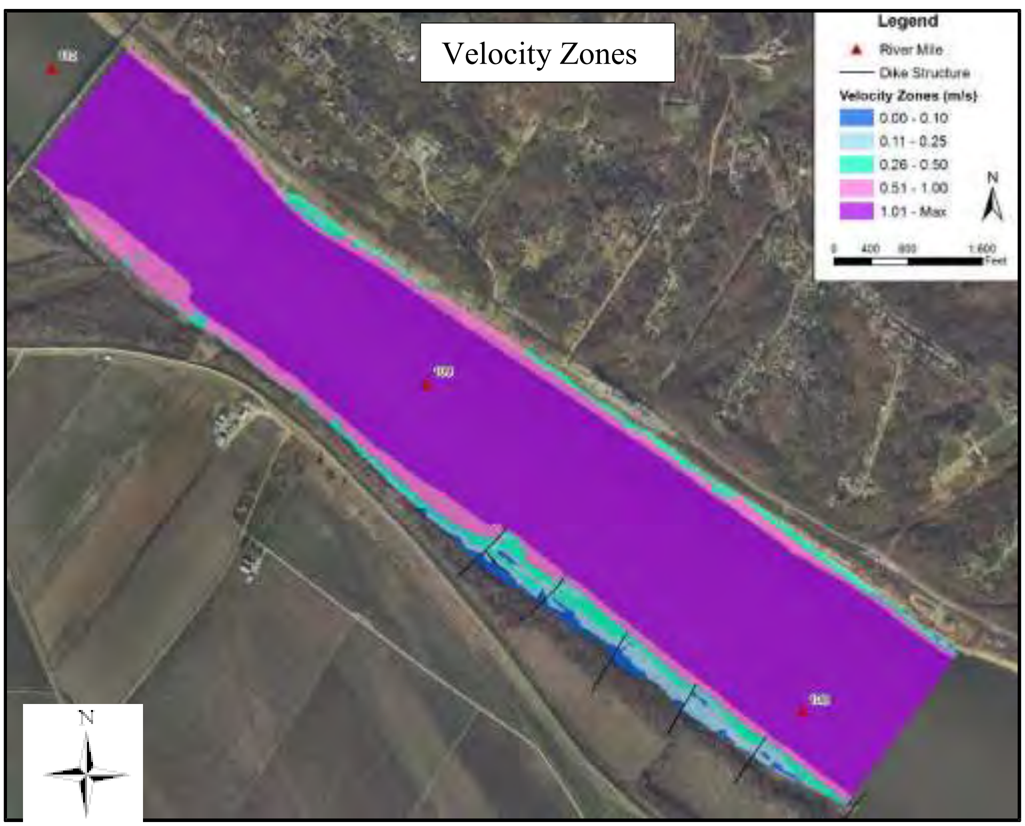


Figure 3-10. CCHE3D velocity results at a depth of 6 m below water surface (flow of 8,580.0 m^3/s)

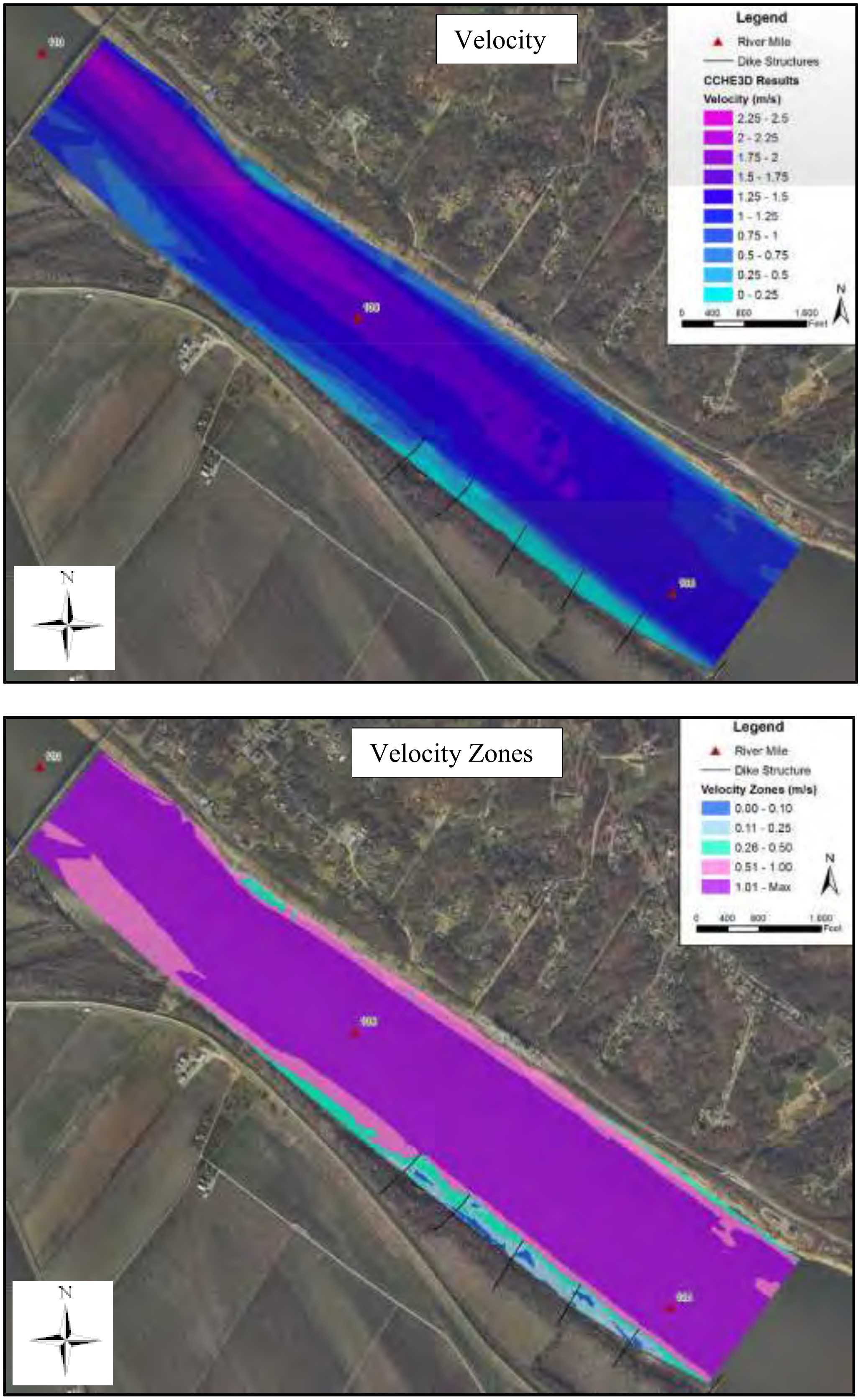


Figure 3-11. CCHE3D velocity results at a depth of 8 m below water surface (flow of 8,580.0 m^3/s)

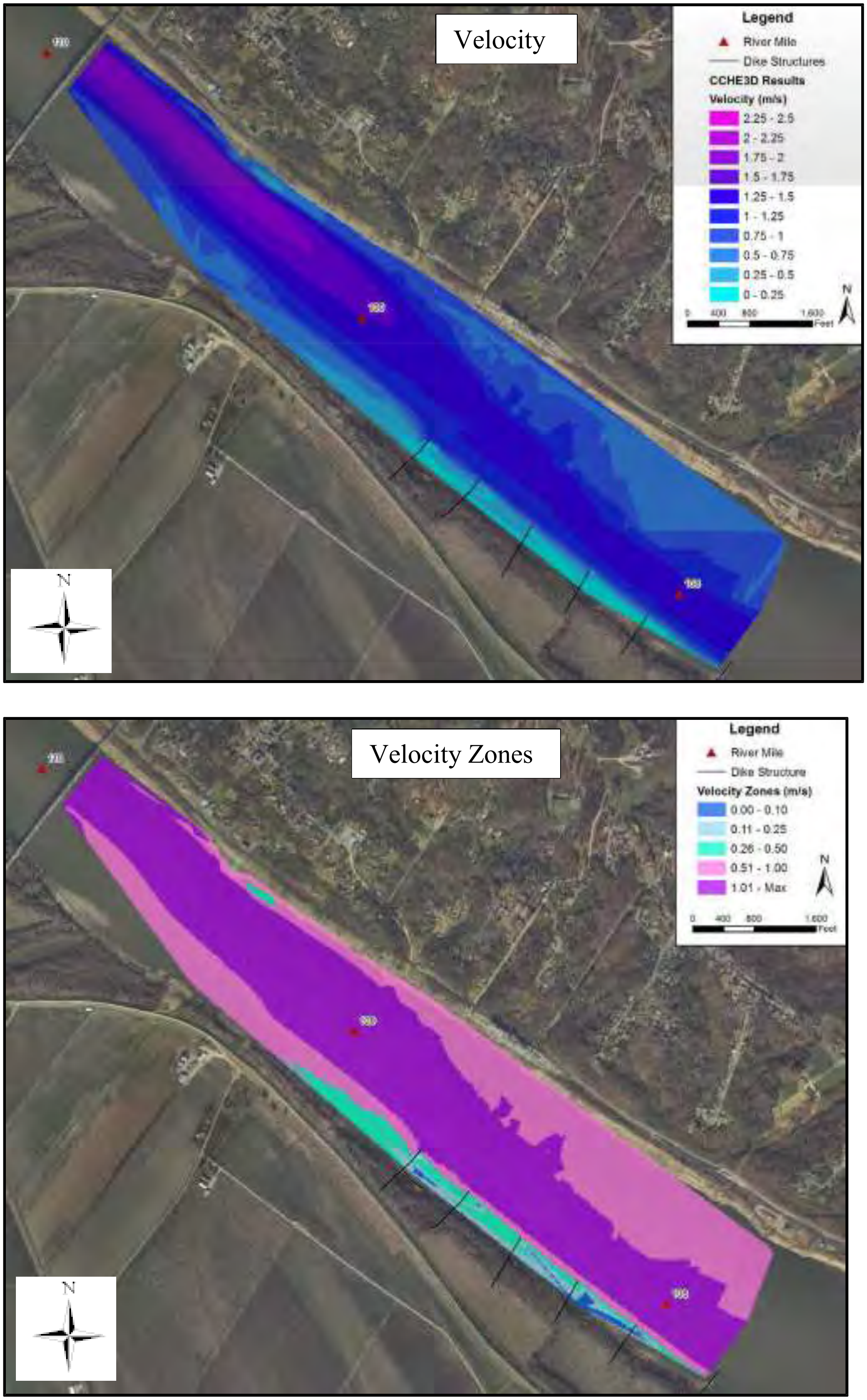


Figure 3-12. CCHE3D velocity results at a depth of 10 m below water surface (flow of 8,580.0 m^3/s)

4 Hydraulic Model of Study Reach

4.1 Introduction

A 3-D hydraulic model was developed for the reach of the Mississippi River between RM 92.0 at the downstream end to RM 110.0 at the upstream end (Figure 4-1) to quantify the volume of habitat available based on velocity within the reach. Information about the development of the 3-D hydraulic model of the study reach is provided in this section of the report.

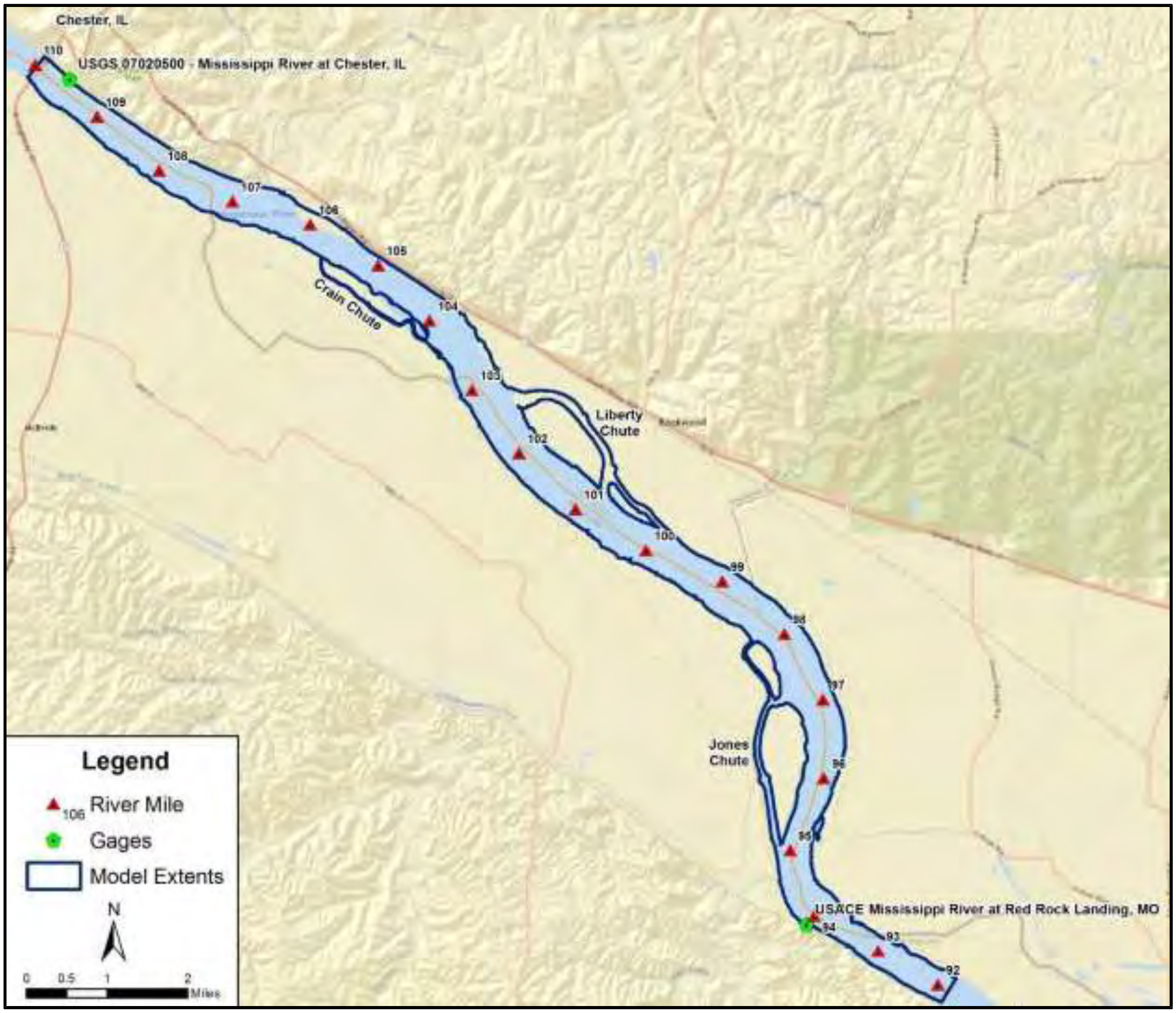


Figure 4-1. Map of study reach model extents

4.2 Description of Numerical Model

As in the local 3-D model, CCHE3D (NCCHE, 2013) was used to develop the 3-D hydraulic model of the study reach. Detailed information about the CCHE3D software is provided in Section 3.2 of this report.

4.2.1 Model Development

The CCHE3D for the study reach was developed using the same approach used in developing 3-D hydraulic model of the local reach discussed in Chapter 3 of this report. The study reach model extends from RM 92.0 at the downstream end to RM 110 at the upstream end, a total distance of 18.0 miles.

4.2.1.1 Mesh Development

The CCHE-MESH software was used to develop a 2-D mesh required for the CCHE3D model. ArcGIS was utilized to define the bed elevation, initial water surface elevation, and roughness characteristics for the 2-D mesh. The final mesh from the CCHE-MESH software is shown in Figure 4-2. The computational mesh extends from the Highway 51 Chester bridge near RM 110 to about 18 miles downstream. The computational mesh covers a total area of about 13 mi^2, and it is comprised of 1,463 x-direction nodes (j nodes in CCHE-MESH), 56 y-direction (i nodes in CCHE-MESH), and 11 vertical layers (k nodes) for a total of 901,208 nodes (81,928 nodes in each of the 2-D layers). The average dimension of 2-D grid elements located away from the river training structures is about 25 meters wide by 60 meters long, while near the river training structures they are about a 5 meter square. The average flow depth within the study reach is about 5.1 meters (maximum depth of 24.9 meters) for a discharge of 3,143.2 m^3/s, about 7.0 meters (maximum depth of 27.8 meters) for a discharge of 6,031.5 m^3/s, and about 8.2 meters (maximum depth of 29.8 meters) for the discharge of 8,580.0 m^3/s.

The elevation data for the mesh was based on the same DEM used for the local model. Information about the DEM and data used to develop it is presented in Section 3.2.1.1 of this report.

4.2.2 Model Boundary Conditions

The hydrodynamic calculation algorithms of CCHE3D require the following boundary and initial conditions: (1) upstream flow boundary condition, (2) downstream elevation boundary condition, and (3) initial water depths and flow velocities. The development of the boundary and initial conditions was accomplished as follows.

4.2.2.1 Boundary Conditions

The CCHE3D model requires information defined at the upstream and downstream boundaries (nodestrings) of the mesh. The upstream and downstream nodestring locations are shown in Figure 4-2. The boundary conditions considered for the study reach model are summarized in Table 4-1. A total discharge was defined at the upstream boundary, and a water surface elevation was defined at the downstream boundary.

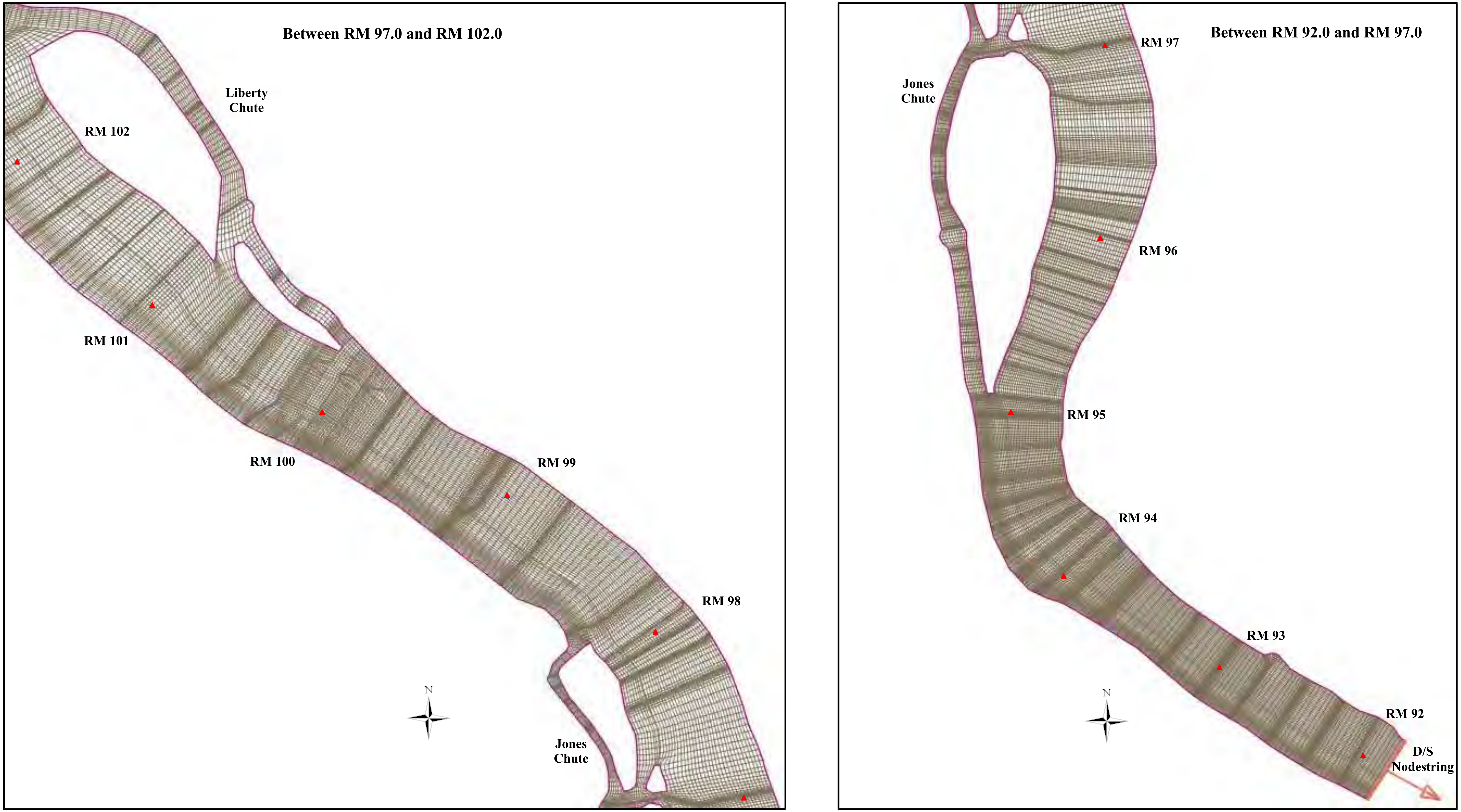


Figure 4-2. 2-D Computational mesh for study reach CCHE3D model

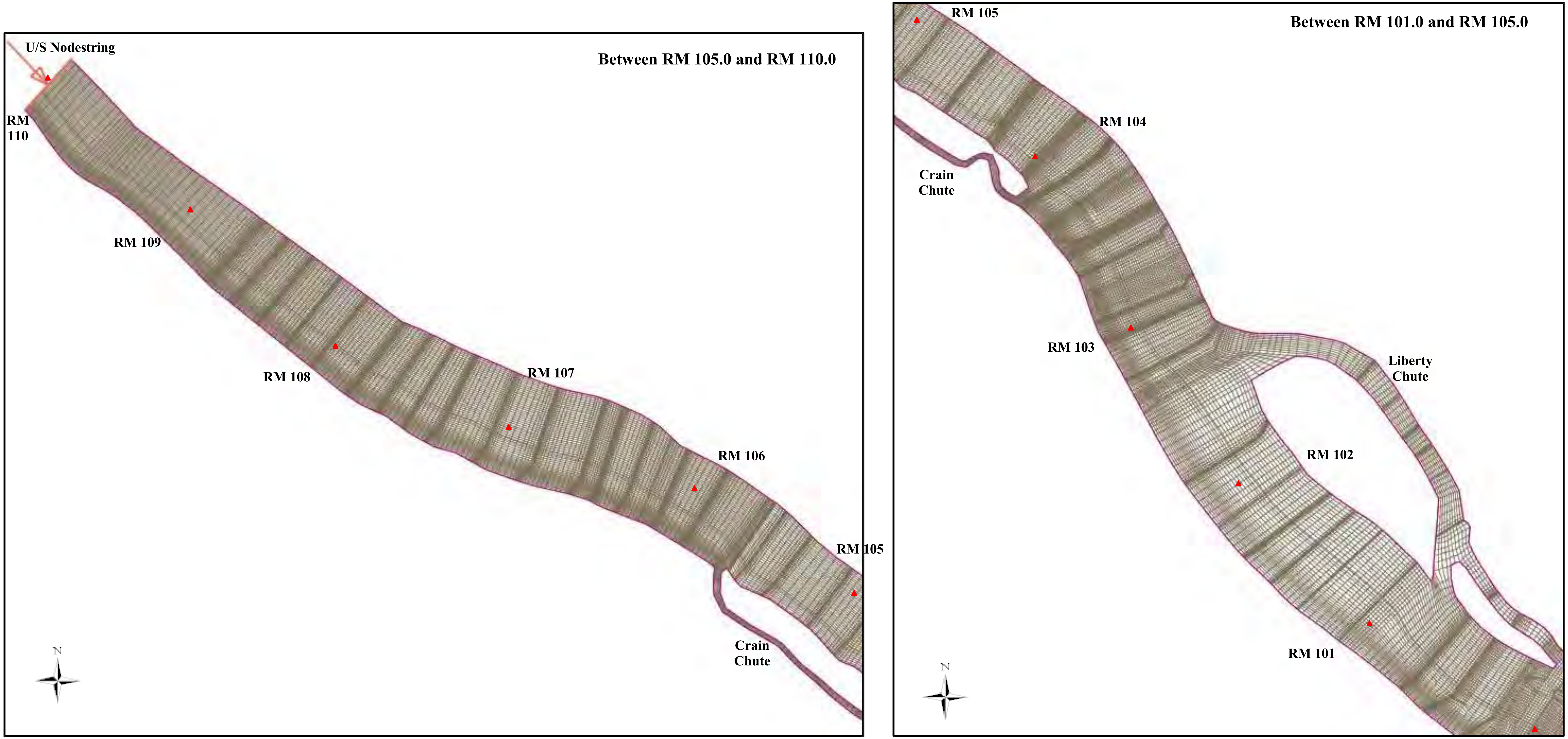


Figure 4-2. 2-D Computational mesh for study reach CCHE3D model

Table 4-1. Boundary Conditions

Flow Condition	U/S Nodestring Discharge		D/S Nodestring (Water Surface Elevation)	
	m^3/s	ft^3/s	m	ft
1	3,143.2	111,000	102.26	335.52
2	6,031.5	213,000	105.17	345.06
3	8,580.0	303,000	107.11	351.43

The water surface elevation at the downstream boundary was initially obtained from the calibrated HEC-RAS model mentioned in Section 3.2.4.1. During the calibration of the CCHE3D model, it became evident that the estimated water surface elevation from the HEC-RAS model needed to be lowered (CCHE3D model overpredicted the water surface elevations at the USACE Red Rock Landing Gage even with extremely low and unrealistic roughness heights). Therefore, the water surface elevation at the downstream boundary was lowered to improve the calibration of the CCHE3D model at the USACE Red Rock Landing Gage.

4.2.2.2 Initial Water Surface and Flow Velocities

CCHE3D requires that the initial water surface elevation and velocity be defined at all of the mesh nodes. This was accomplished using the same procedure used for the local model as discussed in Section 3.2.2.2 of this report.

4.2.3 Model Parameters

4.2.3.1 Hydraulic Roughness Heights

Eight material types were used to define the hydraulic roughness within the study reach. The material type boundaries were defined based on topography, aerial photography, and shapefiles of rock revetment and river training structures. The material types defined are shown in Figure 4-3 through Figure 4-5. Initially, the Manning's n values for each material were estimated using information documented in Chow's *Open-channel Hydraulics* (Chow, 1959) and the HEC-RAS User's Manual (USACE, 2011). CCHE3D model requires that the bed roughness be defined using the roughness height, ks, and not Manning's n-values. Per the CCHE3D User's Manual, the following equation (Strickler's Equation) was used to estimate the equivalent roughness height based on the estimated Manning's n values:

$$n = \frac{ks^{1/6}}{A}$$

Where,

ks = equivalent roughness height
n = manning's coefficient
A = empirical constant that is dependent on sediment size, bed form, vegetation and channel morphology. It can vary between 14 and 29. A value of 19, as recommended by NCCHE was used to estimate the equivalent roughness heights provided in Table 3-3. The adopted values shown in the table were based on the calibration of the CCHE3D model.

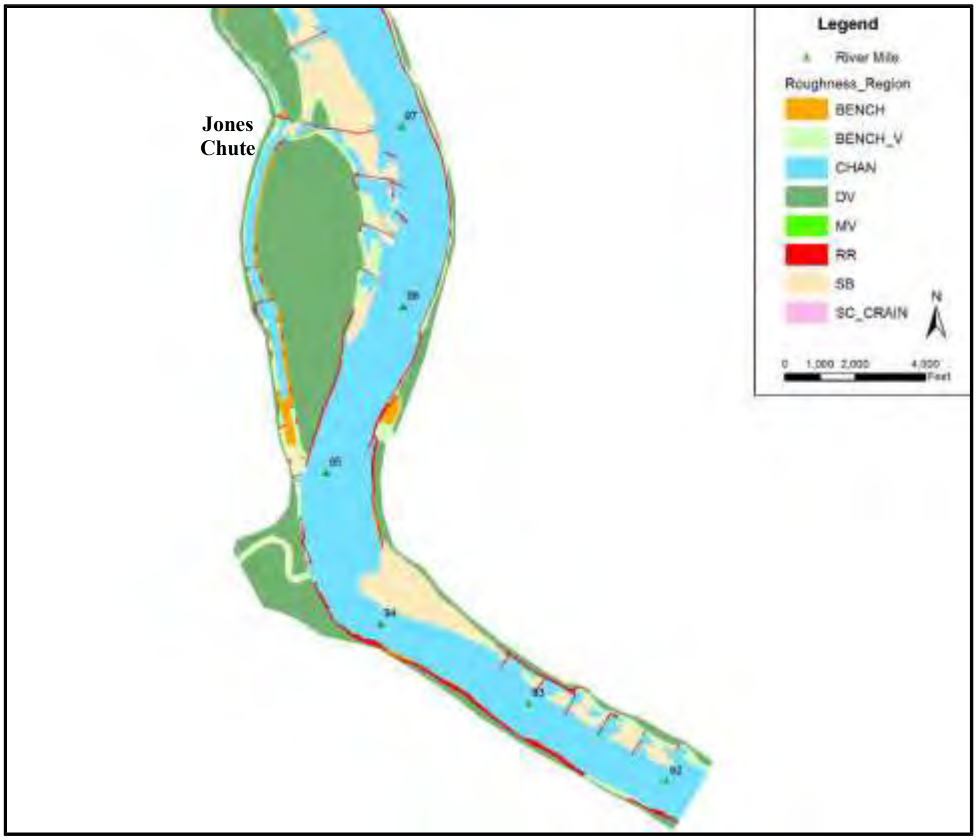


Figure 4-3. Mesh materials for reach between RM 92 and RM 97.5

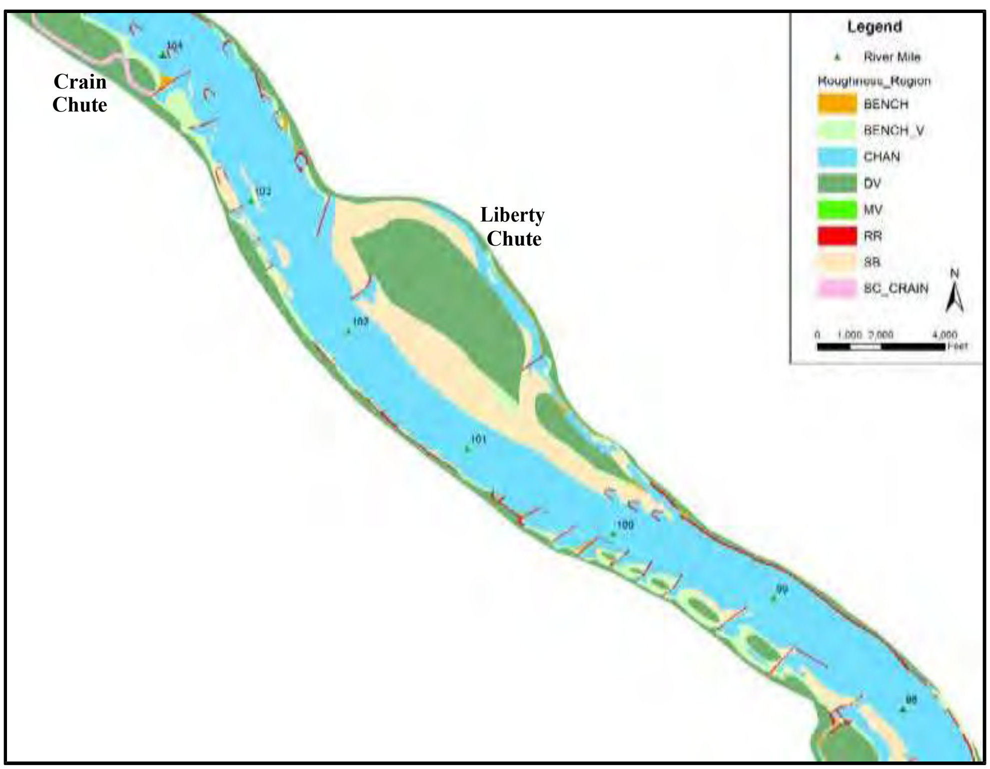


Figure 4-4. Mesh materials for reach between RM 97.5 and RM 104

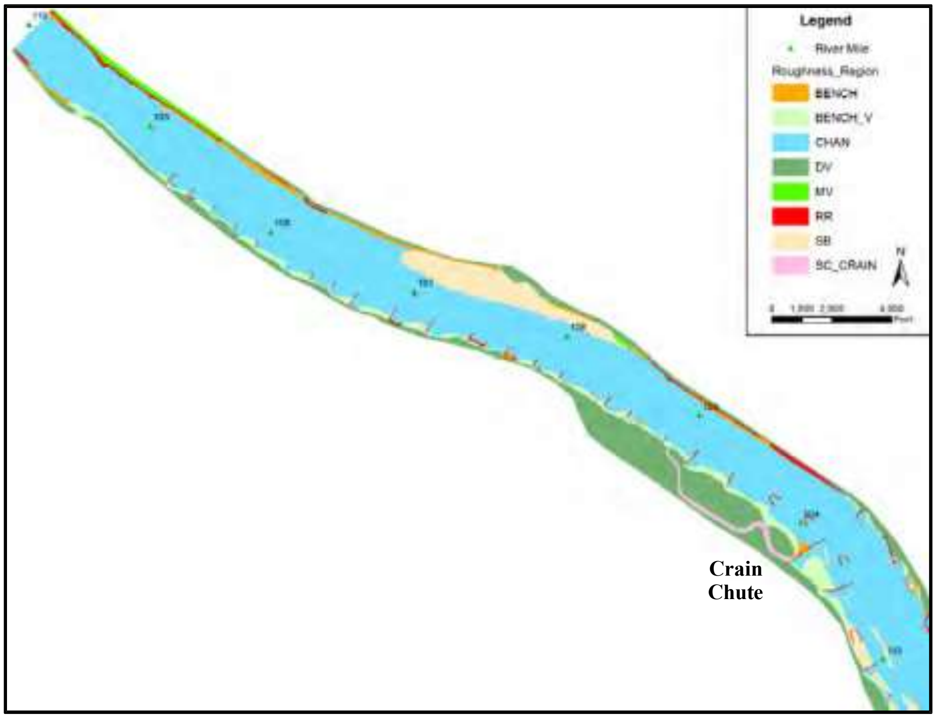


Figure 4-5. Mesh materials for reach between RM 103 and RM 110

Table 4-2. Roughness Heights for the CCHE3D Material Types

Material	Description	Adopted Roughness Height, ks (m) (Equivalent Manning's n Value)[1]		
		Discharge of 3,143.2 m^3/s	Discharge of 6,031.5 m^3/s	Discharge of 8,580.0 m^3/s
Bench	Bench area with sand, cobble, and boulders	0.297 (0.043)	0.224 (0.041)	0.193 (0.040)
Bench_V	Bench area with sand, cobble, and vegetation	1.984 (0.059)	1.451 (0.056)	1.302 (0.055)
Chan	Main channel	0.166 (0.039)[3]	0.102 (0.036)[3]	0.087 (0.035)[3]
DV[2]	Overbank area with dense vegetation	47.046 (0.100)	47.046 (0.100)	47.046 (0.100)
MV	Overbank area with moderately dense vegetation	1.302 (0.055)	0.930 (0.052)	0.735 (0.050)
RR	Riprap (D_{50} of 2 ft and D_{90} of 3.2 ft)	1.351 (0.055)	0.965 (0.052)	0.763 (0.050)
SB	Sand bar within or near main channel	0.061 (0.033)[3]	0.061 (0.033)[3]	0.051 (0.032)[3]
SC_Crain	Crain chute side channel	3.233 (0.064)	2.672 (0.062)	2.195 (0.060)

Note:

1. Equivalent Manning's n value based on an empirical constant (A) value of 19 in Strickler's equation presented in Section 4.2.3.1 on Page 4-5.
2. Majority of the DV material type is located outside of the inundation boundaries for the discharge of 303,000 cfs.
3. The main channel (Chan) was assumed to have a higher roughness height than for the sand bar areas within or near the main channel (SB) to account for bed forms (ripples and dunes) anticipated within the main channel.

4.2.3.2 Eddy Viscosity

Eddy Viscosity represents the turbulence generated in the spreading of momentum that is smaller than can be represented by the grid resolution. Per recommendations from NCCHE, the eddy viscosity is represented in the model using the Mixing Length option with a coefficient of 1.3 for a discharge of 3,143.2 m^3/s, 1.4 for a discharge of 6,031.5 m^3/s, and 1.2 for the discharge of 8,580.0 m^3/s.

As indicated in Section 3.2.3.2 of this report, a coefficient of 1.0 was used for the local model, which was analyzed only for a discharge of 8,580.0 m^3/s. A higher coefficient was necessary for the study reach model to adequately account for additional losses within the study reach and to obtain similar water surface elevation and velocity results for the calibrated events at the upstream measured locations as calculated by the local model.

4.2.3.3 Model Parameters

Additional model parameters defined in the CCHE3D models for the three flow conditions are summarized in Table 4-3.

Table 4-3. Model Parameters

Parameter	Value		
	Discharge of 3,143.2 m^3/s	**Discharge of 6,031.5 m^3/s**	**Discharge of 8,580.0 m^3/s**
Pressure	1st Order Non-hydrostatic	1st Order Non-hydrostatic	1st Order Non-hydrostatic
Time Step (s)	0.5	0.3	0.2
Total No. of Computational Time Steps	28,800	28,800	28,800
Wall Slippage Coefficient	1.2	1.2	1.2
Depth to Consider Dry	0.001	0.001	0.001
Time Iteration Method	Method 1	Method 1	Method 1

4.2.4 Model Calibration

The CCHE3D models were calibrated to observed conditions for the three in-channel flows of interest for this study using observed water surface elevations at the USGS Chester, IL and USACE's Red Rock Landing streamflow gages existing within the study reach, and observed flow velocities measured by the USGS using an ADCP device. The location of the ADCP measurements are shown in Figure 3-1 and a summary of the ADCP data is provided in Table 3-6. As previously discussed, the measurements consist of two transects that generally reflect each of the three in-channel flow conditions of interest for this study. The raw data files provided by MVS were converted to text files using WinRiverII developed by Teledyne RD Instruments. The text files were then imported into Excel for comparison to the calculated velocities from CCHE3D model.

Since CCHE3D requires that the initial water surface elevations and flow velocities be defined with a CCHE2D model, the CCHE2D model was calibrated by adjusting the roughness height so that the calculated average water surface elevation matches the observed water surface elevation at the USGS Chester, IL and USACE's Red Rock Landing gages. The calibrated roughness heights are provided in Table 3-3. The calibration efforts also included adjustment of pressure methodologies, eddy viscosity methods and coefficients, and the side wall boundary assumption to minimize the difference between the computed and observed velocity magnitude and direction.

Information related to the calibration model results is summarized in Table 4-4 thru Table 4-10. Table 4-4 provides a comparison of computed and observed water surface elevations at the two gage stations and the computed average cross sectional velocity values to the average cross sectional velocity values at the ADCP locations. As indicated in this table, the CCHE3D model does a good job at representing the average cross sectional velocity conditions.

Table 4-4. Summary of CCHE3D Calibration Results (Cross Sectional Basis)

Item	Observed	Computed	Delta	Percentage Difference
Discharge of 3,143.2 m^3/s				
WS at USGS Chester, IL Gage (m)	105.72	105.70	-0.02	-0.02%
WS at USACE Red Rock Landing Gage (m)	102.57	102.57	0.00	0.00%
Average Velocity (m/s)	0.93	0.91	-0.02	-2.1%
Average Velocity Direction (degrees)	132.0	132.1	0.1	0.1%
Discharge of 6,031.5 m^3/s				
WS at Gage (m)	108.35	108.32	-0.03	-0.03%
WS at USACE Red Rock Landing Gage (m)	105.60	105.53	-0.07	-0.07%
Average Velocity (m/s)	1.25	1.24	-0.01	-0.8%
Average Velocity Direction (degrees)	132.3	131.5	-0.8	-0.6%
Discharge of 8,580.0 m^3/s				
WS at Gage (m)	110.09	110.07	-0.02	-0.02%
WS at USACE Red Rock Landing Gage (m)	107.55	107.52	-0.03	-0.03%
Average Velocity (m/s)	1.48	1.50	0.02	1.4%
Average Velocity Direction (degrees)	127.9	131.3	3.4	2.7%

A comparison of the velocity magnitude and direction at each measured flow depth is provided in Table 4-5 and Table 4-6, respectively, for the in-channel discharge of 3,143.2 m^3/s, in Table 4-7 and Table 4-8, respectively, for the in-channel discharge of 6,031.5 m^3/s, and Table 4-9 and Table 4-10, respectively, for the in-channel discharge of 8,580.0. The tables include the average computed values, average measured values, delta between the values, percentage difference associated with the delta, absolute delta in the values, and the percentage difference associated with the absolute delta of the values. It should be noted that the percentage of change associated with minor changes in the velocities are larger compared to the changes in the velocity direction

Table 4-5. Summary of CCHE3D Calibration Results (Average Ensemble Velocity per Depth) for a Discharge of 3,143.2 m^3/s

Depth (m)	Observed Velocity (m/s)	Computed Velocity (m/s)	Delta(1)	Percentage Difference	Absolute Delta(1)	Percentage Difference for Absolute Delta
1.712	1.05	0.97	-0.08	-8.0	0.11	10.9
2.212	1.02	0.96	-0.06	-5.5	0.11	11.1
2.712	1.01	0.95	-0.06	-5.1	0.12	12.0
3.212	0.99	0.93	-0.06	-6.2	0.11	11.7
3.712	0.95	0.91	-0.04	-3.4	0.10	10.4
4.212	1.00	0.97	-0.04	-3.1	0.10	10.4
4.712	0.98	0.96	-0.02	-1.9	0.12	12.9
5.212	1.00	1.00	0.00	1.7	0.14	14.2
5.712	0.98	1.01	0.03	4.5	0.10	11.2
6.212	0.98	1.00	0.02	2.7	0.09	9.1
6.712	0.97	0.96	-0.01	0.8	0.10	9.7
7.212	0.85	0.87	0.03	5.7	0.16	18.3
Average			**-0.03**	**-1.5**	**0.11**	**11.8**

Notes:

1. The Delta provided in the table is based on the average delta values provided at each ensemble. It might not equate to the difference between the average computed and measured values in the table due to rounding errors.

Table 4-6. Summary of CCHE3D Calibration Results (Average Ensemble Velocity Direction per Depth) for a Discharge of 3,143.2 m^3/s

Depth (m)	Observed Velocity Direction (Degrees)	Computed Direction (Degrees)	Delta(1)	Percentage Difference	Absolute Delta(1)	Percentage Difference for Absolute Delta
1.712	131.5	132.0	0.5	0.3	3.9	2.2
2.212	131.6	132.0	0.4	0.2	3.9	2.2
2.712	130.8	132.0	1.2	0.7	4.2	2.3
3.212	131.0	132.0	1.0	0.6	4.8	2.7
3.712	130.8	132.0	1.2	0.7	4.4	2.5
4.212	129.2	131.9	2.7	1.5	6.5	3.6
4.712	129.4	132.0	2.6	1.4	6.3	3.5
5.212	129.8	132.0	2.2	1.2	6.9	3.8
5.712	131.1	132.8	1.7	1.0	8.7	4.9
6.212	133.9	133.3	-0.6	-0.3	9.7	5.4
6.712	132.5	134.1	1.5	0.8	7.7	4.3
7.212	131.5	134.8	3.3	1.8	8.6	4.8
Average			**1.5**	**0.8**	**6.3**	**3.5**

Notes:

1. The Delta provided in the table is based on the average delta values provided at each ensemble. It might not equate to the difference between the average computed and measured values in the table due to rounding errors.

Table 4-7. Summary of CCHE3D Calibration Results (Average Ensemble Velocity per Depth) for a Discharge of 6,031.5 m^3/s

Depth (m)	Observed Velocity (m/s)	Computed Velocity (m/s)	Delta[(1)]	Percentage Difference	Absolute Delta[(1)]	Percentage Difference for Absolute Delta
1.662	1.37	1.33	-0.05	-2.7	0.10	7.0
2.162	1.35	1.33	-0.03	-1.2	0.10	7.1
2.662	1.34	1.32	-0.01	-0.2	0.10	7.9
3.162	1.32	1.32	-0.01	0.1	0.10	7.8
3.662	1.34	1.30	-0.04	-2.0	0.11	8.2
4.162	1.30	1.29	-0.01	0.0	0.11	9.2
4.662	1.28	1.27	-0.01	0.4	0.10	8.1
5.162	1.25	1.25	0.00	1.8	0.09	8.5
5.662	1.25	1.25	0.00	1.3	0.09	7.3
6.162	1.24	1.24	0.00	1.2	0.10	8.5
6.662	1.27	1.27	-0.01	1.1	0.13	10.3
7.162	1.27	1.26	0.00	1.1	0.13	10.2
7.662	1.25	1.26	0.01	2.1	0.11	9.2
8.162	1.19	1.23	0.05	4.6	0.13	11.1
8.662	1.19	1.24	0.05	6.2	0.15	13.6
9.162	1.23	1.24	0.02	2.5	0.12	10.1
9.662	1.15	1.19	0.05	5.0	0.11	9.9
10.162	1.10	1.12	0.02	2.4	0.07	6.5
10.662	1.00	0.97	-0.03	-2.4	0.10	9.9
Average			**0.0**	**1.1**	**0.11**	**9.0**

Notes:

1. The Delta provided in the table is based on the average delta values provided at each ensemble. It might not equate to the difference between the average computed and measured values in the table due to rounding errors.

Table 4-8. Summary of CCHE3D Calibration Results (Average Ensemble Velocity Direction per Depth) for a Discharge of 6,031.5 m^3/s

Depth (m)	Observed Velocity Direction (Degrees)	Computed Direction (Degrees)	Delta[(1)]	Percentage Difference	Absolute Delta[(1)]	Percentage Difference for Absolute Delta
1.662	131.8	131.1	-0.7	-0.4	4.1	2.3
2.162	132.4	131.1	-1.3	-0.7	4.3	2.5
2.662	132.7	131.1	-1.5	-0.8	4.4	2.5
3.162	132.4	131.2	-1.2	-0.7	4.5	2.6
3.662	132.1	131.2	-0.9	-0.5	5.1	2.9
4.162	132.2	131.2	-0.9	-0.5	4.8	2.8
4.662	132.5	131.3	-1.2	-0.7	5.3	3.1
5.162	133.0	131.3	-1.7	-0.9	6.2	3.6
5.662	132.8	131.4	-1.4	-0.8	5.7	3.3
6.162	133.0	131.4	-1.6	-0.9	4.9	2.8
6.662	132.7	131.1	-1.6	-0.9	5.5	3.1
7.162	132.5	131.1	-1.4	-0.8	4.9	2.8
7.662	131.6	131.0	-0.7	-0.4	5.0	2.8
8.162	131.8	131.1	-0.7	-0.4	4.9	2.7
8.662	133.3	132.3	-1.0	-0.6	5.8	3.2
9.162	132.2	132.6	0.4	0.2	6.2	3.4
9.662	129.0	131.8	2.8	1.6	6.5	3.6
10.162	131.2	131.9	0.6	0.3	4.4	2.5
10.662	126.9	131.1	4.2	2.3	4.2	2.3
Average			**-0.5**	**-0.3**	**5.1**	**2.9**

Notes:

1. The Delta provided in the table above is based on the average delta values provided at each ensemble. It might not equate to the difference to the average computed and measured values in the table due to rounding errors.

Table 4-9. Summary of CCHE3D Calibration Results (Average Ensemble Velocity per Depth) for a Discharge of 8,580.0 m^3/s

Depth (m)	Observed Velocity (m/s)	Computed Velocity (m/s)	Delta[(1)]	Percentage Difference	Absolute Delta[(1)]	Percentage Difference for Absolute Delta
1.662	1.64	1.60	-0.04	-1.1	0.12	7.1
2.162	1.63	1.60	-0.03	-0.5	0.12	7.4
2.662	1.63	1.60	-0.02	0.0	0.13	8.1
3.162	1.61	1.60	-0.01	0.8	0.13	8.0
3.662	1.60	1.59	-0.01	0.9	0.11	7.3
4.162	1.59	1.58	-0.01	0.6	0.11	7.4
4.662	1.56	1.56	0.00	1.4	0.12	8.3
5.162	1.54	1.55	0.01	2.0	0.13	8.6
5.662	1.52	1.53	0.02	2.3	0.12	8.6
6.162	1.50	1.52	0.02	2.8	0.14	9.5
6.662	1.49	1.52	0.03	3.1	0.13	9.2
7.162	1.46	1.50	0.04	4.1	0.13	9.2
7.662	1.42	1.48	0.06	5.8	0.15	10.9
8.162	1.41	1.48	0.07	6.4	0.14	11.1
8.662	1.41	1.48	0.07	6.5	0.15	11.9
9.162	1.40	1.48	0.08	7.2	0.16	12.1
9.662	1.39	1.46	0.07	6.8	0.15	11.9
10.162	1.38	1.45	0.07	6.8	0.17	13.3
10.662	1.38	1.45	0.06	6.2	0.15	11.7
11.162	1.31	1.48	0.17	14.9	0.22	18.0
11.662	1.18	1.34	0.16	15.9	0.21	19.3
Average			**0.04**	**4.4**	**0.14**	**10.4**

Notes:

1. The Delta provided in the table above is based on the average delta values provided at each ensemble. It might not equate to the difference to the average computed and measured values in the table due to rounding errors.

Table 4-10. Summary of CCHE3D Calibration Results (Average Ensemble Velocity Direction per Depth) for a Discharge of 8,580.0 m^3/s

Depth (m)	Observed Velocity Direction (Degrees)	Computed Direction (Degrees)	Delta[(1)]	Percentage Difference	Absolute Delta[(1)]	Percentage Difference for Absolute Delta
1.662	129.3	130.7	1.4	0.8	2.9	1.7
2.162	128.7	130.7	2.0	1.1	3.3	1.8
2.662	129.0	130.7	1.7	0.9	3.5	2.0
3.162	128.8	130.7	2.0	1.1	3.6	2.1
3.662	128.5	130.8	2.3	1.3	3.9	2.3
4.162	128.0	130.8	2.8	1.5	3.9	2.2
4.662	127.8	130.9	3.0	1.7	4.1	2.4
5.162	127.3	130.9	3.6	2.0	4.6	2.7
5.662	127.9	130.9	3.1	1.7	4.7	2.7
6.162	127.3	130.9	3.7	2.0	5.1	2.9
6.662	127.0	131.1	4.0	2.2	5.3	3.1
7.162	127.2	131.1	3.8	2.1	5.3	3.1
7.662	127.0	131.1	4.1	2.3	5.9	3.4
8.162	126.9	130.9	4.0	2.2	5.6	3.2
8.662	127.0	130.7	3.8	2.1	6.3	3.6
9.162	126.9	130.5	3.6	2.0	6.6	3.6
9.662	127.3	130.5	3.3	1.8	7.1	4.0
10.162	127.4	131.3	3.9	2.2	6.6	3.6
10.662	128.7	131.3	2.6	1.5	6.2	3.4
11.162	126.3	130.7	4.4	2.4	8.0	4.5
11.662	120.9	131.5	10.5	5.8	11.8	6.5
Average			**3.5**	**1.9**	**5.5**	**3.1**

Notes:

1. The Delta provided in the table above is based on the average delta values provided at each ensemble. It might not equate to the difference to the average computed and measured values in the table due to rounding errors.

due to the difference in their relative magnitudes. A review of the results indicates that the CCHE3D does a fairly good job at matching observed conditions. The computed velocity is within ±12% of the observed value for the in-channel discharge of 3,143.2 m^3/s, ±9% of the observed value for the in-channel discharge of 6,031.5 m^3/s, and ±10% of the observed value for the in-channel discharge of 8,580.0 m^3/s. In general, the models for all flow conditions slightly underpredict the velocity in the upper water portion of the water column and overpredicts the velocity in the lower portion of the water column, with the difference increasing as the depth increases.

Potential causes of the differences between the computed and observed data are the same as those previously discussed for the local model: (1) changes in the bathymetry (See Figure 3-6), (2) uncertainty in ADCP observations (ratings indicate measurements are within ±5 to 8%), (3) difference in spatial locations (ADCP measurements are not at the exact same location as computational mesh nodes), and (4) the computational mesh doesn't capture the detailed bed irregularities within the reach.

4.2.5 Model Results

The tools and scripts, discussed in Chapter 2 of this report, were used to evaluate the aquatic habitat relative to velocity. The results of the evaluation are summarized in Table 4-11 for the in-channel discharge of 3,143.2 m^3/s, Table 4-12 for the in-channel discharge of 6,031.5 m^3/s, and Table 4-13 for the in-channel discharge of 8,580.0. Plots of velocity and reclassification of velocity generated from applying the tools are provided in Appendix B. A review of the results (Table 4-11 thru Table 4-13) and the figures in Appendix B indicate the following: (1) the majority of the flow within the study reach is within Zones 4 and 5; (2) the majority of the study reach is comprised of velocities greater than 1.0 m/s with the areas near banks, downstream of the river training structures, and within the side channels comprised of lower flow velocities; (3) the percentage of flow within Zones 4 and 5 increase with increasing discharge; and (4) the percentage within each zone becomes more uniform throughout the water column with increase in discharge, i.e., the higher velocity zone extends deeper as the discharge increases.

Table 4-11. Summary of Aquatic Habitat Evaluation of Local Model Reach (Flow of 3,143.2 m^3/s)

	Volume (m^3 per Depth) per Velocity Zone (m^3/s)				
	1	2	3	4	5
Depth (m)	0.0 – 0.10	0.11 – 0.25	0.26 – 0.50	0.51 – 1.0	1.01 – Max
0 – 1	1,309,515	582,138	858,388	3,822,365	8,863,675
1 – 2	873,475	456,913	722,288	3,682,915	8,442,900
2 – 3	567,888	350,188	583,950	3,457,940	7,889,550
3 – 4	452,525	267,588	448,700	3,213,875	7,172,350
4 – 5	341,100	192,800	339,963	2,978,865	6,191,740
5 – 6	240,313	134,425	255,788	2,839,980	4,824,830
6 – 7	166,188	92,125	192,750	2,624,055	3,153,465
7 – 8	105,063	64,288	151,363	1,958,215	1,624,038
8 – 9	58,438	41,113	97,838	1,032,463	713,888
9 – 10	29,188	21,300	47,550	436,888	318,925
10 – 11	13,625	9,750	19,000	200,675	130,350
11 – 12	5,738	3,713	9,088	92,488	58,138
12 – 13	3,325	1,388	4,838	47,013	34,975
13 – 14	1,813	900	2,988	28,363	23,000
14 – 15	663	800	2,025	17,313	15,150
15 – 16	288	538	1,238	11,688	9,063
16 – 17	138	313	1,025	9,200	4,888
17 – 18	88	238	825	7,450	2,550
18 – 19	100	225	563	6,100	775
19 – 20	75	88	350	3,788	38
20 – 21	25	50	238	2,113	0
21 – 22	13	63	238	1,475	0
22 – 23	25	75	188	625	0
23 – 24	13	50	75	113	0
Total (Percentage of Total)	**4,169,615 (5%)**	**2,221,063 (3%)**	**3,741,250 (4%)**	**26,475,960 (31%)**	**49,474,285 (57%)**

Table 4-12. Summary of Aquatic Habitat Evaluation of Local Model Reach (Flow of 6,031.5 m^3/s)

	Volume (m^3 per Depth) per Velocity Zone (m^3/s)				
	1	2	3	4	5
Depth (m)	0.0 - 0.10	0.11 - 0.25	0.26 - 0.50	0.51 - 1.0	1.01 - Max
0 – 1	615,788	1,080,440	1,690,115	2,961,180	12,074,300
1 – 2	514,988	976,125	1,548,215	2,820,180	11,860,000
2 – 3	434,250	843,288	1,336,830	2,588,355	11,569,450
3 – 4	356,463	679,150	990,078	2,227,765	11,194,800
4 – 5	263,125	514,338	620,563	1,848,000	10,734,150
5 – 6	198,100	389,825	403,488	1,591,275	10,049,740
6 – 7	160,575	296,363	291,225	1,383,240	9,063,465
7 – 8	120,725	213,075	212,363	1,150,815	7,880,800
8 – 9	90,263	144,950	159,950	970,400	6,388,625
9 – 10	68,075	97,975	114,525	936,538	4,360,965
10 – 11	45,263	64,025	77,825	725,325	2,339,015
11 – 12	25,000	37,213	45,825	356,913	1,079,063
12 – 13	12,813	17,800	22,413	154,538	499,563
13 – 14	6,400	7,575	9,975	71,800	228,575
14 – 15	3,213	3,288	4,763	32,775	109,800
15 – 16	1,738	1,675	2,575	13,938	67,038
16 – 17	800	1,050	1,650	9,088	43,163
17 – 18	463	750	1,075	5,925	27,688
18 – 19	288	525	725	3,688	18,300
19 – 20	188	450	313	2,725	12,413
20 – 21	175	213	275	2,100	8,588
21 – 22	125	125	338	1,863	5,425
22 – 23	38	113	200	1,238	2,838
23 – 24	25	50	88	775	1,475
24 – 25	50	13	50	863	763
25 – 26	25	13	50	538	188
26 – 27	0	13	63	125	0
Total (Percentage of Total)	**2,567,888 (2%)**	**4,830,238 (4%)**	**6,688,998 (6%)**	**18,924,520 (15%)**	**99,273,165 (73%)**

Table 4-13. Summary of Aquatic Habitat Evaluation of Local Model Reach (Flow of 8,580.0 m³/s)

Depth (m)	Volume (m³ per Depth) per Velocity Zone (m³/s)				
	1	2	3	4	5
	0.0 - 0.10	0.11 - 0.25	0.26 - 0.50	0.51 - 1.0	1.01 - Max
0 – 1	208,775	539,950	1,454,680	3,851,950	13,789,200
1 – 2	166,825	452,175	1,332,780	3,699,625	13,609,300
2 – 3	144,638	415,338	1,231,580	3,479,840	13,330,750
3 – 4	128,475	390,438	1,136,840	3,189,990	12,965,650
4 – 5	110,538	352,438	1,023,625	2,771,065	12,528,750
5 – 6	95,938	312,175	836,875	2,150,915	11,982,300
6 – 7	71,213	252,538	607,375	1,568,115	11,371,050
7 – 8	48,063	204,850	459,525	1,177,540	10,613,350
8 – 9	41,763	176,538	351,013	882,300	9,550,940
9 – 10	37,400	138,988	246,650	696,900	8,225,705
10 – 11	35,613	105,750	175,638	579,113	6,588,605
11 – 12	31,313	76,525	126,913	539,400	4,467,840
12 – 13	24,138	50,238	85,650	413,188	2,392,575
13 – 14	14,963	28,725	46,838	207,888	1,108,725
14 – 15	6,950	13,963	21,675	96,413	516,688
15 – 16	3,225	6,838	10,725	48,813	238,175
16 – 17	1,588	3,625	5,600	23,688	113,225
17 – 18	775	1,863	3,050	9,275	69,675
18 – 19	425	1,300	1,788	5,975	46,100
19 – 20	375	738	1,125	4,075	29,763
20 – 21	363	438	725	2,513	19,663
21 – 22	238	413	425	1,475	13,700
22 – 23	163	250	275	1,263	9,625
23 – 24	88	163	250	1,150	6,375
24 – 25	0	113	175	563	3,675
25 – 26	13	63	63	238	2,075
26 – 27	25	38	50	250	1,388
27 – 28	13	13	50	250	513
28 – 29	13	13	25	150	13
Total (Percentage of Total)	**1,173,900 (1%)**	**3,526,488 (2%)**	**9,161,980 (5%)**	**25,403,915 (15%)**	**133,595,390 (77%)**

5 Summary

The St. Louis District (MVS) is in the process of preparing a supplemental environmental impact statement (SEIS) on the Regulating Works Project on the Middle Mississippi River (MMR), which is defined as the reach of the Mississippi River between its confluences with the Missouri and Ohio Rivers. A quantification of aquatic habitat based on velocity characteristics is necessary to understand what currently exists and to forecast what changes will occur through the implementation of the proposed alternatives.

In support of the SEIS, WEST was contracted by MVS to develop a 3-D hydraulic model of the MMR between RM 92.0 and RM 109.9; run the model for three in-channel discharges; and evaluate the model results to quantify the volume of habitat available based on velocity. A map of the study reach is provided in Figure 1-1. An aerial photo of the study reach is provided in Figure 1-2 through Figure 1-5.

Tools and scripts were developed as part of this study to assist in the quantification of habitat volume from the 3-D hydraulic model results. Detailed information about the tools and scripts is provided in Chapter 2 of this report, and the User's Manual for the tools and scripts is included in Appendix A.

As part of the study, a CCHE3D hydraulic model was developed for a short reach near the upstream end of the study reach to obtain a more refined understanding of the computational requirements for the entire 18 mile study reach and for applying post-processing tools and scripts developed as part of the study. The extents of the local model are shown in Figure 3-1. The local model was used to compute the hydrodynamics for the largest of the three in-channel flows of interest for this study. Detailed information about CCHE3D and development of the local 3-D hydraulic model are provided in Chapter 3 of this report.

A CCHE3D hydraulic model was also developed for the reach of the Mississippi River between RM 92.0 at the downstream end to RM 110.0 at the upstream end (Figure 4-1). The study reach model was used to compute the hydrodynamics for the three in-channel flows of interest for this study. The models were calibrated using observed water surface elevations at USGS Chester, IL and USACE's Red Rock Landing streamflow gages existing within the study reach, and observed flow velocities measured by the USGS using an ADCP device. The location of the ADCP measurements are shown in Figure 3-1, and a summary of the ADCP data is provided in Table 3-6. Information related to the calibration model results are provided in Table 4-4 thru Table 4-10. The CCHE3D model does a good job at representing the average cross sectional conditions and matching the observed velocities. In terms of the velocity, the models slightly underpredicts the velocity in the upper portion of the water column and overpredicts the velocity in the lower portion of the water column, with the difference increasing as the depth increases. More information about the development of the study reach CCHED3D model is provided in Chapter 4 of this report.

The aquatic habitat associated with flow velocity within the study reach is summarized in Table 4-11 for the in-channel discharge of 3,143.2 m^3/s, Table 4-12 for the in-channel discharge of 6,031.5 m^3/s, and Table 4-13 for the in-channel discharge of 8,580.0. Plots of velocity and reclassification of velocity for the study reach are provided in Appendix B. A review of the results (Table 4-11 thru Table 4-13) and the figures in Appendix B indicate the following: (1) the majority of the flow within the study reach is within Zones 4 and 5; (2) the majority of the study reach is comprised of velocities greater than 1.0 m/s with the areas near banks, downstream of the river training structures, and within the side channels comprised of lower flow velocities; (3) the percentage of flow within Zones 4 and 5 increase with increasing discharge; and (4) the percentage within each zone becomes more uniform throughout the water column with increase in discharge, i.e., the higher velocity zone extends deeper as the discharge increases.

The CCHE3D model was run on a 64-bit Dell laptop with a 2.7 GHz Intel Core processor and 8.00 GB of RAM. The model run time for the study reach model (18 miles with 901,208 nodes) ranged from about 51 hours for the in-channel discharge of 3,143.2 m^3/s, about 64 hours for the in-channel discharge of 6,031.5 m^3/s, and 84 hours for the in-channel discharge of 8,580.0 m^3/s.

The CCHE3D was developed utilizing the best available data within the study reach. The uncertainty in the model results could be reduced with the following improvements: (1) further calibration of the model using highwater marks and ADCP measurements obtained at various locations within the study reach; (2) make additional refinement to computational mesh; and (3) utilize a comprehensive bathymetric data set obtained during a period where fish migration is important.

6 References

Chow, V.T., 1959. *Open-Channel Hydraulics*.

National Center for Computational Hydroscience and Engineering (NCCHE), School of Engineering, The University of Mississippi, 2013 (January), *CCHE-GUI – Graphical Users Interface forCCHE Models User's Manual – Version 4.0*.

National Center for Computational Hydroscience and Engineering (NCCHE), School of Engineering, The University of Mississippi, 2013 (January), *CCHE-GUI – Graphical Users Interface for NCCHE Models Quick Start Guide – Version 4.x*.

National Center for Computational Hydroscience and Engineering (NCCHE), School of Engineering, The University of Mississippi, 2013 (January), *CCHE-MESH: 2D Mesh Generator for Structured and Unstructured Meshes, User's Manual, Version 4.0*.

National Center for Computational Hydroscience and Engineering (NCCHE), School of Engineering, The University of Mississippi, 2013 (January), *CCHE-MESH: 2D Mesh Generator for Structured and Unstructured Meshes, Quick Start Guide, Version 4.0*.

National Center for Computational Hydroscience and Engineering (NCCHE), School of Engineering, The University of Mississippi, 2013 (January), *Technical Manual of CCHE3D, Version 1.1*.

Teledyn RD Instruments, 2014 (April). *WinRiverII, Software User's Guide*.

USACE, 1990 (January). *Engineering Manual (EM) 1110-2-1601, Hydraulic Design of Flood Control Channels*.

USACE, 2010 (January). *HEC-RAS River Analysis System User's Manual, Version 4.1*, Hydrologic Engineering Center, Davis, CA.

USACE, St. Louis District. Stone Gradations for Rock Structures.

USACE, St. Louis District. LiDAR and hydrographic survey data furnished by MVS.

Appendix A

User's Guide for the Scripts and Tools Developed for this Study

This Appendix is a User's Guide for the four tools developed as part of this study for quantification of habitat volume. This guide provides information about each tool, including the type, purpose, required input files, and output files generated, and a step-by-step approach for applying each tool. The tools are presented in the order of execution.

1. CCHE3D_Output_TxtFile_Creation.xlsm

1.1 Type

Visual Basic (VBA) program in Excel

1.2 Purpose

Converts the CCHE3D model results to x-direction (x), y-direction (y), and velocity (v) ASCII files for 1 meter depth increments from the water surface to within about 1 meter of the existing bed elevation (Note: The elevation of each depth layers varies due to the variation in the water surface elevation within the reach of interest).

1.3 Required Input Files

This tool needs the following files from a CCHE3D model simulation:

(1) *.geo file, which contains information related to the computational mesh
(2) *.fuz, which contains information related to each of the vertical planes considered in the CCHE3D simulation
(3) *.flw, which contains the model results from the 2-D simulation
(4) *.flw3D, which contains the CCHE3D model results

1.4 Optional Input Data

This tool includes the option to write the GMS files (CCHE3D.3dm and Vel_Results.dat) between an upstream and downstream RM defined by the user.

1.5 Output Files

This tool creates individual x, y, v ASCII files for 1 meter depth increments from the water surface to within about 1 meter of the existing bed elevation. The tool will create ASCII files will the name of "Depth_#" where the # represents the depth below the water surface elevation.

Three additional ASCII files will also be created:

(i) CCHE3D.3dm is a 3D mesh file that represents the computation mesh. It consists of a title line of "MESH3D" followed by records to describe the all of the elements in a consecutive order by ID, followed by all of the nodes, also in consecutive order. The elements are described with an "E8H" record that includes the element ID, nodal connectivity ID, and material ID. The nodal connectivity ID involves eight nodes defining the element with the first four nodes defining the base of the element in a counterclockwise direction followed by second four nodes defining the top of the element also in a counterclockwise direction starting in the same corner as the base. The material ID can used to define different regions of the computation mesh. A material ID was set to 1 for all elements. The nodes are described with an "ND" record that includes the node ID, and x-, y-, z-coordinate location. This file can be imported into Aquaveo's Goundwater Modeling Software (GMS).

(ii) Vel_Results.dat is a dataset file of the flow velocity at each of the computational mesh nodes in a format that can be imported into Aquaveo's GMS. It includes information about the total number of nodes and elements, type of data (scalar or vector), name of the dataset, and then the values are listed for each node on separate lines.

(iii) WS_VolCal.txt is an ASCII file that contains the CCHE3D water surface elevation results (x, y, and wsel).

The output files from this tool are written to the same directory as the Excel file, and the x- and y- coordinate location in the ASCII files are based on a horizontal datum of NAD83 UTM Zone 16 (metric) with the z value based on a vertical datum of NAVD88.

1.6 Steps for Applying the Tool

The steps for applying the tool are as follows:

(1) Open the Excel file (CCHE3D_Output_TxtFile_Creation.xlsm) and enable the macro by clicking the button near the top of the spreadsheet. Spreadsheet should open up to the Input worksheet. (Figure 1).

(2) Click the "Clear All" macro button.

(3) Enter the directory of where the CCHE3D files exist and filenames for the *.geo, *.fuz, *.flw, and*.flw3d CCHE3D files.

(4) OPTIONAL: To generate the GMS file for a localized reach, enter the upstream and downstream RM of the localized reach. Warning messages will show up if: (a) user defined River Miles (either U/S or D/S) are greater than the upstream RM of the model (RM 110) or less than the downstream RM of the model (RM 91.8), or (b) user defined downstream RM is greater than the user defined upstream RM.

(5) Click the "Preprocessing" macro button. The status bar on the lower left side below the worksheet tabs show the status of the processing.

(6) Click the "Output Extract and TXT File Creation" macro button.

(7) Save and exit the Excel file.

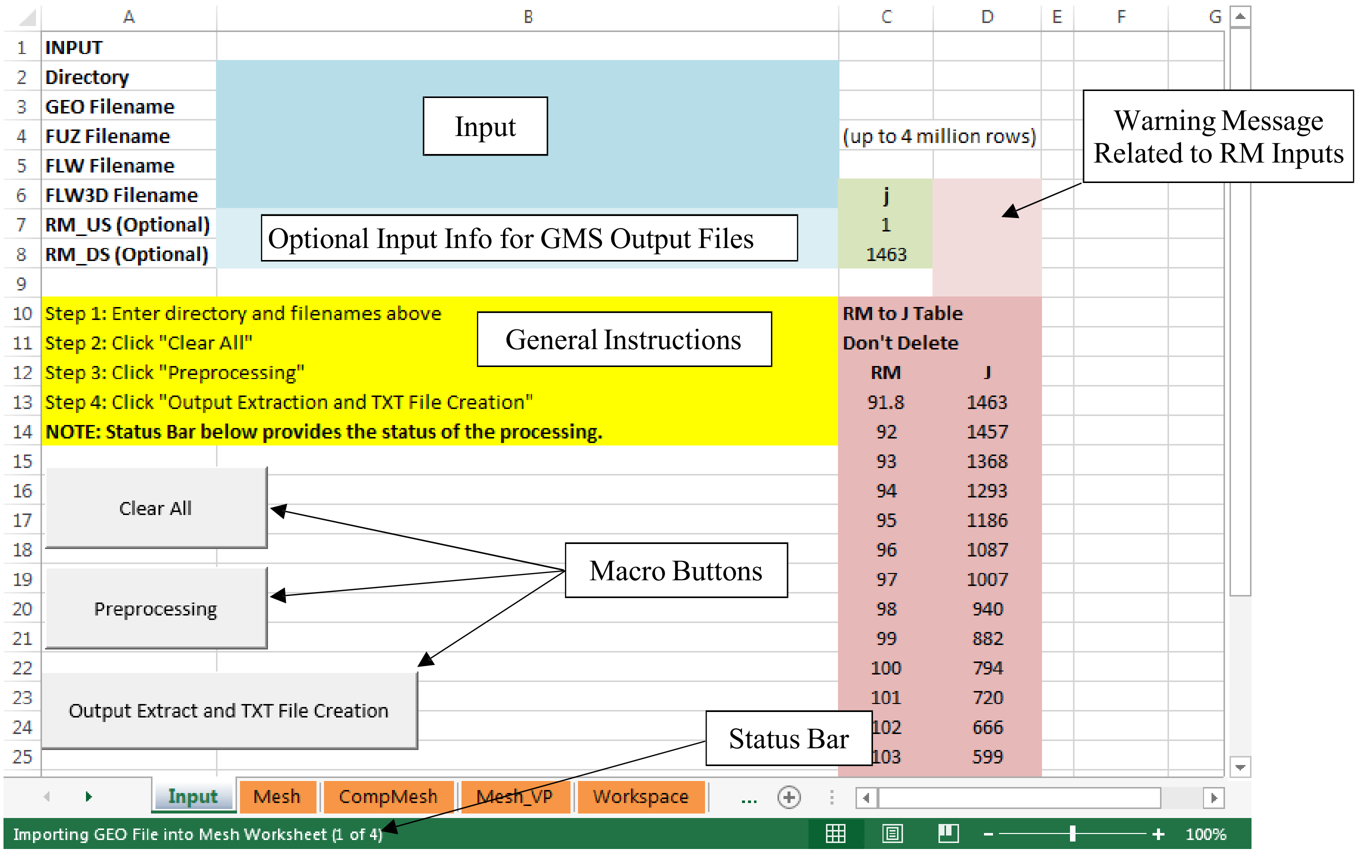


Figure 1. Input Worksheet for Tool No. 1 (CCHE3D_TxtFile_Creation.xlsm)

2. Middle Mississippi River Aquatic Evaluation.tbx (Create Output Workspace)

2.1 Type

ArcGIS Version 10.1 Toolbox function

2.2 Purpose

Creates workspace directories for Tool No. 3 (Classify Velocity Range and Calculate Area).

2.3 Required Input Files

None.

2.4 Output Files

This tool generates the following subdirectories under the defined output directory:

(i) \Rasters
(ii) \Rasters\StatePlane
(iii) \Rasters\ Reclass_Rasters
(iv) \Rasters\Reclass_Rasters\StatePlane
(v) \Shapefiles
(vi) \TIN

The default directory is C:\MVS\MMR\Velocity. The tool can be edited in ArcGIS if a different default directory is desired. The tool needs to be run only once prior to running Tool No. 3 (Classify Velocity Range and Calculate Area).

2.5 Steps for Applying the Tool

The steps for applying the tool are as follows:

(1) Open up ArcToolbox.

(2) Add the Middle Mississippi River Aquatic Evaluation Tool by clicking the right mouse button while hovering over ArcToolbox and selecting "Add Toolbox". Then, select the Toolbox from the "Add Toolbox" Editor and press the "Open" button on the "Add Toolbox" Editor (Figure 2).

(3) Access the tool by clicking the left mouse button over the plus symbol in front of the Middle Mississippi River Aquatic Evaluation Tool and selecting the "Create Output Workspace" function (Figure 2).

(4) Input the Directory of the Output Location (Figure 3).

(5) Click the "OK" button to run the program.

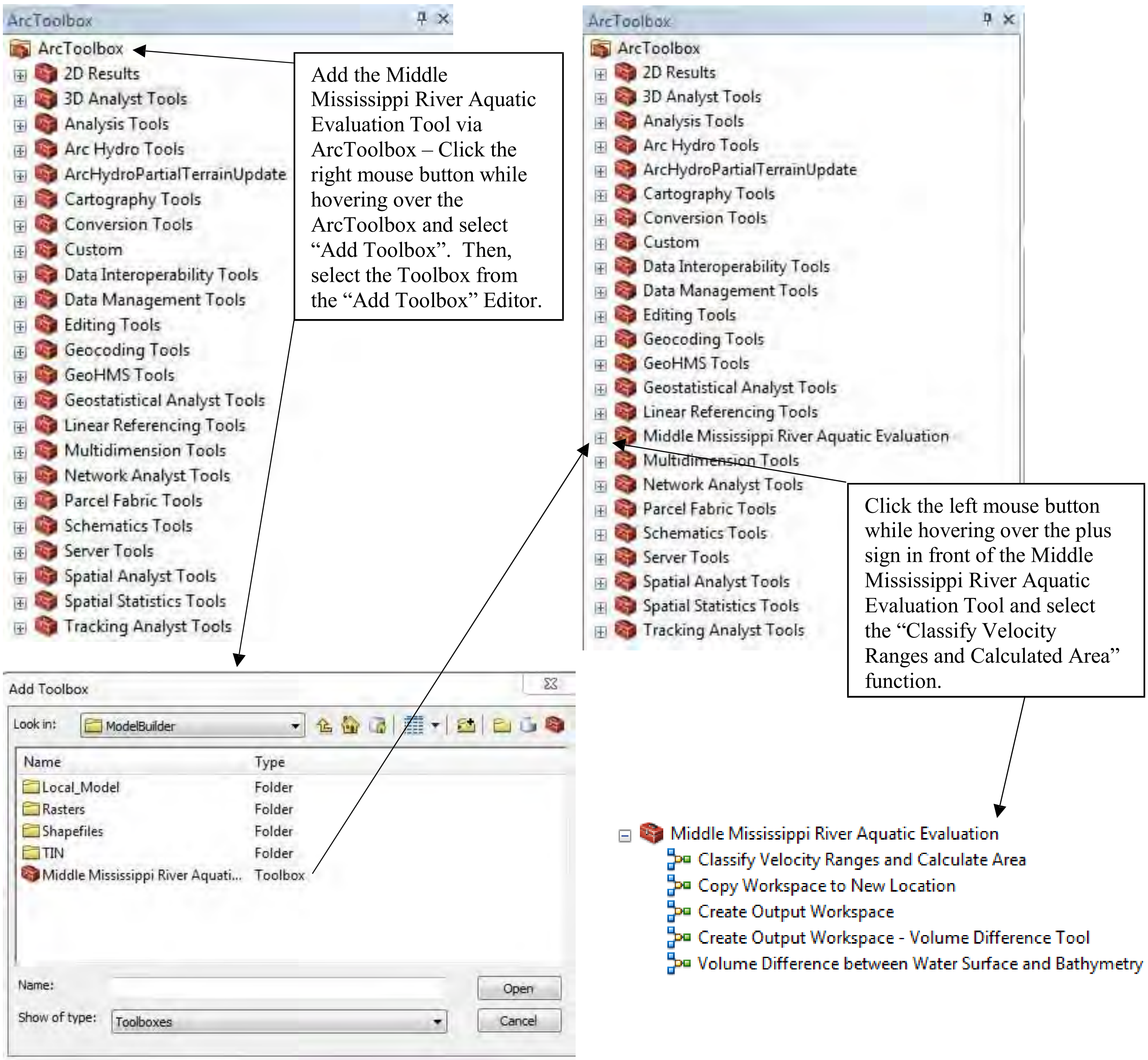


Figure 2. Adding and Accessing Tool No. 2 through No. 6 (Middle Mississippi River Aquatic Evaluation.tbx)

Figure 3. Middle Mississippi River Aquatic Evaluation (Create Output Workspace) Toolbox Input Editor

3. Middle Mississippi River Aquatic Evaluation.tbx (Classify Velocity Range and Calculate Area)

3.1 Type

ArcGIS Version 10.1 Toolbox function

3.2 Purpose

Converts the x, y, v ASCII file for 1 meter depth increments to raster files that are classified into five velocity zones:

(i) Zone 1 is for velocities between 0 m/s and 0.10 m/s
(ii) Zone 2 is for velocities between 0.11 m/s and 0.25 m/s
(iii) Zone 3 is for velocities between 0.26 m/s and 0.50 m/s
(iv) Zone 4 is for velocities between 0.51 m/s and 1.0 m/s
(v) Zone 5 is for velocities greater than 1.0 m/s.

This tool also computes the area of each velocity zone for all of the 1 meter depth layers.

3.3 Required Input Files

The x, y, v files (Depth_#.txt) generated from Tool No. 1, and a schema.ini file that contains configuration information for the x, y, v ASCII file. A polygon shapefile of the evaluation extents is optional, but it is highly recommended to prevent additional volume outside of the effective flow area.

3.4 Output Files

This tool generates five different output files for each 1 meter depth increment:

(vii) point shapefile of x, y, v data
(viii) TIN file of the x, y, v data
(ix) ArcGIS raster file of the x, y, v data
(x) ArcGIS raster file of the re-classified velocity zones
(xi) DBF file containing the area for each velocity zones

The TIN and raster files generated from this tool will have the same name as the x, y, v ASCII text file generated from Tool No. 1, i.e., "Depth_#.*", and the name of the DBF files generated from this tool will be "Area_Depth_#.dbf" where the # represents the depth below the surface elevation. The velocity and classified velocity zone raster files are provided for two horizontal datums: (i) NAD83 UTM Zone 16 (metric), and (ii) NAD 1983 Missouri State Plane East (feet).

3.5 Steps for Applying the Tool

The steps for applying the tool are as follows:

(1) Access the tool by clicking the left mouse button over the plus symbol in front of the Middle Mississippi River Aquatic Evaluation Tool and selecting the "Classify Velocity Ranges and Calculated Area" function (Figure 2).

(2) Input the following information in the "Classify Velocity Ranges and Calculated Area" editor (Figure 4):

(i) Folder Containing Input Files

(ii) Directory of Output Point Features (Note A)

(iii) Directory of TIN Polygon Boundary (optional) (Note B)

(iv) Directory of Output Velocity TIN (Note C)

(v) Directory of Output Velocity Raster (Note C and D)

(vi) Directory of Projected Velocity Raster (Note C and E)

(vii) Directory of Output Reclassified Raster (Note C and D)

(viii) Directory of Projected Reclassified Raster (Note C and E)

(ix) Directory of Zonal Geometry Table (Note F)

Notes:

A. Defined the directory and then use %Filename%.shp to define the name of the shapefiles that will be created for each of the multiple input ASCII files. The use of %Filename% will result in the point shapefiles to have the same name as the input ASCII files.
B. A polygon shapefile of the evaluation extents is optional, but it is highly recommended to prevent additional volume outside of the effective flow area.
C. Defined the directory and then use %Filename% to define the filename for the output files.
D. Outputs from Steps (v) and (vii) are based a horizontal datum of NAD83 UTM Zone 16 (metric).
E. Outputs from Steps (vi) and (viii) are based a horizontal datum of NAD 1983 Missouri State Plane East (feet).
F. Defined the directory and then use Area_%Filename% to define the filename for the output files.
G. A schema.ini must exist within the same directory as the input ASCII files. This file defines the configuration of the input ASCII files, and the contents of the file is shown in Figure 5.
H. It is important that all of the directories specified in the ArcGIS Toolbox input editor exists.
I. This tool must be run from a local drive and will not replace existing files. If files exists with similar names, the "Classify Velocity Ranges and Calculated Area" editor will include Error and Warning Icons (Figure 6). The icons can be eliminated by changing all of the %Filename% references to %Filename_1% (Figure 6).

(3) Click the "OK" button to run the program.

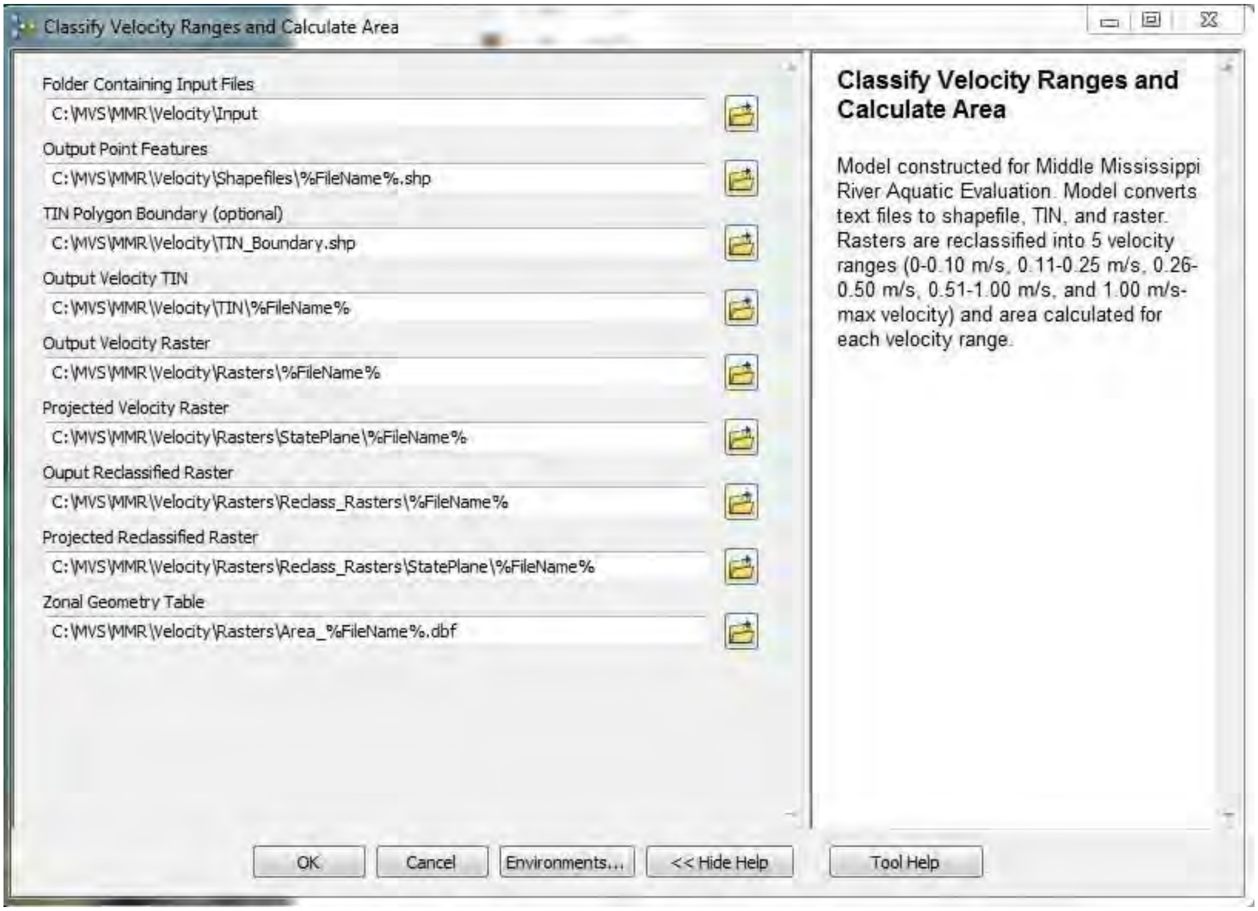


Figure 4. Middle Mississippi River Aquatic Evaluation (Classify Velocity Ranges and Calculate Area) Toolbox Input Editor

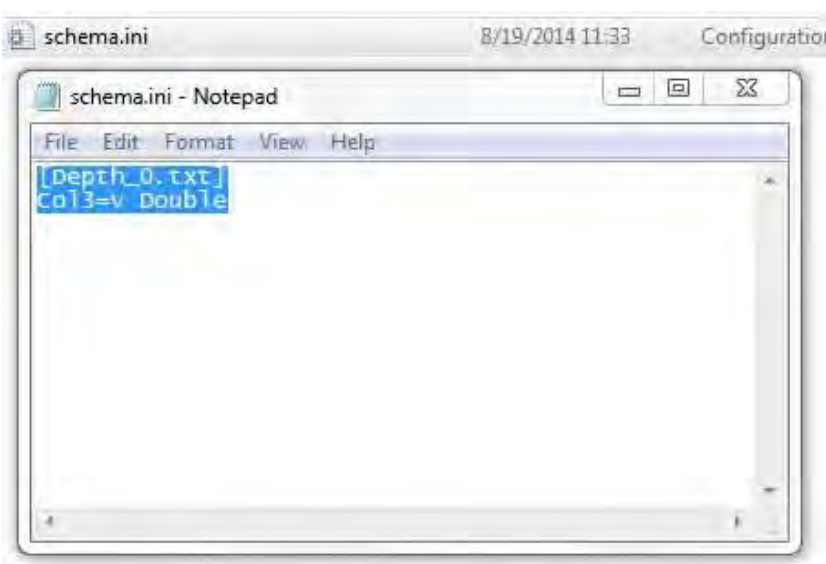


Figure 5. Format of schema.ini File Requried for Middle Mississippi River Aquatic Evaluation (Classify Velocity Ranges and Calculate Area) Toolbox

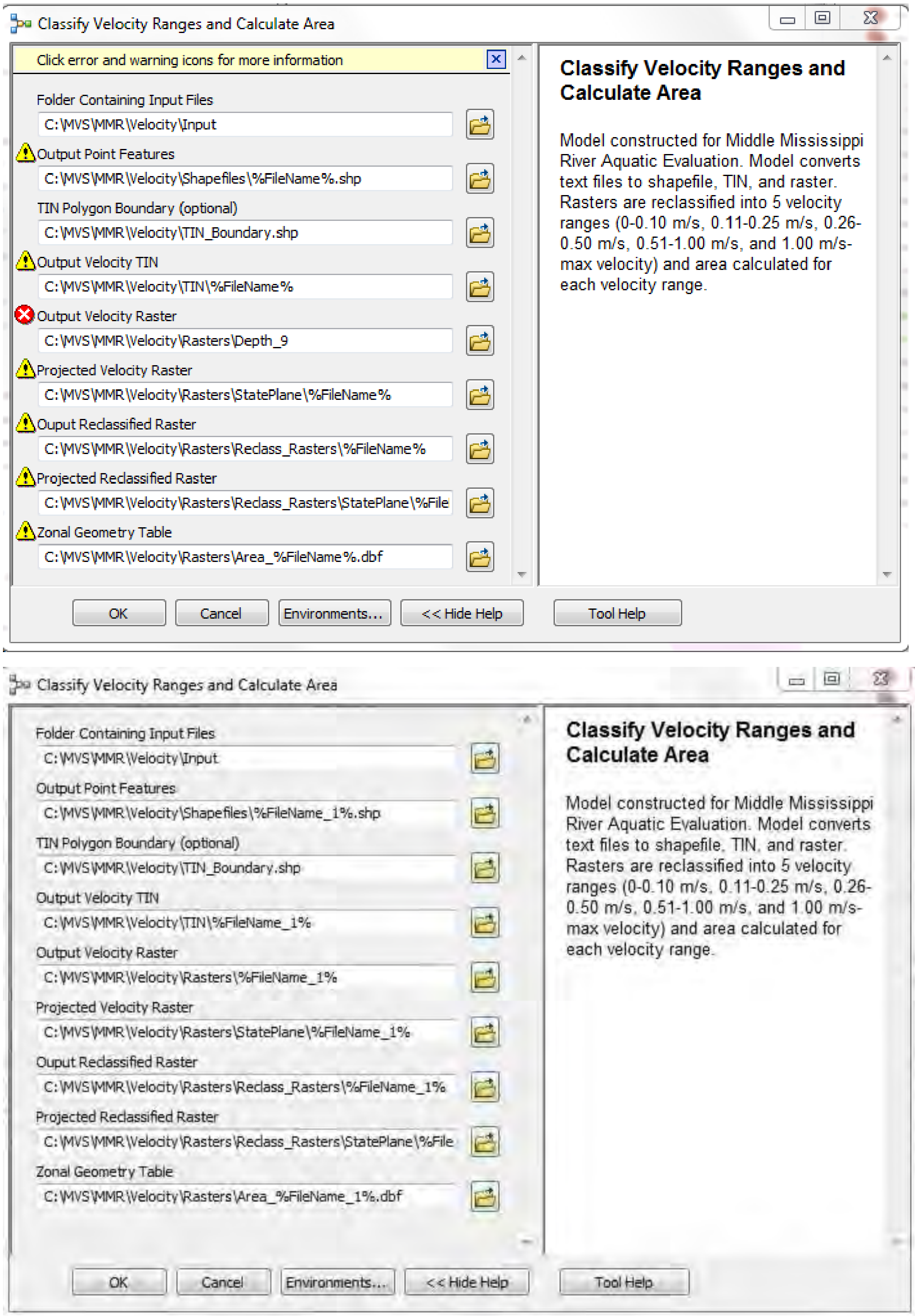


Figure 6. Error and Warning Icons Associated with Filenames

4. Middle Mississippi River Aquatic Evaluation.tbx (Create Output Workspace – Volume Difference Tool)

4.1 Type

ArcGIS Version 10.1 Toolbox function

4.2 Purpose

Creates workspace directories for Tool No. 5 (Volume Difference Between Water Surface and Bathymetry).

4.3 Required Input Files

None.

4.4 Output Files

This tool generates the following subdirectories under the defined output directory:

(i) \Raster
(ii) \Raster\Volume_Change
(iii) \Shapefiles
(iv) \TIN

The default directory structure is C:\MVS\MMR\CutFill. The tool can be edited in ArcGIS if a different default directory is desired. The tool only needs to be run once prior to running Tool No. 5 (Volume Difference Between Water Surface and Bathymetry).

4.5 Steps for Applying the Tool

The steps for applying the tool are as follows:

(1) Access the tool by clicking the left mouse button over the plus symbol in front of the Middle Mississippi River Aquatic Evaluation Tool and selecting the "Create Output Workspace – Volume Difference Tool" function (Figure 2).

(2) Input the Directory of the Output Location (Figure 7).

(3) Click the "OK" button to run the program.

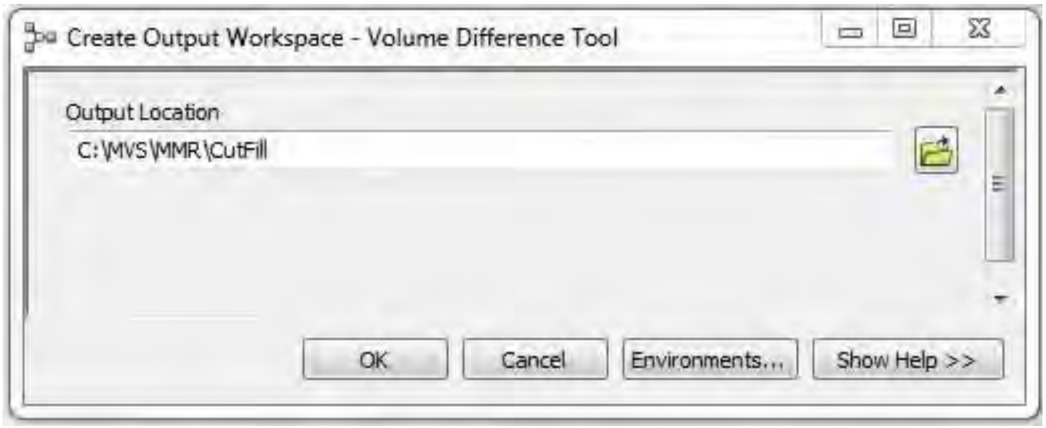


Figure 7. Middle Mississippi River Aquatic Evaluation (Create Output Workspace – Volume Difference Tool) Toolbox Input Editor

5. Middle Mississippi River Aquatic Evaluation.tbx (Volume Difference between Water Surface and Bathymetry)

5.1 Type

ArcGIS Version 10.1 Toolbox function

5.2 Purpose

Computes the total volume between the CCHE3D water surface elevation and a raster file of the bathymetry data.

5.3 Required Input Files

WS_VolCal.txt file generated from Tool No. 1 and raster file of the bathymetry data. The raster of the bathymetry data must be based on a horizontal datum of NAD83 UTM Zone 16, a vertical datum of NAVD88, and the metric unit system.

5.4 Output Files

This tool generates a raster file of the CCHE3D water surface elevation, and a raster file and DBF file of the Cut\Fill volume computed between the CCHE3D water surface elevation and the specified bathymetric data. Output raster file is based on NAD83 UTM, Zone 16 datum. The name of the DBF output file is "Vol_Change_WS_VolCal.dbf".

5.5 Steps for Applying the Tool

The steps for applying the tool are as follows (Note: Steps are based on the Middle Mississippi River Aquatic Evaluation Tool already existing in the Toolbox. If it does not exist, than complete Steps 1 and 2 in Section 2.5):

(1) Access the tool by clicking the left mouse button over the plus symbol in front of the Middle Mississippi River Aquatic Evaluation Tool and selecting the "Classify Velocity Ranges and Calculated Area" function (Figure 2).

(2) Input the following information in the "Classify Velocity Ranges and Calculated Area" editor (Figure 8):

(i) Folder Containing Input Files

(ii) Directory of Output Point Features (Note A)

(iii) Directory of TIN Polygon Boundary (optional) (Note B)

(iv) Directory of Output WSEL TIN (Note C)

(v) Directory of Output WSEL Raster (Note C and D)

(vi) Bathymetry Surface (Note E)

(vii) Directory of Output Volume Change Raster (Note C and D)

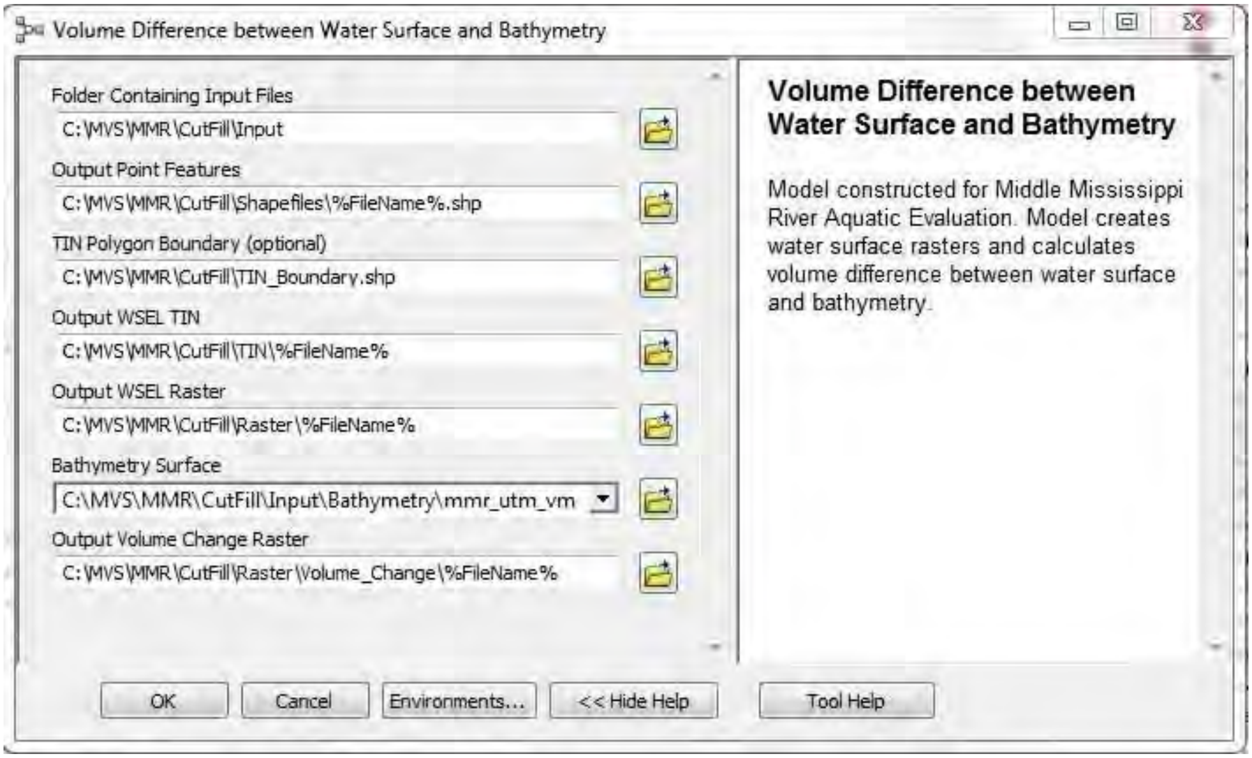


Figure 8. Middle Mississippi River Aquatic Evaluation (Volume Difference between Water Surface and Bathymetry) Toolbox Input Editor

Notes:

A. Defined the directory and then use %Filename%.shp to define the name of the shapefiles that will be created for each of the multiple input ASCII files. The use of %Filename% will result in the point shapefiles to have the same name as the input ASCII files.
B. A polygon shapefile of the evaluation extents is optional, but it is highly recommended to prevent additional volume outside of the effective flow area.
C. Defined the directory and then use %Filename% to define the filename for the output files.
D. Outputs from Steps (v) and (vii) are based a horizontal datum of NAD83 UTM Zone 16 (metric).
E. Bathymetry raster must be based on a horizontal datum of NAD83 UTM Zone 16, a vertical datum of NAVD88, and metric unit system.

6. Middle Mississippi River Aquatic Evaluation.tbx (Copy Workspace to New Location)

6.1 Type

ArcGIS Version 10.1 Toolbox function

6.2 Purpose

Copies files from an existing workspace directory to a new workspace directory.

6.3 Required Input Files

None.

6.4 Output Files

This tool copies all of the files within a specified directory to a new directory. It can be used to copy all of generated from the Tools No. 3 (Classify Velocity Range and Calculate Area) and No. 5 (Volume Difference Between Water Surface and Bathymetry) to a new location prior to running the tools again for another condition.

6.5 Steps for Applying the Tool

The steps for applying the tool are as follows:

(1) Access the tool by clicking the left mouse button over the plus symbol in front of the Middle Mississippi River Aquatic Evaluation Tool and selecting the "Copy Workspace to a New Location" function (Figure 2).

(2) Input the Directory of the Original Workspace Location and New Workspace Location (Figure 7).

(3) Click the "OK" button to run the program.

Figure 9. Middle Mississippi River Aquatic Evaluation (Copy Workspace to New Location) Toolbox Input Editor

7. Volume_Summary.xlsm

7.1 Type

Visual Basic (VBA) program in Excel.

7.2 Purpose

Extracts the area of classified velocity zones from the DBF files generated from Tool No. 3, and creates a summary table of area (m^2) and volume (m^3) for each zone per 1 meter depth increments and total fractional volume for each velocity zone.

7.3 Required Input Files

This tool needs the DBF files generated from Tool No. 3 for each 1 meter depth increment.

7.4 Output Files

No output files are created from this tool. This tool creates a summary table of the area (m^2) and volume (m^3) for each zone per 1 meter depth increments, and the total volume (m^3) with percentage of the volume for each velocity zone. The summary table is provided on the "Summary" worksheet, which will be the active worksheet after running this tool.

7.5 Steps for Applying the Tool

The steps for applying the tool are as follows:

(1) Open the Excel file (Volume_Summary.xlsm) and enable the macro by clicking the button near the top of the spreadsheet. Spreadsheet should open up to the Start worksheet (Figure 10).

(2) Enter the directory where the DBF files are located and the filename of the Excel file.

(3) Click the "Extract Data from DBF" macro button. The processing status is provided in the status bar on the lower left side below the worksheet tabs.

(4) Save and exit the Excel file.

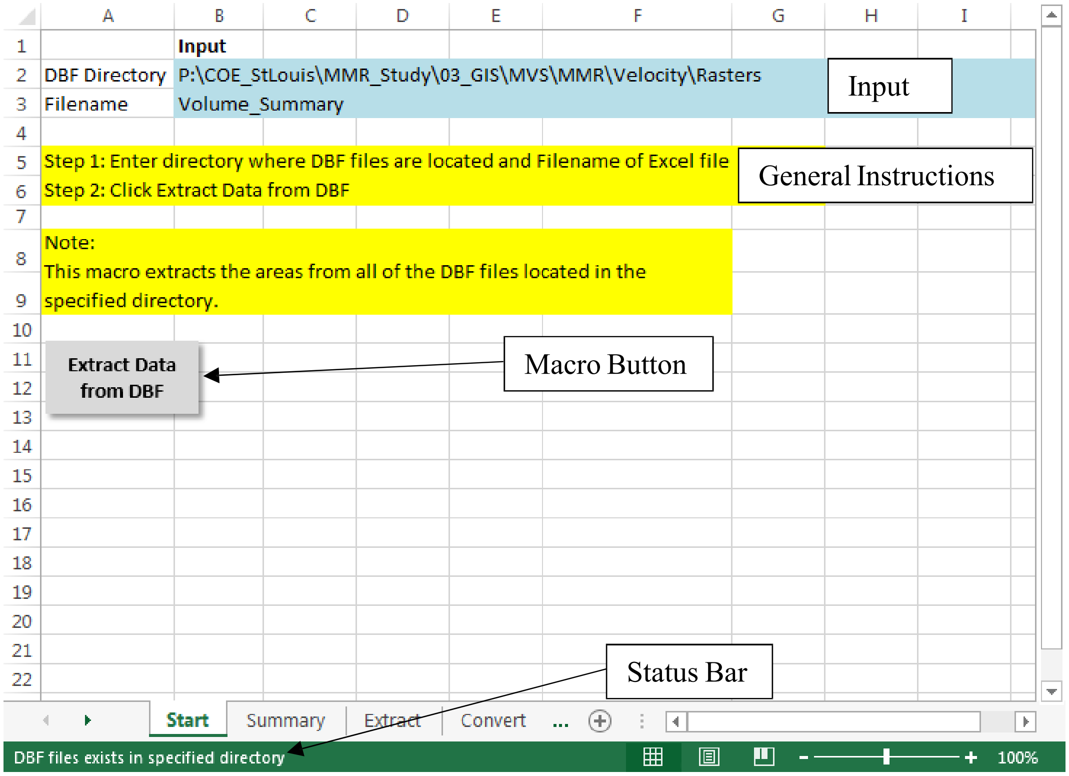
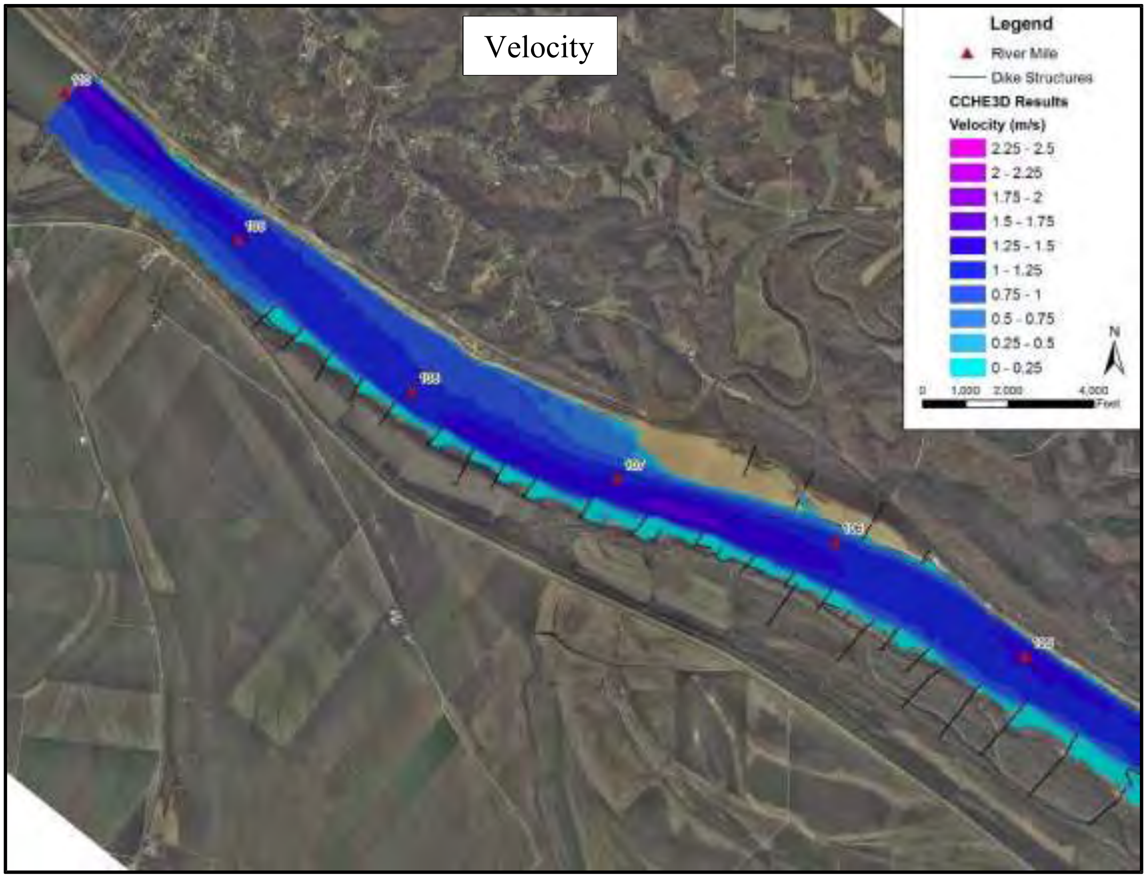
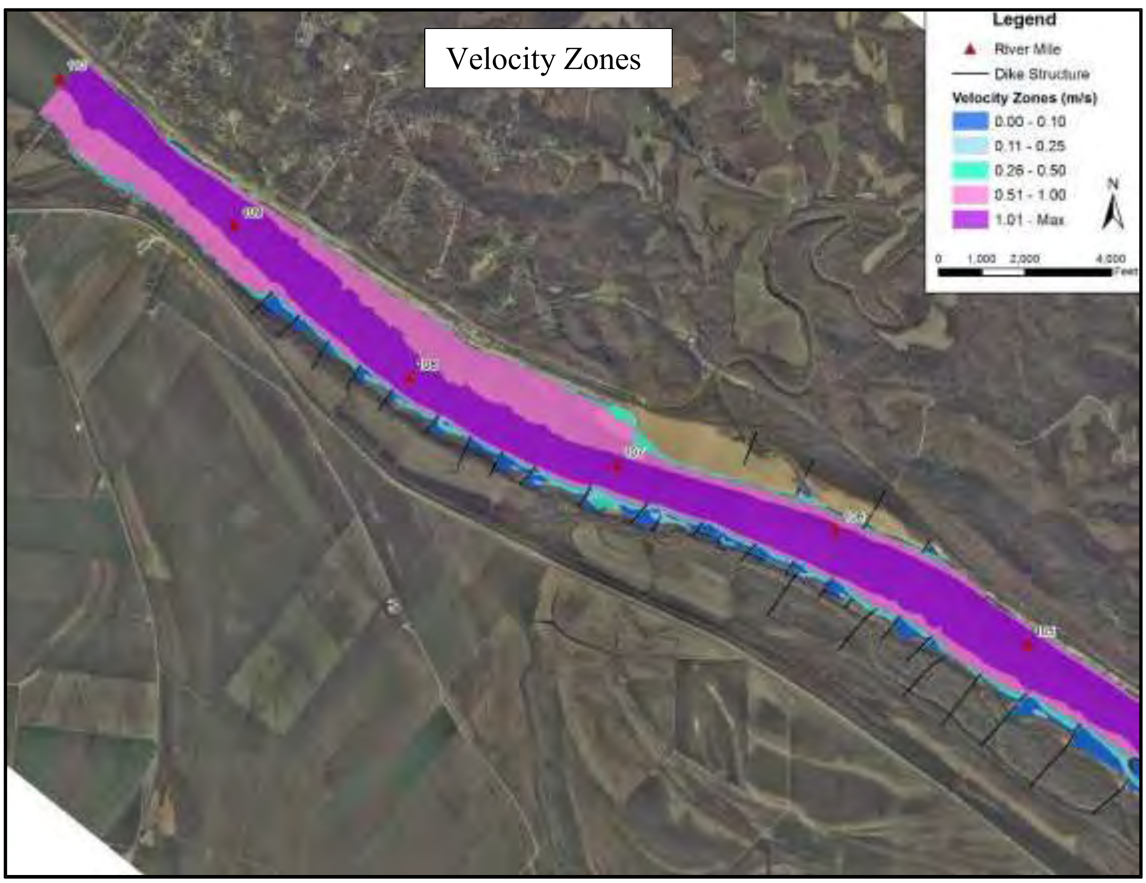


Figure 10. Start Worksheet for Tool No. 7 (Volume_Summary.xlsm)

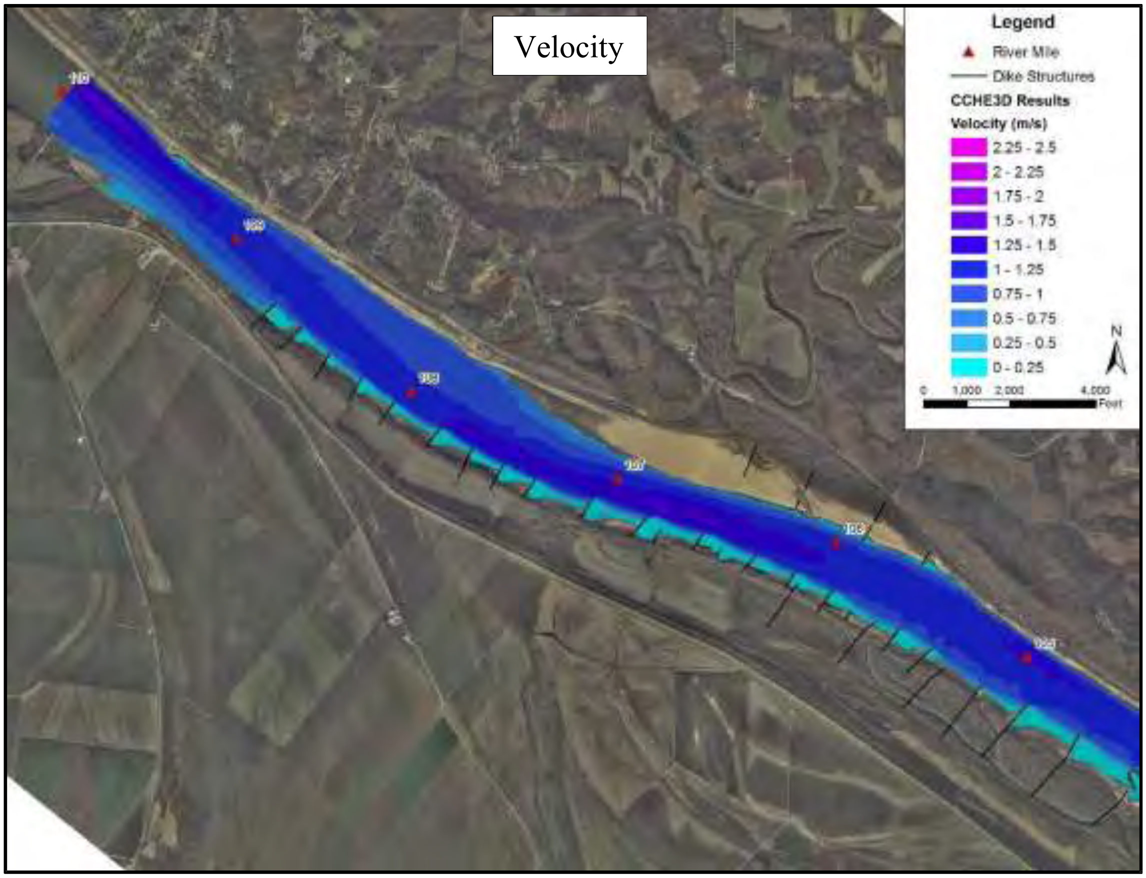
APPENDIX B.1

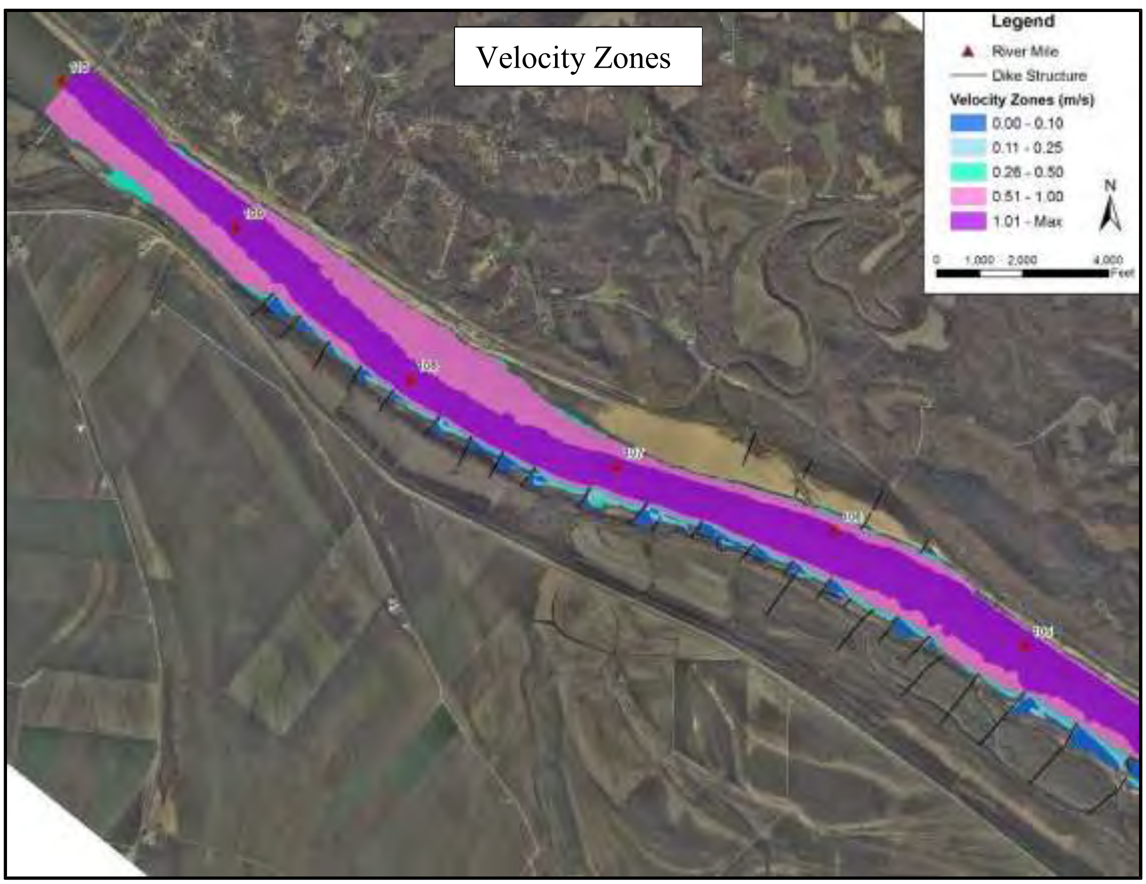
STUDY REACH CCHE3D MODEL VELOCITY AND VELOCITY RECLASSIFICATION RESULTS (FLOW OF 3,143.2 M^3/S)



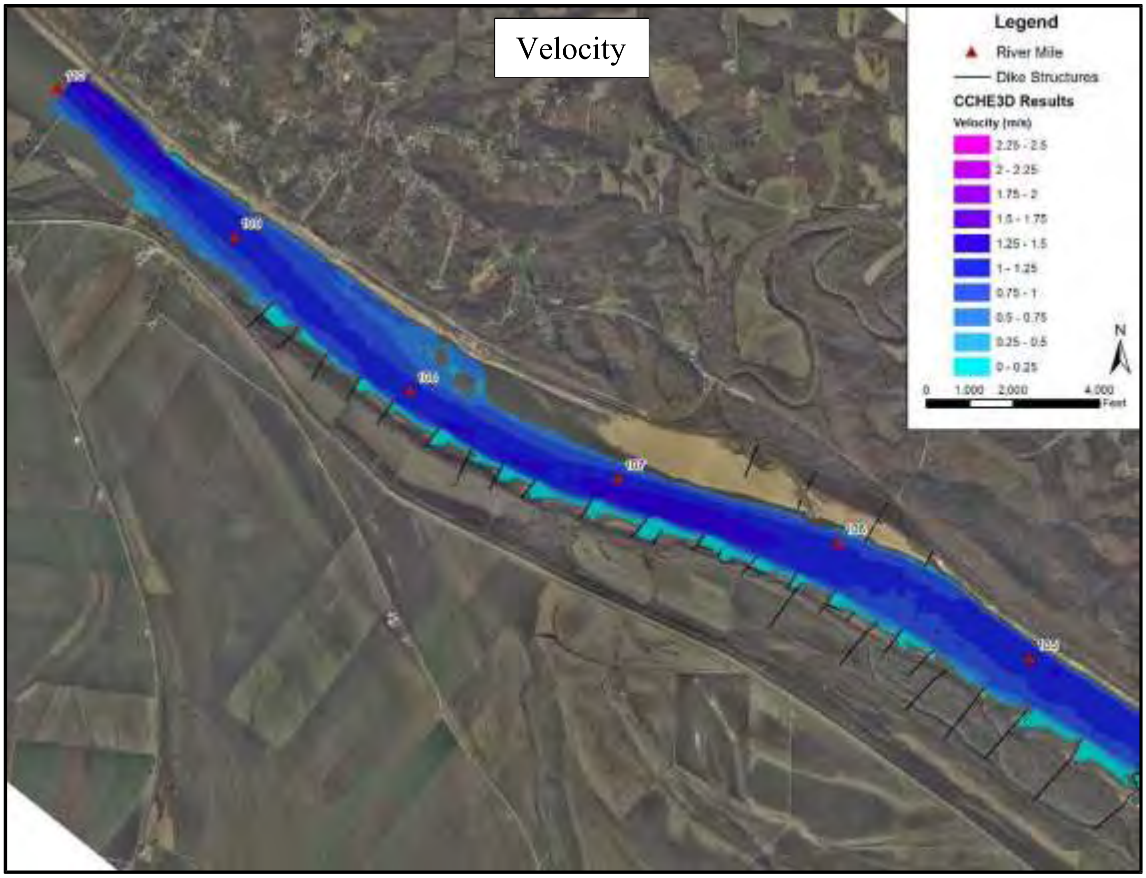


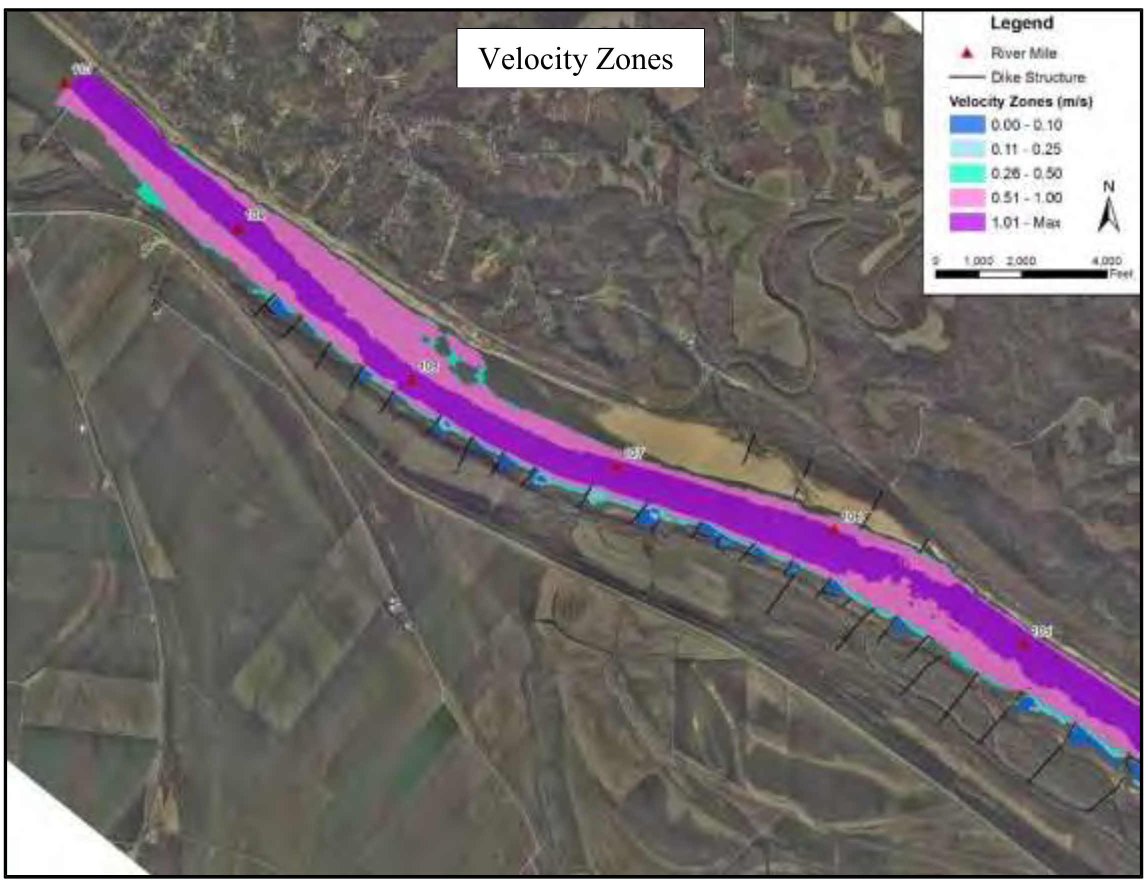
CCHE3D velocity results (flow of 3,143.2 m^3/s) at water surface for the study reach between RM 110 to RM 105



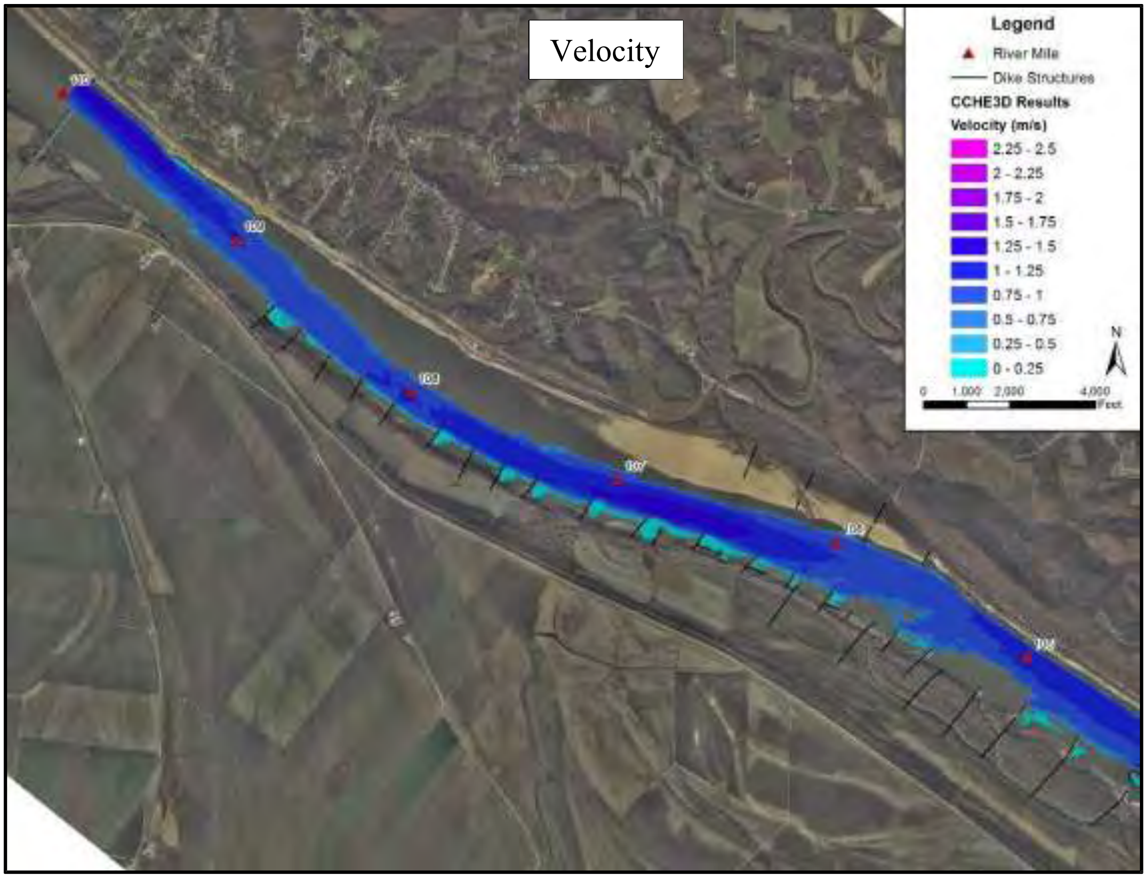


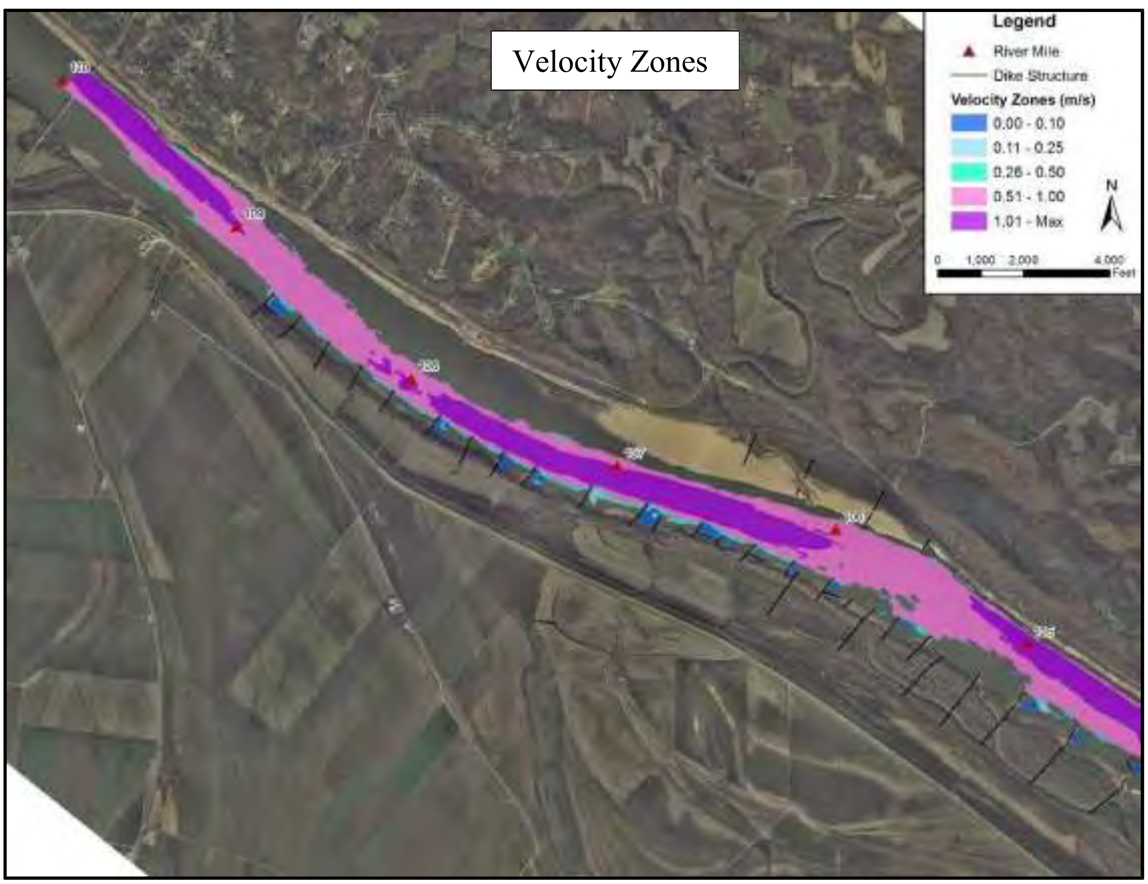
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 2 m below water surface for the study reach between RM 110 to RM 105



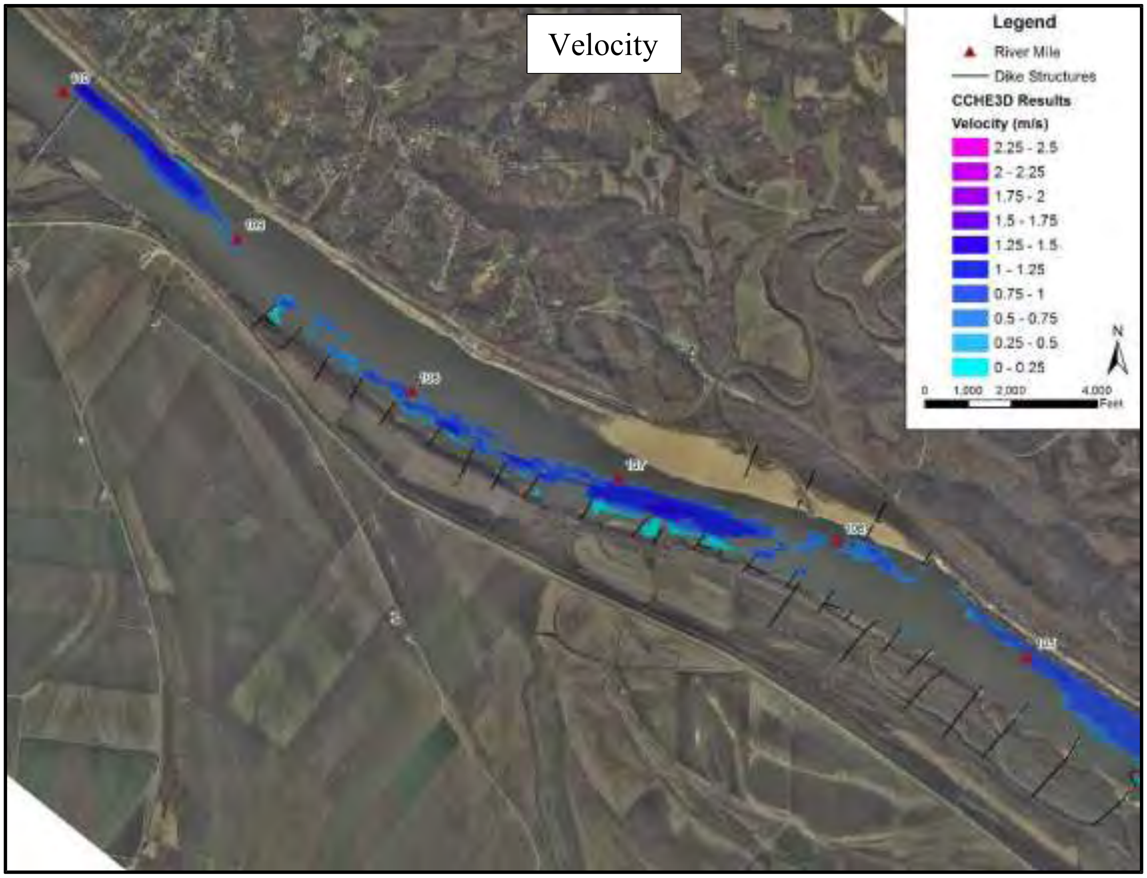


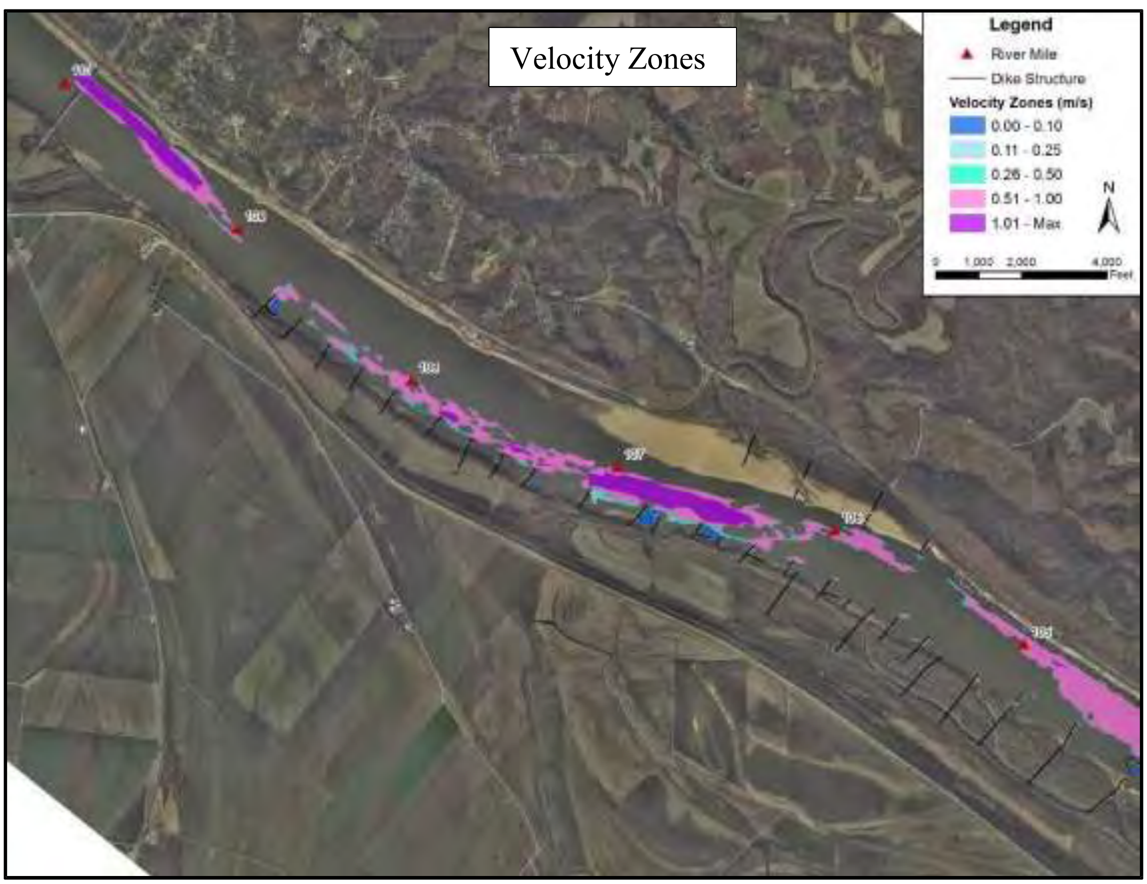
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 4 m below water surface for the study reach between RM 110 to RM 105



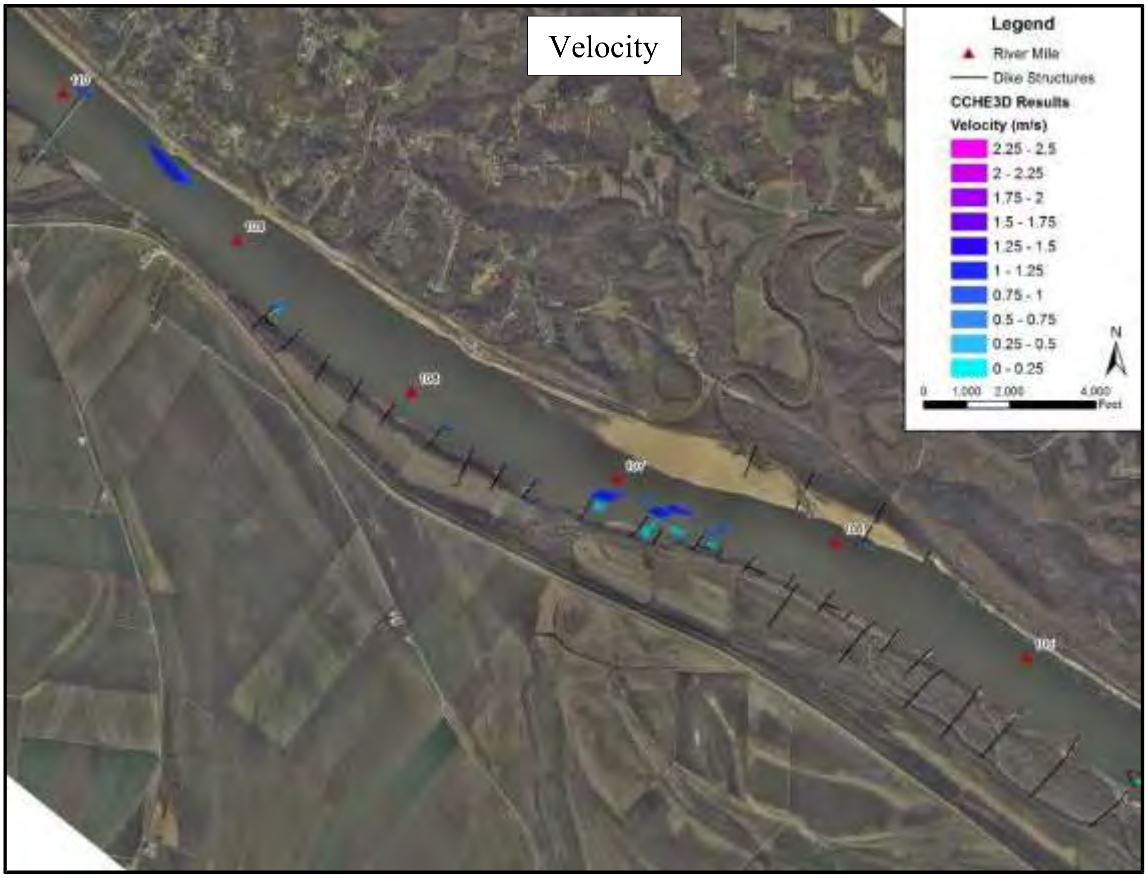


CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 6 m below water surface for the study reach between RM 110 to RM 105

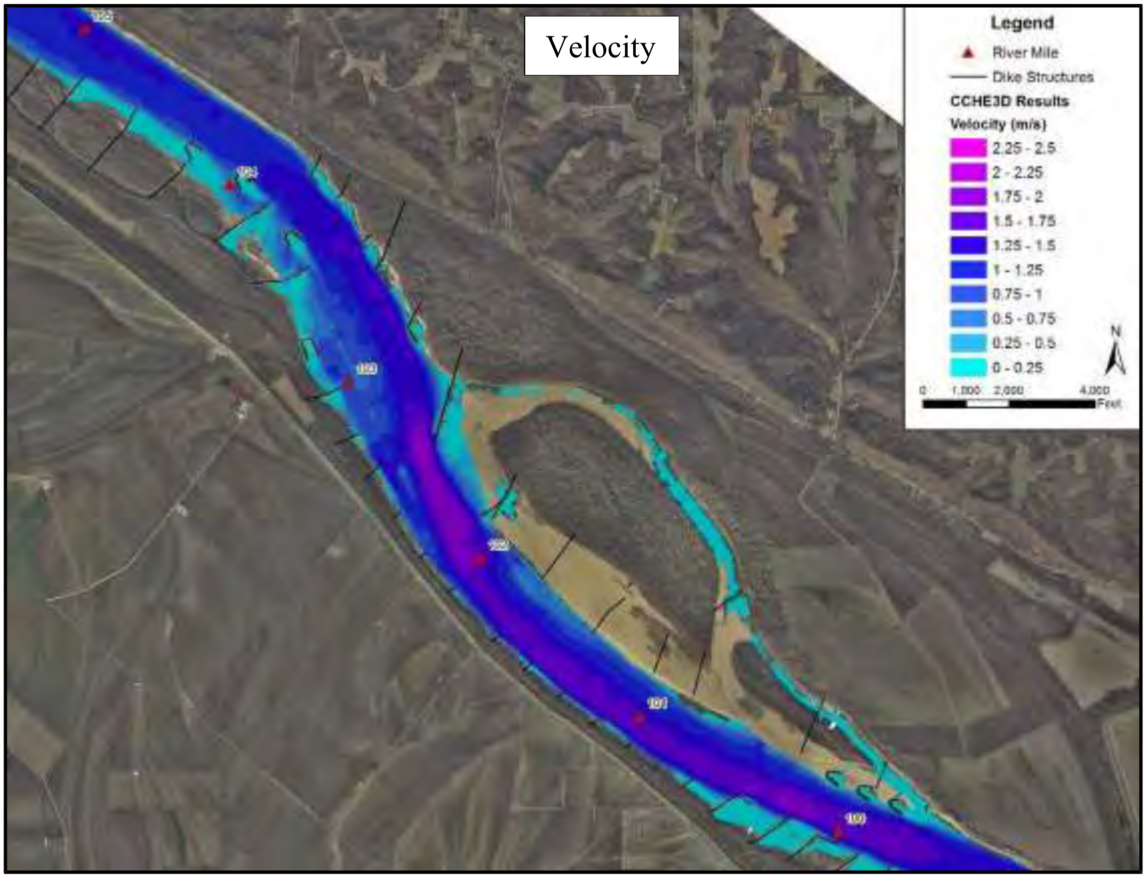


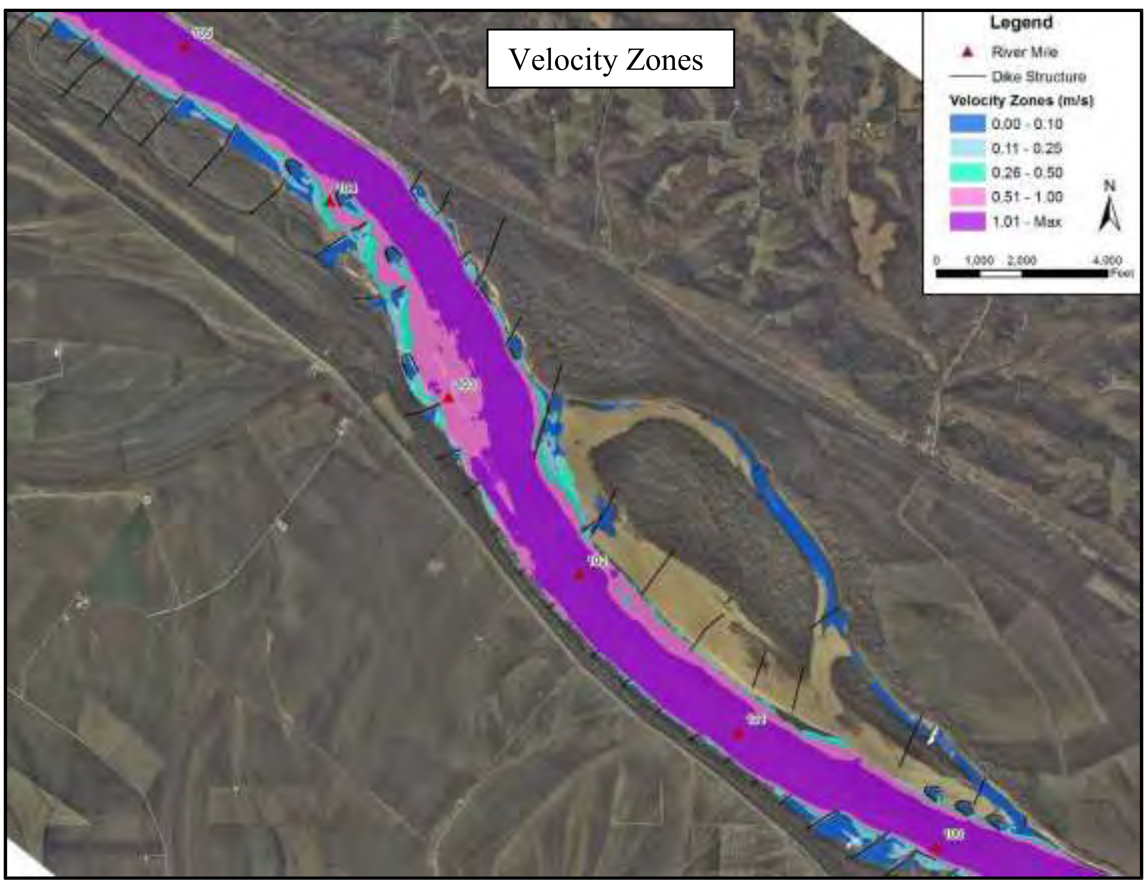


CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 8 m below water surface for the study reach between RM 110 to RM 105

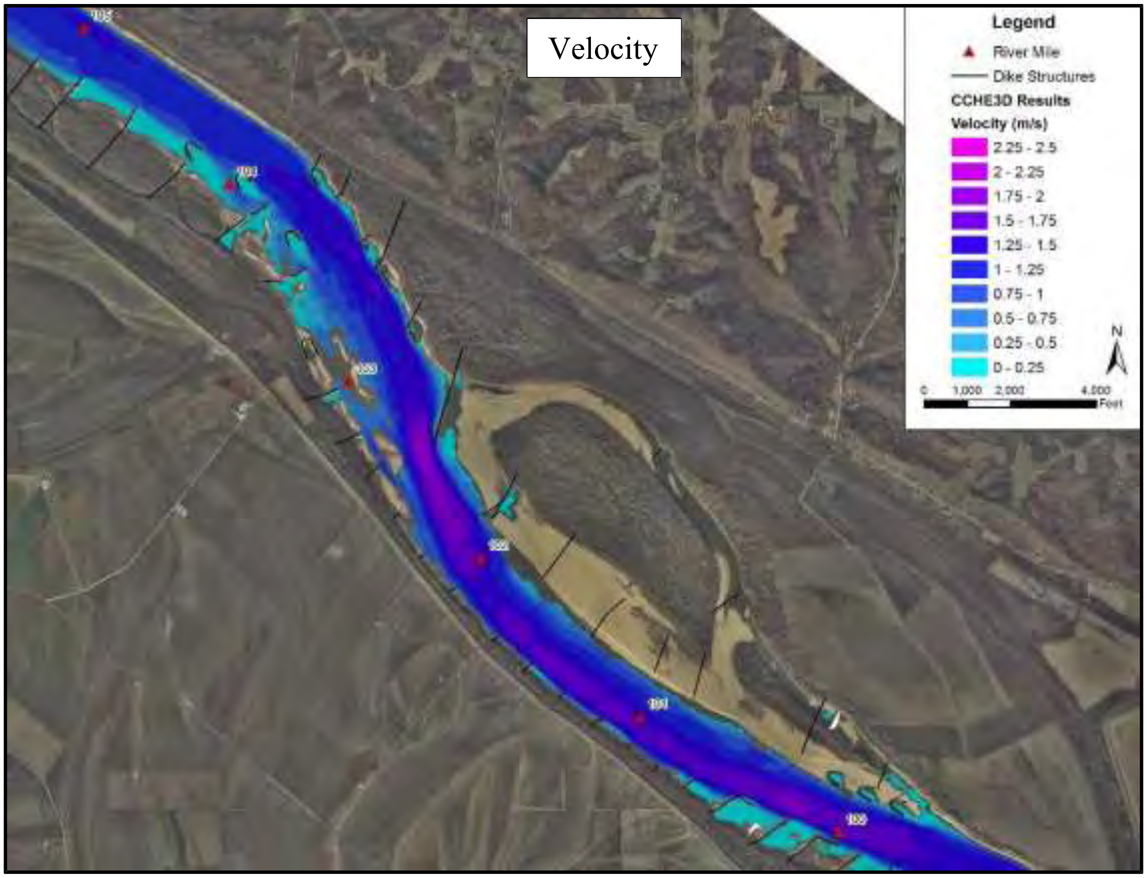


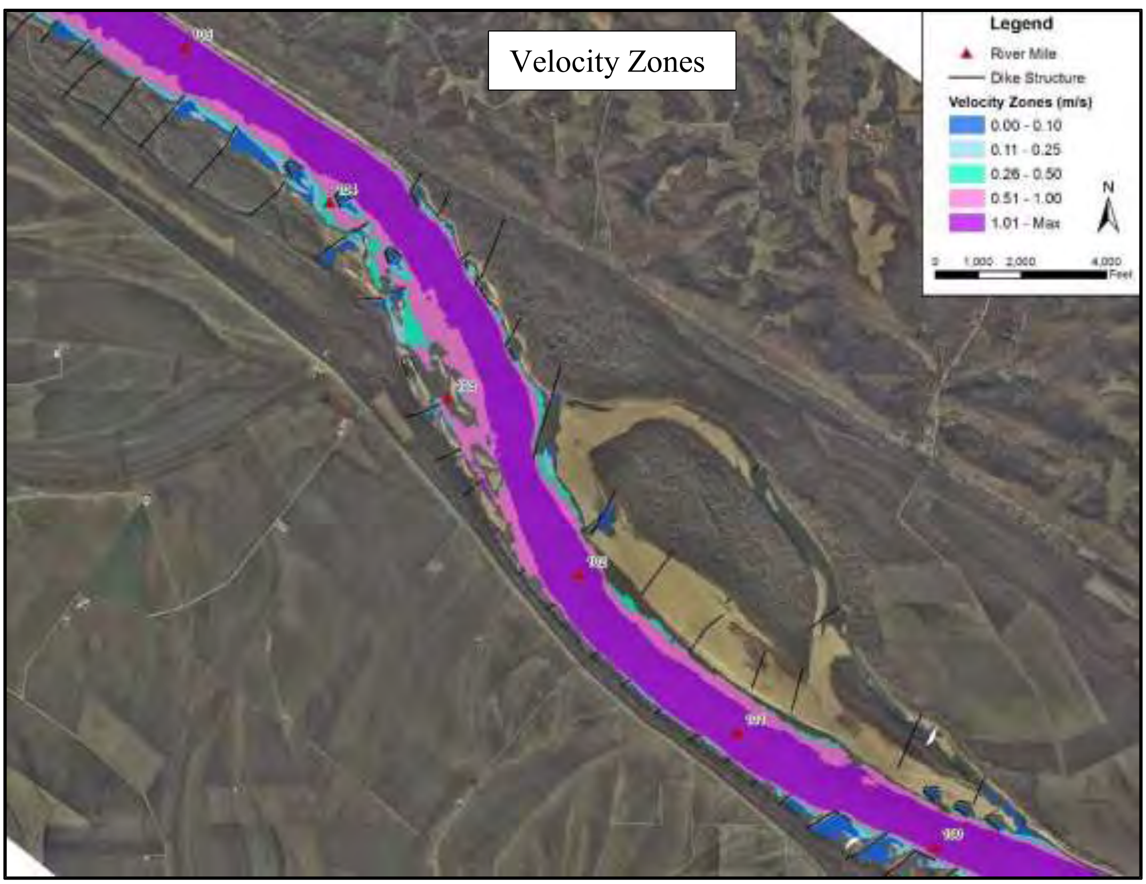
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 10 m below water surface for the study reach between RM 110 to RM 105



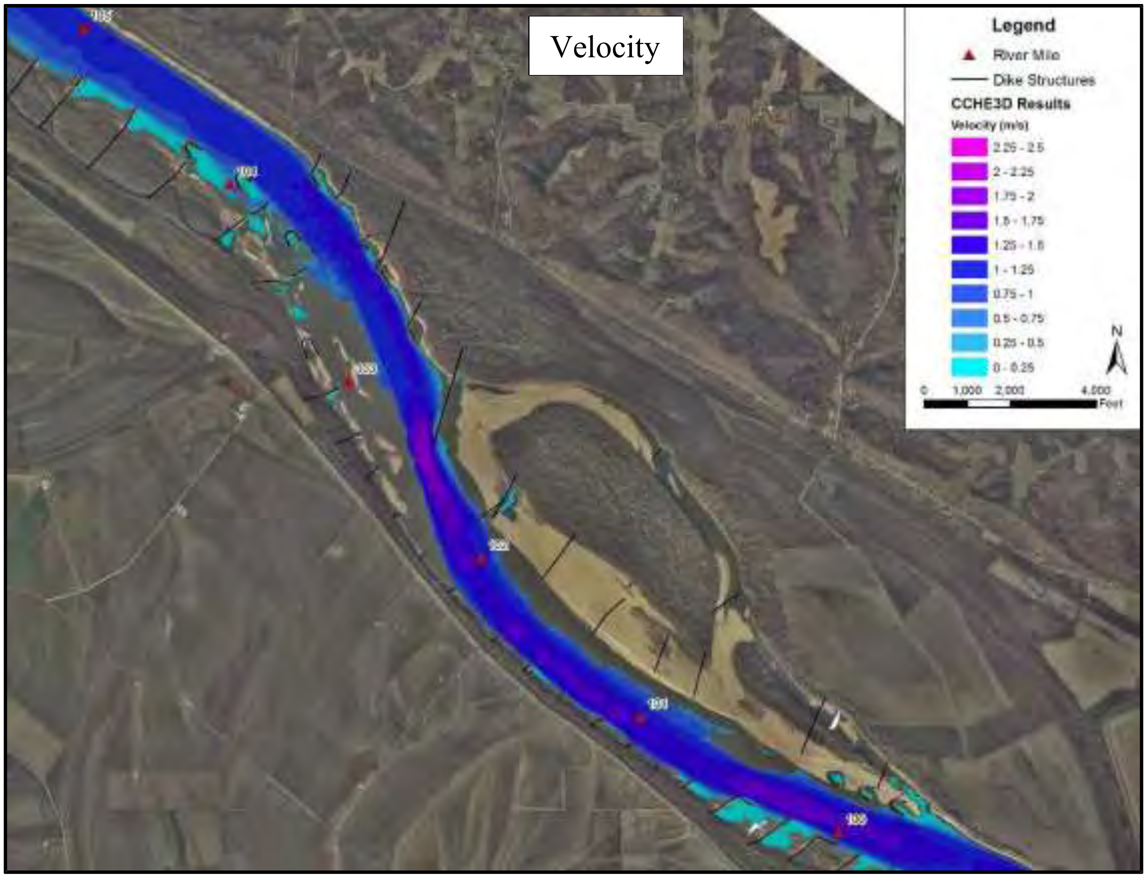


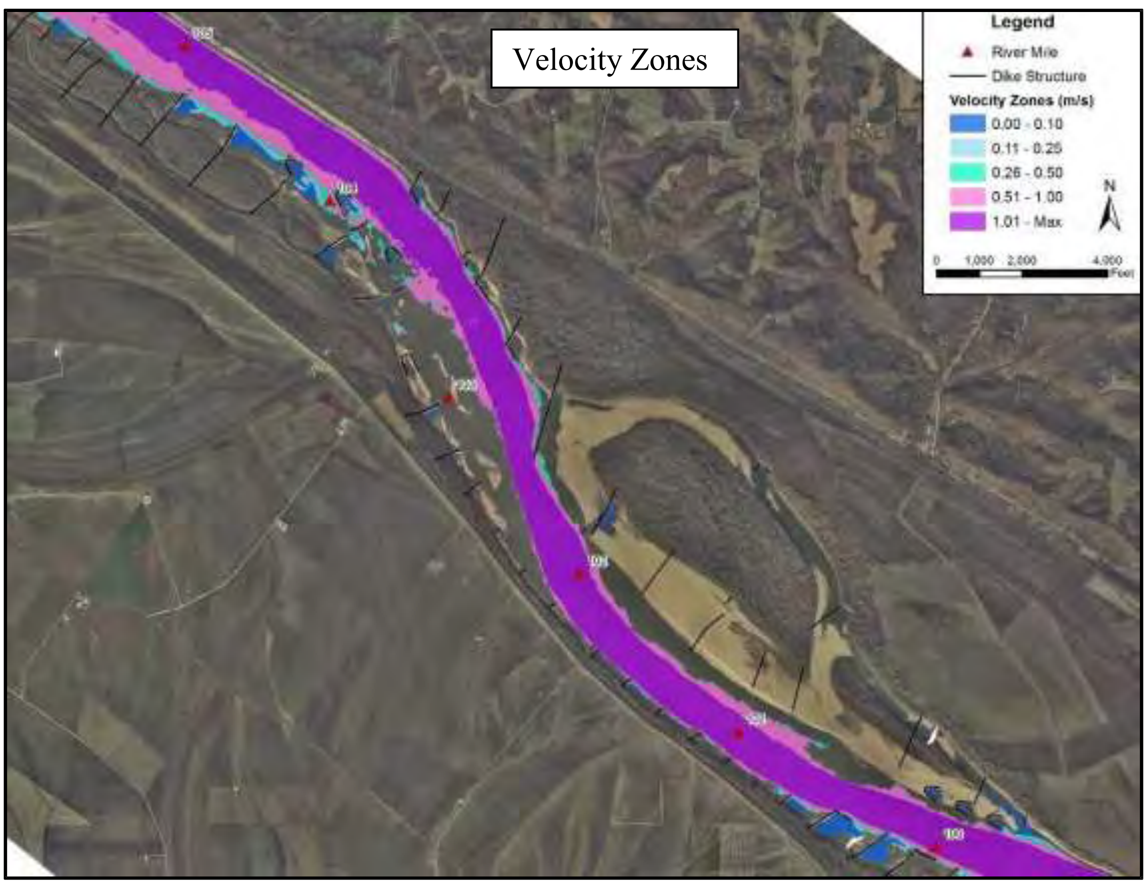
CCHE3D velocity results (flow of 3,143.2 m^3/s) at water surface for the study reach between RM 105 to RM 100



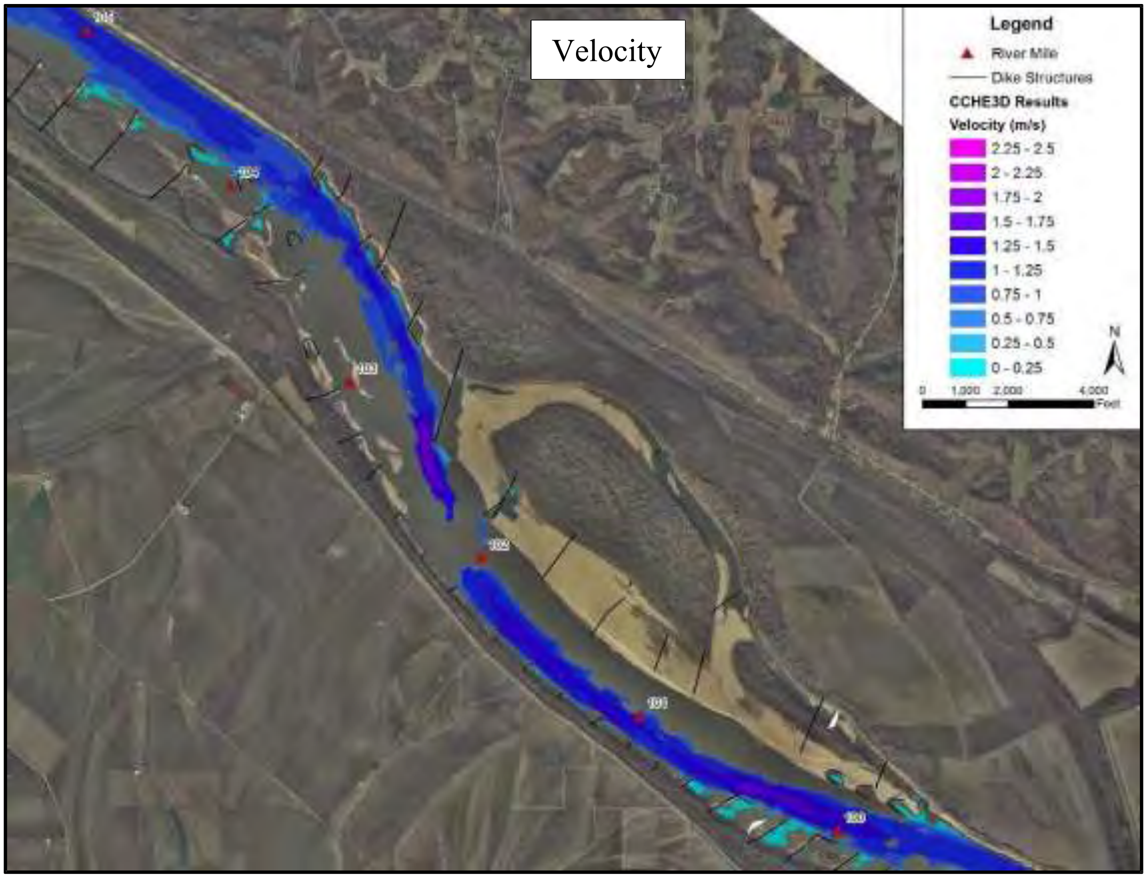


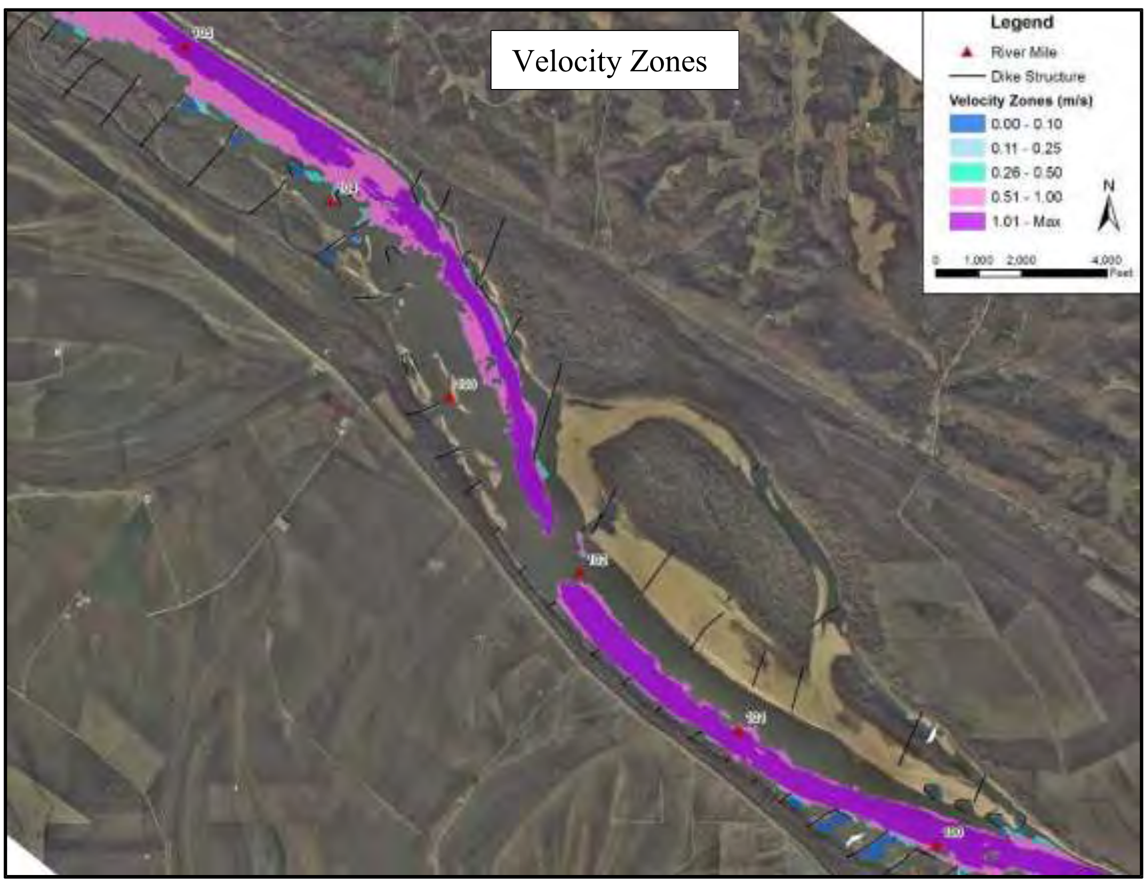
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 2 m below water surface for the study reach between RM 105 to RM 100



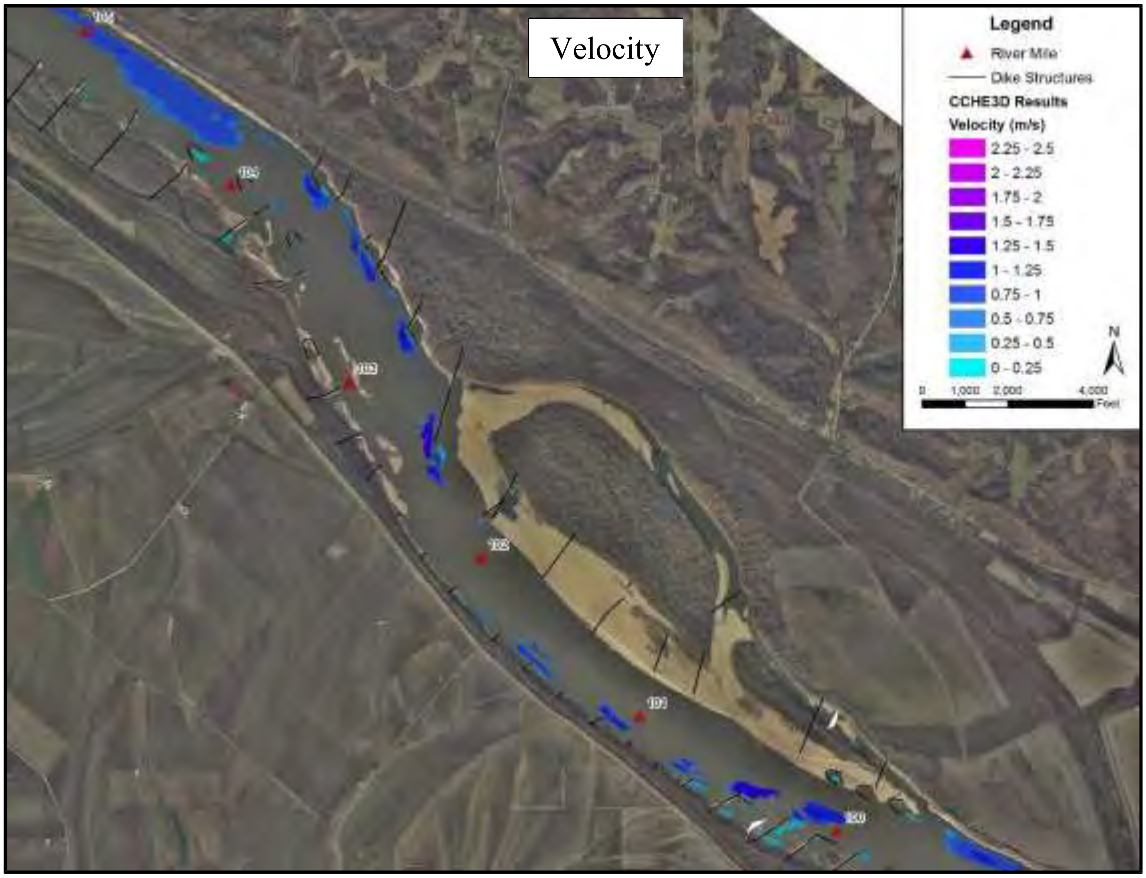


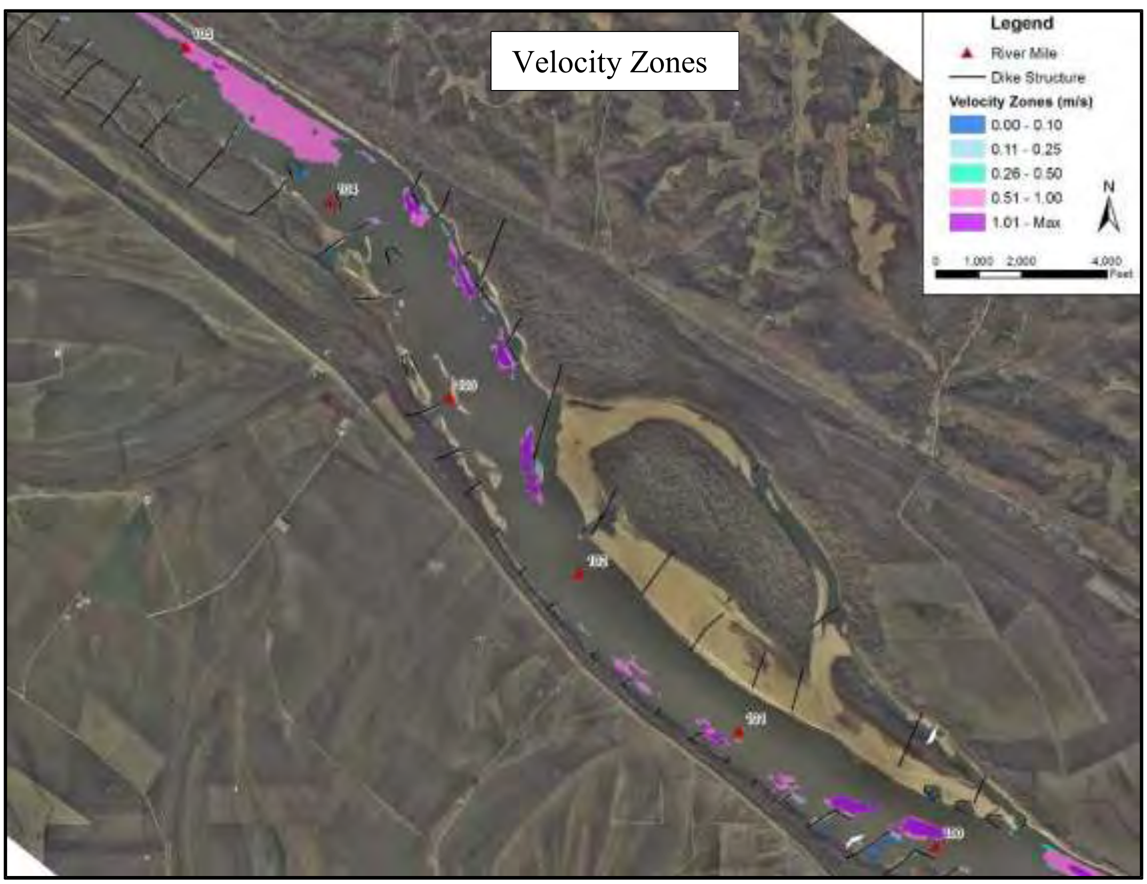
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 4 m below water surface for the study reach between RM 105 to RM 100



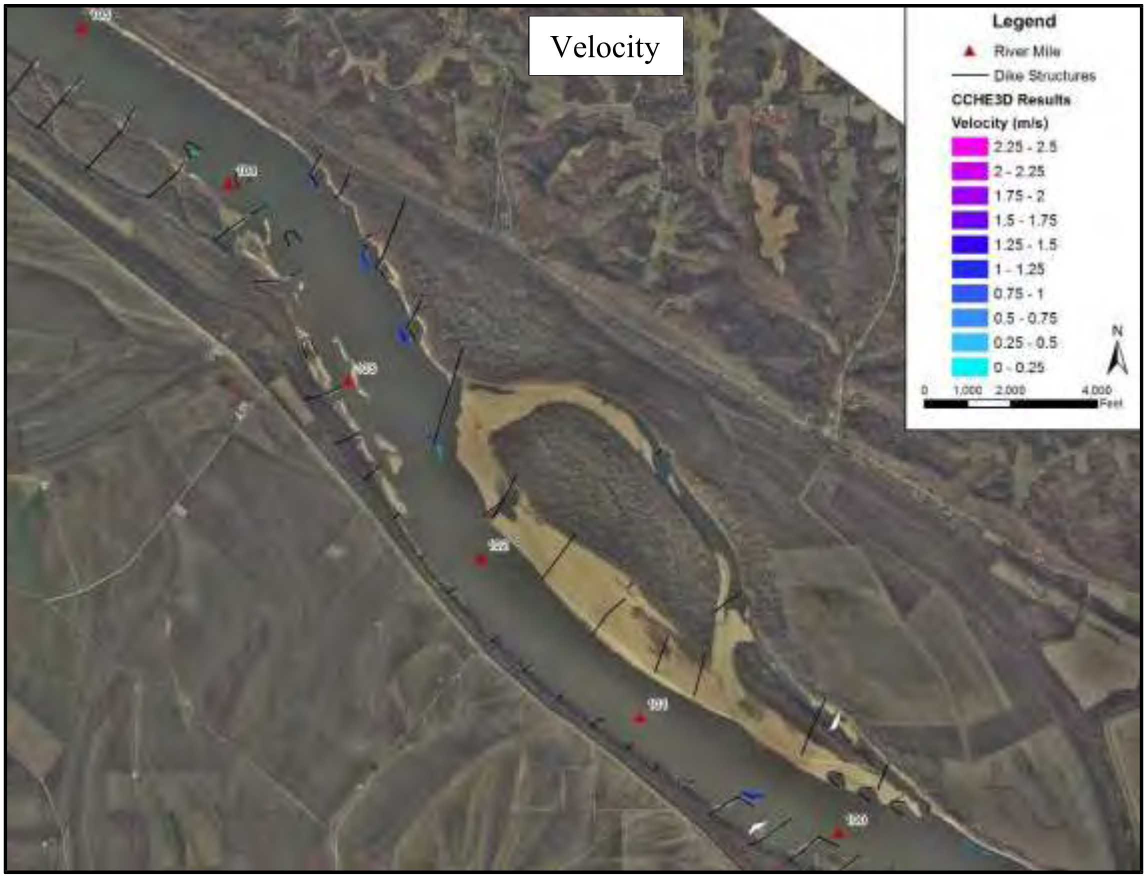


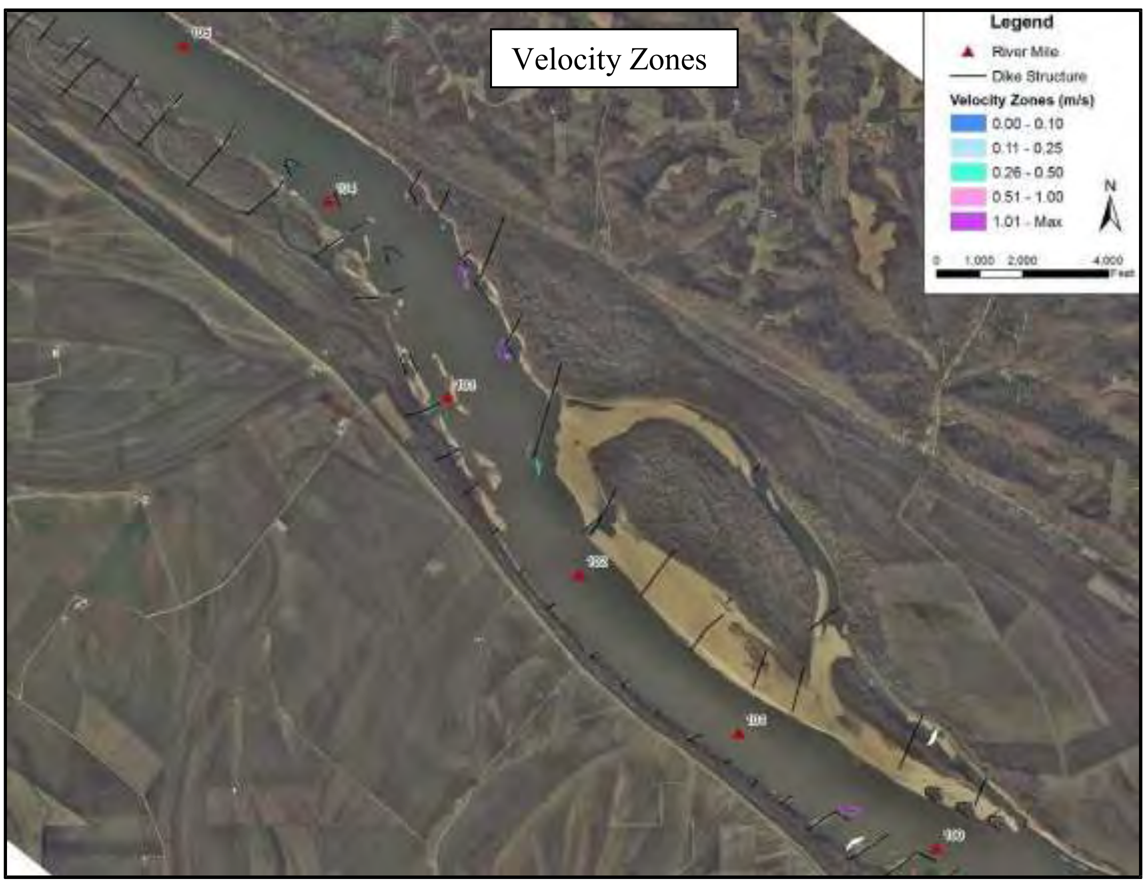
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 6 m below water surface for the study reach between RM 105 to RM 100



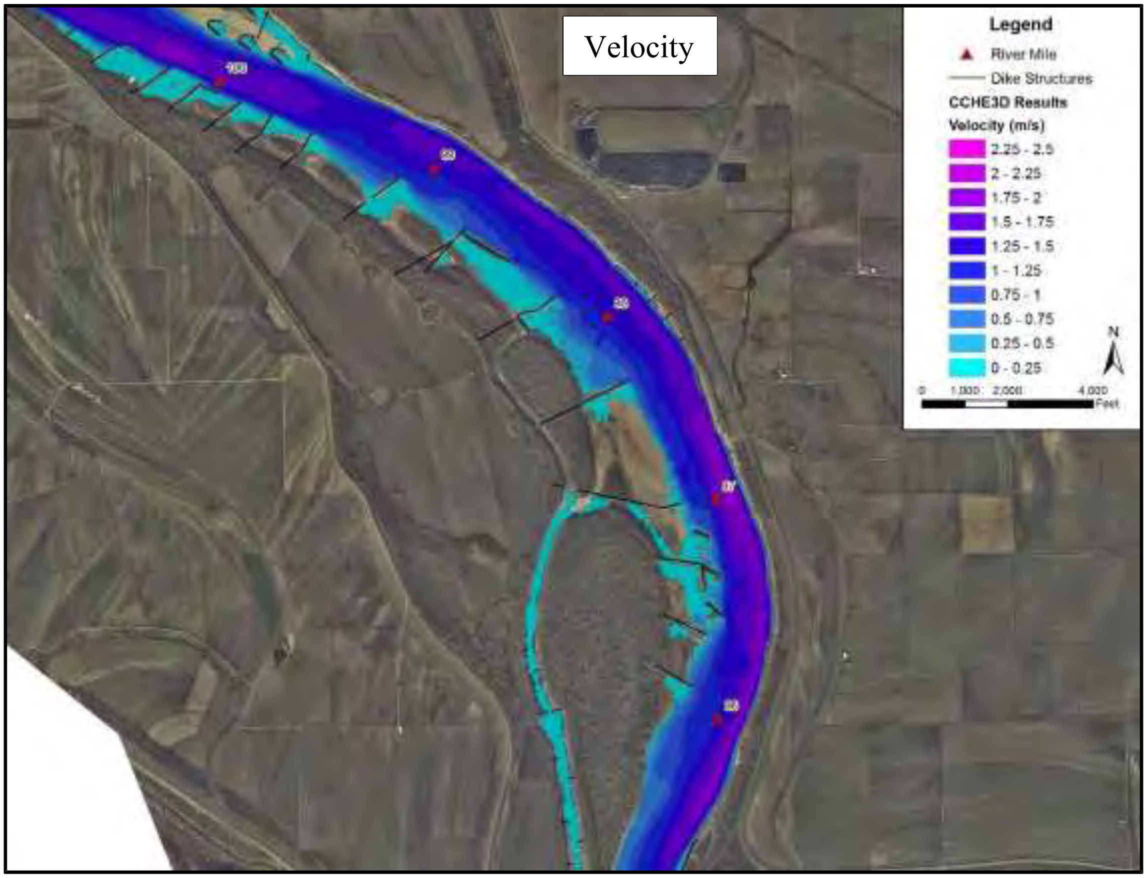


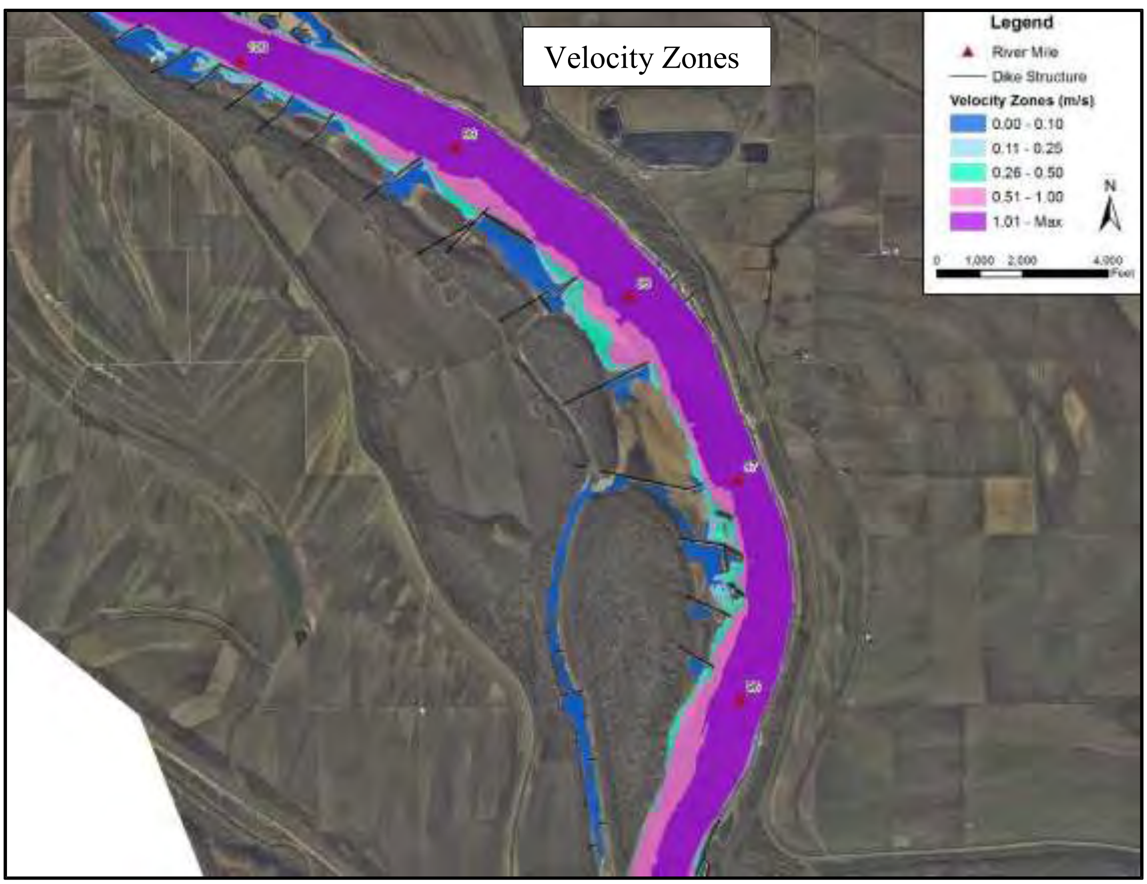
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 8 m below water surface for the study reach between RM 105 to RM 100



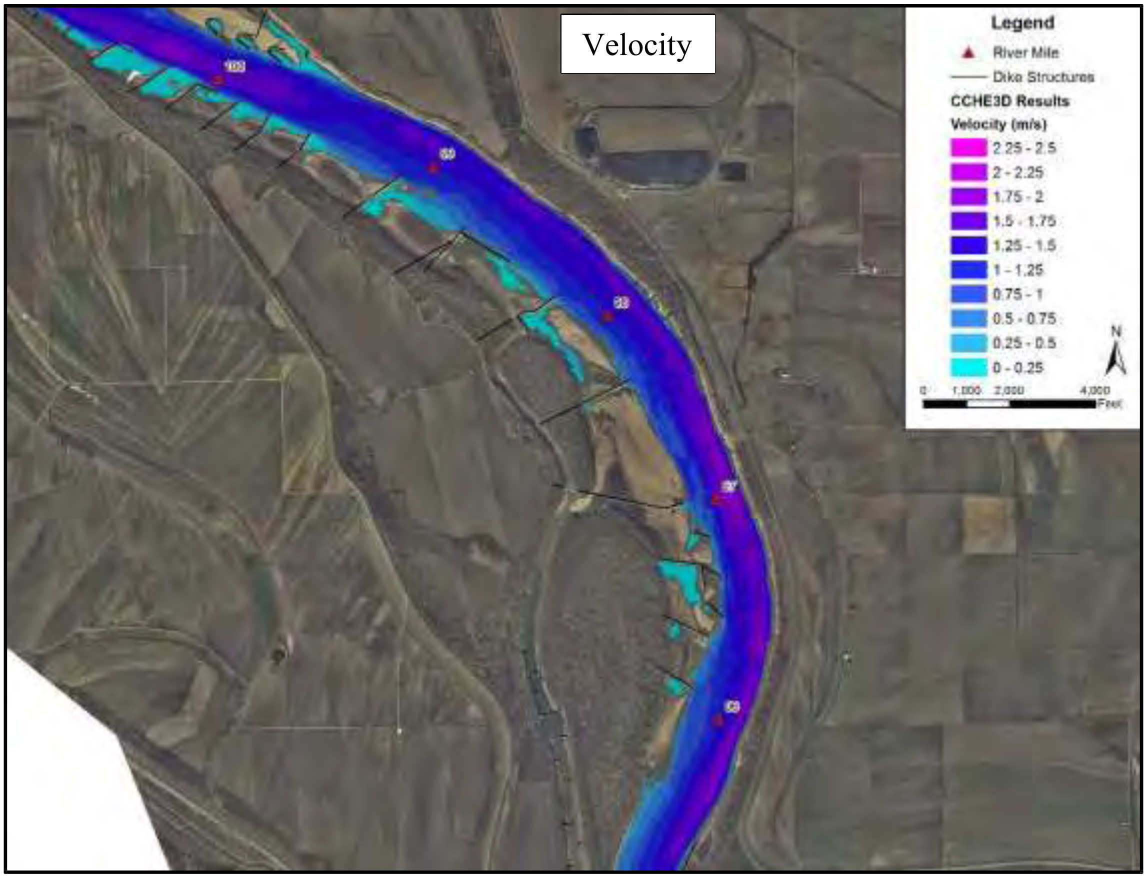


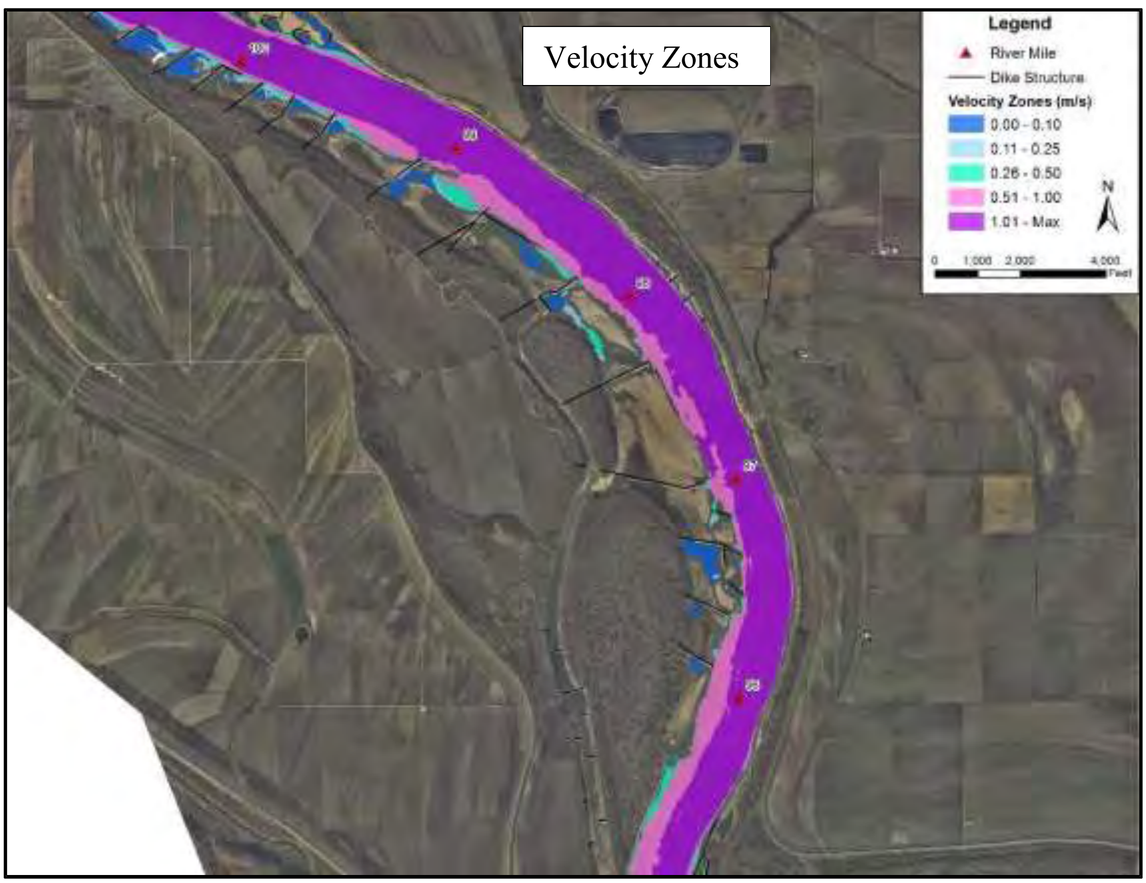
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 10 m below water surface for the study reach between RM 105 to RM 100



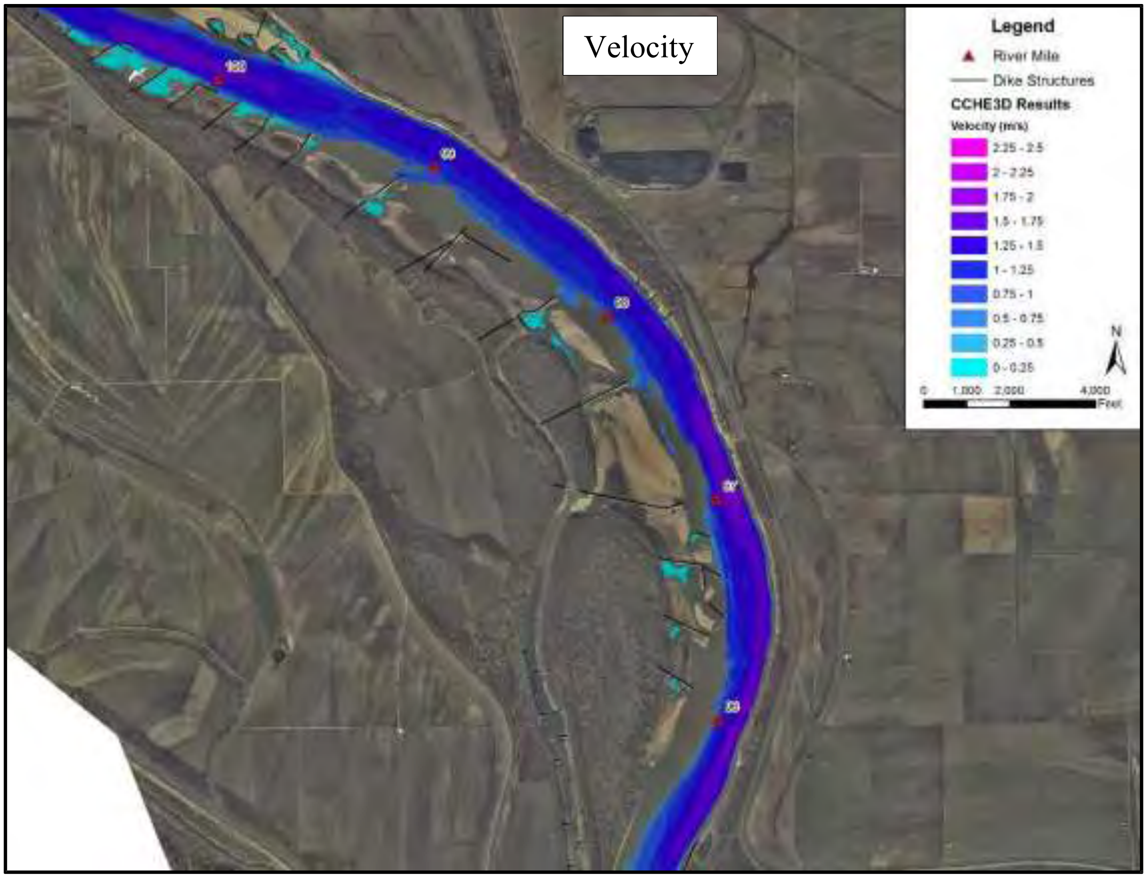


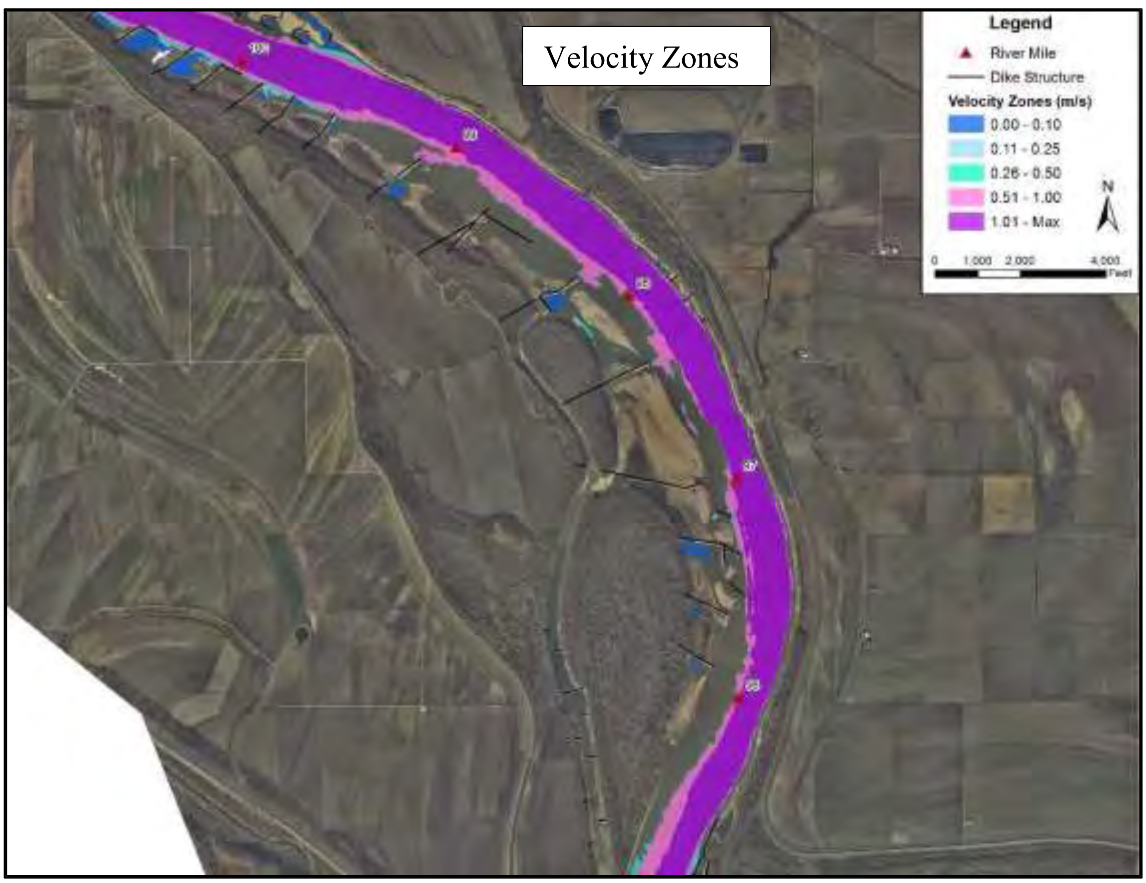
CCHE3D velocity results (flow of 3,143.2 m^3/s) at water surface for the study reach between RM 100 to RM 96



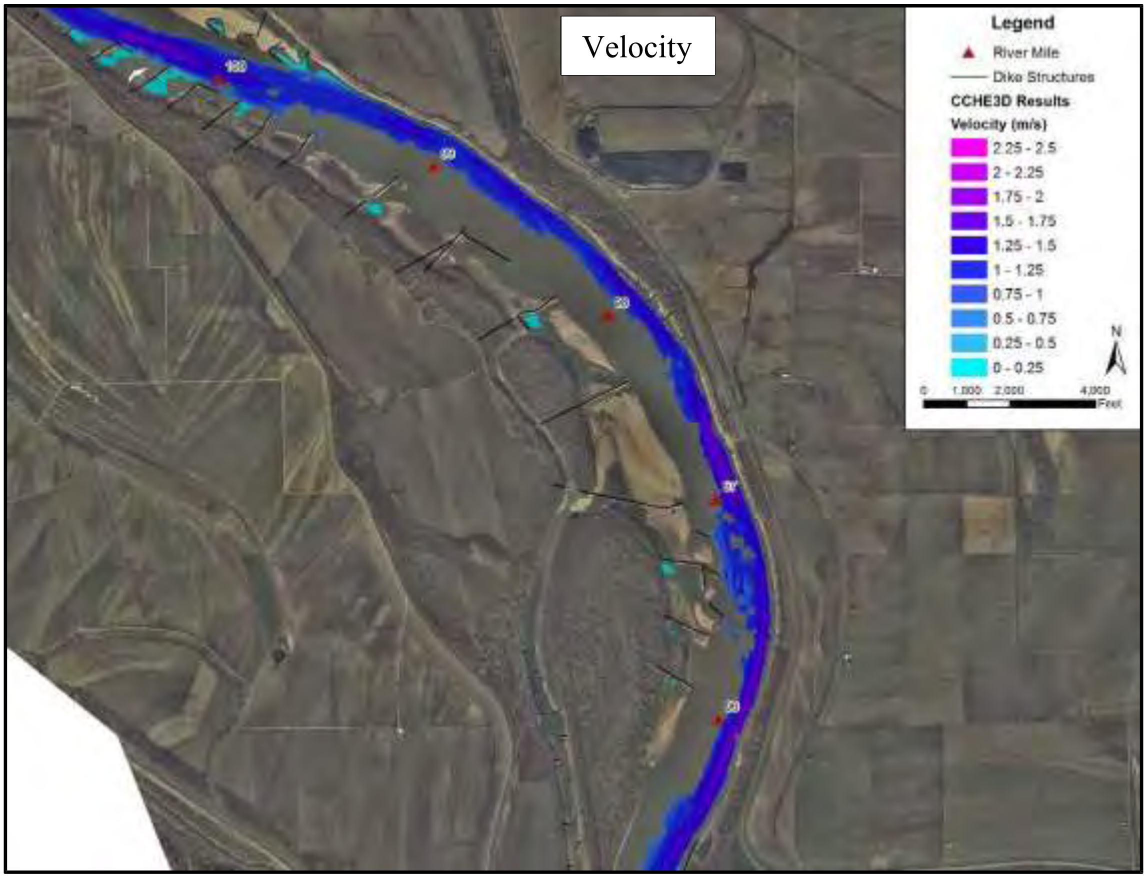


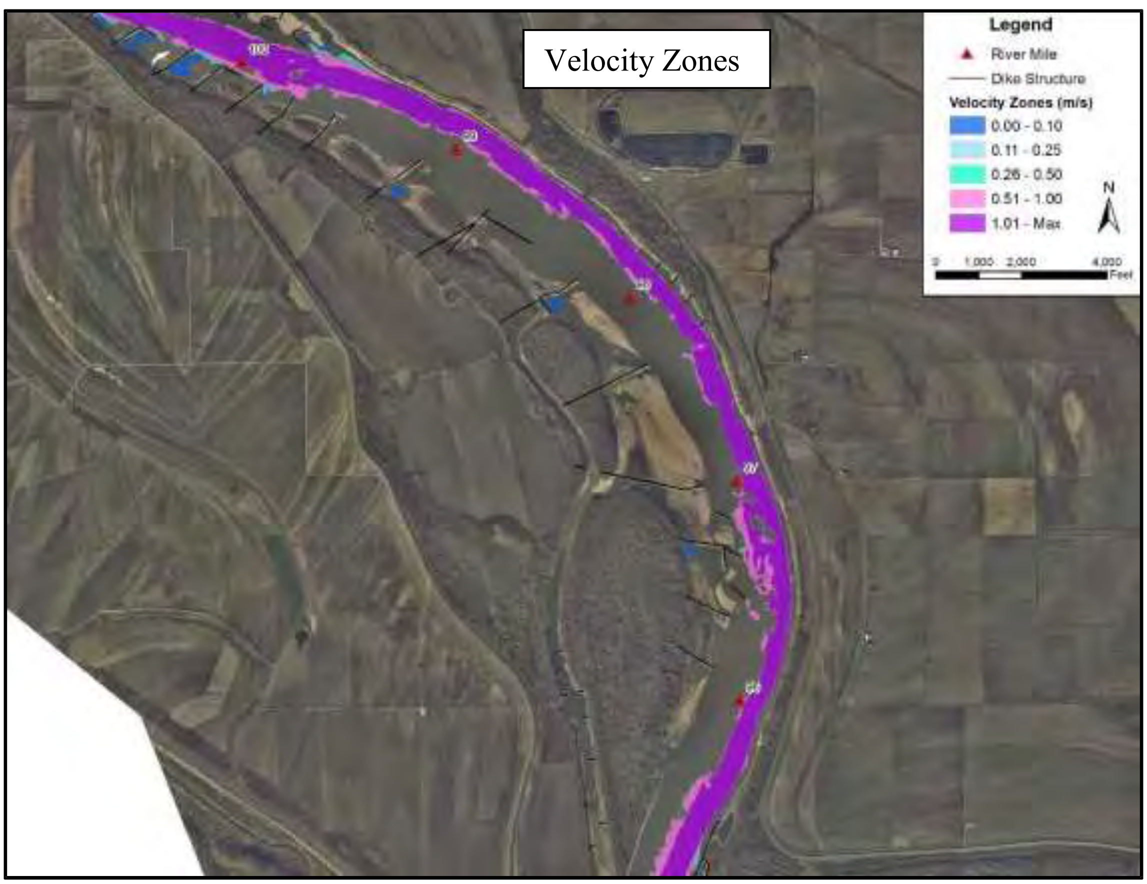
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 2 m below water surface for the study reach between RM 100 to RM 96



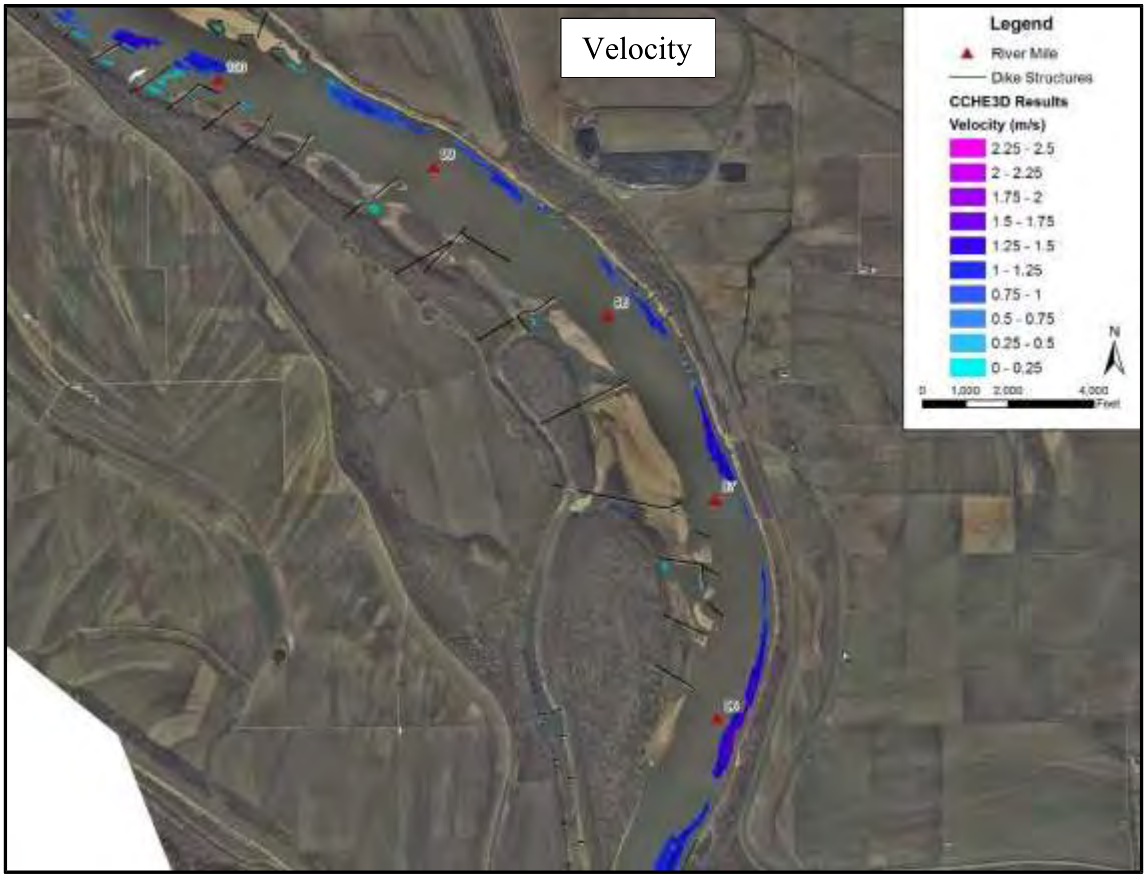


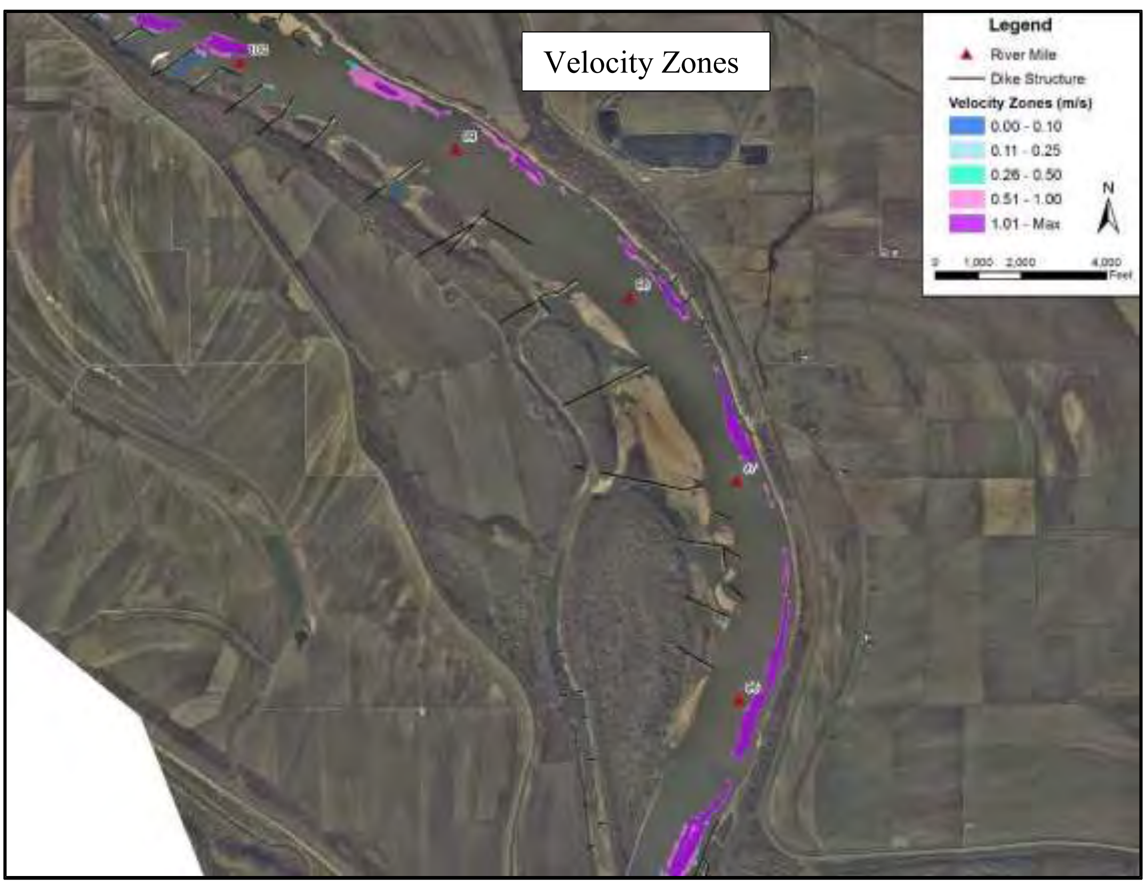
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 4 m below water surface for the study reach between RM 100 to RM 96



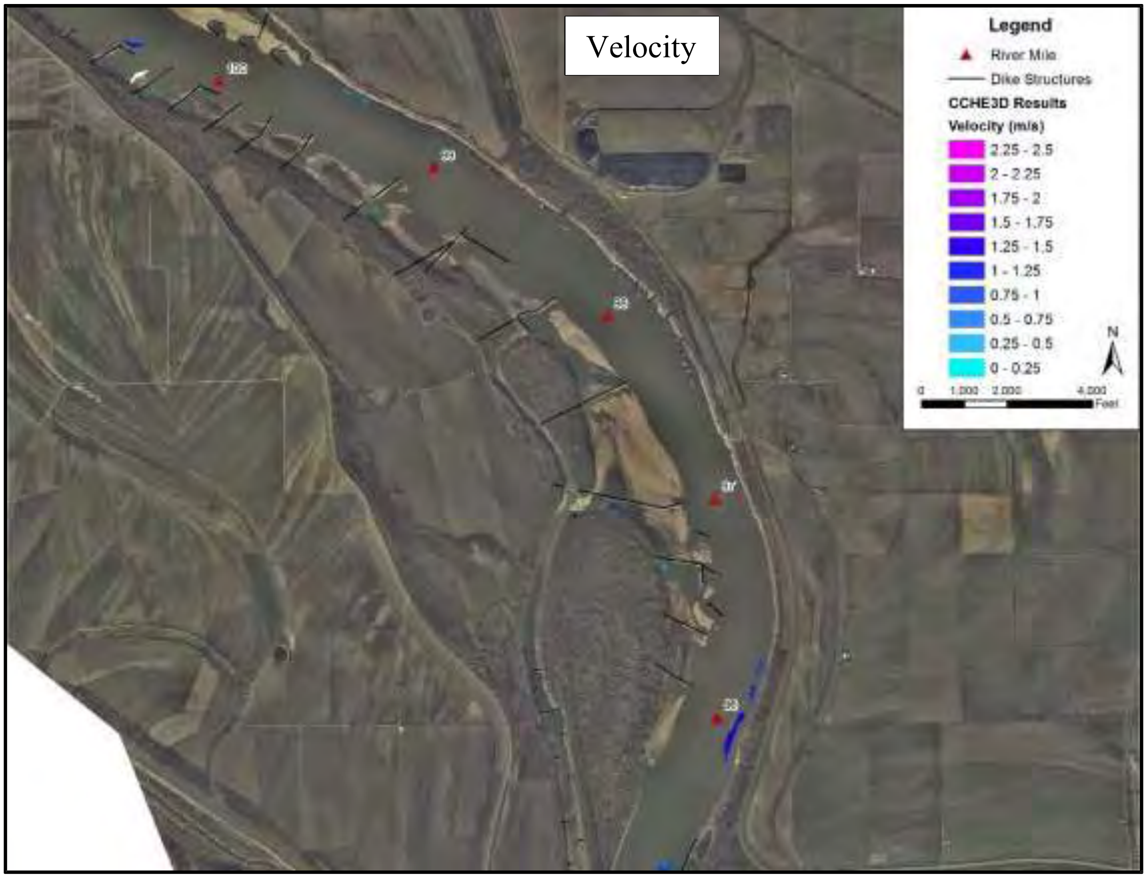


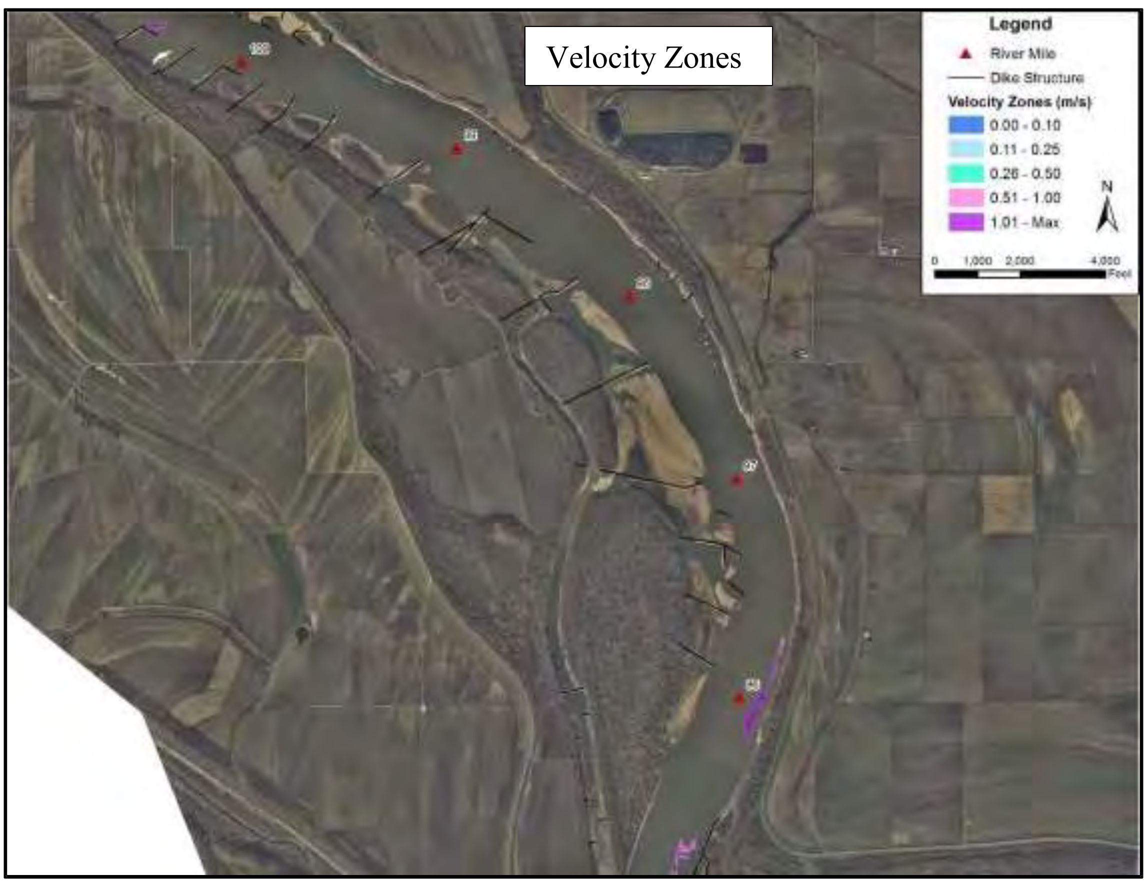
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 6 m below water surface for the study reach between RM 100 to RM 96



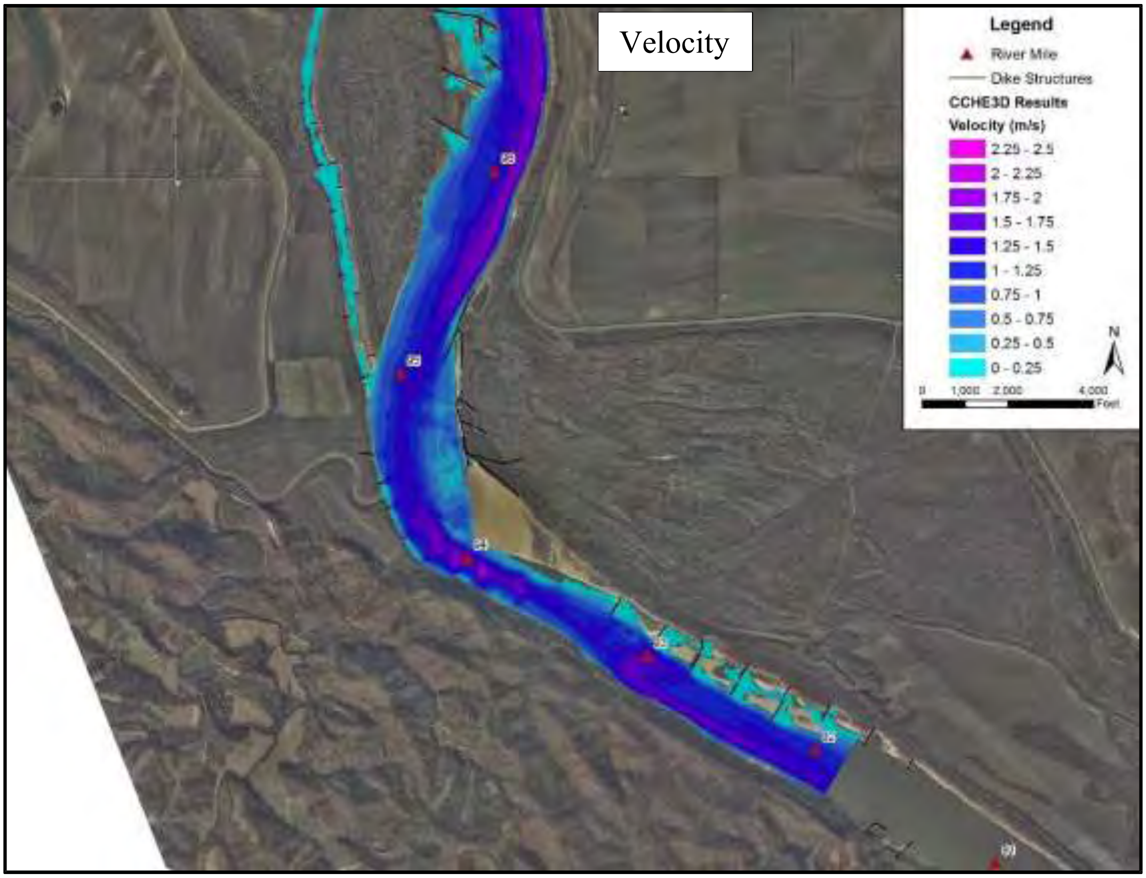


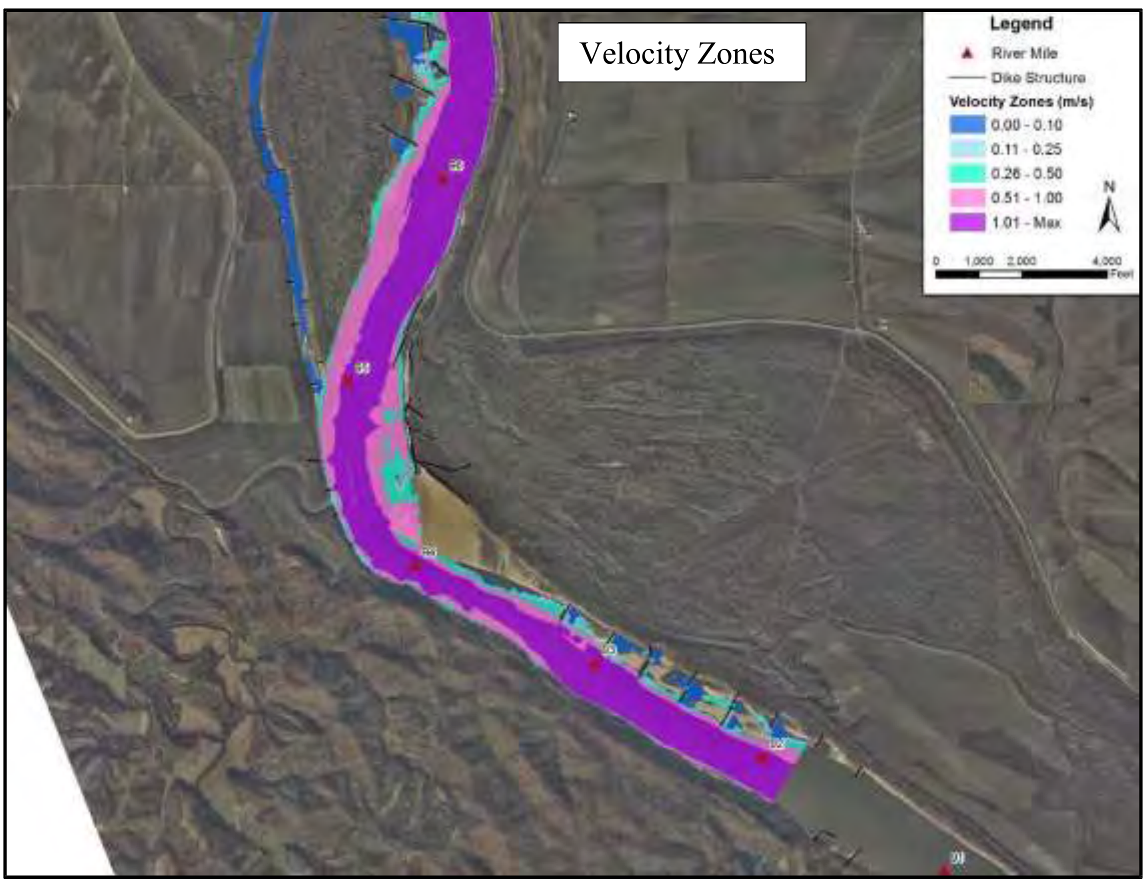
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 8 m below water surface for the study reach between RM 100 to RM 96



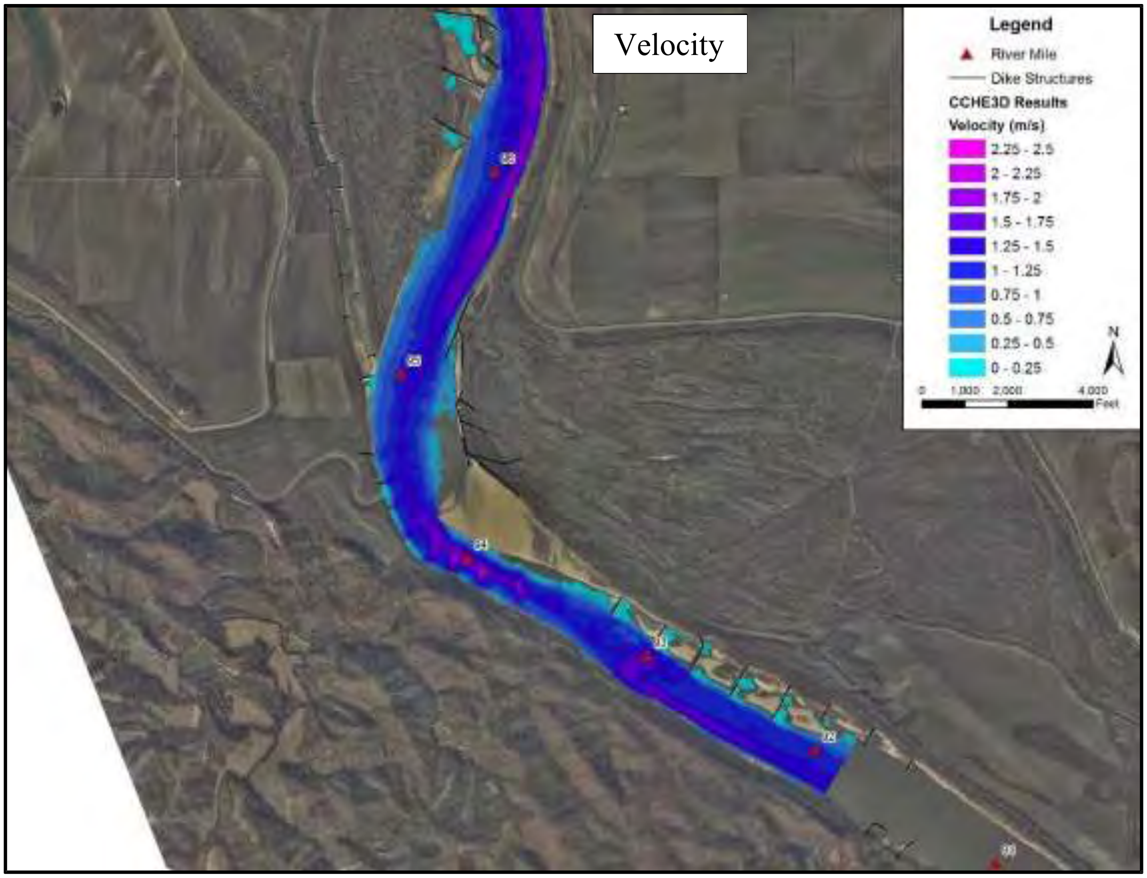


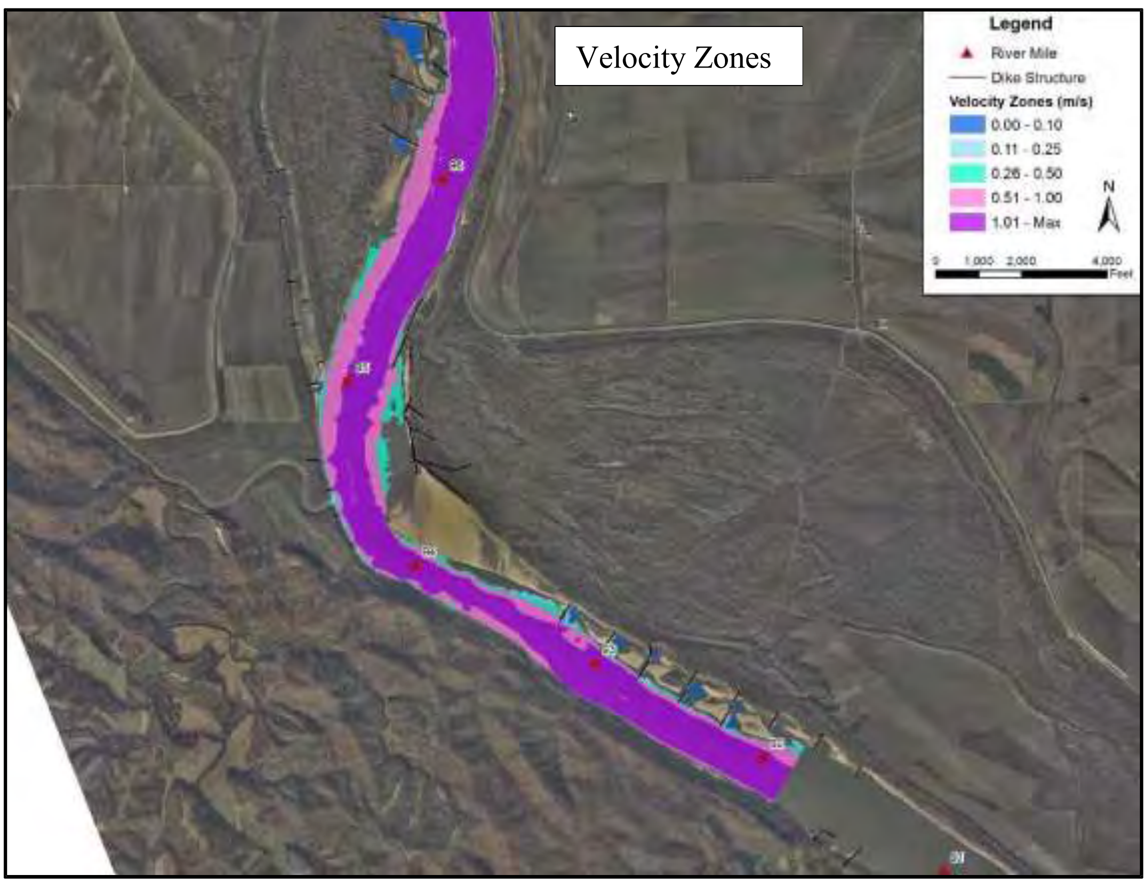
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 10 m below water surface for the study reach between RM 100 to RM 96



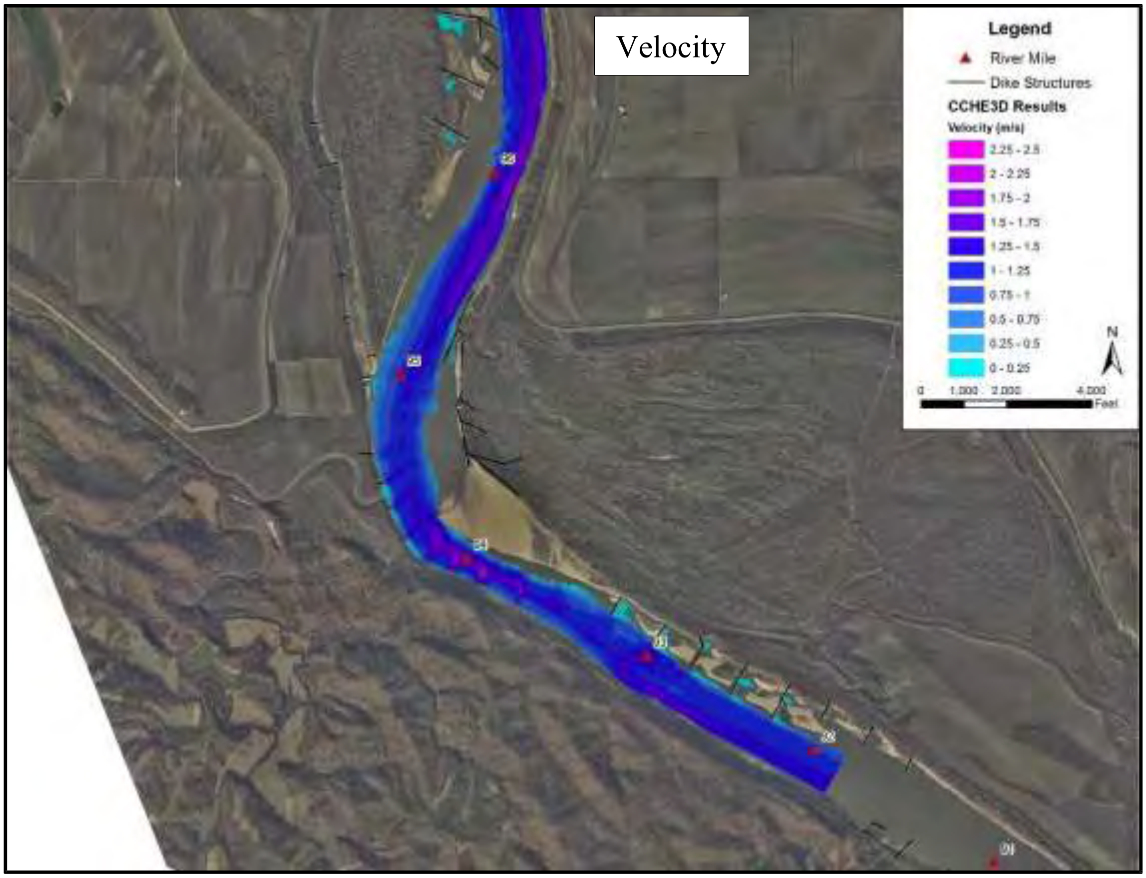


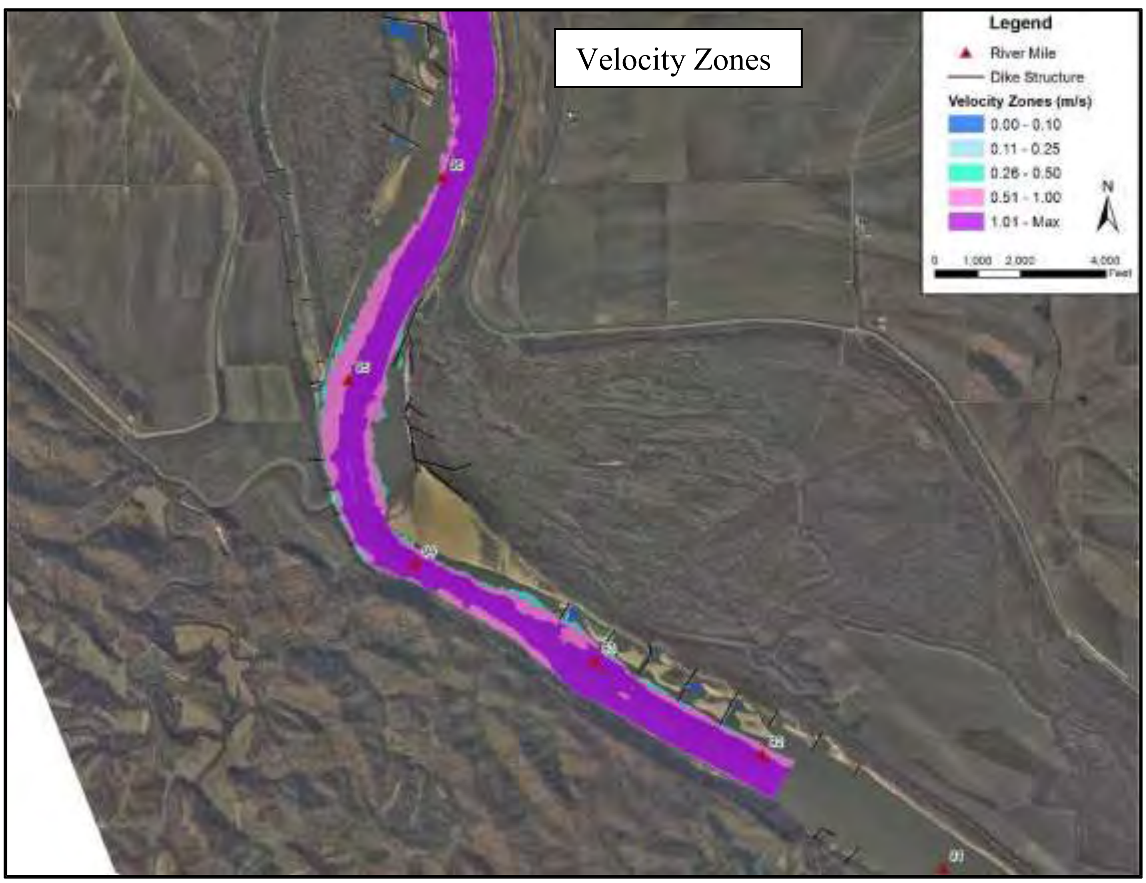
CCHE3D velocity results (flow of 3,143.2 m^3/s) at water surface for the study reach between RM 96 to RM 91



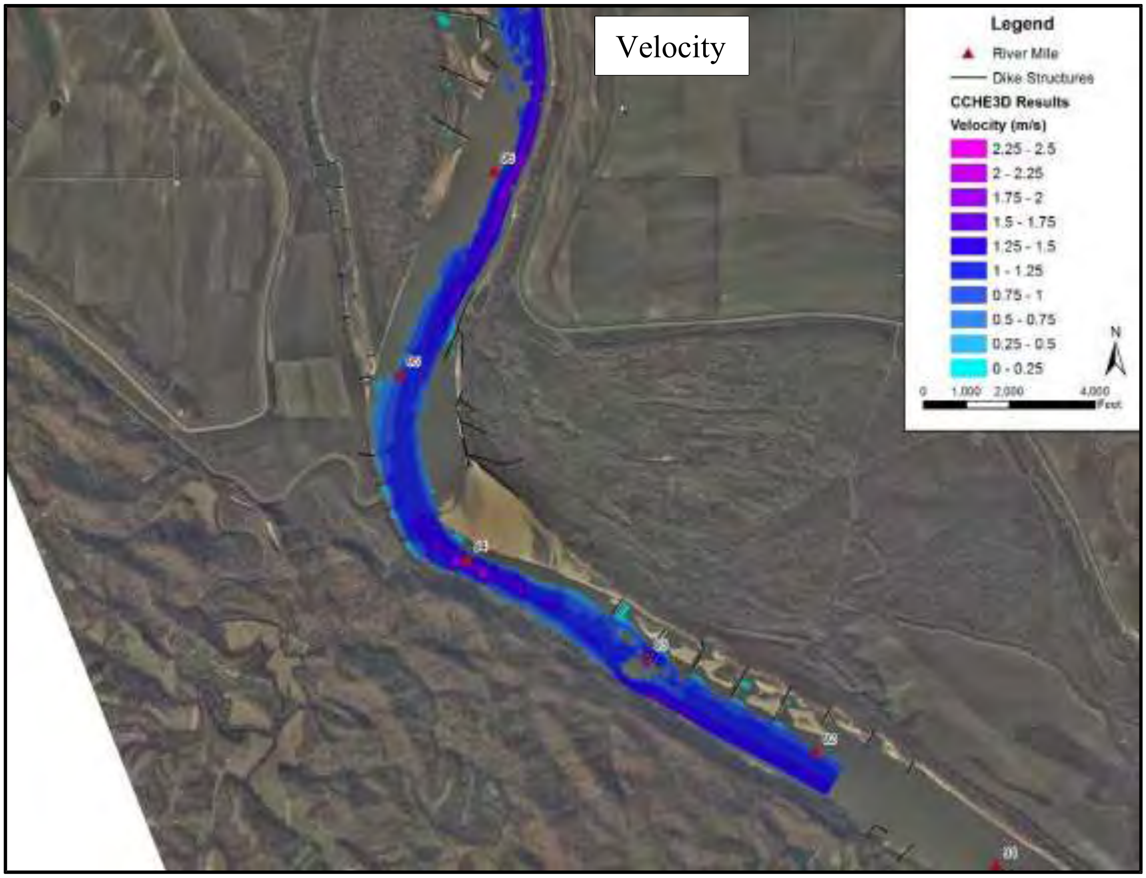


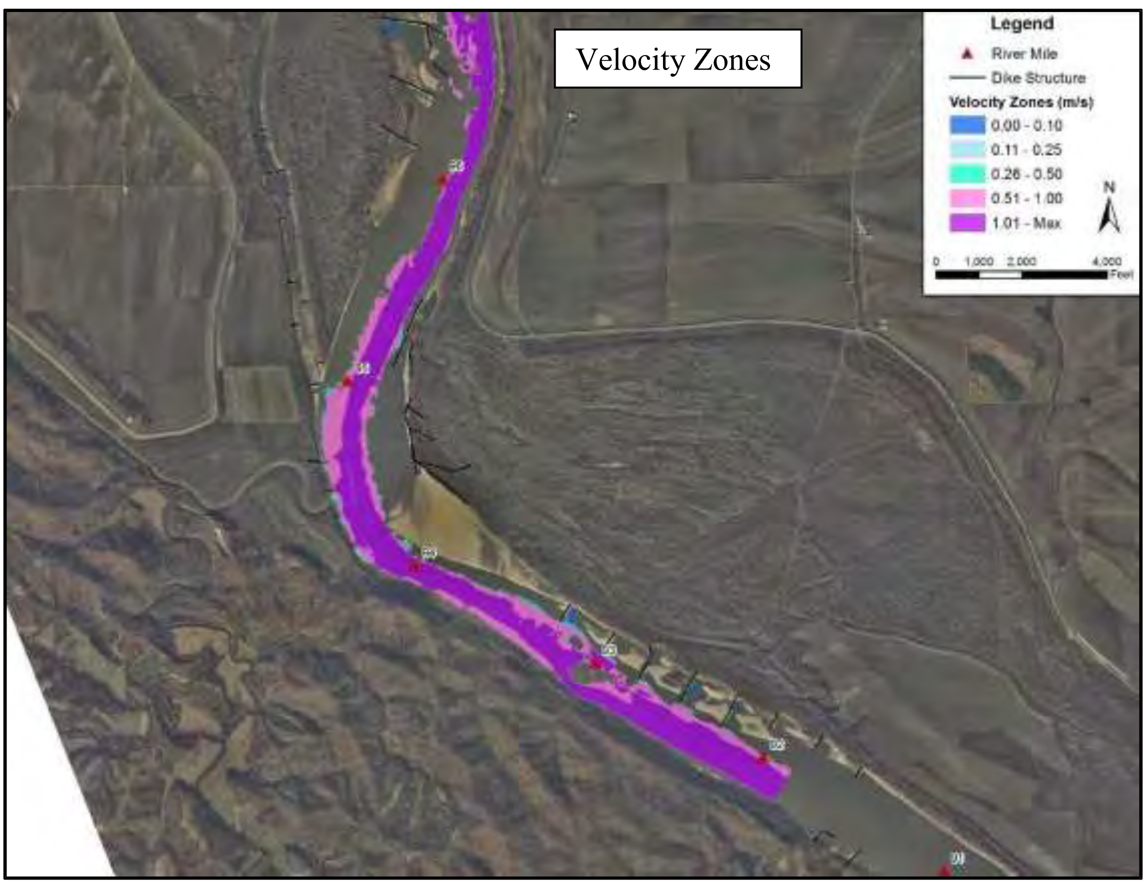
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 2 m below water surface for the study reach between RM 96 to RM 91



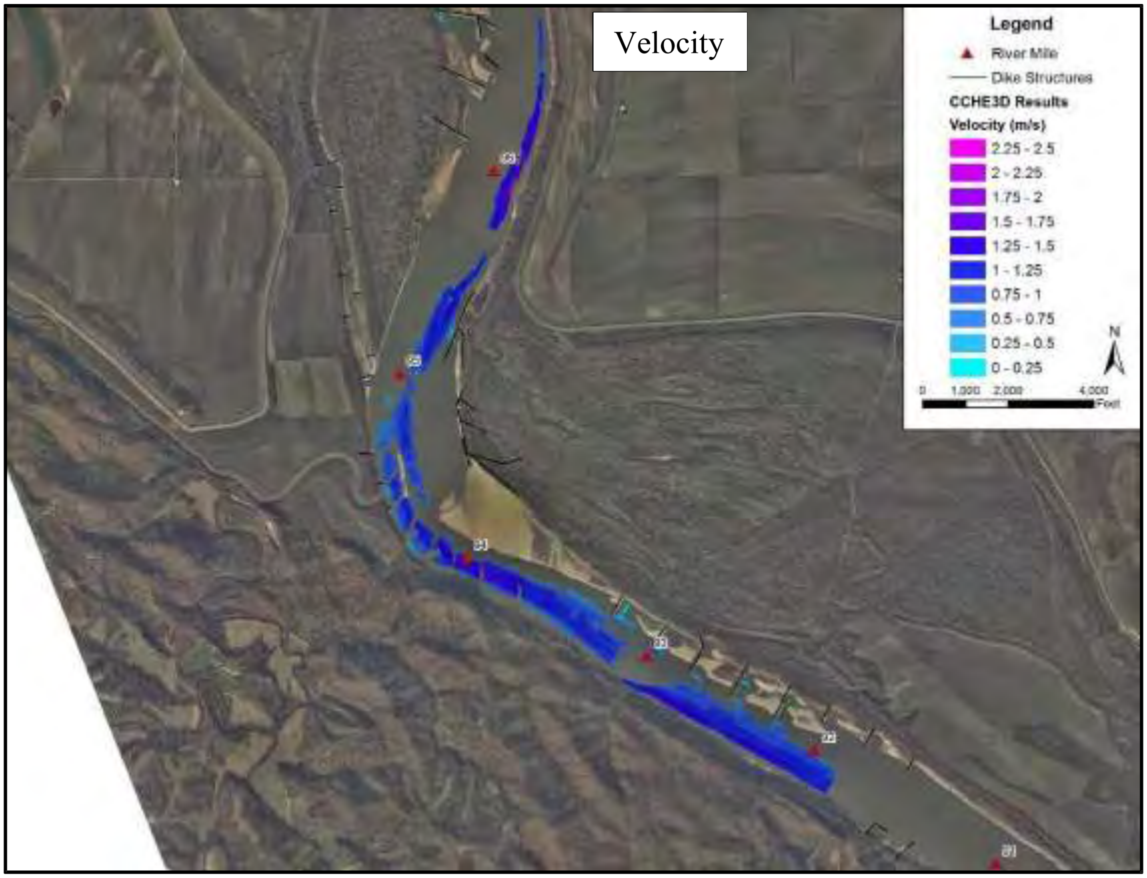


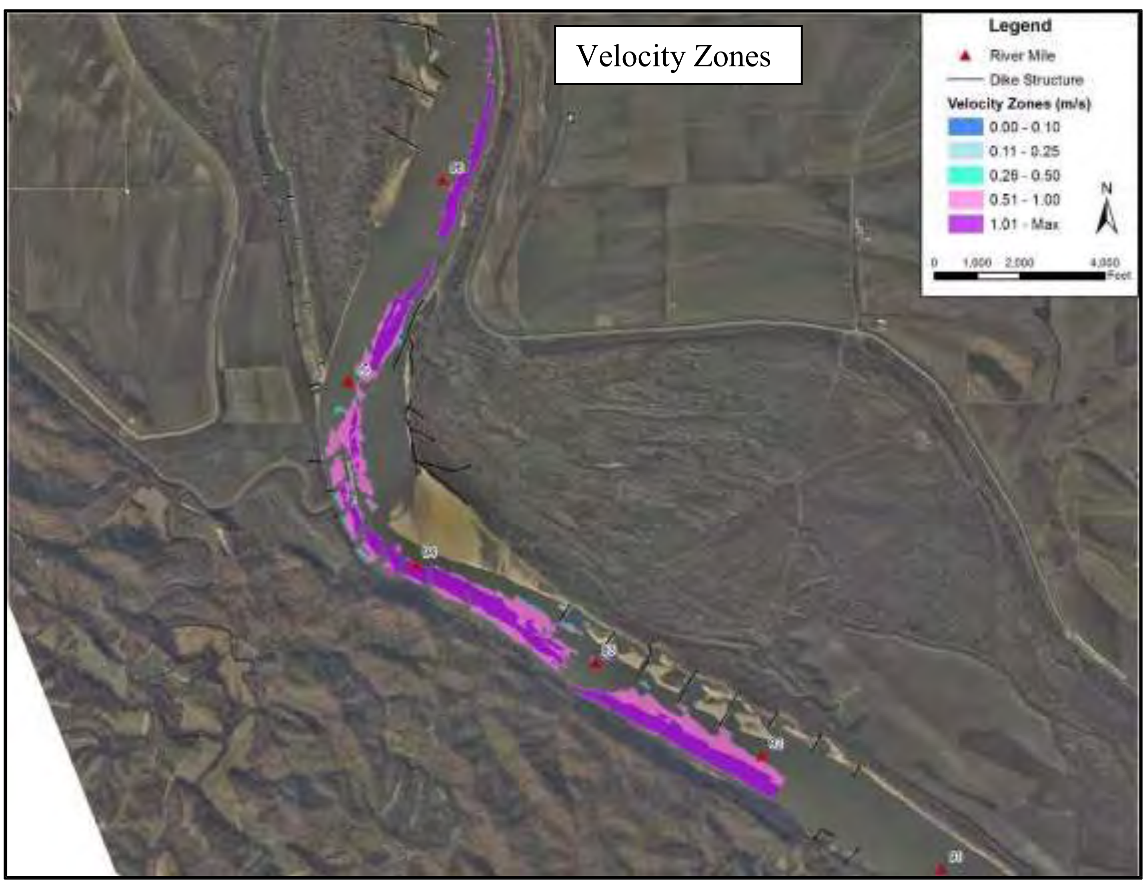
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 4 m below water surface for the study reach between RM 96 to RM 91



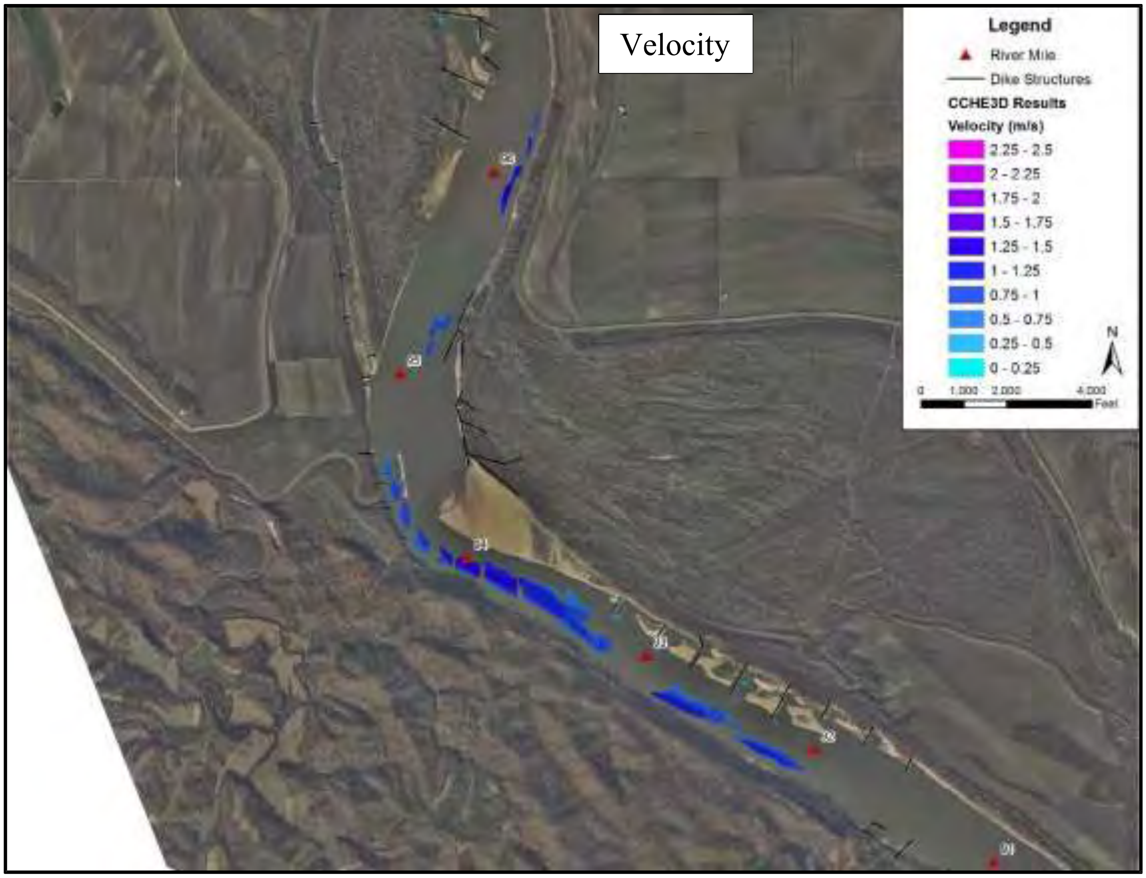


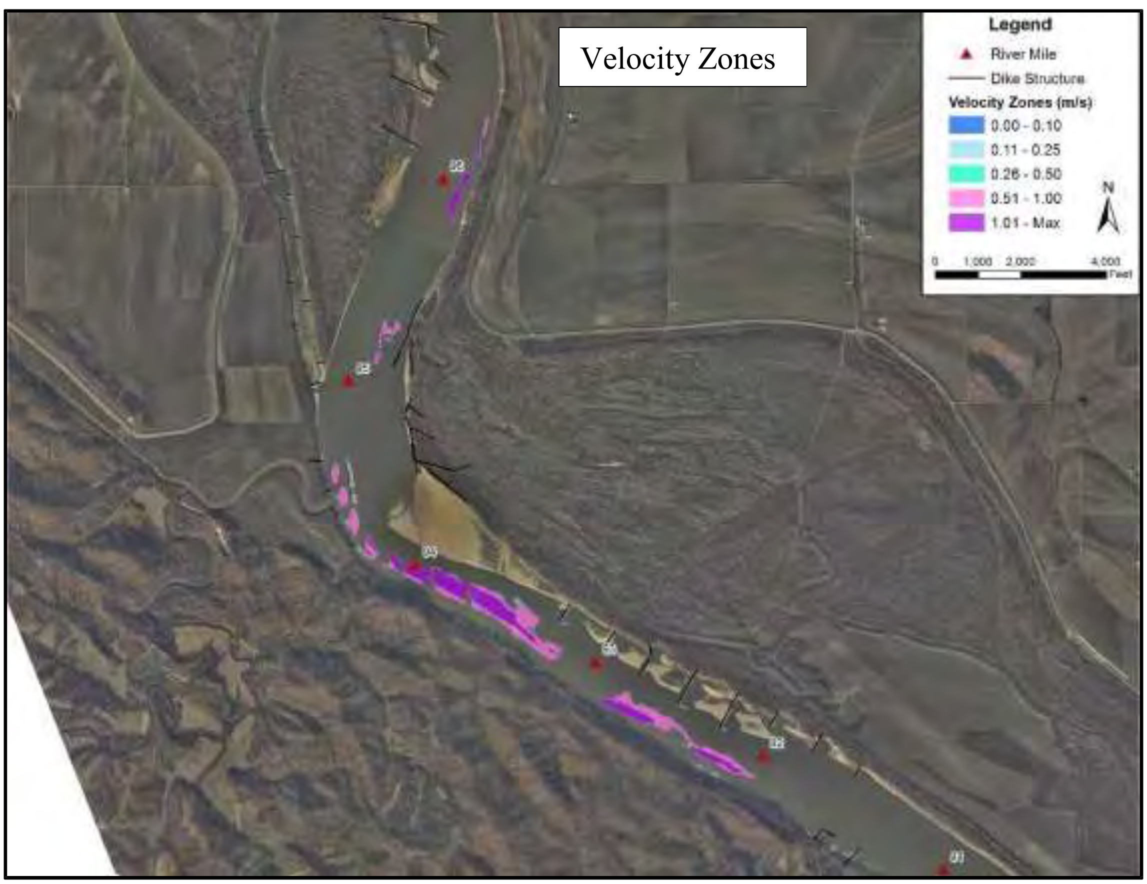
CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 6 m below water surface for the study reach between RM 96 to RM 91





CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 8 m below water surface for the study reach between RM 96 to RM 91

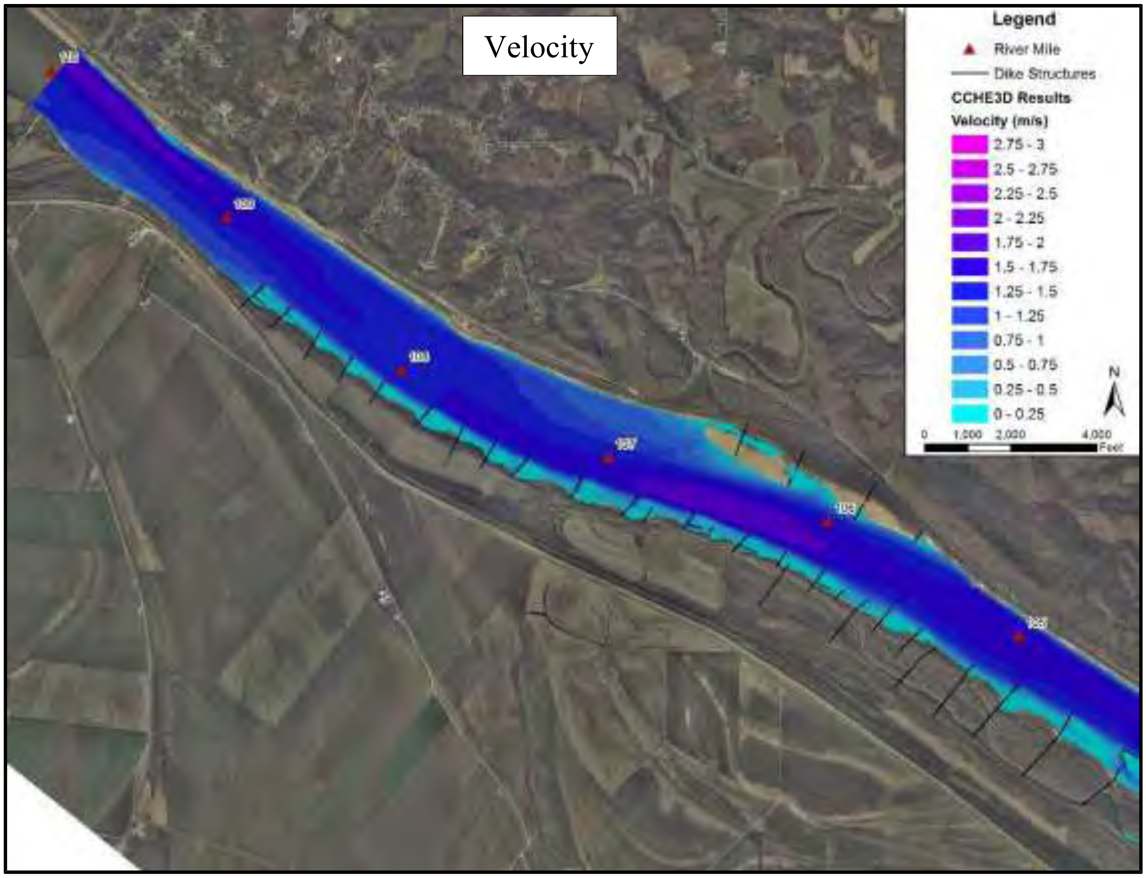


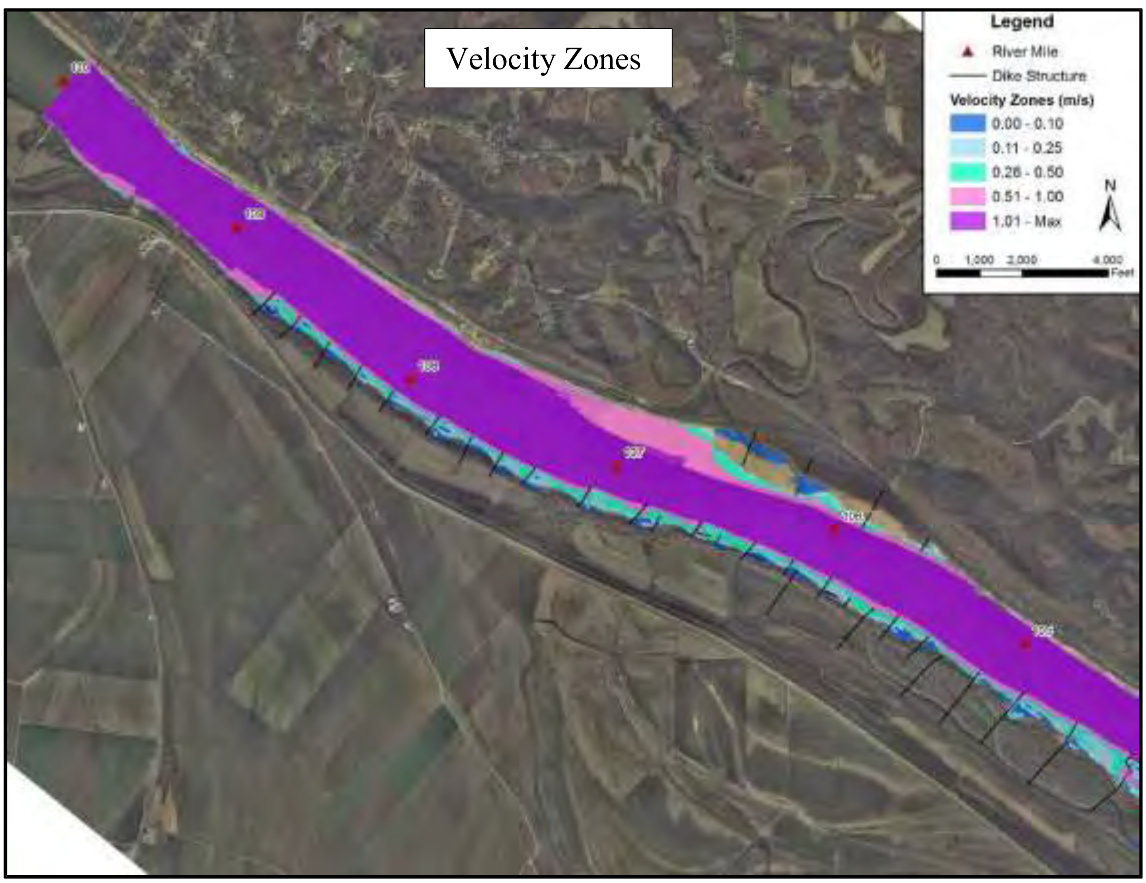


CCHE3D velocity results (flow of 3,143.2 m^3/s) at a depth of 10 m below water surface for the study reach between RM 96 to RM 91

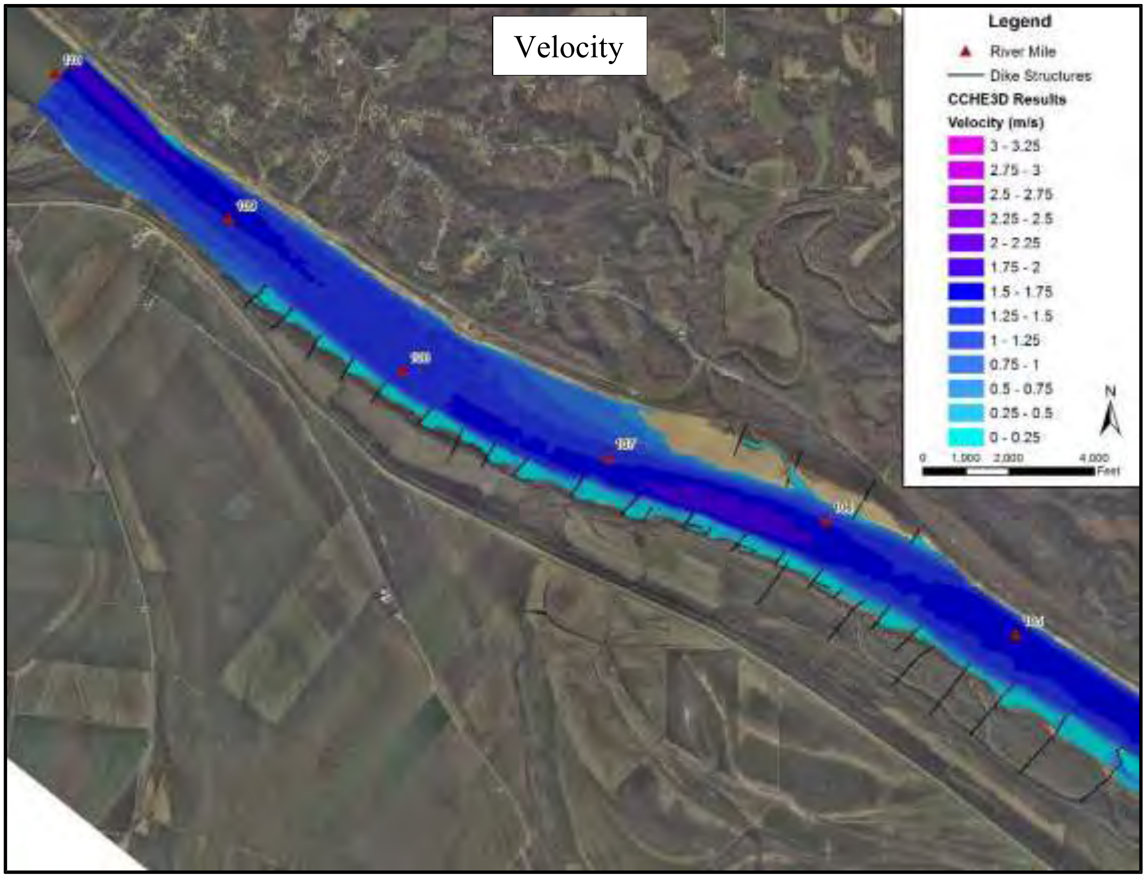
APPENDIX B.2

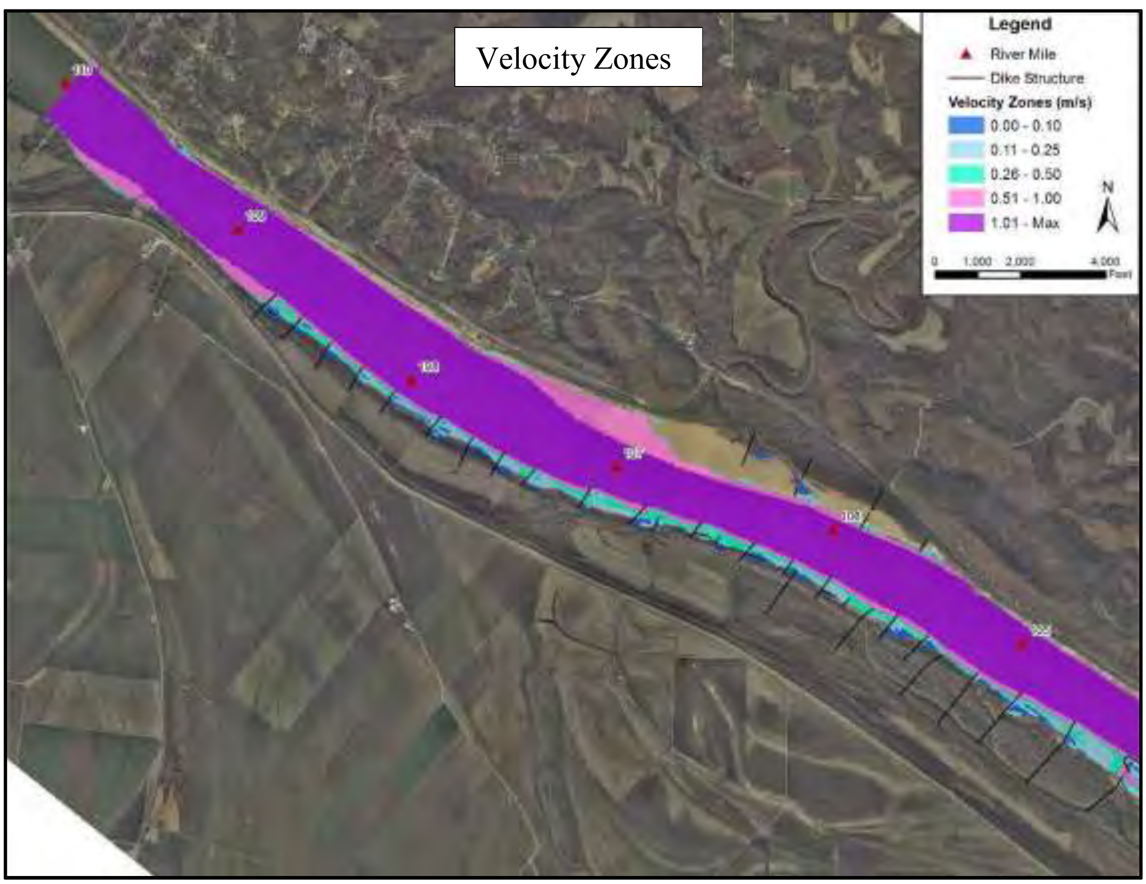
STUDY REACH CCHE3D MODEL VELOCITY AND VELOCITY RECLASSIFICATION RESULTS (FLOW OF 6,031.5 M^3/S)



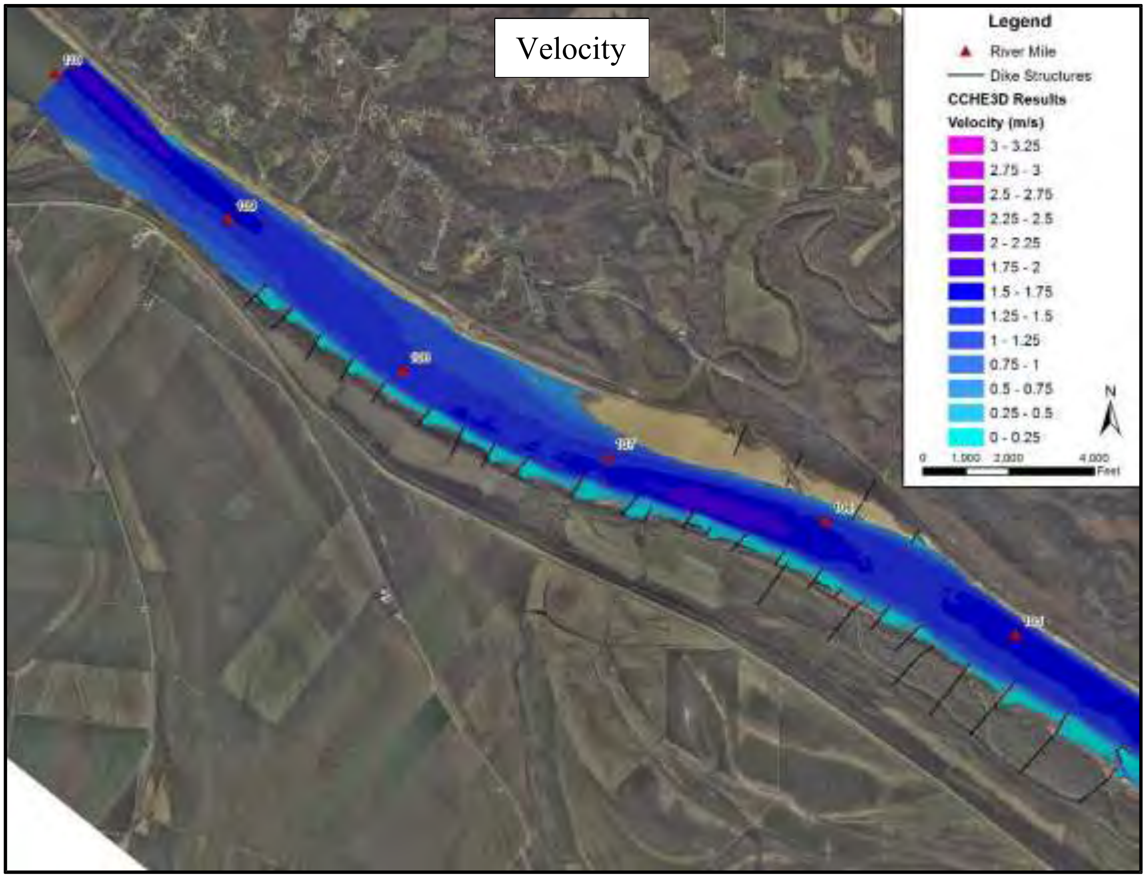


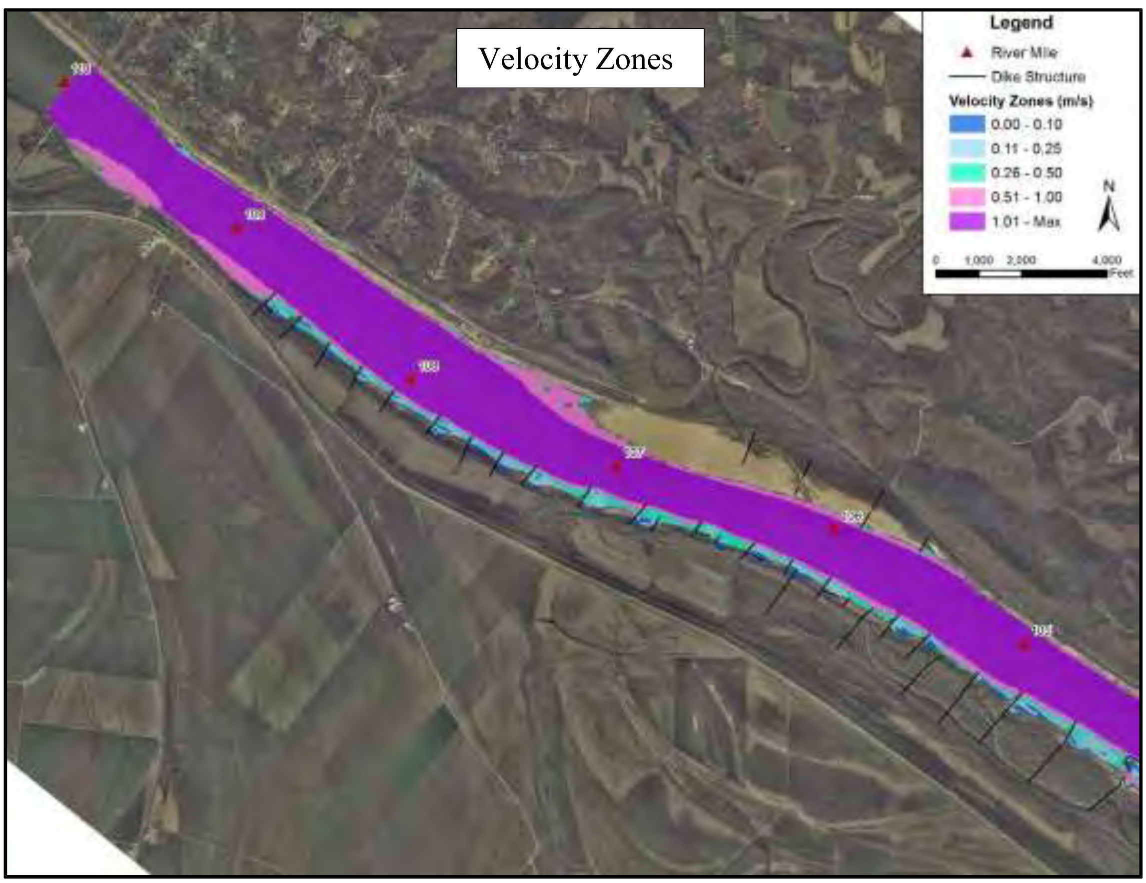
CCHE3D velocity results (flow of 6,031.5 m^3/s) at water surface for the study reach between RM 110 to RM 105



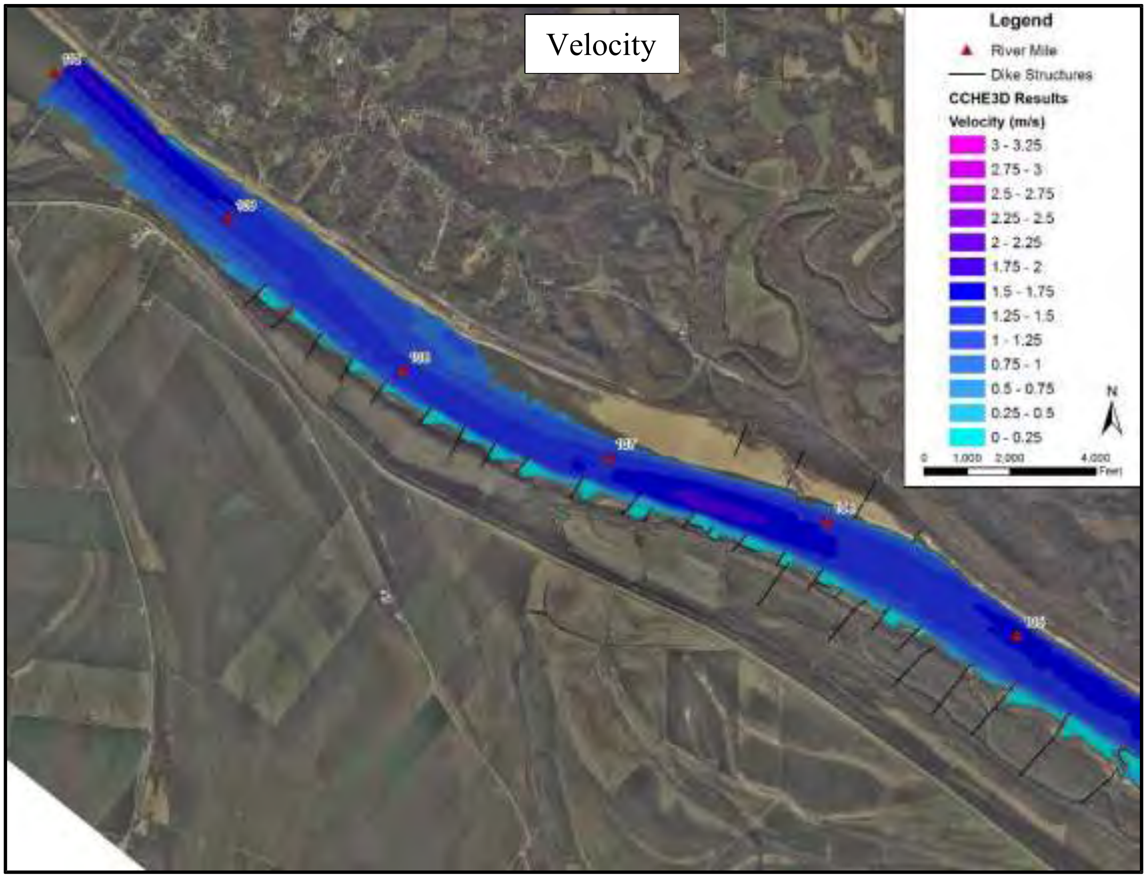


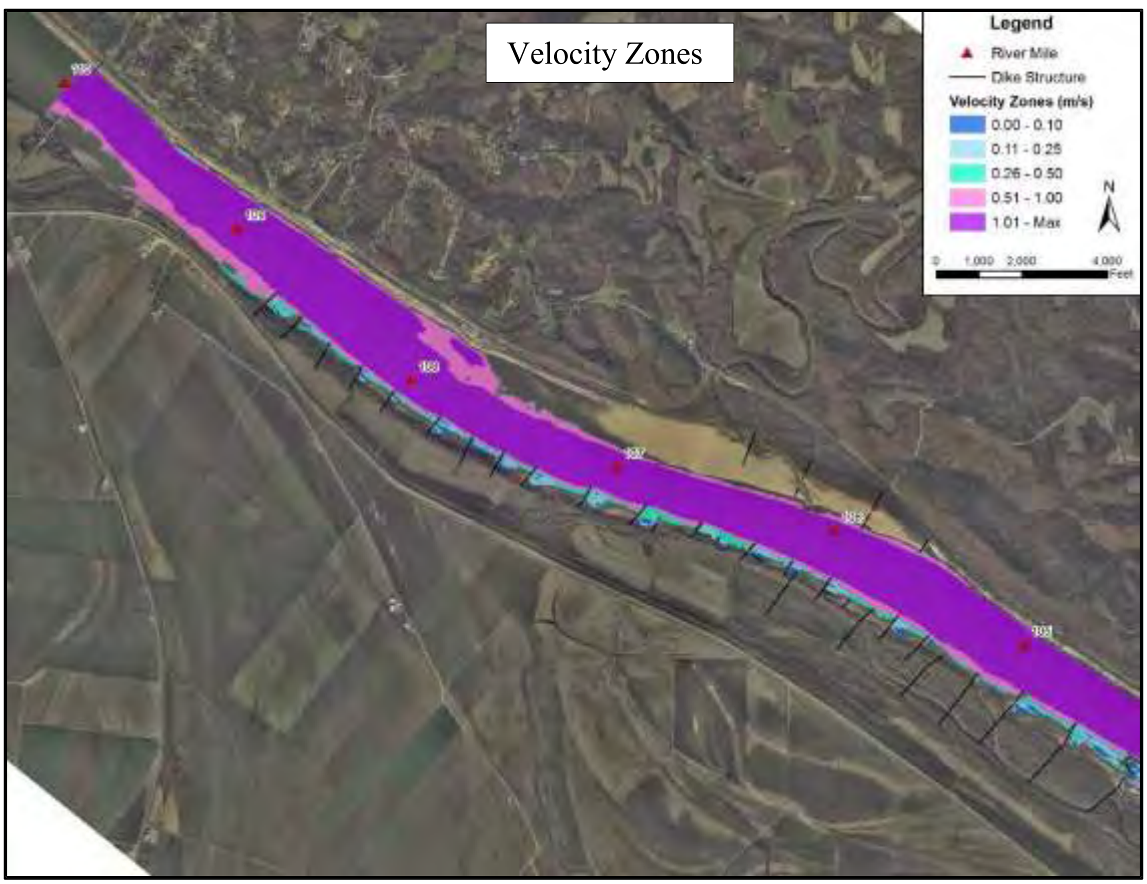
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 2 m below water surface for the study reach between RM 110 to RM 105



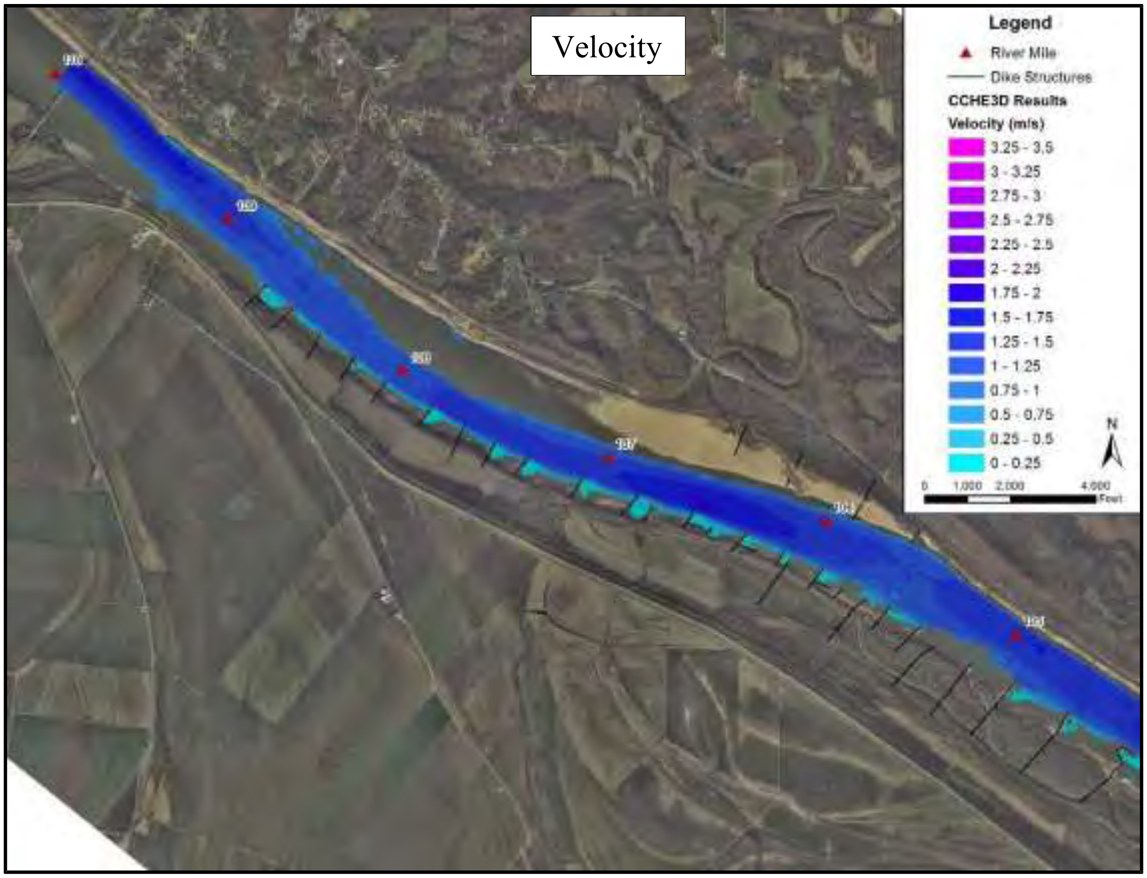


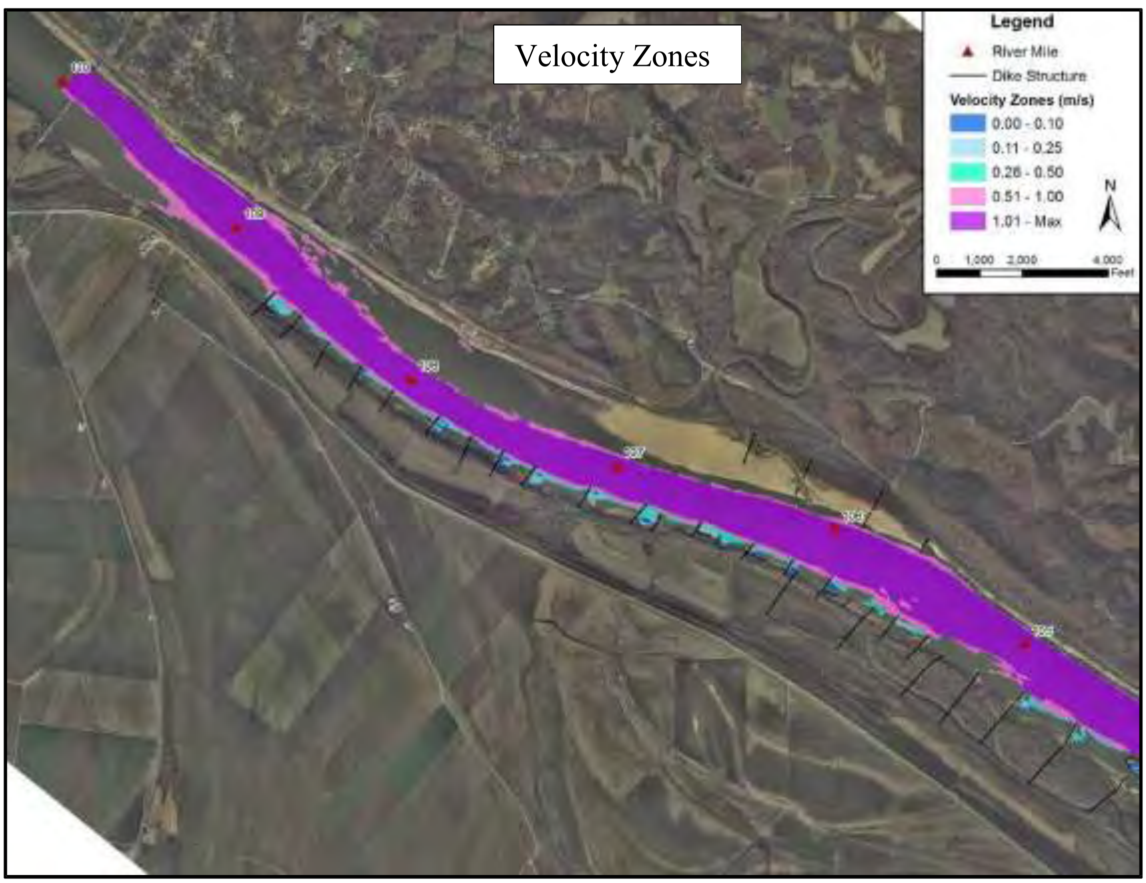
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 4 m below water surface for the study reach between RM 110 to RM 105



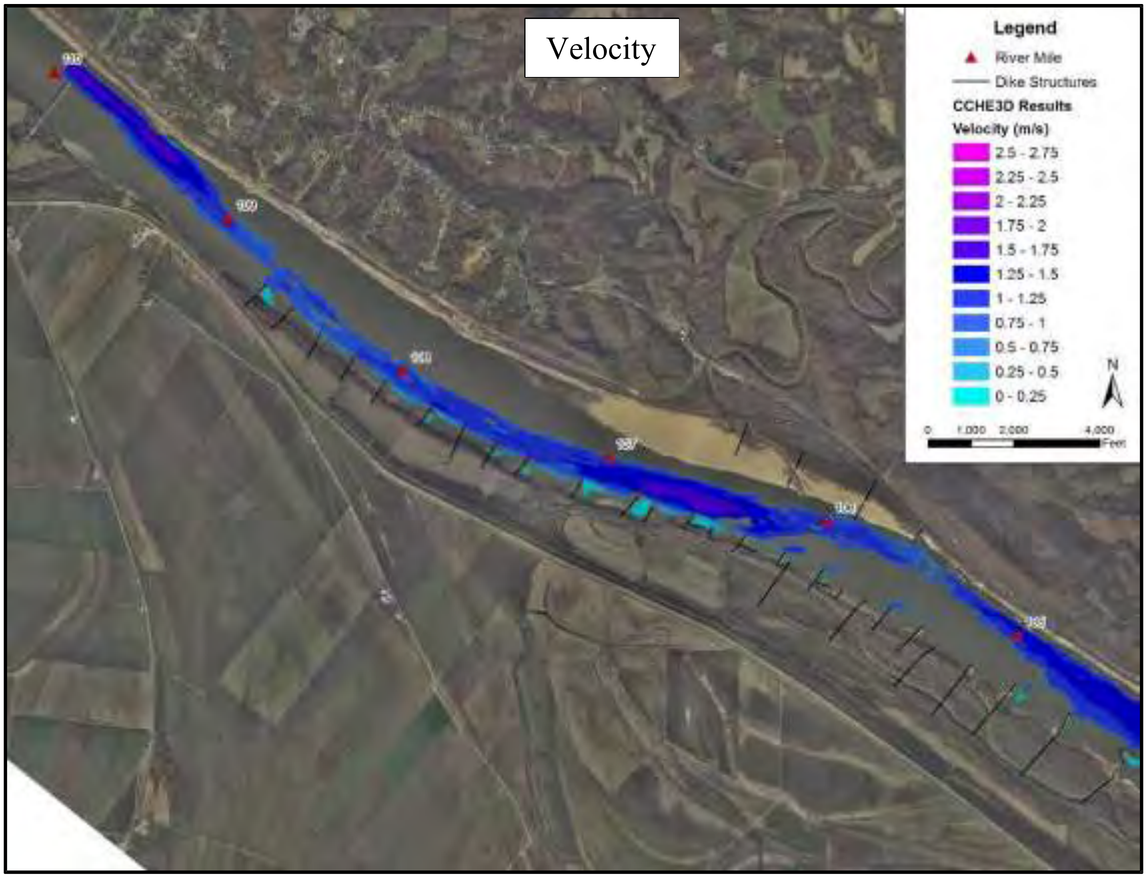


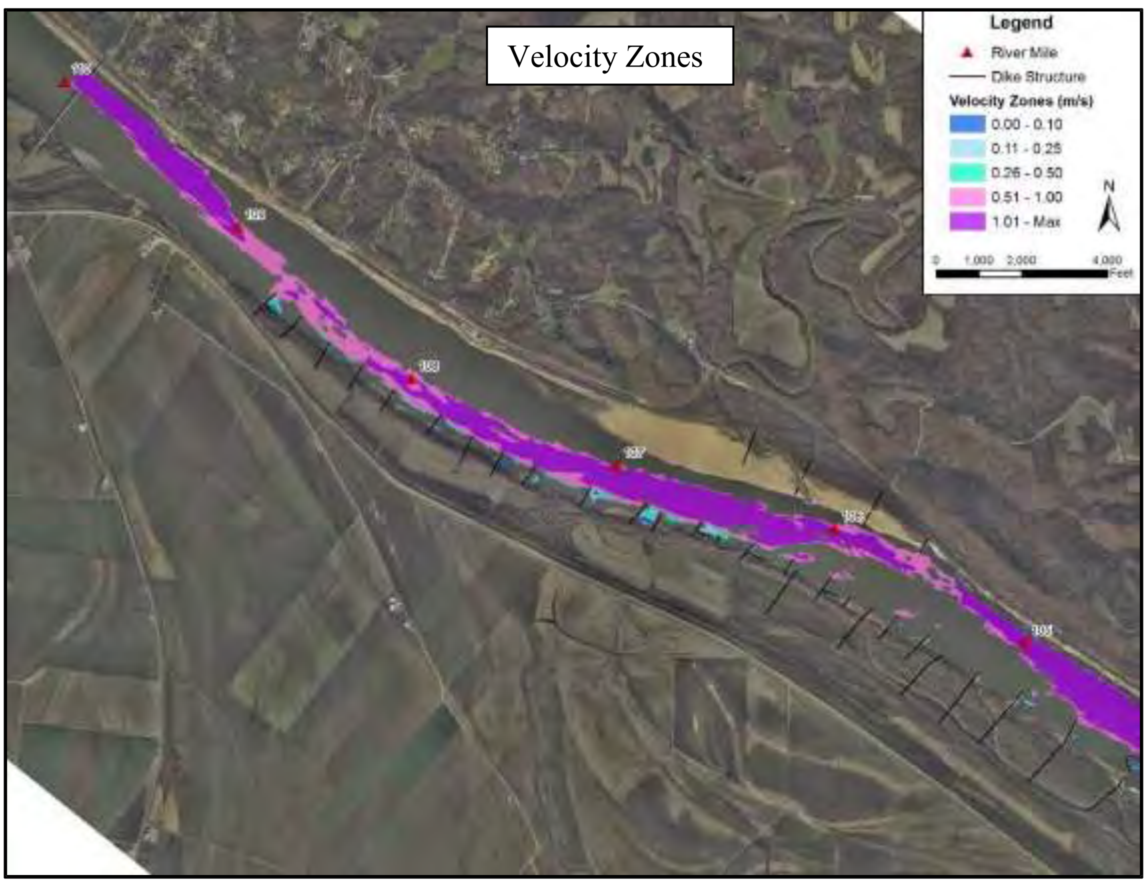
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 6 m below water surface for the study reach between RM 110 to RM 105



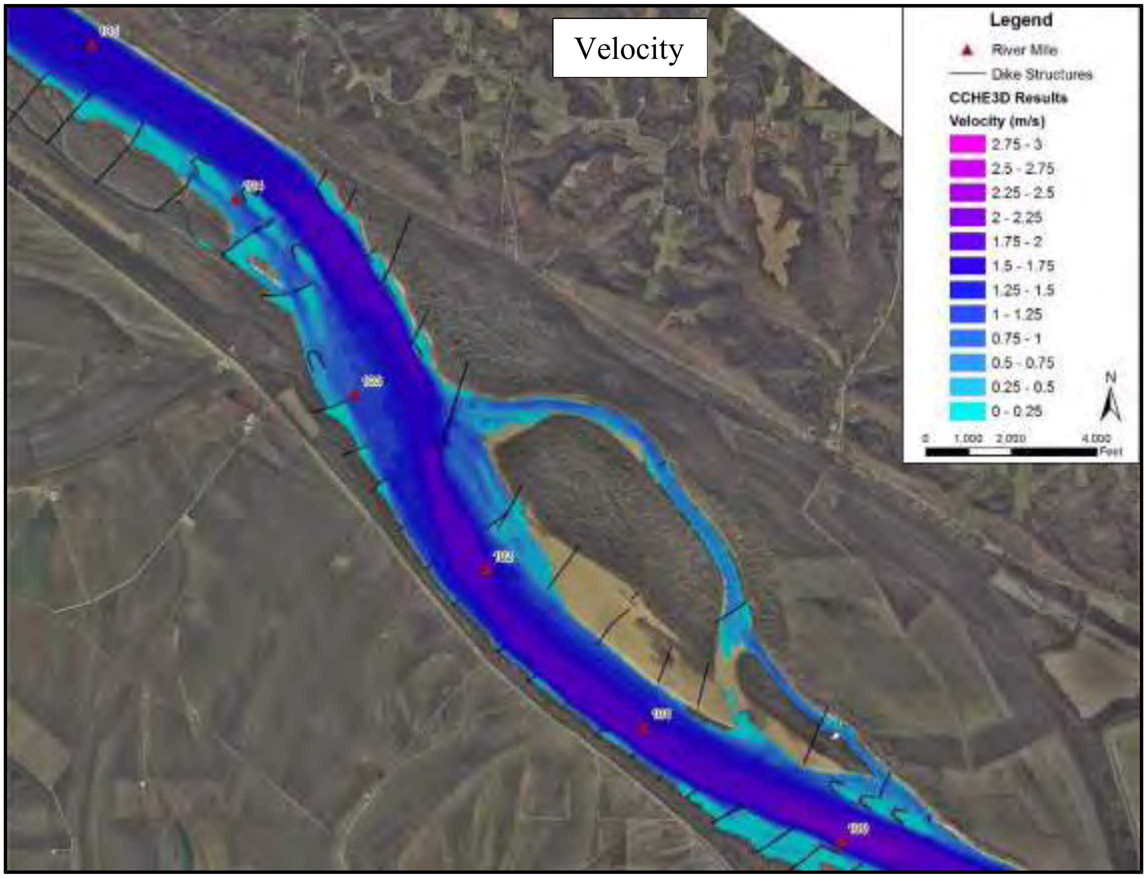


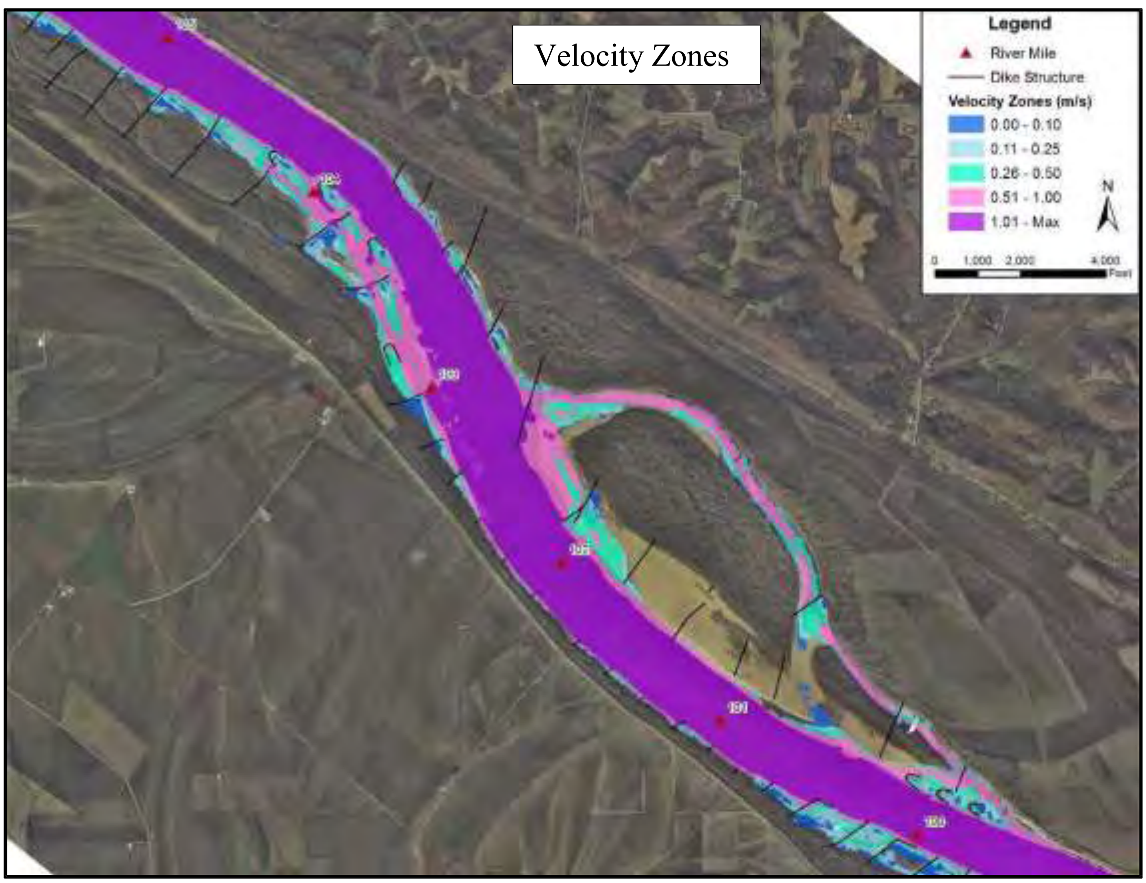
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 8 m below water surface for the study reach between RM 110 to RM 105



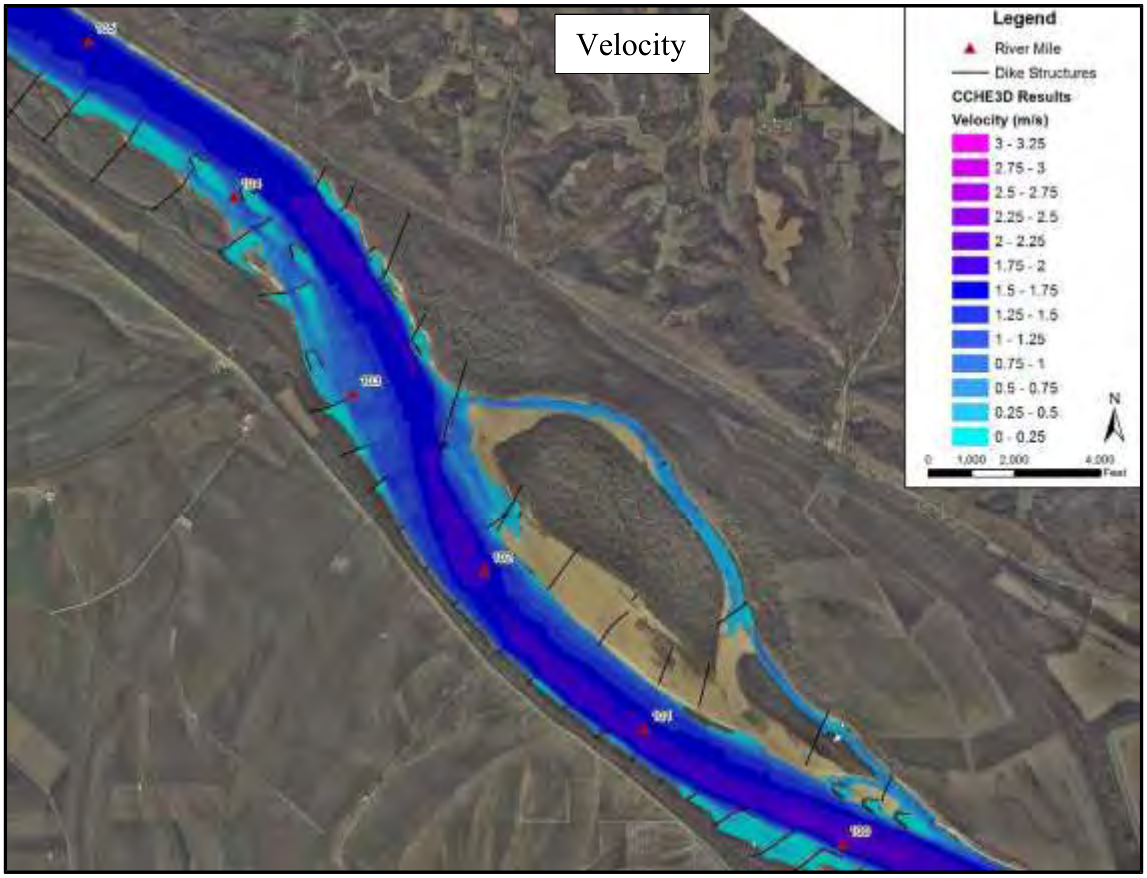


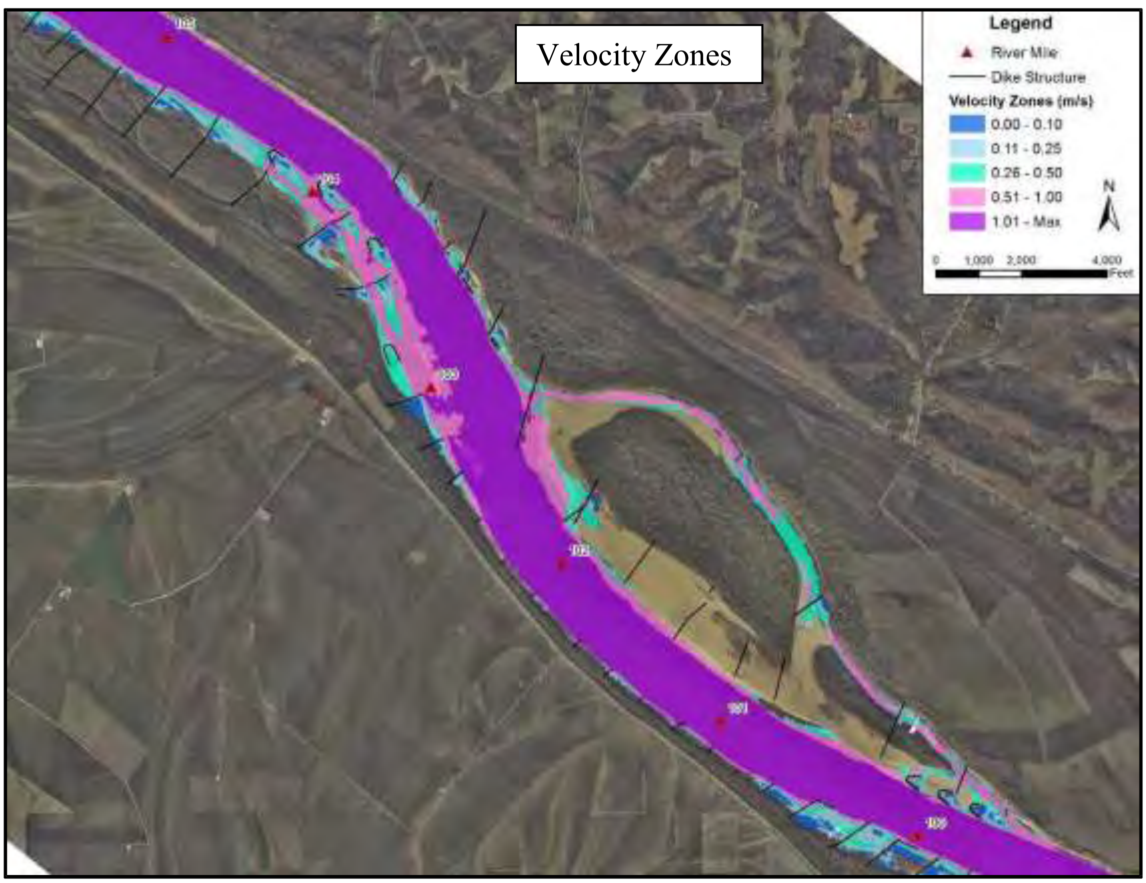
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 10 m below water surface for the study reach between RM 110 to RM 105



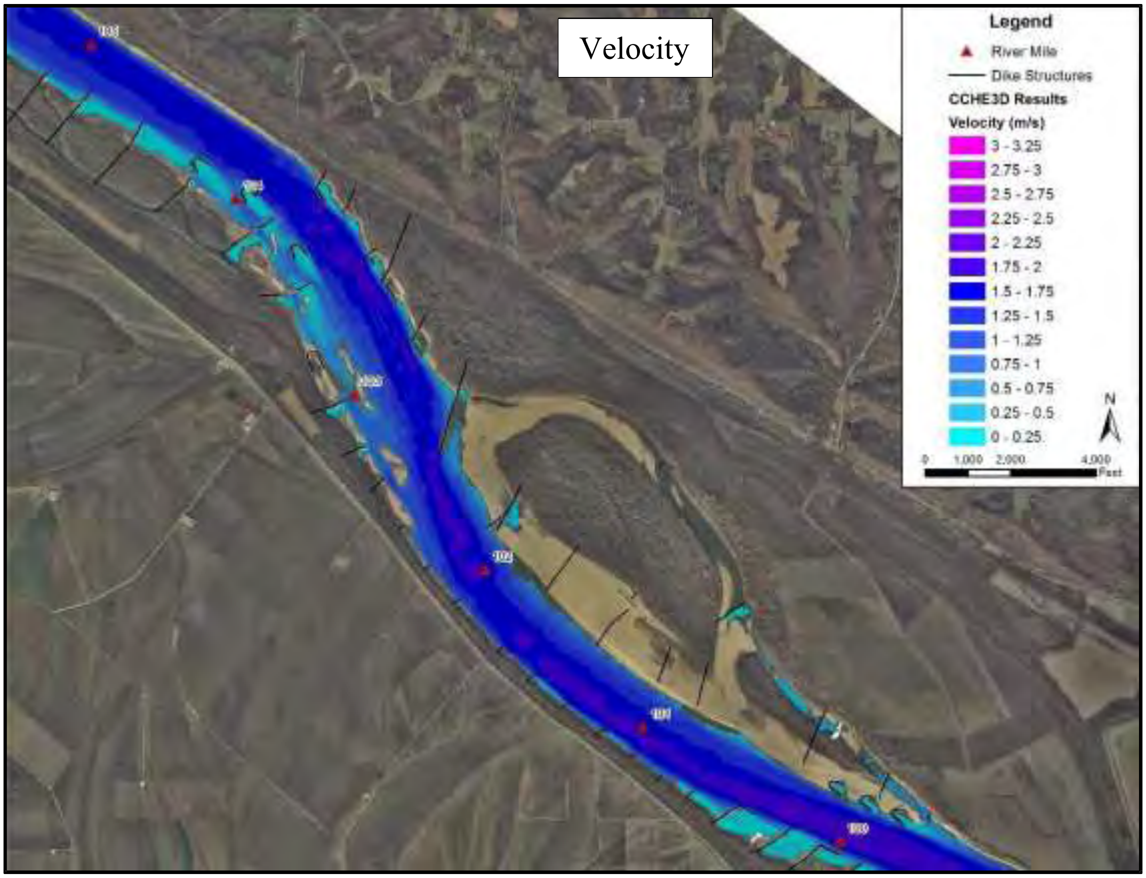


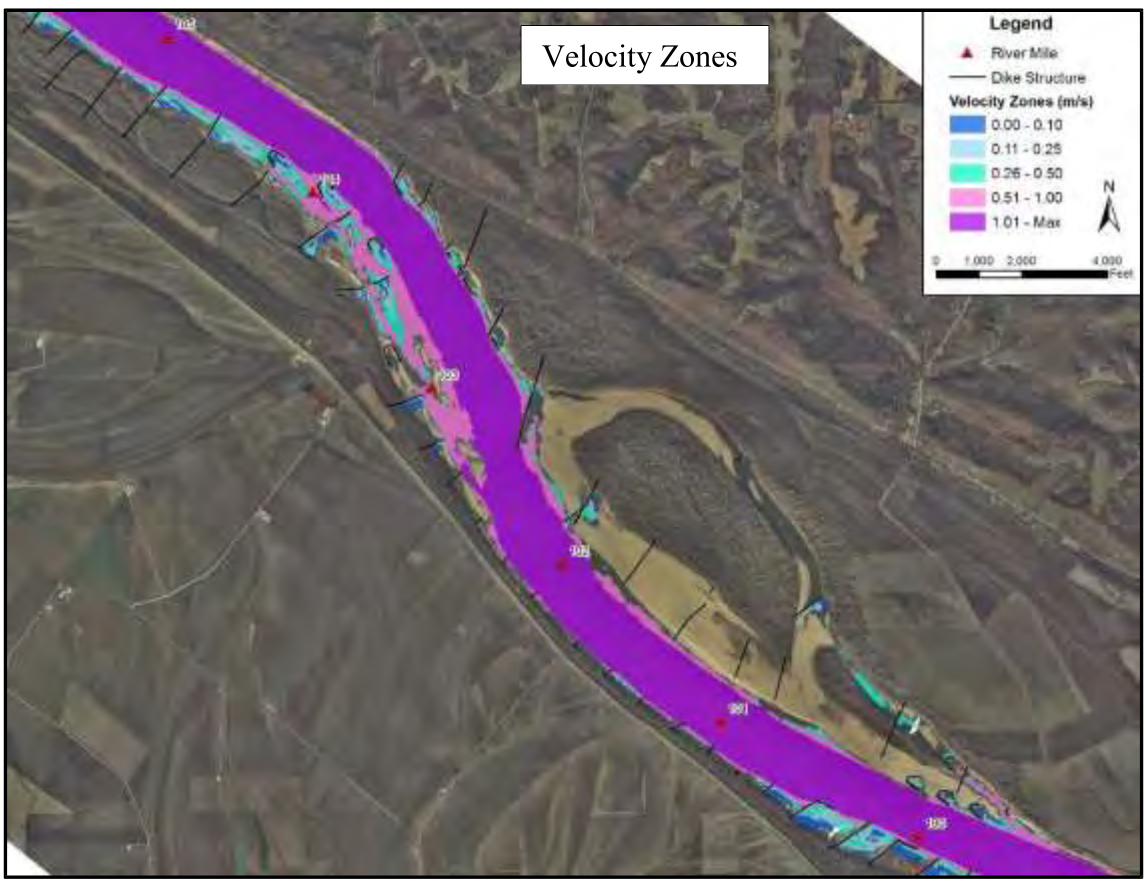
CCHE3D velocity results (flow of 6,031.5 m^3/s) at water surface for the study reach between RM 105 to RM 100



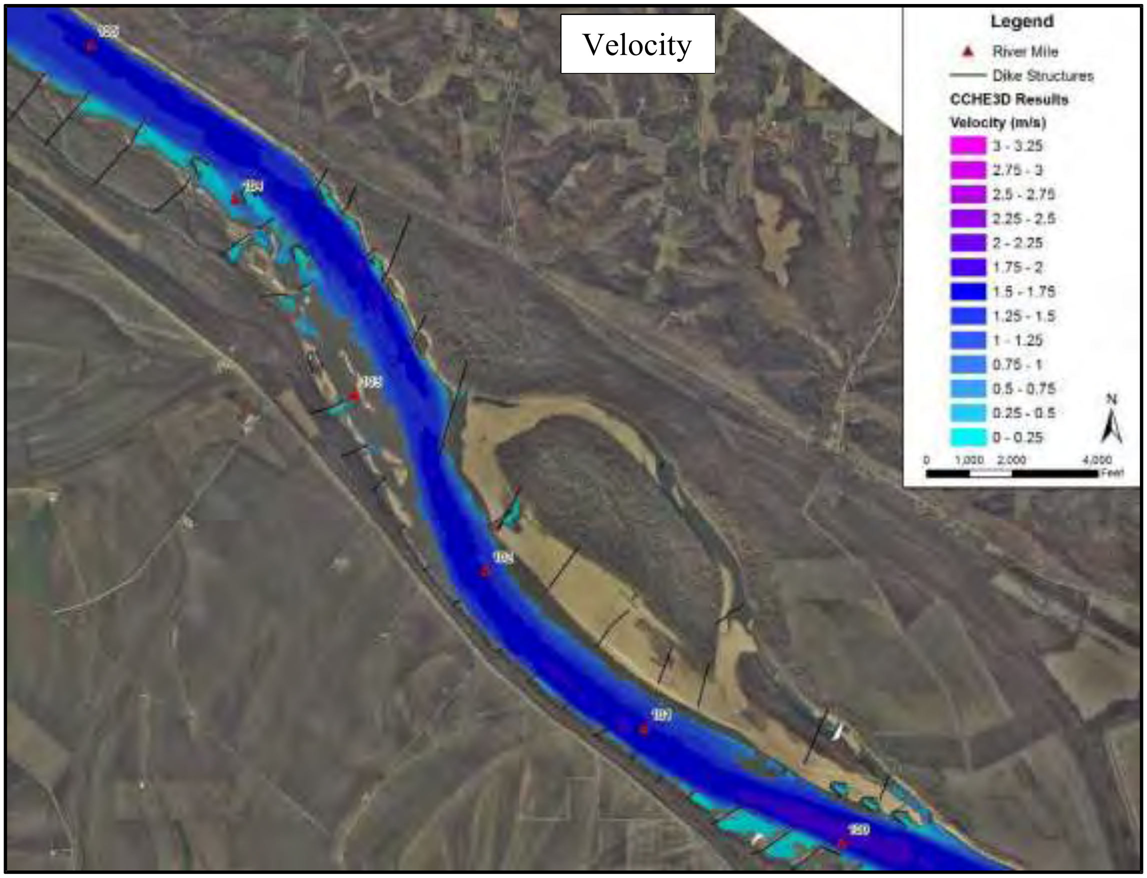


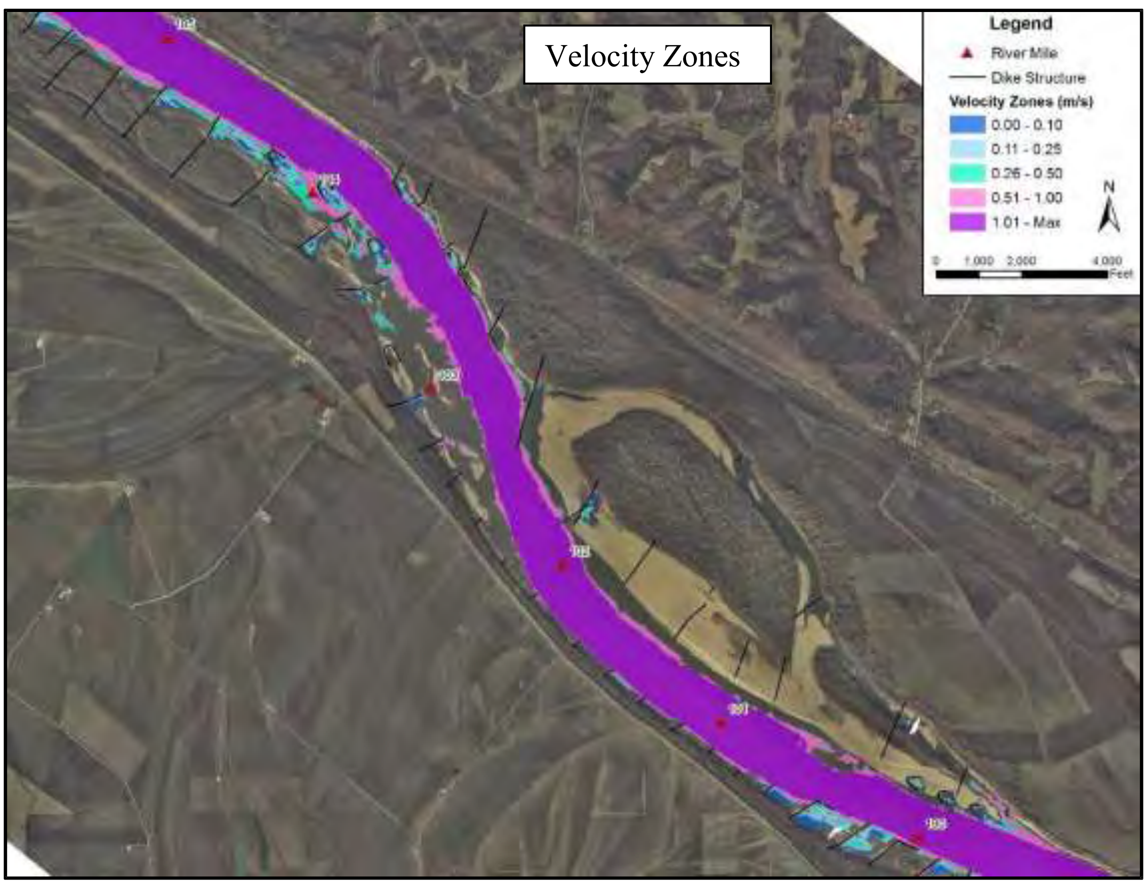
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 2 m below water surface for the study reach between RM 105 to RM 100



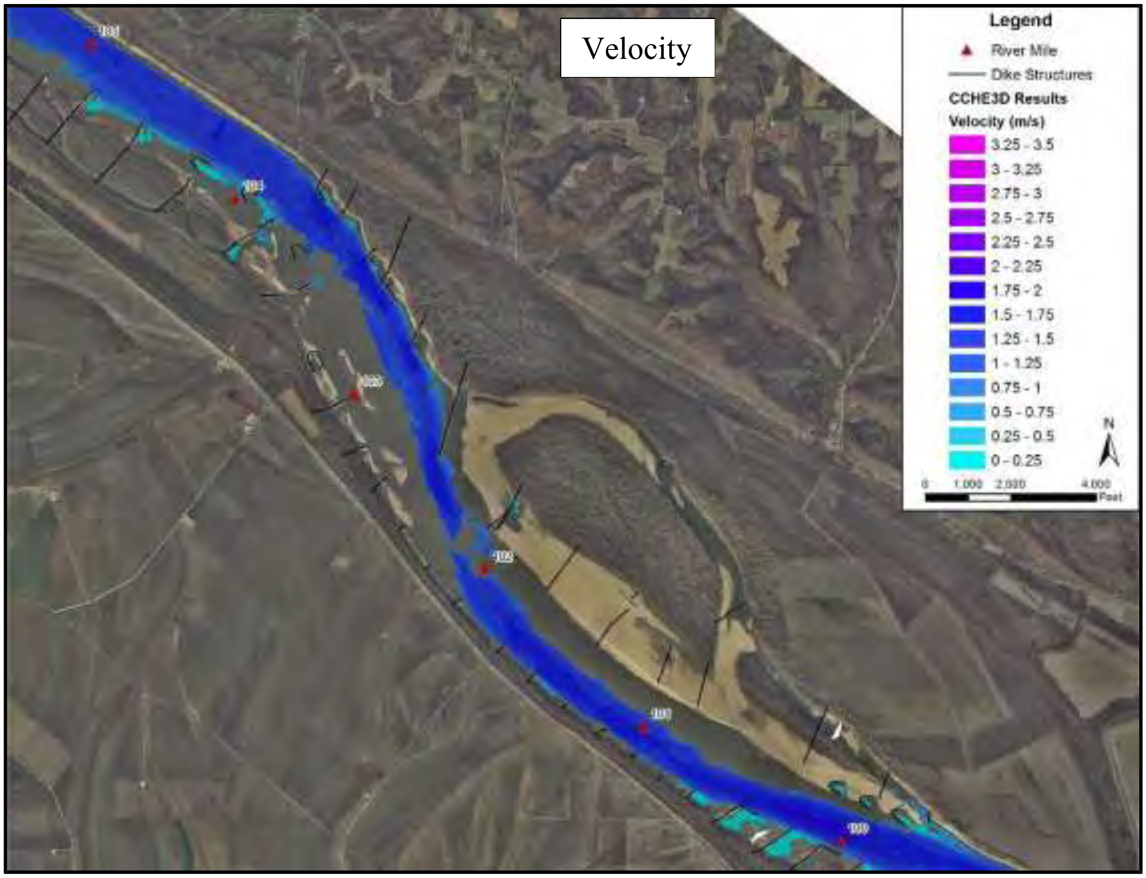


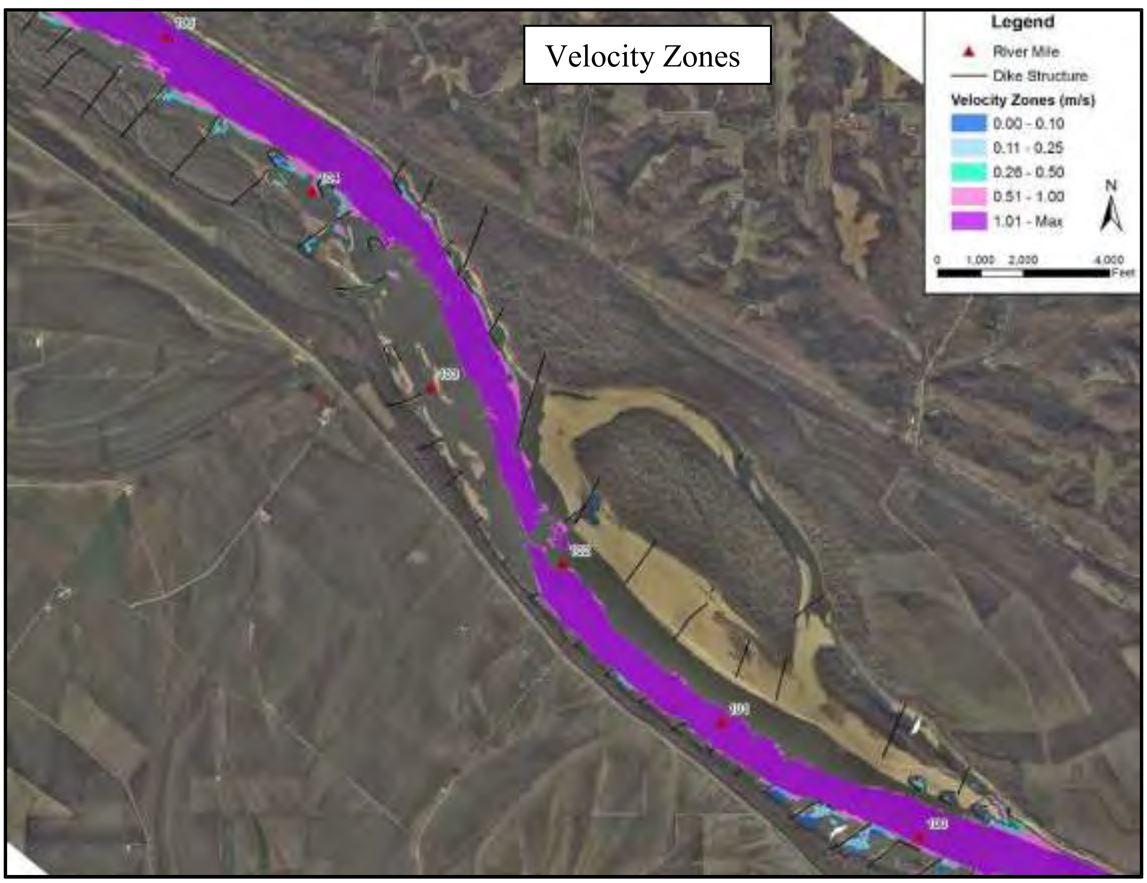
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 4 m below water surface for the study reach between RM 105 to RM 100



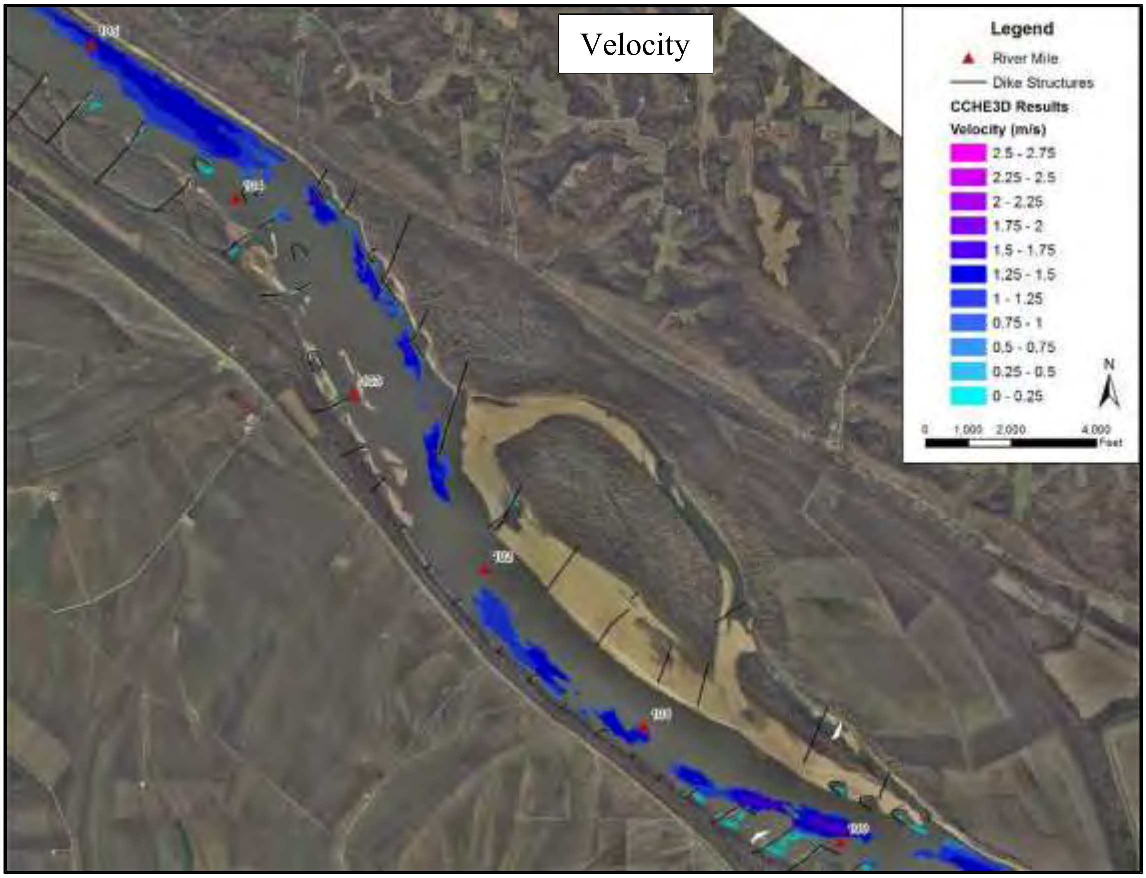


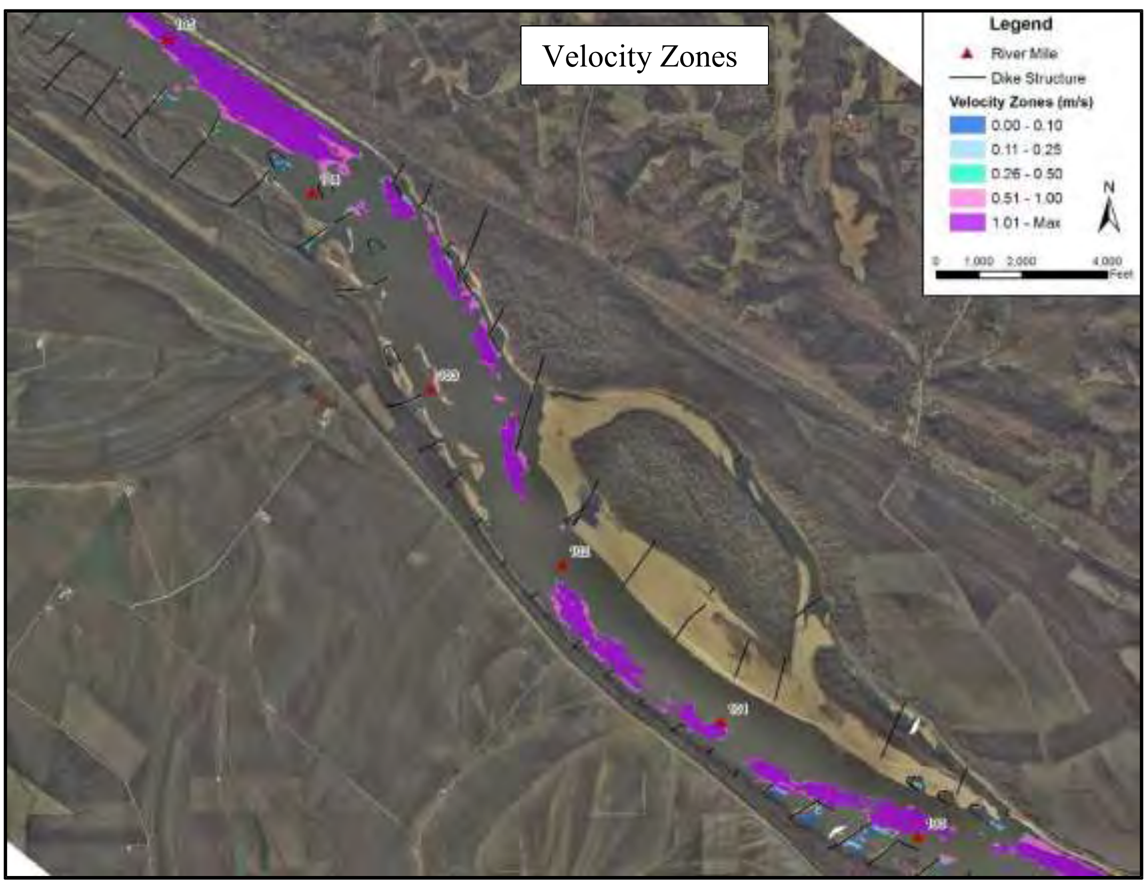
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 6 m below water surface for the study reach between RM 105 to RM 100



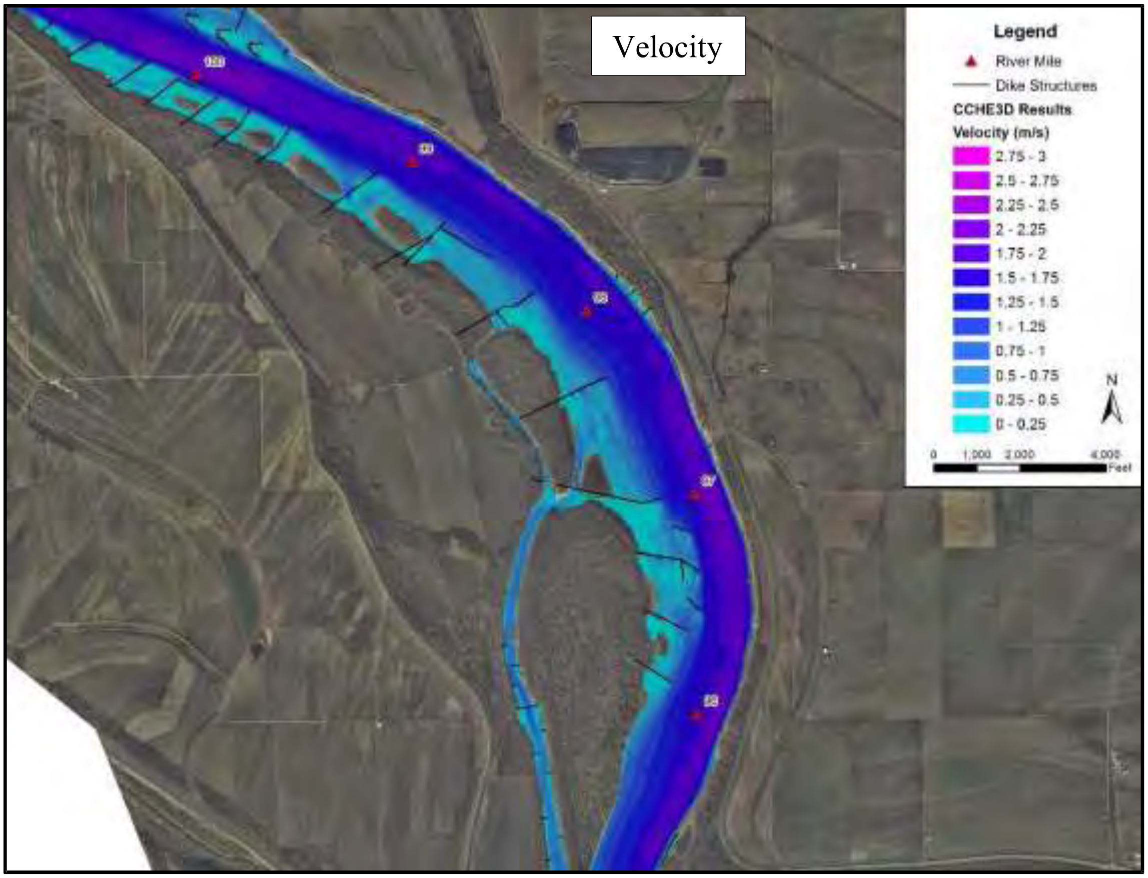


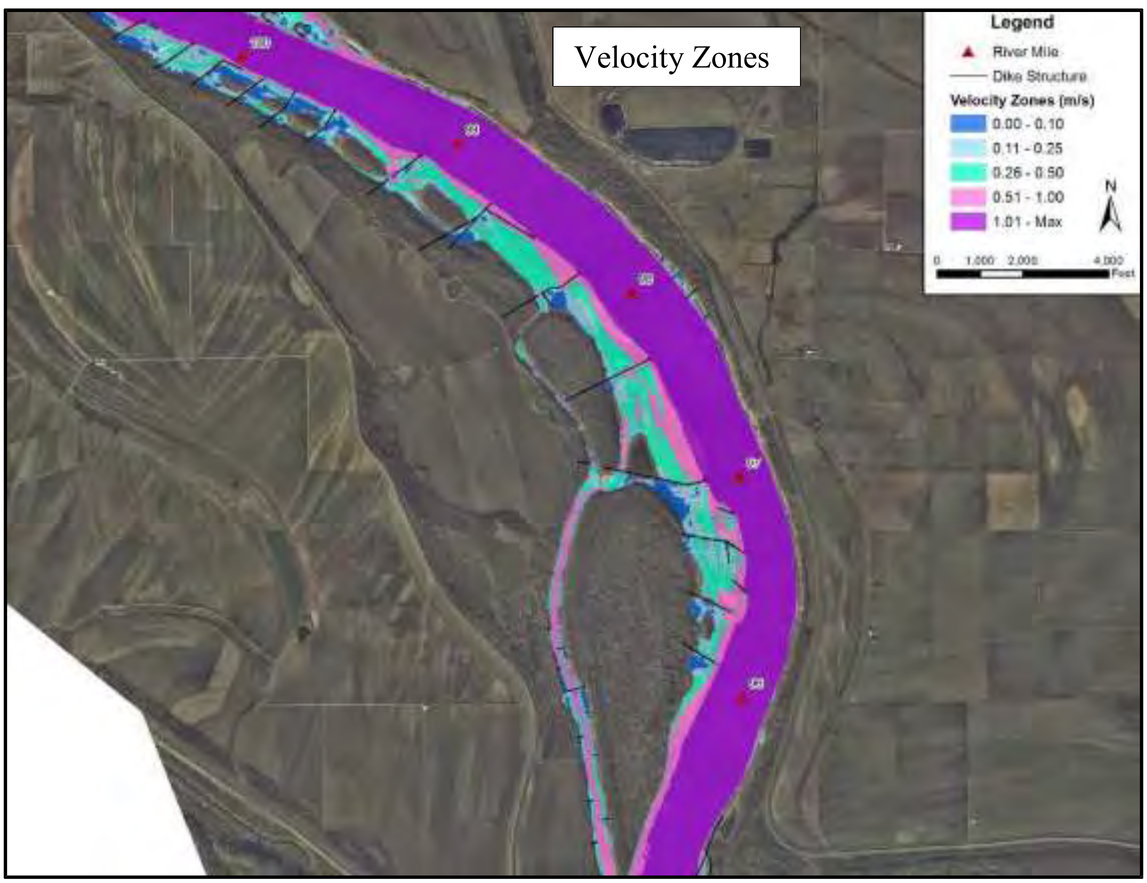
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 8 m below water surface for the study reach between RM 105 to RM 100



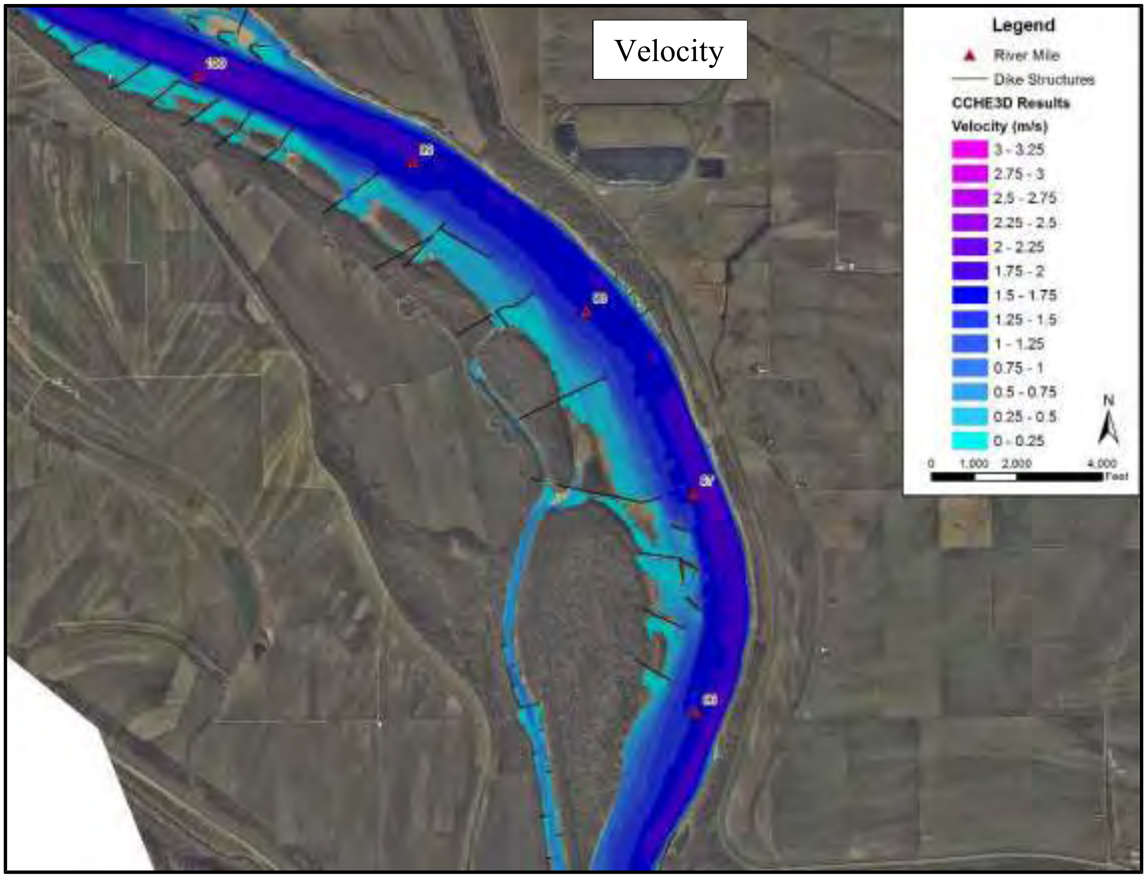


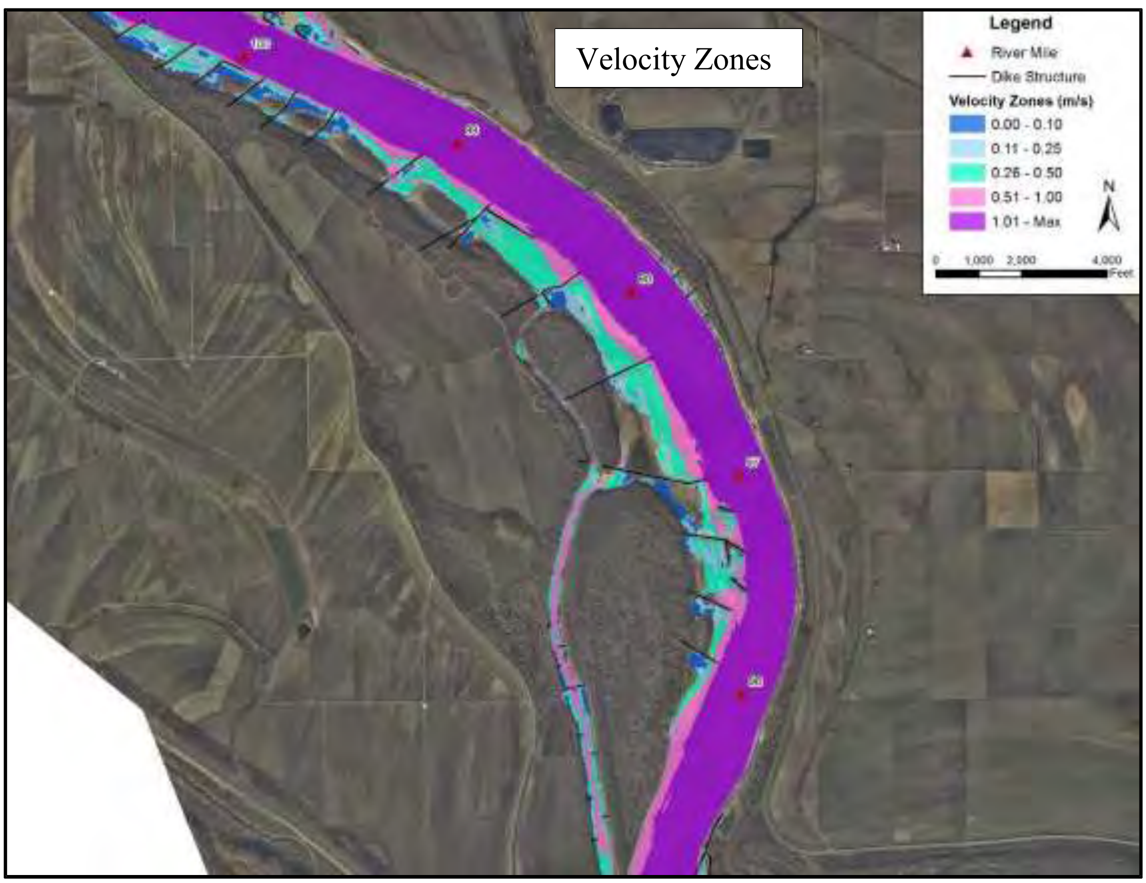
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 10 m below water surface for the study reach between RM 105 to RM 100



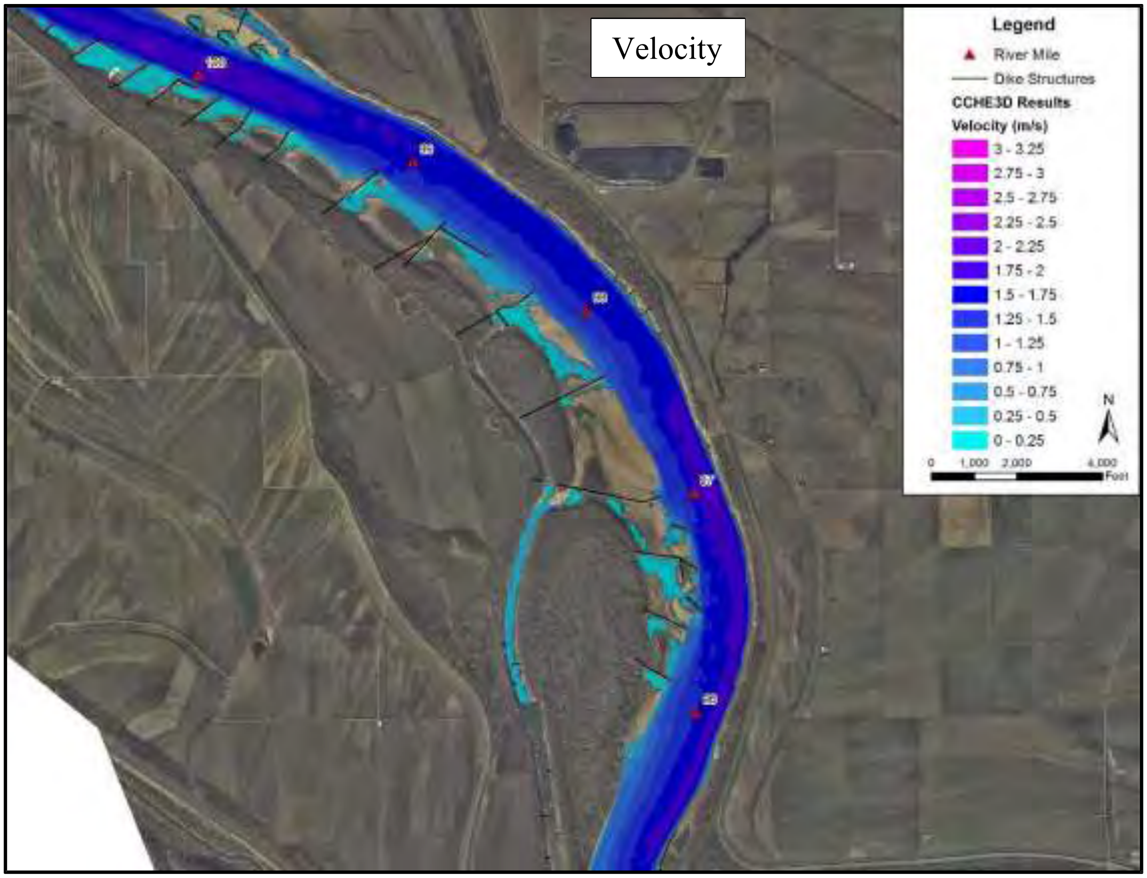


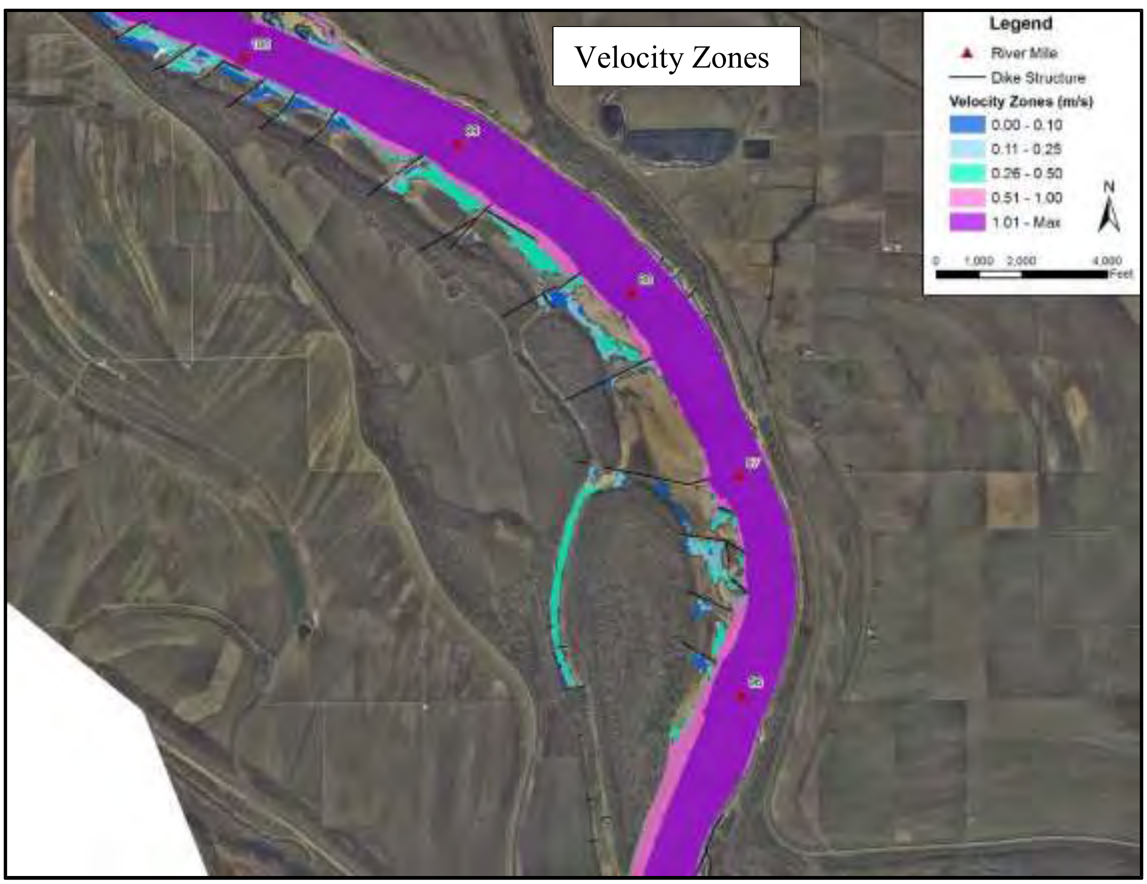
CCHE3D velocity results (flow of 6,031.5 m^3/s) at water surface for the study reach between RM 100 to RM 96



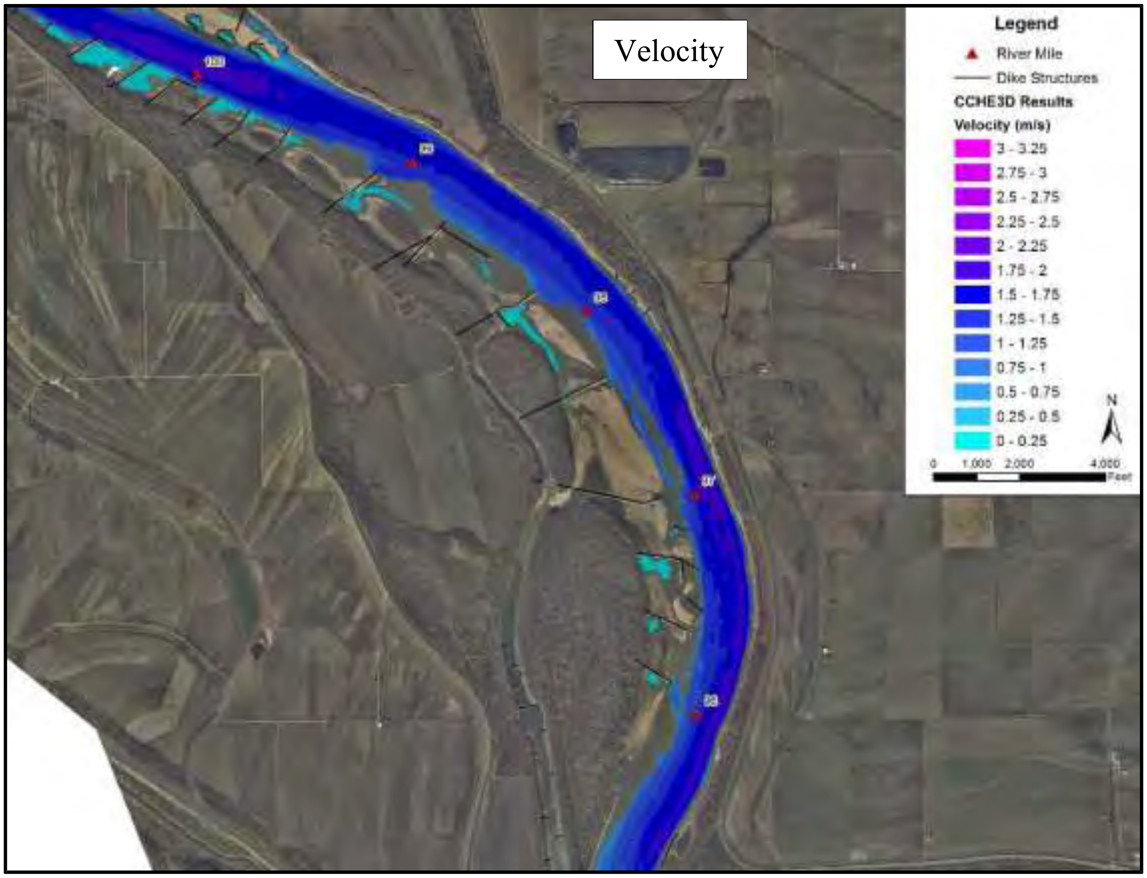


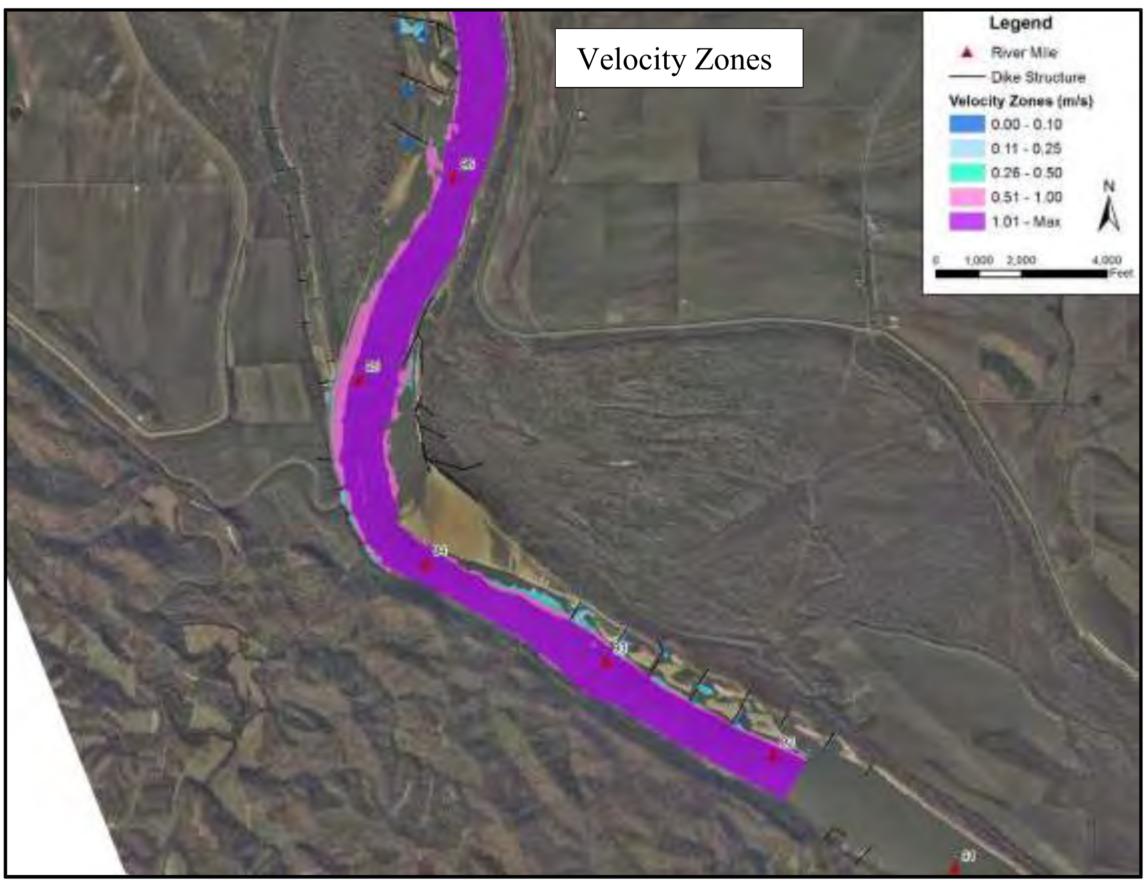
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 2 m below water surface for the study reach between RM 100 to RM 96



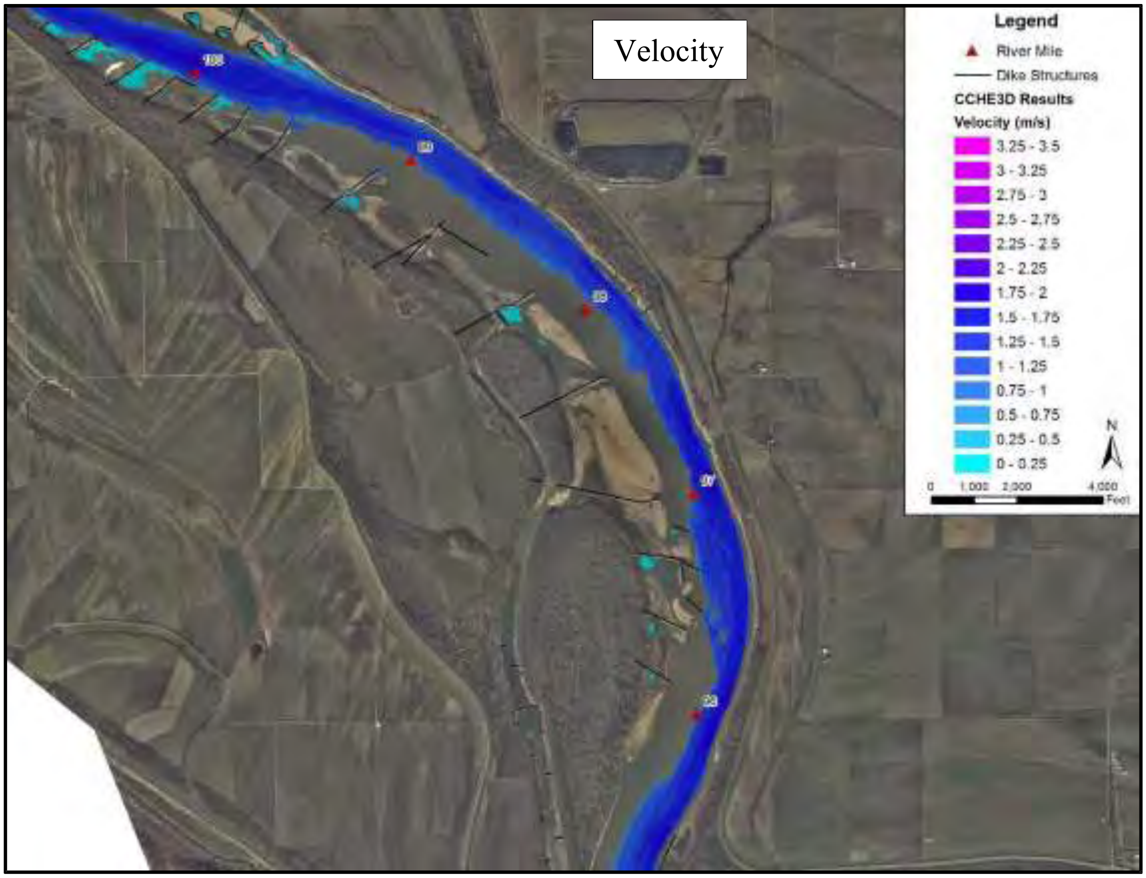


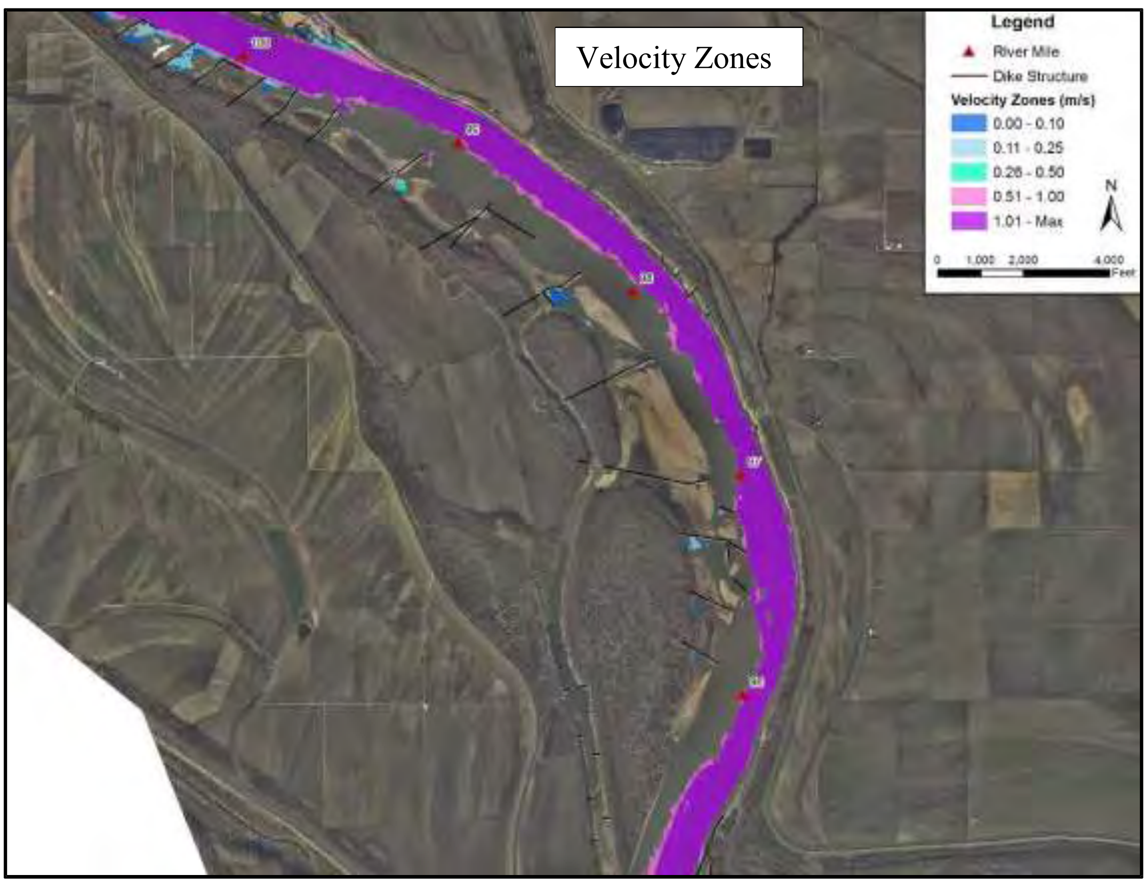
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 4 m below water surface for the study reach between RM 100 to RM 96



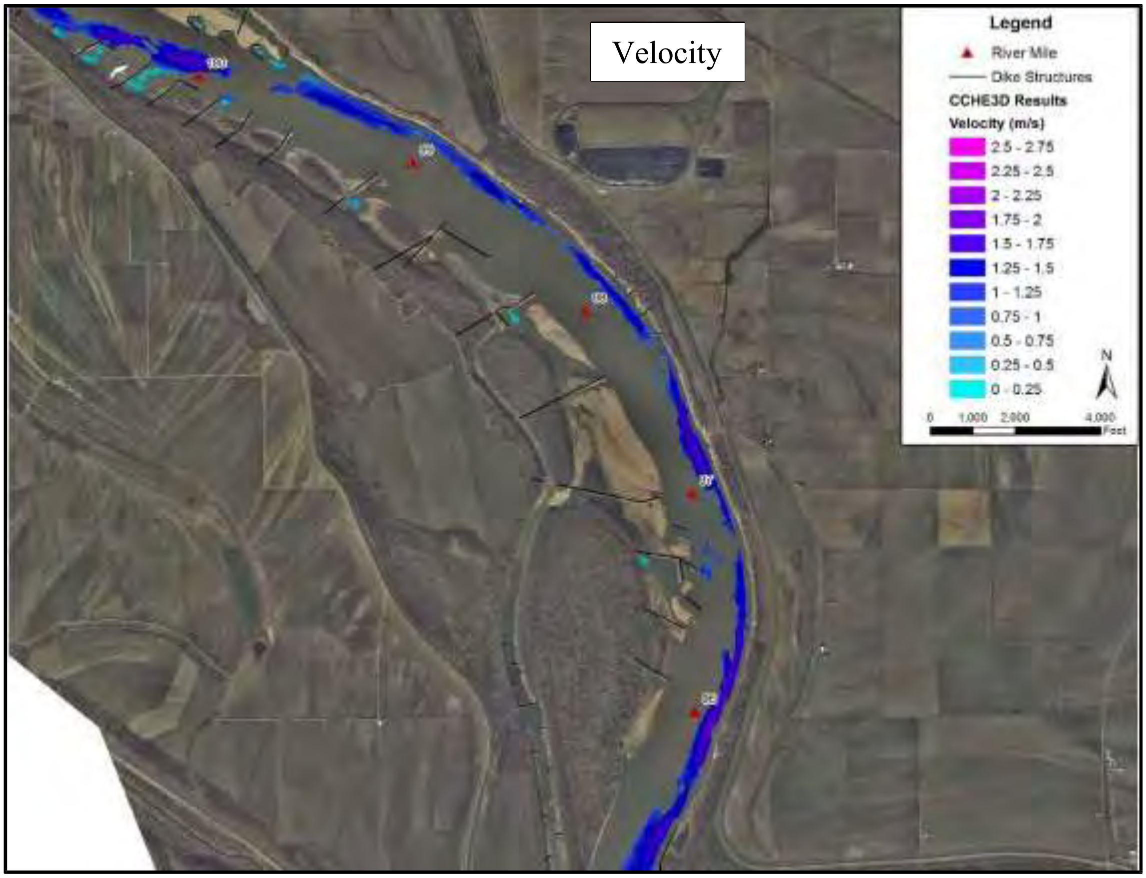


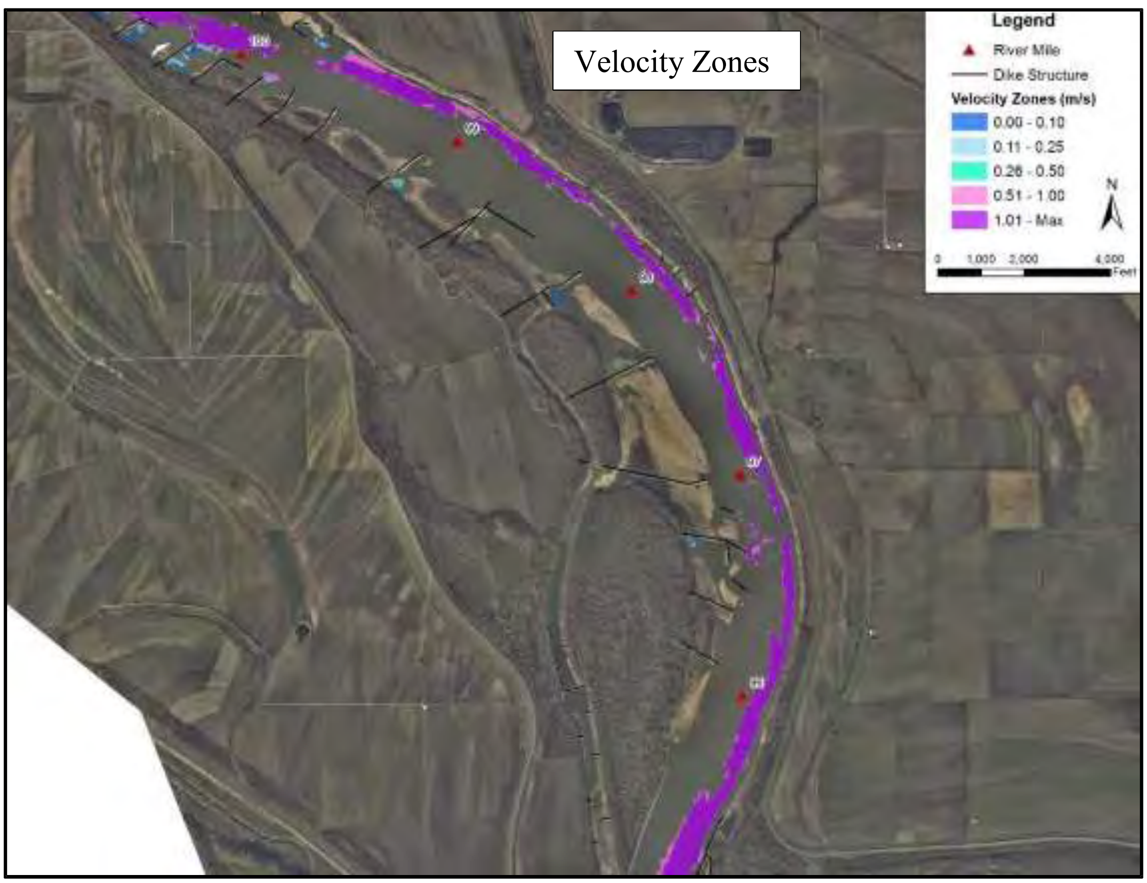
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 6 m below water surface for the study reach between RM 100 to RM 96



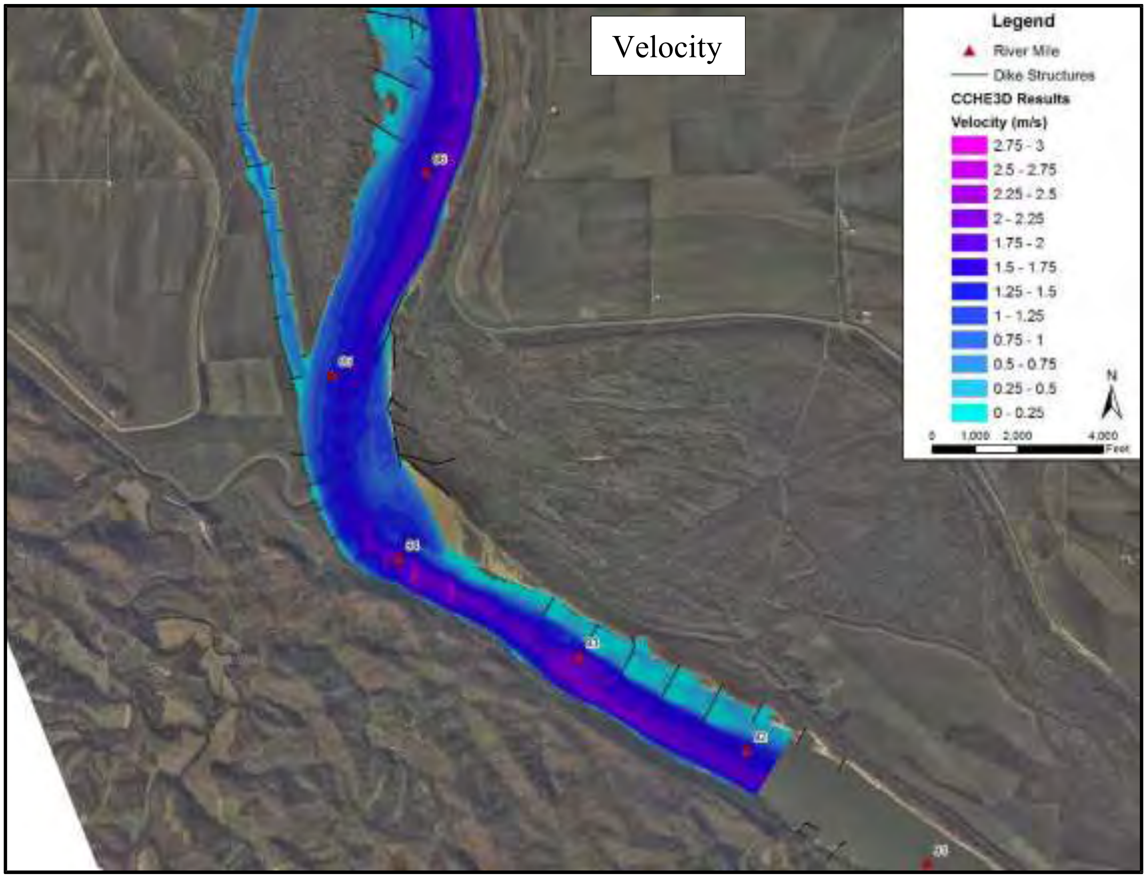


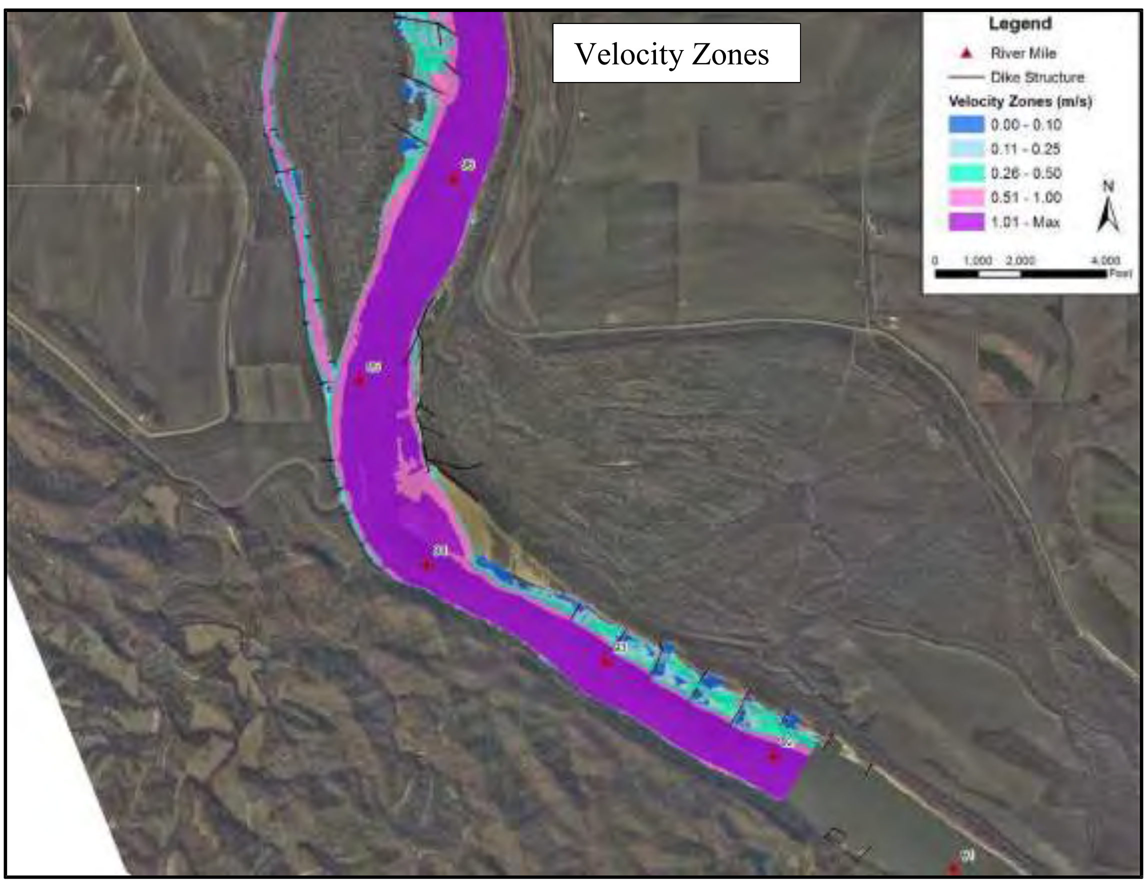
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 8 m below water surface for the study reach between RM 100 to RM 96



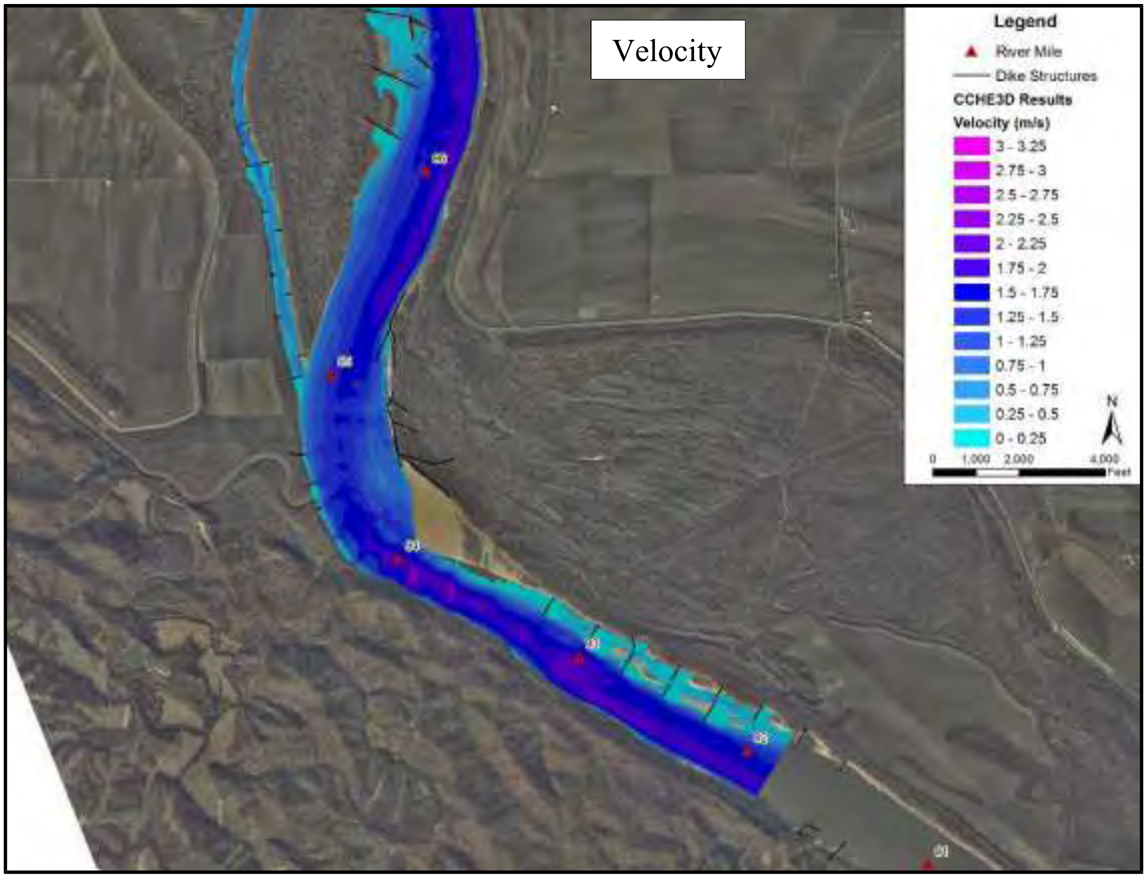


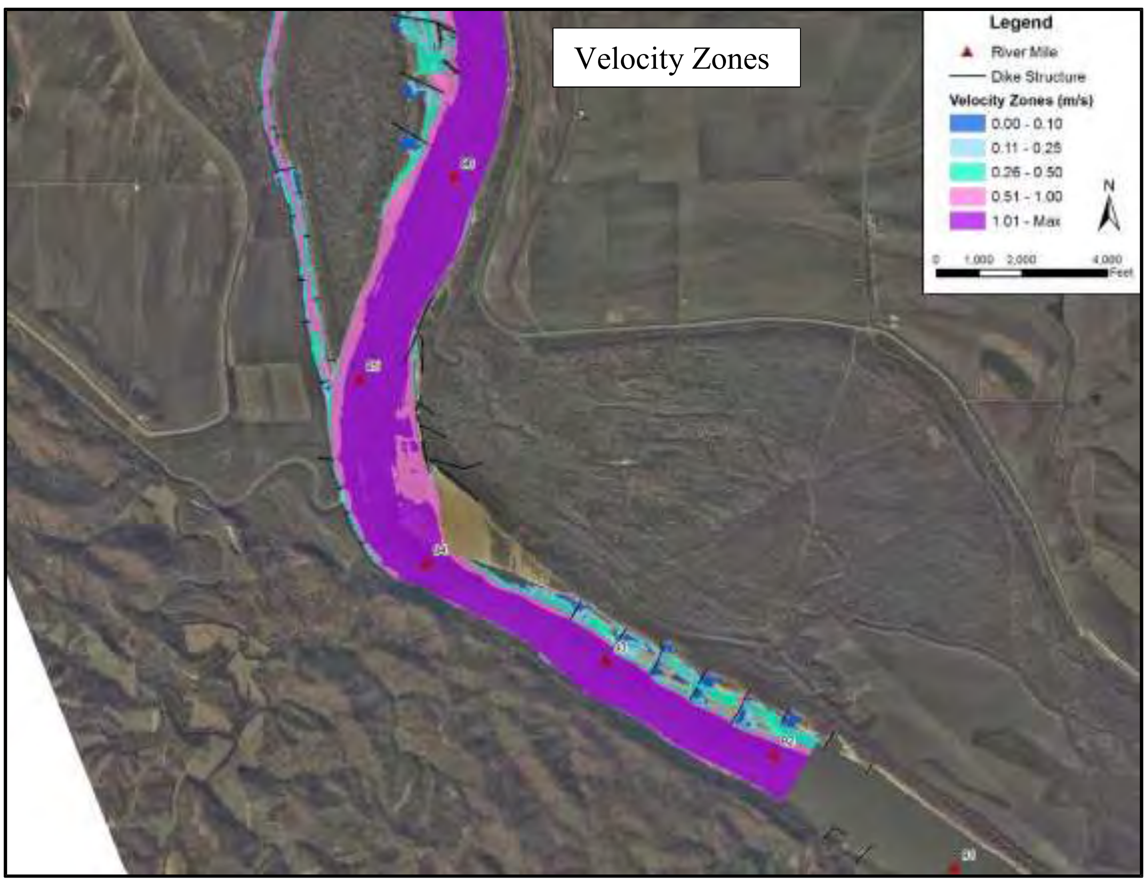
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 10 m below water surface for the study reach between RM 100 to RM 96



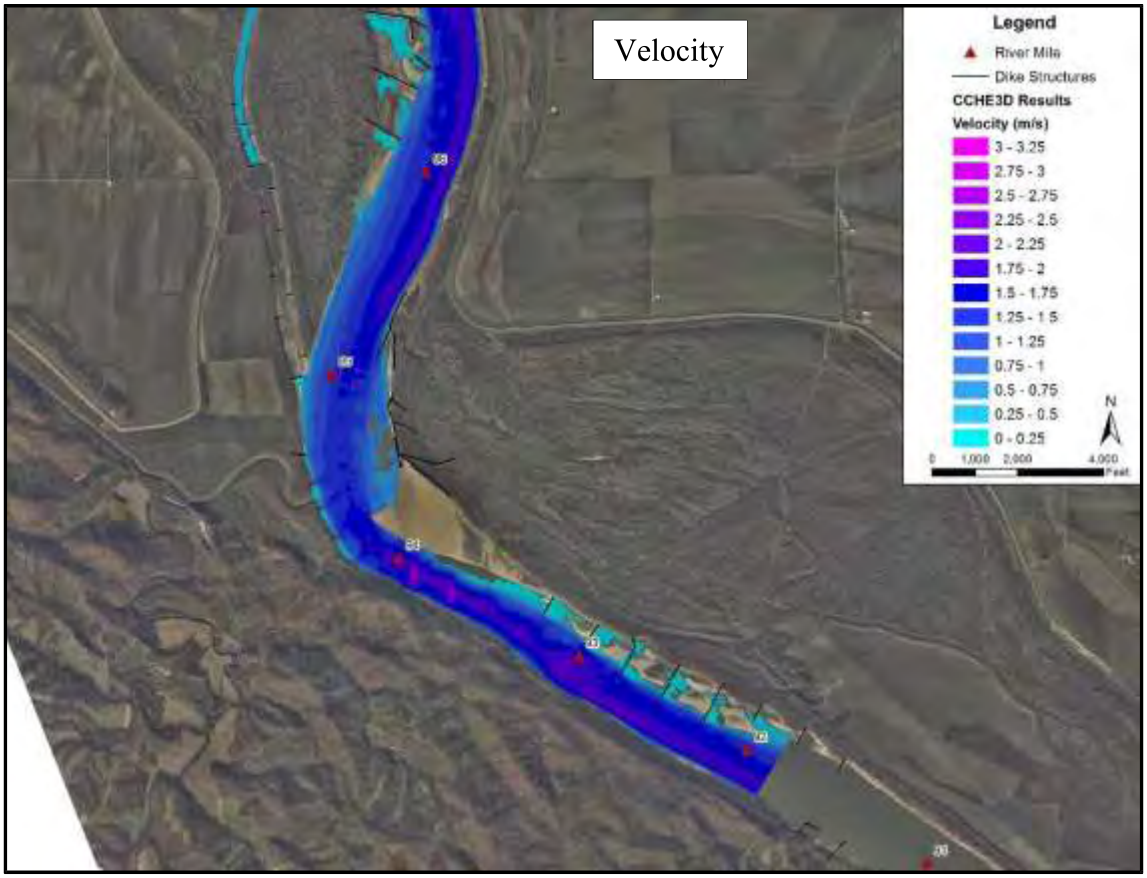


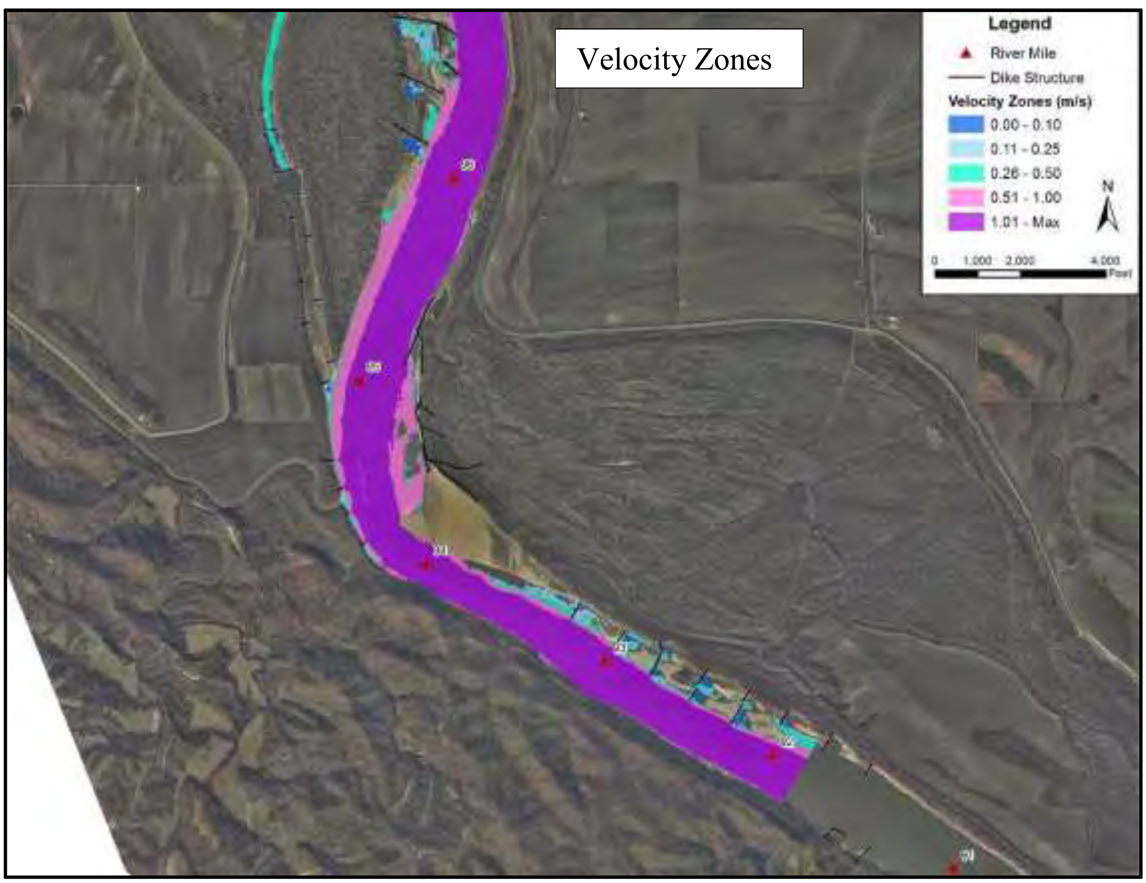
CCHE3D velocity results (flow of 6,031.5 m^3/s) at water surface for the study reach between RM 96 to RM 91



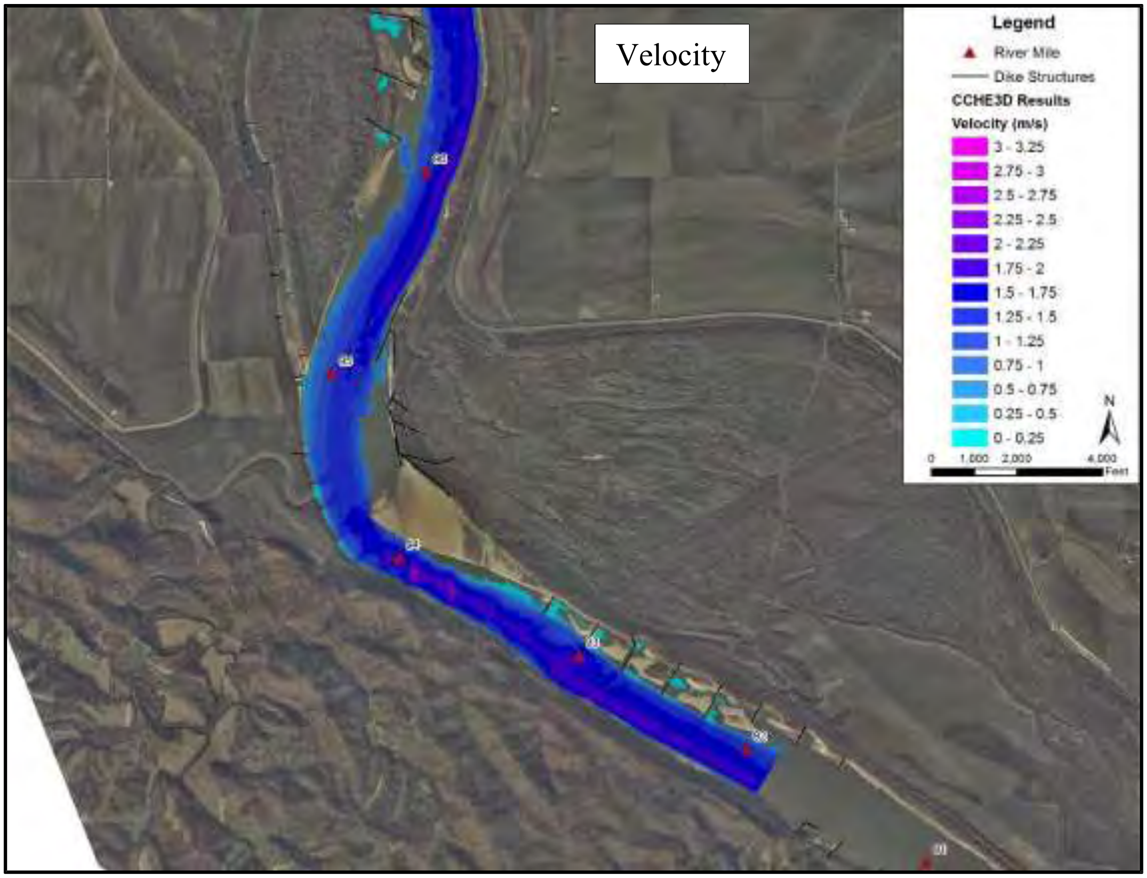


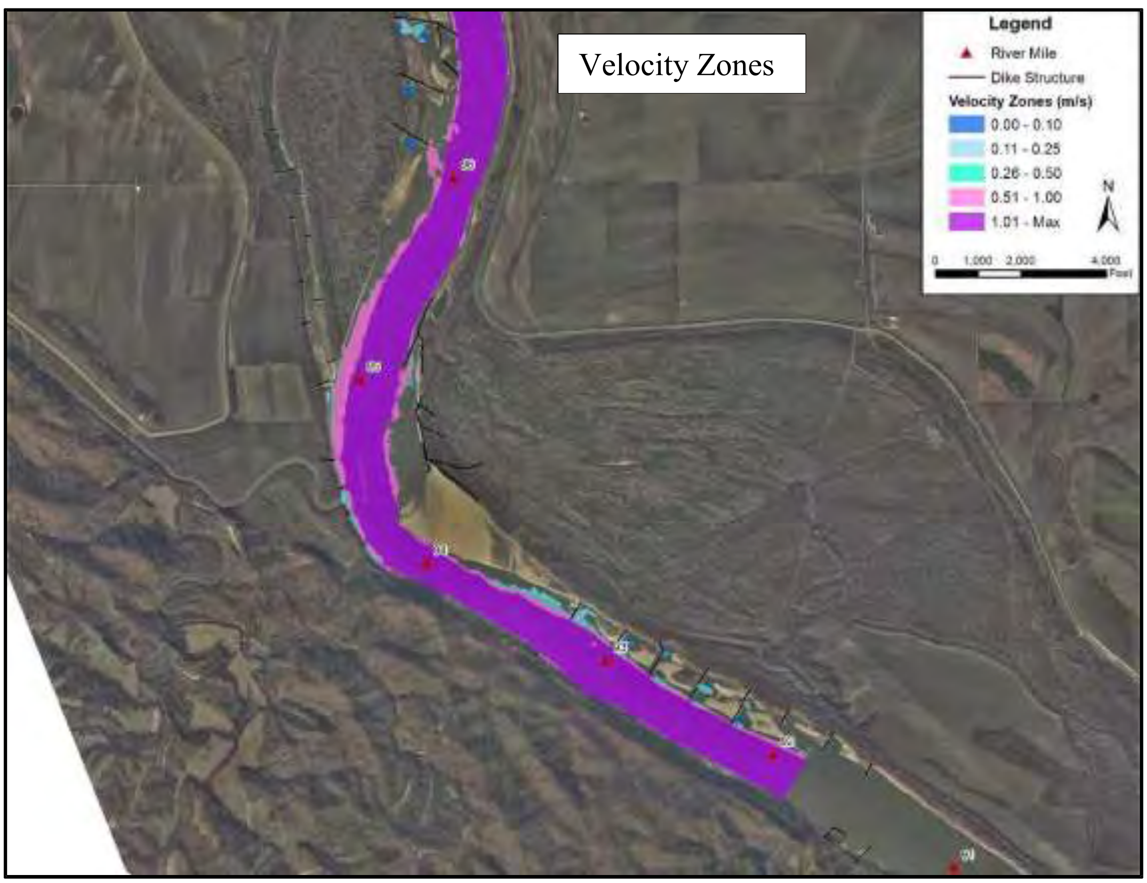
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 2 m below water surface for the study reach between RM 96 to RM 91



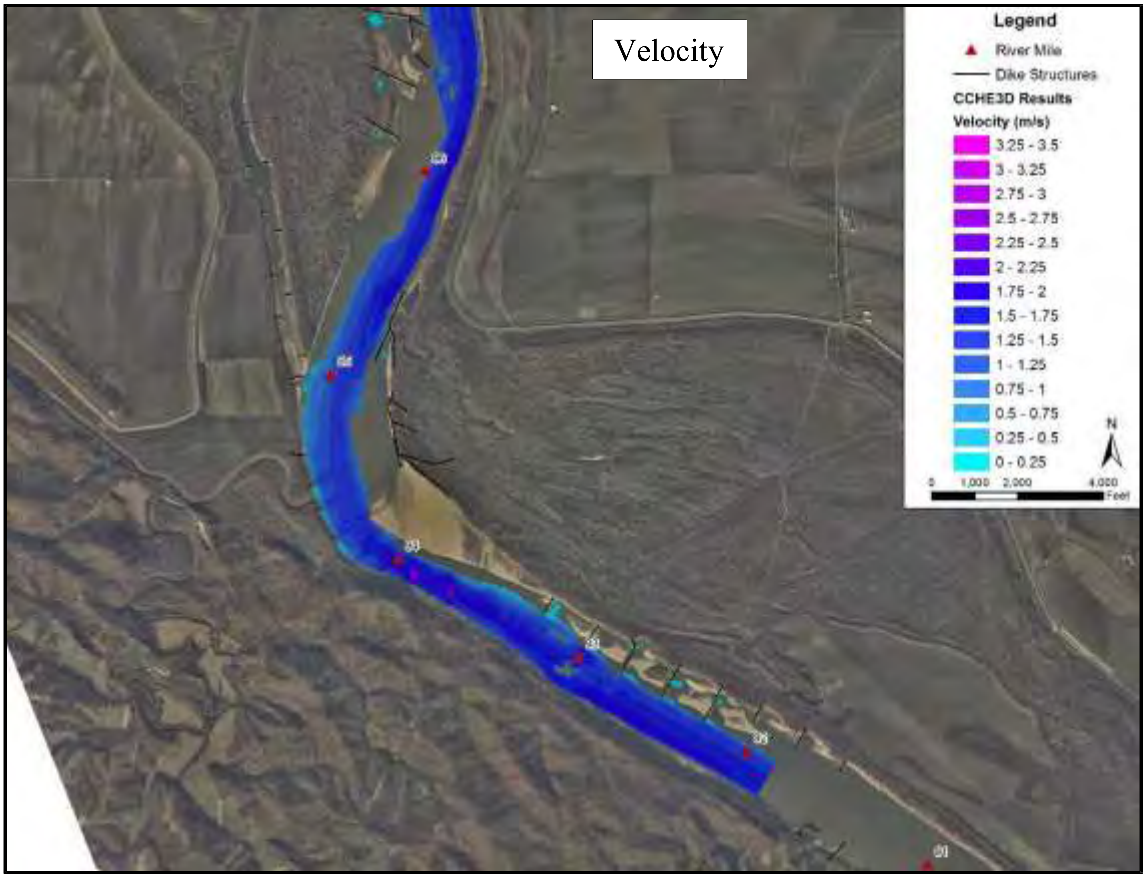


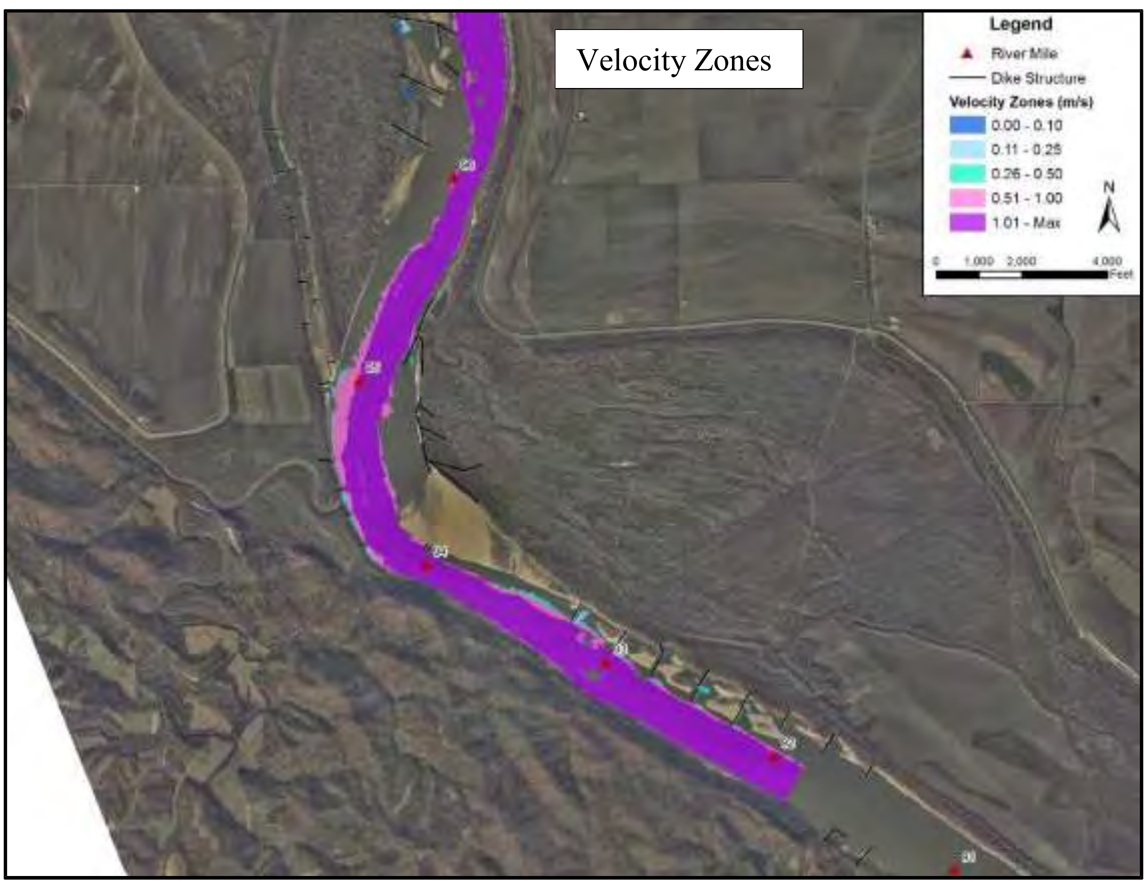
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 4 m below water surface for the study reach between RM 96 to RM 91



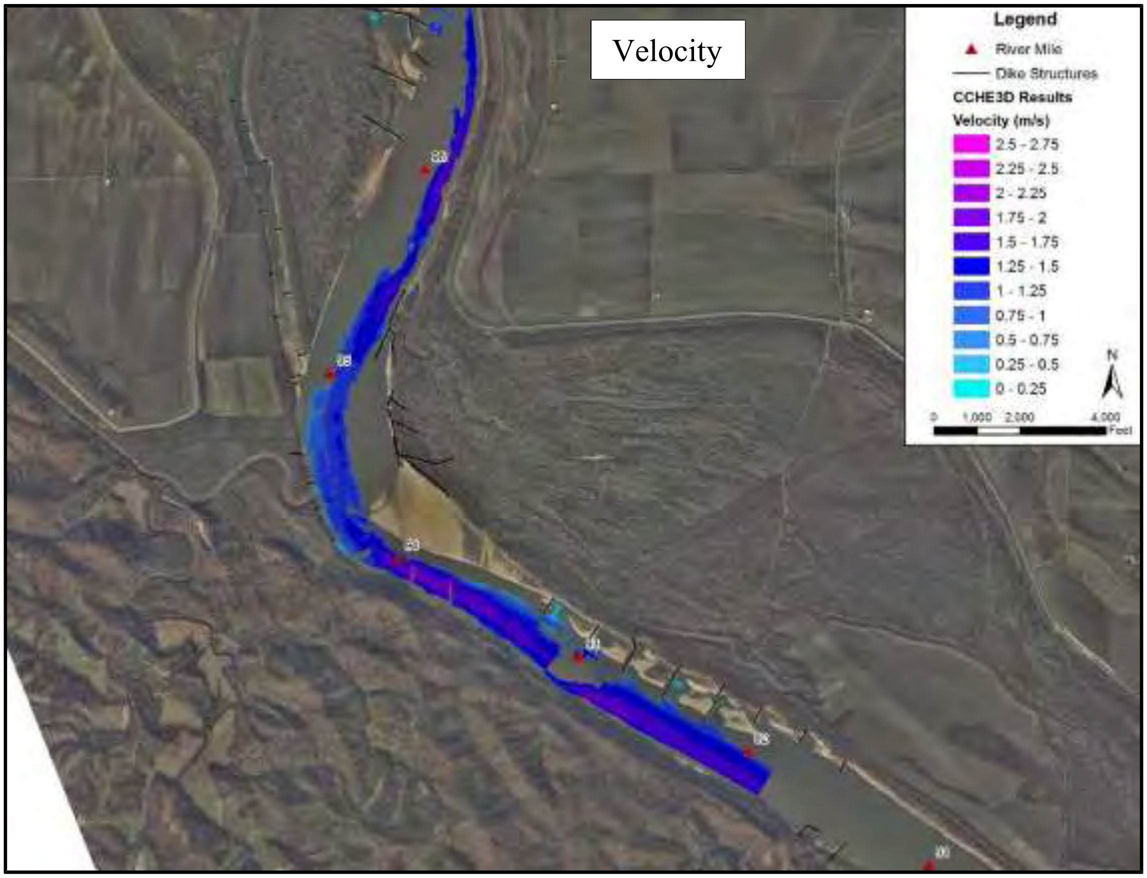


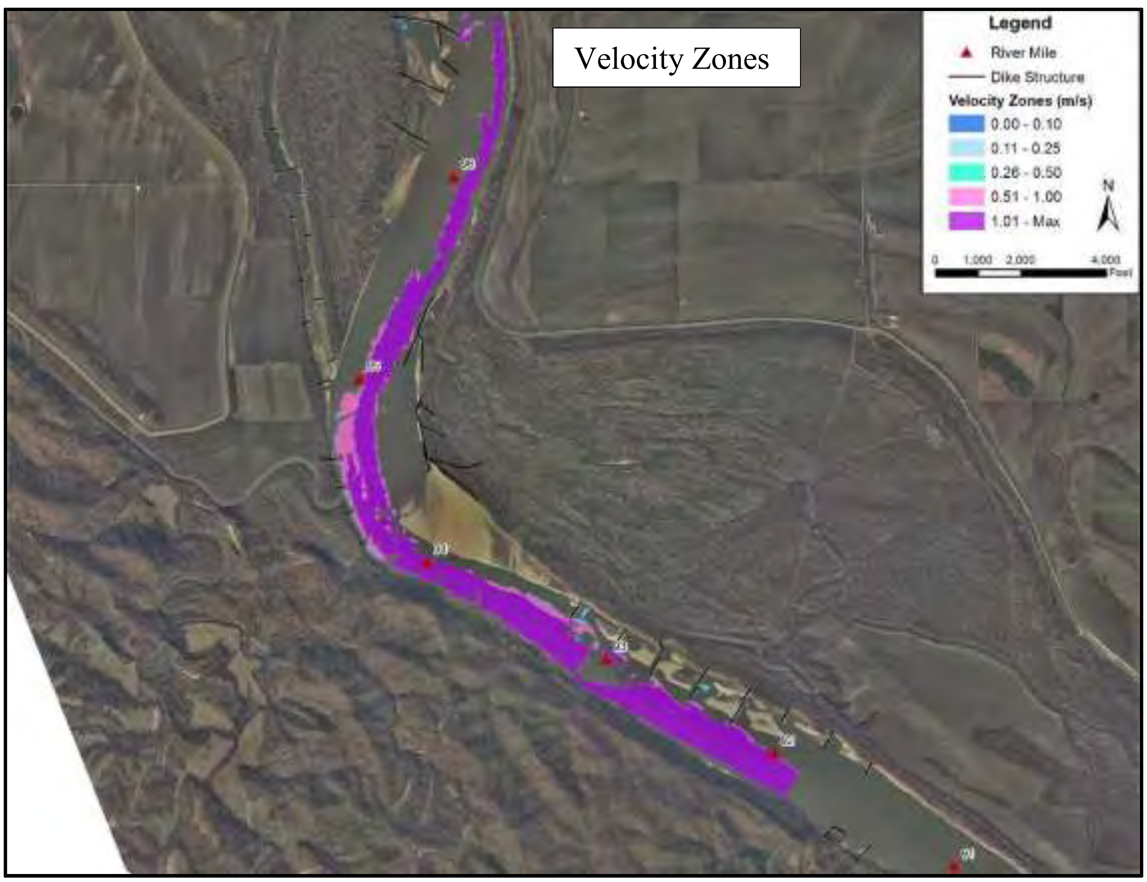
CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 6 m below water surface for the study reach between RM 96 to RM 91





CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 8 m below water surface for the study reach between RM 96 to RM 91

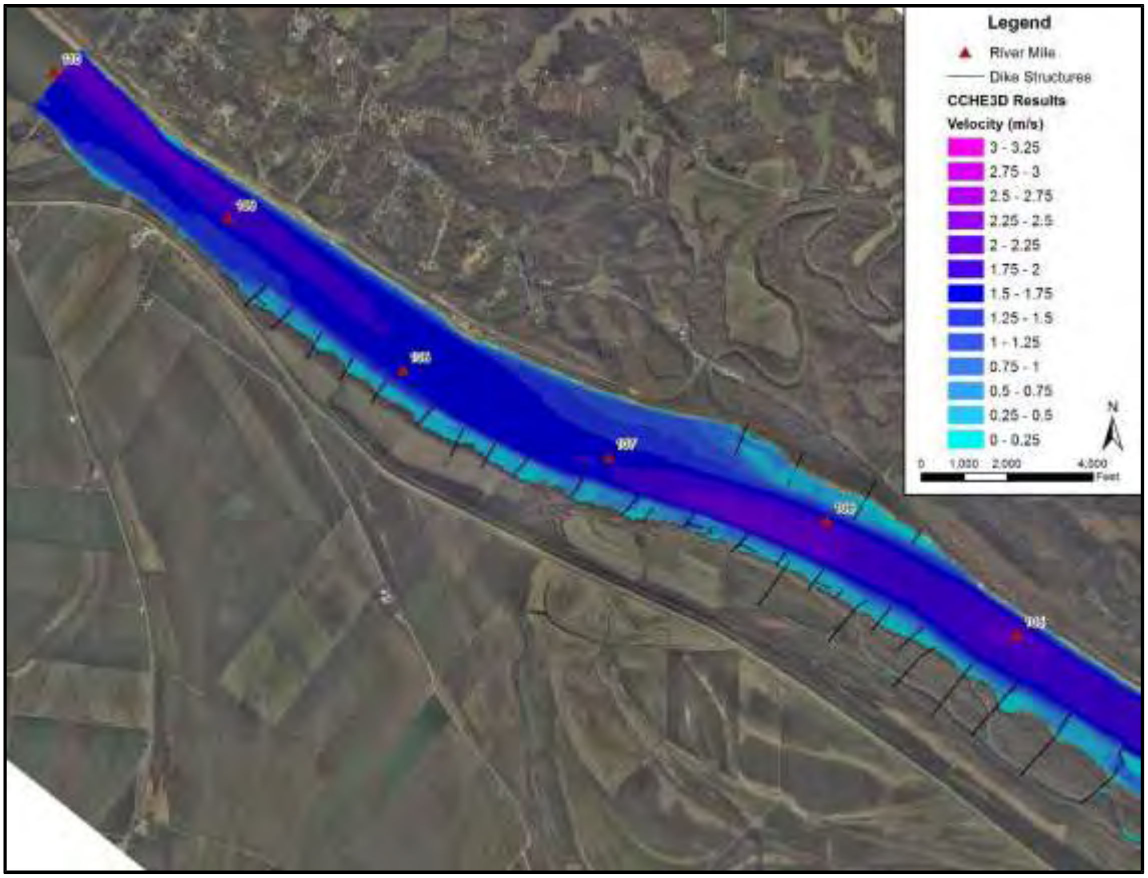


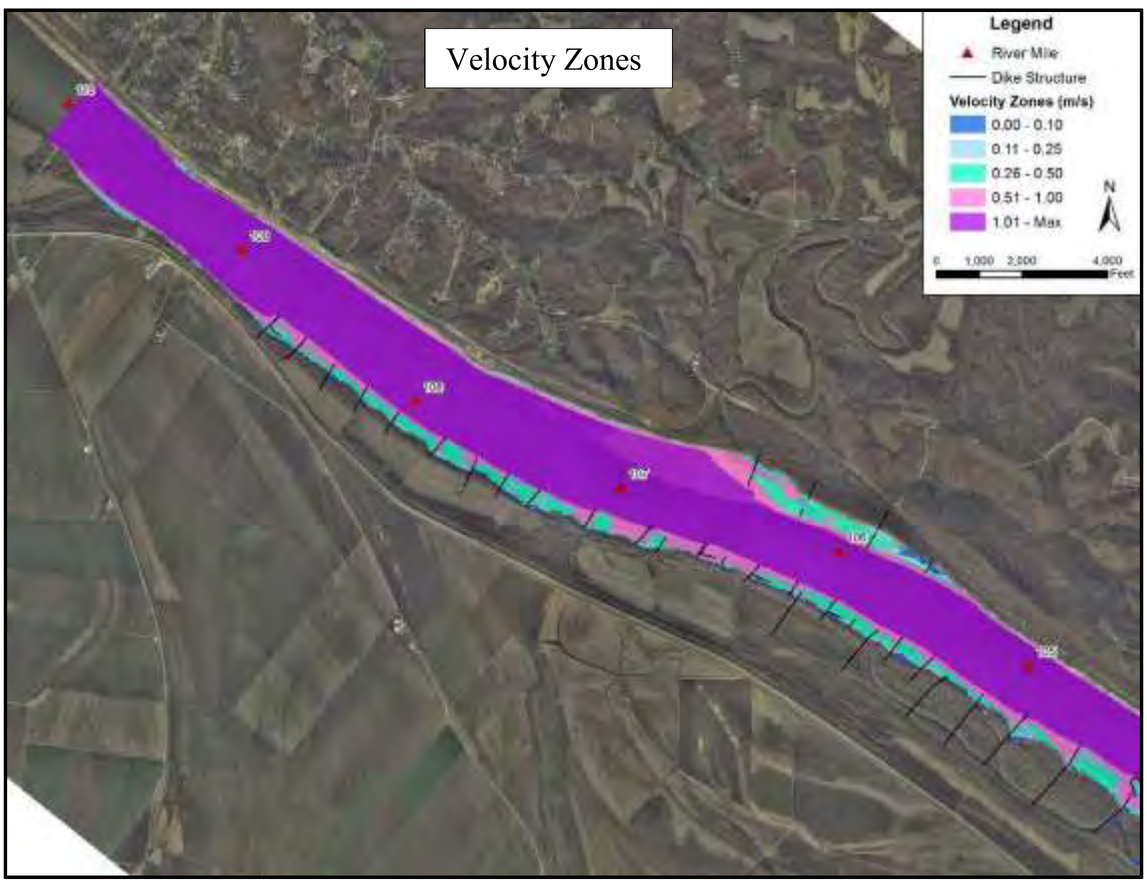


CCHE3D velocity results (flow of 6,031.5 m^3/s) at a depth of 10 m below water surface for the study reach between RM 96 to RM 91

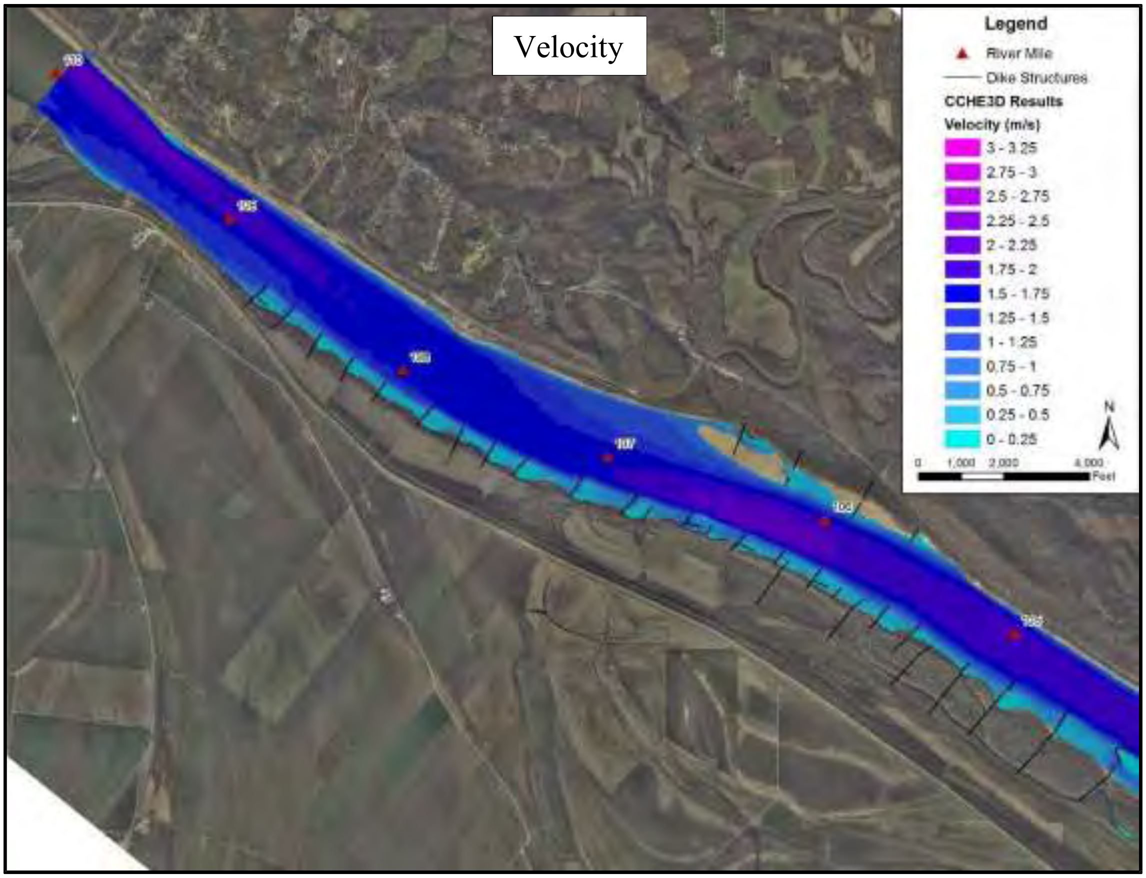
APPENDIX B.3

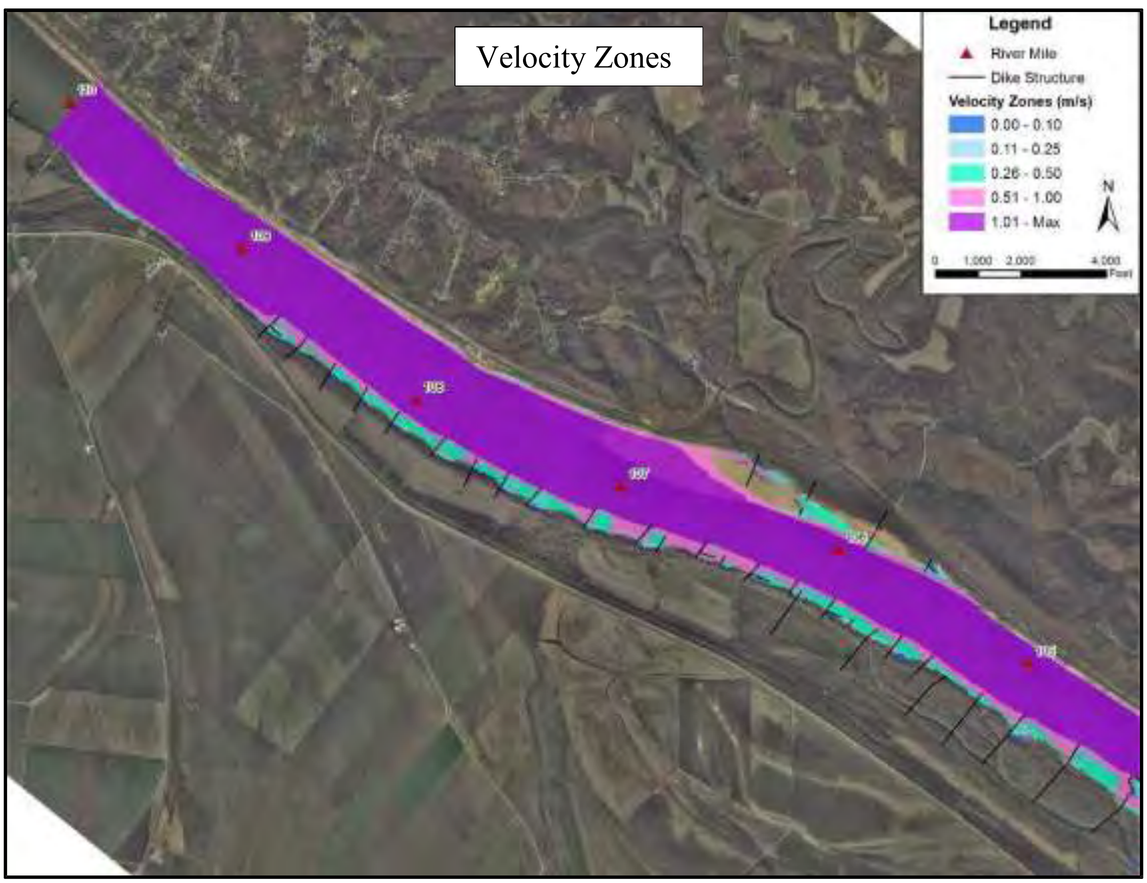
STUDY REACH CCHE3D MODEL VELOCITY AND VELOCITY RECLASSIFICATION RESULTS (FLOW OF 8,580.0 M^3/S)



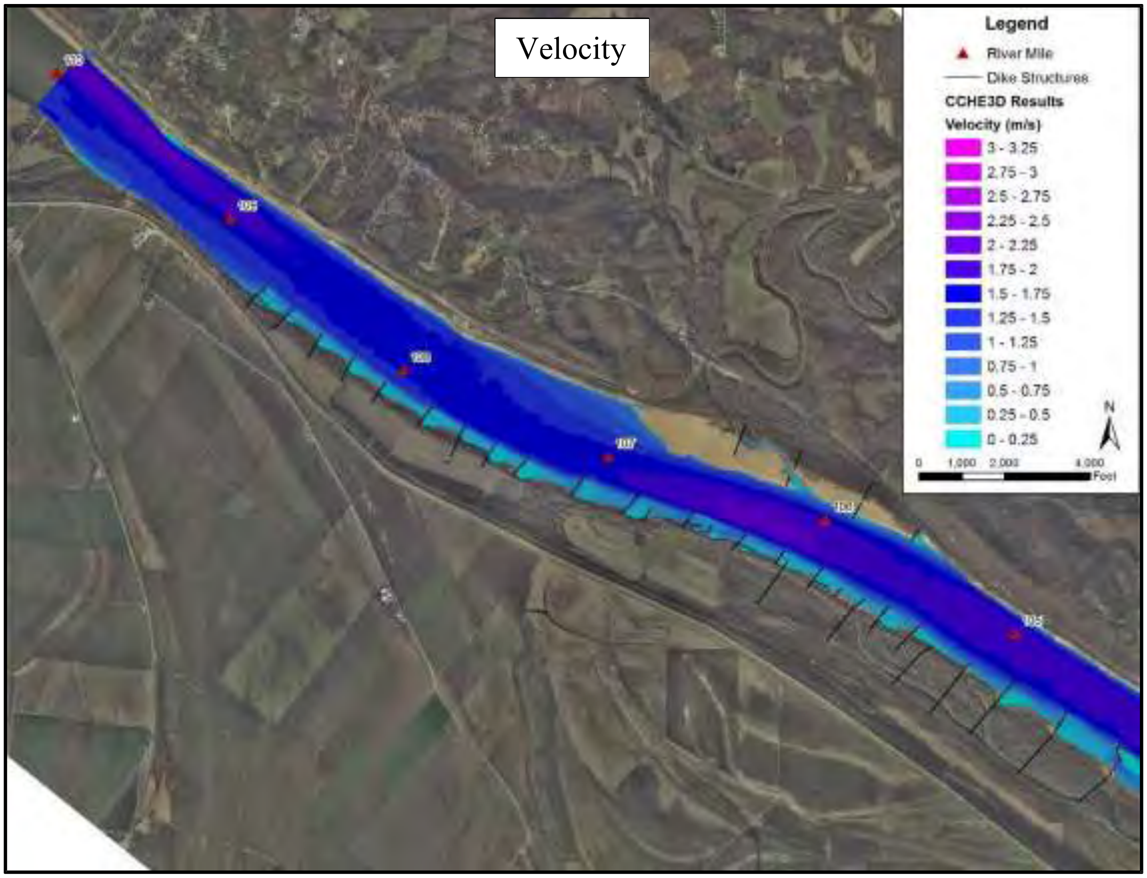


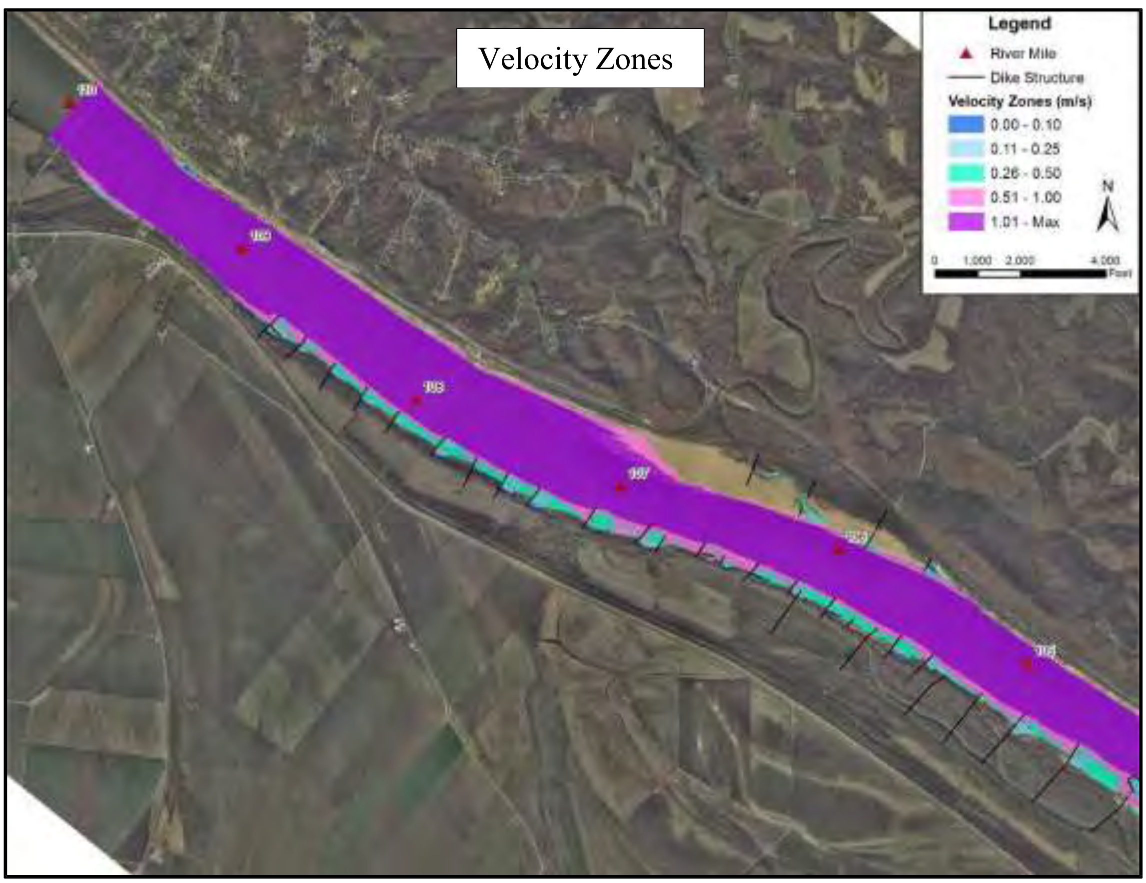
CCHE3D velocity results (flow of 8,580.0 m^3/s) at water surface for the study reach between RM 110 to RM 105



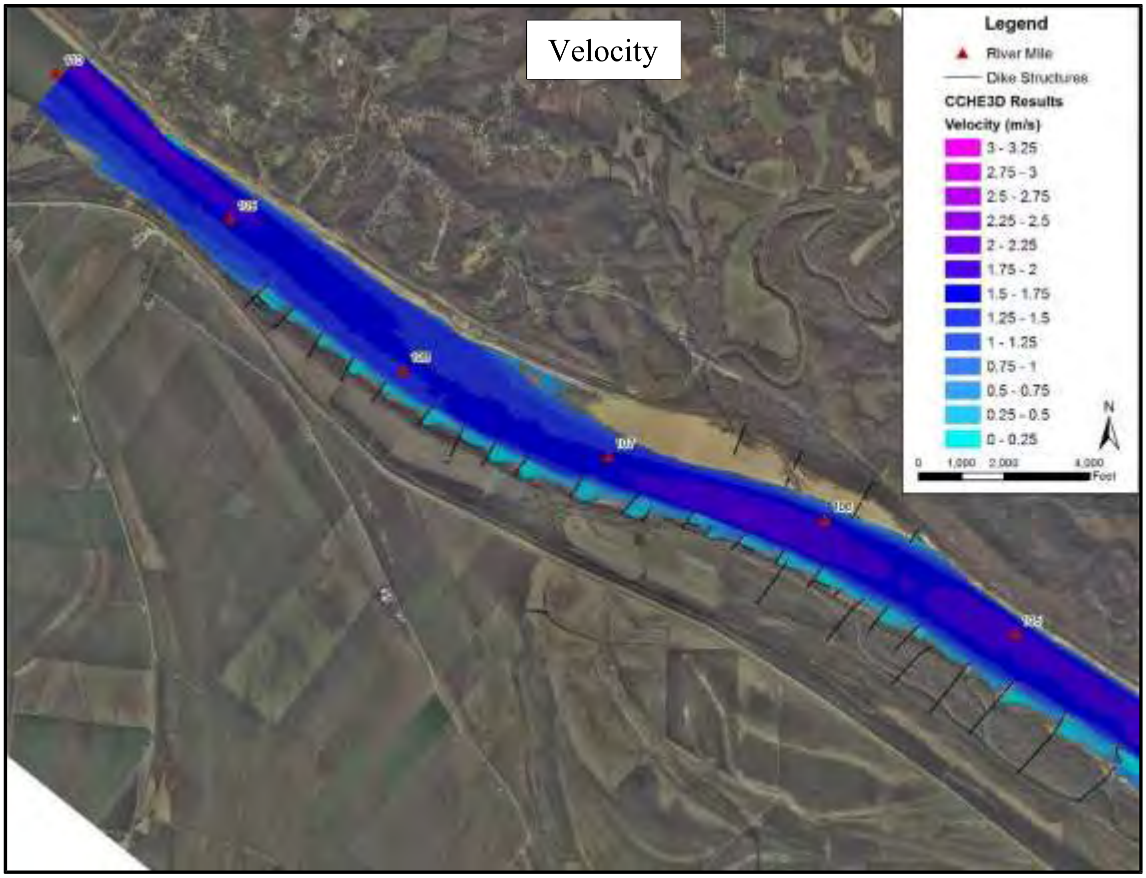


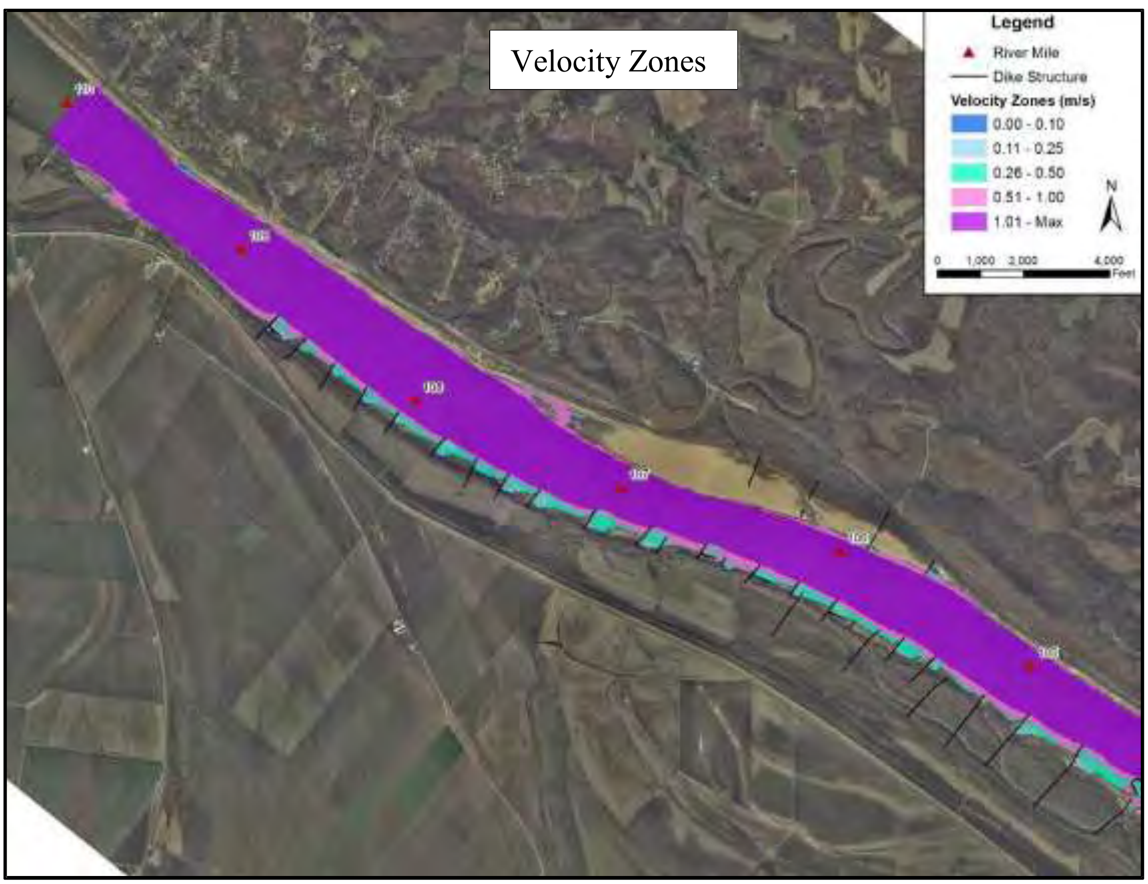
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 2 m below water surface for the study reach between RM 110 to RM 105



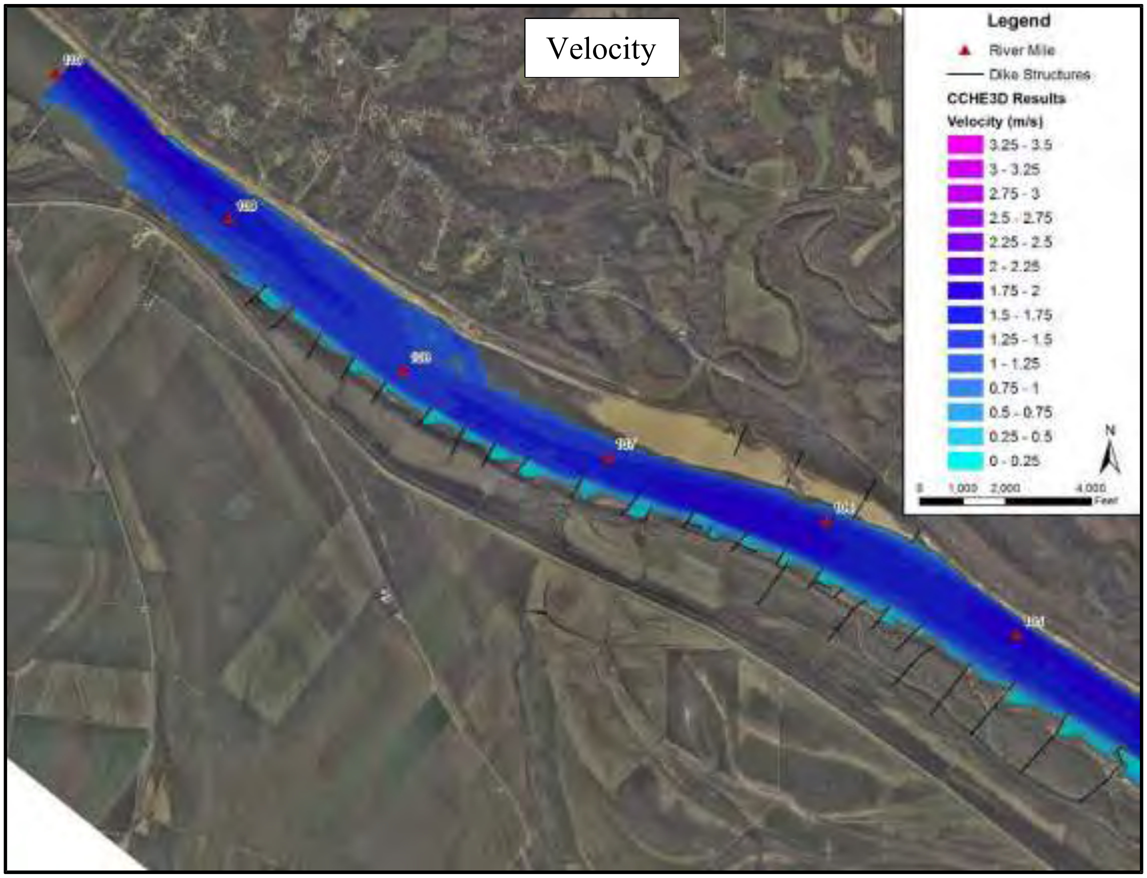


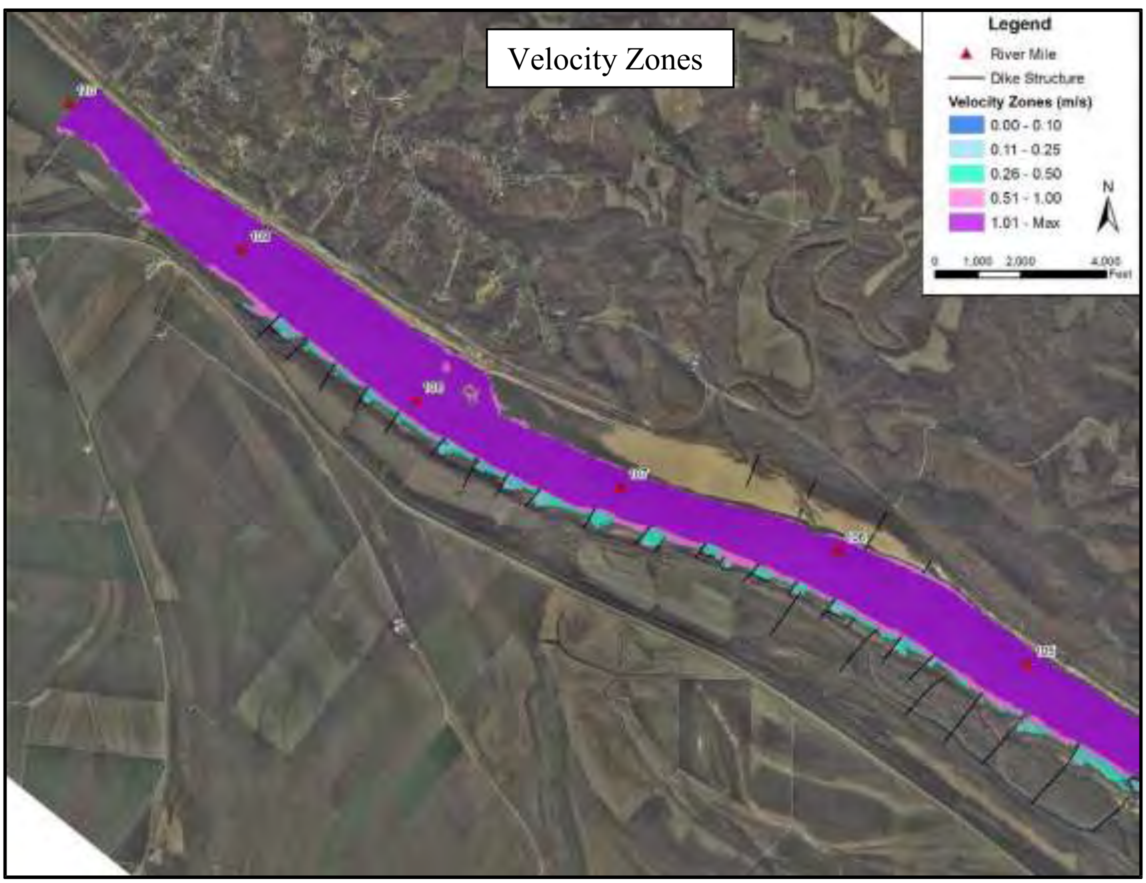
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 4 m below water surface for the study reach between RM 110 to RM 105



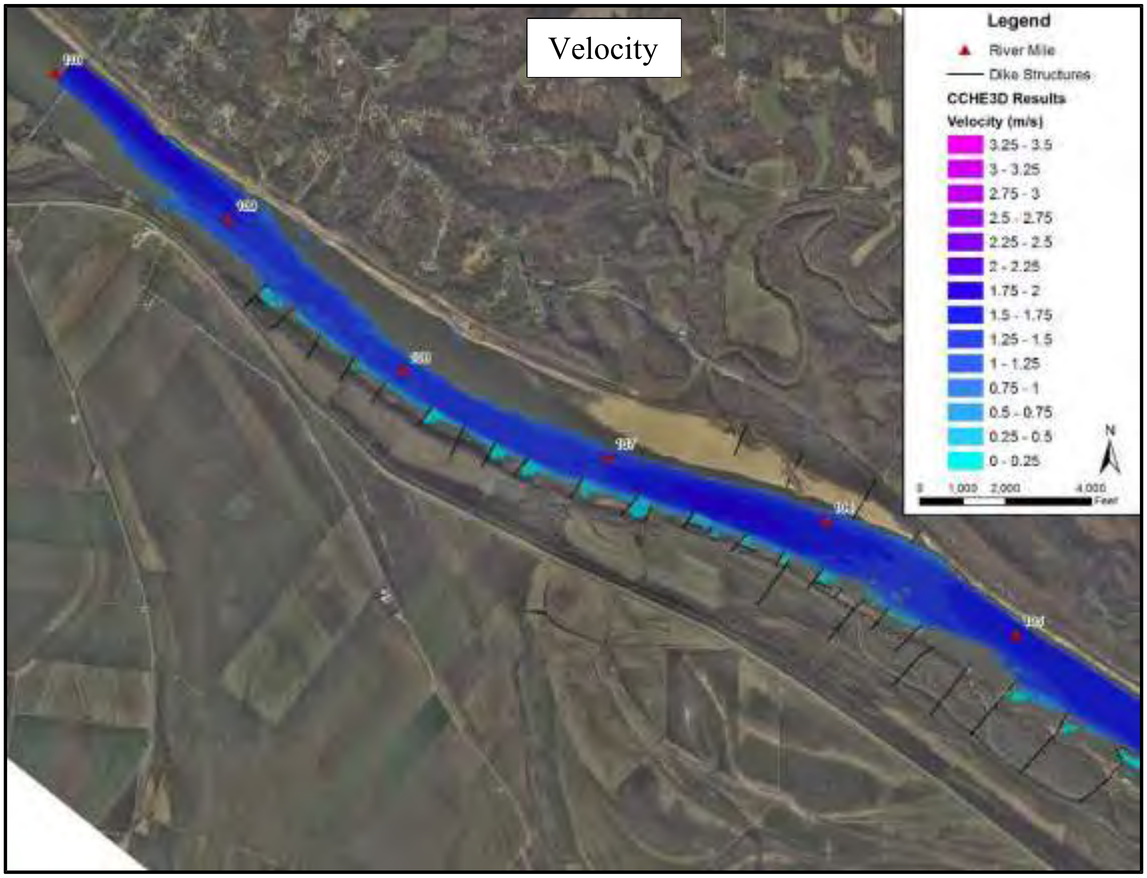


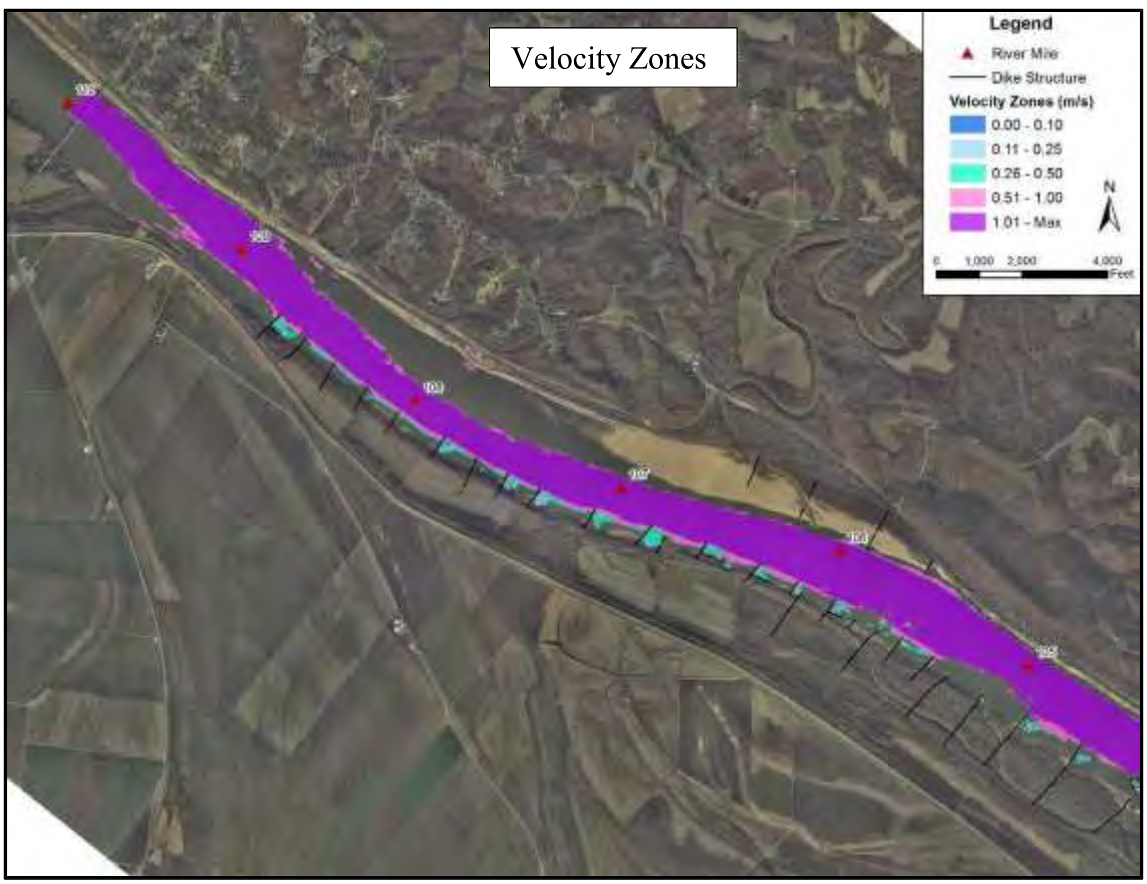
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 6 m below water surface for the study reach between RM 110 to RM 105



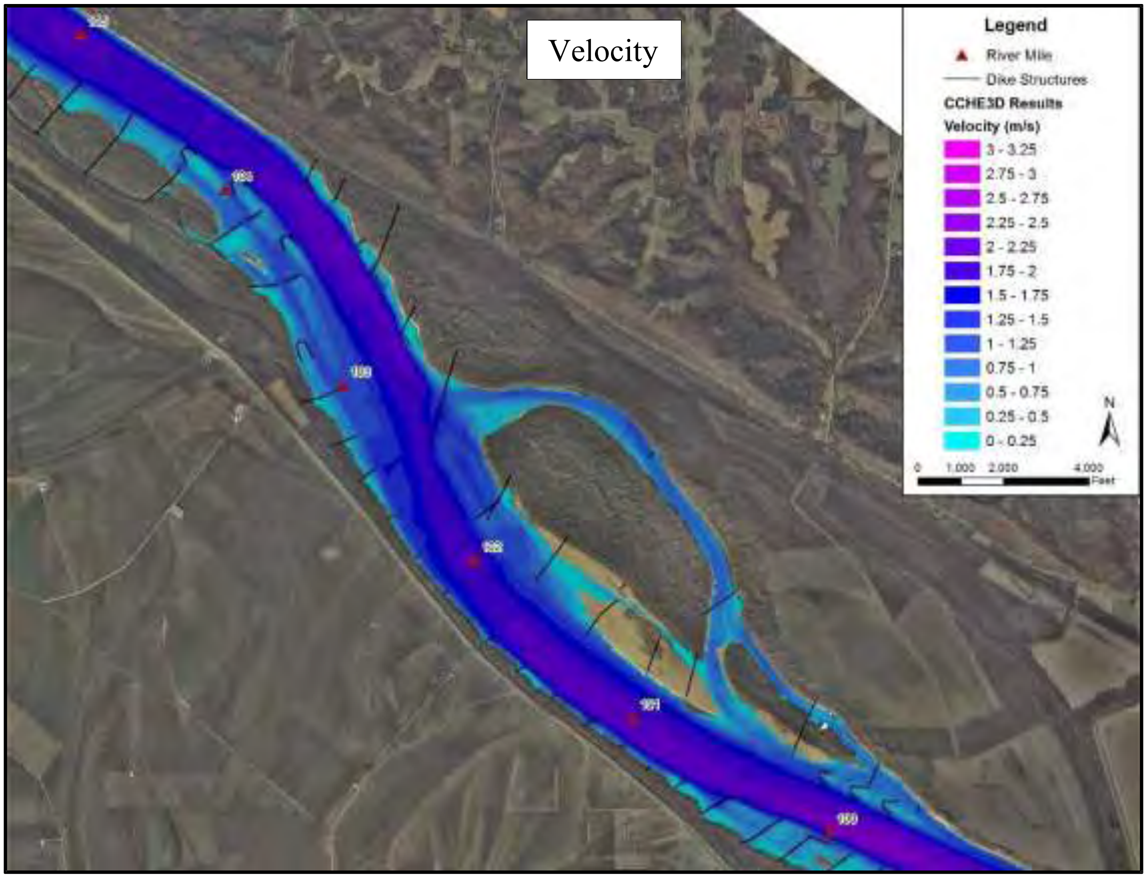


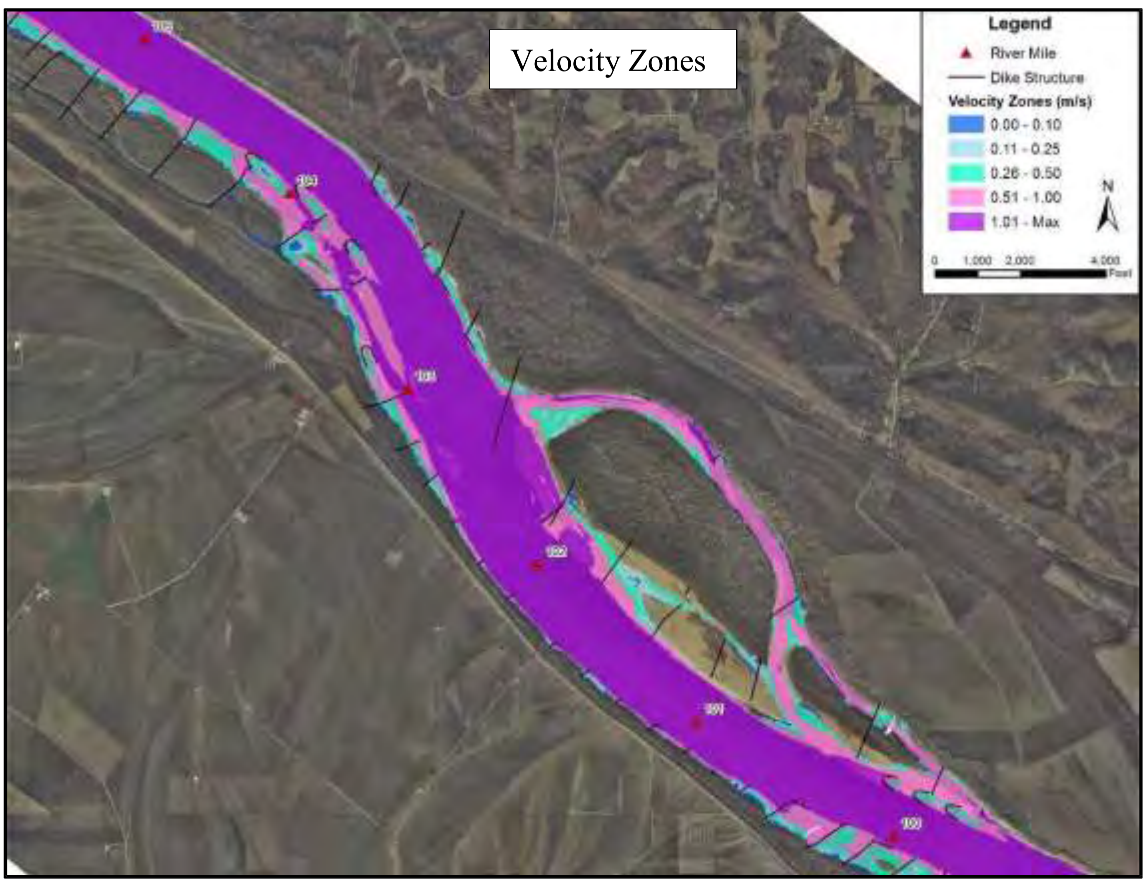
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 8 m below water surface for the study reach between RM 110 to RM 105



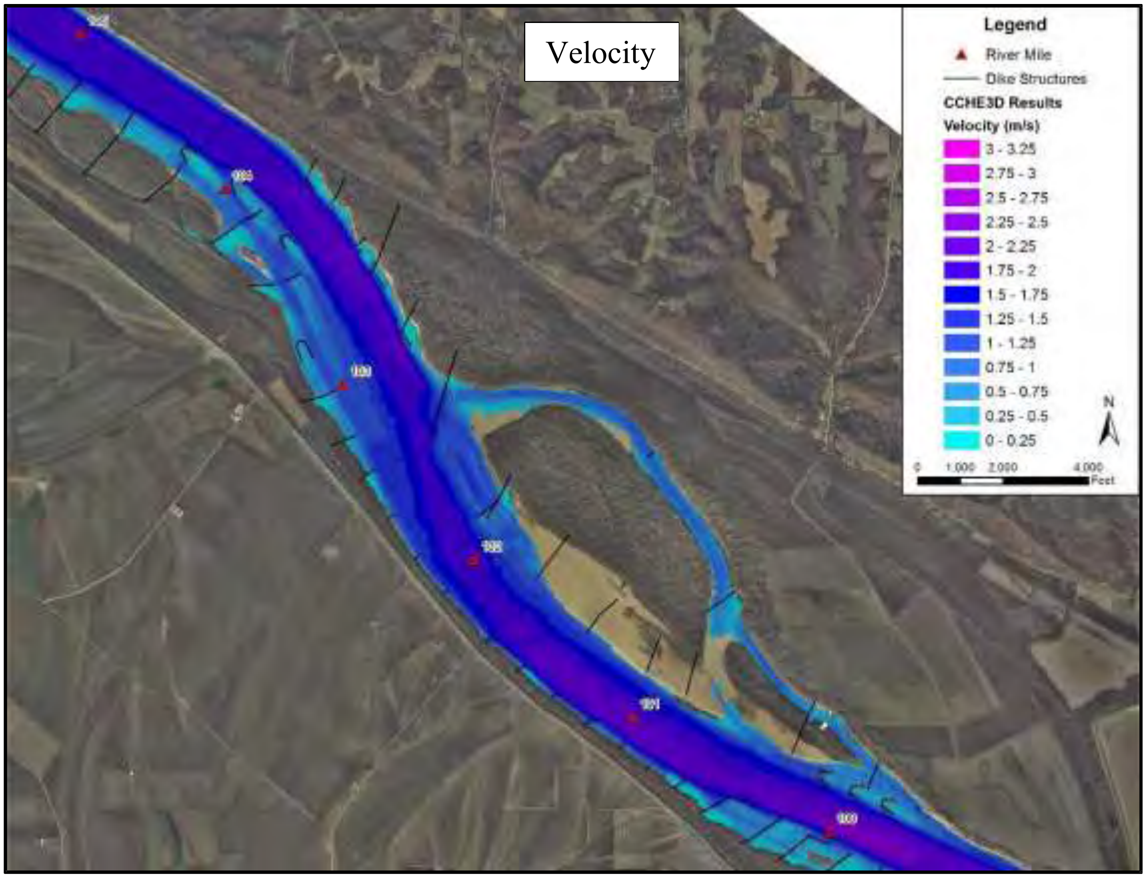


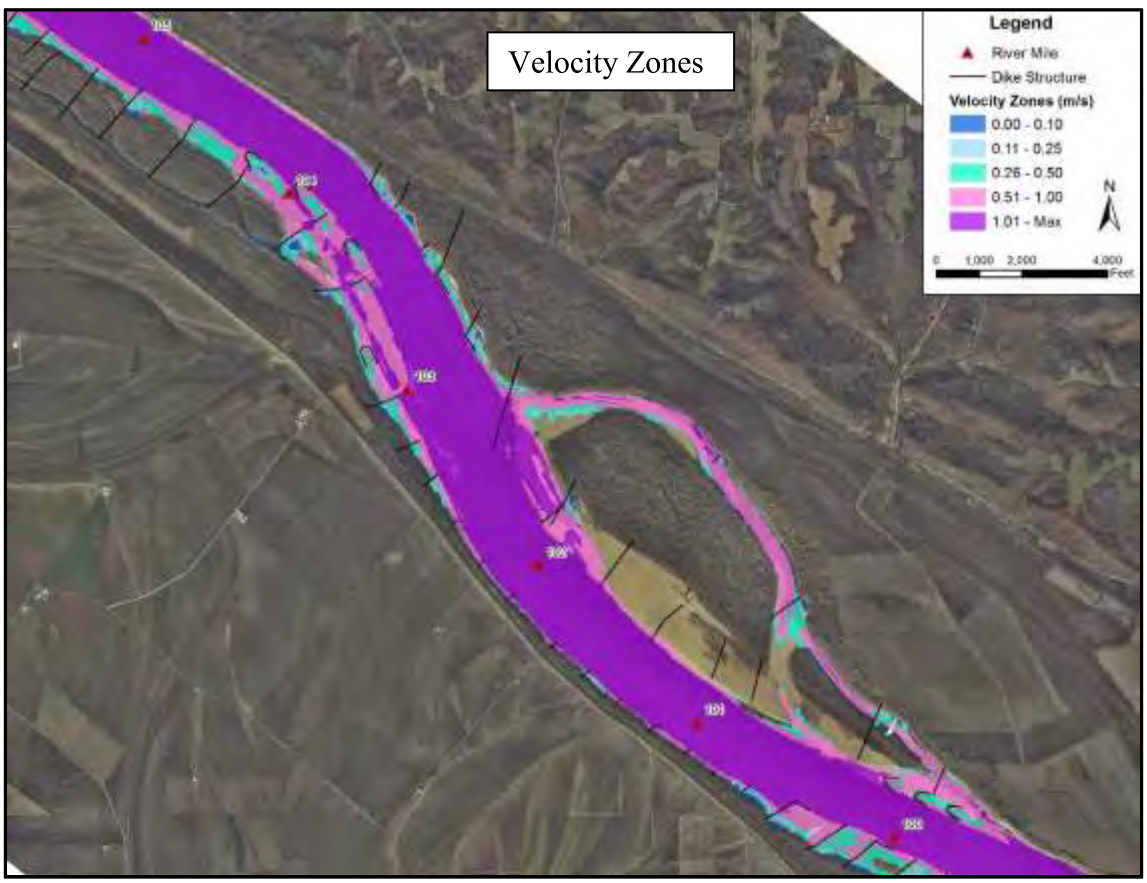
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 10 m below water surface for the study reach between RM 110 to RM 105



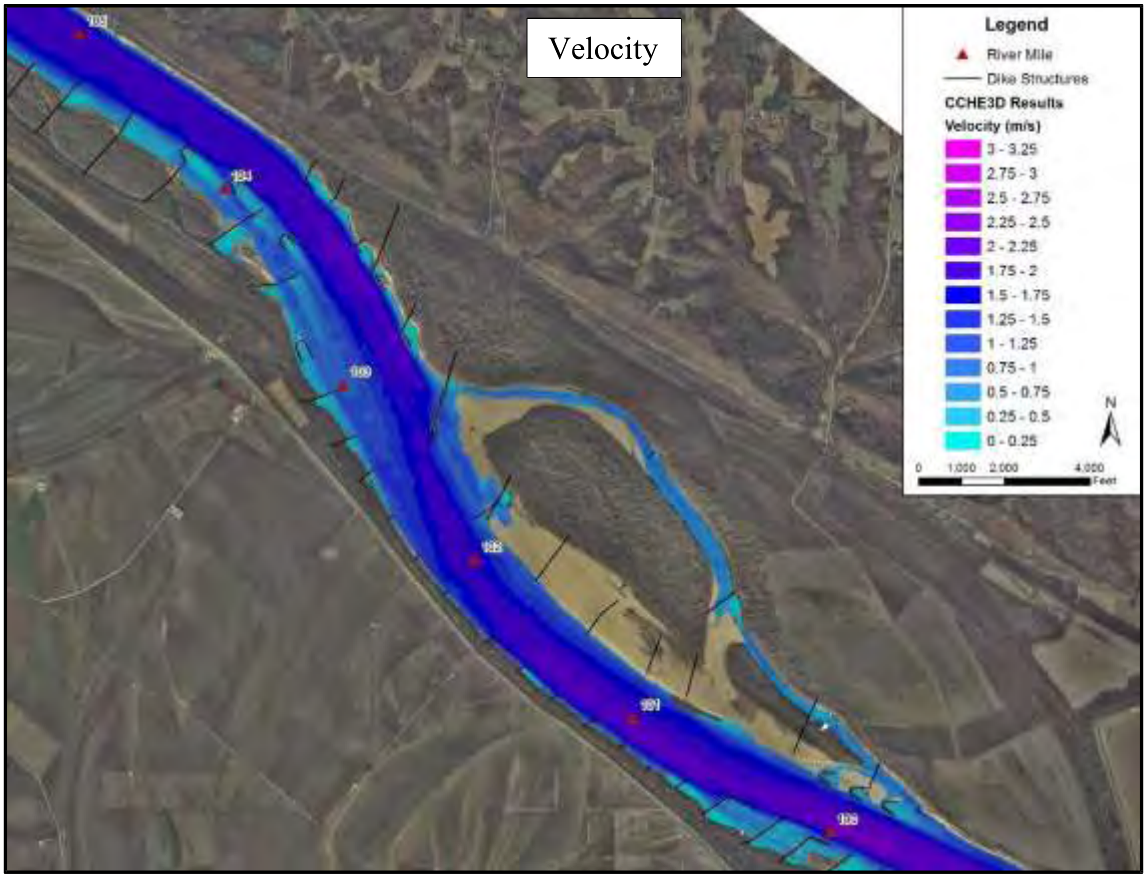


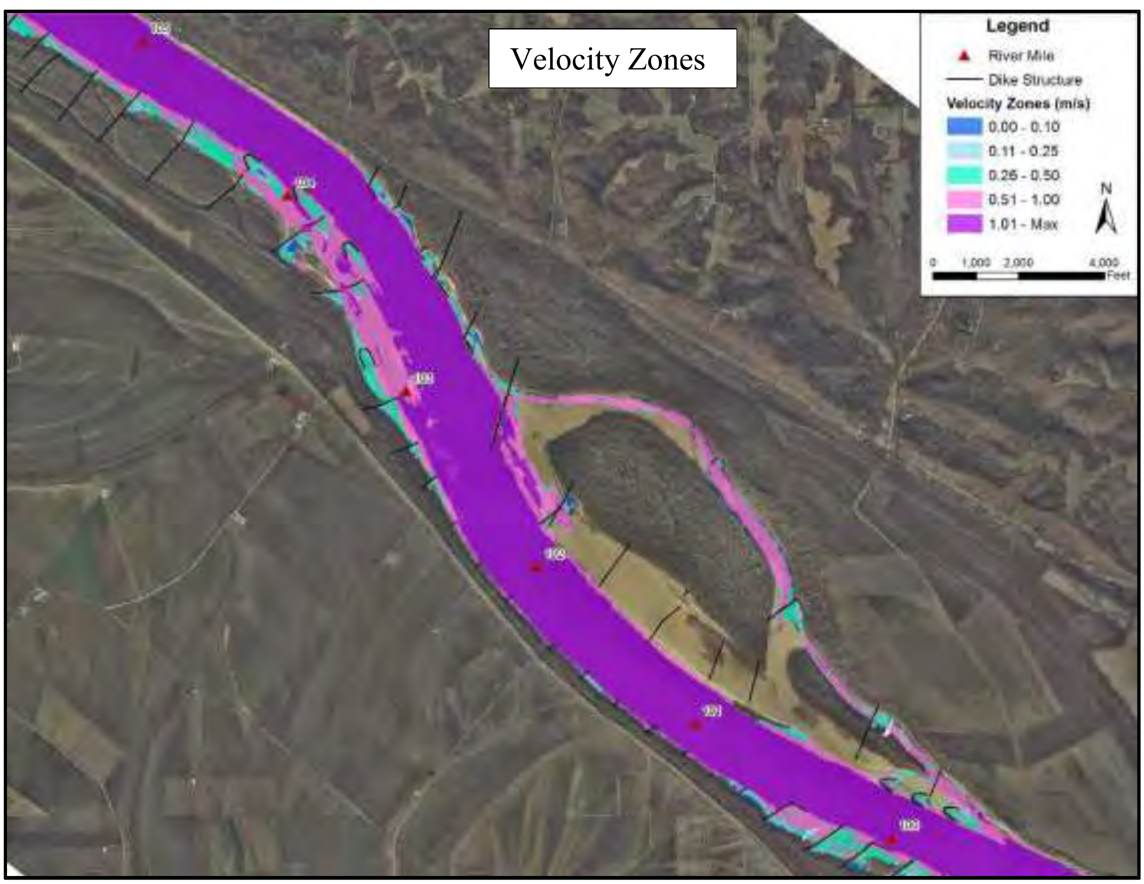
CCHE3D velocity results (flow of 8,580.0 m^3/s) at water surface for the study reach between RM 105 to RM 100



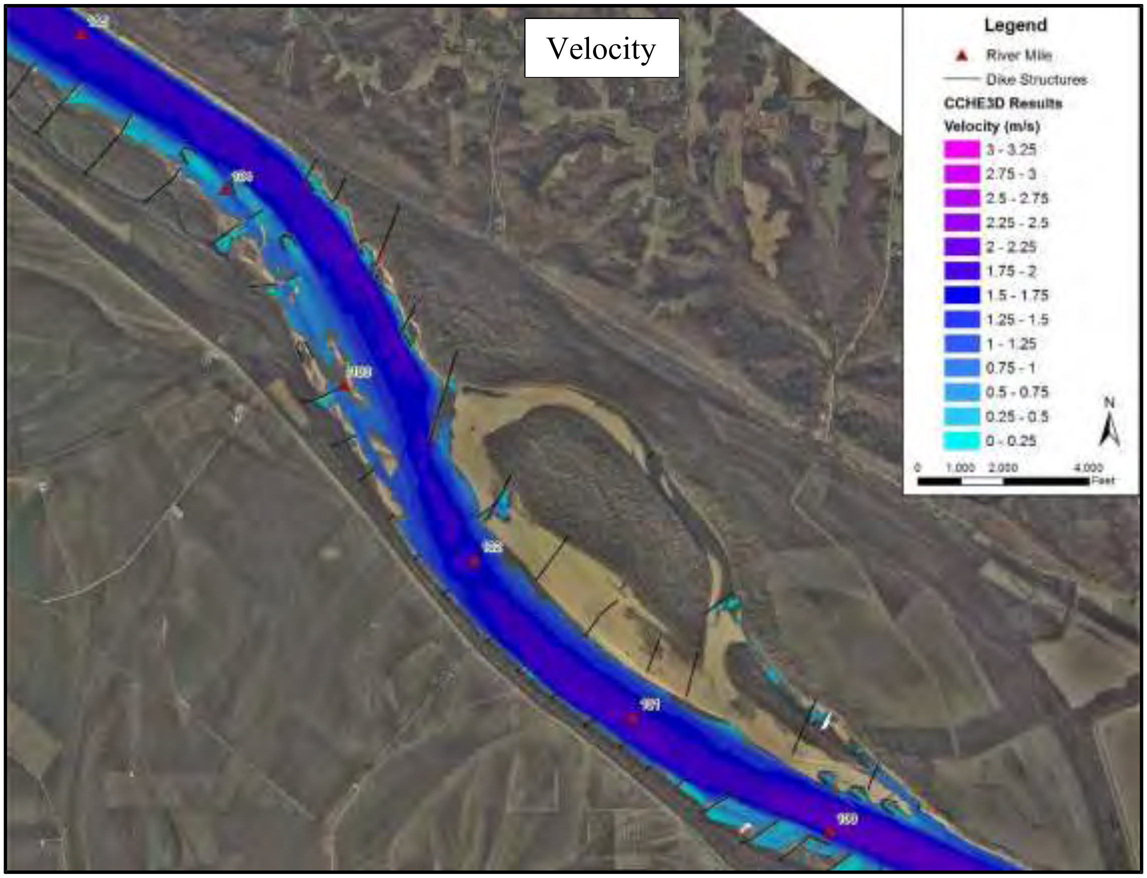


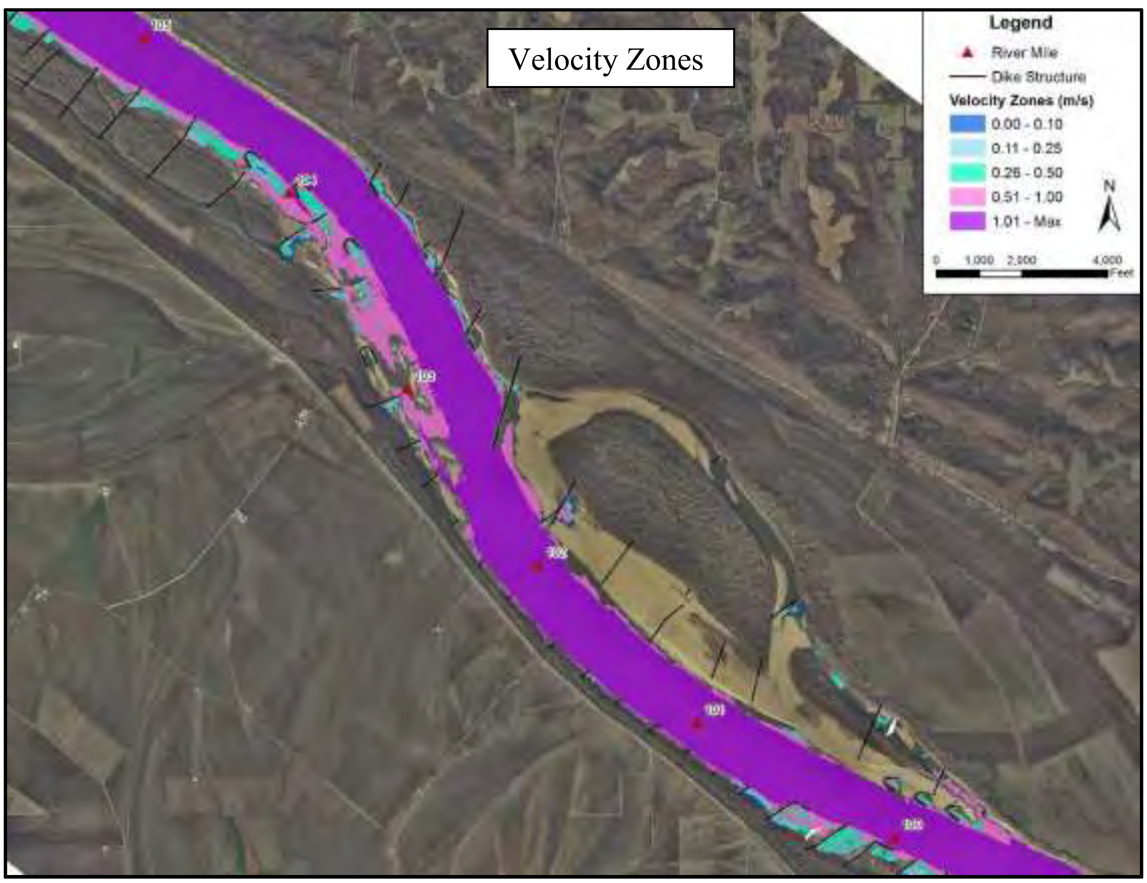
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 2 m below water surface for the study reach between RM 105 to RM 100



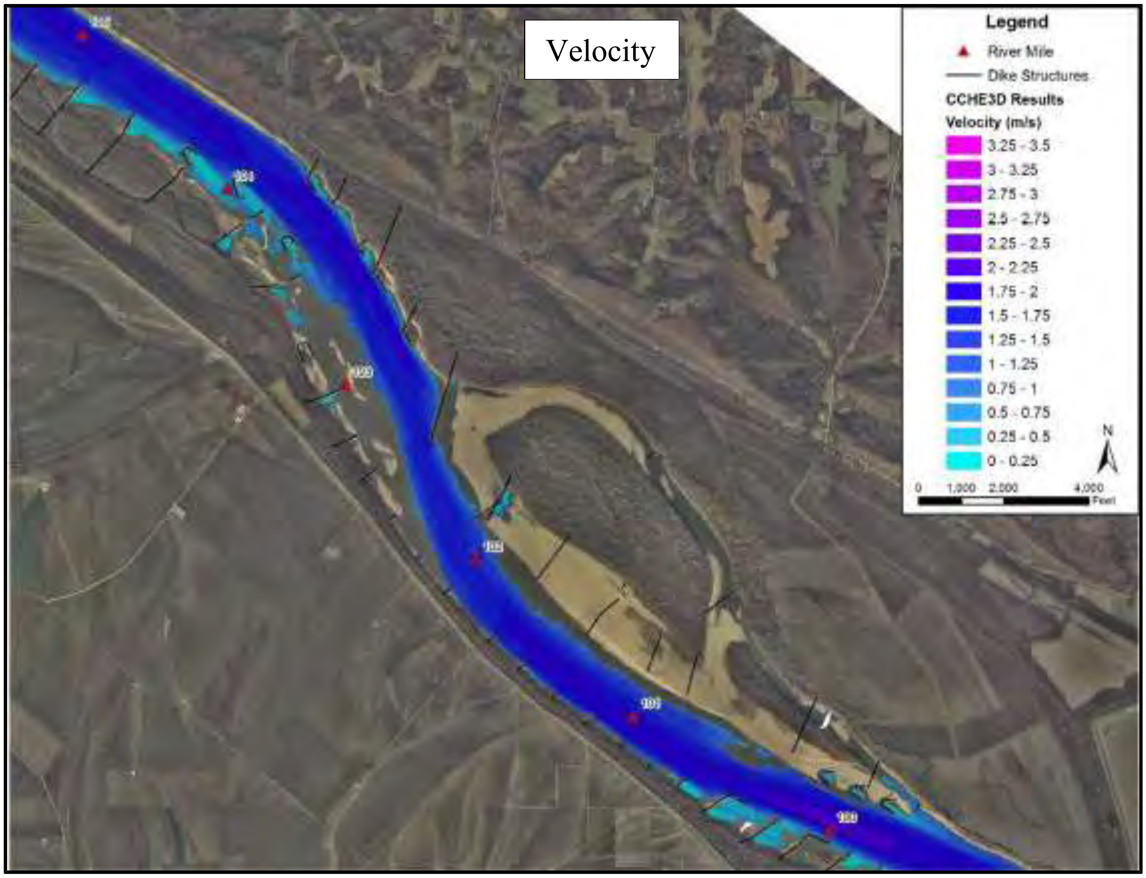


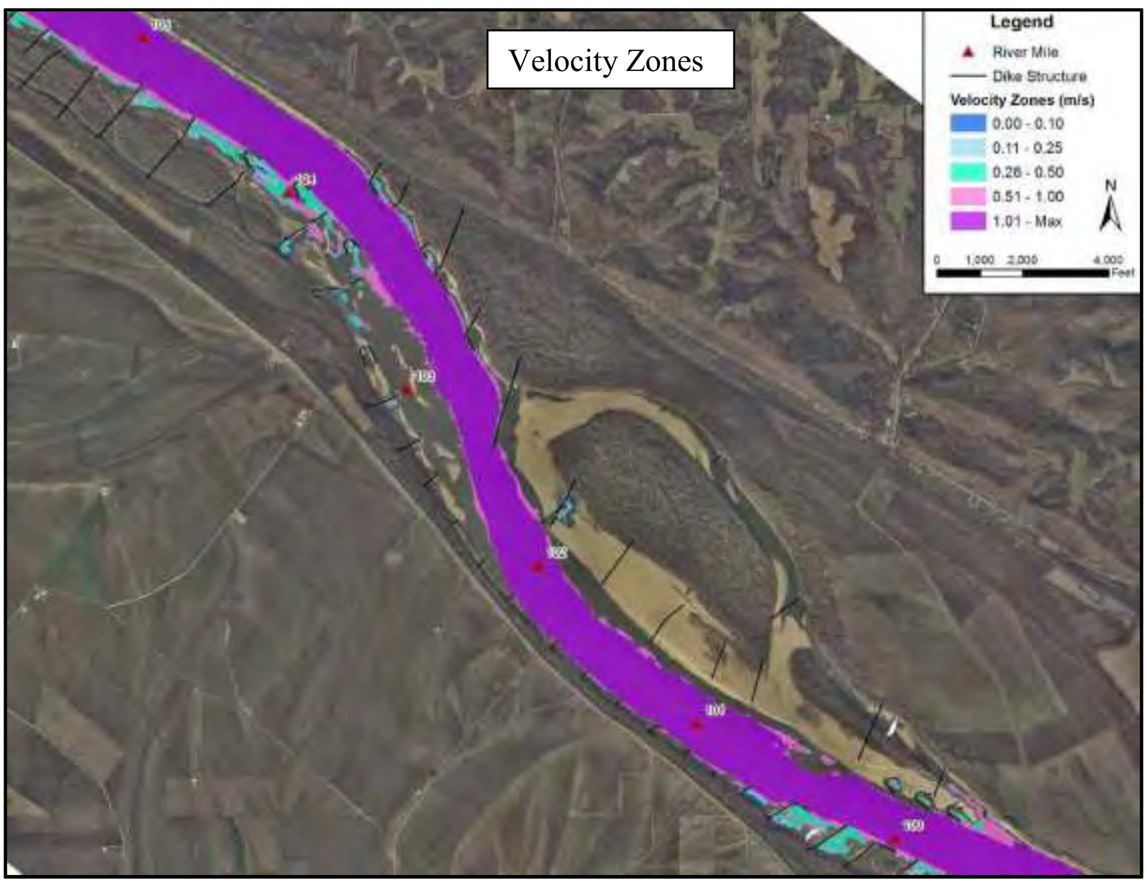
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 4 m below water surface for the study reach between RM 105 to RM 100



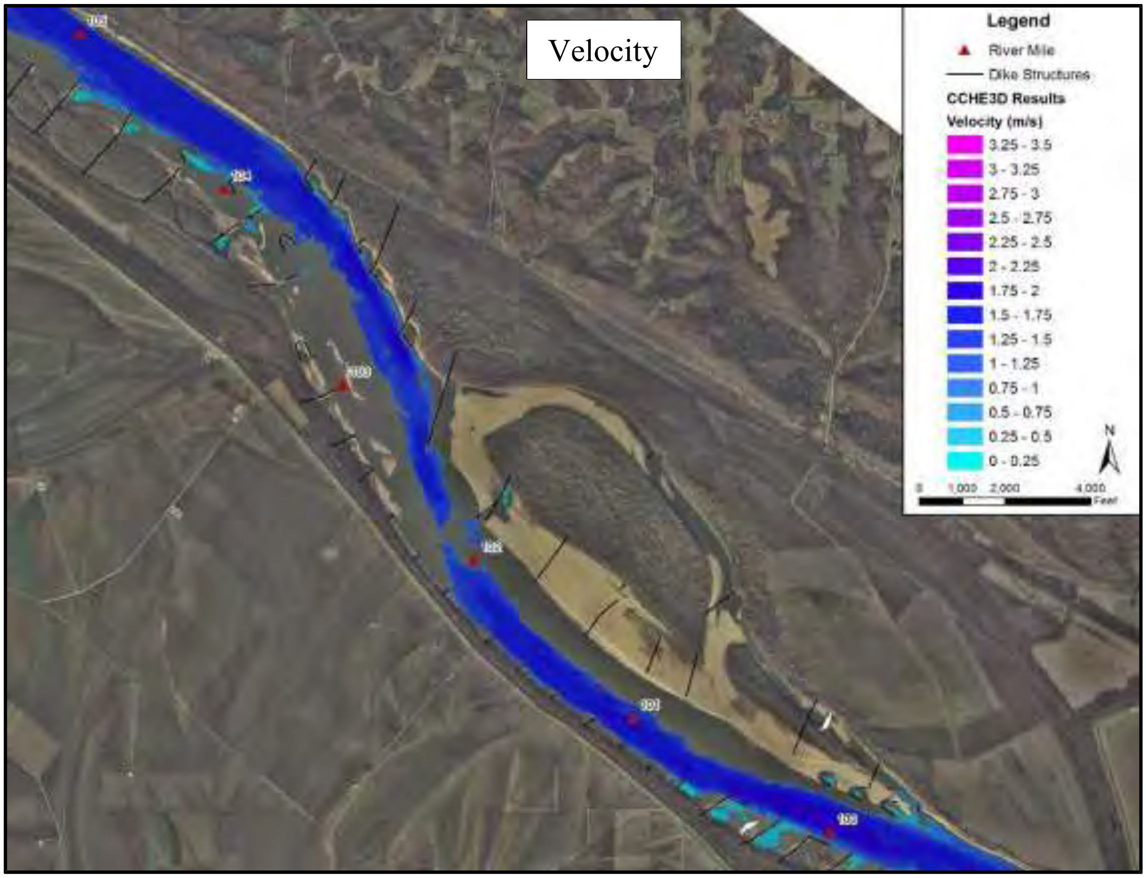


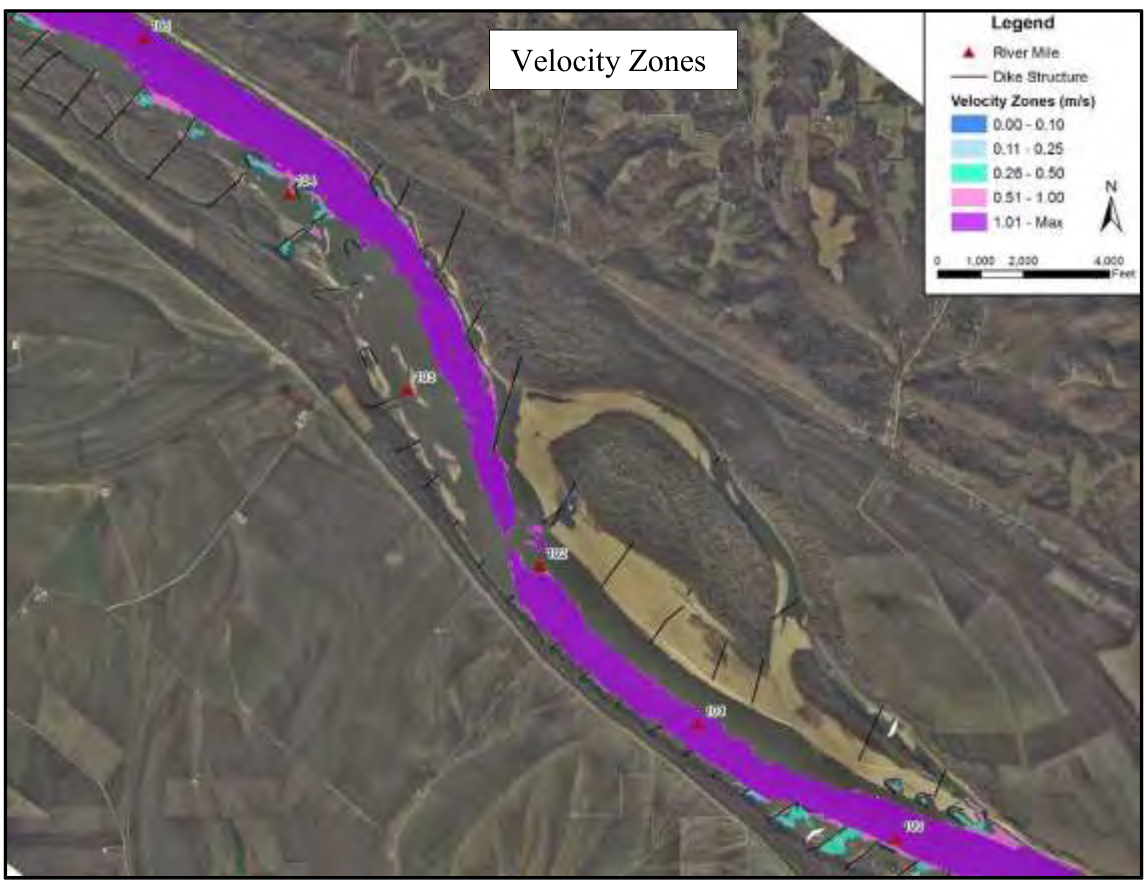
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 6 m below water surface for the study reach between RM 105 to RM 100



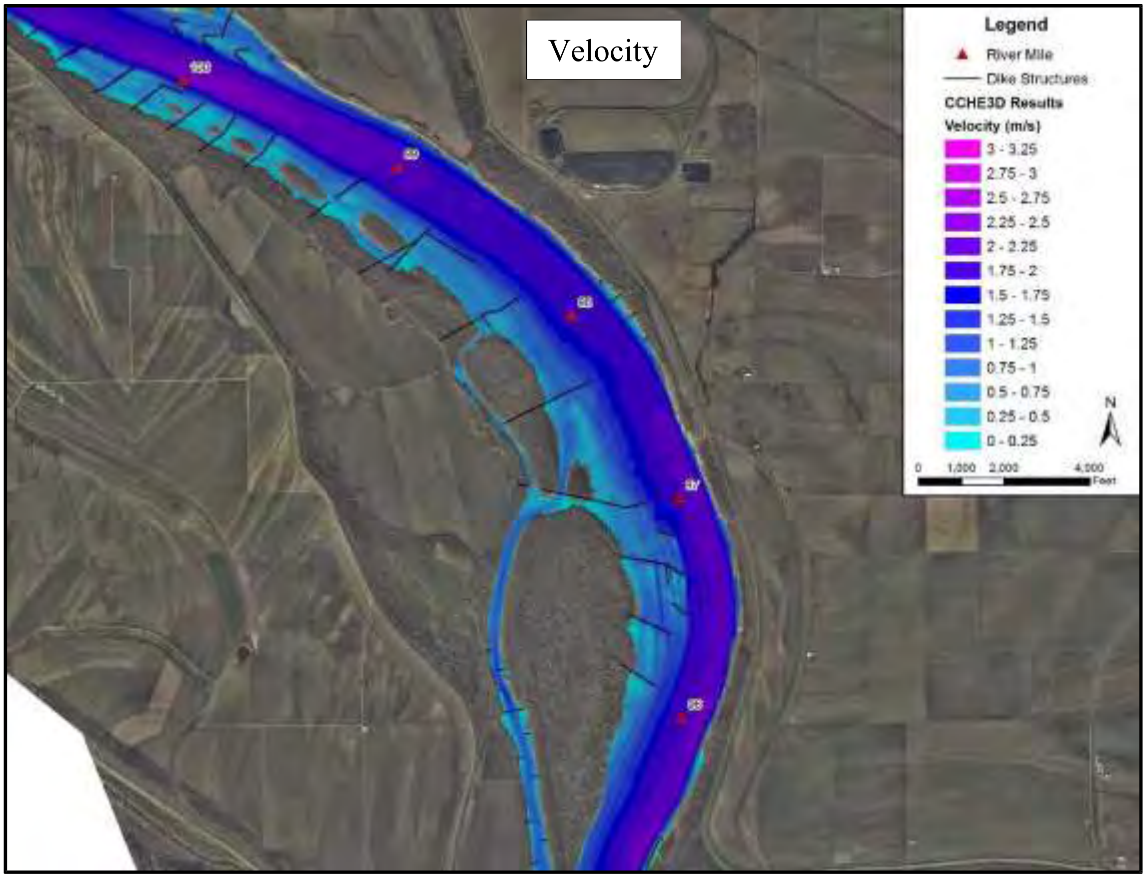


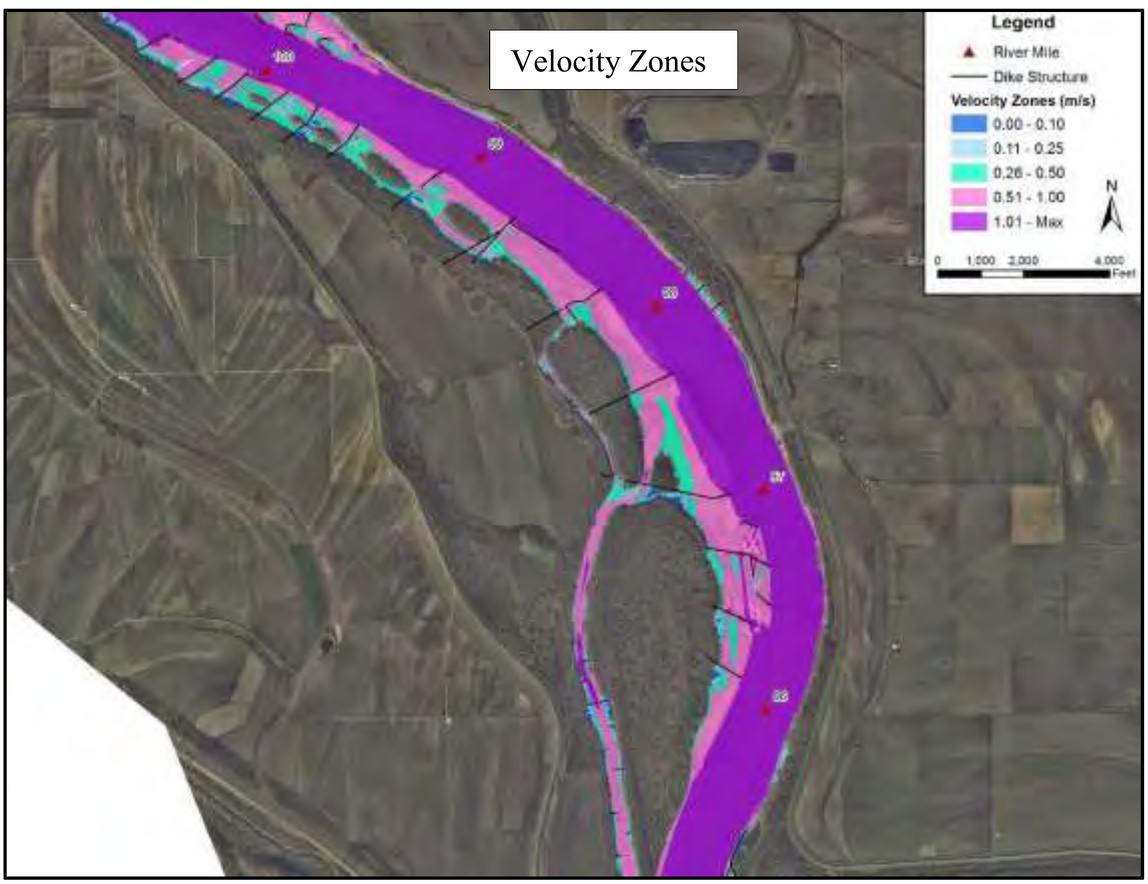
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 8 m below water surface for the study reach between RM 105 to RM 100



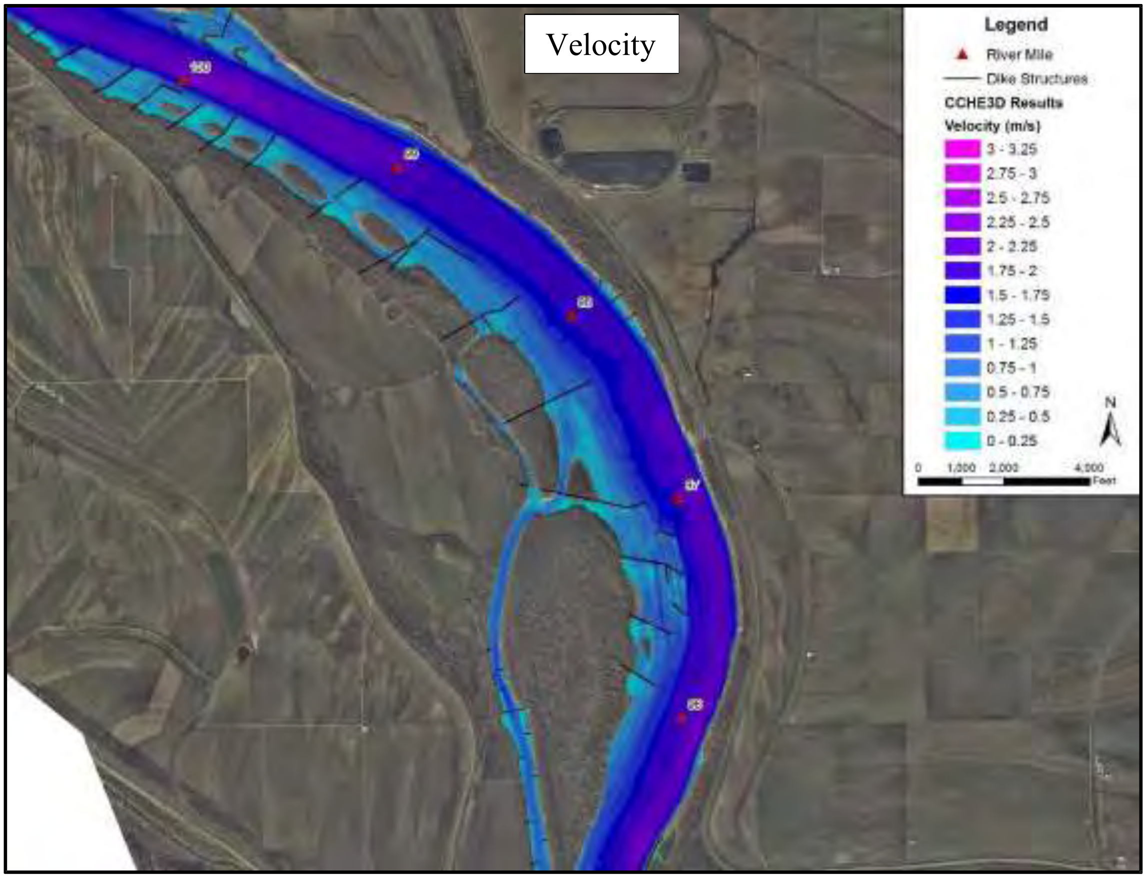


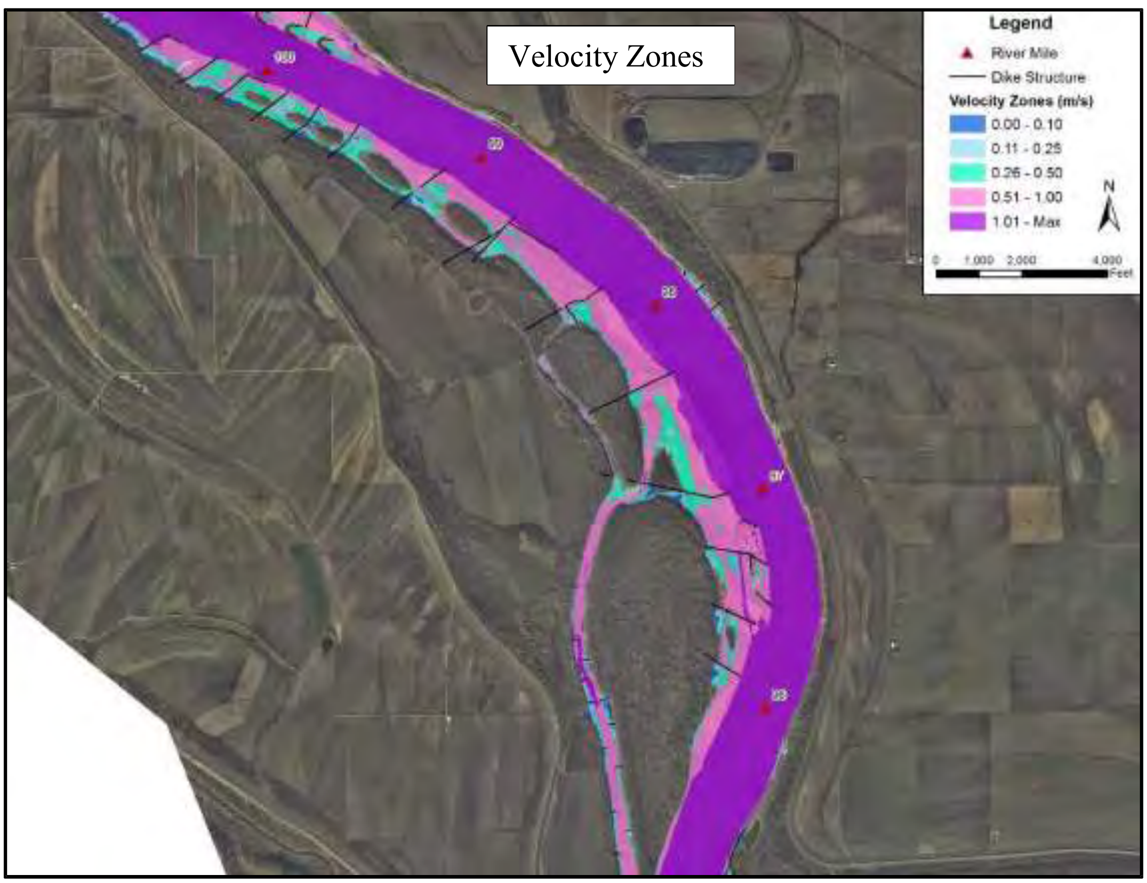
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 10 m below water surface for the study reach between RM 105 to RM 100



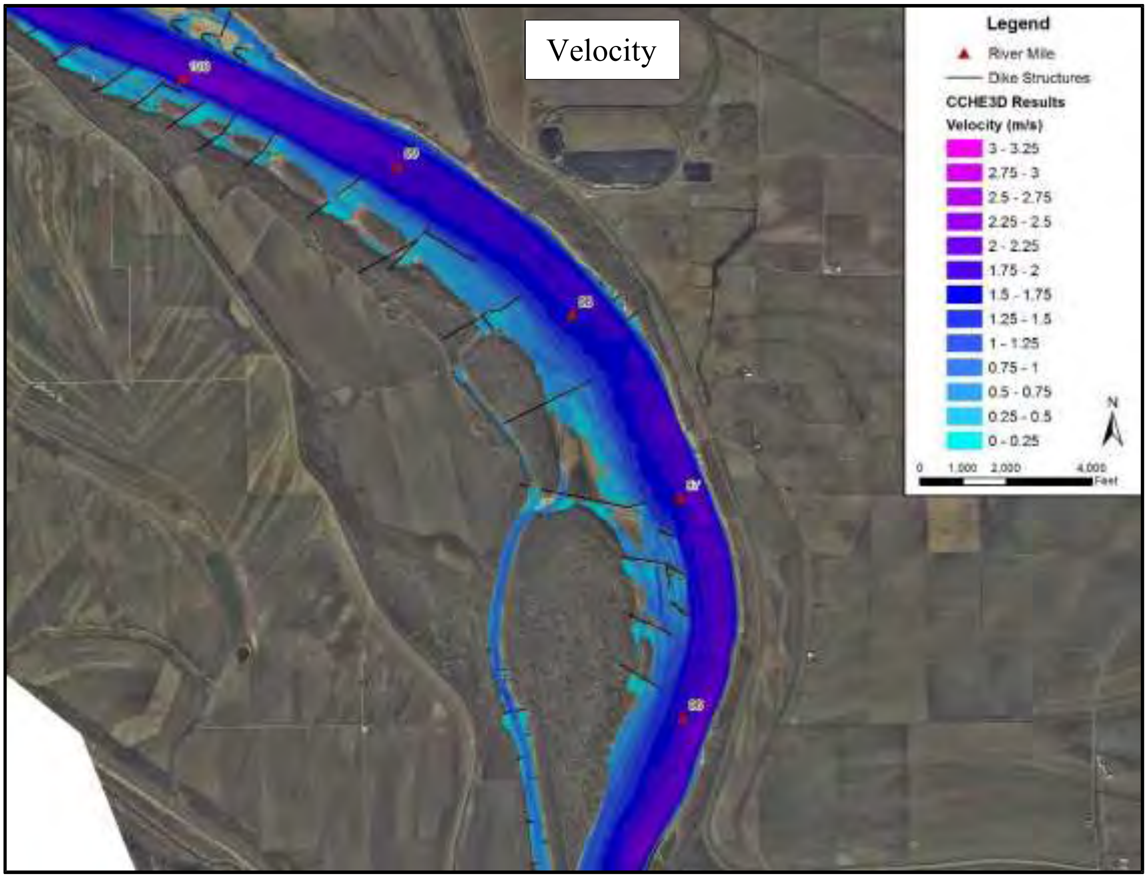


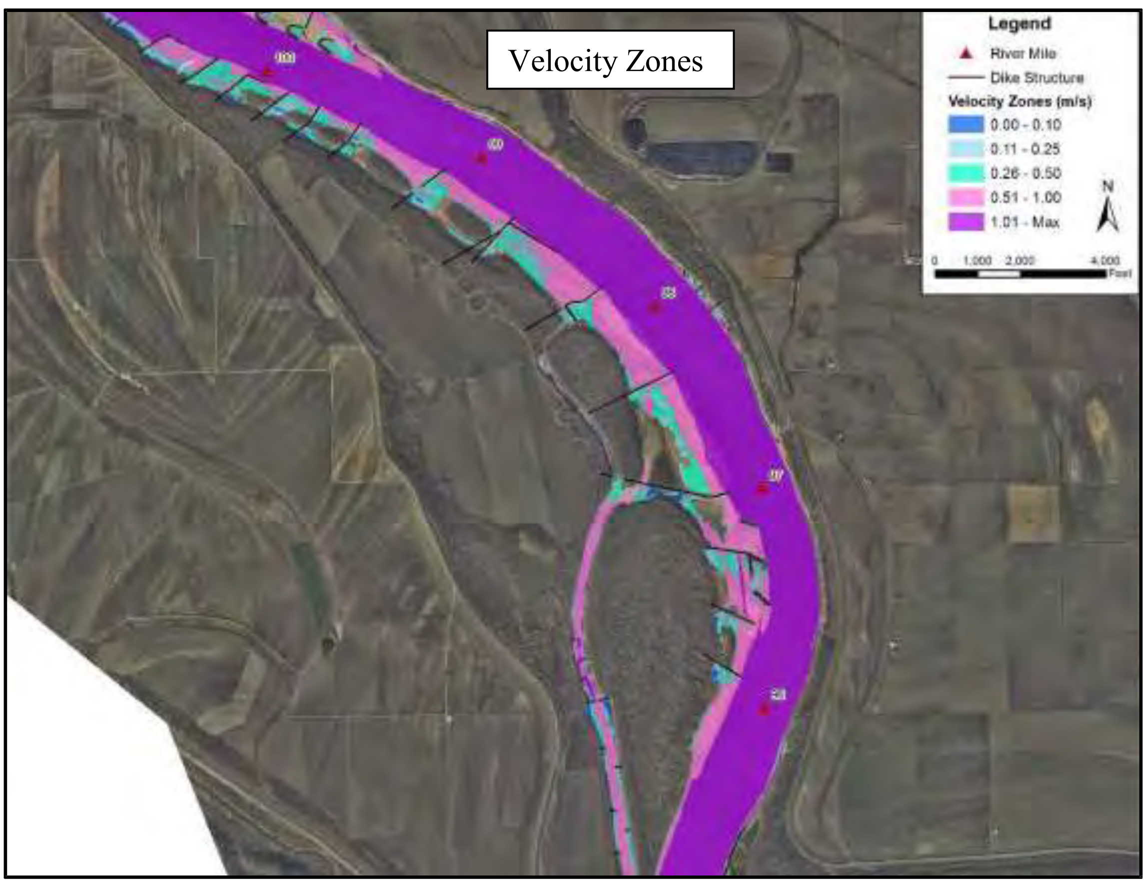
CCHE3D velocity results (flow of 8,580.0 m^3/s) at water surface for the study reach between RM 100 to RM 96



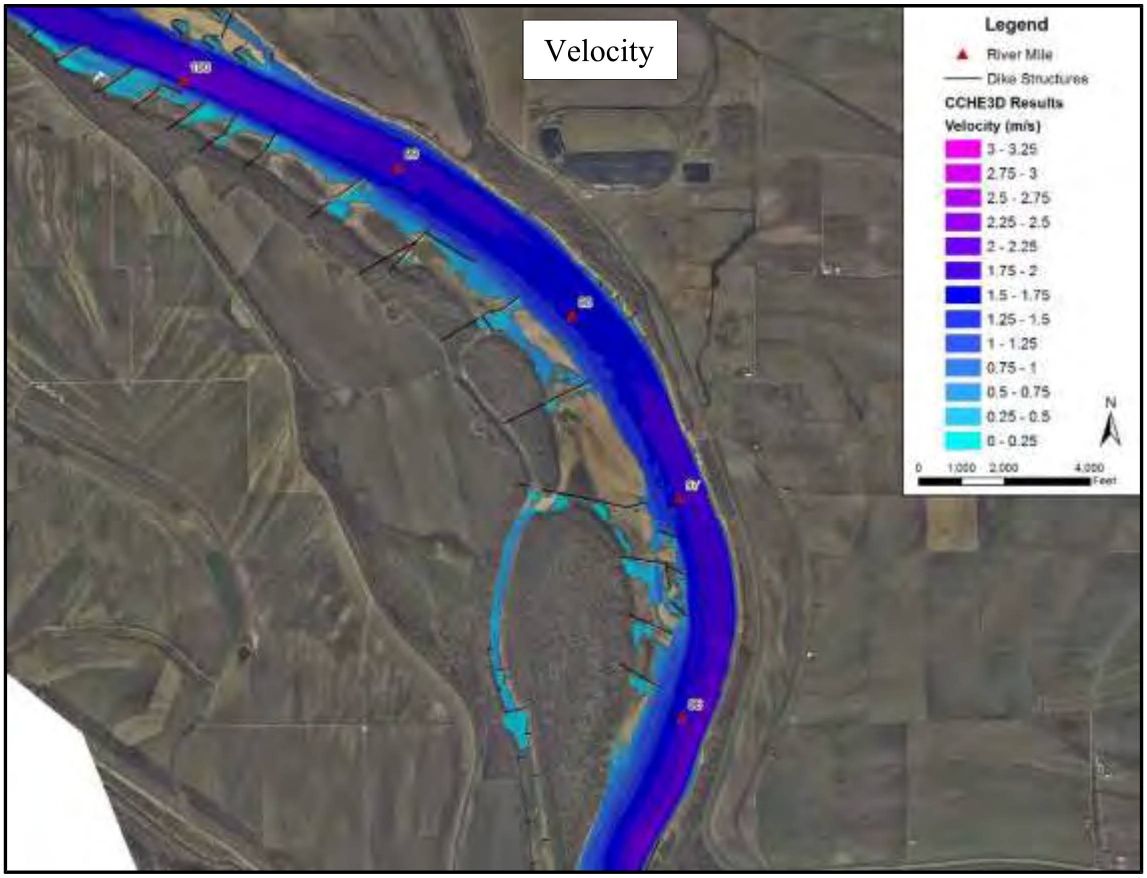


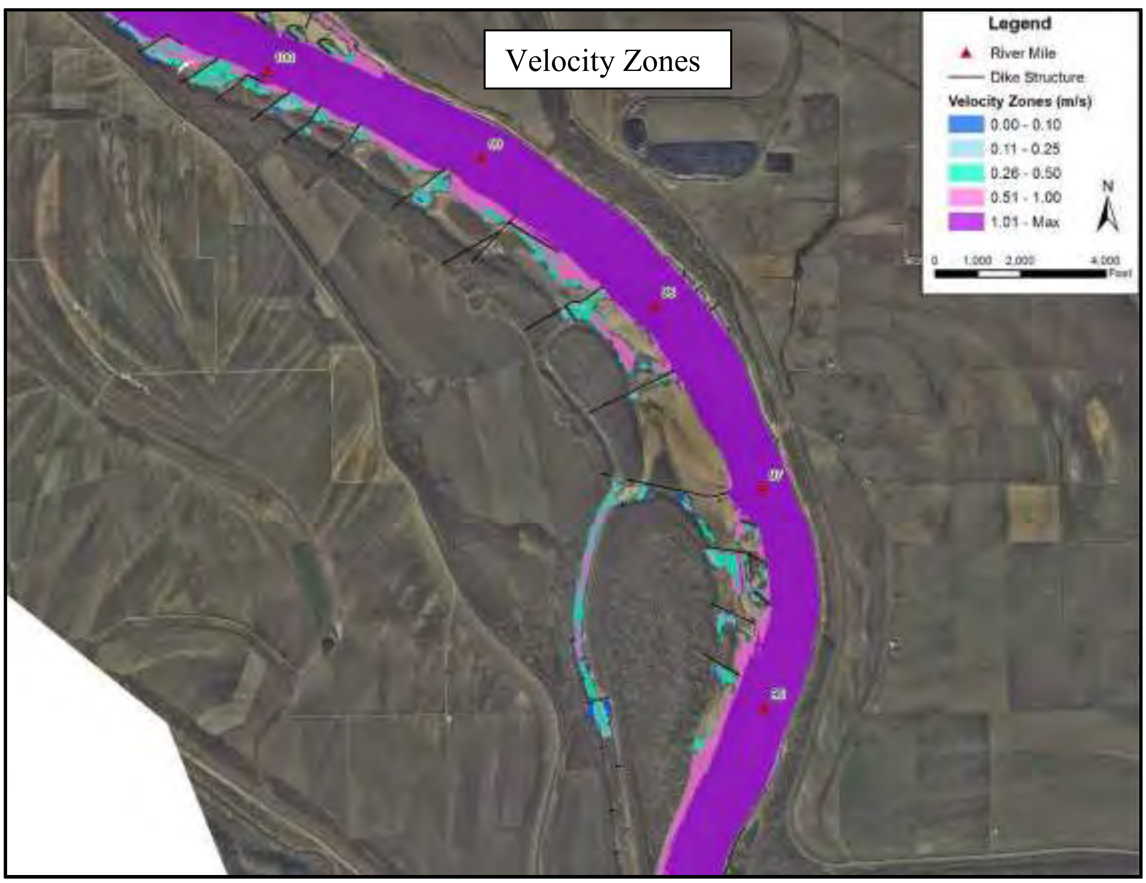
CCHE3D velocity results (flow of 8,580.0 m³/s) at a depth of 2 m below water surface for the study reach between RM 100 to RM 96



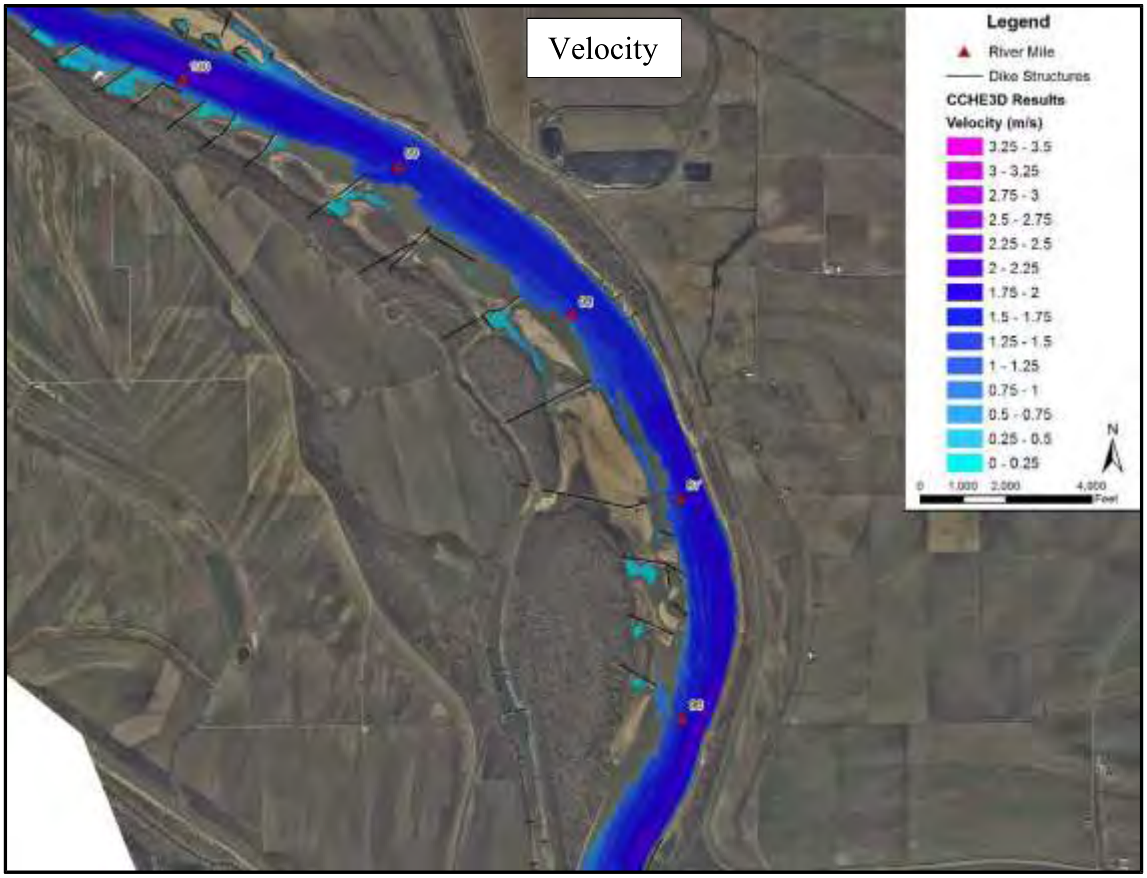


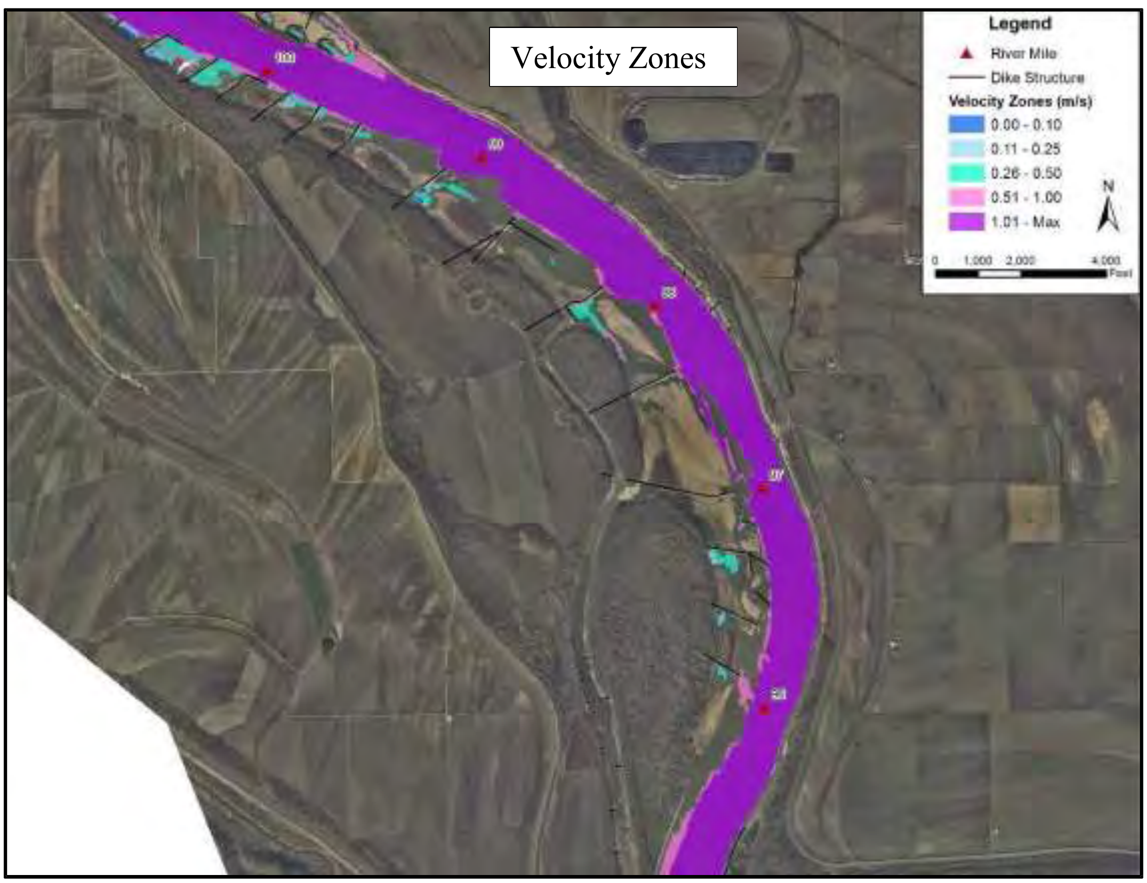
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 4 m below water surface for the study reach between RM 100 to RM 96



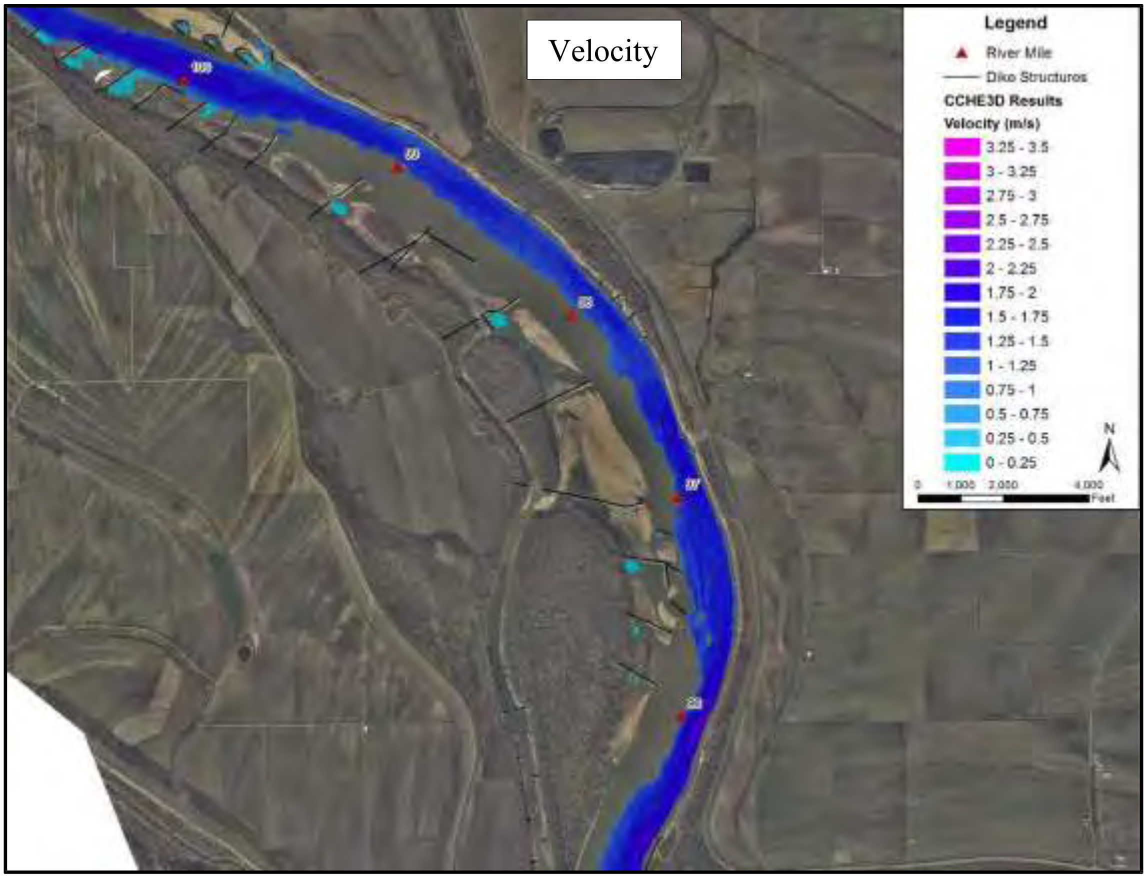


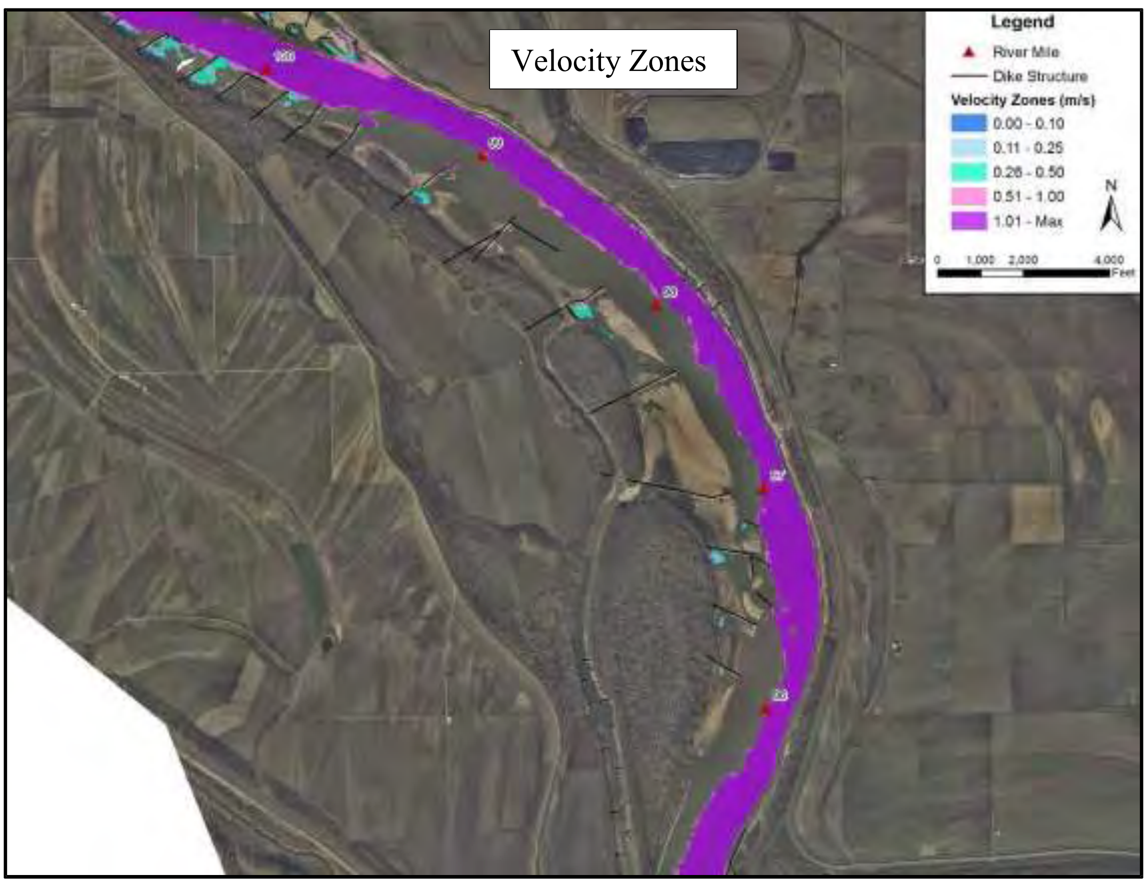
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 6 m below water surface for the study reach between RM 100 to RM 96



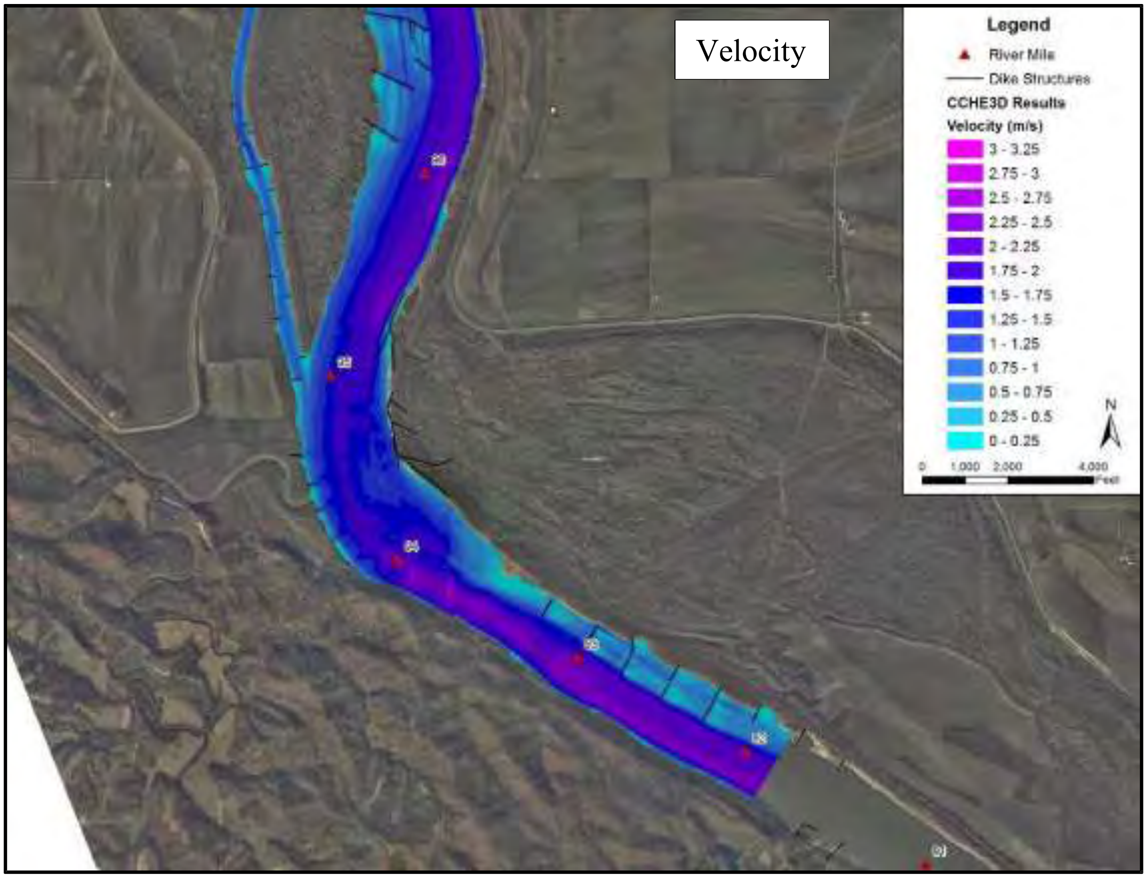


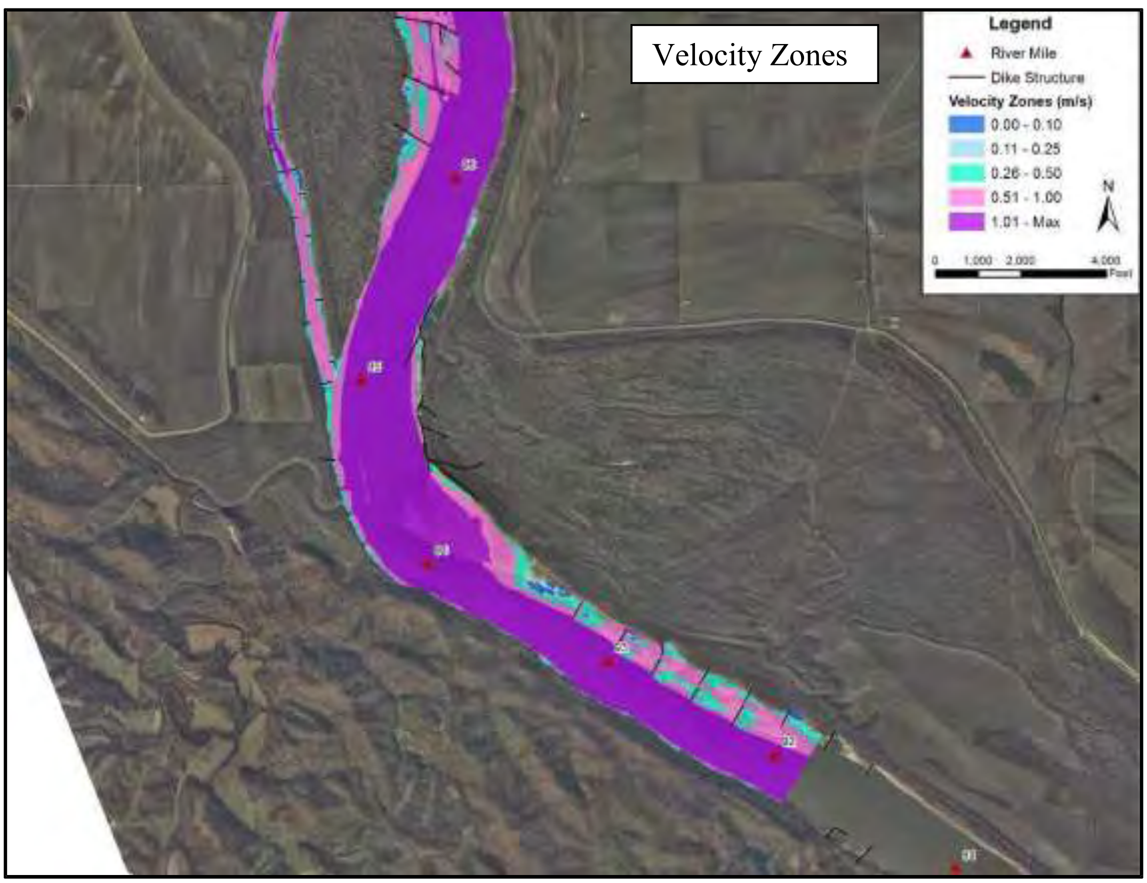
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 8 m below water surface for the study reach between RM 100 to RM 96



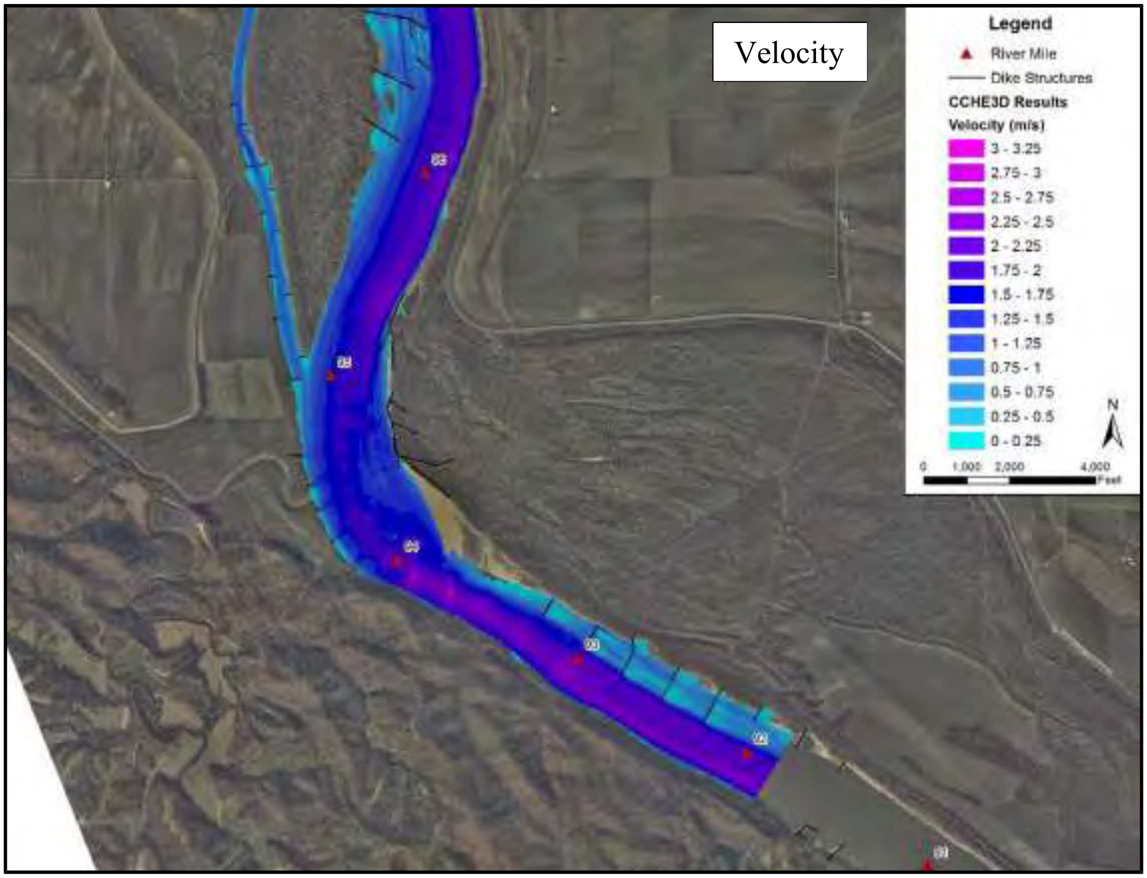


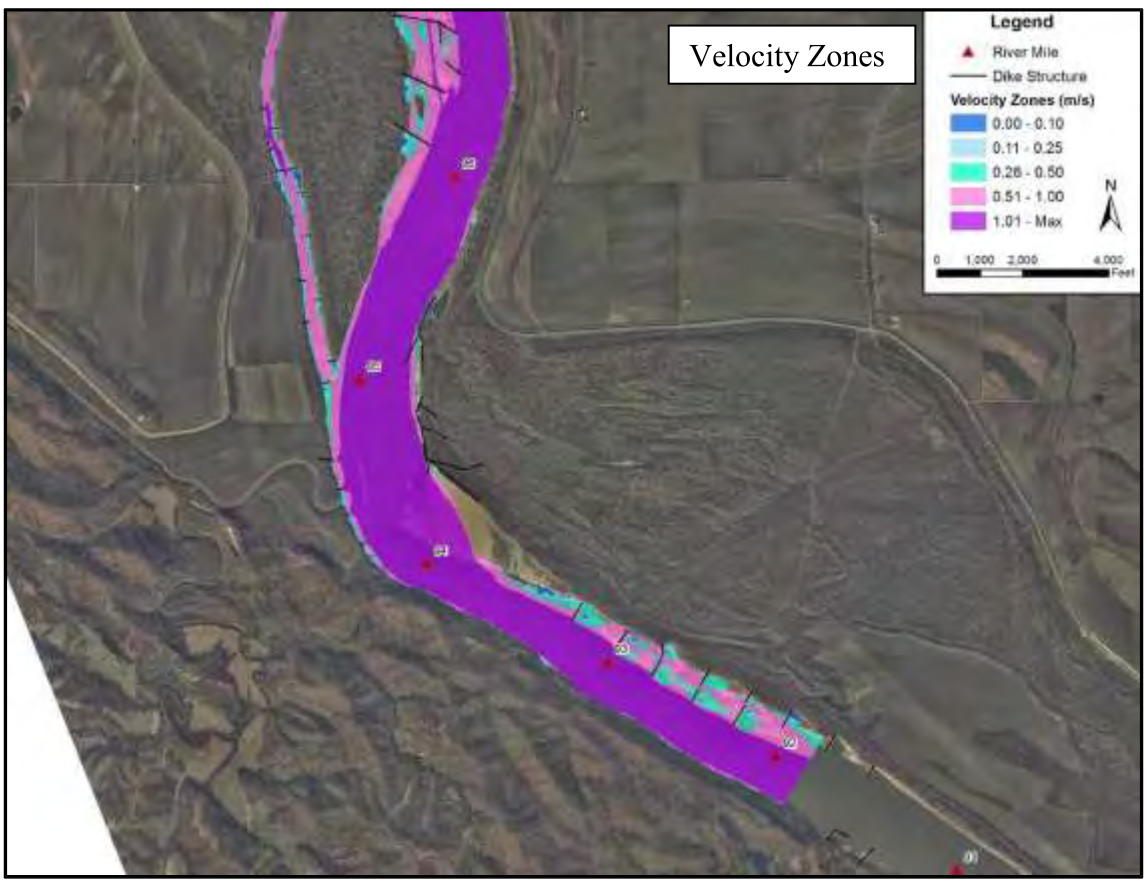
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 10 m below water surface for the study reach between RM 100 to RM 96



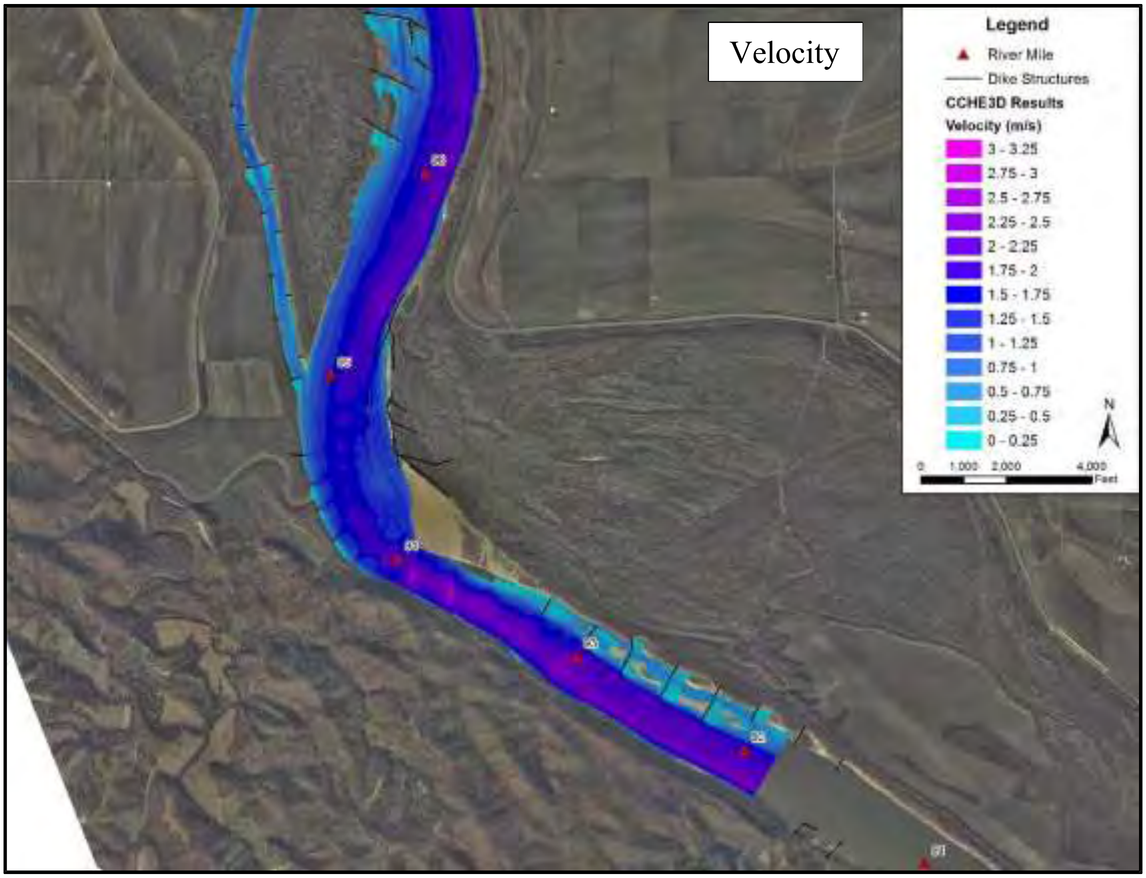


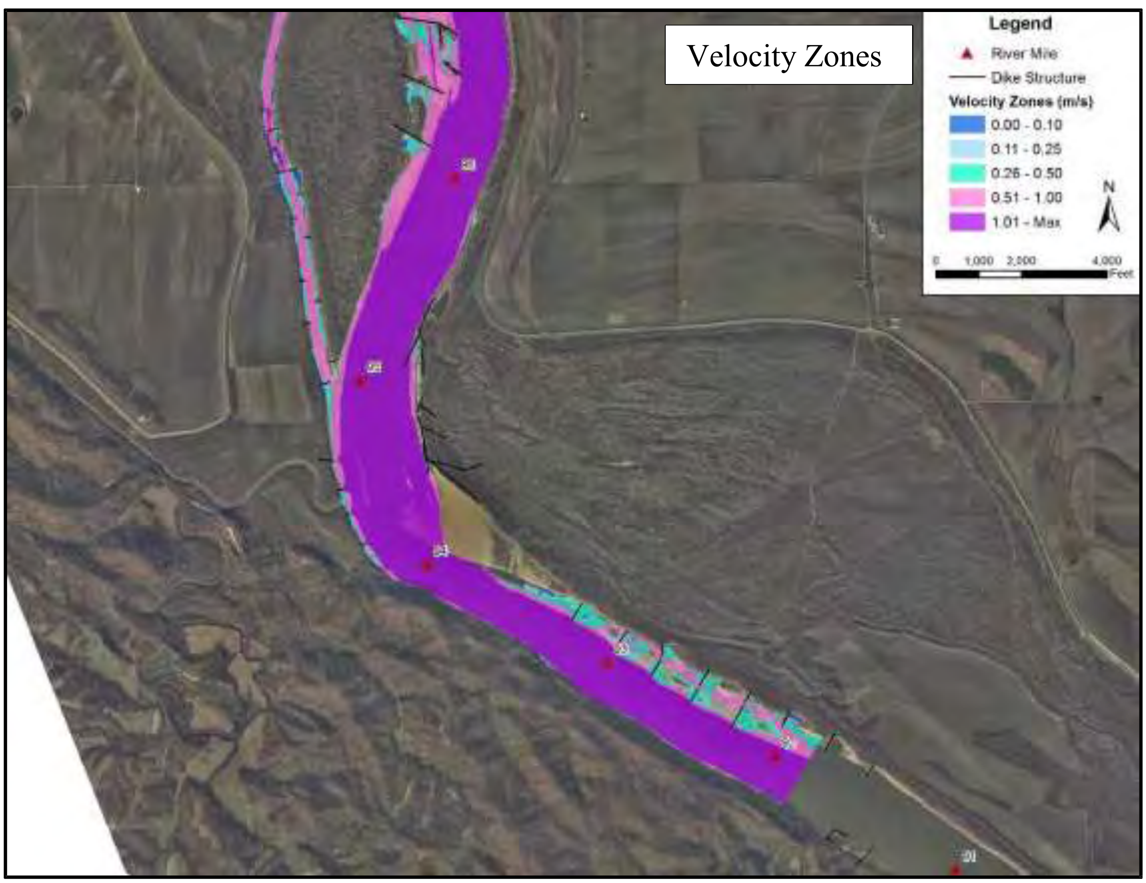
CCHE3D velocity results (flow of 8,580.0 m^3/s) at water surface for the study reach between RM 96 to RM 91



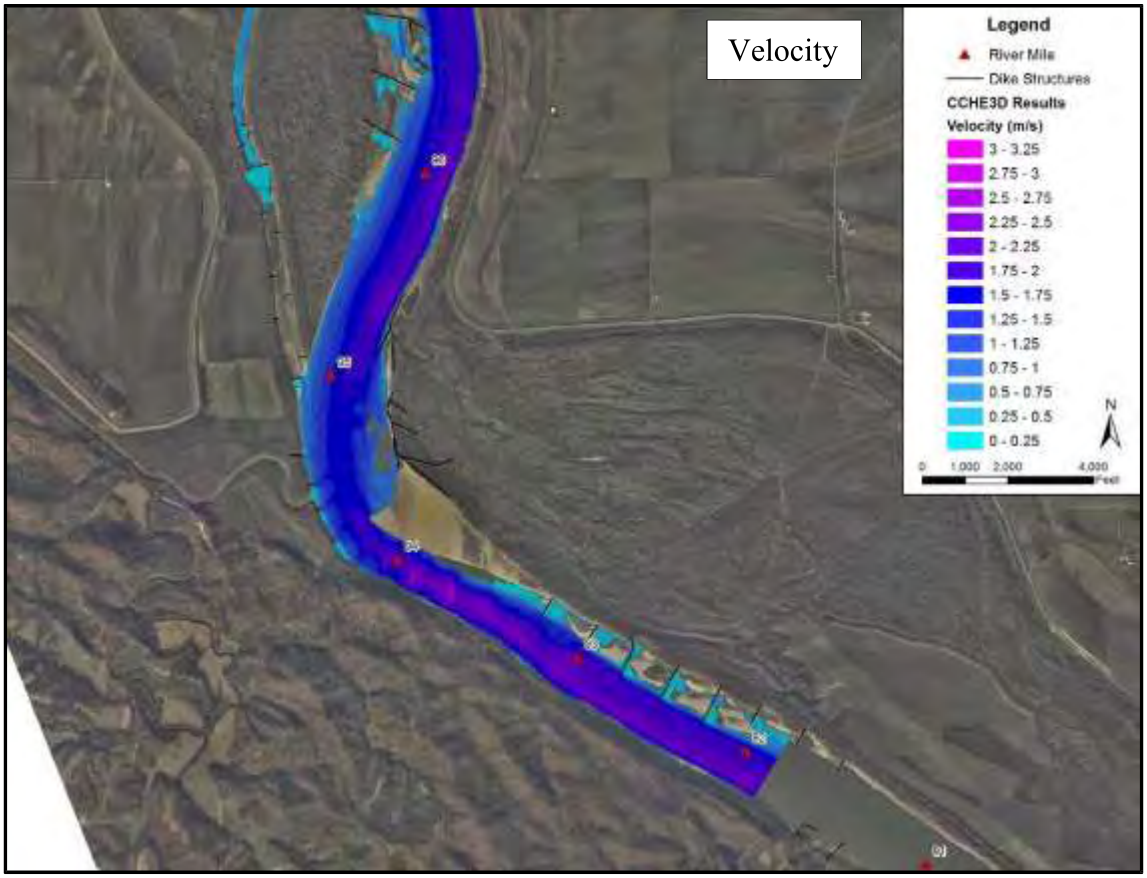


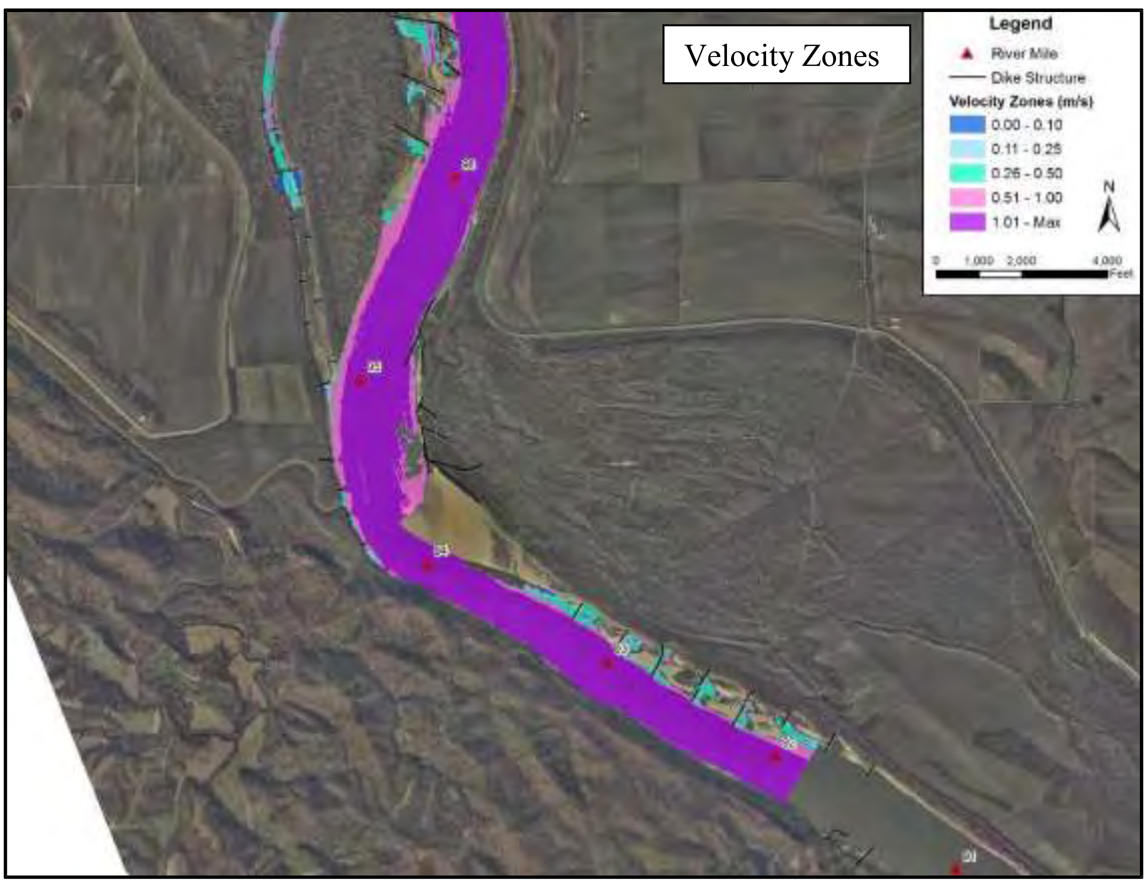
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 2 m below water surface for the study reach between RM 96 to RM 91



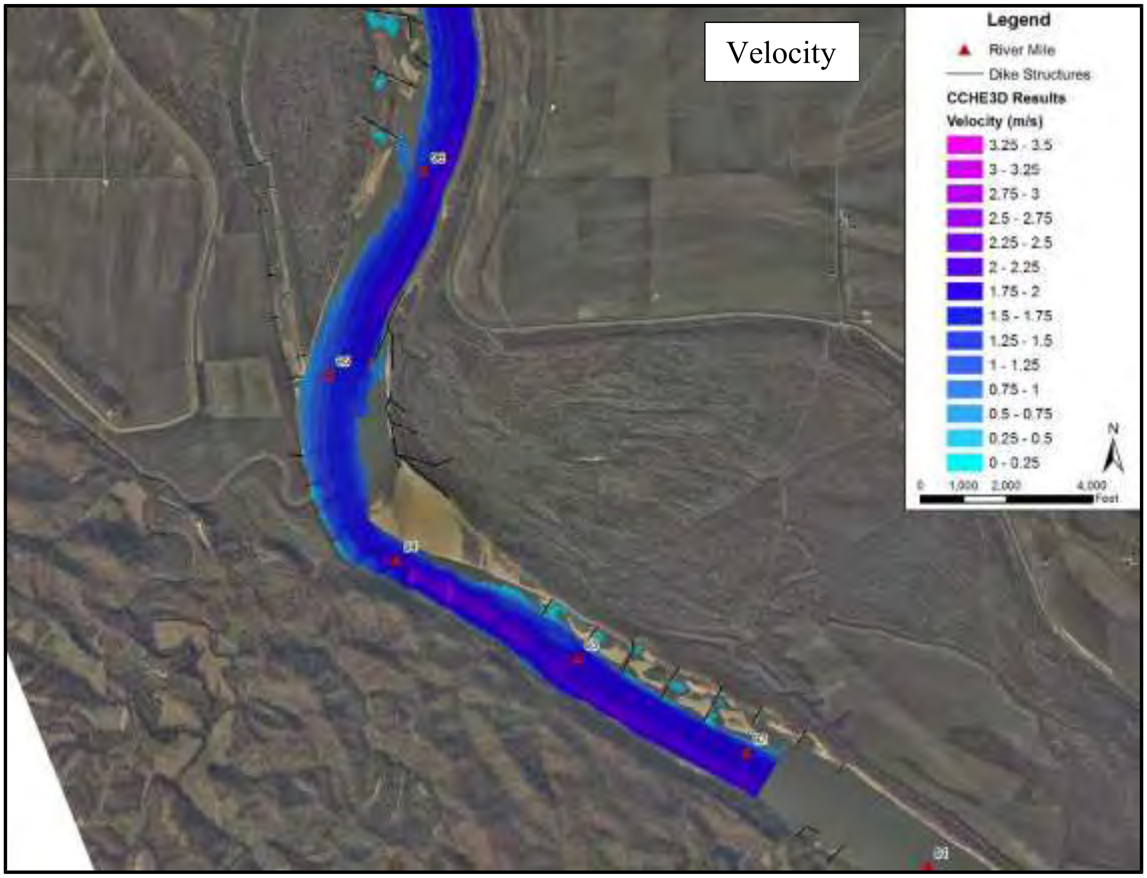


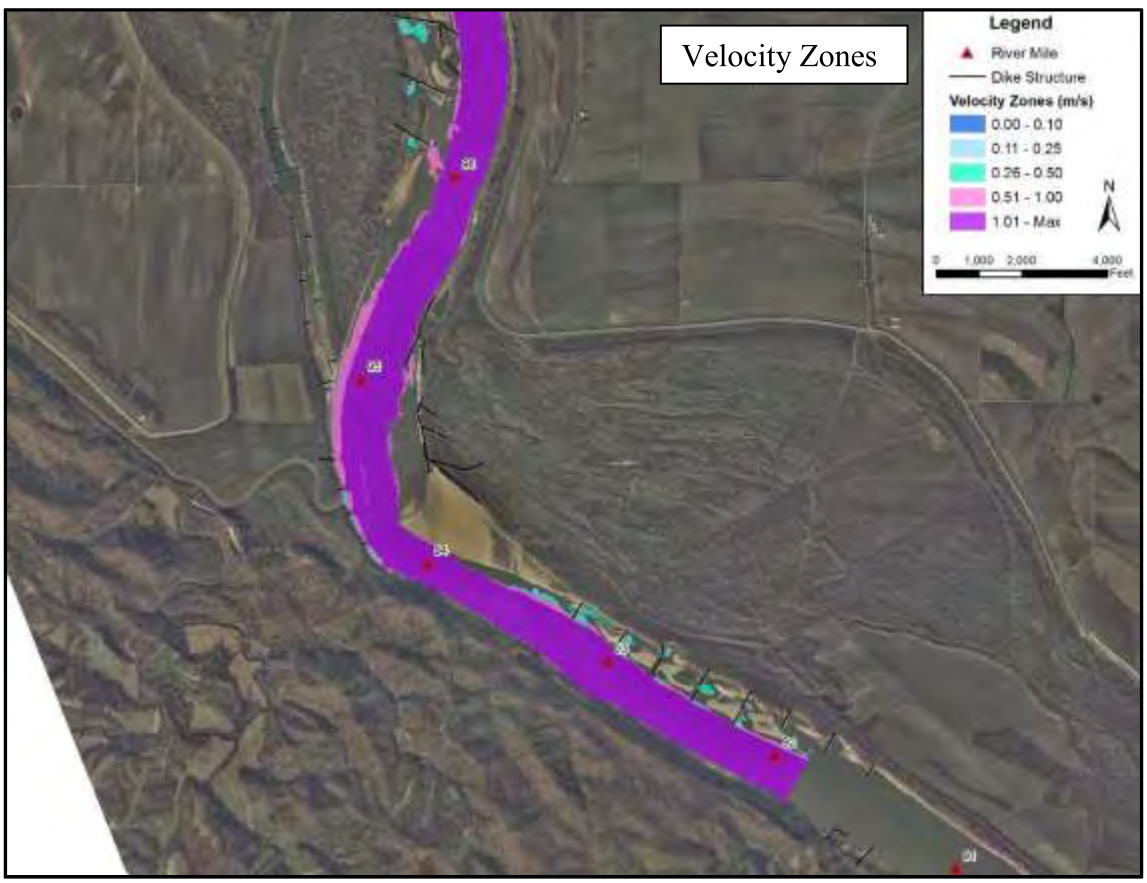
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 4 m below water surface for the study reach between RM 96 to RM 91



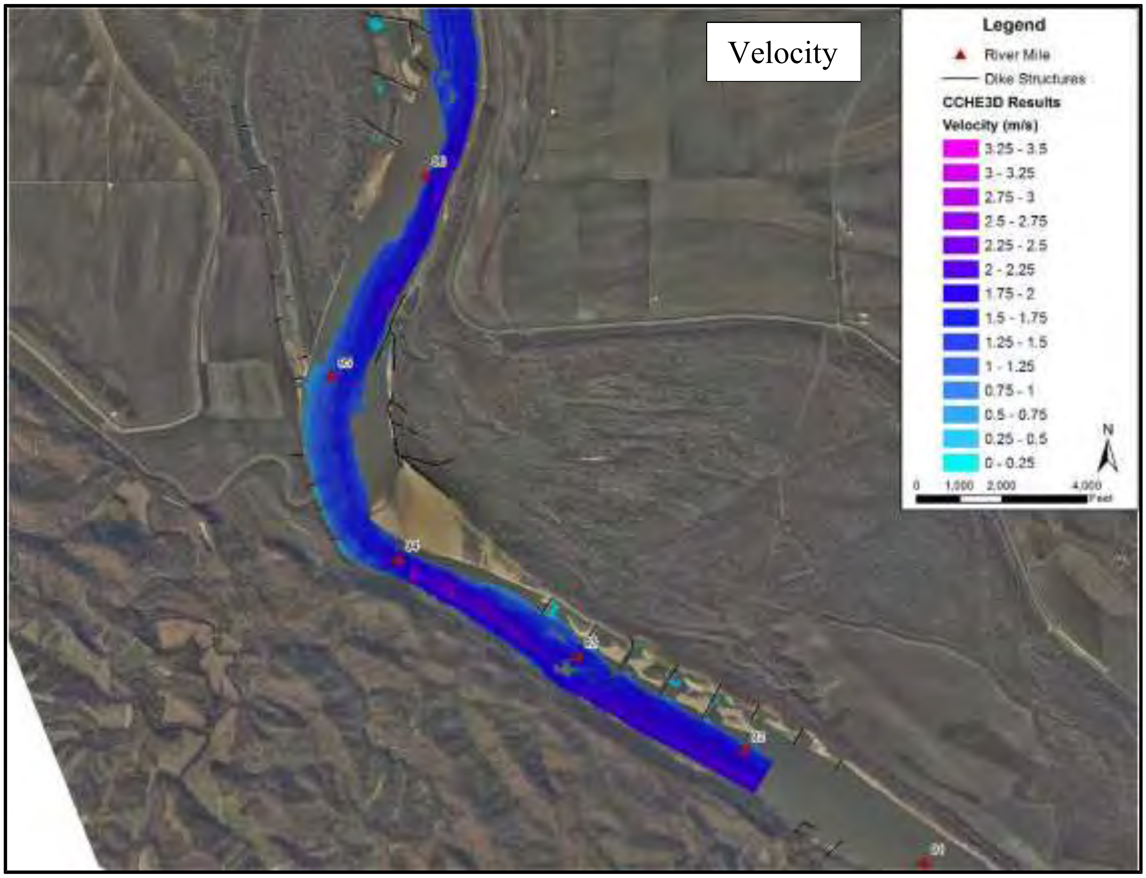


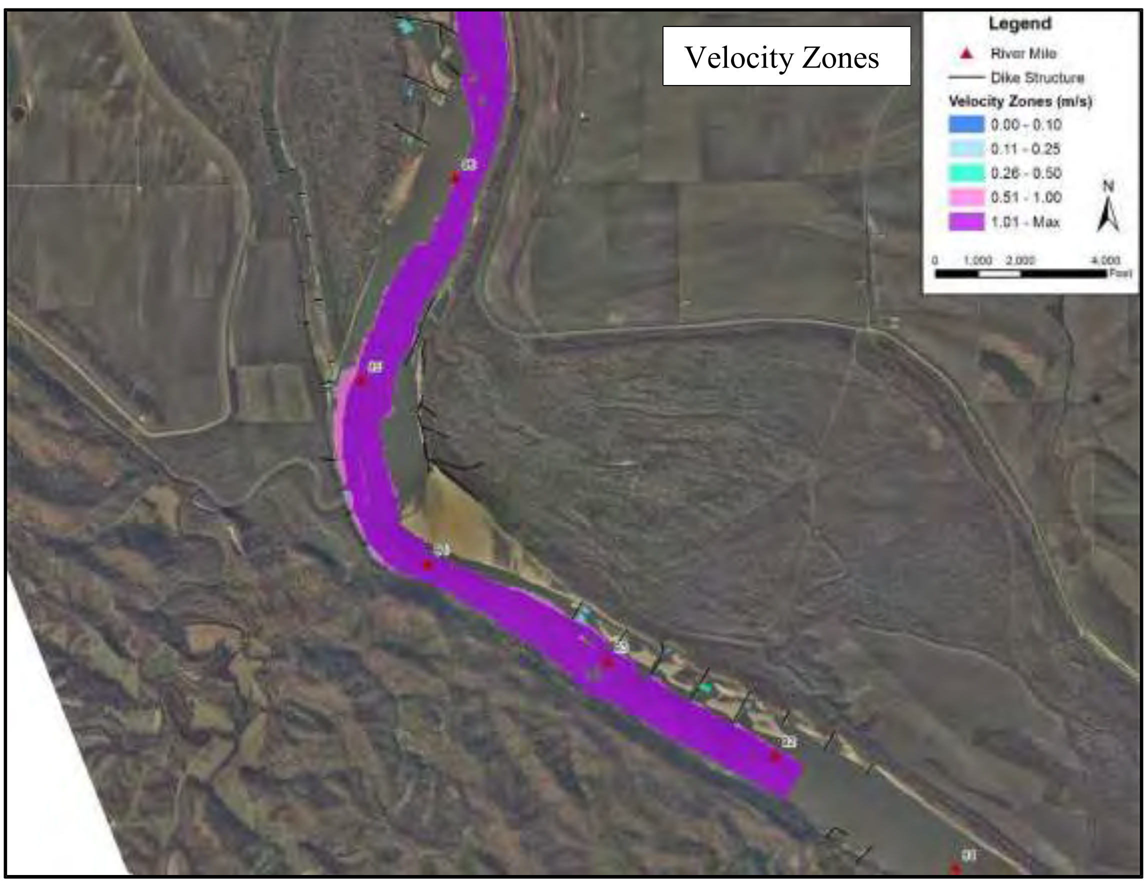
CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 6 m below water surface for the study reach between RM 96 to RM 91





CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 8 m below water surface for the study reach between RM 96 to RM 91





CCHE3D velocity results (flow of 8,580.0 m^3/s) at a depth of 10 m below water surface for the study reach between RM 96 to RM 91