In cooperation with the U.S. Environmental Protection Agency

Hydrodynamic-Assessment Data Associated with the July 2010 Line 6B Spill into the Kalamazoo River, Michigan, 2012–14

Open-File Report 2015–1205

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

Cover. Morrow Lake near Kalamazoo, Michigan (Photo by Tim Hanson)

Hydrodynamic-Assessment Data Associated With the July 2010 Line 6B Spill into the Kalamazoo River, Michigan, 2012–14

By Paul C. Reneau, David T. Soong, Christopher J. Hoard, and Faith A. Fitzpatrick

Prepared in cooperation with the U.S. Environmental Protection Agency

Open-File Report 2015–1205

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

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod/.

Suggested citation:
Reneau, P.C., Soong, D.T., Hoard, C.J., and Fitzpatrick, F.A., 2015, Hydrodynamic-assessment data associated with the July 2010 Line 6B spill into the Kalamazoo River, Michigan, 2012–14: U.S. Geological Survey Open-File Report 2015–1205, 26 p., http://dx.doi.org/10.3133/ofr20151205.

ISSN 2331-1258 (online)

Contents

Figures

Tables

Conversion Factors

[Inch/Pound to International System of Units]

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
	Pressure	
pound-force per square inch (lbf/in^2)	6.895	kilopascal (kPa)
pound per square foot (lb/ft^2)	0.04788	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as:

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Hydrodynamic-Assessment Data Associated With the July 2010 Line 6B Spill Into the Kalamazoo River, Michigan, 2012–14

By Paul C. Reneau, David T. Soong, Christopher J. Hoard, and Faith A. Fitzpatrick

Abstract

Hydrodynamic-assessment data for the Kalamazoo River were collected by the U.S. Geological Survey (USGS) during 2012–14 to augment other hydrodynamic data-collection efforts by Enbridge Energy L.P. and the U.S. Environmental Protection Agency associated with the 2010 Enbridge Line 6B oil spill. Specifically, the USGS data-collection efforts were focused on additional background data needed for 2013–14 updates to Enbridge's 2012 hydrodynamic and sediment-transport models for simulating resuspension and deposition of submerged oil. The main data-collection activities consisted of the following along the Kalamazoo River: (1) a survey done by use of a Real-Time Network Global Navigation Satellite System, (2) water-level measurements in impounded sections, (3) velocity, discharge, and bathymetry measurements at transects and stationary points along the oil-affected reach of the river and in Morrow Delta and Lake, (4) estimates of tributary inflows, and (5) suspended-sediment concentrations and particle-size data at USGS streamgages along the Kalamazoo River. The method used to estimate bed shear stress from stationary velocity data is described. Averaged transect-based velocity data that were processed to match model grids also are included. In addition to model inputs and checks, these hydrodynamic-related data were used in submerged oil containment and recovery operations focused in impoundments and designated sediment traps. This report contains a description of the scope and methods associated with the hydrodynamic data collection and supplementary files of the USGS data that were used in modeling activities.

Introduction

About 38 miles (mi) of the Kalamazoo River were affected by the July 2010 Enbridge pipeline release of oil (specifically, diluted bitumen), extending from Marshall, Michigan, at the confluence of Talmadge Creek, to Kalamazoo, Mich., and Morrow Lake Dam (fig. 1). A significant proportion of the oil was recovered by using conventional skimming techniques, but containment and recovery operations switched to a focus on submerged oil and oiled sediment within a month after the spill, and submerged oil remained the focus of the cleanup through 2014 (Dollhopf and others, 2014). Hydrodynamic-assessment data were collected throughout the cleanup by a variety of Enbridge Energy L.P. and U.S. Environmental Protection Agency (EPA) contractors to assist with containment and recovery of submerged oil. Hydrodynamic modeling, and in particular sediment-transport modeling, was used to simulate the potential resuspension and deposition of submerged oil and oiled sediment using a range of flow conditions along the 38 mi of the Kalamazoo River that were affected by the Line 6B oil release (Dollhopf and others, 2014). Three impoundments were of special interest because of considerable submerged oil accumulation and potential release during high flows—Ceresco, Battle Creek Millponds, and Morrow Lake.

The spill of oil into the Kalamazoo River (and cleanup and concern with submerged oil) was one of the first of its kind in a freshwater riverine system. Water levels, velocity and discharge, tributary inflows, and suspended-sediment concentration and particle size represent the types of data that are needed to assess and simulate the fate and transport of submerged oil over a variety of flow conditions typically found in a riverine environment. The Kalamazoo River, with its abundant impoundments and a variety of water depths, velocities, and sediment-transport characteristics, is typical for many lowland streams tributary to the Great Lakes.

Multiple models were needed to be able to simulate submerged-oil transport at multiple scales because of the hydrodynamic complexities associated with the Kalamazoo River. Enbridge quickly developed hydrodynamic and sediment-transport models by use of the two-dimensional (2D) Environmental Fluid Dynamics Code (EFDC) in 2011–12, using available data for the 38 mi of the spill-affected Kalamazoo River (Hamrick, 2007a, 2007b, and 2007c; Enbridge Energy L.P., 2012). A major assumption in this early modeling effort was that the submerged oil migrated under the same flow conditions as silt-sized particles.

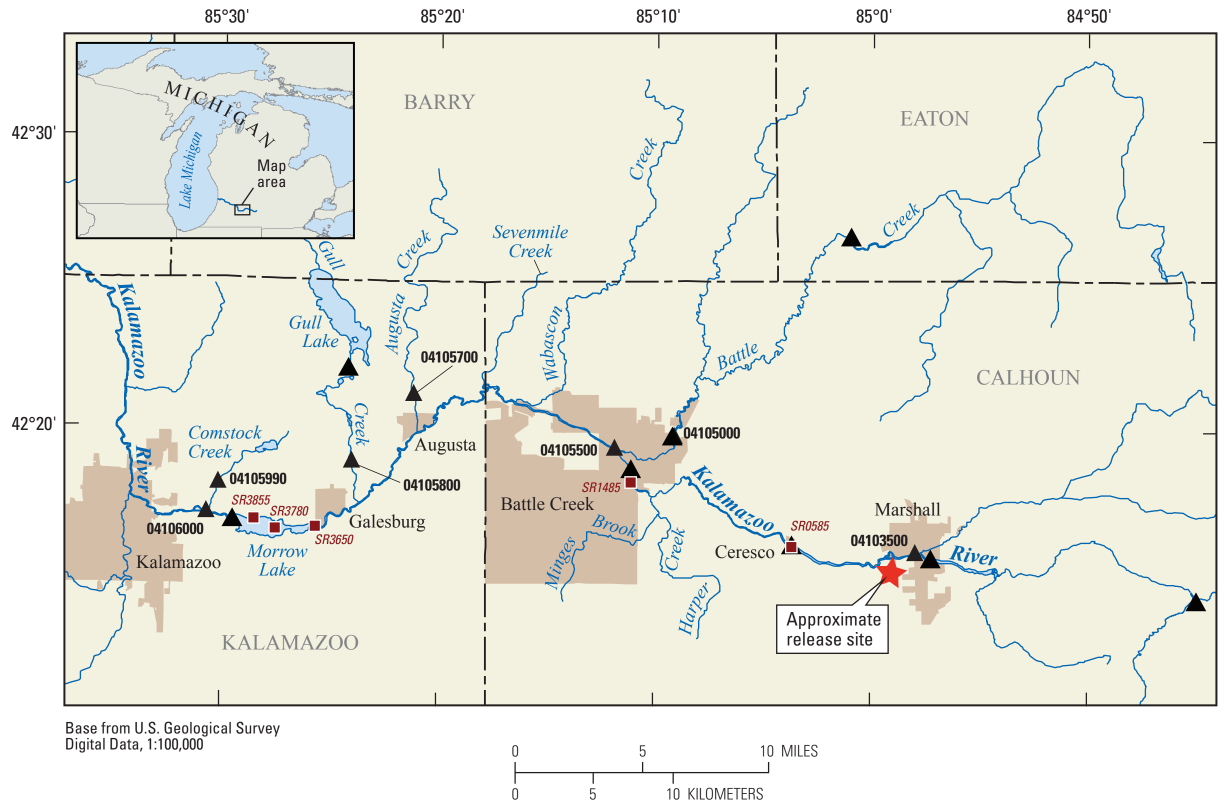

Figure 1. Location of the approximately 38 miles of the Kalamazoo River and nearby towns affected by the 2010 Enbridge Line 6B pipeline release of diluted bitumen near Marshall, Michigan. Morrow Lake is approximately 70 river miles upstream of Lake Michigan. U.S. Geological Survey streamgages and stage gages shown with black triangles.

Later in 2013–14, the EPA, with a team of scientists and engineers from the U.S. Geological Survey (USGS), U.S. Army Corps of Engineers, University of Illinois, New Jersey Institute of Technology, LimnoTech, Inc.,, and Weston/START, updated Enbridge's 2D EFDC hydrodynamic and sediment-transport models with additional hydrodynamic data (Jones and Lick, 2001). New 2D hydrodynamic and sediment-transport models using the University of Illinois Ven Te Chow Hydrosystems Laboratory's (VTCHL) HydroSed2D program (Liu and others, 2008; Zhu, 2011) were developed for simulating erosion and deposition in four enhanced sediment traps along the river. The sediment-trap models have an unstructured triangular mesh that provided a more detailed representation of hydrodynamics compared to the 2D EFDC model for backwater areas, side channels, and oxbows, and flows around islands and bars of the river that naturally accumulated fine sediment and, likely, associated submerged oil.

Lastly, Morrow Lake, an impoundment at the downstream end of the oil-affected reach of the Kalamazoo River, needed a three-dimensional (3D) EFDC model (Hamrick, 1992) to accurately capture the effects of wind and bottom-draw powerhouse intakes at Morrow Dam. In addition to the hydrodynamics of EFDC, VTCHL also implemented a Lagrangian particle tracking model into EFDC, similar to what has been used on the Chicago River (Sinha and others, 2012; 2013) to determine the potential flows needed for submerged oil and oiled sediment to reach Morrow Dam.

The spill response lasted for 4 years because of the presence of submerged oil and oiled sediment, especially in impoundments (Dollhopf and others, 2014). This extended time period for the emergency response allowed for additional data to be collected to refine and constrain all the models. Multiple types of data were collected by Enbridge, EPA contractors, and the USGS. This report contains data collected by the USGS in 2012–14. These data included (1) continuous water-level measurements in impounded sections, (2) velocity and discharge[1] measurements with acoustic sensors, (3) calculations of estimated tributary inflows for model inputs, and (4) suspended-sediment concentration and particle size at six locations along the Kalamazoo River. In addition to containing electronic files of these data, this report describes the scope of the data-collection efforts and the field and data-compilation methods.

Previously Published Data

Previously published data collected by the USGS were used throughout the Enbridge and EPA modeling efforts and included continuous streamflow at five streamgages: Kalamazoo River at Marshall, MI (USGS ID 04103500), Battle Creek at Battle Creek, MI (USGS ID 04105000), Kalamazoo River near Battle Creek, MI (USGS ID 04105500), Augusta Creek near Augusta, MI (04105700), and Kalamazoo River at Comstock (USGS ID 04106000). These streamgages bracket the upstream and downstream boundaries of the oil-affected reach (Marshall and Comstock, respectively). Battle Creek enters the Kalamazoo River about halfway through the spill affected reach (fig. 1). These data are available at http://waterdata.usgs.gov/mi/nwis/rt.

The USGS developed a HEC–RAS model (U.S. Army Corps of Engineers–Hydrologic Engineering Center, 2010) and flood inundation maps for the upper part of the oil-affected reach from Marshall to Battle Creek because the pipeline release happened during a flood with an exceedance probability of 4 percent (Hoard and others, 2010). The cross sections, dam configurations, and water levels used in the HEC–RAS model were used in the Enbridge and EPA models for inputs, calibration, and validation.

Purpose and Scope

The purpose of the report is to describe the hydrodynamic datasets, which include water levels, velocity and discharge measurements, tributary inflows, and suspended-sediment concentration and particle size that were collected from 2012 through 2014 along the oil-spill-affected reach of the Kalamazoo River as part of USGS hydrodynamic assessment and modeling activities. Estimated roughness heights and bed shear stresses were estimated from vertical profiles of velocity from stationary measurements. Reference points used for water-level recorders and velocity measurements are described. The data were collected during a variety of flows and for specific purposes where there were known data gaps in existing hydrodynamic data that were needed for hydrodynamic modeling, as well as decision making by the Federal On-Scene Coordinator and operations staff regarding submerged oil recovery and containment.

Reference Points and Vertical Datums

Surveyed reference points were established by the USGS in April 2013 for vertical datums and water levels related to the establishment of five water-level recorders and velocity transect measurements along the Kalamazoo River and Morrow Lake (table 1). The reference points were surveyed with a Real-Time Network (RTN) Global Navigation Satellite System (GNSS) Topcon GR-5 running TopSurv software. A third-order survey was conducted by using the North American Vertical Datum of 1988 (NAVD 88) (Rydlund and Densmore, 2012). A third-order survey has vertical accuracies of 0.07 meter or about 0.23 foot (ft).

The vertical and horizontal accuracy of the reference points was checked against seven control points established by Enbridge for the Kalamazoo oil spill response, plus two Michigan Department of Transportation benchmarks. Surveys of two Enbridge control points were well out of the accuracy

[1] With respect to flow of water in natural channels, the terms "discharge" and "streamflow" are synonymous. They are used interchangeably in this report and are expressed as volume per unit time.

Table 1. Location, elevation, and description of reference points (RPs) used for Kalamazoo River and Morrow Delta and Lake velocity transects.

[Locations in Universal Transverse Mercator (UTM) coordinates in NAD 83 and elevations (ELEV.) in NAVD 88. Abbreviations: d/s, downstream; ft, feet; GRP, Gage Reference Point; ID, identification; MP, mile post; REW, right edge of water; RP, reference point; u/s, upstream]

ID	UTM East	UTM North	ELEV. (ft)	Description
RP-1.29	665954.864	4679698.957	897.3887	Top of upstream right culvert lip at crossing with 15.5 mile road.
RP-2.22	665107.974	4680404.859	886.3848	Three marks on fifth I-beam from right edge of water downstream side of bridge. Marks are located in left downstream side of I-beam. At 15 mile road crossing.
RP-5.07	661004.043	4681029.292	870.1791	Half-inch inch rebar. DESTROYED.
RP-5.62	660140.176	4681420.127	870.1414	Half-inch inch rebar. DESTROYED.
RP-5.80	659932.552	4681499.541	870.1003	Half-inch inch rebar. DESTROYED.
RP-7.18	658220.699	4682017.921	853.0865	Half-inch inch rebar. DESTROYED.
RP-12.05	652857.082	4685655.146	858.1564	Eleventh post from downstream right edge of water. Located on the downstream left corner of the post. Raymond Road crossing.
RP-13.77	651003.082	4684424.227	843.1679	Painted square about 68 ft from start of concrete on REW downstream side of bridge. Beadle Lake Road Crossing.
RP-13.89	650842.064	4684437.681	844.9642	Painted square on fifth post from the downstream right edge of water. Located on the left downstream corner of the post. Main Street crossing.
RP-14.5	650048.136	4684840.646	828.4648	Top of MP 14.5 post. REW.
RP-14.73	649887.785	4685141.311	827.638	Half-inch inch rebar. DESTROYED.
GRP-14.9	649621.522	4685236.403	826.1371	One-inch rebar used for the gage located in the Mill Pond.
RP-15.25	649257.966	4685585.98	829.0472	MP15.25 fencepost on REW.
RP-15.5	649365.807	4685835.02	827.7398	D/s most fencepost off bottom step 80 ft streamward of green bench and 300 ft u/s of United Education Credit Union.
RP-18.83	645563.03	4688770.458	820.2923	Three marks on 23rd post from downstream left edge of water. At Bedford Road crossing.
RP-21.31	642022.683	4690196.481	814.2752	Painted square about 51 ft from right edge of water on downstream side. At Custer Drive crossing.
RP-28.8	636300.416	4688309.346	787.9235	High point on metal rod protruding from large concrete boulder. Twenty ft downstream of bridge on right edge of water. At Dickman Road crossing.
RP-34.12	631740.789	4683063.763	792.0978	Three marks on third I-post form downstream right edge of water. At E. Michigan Ave. crossing.
GRP-36.5	629583.711	4682057.861	775.4727	One-inch rebar used for gage just upstream of 35th street bridge in left edge of water.
RP-36.55	629541.251	4682104.373	790.8478	Three marks on fourth downstream I beam from right edge of water. At 35th Street crossing.
RP-37.42	628203.803	4681768.301	775.3228	Half-inch inch rebar. DESTROYED.
RP-37.8	627607.461	4681782.107	774.9029	Half-inch rebar. DESTROYED.
GRP-37.8	627611.774	4681828.727	774.9363	One-inch rebar between 42nd and 43rd concrete boat launch pads near downstream edge flush with concrete 4 inches from downstream edge of pad.
GRP-38.5	626443.116	4682290.731	775.0095	One-inch rebar used for Morrow Lake gage.
RP-39.3	625244.522	4682226.006	775.933	Half-inch rebar. DESTROYED.
RP-39.4	625355.351	4682247.837	775.774	Half-inch rebar. DESTROYED.

tolerance: CP1024 was −0.45 ft off, and CP36 was −0.36 ft off. These points were not used because of either poor satellite reception or location of the control point. With these two control points removed, the average error was 0.0839 ft.

Two Continuously Operating Reference Stations (CORS) base stations were used during the survey, one designated MIBC and located in Battle Creek, Mich., and the other designated SOWR and located northeast of Portage, Mich. Control points shot when using MIBC indicated a 0.128-ft error, and control points shot when using SOWR indicated a 0.018-ft error. These errors were used to adjust the reference point elevations by the error indicated by the two base stations.

Water Levels

Water-level data were collected from five locations with continuous stage gages from April through August 2013 (table 2, fig. 1). The locations were selected to be in the Ceresco impoundment, Battle Creek Millponds, and Morrow Delta and Lake to determine how the dam configurations affected water levels, velocities, and flows through the three impounded reaches and to fill data gaps between the three main river USGS streamgages (Kalamazoo River at Marshall, near Battle Creek, and at Comstock). Preliminary data suggested that stage fluctuations of a few tenths of a foot can happen very quickly on Morrow Lake and upstream into the delta from powerplant operations at Morrow Dam.

These data also augmented other water-level data manually collected by Enbridge and EPA staff from visual observations at multiple staff gages along the river. Daily water-level fluctuations in the Kalamazoo River were tracked by Enbridge, using visual observations from staff gages starting in 2010 and continuing through summer 2012. These staff gages were used to help with boating conditions and recovery operations.

Methods

Each stage gage consisted of an In Situ Level Troll 700 pressure transducer that was mounted to the streambed on 1-inch (in.) rebar. The access port and atmospheric vent on the pressure transducer were enclosed in a locked 6-in. by 6 in. by 4 in. environmental enclosure mounted to a uni-strut well above the water surface. These sensors had an accuracy of ± 0.014 ft range in less than 10 ft of head and were capable of logging data as well as compensating for changing atmospheric pressure. The gages were installed in April 2013 by the USGS and set to record data every 5 minutes. Gages were inspected and data were downloaded by Weston Inc., technicians. Datums for the gages were established by using RTN GNSS. The five stage gages were removed in August 2013.

Data

Water-level data are in spreadsheet format in appendix A. The spreadsheet contains multiple worksheets:

The first five worksheets contain raw and corrected data for each of the five gages. The worksheets are named for each site. Column A is the date and time the data were recorded; Column B is pressure, in pounds per square inch measured by the instrument; Column C is temperature, in degrees Celsius, which was not officially analyzed for accuracy; Column D is the depth of water over the sensor, in feet; Column E is any corrections applied to the depth data (Column D); and Column F is the final water-surface elevation, in feet. All columns to the right of Column G represent gage verification data collected in the field to ensure the gages were working correctly.

All Gages Plot: Graphs of stage recorder data for each of the five recorders, April–August 2013

38.55 and 37.8 Adjusted Graphs: Graphs showing the final data for SR3855 and SR3780.

Cor. To line up 37.8 and 38.55: Graphic display and corrections used to adjust SR3780 data.

Table 2. Locations where the U.S. Geological Survey collected continuous water-level data with stage gages, April–August 2013.

[Locations in NAD 83 and elevations in NAVD 88. Abbreviations: ft, feet; mi, mile]

Stage gage identification code	River mile post (MP)	Location description	Location latitude and longitude (decimal degrees)	Datum elevation (ft)
SRO585	5.85	Ceresco impoundment, 60 ft upstream of Ceresco Dam on right edge of water.	42.27036/−85.06055	866.8
SR1485	14.85	Battle Creek Millponds, 10 ft down stream of I-194 on right edge of water.	42.30496/−85.18454	824.9
SR3650	36.5	Morrow Lake Delta, 120 ft upstream of 35th St. Bridge on left edge of water.	42.28000/−85.42839	774.9
SR3780	37.8	Connecting channel between Morrow Delta and Lake on Island at Morrow Lake boat launch.	42.27782/−85.45242	774.2
SR3855	38.55	Morrow Lake 1.25 mi upstream of Morrow Lake Dam on right edge of water.	42.28249/−85.46637	774.2

No data corrections were applied at any of the stage gages except SR3780. It was assumed that during calm days when no flow event was taking place, SR3780 and SR3855 both were measuring Morrow Lake water-surface elevations (in other words, a flat pool was assumed for Morrow Lake). Corrections to adjust SR3780 to match SR3855 were based on those overlapping days. It was assumed that the sensor at SR3780 was drifting.

Velocity, Discharge, and Bathymetry

Velocity and discharge (and related bathymetry) data used in the modeling came from two sources: Tetra Tech, Inc., and the USGS. Tetra Tech, Inc., collected velocity data in fall 2011 and June 2012 along transects, as well as at stationary points. The fall 2011 measurements were made in Morrow Lake and along the Kalamazoo River during high base-flow conditions (700–800 cubic feet per second [ft^3/s] at the Kalamazoo River near Battle Creek USGS streamgage). In June 2012, during low flow (about 400 ft^3/s), Tetra Tech Inc., again measured velocity along transects and at stationary points in Morrow Lake and along the Kalamazoo River.

The USGS subsequently measured velocity and discharge in the Kalamazoo River and Morrow Lake three times: June 25–28, 2012, at flows of about 450 ft^3/s; August 27–28, 2012, at flows of about 300 ft^3/s; and April 12–16, 2013, at flows of about 2,000 ft^3/s. Stationary velocity profile measurements at specific points along a transect also were completed in April 2013 to estimate near-bed velocities and calculate bed shear stresses for modeling entrainment and also for ensuring that proper anchors were used for the containment structures. Bathymetry data (bed elevations) were generated from water depths collected as part of the velocity measurements. The acoustic Doppler current profiler (ADCP) has four independent divergent beams that each measure a depth. Files containing an average of the four independent depths and files containing each individual depth were produced. The following description is for USGS measurements only.

Methods

Velocity was measured along transects or at stationary points by USGS crews in boats or kayaks with four different ADCPs—Teledyne RD Instruments (TRDI) StreamPro, 2000 kHz; TRDI Work Horse Rio Grande, 600 and 1200 kHz, using WinRiver 2.10; and Sontek M9 using River Surveyor Live 3.6—depending on water depths. The ADCPs were integrated with an external differentially corrected global positioning system (DGPS) to georeference the measurements. A FlowTracker acoustic Doppler velocimeter (ADV) was used for wadeable locations. To ensure data quality standards, procedures outlined in “Measuring Discharge with Acoustic Doppler Current Profilers from a Moving Boat” (Mueller and Wagner, 2009), were adhered to. Standard data-collection procedures were used consistently, except for a few times because of time constraints.

Standard collection procedures were often not adhered to in the Morrow Lake Delta and in Morrow Lake itself. In order to collect all of the data needed before a change in the hydrologic conditions and (or) before sunset, reciprocal transects were often not done. When possible, these transects were compared with cross-section transects made upstream or downstream to ensure that the measured discharge was accurate.

Data from every cross section made was rated good, fair, or poor. “Good” indicates that the mean discharge is within 5 percent of actual; “fair,” within 10 percent; and “poor,” greater than 10 percent. When it was felt that the data were affected negatively because standard procedures could not be followed or field conditions were poor, the data were downrated. At every cross section, two transects were made if possible. If the discharge was different between the two transects by more than 5 percent, then additional transects were made. In the field, the USGS crews used predetermined RTN GNSS locations to retrace previous transect locations. ADCP data are typically noisy, especially at low velocities below 0.1 ft/s, which were common in Morrow Lake. Raw data were averaged in order to obtain meaningful velocities at certain points in the transect.

Two software packages were used to postprocess ADCP data: AdMap Version 2.0.0 and Velocity Mapping Software 1.0 (VMS). Each program was used when needed to provide appropriate data to interested parties. AdMap Version 2.0.0 is a MATLAB script developed by David Mueller (USGS)[2]. AdMap is able to export ADCP data into a user-friendly format, average data together at user-supplied intervals, and average top or bottom velocities at user-supplied intervals. VMS, a software package developed by U.S Army Corps of Engineers in collaboration with the USGS, allows the user to average data together at user-determined distances along the transect. Unlike AdMap, VMS allows the merging of two transects made at the same cross section into one file. Figure 2 is a snapshot out of the VMS software and shows how the data were averaged. The number of averaged points that are created and the spatial averaging are determined by two components. The averaging interval determines how many points are going to be created along the transect. The search radius is how far from the predetermined averaging interval point the software will search in order to create an averaged point from all data located within the search radius.

VMT version 2.3 beta (Parsons and others, 2013) was used to generate preliminary contour plots showing streamwise velocity and transverse velocity. The preliminary contour plots were not used in model development or calibration and are not included in this report. However, it is worth mentioning that VMT version 4.06 has improved capability for contour plots. Figures 3*A* and *B* show contour plots of the same data set using VMT 2.3 beta (fig. 3*A*) and VMT 4.06 (fig. 3*B*).

[2] AdMap is used within the USGS but is not published for use outside the bureau.

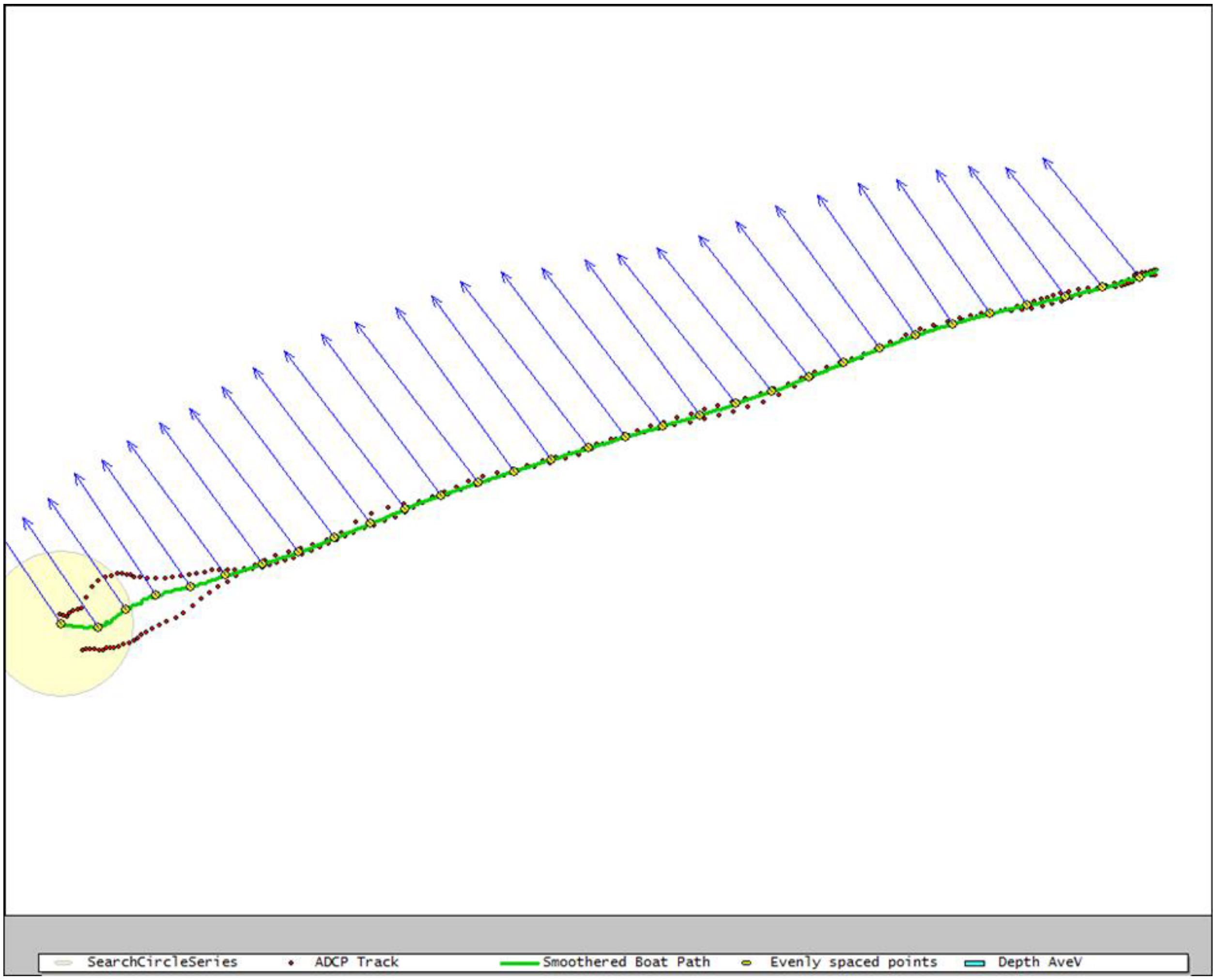

Figure 2. Example screen shot of how velocity data were processed with VMS (Velocity Mapping Software). Red dots represent raw data points, yellow dots along the green line show the resulting depth-averaged velocity positions in the horizontal (mean velocity), the large light yellow circle shows the search radius and which raw data points were used to generate the first mean velocity point, and the blue arrows show the speed and direction of each mean velocity point generated. In this example the lengths of the blue arrows are equal to approximately 1 foot per second.

A

B

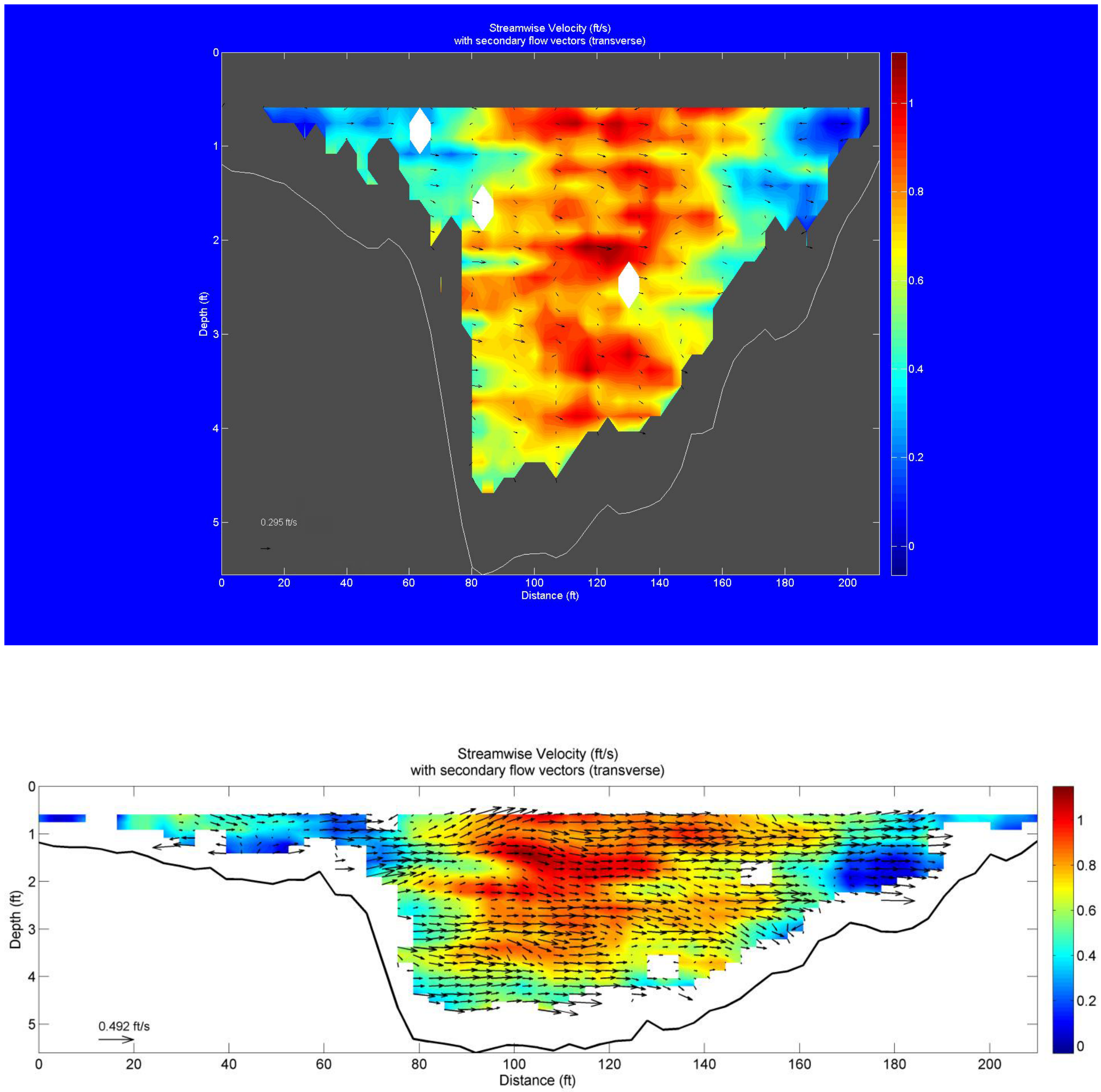

Figure 3. Contour plots generated by using two versions of VMT (Velocity Mapping Toolbox) (ft, feet; ft/s, feet per second). *A*, Version 2.3 beta. *B*, Version 4.06.

ADCPs measure the velocity in multiple areas in the vertical; each area in the vertical is called a bin. Because the ADCP is capable of creating this vertical profile (ensemble) of bins, certain bins in the vertical can be pulled from the data to better understand velocities at any given depth from the surface. However, because of acoustic interference and possible invalid velocities created by the ADCP itself, the top and bottom of the water column cannot be measured and are instead estimated. The thickness of these unmeasured layers depends on the depth of the ADCP in the water column, the frequency of the ADCP, and the way that the ADCP was programmed prior to data collection. AdMap was used to produce three files: ".vav," the mean velocity in the vertical; ".top," the first bin collected from the surface of the water column; and ".bot," the last bin collected in the water column. All files can be imported into Microsoft Excel® by using the space-delimited text file option.

June 2012

The USGS measured discharge at 12 sites along the Kalamazoo River and selected tributaries for gathering information about how springs and tributary inflows affected low flows in the Kalamazoo River (table 3). All measurements were made by using a TRDI Streampro except the two tributary sites, which were measured using a FlowTracker ADV. Discharge calculations followed methods in Turnipseed and Sauer (2010).

In addition to the discharge measurements, velocity was measured at 13 cross sections in Morrow Lake Delta from the 35th Street Bridge to the narrows, also known as the neck, between the wider Morrow Lake Delta and Morrow Lake. No more than two transects were made at each cross section because of time constraints.

All velocity data were postprocessed by using AdMap Version 2.0.0. The output for each of the 12 discharge measurements consists of a mean velocity (.vav) file (appendix B1). The outputs for the 13 transects in the delta consist of mean velocity (.vav), top velocity (.top), and bottom velocity (.bot).

August 2012

Velocity and discharge data were collected along eight cross sections in Morrow Lake Delta (appendix B2). Cross sections were selected with the guidance of EPA operations staff in terms of maximizing the use of the data for containment designs that included surface booms and bottom half curtains for keeping floating and submerged oil from migrating downstream. In addition, velocity data were collected within the neck area of Morrow Delta and Morrow Lake along seven cross sections. Some of the cross sections were located along both sides of containment booms and half curtains deployed in early July 2012.

All data were collected by using a TRDI StreamPro tethered to a kayak. AdMap was used to generate top velocity (.top), bottom velocity (.bot), and average velocity (.vav) files (appendix B2).

Table 3. Kalamazoo River discharge measurements between Marshall, Michigan, and Morrow Lake during low flow, June 2012.

[ft^3/s, cubic feet per second; MP, river mile post]

Site number	Start date and time	MP	Bridge crossing	Discharge (ft^3/s)	Rating
1	6/25/2012 13:57	2.25	15 Mile Road/Saylors Landing	278.4	Fair.
2	6/25/2012 15:07	7.17	11 Mile Road	274.7	Good.
3	6/25/2012 16:21	12.1	Raymond Rd, Hwy 96	299.4	Fair.
3.1	6/26/2012 9:58	13.75	Beadle Lake Road	276.5	Good.
3.2	1/0/1900 11:04			309.9	Fair.
4	6/26/2012 12:16	15.25	East Burnham St.	282.2	Good.
5	6/26/2012	18.75	Bedford Road	----	(Too shallow).
6	6/26/2012 14:41	21.25	Custer Drive	408.5	Good.
7	6/27/2012 11:40	28.75	East Michigan Ave., Hwy 96	417.4	Good.
8	6/27/2012		None	----	----
9	6/26/2012 17:22	34.17	East Michigan Ave.	461.7	Good.
10	6/27/2012 16:57	36.5	South 35th St.	444.1	Good.
11	6/27/2012 14:03	Gull Lake Outlet	Augusta Road	9.88	Fair.
12	6/27/2012 11:41	Augusta Creek	At mouth	12.8	Poor.

April 2013

Forty-three cross-section measurements and 47 stationary measurements were made from Talmadge Creek to Morrow Lake in April 2013 (table 4, appendix B3). Because of time constraints, only one transect was made at cross sections 38.75, 38.5, 38.25, 38, 38_S, and 38_N. Other than 38_S and 38_N, discharges at these cross sections were within 5 percent of the discharge measured at the next cross section upstream (cross section 38.75 was within 4 percent of cross section 38.5). Because of time constraints at cross sections 38_N and 38_S and the relatively low importance of the data to the model, only one transect was made. The integrated DGPS was used for measurements at every cross section except 1.29, 7.18, 12.05, 18.83, and 34.12. The DGPS did not work at these locations because of steep banks and (or) tree cover. When DGPS data were not available, the initial start position of the ADCP for the cross section was established from field observations and aerial photos.

Table 4. Summary information for each cross section where velocity measurements were made in April 2013.

[Discharge was not calculated for 38_S and 38_N because the velocity measurement was parallel to the river flow direction; EDT, eastern daylight time; ft, feet; ft^3/s, cubic feet per second; ft/s, feet per second; NA, not applicable; G, good; F, fair; P, poor]

Cross section number	Start (EDT)	Water surface elevation (ft)	Discharge (ft^3/s)	Mean velocity (ft/s)	Percent difference between transects	Instrument	Rating	Averaging interval	Search radius (ft)
39.82	4/12/2013 14:40	775.81	2100	0.34	1.0	600	G	10	20
39.79	4/12/2013 15:31	775.79	2220	0.31	7.9	600	F	10	20
39.75	4/12/2013 17:00	775.77	2310	0.15	2.6	600	G	20	40
39.7	4/12/2013 16:23	775.77	2090	0.15	0.0	600	G	20	40
39.6	4/12/2013 17:54	775.77	2350	0.17	2.8	600	G	20	40
39.5	4/12/2013 18:29	775.77	2150	0.12	9.2	600	F	20	40
39.25	4/14/2013 12:13	775.88	1420	0.06	0.0	600	P	20	40
39	4/14/2013 13:07	775.88	1350	0.062	4.0	600	P	20	40
39_Repeat	4/15/2013 16:02	775.86	1930	0.087	9.8	1200	P		
38.75	4/15/2013 17:31	775.86	2052	0.1	*4.2	M9	F	60	30
38.5	4/15/2013 18:20	775.87	2232	0.12	*2	M9	F	60	30
38.25	4/15/2013 19:01	775.91	2324	0.16	*1.8	M9	F	60	30
38_S	4/15/2013 20:54	775.98	NA	-0.02	NA	M9	P	60	30
38_N	4/15/2013 19:56	775.95	NA	-0.03	NA	M9	P	60	30
38	4/15/2013 20:16	775.98	2408	0.195	*1.8	M9	F	60	30
37.75	4/15/2013 12:03	775.83	2070	0.57	4.2	StreamPro	F	15	30
37.66	4/15/2013 11:40	775.82	2150	0.88	0.0	StreamPro	G	15	25
37.55	4/15/2013 11:12	775.82	2150	0.84	1.9	StreamPro	G	10	20
37.25-37.5	4/15/2013 9:23	775.84	1120	0.27	17.7	StreamPro	G	10	20

Table 4. Summary information for each cross section where velocity measurements were made in April 2013.—Continued

[Discharge was not calculated for 38_S and 38_N because the velocity measurement was parallel to the river flow direction; EDT, eastern daylight time; ft, feet; ft³/s, cubic feet per second; ft/s, feet per second; NA, not applicable; G, good; F, fair; P, poor]

Cross section number	Start (EDT)	Water surface elevation (ft)	Discharge (ft³/s)	Mean velocity (ft/s)	Percent difference between transects	Instrument	Rating	Averaging interval	Search radius (ft)
37.18	4/15/2013 10:05	775.84	684	1.51	0.1	StreamPro	G	10	20
37.14	4/15/2013 10:36	775.82	263	0.559	6.1	StreamPro	F	5	10
36.55	4/14/2013 11:04	776.12	2070	2.02	3.1	StreamPro	G	5	10
34.12	4/13/2013 14:57	780.92	1760	1.68	3.6	StreamPro	G	5	10
28.8	4/14/2013 12:16	788.12	1840	1.79	3.5	StreamPro	G	5	10
21.36	4/14/2013 13:23	799.52	260	0.489	0.0	StreamPro	G	5	10
21.31	4/14/2013 13:53	799.52	2040	1.17	1.8	StreamPro	G	5	10
18.83	4/14/2013 15:07	800.7	1990	1.89	0.0	StreamPro	G	5	10
15.5	4/13/2013 14:43	826.948	981	0.937	3.6	StreamPro	F	5	25
15.24	4/13/2013 15:15	827.0372	1000	1.57	0.0	StreamPro	F	5	10
15.22	4/13/2013 16:08	827.0372	903	1.34	0.0	StreamPro	G	5	10
15.17	4/13/2013 16:30	827.0372	869	1.39	0.1	StreamPro	G	5	10
14.75	4/13/2013 17:11	827.338	1000	1.49	3.4	StreamPro	G	5	10
14.71	4/13/2013 17:43	827.338	193	1.38	0.0	StreamPro	G	5	10
14.52	4/13/2013 18:30	827.4548	1010	1.33	2.2	StreamPro	G	5	10
13.89	4/13/2013 16:20	828.5	959	1.9	2.1	StreamPro	F	5	10
12.05	4/13/2013 16:59	834.1064	830	2.5	0.0	StreamPro	G	5	10
7.18	4/16/2013 14:01	853.087	689	3.09	2.0	StreamPro	G	5	10
5.75	4/13/2013 10:37	870.1	832	0.551	0.1	StreamPro	G	5	10
5.62	4/13/2013 11:16	870.14	801	0.32	4.0	StreamPro	G	5	10
5.32	4/13/2013 11:52	870.14	822	0.73	4.5	StreamPro	G	5	10
5.03	4/13/2013 12:26	870.18	824	0.791	2.7	StreamPro	G	5	10
2.22	4/14/2013 17:49	874.405	751	1.88	1.6	StreamPro	G	5	10
1.29	4/14/2013 18:24	895.2087	5.6	0.53	2.0	StreamPro	P	2	2

* Two transects not made for cross sections 38.75, 38.5, 38.25, or 38.0, but the single-transit discharges were within 5 percent of each other.

All TRDI StreamPro-measured cross sections were processed by using VMS. Cross sections measured with the Sontek M9 were processed by using AdMap and Excel. Data in the vertical were not averaged in order to preserve the vertical velocity profile present at each location. Table 4 lists how much many data values were averaged in the horizontal direction (averaging interval) in order to output the averaged data into plots.

Five files were output for each cross section: top velocity, bottom velocity, mean velocity, 3_d velocity, and bathymetry (appendix B3). The top velocity file represents averages of measured velocity in the top of the water column. This is not a measure of water surface velocity. The ADCP is not able to measure the velocity at the very bottom of the water column due to interference, so the bottom velocity is the lowest measured velocity in the water column. The average velocity is the average of all the measured velocities in the measured portion of the water column.

The top, bottom, and depth-averaged data Excel files have the format shown in table 5. The data for all of the transect were combined into one file for each of the measures (top, bottom, and average) (appendix B3).

Stationary Measurements

A minimum of a 5-minute stationary velocity measurement was made at a point along each cross section during the April 2013 measurements (appendix B3). The location of the stationary point was determined by depth and (or) velocity. Based on the ADCP data, the location chosen for the stationary measurement was the deepest and fastest point in the section (table 6). The stationary points covered a range of velocities in the Kalamazoo River, from a high of 4.46 ft/s in the main channel of the Kalamazoo River to 0.03 ft/s in the widest part of Morrow Lake. “Distance made good” in table 6 represents the boat movement; it is the horizontal distance or offset between the starting and ending position of the boat during the stationary measurement. All TRDI measurements were processed by using VMS. The Sontek measurements were processed by using the R language/environment (R Core Team, 2014). Table 7 contains an example of a stationary data file. In the example of the stationary velocity data file, Tran_ID is the name of the measurement, UTM_N and UTM_E represent the Universal Transverse Mercator starting position (in meters), T_Depth is the total depth at the starting position, Sample_Depth is the depth the velocity was measured, R_Samp_Depth is the depth of the sample referenced to the total depth, AveV_E(ft/s) is the east velocity, AveV_N(ft/s) is the north velocity, AveV_mag(ft/s) is the velocity magnitude, Average_Velocity is the mean velocity for the measurement, Rel_Velocity is the measured velocity magnitude divided by the mean velocity, and AveV_dir(deg) is the velocity direction. The mean velocity column represents the mean velocity for the entire measurement. The Average_Velocity and Rel_Velocity columns were used to better display the data in ArcMap 10.1.

The vertical velocity profiles from the April 2013 stationary measurements were used to estimate bed shear stress and hydrodynamic roughness for model validation and comparison. At each stationary measurement location, a LOWESS fit (Helsel and Hirsch, 2002) of the u-component (downstream direction) of the velocity in each bin (depth interval) of the ensemble was computed first by using MATLAB (http://www.mathworks.com/help/curvefit/smooth.html, accessed May 2013). The entire bin of u-velocity component was also fit with the log law. In an ideal case, the vertical distribution of velocity magnitude in the water column of an open channel is represented by a logarithmic profile (Dingman, 2009). Examining the shape of the LOWESS fit (trend) curve and the logarithmic profile provided a first level of quality check of the data. In some instances, greater discrepancies showed at the top bins close to the water surface, which could result from wind-induced current (a likely case in Morrow Lake). When great discrepancies showed, portions of the u-velocity data were excluded from the logarithmic profile fit until a better fit was reached. In figure 4, the red line is the LOWESS trend curve fitted to the each bin of the entire ensemble, and the black line is the logarithmic velocity profile fitted to portion of the bin data (in black dots) that can represent the less disturbed data. Because not all of the external disturbances that affected the data were known, the logarithmic profile development had to be evaluated in case-by-case manner. Once a logarithmic profile was determined at

Table 5. Example top, bottom, and averaged file structure for velocity measurements.

[Tran_ID, cross-section name; UTM, Universal Transverse Mercator; V_mag [ft/s], is the horizontal velocity magnitude, in feet per second; V_dir, direction of the velocity in the horizontal. Vavg (mean velocity for the transect) and V_mag/Vavg (velocity magnitude for the point divided by the cross-sectional mean velocity) were used to scale the graphed vectors in ArcMap 10.1]

Tran_ID	UTM_X	UTM_Y	V_mag [ft/s]	V_dir	Vavg	V_mag/Vavg
39.82	624378.81	4682327.08	0.08	208.03	0.34	0.235294
39.82	624381.62	4682325.98	0.11	211.37	0.34	0.323529
39.82	624384.56	4682325.2	0.13	217.67	0.34	0.382353
39.82	624387.56	4682324.67	0.18	224.47	0.34	0.529412

Table 6. Summary of all the stationary measurements made in April 2013.

[ID, identification number; ft, feet; ft/s, feet per second; UTM, Universal Transverse Mercator]

Stationary ID	Start	UTM_X	UTM_Y	Depth (ft)	Mean velocity (ft/s)	Distance made good (ft)
S_1-39.82	4/12/13 13:59	624403.5	4682215.51	10.47	0.28	18.4
S_2-39.82	4/12/13 14:11	624425.9	4682275.11	19.81	0.31	16.0
S_3-39.82	4/12/13 14:20	624398.9	4682323.12	9.31	0.21	15.6
S_1-39.79	4/12/13 14:48	624409.8	4682356.31	7.62	0.14	13.2
S_2-39.79	4/12/13 14:57	624457.2	4682261.46	15.27	0.26	8.9
S_3-39.79	4/12/13 15:07	624414.1	4682189.8	10.9	0.22	11.4
S-39.75	4/12/13 16:22	624540.5	4682126.43	12.65	0.2	35.0
S-39.70	4/12/13 15:47	624602.1	4682094.36	11.82	0.2	19.4
S-39.60	4/12/13 17:19	624756	4682105.83	10.77	0.19	3.9
S-39.50	4/12/13 17:55	624838.6	4681856.61	9.54	0.16	4.4
S-39.25	4/14/13 11:47	625267.7	4681841.1	8.87	0.07	5.8
S-39.00	4/14/13 12:34	625660.2	4681819.37	7.07	0.08	9.0
S-38.75	4/15/13 17:01	626069.7	4681858.81	6.13	0.03	31.1
S-38.50	4/15/13 17:46	626481.9	4681771.29	6.07	0.19	5.1
S-38.25	4/15/13 18:28	626898.5	4681970.59	5.35	0.13	55.0
S-38.0	4/15/13 19:41	627246.5	4681628.8	4.35	0.24	13.0
S-38_N	4/15/13 19:06	627101.7	4681987.34	5.31	0.04	5.1
S-38_S	4/15/13 20:13	627071.8	4681160.85	4	0.04	0.9
S-37.75	4/15/13 11:22	627696.8	4681680.12	5.96	0.8	24.2
S-37.66	4/15/13 10:51	627832.6	4681708.06	9.19	1.03	3.6
S-37.55	4/15/13 10:25	627998.8	4681736.06	7.28	0.88	6.6
S-37.25-37.5	4/15/13 8:44	628072.6	4681595.12	6.37	1.01	1.6
S-37.18	4/15/13 9:11	628579.3	4681797.85	3.4	1.63	1.6
S-37.14	4/15/13 9:46	628734.9	4681348.71	2.19	0.49	1.2
S-36.55	4/14/13 9:54	629538	4682086.39	10.56	2.16	4.8
S-34.12	4/13/13 13:51	631756.2	4683056.87	8.21	2.45	2.0
S-28.8	4/14/13 11:10	636308.7	4688314.2	9.53	3.11	7.0
S-21.36	4/14/13 12:31	641936.9	4690393.33	5.88	0.56	8.5
S-21.31	4/14/13 12:58	641992.3	4690191.15	10.07	1.81	30.2
S-18.83	4/14/13 14:02	645560	4688779.89	6.07	2.1	1.4
S-15.5	4/14/13 13:55	649495.2	4685869.91	6.71	1.47	6.4
S-15.24	4/13/13 14:23	649236	4685619.46	8.61	2.29	3.0
S-15.22	4/13/13 15:16	649224	4685565.38	6.95	1.57	3.8
S-15.17	4/13/13 15:38	649269.8	4685485.86	4.77	1.72	1.7
S-14.75	4/13/13 16:20	649818.8	4685143.52	5.74	1.73	2.2
S-14.71	4/13/13 16:47	649885.6	4685137.75	4.11	1.62	1.7
S-14.52	4/13/13 17:37	650024.6	4684823.84	5.01	1.79	3.2
S-13.89	4/14/13 15:11	650838.6	4684447.52	5.03	4.46	3.8
S-12.05	4/14/13 15:53	652854.9	4685647.72	3.86	4.07	3.4
S-7.18	4/16/13 12:55	658218.3	4682039.03	2.8	3.34	2.1
S-5.75	4/13/13 9:52	660087.5	4681528.54	5.36	0.89	0.7
S-5.62	4/13/13 10:33	660206.3	4681412.56	5.38	0.82	1.2
S-5.32	4/13/13 11:03	660641.9	4681163.72	4.78	0.83	9.0
S-5.03	4/13/13 11:43	661082.6	4680994.55	7.61	0.72	16.4
S-2.22	4/14/13 16:43	665110.5	4680425.06	4.06	2.16	1.0
S-1.29	4/14/13 17:17	665956.5	4679697.96	1.26	0.93	0.6

Table 7. Example of a stationary velocity data file.

[Tran_ID, transect number the data point belongs to; UTM_E[m], Universal Transverse Mercator easting coordinate, in meters; UTM_N[m], Universal Transverse Mercator northing coordinate, in meters; UTM_E_FAKE, display velocity data in the vertical; T_Depth, total depth at the starting position; Sample_Depth, depth the velocity was measured; R_Samp_Depth, depth of the sample referenced to the total depth; AveV_E(ft/s), east velocity; AveV_N(ft/s), north velocity; AveV_mag(ft/s), velocity magnitude; Average_Velocity, mean velocity for the measurement; Rel_Velocity, measured velocity magnitude divided by the mean velocity; AveV_dir(deg), velocity direction; ft/s, feet per second; deg, degrees]

Tran_ ID	UTM_E	UTM_N	UTM_E_FAKE	T_ Depth	Sample_ Depth	R_Samp_ Depth	AveV_E (ft/s)	AveV_N (ft/s)	AveV_ mag (ft/s)	Average_ Velocity	Rel_ Velocity	AveV_ dir (deg)
1.29	665956.54	4679697.96	665956.5415	1.26	0.95	0.753968254	–0.65	0.71	0.96	0.93	1.032258065	317.81
1.29	665956.54	4679697.96	665959.5415	1.26	0.89	0.706349206	–0.67	0.75	1	0.93	1.075268817	318.12
1.29	665956.54	4679697.96	665962.5415	1.26	0.82	0.650793651	–0.6	0.63	0.87	0.93	0.935483871	316.17
1.29	665956.54	4679697.96	665965.5415	1.26	0.76	0.603174603	–0.63	0.73	0.97	0.93	1.043010753	319.36

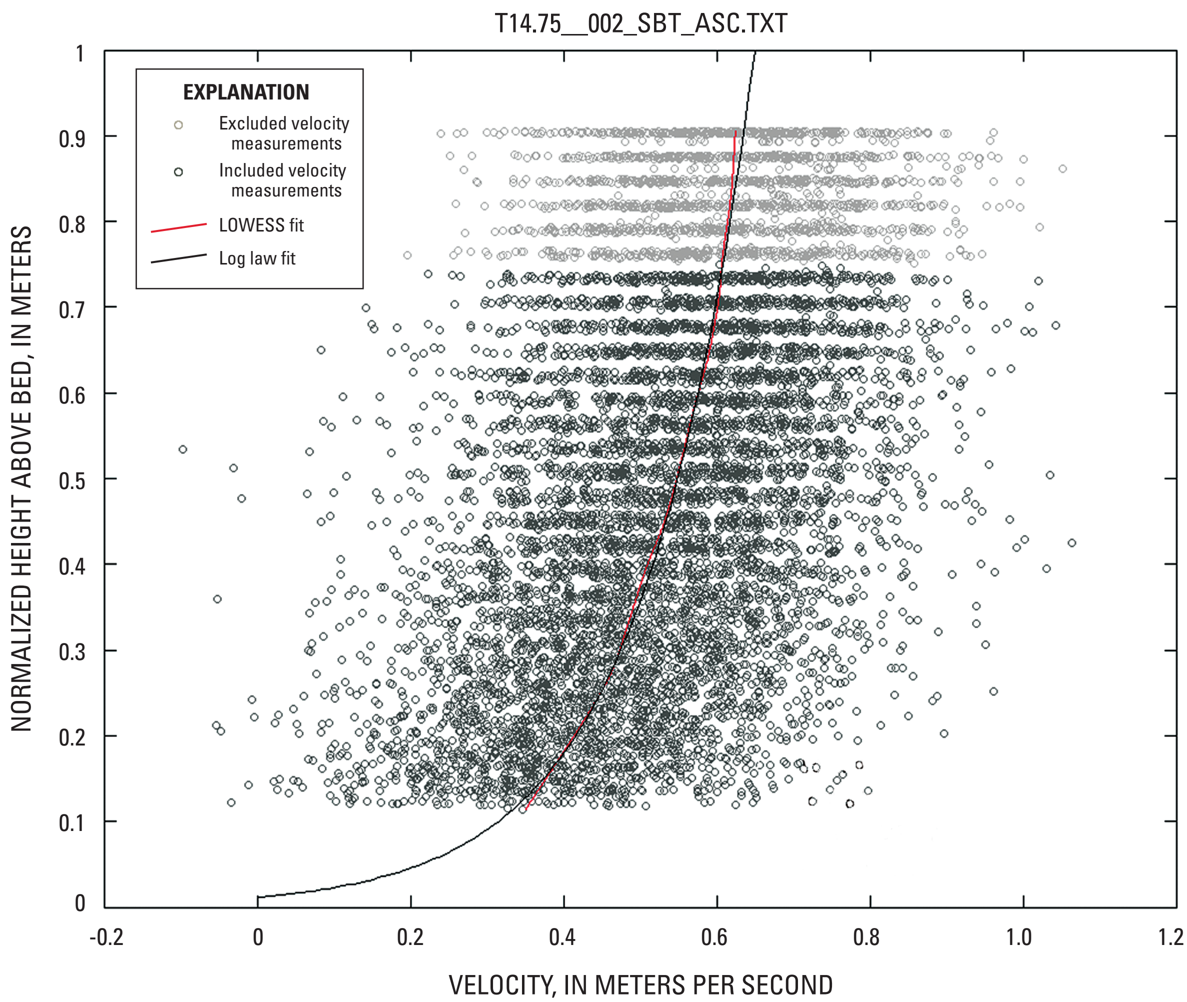

Figure 4. Example of a vertical velocity profile determined from a stationary measurement.

a stationary measurement location, the hydrodynamic roughness length and bed shear stress were determined with the following analysis.

The logarithmic profile (Dingman, 2009) generally has the following form:

$$u = \frac{u_*}{K}\log\left(\frac{Z}{Z_0}\right) \quad (1)$$

where u is velocity component in the longitudinal direction (downstream, in this case), u_* is the shear velocity, K is the Von Karman constant, z is the depth variable positive upward, and z_0 is the hydrodynamic roughness length. Equation 1 is expanded to a linear algebra form as

$$u = \frac{u_*}{K}logz - \frac{u_*}{k}logz_0\ , \quad (2)$$

and compared to the linear logarithmic equation $y = a \times logx + b$; from the mean u-velocity fit, we obtain

$$a = \frac{u_*}{K},\ and\ b = -\frac{u_*}{K}logz_0,\ or\ b = \frac{u_*}{K}log\frac{k_s}{30} \quad (3)$$

where k_s is the dominant roughness height. An assumption made here is that sediment grain sizes are the dominant form of roughness that cause the hydrodynamic roughness (with recognition that a large portion of the river bottom is covered with vegetation during summer months). For rough turbulent flows, Nikuradse (1993) derived the hydrodynamic roughness length due to sediment grains as $z_0 = {k_s}/{30}$. Because the values of a (slope) and b (intercept) are known from the fitted curve, the shear velocity and roughness length can therefore be obtained as

$$u_* = a \times k,\ and\ k_s = e^{\left(\frac{b \times K}{u_*}\right)} \times 30 \quad (4)$$

Finally, bed shear stress (τ_{oe}) is related to shear velocity by the equation $u_* = (\tau_{oe}/\rho)^{1/2}$, where ρ is the fluid density. The derived hydrodynamic roughness length and bed shear stress are presented in table 8. The data were also reported in the file April2013_Stationary_analysis&numerical_results-042014upate.xlsx in appendix B3.

Model Grid Specific Velocity

In order to more easily calibrate and validate the 2D and 3D models, the velocity data were further processed to correspond to the horizontal and vertical dimensions of the grid cells being used in the modeling. Upstream of the Morrow Lake Delta and 35th Street bridge crossing, the velocity data were evaluated at the 2D EFDC model grid cells. For Morrow Lake Delta and Morrow Lake, the velocity data were evaluated at the 3D EFDC model grid cells.

Although the basic processing of the velocity data was the same as described above, it was grouped differently to reflect the two model grids. Raw unaveraged data were output from WinRiver 2.10 by using AdMap. These data were then loaded into ArcMap 10.1 and spatially joined to the corresponding model grid cells (fig. 5). Each raw velocity data point then had a grid cell number associated with it, and the data were exported from ArcMap 10.1 and imported into R (R Core Team, 2014) for further analysis. For the 3D model grid, velocity data were further grouped by relative depths and then averaged. Relative depths were calculated by dividing the measured depth by the total depth for each velocity data point. These data were then assigned and averaged into the eight vertical bins used in the 3D model grid.

A few methods were used to help determine the velocity data quality assigned for each grid cell. A simple count was done to see how many data points were in each bin. In addition, for data fitted to the 3D model grid, vertical profile plots that showed the averaged data as well as the raw data were examined (fig. 6). The only difference in the data processing for the 2D and 3D model grids was that bins in the vertical were not computed for the 2D model except for a relative depth of 0.6. The 0.6 relative depth bin was computed to compare to the average velocity among grid cells. This was done to check and see whether the velocity profile followed a standard logarithmic shape, where the velocity at 6/10 depth should represent the mean velocity for the profile. Rose diagrams showing the direction and magnitude of raw data for each grid cell also were produced (fig. 7). The rose diagrams display the direction of raw velocity data relative to the mean flow direction for the grid cell. If all of the raw data are to the left and right of the mean flow direction (0 in the graph), the pattern would suggest that velocity data in that particular cell are highly variable and probably would not be used to check the model. The vertical profile plots and the rose diagrams are intended only as a reference to the modeler to explain differences in the measured and modeled velocities.

Table 8. Derived hydrodynamic roughness length and bed shear stress for the stationary data collected in April 2013.

[ID, identification number; m, meters; Pa, pascals; ft, feet; ft/s, feet per second; ––, not analyzed]

Stationary ID	Hydrodynamic roughness length Z_0 (m)	Bed shear stress u* (Pa)	Mean depth (ft)	Mean velocity (ft/s)
S-1.29	––	––	1.26	0.93
S-2.22	0.0316	8.68	4.06	2.16
S-5.03	0.0394	0.89	7.61	0.72
S-5.32	0.0024	0.34	4.78	0.83
S-5.62	0.0019	0.29	5.38	0.82
S-5.75	0.0021	0.36	5.36	0.89
S-7.18	0.0373	32.89	2.8	3.34
S-12.05	––	––	3.86	4.07
S-13.89	0.0084	17.29	5.03	4.46
S-14.52	0.0002	0.79	5.01	1.79
S-14.71	0.0018	1.23	4.11	1.62
S-14.75	0.0202	3.57	5.74	1.73
S-15.17	0.0024	1.48	4.77	1.72
S-15.22	0.0030	1.20	6.95	1.57
S-15.24	0.0051	2.86	8.61	2.29
S-15.5	0.0146	1.99	6.71	1.47
S-18.83	0.0026	1.95	6.07	2.1
S-21.31	0.0028	0.99	10.07	1.81
S-21.36	––	––	5.88	0.56
S-28.8	0.0460	13.98	9.53	3.11
S-37.75	––	––	5.96	0.8
S-34.12	0.1231	19.16	8.21	2.45
S-36.55	0.5186	53.66	10.56	2.16
S-37.14	––	––	2.19	0.49
S-37.18	0.0041	1.83	3.4	1.63
S-37.25-37.5	0.0000	0.10	6.37	1.01
S-37.55	0.0005	0.22	7.28	0.88
S-37.66	0.0027	0.43	9.19	1.03
S-39.00	0.0091	0.00	7.07	0.08
S-39.25	0.0008	0.00	8.87	0.07
S-39.50	0.0030	0.01	9.54	0.16
S-39.60	0.0000	0.00	10.77	0.19
S-39.70	0.0334	0.04	11.82	0.2
S-39.75	0.0289	0.06	12.65	0.2
S_1-39.79	0.0004	0.01	7.62	0.14
S_2-39.79	0.0642	0.14	15.27	0.26
S_3-39.79	0.0044	0.03	10.9	0.22
S_1-39.82	0.0504	0.12	10.47	0.28
S_2-39.82	0.0145	0.06	19.81	0.31
S_3-39.82	0.0129	0.05	9.31	0.21

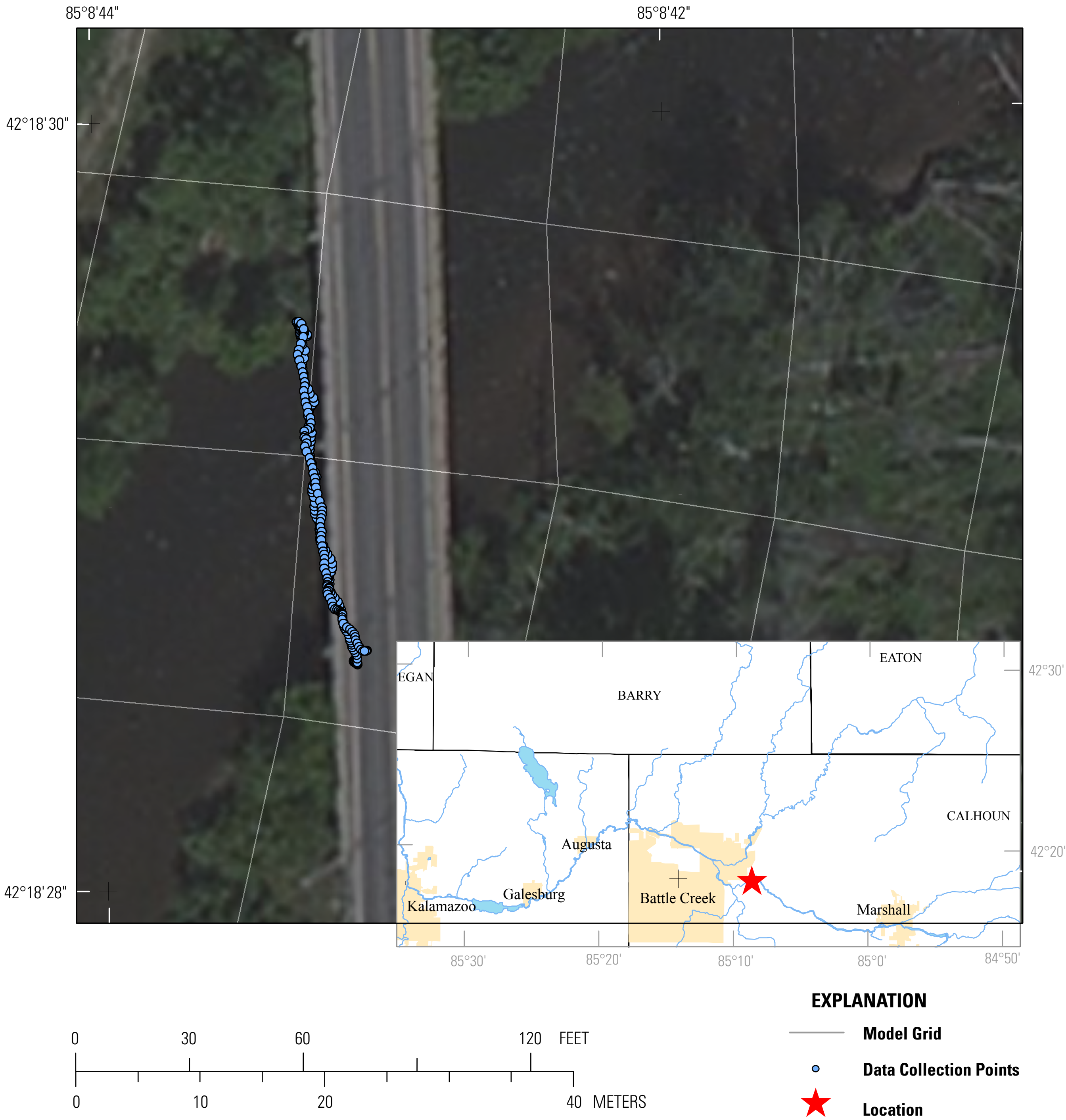

Figure 5. Velocity data-collection points overlain on the two-dimensional Environmental Fluid Dynamics Code model grid.

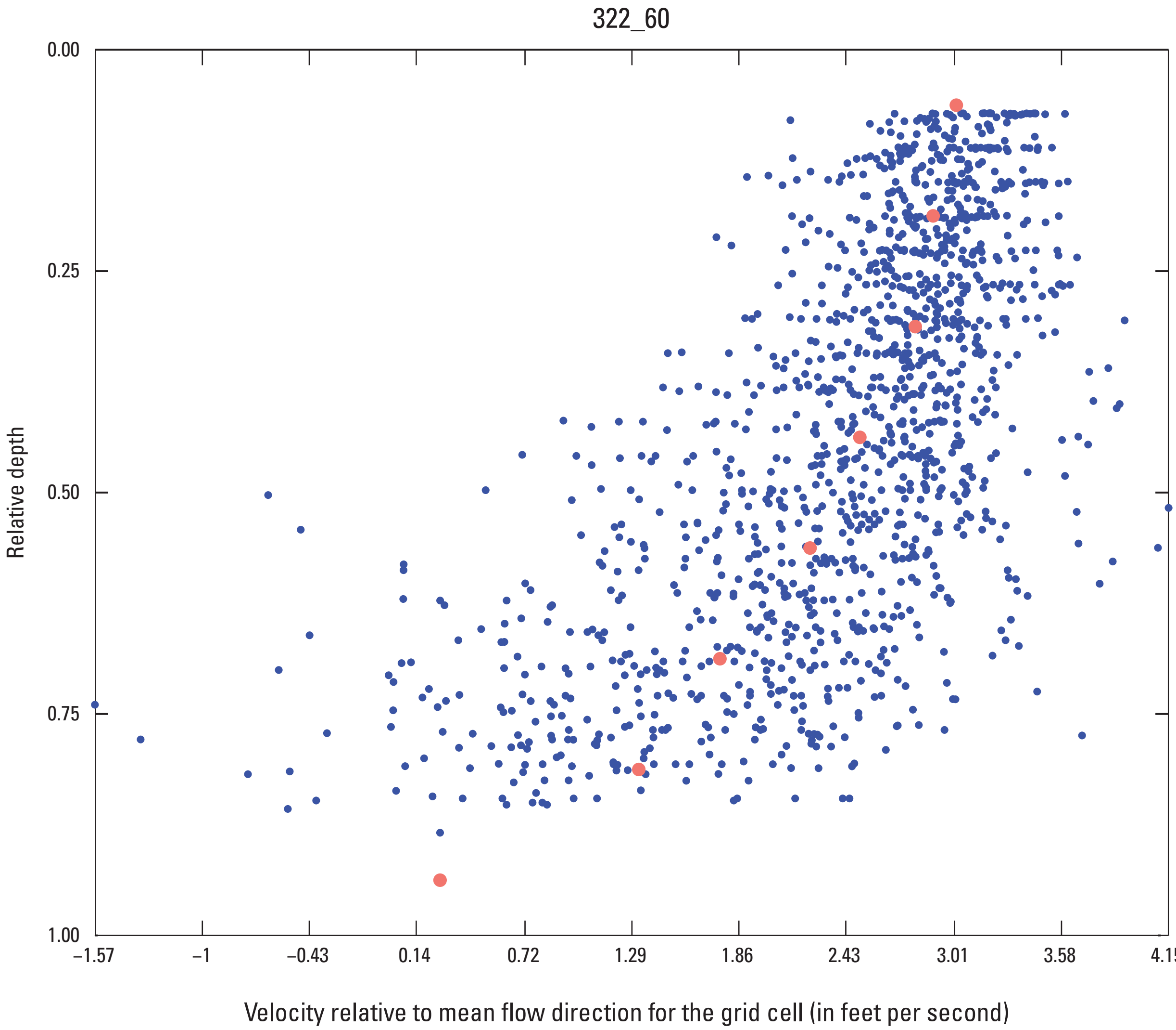

Figure 6. Example of a vertical profile plot of raw and averaged velocity data for an individual three-dimensional model grid cell. Blue points represent raw velocity; red points are the mean velocities calculated for each bin in the vertical. The different shaded and unshaded regions represent the bins in the vertical.

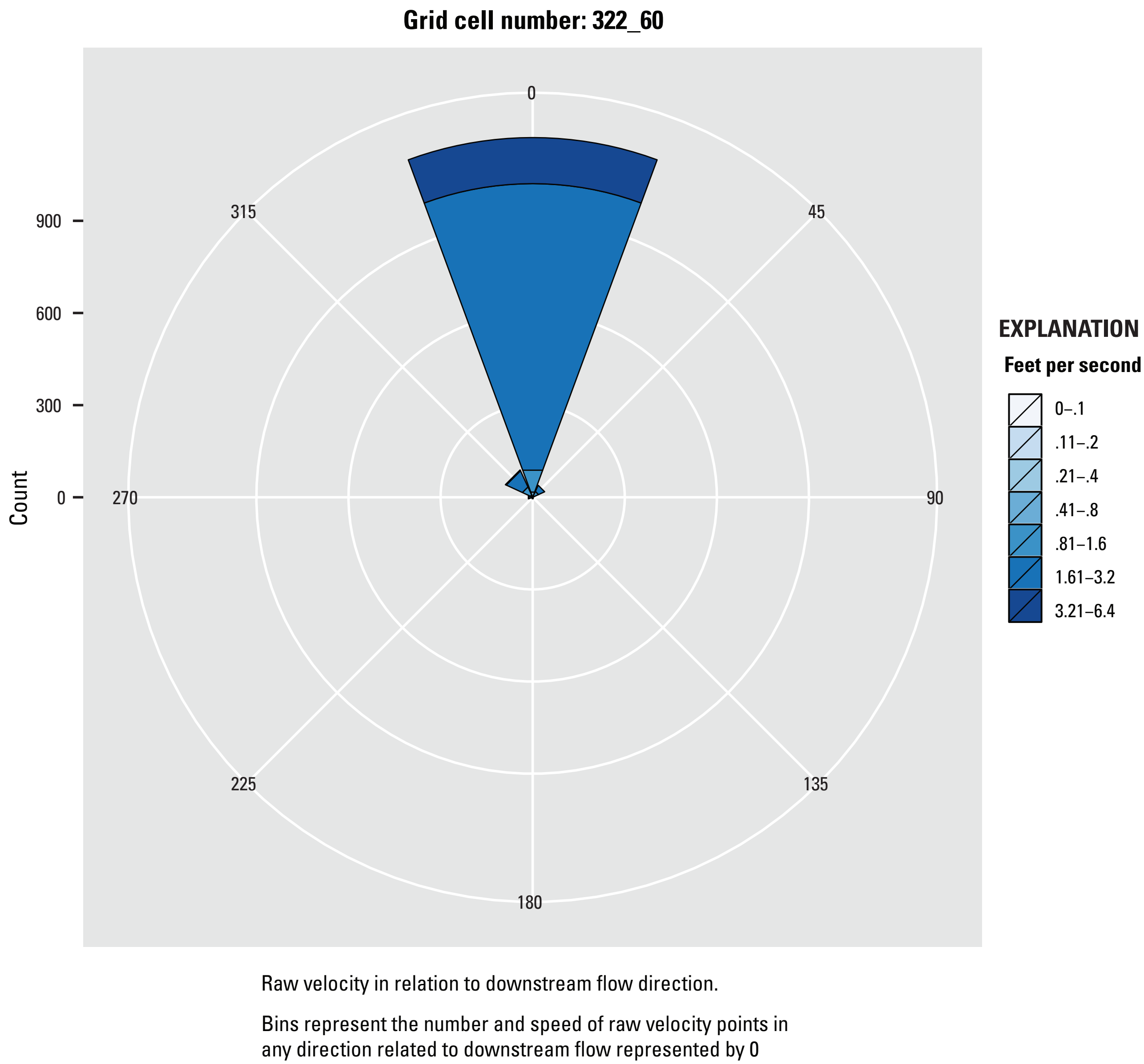

Figure 7. Example of a rose diagram showing the direction and magnitude of the raw velocity data relative to the mean flow direction for a three-dimensional model grid cell.

Table 9. Example bathymetry file.

[Tran_ID, transect number the data point belongs to; UTM_E[m], Universal Transverse Mercator easting coordinate, in meters; UTM_N[m], Universal Transverse Mercator northing coordinate, in meters; Mean Depth [ft], depth, in feet, at that point; Bed_Elev(ft)_NAVD88, bed elevation, in feet above NAVD 88].

Tran_ID	UTM_E[m]	UTM_N[m]	Mean Depth (ft)	Bed_Elev(ft)_NAVD88
39.82	624382.9208	4682212.458	6.02	769.79
39.82	624382.9787	4682212.458	6.08	769.73
39.82	624383.0336	4682212.461	6.08	769.73
39.82	624383.0945	4682212.491	6.19	769.62
39.82	624383.1616	4682212.531	6.07	769.74
39.82	624383.2287	4682212.567	6.24	769.57
39.82	624383.2896	4682212.601	6.24	769.57

Bathymetry

Bathymetry data were calculated from the velocity measurements. Before or after each transect measurement, water-surface elevations were recorded at the preestablished reference points. With a known water-surface elevation at the time of each measurement, bed elevations could be calculated from water depths measured by the ADCP. The ADCP measures an individual water depth for each of its four beams; these depths were then averaged together to compute a mean water depth for every reading. The transect that had the more accurate DGPS data was used for the bathymetry data. An example bathymetry file is shown in table 9.

Data

Velocity data are in various formats and are organized into four appendixes. The first three (appendixes B1–B3) contain raw and processed data collected by date, and the fourth (appendix B4) contains raw and processed data fitted to the 2D and 3D EFDC model grids.

Velocity data consist of the following from the June 2012 measurements (appendix B1):

- Delta Msmts June 2012:
  - Measured Folder: Contains unprocessed ADCP data
  - Processed Folder: Contains processed ADCP data
- Discharge Msmts 2012.zip:
  - Measured Folder: Contains unprocessed ADCP data
  - Processed Folder: Contains processed ADCP data
- June_2012_Discharge.xlsx: Table of discharge measurements made.

Velocity data files for August 2012 (appendix B2) include:

- Measured.zip: Measured ADCP Data
- Processed.zip: Processed ADCP data.
- August_2012.mpk: ARC Map package showing locations of transects and embedded velocity data output for transects

April 2013 data are in appendix B3 and also contain a variety of folders and file types:

- MorrowLake_Processed: Folder with files of processed stationary and transect data from Morrow Lake.
- Processed: File Folder with files of processed stationary and transect data from the Kalamazoo River.
- April_2013_Kazoo_Final_Survey.mpk: Spatially referenced data.
- April2013_Stationary_analysis&numerical_results-042014upate.xlsx: Stationary data and analyses used for computing bed shear stress and roughness height.
- Original Data.zip: Raw ADCP data.

The map package (April_2013_Kazoo_Final_Survey.mpk) in ArcMap 10.1 was created to summarize all of the data collected. The following is a brief summary of the various layers in the ArcMap 10.1 Map Package in appendix B3:

- **Kalamazoo_Average_Velocity:** Arrow direction represents flow direction, arrow color is the velocity magnitude, and arrow size is the velocity magnitude relative to each individual transect.
- **Kalamazoo_Bottom_Velocity:** Arrow direction represents flow direction, arrow color is the velocity magnitude, and arrow size is the velocity magnitude relative to each individual transect.
- **Kalamazoo_Top_Velocity:** Arrow direction represents flow direction, arrow color is the velocity magnitude, and arrow size is the velocity magnitude relative to each individual transect.
- **Kalamazoo_Bathymetry:** Points that show the elevation of the bed relative to NAVD 88.

- **Kalamazoo_Depth:** Points that show the depth from water surface for each measurement.
- **Kalamazoo_RP:** Points where Reference Points were established for the survey.

Model Confirmation Velocities are in appendix B4 and also contain a variety of file types:

- 35th Street to Morrow Dam: Contains three folders for the three dates when velocity data were collected. These contain the data fitted to the 3D EFDC model grid. Each folder includes a zip file with the following:
    - [DATE]_Graphs: Folder with graphs of the vertical profile and rose diagram.
    - [DATE]_Final_Data.xlsx: Final computed values for each grid cell.
    - Averaging Velocity Data_8depths_Zhendou_April2013_Centroid_I_J_2.r: R script used to manipulate raw data.
    - Final_Data.csv: Final data in CSV format.
- Talmadge Creek to 35th Street: Folder contains one file of velocity data fitted to the 2D EFDC model grid:
    - Mean_Velocity.xlsx: Contains final data processed for 2D model comparison.

Estimates of Tributary Inflows

Estimates of tributary inflows were needed for determining flow and sediment influxes to the main stem Kalamazoo River for the 2D EFDC model. For unsteady flow and sediment-transport modeling, properly determined tributary inflow time series were important for model calibration, for describing effects of the influx from tributaries, and for balancing and assessing the spatial patterns and variations of discharge and sedimentation along the modeled reach. Eight tributaries were included in the Enbridge 2D EFDC model of the Kalamazoo River (Enbridge Energy, L.P., 2012). They are, in upstream to downstream order, Talmadge Creek, Bear Creek, Minges Brook-Harper Creek, Battle Creek, Wabascon Creek, Sevenmile Creek, Augusta Creek, and Gull Creek (fig. 1). Among them, Battle Creek and Augusta Creek have USGS streamgages; the remaining six tributaries are ungaged (table 8). Note that the drainage areas for ungaged tributaries reported in table 10 were obtained from a separate watershed model of the Kalamazoo River presently being developed by the USGS for a Great Lakes Restoration Initiative study and are slightly different from those reported earlier (Enbridge Energy, L.P., 2012).

Table 10 Summary of available discharge and drainage-area data for the main stem and tributary watersheds.

[mi², square miles]

Stream and streamgage names	Drainage area (mi^2)	Streamgage number or ungaged designation
Kalamazoo River at Marshall	449	04103500.
Talmadge Creek	3.3	Ungaged.
Bear Creek	14.8	Ungaged.
Minges Brook-Harper Creek	54.9	Ungaged.
Battle Creek at Battle Creek[1]	241	04105000.
Kalamazoo River near Battle Creek	824	04105500.
Wabascon Creek	43.1	Ungaged.
Sevenmile Creek	16.4	Ungaged.
Augusta Creek[2]	38.9	04105700.
Gull Creek[3]	39.0	Ungaged.
Kalamazoo River at Comstock[4]	1,100	04106000.

[1]The gage is upstream of the confluence with the Kalamazoo River. The drainage area at the confluence is 282 mi^2.

[2]The Enbridge Energy L.P. (2012) hydrodynamic modeling report listed the drainage area for Augusta Creek to be 38.9 square kilometers.

[3]The reported drainage area is at the confluence with Kalamazoo River. The drainage area at the USGS streamgage on the Gull Creek, number 04105800, is 38.1 mi^2.

[4]This is the drainage area at the U.S.Geological Survey Kalamazoo River at Comstock streamgage, which is downstream of Morrow Dam. For evaluating tributary areas, it is appropriate to exclude the drainage area for the Crooked Creek watershed (about 23 mi^2) and the Comstock watershed (17.5 mi^2).

Methods

Approximating flow time series at ungaged tributaries consisted of two parts: (1) estimating and assembling daily flow time series and (2) disaggregating the daily time series into 15-minute time intervals. The latter part is necessary to produce time series with the time step used in the hydrodynamic model simulations.

Two flow-approximation methods based on drainage area (DA) were applied to selected index stations for estimating flows for the six ungaged tributaries: the DA-ratio method that was used in the Enbridge modeling and the Flow Anywhere method (Linhart and others, 2012) used in the EPA modeling. The two method-index station pairs (models) that produced best tributary inflow estimates are (1) the DA-ratio method with Augusta Creek near Augusta as the index station, and (2) The Flow Anywhere method with Battle Creek at Battle Creek as the index station. Based on the goodness-of-fit obtained from comparing measured records at three gaged stations (Battle Creek at Battle Creek, Augusta Creek, Wanadoga Creek) for the period October 1, 2001, to September 30, 2012, the Flow Anywhere method with Battle Creek at Battle Creek as the index station, described as equation 5 below, was selected for estimating daily flows for the six ungaged tributaries:

$$Q_u = C\left(\frac{A_u}{A_I}\right)^{1.1137} Q_I^{0.6994} \quad (5)$$

where

Q_u is the streamflow at the ungaged location,
A_u is the drainage area at the ungaged location,
A_I is the drainage area at the index streamgage, and
Q_I is the streamflow at the index streamgage.

For the modeling, mean daily time series data at the gaged index station at Battle Creek at Battle Creek and Augusta Creek were used for the selected simulation period. The mean daily flow time series at six other ungaged sites was estimated with equation 5.

There are small watersheds besides the eight tributaries in the study, and their total drainage areas are not negligible. These unaccounted-for areas, located between the upstream and downstream boundary and the eight specified tributaries, also contribute flows and sediment to the Kalamazoo main channel and potentially can induce imbalance in flows and sediment if not considered. Daily flows from unaccounted-for areas were also estimated with equation 5 and assigned to the nearest tributary.

Daily flows for the tributaries were disaggregated into 15-minute intervals for a better match with the time step used in the hydrodynamic flow modeling. A daily hydrograph was constructed by connecting the midpoint of each mean daily mean discharge. Within a day, a finer time interval was obtained by adjusting the slope of finer time interval until the volume under the slope of the finer time interval matched the daily volume. Estimated tributary flows were calculated at 15-minutes intervals for the five 2D EFDC modeled events:

- 7/23/2010–8/23/2010 (oil spill)
- 5/13/2011–5/24/2011 (high flow)
- 5/25/2011–6/8/2011 (high flow)
- 10/28/2011–11/9/2011 (high base flow)
- 4/10/2013–4/22/2013 (spring runoff event)

Data

The data file for the tributary inputs is in spreadsheet format with worksheets for each of the five flow events (appendix C). The data file is called Appendix C disagg_15m_trib_inflows_for_5_events.

Suspended Sediment

Suspended-sediment concentration and particle-size data were not available for the oil-affected reach of the Kalamazoo River during the 2012 Enbridge modeling, and Tetra Tech Inc., applied a discharge/concentration rating from available suspended-sediment concentration data collected upstream at the South Branch of the Kalamazoo River near Albion, MI (04102850) in 1971–72. The regression for the Albion curve was

$$Y = 0.0194x^{1.239} \quad (6)$$

where x is equal to discharge (ft^3/s) and Y is equal to suspended-sediment concentration (milligrams per liter [mg/L]). An upper limit of 120 mg/L was put on the rating (Enbridge Energy, L.P., 2012) on the basis of these data and others from downstream of the spill-affected reach, indicating that the Kalamazoo River is generally a sediment-supply-limited system. Tetra Tech, Inc., used a distribution of sand, silt, and clay-sized fractions based on average particle-size distribution from sediment cores collected from the oil-affected reach of the Kalamazoo River in 2011 (Enbridge Energy, L.P., 2012).

From 2012 through 2014, the USGS collected suspended-sediment concentration and particle-size data within the oil-affected reach at six sites (table 11). Each site but one, the Kalamazoo River at 35th Street Bridge, was at a USGS streamgage, and each site was sampled for suspended-sediment concentration and particle size a total of six times between August 2012 and April 2014 during a range of flow conditions (table 12). The Kalamazoo River at 35th Street was sampled only once, during the last flow event sampled in March 2014. Particle-size data were not collected for the January 15, 2013, sampling.

Table 11. Locations with suspended-sediment concentration and particle-size data.

U.S.Geological Survey identification number	Streamgage name
04103500	Kalamazoo River at Marshall.
04105000	Battle Creek at Battle Creek.
04105500	Kalamazoo River near Battle Creek.
04105700	Augusta Creek near Augusta.
04105820	Kalamazoo River at 35th Street at Galesburg.
04106000	Kalamazoo River at Comstock.

Table 12. Dates sampled for suspended-sediment concentration and particle size with instantaneous streamflow for the Kalamazoo at Marshall, Michigan (U.S. Geological Survey identification number 04103500) streamgage.

[Only concentration data, not particle size, are available for 1/15/2013; ft^3/s, cubic feet per second].

Date	Kalamazoo River at Marshall, MI, instantaneous discharge (ft^3/s)
8/16/2012	254
1/15/2013	414
2/1/2013	575
3/18/2013	272
4/22/2013	1,130
3/31/2014	826

Methods

Suspended sediment was collected with a depth-integrated sampler (DH-59) by the USGS, using standard procedures for the equal-width-increment (EWI) method (Edwards and Glysson, 1999; Nolan and others, 2005). Water temperature and specific conductance also were collected with a Yellow Springs Instruments 600OMS multiparameter water-quality sonde.

Samples were analyzed for sediment concentration at the USGS Kentucky Water Science Center Laboratory, in accordance with standard protocols (Guy, 1969; Shreve and Downs, 2005). Particle-size analyses were done in the USGS Wisconsin Water Science Center prep laboratory on a LISST-Streamside portable particle-size analyzer. Samples were analyzed in a wet state. Particle-size categories range from less than 2 micrometers to fine to medium sand-sized (356 micrometers). The particle-size distributions likely include silt and organic-matter aggregates, especially those in the sand-sized range. Two replicates were analyzed from most samples.

Instantaneous loads were calculated by using equation 7 (from Porterfield, 1972):

$$Q_s = Q_w C_s K \tag{7}$$

where Q_s is sediment discharge, in tons (short tons) per day (ton/d); Q_w is the instantaneous streamflow (water discharge), in cubic feet per second (ft^3/s); C_s in the suspended-sediment concentration, in milligrams per liter (mg/L); and K is a coefficient (0.0027) to convert units of measurement of water discharge and suspended-sediment concentration into tons per day and assumes a specific gravity of 2.65 grams per cubic centimeter for sediment.

For particle size, Sequoia Scientific's laser-diffraction-based portable LISST instrument was used (Agrawal and Pottsmith, 2000). Assumptions for the instrument included that the data represent a distribution of spheres, and an empirical calibration correction was applied to account for random particle shapes.

Data

Suspended-sediment concentration and particle-size data are in appendix D in multiple spreadsheets. Concentration data are in two files:

- kzoosed_concentration.xlsx: All suspended-sediment concentration data with associated discharge, water temperature, specific conductance, and instantaneous load, collected from August 2012 through March 2014.
- kzoosed_Marshall_susp_sed_ratings.xlsx: Concentration and sediment load data plotted against discharge for the Kalamazoo River at Marshall, MI, streamgage. These data were used for 2D EFDC model inputs.

Particle-size data are in separate files for each collection date and consist of raw particle-size data in volume concentrations per class, cumulative frequency calculations, and cumulative frequency graphical plots. Data for random shape particles is shown in the graphical displays.

- kzoo.ss.LISST.20120816.xlsx: Particle-size data for the August 16, 2012, sampling.
- kzoo.ss.LISST.20130201.xlsx: Particle-size data for the February 1, 2013, sampling.
- kzoo.ss.LISST.20130318.xlsx: Particle-size data for the March 18, 2013, sampling.
- kzoo.ss.LISST.20130422.xlsx: Particle-size data for the April 22, 2013, sampling.
- kzoo.ss.LISST.20140331.xlsx: Particle-size data for the March 31, 2014, sampling.
- kzoo.ss.Marshall.LISST.xlsx: Cumulative frequency plots of suspended-sediment particle-size data for all sampling events for the Kalamazoo River at Marshall.

Summary

The U.S. Geological Survey collected hydrodynamic-assessment data related to the containment and recovery of submerged oil in the Kalamazoo River associated with the July 2010 Enbridge Line 6b Pipeline release of oil (diluted bitumen) in Marshall, Michigan. The data were collected during 2012–14 and consisted of the following: (1) a survey done by use of a Real-Time Network (RTN) Global Navigation Satellite System, (2) water-level measurements, (3) velocity, discharge, and bathymetry data, (4) tributary inflows estimates, and (5) suspended-sediment concentrations and particle-size data.

The RTN survey was used tie bathymetry and water level data into a common vertical datum. Twenty-six reference points were established, all tied into NAVD 88, along the reach of the river from Marshall, Michigan to Morrow Lake.

Water-level measurements were collected at 5 minute intervals from April 2013 to August 2013 at five locations including: Ceresco impoundment, Battle Creek Millponds, entrance to Morrow Lake Delta, Morrow Delta, and Morrow Lake.

Velocity, discharge, and bathymetry data were collected at over 50 locations along the Kalamazoo River. The data were collected June 2012, August 2012, and April 2013.

Ungaged tributary inflows were estimated for five events during the study period. Three gaged creeks were used to develop the estimates: 0410500 Battle Creek at Battle Creek, Michigan, 04105700 Augusta Creek near Augusta, Michigan, and 04104945 Wanadoga Creek near Battle Creek, Michigan.

Suspended sediment concentration and particle size were measured at six locations from 2012 to 2014.

These data were mainly used in association with the U.S. Environmental Protection Agency (EPA) hydrodynamic and sediment-transport modeling. In addition to modeling, the data were helpful for submerged oil containment and recovery operations that were focused in impoundments and designated sediment traps. The data also augmented data collections of water levels and velocity by Enbridge Energy L.P. and EPA contractors.

Acknowledgments

The authors would like to doubly thank Thomas Weaver, Don James, Josh Loewel, and Ryan Oster from the USGS Michigan Water Science Center and Timothy Hanson and Frank Younger from the USGS Wisconsin Water Science Center, who were involved in the data-collection efforts. This work required diligent responsiveness to changing flow conditions when weather conditions were not necessarily at their most favorable. Long days were the norm.

Estimation of tributary flow inputs used a version of the Flow Anywhere Program modified by the Lamar Sanders, a retiree of the USGS. Interpreting mean daily values to hourly or 15-minute values was done by using a TDL program developed by Dr. Tom Over at the USGS Illinois Water Science Center. Ronald Zelt, USGS Nebraska Water Science Center, provided technical comments on the methods. Their assistance is sincerely appreciated.

References Cited

Agrawal, Y.C., and Pottsmith, H.C., 2000, Instruments for particle size and settling velocity observations in sediment transport: Marine Geology, v. 168, no. 1–4, p. 89–114.

Dingman, S.L., 2009, Fluvial hydraulics: Oxford and New York, Oxford University Press, 559 p.

Dollhopf, R.H., Fitzpatrick, F.A., Kimble, J.W., Capone, D.M., Graan, T.P., Zelt, R.B., and Johnson, R., 2014, Response to heavy, non-floating oil spilled in a Great Lakes river environment—A multiple-lines-of-evidence approach for submerged oil assessment and recovery, *in* Proceedings, 2014 International Oil Spill Conference, Savannah, Georgia, May 7–9, 2014: p. 434–448.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 89 p.

Enbridge Energy, L.P., 2012, Kalamazoo River hydrodynamic and sediment transport model—Enbridge Line 6B MP 608, Marshall, MI: 70 p., attachments.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, accessed June 13, 2005, at http://pubs.er.usgs.gov/publication/twri05C1.

Hamrick, J.M.,1992, A three-dimensional environmental Fluid Dynamics Computer code—Theoretical and computational aspects: Virginia Institute of Marine Science, Gloucester Point, Va., Applied Marine Science and Ocean Engineering Special Report No. 317, p. 1–64.

Hamrick, J.M., 2007a, The Environmental Fluid Dynamics Code user manual: Fairfax, Va., Tetra Tech, Inc.,, version 1.01, prepared for U.S. Environmental Protection Agency.

Hamrick, J.M., 2007b, The Environmental Fluid Dynamics Code, theory and computation, Volume 1—Hydrodynamics and mass transport: Fairfax, Va., Tetra Tech, Inc.

Hamrick, J.M., 2007c, The Environmental Fluid Dynamics Code, theory and computation, Volume 2—Sediment and contaminant transport and fate: Fairfax, Va., Tetra Tech, Inc.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3 , 510 p.

Hoard, C.J., Fowler, K.K., Kim, M.H., Menke, C.D., Morlock, S.E., Peppler, M.C., Rachol, C.M., and Whitehead, C.M., 2010, Flood-inundation maps for a 15-mile reach of the Kalamazoo River from Marshall to Battle Creek, Michigan: U.S. Geological Survey Scientific Investigations Map 3135: 6-p. pamphlet, 6 sheets, scale 1:100,000.

Jones, C., and Lick, W., 2001, SEDZLJ, A sediment transport model—Final Report: Santa Barbara, Calif., University of California, Department of Mechanical and Environmental Engineering, May 29, 2001.

Liu, X., Landry, B.J., and García, M.H., 2008, Two-dimensional scour simulations based on coupled model of shallow water equations and sediment transport on unstructured meshes: Coastal Engineering, v. 55, no. 10, p. 800–810.

Linhart, S.M., Nania, J.F., Sanders, L., and Archfield, S.A., 2012, Computing mean daily streamflow at ungaged locations in Iowa by using the Flow Anywhere and Flow Duration Curve Transfer statistical methods: U.S. Geological Survey Scientific Investigations Report 2012–5232, 50 p.

Mueller, D.S., and Wagner, C.R., 2009, Measuring discharge with acoustic Doppler current profilers from a moving boat: U.S. Geological Survey Techniques and Methods, book 3, chap. A22, 72 p., accessed March 5, 2015, at http://pubs.water.usgs.gov/tm3a22.

Nolan, K.M., Gray, J.R., and Glysson, G.D., 2005, Introduction to suspended-sediment sampling: U.S. Geological Survey Scientific Investigations Report 2005–5077, accessed March 2, 2015, at http://pubs.er.usgs.gov/pubs/sir/sir20055077.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C3, 66 p., accessed March 2, 2015, at http://pubs.usgs.gov/twri/twri3-c3/.

Parsons, D.R., Jackson, P.R., Czuba, J.A., Engel, F.L., Rhoads, B.L., Oberg, K.A., Best, J.L., Mueller, D.S., Johnson, K.K., and Riley, J.D., 2013, Velocity Mapping Toolbox (VMT)—A processing and visualization suite for moving-vessel ADCP measurements: Earth Surface Processes and Landforms, v. 38, p. 1244–1260.

R Core Team, 2014, R—A language and environment for statistical computing: Vienna, Austria, R Foundation for Statistical Computing, accessed November 2, 2015, at http://www.R-project.org/.

Rydlund, P.H., Jr., and Densmore, B.K., 2012, Methods of practice and guidelines for using survey-grade Global Navigation Satellite Systems (GNSS) to establish vertical datum in the United States Geological Survey: U.S. Geological Survey Techniques and Methods, book 11, chap. D1, 102 p. with appendixes.

Shreve, E.A., and Downs, A.C., 2005, Quality-assurance plan for the analysis of fluvial sediment by the U.S. Geological Survey Kentucky Water Science Center Sediment Laboratory: U.S. Geological Survey Open-File Report 2005–1230, 28 p.

Sinha, S., Liu, X., and García, M.H., 2012, Three-dimensional hydrodynamic modeling of the Chicago River, Illinois: Environmental Fluid Mechanics, v. 12, p. 471–494.

Sinha, S., Liu, X., and García, M.H., 2013, A three-dimensional water quality model of Chicago Area Waterway System (CAWS): Environmental Modeling and Assessment, v. 18, p. 567–592.

Turnipseed, D.P., and Sauer, V.B., 2010, Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods, book 3, chap. A8, 87 p.

U.S. Army Corps of Engineers–Hydrologic Engineering Center, 2010, HEC–RAS River Analysis System, user's manual, ver. 4.1 [variously paged].

Zhu, Z., 2011, Simulation of suspended sediment and contaminant transport in shallow water using two-dimensional depth-averaged model with unstructured meshes: University of Illinois at Urbana-Champaign, Ill., Master's Thesis.

Reneau and others—**Hydrodynamic-Assessment Data Associated with the July 2010 Line 6B Spill into the Kalamazoo River, Michigan, 2012–14**—Open-File Report 2015–1205

ISSN 2331-1258 (online)
http://dx.doi.org/10.3133/ofr20151205