

Prepared in cooperation with the Great Lakes Restoration Initiative

Hydraulic and Water-Quality Data Collection for the Investigation of Great Lakes Tributaries for Asian Carp Spawning and Egg-Transport Suitability



Scientific Investigations Report 2013–5106

Cover images:

Upper left: U.S. Geological Survey (USGS) personnel collecting data on the Sandusky River, September 2012. (Photograph by David Straub, USGS)

Upper right: USGS personnel collecting data on the Milwaukee River, July 2010. (Photograph by Leah Kammel, USGS)

Lower left: Boat set-up with acoustic Doppler current profiler, water-quality probe, and global positioning system for data collection on the Milwaukee River, July 2010. (Photograph by Rob Waschbusch, USGS)

Lower right: Grafton Dam on the Milwaukee River, August 2010. (Photograph by Rob Waschbusch, USGS)

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By Elizabeth A. Murphy and P. Ryan Jackson

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

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Conversion Factors, Datums, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Flow rate	
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Flow rate	
centimeter per second (cm/s)	0.032	foot per second (ft/s)
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m ³ /s)	35.31	cubic foot per second (ft ³ /s)
	Hydraulic gradient	
meter per meter (m/m)	1	foot per foot (ft/ft)

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

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

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.

Specific conductance is given in millisiemens per centimeter (mS/cm).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

ADCP	acoustic Doppler current profiler
CAWS	Chicago Area Waterway System
dGPS	differentially corrected global positioning system
eDNA	environmental DNA
GIS	geographic information system
GLMRIS	Great Lakes and Mississippi River Interbasin Study
NTU	nephelometric turbidity units
u^*	shear velocity
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Hydraulic and Water-Quality Data Collection for the Investigation of Great Lakes Tributaries for Asian Carp Spawning and Egg-Transport Suitability

By Elizabeth A. Murphy and P. Ryan Jackson

Abstract

If the invasive Asian carps (bighead carp *Hypophthalmichthys nobilis* and silver carp *Hypophthalmichthys molitrix*) migrate to the Great Lakes, in spite of the efforts to stop their advancement, these species will require the fast-flowing water of the Great Lakes tributaries for spawning and recruitment in order to establish a growing population. Two Lake Michigan tributaries (the Milwaukee and St. Joseph Rivers) and two Lake Erie tributaries (the Maumee and Sandusky Rivers) were investigated to determine if these tributaries possess the hydraulic and water-quality characteristics to allow successful spawning of Asian carps. To examine this issue, standard U.S. Geological Survey sampling protocols and instrumentation for discharge and water-quality measurements were used, together with differential global positioning system data for georeferencing. Non-standard data-processing techniques, combined with detailed laboratory analysis of Asian carp egg characteristics, allowed an assessment of the transport capabilities of each of these four tributaries. This assessment is based solely on analysis of observed data and did not utilize the collected data for detailed transport modeling.

All four tributaries exhibited potential settling zones for Asian carp eggs both within the estuaries and river mouths and within the lower 100 kilometers (km) of the river. Dams played a leading role in defining these settling zones, with the exception of dams on the Sandusky River. The impoundments created by many of the larger dams on these rivers acted to sufficiently decelerate the flows and allowed the shear velocity to drop below the settling velocity for Asian carp eggs, which would allow the eggs to fall out of suspension and settle on the bottom where it is thought the eggs would perish. While three rivers exhibited these settling zones upstream of the larger dams, not all settling zones are likely to have such effects on egg transport. The Milwaukee River exhibited only a short settling zone upstream of the Grafton Dam, whereas the St. Joseph and Maumee Rivers both had extensive settling zones (>5 km) behind major dams. These longer settling zones are likely to capture more eggs than shorter settling reaches.

All four rivers exhibited settling zones at their river mouths, with the Lake Erie tributaries having much larger settling zones extending more than 10 km up the tributaries.

While hydraulic data from all four rivers indicated settling of eggs is possible in some locations, all four rivers also exhibited sufficient temperatures, water-quality characteristics, turbulence, and transport times outside of settling zones for successful suspension and development of Asian carp eggs to the hatching stage before the threat of settlement. These observed data indicate that these four Great Lakes tributaries have sufficient hydraulic and water-quality characteristics to support successful spawning and recruitment of Asian carps. The data indicate that with the right temperature and flow conditions, river reaches as short as 25 km may allow Asian carp eggs sufficient time to develop to hatching. Additionally, examining the relation between critical shear velocity and mean velocity, egg settling appears to take place at mean velocities in the range of 15–25 centimeters per second, a much lower value than is generally cited in the literature. A first-order estimate of the minimum transport velocity for Asian carp eggs in a river can be obtained by using mean flow depth and river substrate data, and curves were constructed to show this relation. These findings would expand the number of possible tributaries suitable for Asian carp spawning and contribute to the understanding of how hydraulic and water-quality information can be used to screen additional rivers in the future.

Introduction

Two species of invasive Asian carps (bighead carp *Hypophthalmichthys nobilis* and silver carp *Hypophthalmichthys molitrix*) are threatening to migrate into the Great Lakes from the Mississippi River Basin. If Asian carps become established in the Great Lakes, several tributary rivers may provide suitable spawning habitats. Although the carps primarily live in slow-moving water, they are thought to require streams with sufficient length, velocity, and turbulence to spawn

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(Kolar and others, 2007). Following spawning, the eggs drift in the current while developing. The eggs are slightly heavier than water, but remain in the drift because of the turbulence of flowing water. If the eggs sink to the bottom and remain there, they generally are not thought to survive (Soin and Sukhanova, 1972; Yi and others, 1988; Pflieger, 1997). Thus, a river with adequate current and reach length to keep the eggs adrift until hatching is considered a requirement for reproduction of Asian carps and survival of their eggs. One hundred kilometers (km) often is given as a rough estimate of the minimum river length required (Krykhtin and Gorbach 1981; Yi and others, 1988), but the actual minimum length of river would vary among rivers, depending upon variables such as water temperature (which controls the developmental rate of the eggs), current velocity, and the longitudinal dispersal of the eggs in the drift. Also, a minimum current velocity likely must be maintained throughout the drift to keep the eggs from settling to the river bottom. The values of minimum velocity in the literature are based on observations of spawning rivers and do not necessarily reflect the minimum velocities required to keep eggs in suspension and transport them. The range of velocities of rivers where silver carp successfully spawn was summarized in Kolar and others (2007) to be from 0.3 to 3.0 meters per second (m/s). However, Yi and others (2010) and Tang and others (1989) suggest the lower limit to velocity in spawning rivers is 0.25 m/s.

There have been previous efforts to assess the suitability of Great Lakes tributaries for Asian carp spawning and recruitment. Kolar and others (2007) took a geographic information system (GIS) analysis approach by characterizing which Great Lakes tributaries had undammed lengths greater than 100 kilometers (km). Kocovsky and others (2012) examined temperatures in Lake Erie and its tributaries and analyzed hydraulic conditions based on data limited to available U.S. Geological Survey (USGS) streamgages. Both studies concluded there was high likelihood of the tributaries being used for spawning by Asian carps. This study uses a more intensive hydraulic approach with data collected along the selected tributaries to address the issues of spawning and egg transport.

This report describes the hydraulic and water-quality data-collection effort by the USGS, in cooperation with the Great Lakes Restoration Initiative as administered by the U.S. Environmental Protection Agency, on four Great Lakes tributaries and uses new information about egg-transport characteristics to provide insight into the spawning and recruitment suitability of these tributaries. This study utilizes recent USGS research on Asian carp development, which has quantified the relation between development rate and water temperature

(Chapman and George, 2011) and the settling rates of bighead and silver carp eggs (Duane Chapman, U.S. Geological Survey, unpub. data, 2011). The information in this report can be used to plan sampling efforts and data analyses in other rivers possibly impacted by Asian carps so that control strategies can be applied.

Objective and Scope

The objective of this study is to characterize Great Lakes tributaries in terms of providing suitable spawning conditions for Asian carps and sufficient length and hydraulic conditions for eggs to be kept in suspension until hatching. The adequacy of rivers for survival of Asian carp in early-life stages is thought to depend upon a number of river conditions including reach length, channel depth, velocity, shear velocity, channel slope, temperature and turbidity distribution, longitudinal dispersion coefficients, and turbulence (Kolar and others, 2007). Unfortunately, a suitable spawning river cannot simply be defined in terms of river length or any single characteristic. Rather, what determines if a river is suitable for spawning is a complex relation between the hydraulic and water-quality characteristics of a river and the egg development stages of a particular species.

This study integrates physical observations and hydraulic characteristics from potential spawning rivers with Asian carp egg characteristics to evaluate whether successful spawning and recruitment is likely in the subject rivers. The biological components of this study, which provide information about Asian carp egg characteristics used in the hydraulic data analysis, are described elsewhere (Chapman and George, 2011; Amy George and Duane Chapman, U.S. Geological Survey, unpub. data, 2011, 2012; and Duane Chapman, U.S. Geological Survey, unpub. data, 2011). Another component of this study, development of a three-dimensional fluvial egg transport model (FluEgg) for rapid assessment of potential spawning rivers, also is underway in collaboration with the University of Illinois at Urbana-Champaign. This report focuses on the final component of this study, the methodology for characterization of the spawning suitability of rivers based on observed hydraulic and water-quality distributions. Specifically, this report discusses the data collected on the Milwaukee River in Wisconsin, the St. Joseph River in Michigan and Indiana, and the Maumee and Sandusky Rivers in Ohio (fig. 1), and the processing and analysis of those data for potential egg-settling zones and estimates of egg-transport time.

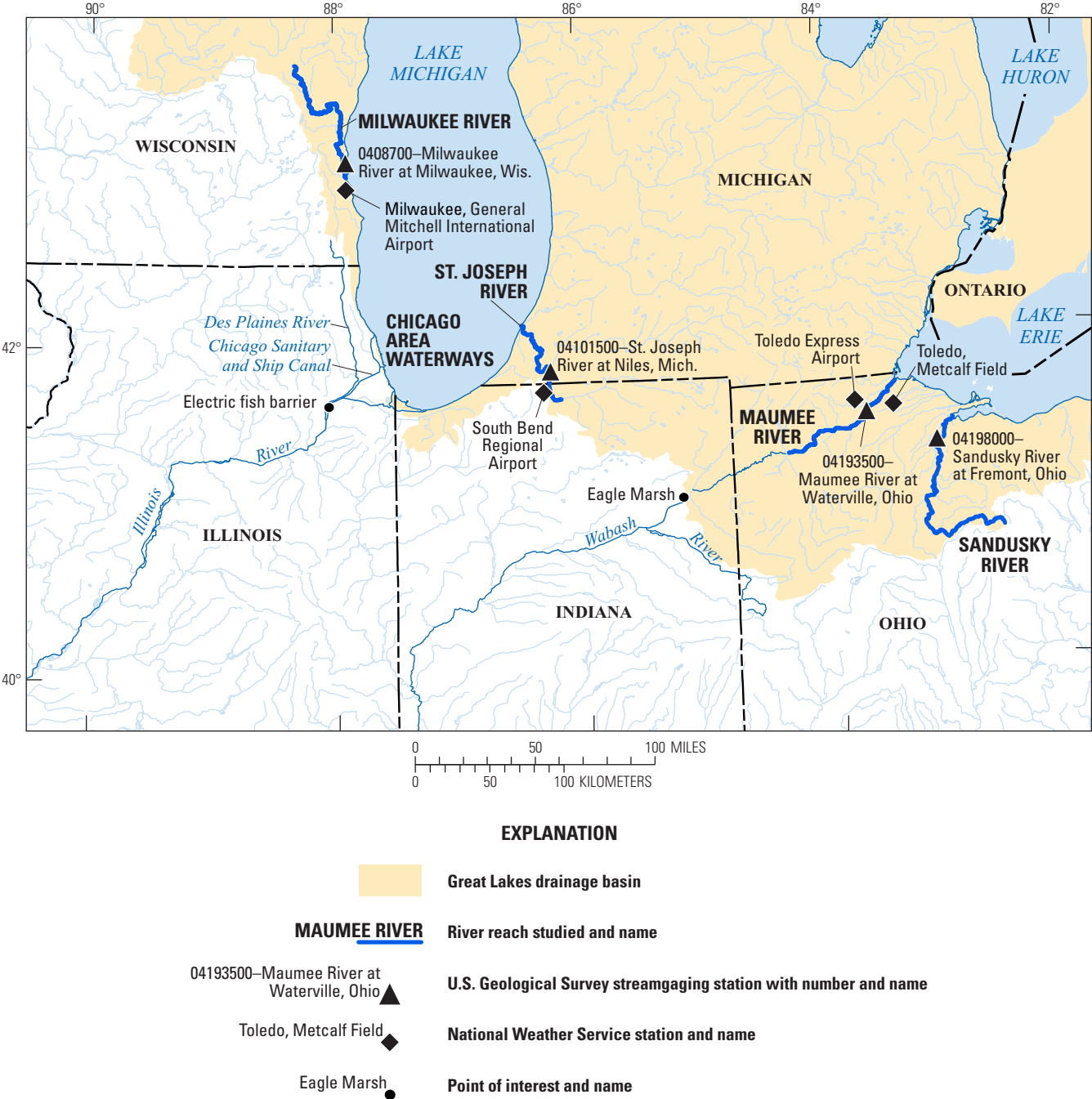


Figure 1. Location of field data collection and other areas of interest.

Site Selection

To date, the greatest resource for information about potential spawning rivers has been Kolar and others (2007), which contains a map of 22 rivers that may meet the 100 km free-flowing criteria for spawning (fig. 2). However, this map was based solely on a GIS analysis of river length, and although it incorporated available dam-inventory information, that information is currently (2013) out of date due to dam removals since that analysis. Dams have the potential to block fish from moving upstream and, therefore, shorten the accessible length of river for the carps. In addition, dams generally decelerate the flow, which can settle eggs out of suspension. The majority of the dams on the present study reaches are either low enough for Asian carps to pass over or have fish passages installed (table 1).

The Great Lakes and Mississippi River Interbasin Study (GLMRIS) has identified numerous potential interbasin pathways for aquatic- nuisance species in the Chicago Area Waterway System (CAWS) (U.S. Army Corps of Engineers, 2012a). An electric fish barrier was erected on the CAWS upstream of the confluence with the Des Plaines River to prevent invasive species movement between the two basins (fig. 1). The selection of the tributaries for data collection in the first year of the study (2010) was based on proximity to the CAWS, which is perceived to be the greatest threat for interbasin transfer between the Mississippi and Great Lakes River Basins (fig. 1). After looking at the Lake Michigan tributaries close to the entry of the CAWS, the Milwaukee River was chosen because the proposed removal of Grafton Dam or the addition of a fish passage to the dam would give it sufficient reach length (Ozaukee County, 2012), and the St. Joseph River was chosen because of its sufficient fish-passable length.

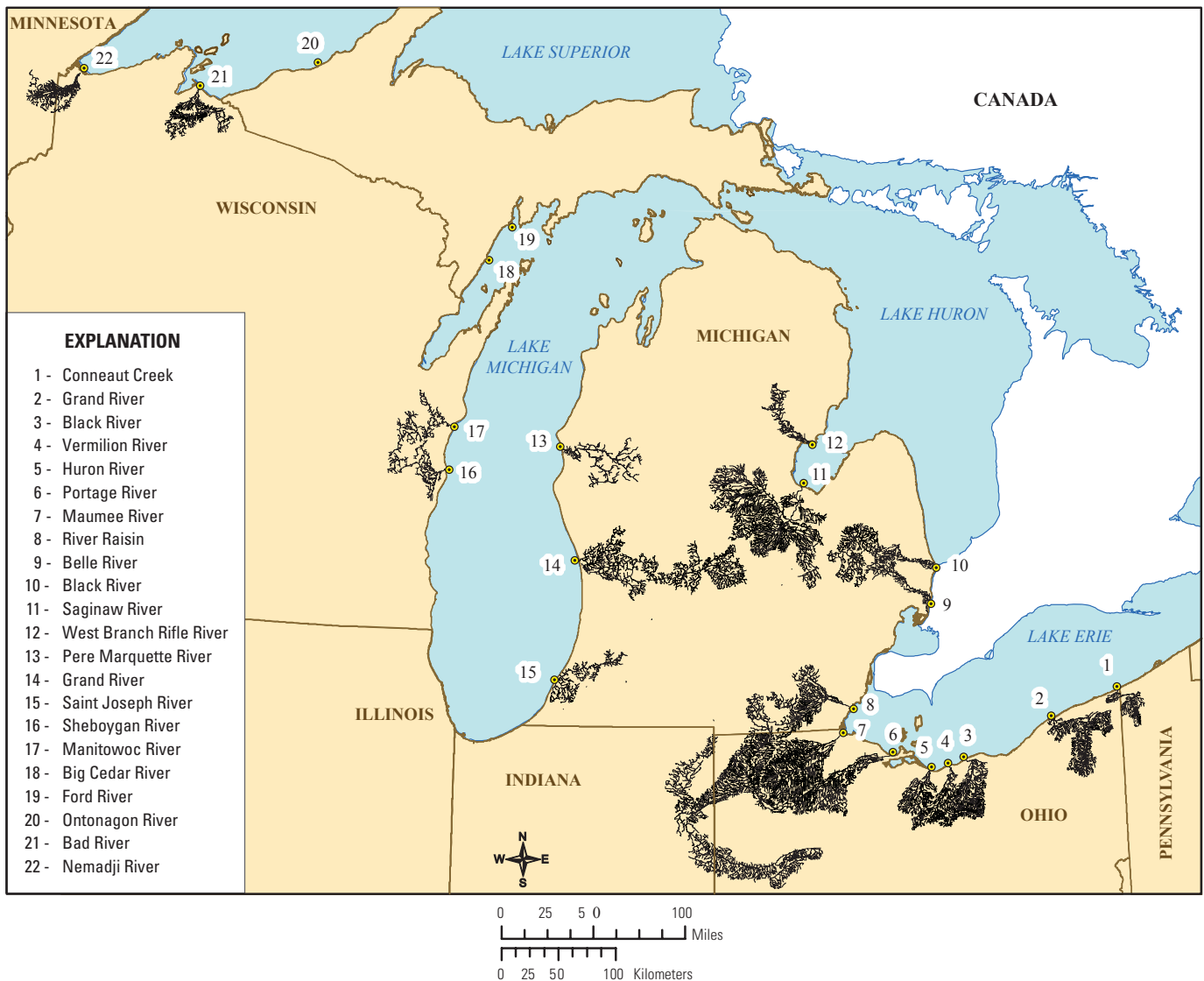


Figure 2. Lakes Erie, Huron, St. Clair, Michigan, and Superior indicating rivers lacking dams and having a minimum length of 100 kilometers, which may be suitable for spawning by bighead and silver carp. (From Kolar and others, 2007.)

Table 1. Dams on the study reaches.

[km, kilometer; m, meter; Wis., Wisconsin; Ind., Indiana; Mich., Michigan; data provided by the Wisconsin Department of Natural Resources (DNR), the Michigan DNR, and the Ohio DNR]

Dam name	River	City and State	Distance (km)	Height (m)	Hydraulic height (m)	Fish passable
West Bend	Milwaukee	West Bend, Wis.	107.9	4	2.1	Y
Grafton (Bridge Street Dam)	Milwaukee	Grafton, Wis.	48.1	6.1	3.7	N
Thiensville	Milwaukee	Thiensville, Wis.	31.9	4	1.8	Y
Kletzsch Park	Milwaukee	Glendale, Wis.	16.6	2.4	1.2	Y
Estabrook Park	Milwaukee	Shorewood, Wis.	11.1	4.6	2.4	Y
Ball Band Dam	St. Joseph	Mishawaka, Ind.	97.5	3	2	Y
South Bend Dam	St. Joseph	South Bend, Ind.	90.4	3.7	0	Y
French Paper Company Dam	St. Joseph	Niles, Mich.	69.6	6.7	6.7	Y
Buchanan	St. Joseph	Berrien Springs, Mich.	54.7	4.3	4.1	Y
Berrien Springs Dam	St. Joseph	Berrien Springs, Mich.	38.8	11	11	Y
Independence Dam	Maumee	Defiance, Ohio	97.5	3.6	3.6	Y
Grand Rapids Dam	Maumee	Grand Rapids, Ohio	52.4	2.4	2.4	Y
Providence Dam	Maumee	Providence, Ohio	52.4	2.6	2.6	Y
Ballville Dam	Sandusky	Fremont, Ohio	25.7	10.5	7.4	N

In addition to the CAWS potential connections, the GLMRIS Other Pathways Preliminary Risk Characterization found 31 potential connections between the 2 basins, of which 18 were deemed a large enough risk to warrant more in-depth study (U.S. Army Corps of Engineers, 2010). One potential connection identified between the Mississippi River Basin and the Great Lakes Basin is located in Eagle Marsh near Fort Wayne, Indiana. This connection was singled out by the U.S. Army Corps of Engineers (USACE) GLMRIS as the highest risk, outside of the CAWS, for aquatic-nuisance species transfer between the two basins. During high water, Eagle Marsh can connect the Wabash River, which contains Asian carps, with the Maumee River, which is a tributary to Lake Erie (fig. 1). A chain-link fence was erected in October 2010 to prevent adult Asian carps from entering the Maumee River from the Wabash River (U.S. Army Corps of Engineers, 2010), but that fence does not prevent eggs or small, juvenile fish from moving between the basins.

Water samples are collected in the CAWS upstream of the electric fish barrier to analyze for bighead and silver carp environmental DNA (eDNA), which is used as an indicator that Asian carps may have been present in that location. The eDNA results for the CAWS sampling in 2012 are 119 samples positive for silver carp out of 1,110 samples collected. There were no samples positive for bighead carp eDNA above the electric barrier (U.S. Army Corps of Engineers, 2012b). In June 2012, a bighead carp was caught by a commercial fisherman in

Lake Calumet, which is part of the CAWS system. No other bighead or silver carp have been caught above the electric barrier as part of the USACE surveillance efforts. Water samples for eDNA analysis also were collected by the Ohio Department of Natural Resources, Michigan Department of Natural Resources, U.S. Fish and Wildlife Service, and the USACE in the Maumee Bay and River and the Sandusky Bay and River during July–August 2012 (Asian Carp Regional Coordinating Committee, 2012). Three of 350 samples collected in the Maumee system and 20 of 150 samples collected in Sandusky Bay tested positive for silver carp eDNA. Subsequent netting and electrofishing efforts in the Maumee and Sandusky systems failed to locate any live silver or bighead carp. These eDNA results are being used to direct monitoring and planning efforts by the many agencies involved with Asian carp control.

The selection of the Maumee River for data collection in the second year of the study was based on the potential for interbasin transfer at Eagle Marsh in Indiana (fig. 1), which can connect the Wabash and Maumee Rivers during high-flow events. In addition to the interbasin transfer potential identified, five bighead carp have been individually collected between 1995 and 2003 in western Lake Erie (Asian Carp Regional Coordinating Committee, 2013). Unlike the St. Joseph and Milwaukee Rivers in which the movement of carps would progress upriver, the Maumee River may be susceptible to migration from both the Lake Erie side and the headwaters.

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The selection of the Sandusky River for data collection was due to the increasing concerns about Asian carp in Lake Erie and was made more urgent by detection of Asian carp eDNA in Sandusky Bay water samples (Asian Carp Regional Coordinating Committee, 2012). The Sandusky River has an impassible dam (Ballville Dam, table 1), which significantly shortens the river reach that would be available to carps entering the system from Lake Erie. However, removal of that dam has been planned, which would increase the length of the river accessible to migratory fish, and, therefore, increase the likelihood of suitability for Asian carp spawning and recruitment.

Methodology

In addition to publishing the data collected as part of this study, this report shares the methodology developed to collect the required field data for assessment. The ideal field data-collection methods are described in the “Target River Conditions and Sampling Locations” and “Measurement Procedures” sections, which summarize the planned approach and can be used by others for future studies. Field crews were briefed on these methods during conference calls before field-data collection and provided written instructions for their reference. Field crews were given flexibility to use their judgment and experience to adjust aspects of the data collection such as cross section placement and spacing to collect the most representative data in a safe manner. Departures from the ideal methods that occurred during the field data collection on the tributaries are described in the “Data Collection” section.

Target River Conditions and Sampling Locations

Field procedures for hydraulic and water-quality data collections were developed for this study based on the spawning behavior of Asian carps, field experience from previous studies, and potential data needs for assessments. This section describes the ideal field data-collection scenario and can be used as a guide for others planning similar data-collection efforts.

Hydraulic and water-quality measurements at cross sections and along the longitudinal profile should be collected during conditions conducive to Asian carp spawning. Measurements should be collected following an increase in water level and (or) flow as that triggers spawning behavior in Asian carps. If possible, measurements should begin on the rising limb of the hydrograph for a flow event, starting at the most upstream sampling location and moving downstream with the flood wave. Water temperatures should be in the range of 18 to 30 degrees Celsius (°C) (64 to 86°F) to match the temperature range during which Asian carps may spawn (Kolar and others, 2007), although spawning is reported to have occurred in the Lower Volga River in Russia at temperatures in the 14 to 15°C range (Opuszynski and Shireman, 1994). While this simple temperature threshold is sufficient for this study (since the

focus is on variations in water quality along the river), a true measure of the onset of spawning is not based solely on water temperature in the tributary, but rather on the maturation rates of the fish, which depend on the thermal load to which the fish was exposed in both the lake and tributary habitats (Kocovsky and others, 2012). Therefore, it is important to note that while water temperatures in early June may be suitable for egg development, fish may not spawn at these temperatures if they have not reached the total heat required for maturation during that year.

The spacing of cross sections for collecting hydraulic data is dependent upon the variability of the flows and the bathymetry of the river. The maximum spacing should be such that the general hydraulics are relatively constant within each reach defined by the cross section. In this study, planned cross sections were spaced approximately 1.6 km (1 river mile) apart from the mouth of the river to the first impassible structure or to the headwater of the stream using GIS and aerial images. The locations of the cross sections should be selected to avoid bridges or other structures as these structures generally produce flow conditions that are uncharacteristic of the reach. Sharp bends where cross-channel velocities may be large also should be avoided. The study crews were instructed to use the planned cross sections as a guide for locating cross sections in the field, but were to use their judgment as hydrographers to identify the most representative section for each reach. In addition to the regular cross-section sampling locations, field teams should collect a minimum of two transects in low-velocity pools above dams or other low-velocity cross sections for evaluation of the potential for egg settlement. Finally, hydraulic and water-quality data must be continuously collected as the boat moves down the river between cross sections. These data should include, at a minimum, the velocity, depth, and temperature of the flow measured along the thalweg.

Measurement Procedures

The measurement procedures are designed to characterize the velocity and water quality of the river system for spawning and egg transport. As such, even though the data collection should be completed during a period of high flows, pools and other areas of low velocity are of interest for egg-settlement potential. Conversely, areas of elevated turbulence and turbidity are of interest for potential spawning locations.

Hydraulic data should be collected with acoustic Doppler current profilers (ADCP) and water-quality data with multiparameter water-quality sondes. A differentially corrected global positioning system (dGPS) should be used to georeference the data collected with a horizontal resolution generally less than 1 meter (m). Photographs and field notes should be taken to document sampling conditions and general channel characteristics. Repeat transects should be collected at each cross section to provide a measurement discharge and assess the temporal variability of the discharge at each section

(Mueller and Wagner, 2009). Collecting eight repeat transects allows for estimation of the longitudinal dispersion coefficient (Carr and Rehmann, 2007), a parameter not computed in this study, but one that may be of use in future assessment models. A longitudinal profile of velocity and bathymetry should be collected along the thalweg or region of greatest flow as the boat moves between cross sections to provide a continuous trace of data through the study reach. In addition to collecting ADCP data along eight transects, a stationary measurement should be performed at each cross section for a minimum of 5 minutes so that a time-averaged velocity profile can be obtained. This velocity profile allows for calculation of the shear velocity, which is a critical value in determining whether eggs will settle out of suspension. In all cases, the ADCP should be configured and operated in a manner that yields high-quality data, minimizes lost and bad data, and maintains bottom track and GPS lock when possible. In general, following USGS discharge-measurement procedures for instrument configuration and operation (Mueller and Wagner, 2009) will yield adequate results, though custom configurations may be required to achieve the best data. Care should be taken when choosing the proper instrument for the expected field conditions to ensure that the highest vertical resolution is achieved with the lowest noise possible.

The water-quality sonde should be used to collect temperature, specific conductance, dissolved oxygen, pH, and turbidity (when available). Although temperature is the most critical water-quality parameter, the specific conductance, dissolved oxygen, and pH provide information about the general water-quality distribution of the river and the conditions to which the eggs are exposed. Turbidity measures visibility in the water column and larger values indicate less visibility which may aid in successful recruitment by decreasing predation on the eggs. The water-quality sonde should be set to collect data continuously with a sampling period of no greater than 15 seconds. Sampling intervals larger than 15 seconds will result in poor distribution across the channel. Data should be collected during all ADCP transects at each cross section and continuously as the boat moves longitudinally downstream from cross section to cross section. The water-quality sonde is required to be calibrated prior to deployment following necessary protocol (U.S. Geological Survey, variously dated), and it is recommended that the sonde be checked periodically for drift and fouling during deployment to ensure the data are satisfactory. If one is not using a sonde with built-in or external GPS, the sonde clock must be synced with the clock on the computer operating the ADCP and dGPS to ensure that the water-quality data can be georeferenced with the positional data logged from the ADCP GPS unit. The time sync must occur prior to deployment.

Data Collection

Data collection for the four tributaries in this study utilized a range of small boats equipped with ADCPs and multiparameter water-quality sondes. The survey on the

Milwaukee River utilized a single crew using a combination of a small Jon boat, a tethered boat, and a remote-control boat. The surveys on the St. Joseph, Maumee, and Sandusky Rivers utilized two separate crews in small manned boats working in unison to allow for a more efficient survey. All four surveys utilized Teledyne RDI ADCPs (StreamPro and 1,200 kilohertz Rio Grande) and YSI multiparameter sondes. In addition, survey crews were equipped with sub-meter accuracy dGPS receivers (Trimble AG132 and Hemisphere Crescent A100), GPS-enabled digital cameras, laser rangefinders, and navigation software (Hypack® or Fugawi®).

The Milwaukee River data were collected over a period of 12 days during July–August 2010 (fig. 3). Air temperatures recorded at the General Mitchell International Airport in Milwaukee (National Oceanic and Atmospheric Administration, 2012) and the hydrograph for the Milwaukee River at the USGS streamgage at Milwaukee, Wisconsin (04087000), are shown in figure 3. The Milwaukee River Basin experienced two large storms in quick succession so sampling occurred during a double-peaked hydrograph (fig. 3). The largest daily averaged flow during the event was 121.5 cubic meters per second (m^3/s) (4,290 cubic feet per second (ft^3/s)), which is exceeded less than 1-percent of the time ($44.5 \text{ m}^3/\text{s}$) at that streamgage (U.S. Geological Survey, 2012a). The sampling did not proceed from upstream to downstream as planned (fig. 8) owing to safety concerns and access issues. The head-water reaches were deemed too dangerous for data collection to occur at the beginning of sampling because of swift, non-navigable water. The distance between cross sections averaged approximately 1.6 km (1 mile (mi)), with a maximum distance of 4.5 km (2.8 mi), due to issues with limited access in a shallow reach downstream of Grafton Dam.

The hydraulic characteristics of the lower St. Joseph River were surveyed over 6 days during November–December 2010 (fig. 4). The water-quality data for the St. Joseph River were collected in a separate field effort (for a similar magnitude event) during September 2011 because the water temperatures on the St. Joseph River were outside of the Asian carp spawning temperature range when the hydraulic data were collected. The September 2011 event occurred just a few days after the temperatures in the river fell below the 18°C spawning threshold. Air temperatures recorded at the South Bend Regional Airport in South Bend, Indiana (National Oceanic and Atmospheric Administration, 2012), and the hydrographs for the St. Joseph River at the USGS streamgage at Niles, Michigan (04101500), are shown in figure 4. The largest daily averaged flow during the November–December 2010 event was $83.5 \text{ m}^3/\text{s}$ ($2,950 \text{ ft}^3/\text{s}$), and the largest daily averaged flow during the September 2011 event was $84.1 \text{ m}^3/\text{s}$ ($2,970 \text{ ft}^3/\text{s}$), which is exceeded just less than 50 percent of the time at that streamgage (U.S. Geological Survey, 2012b). The distance between cross-section locations averaged 2.2 km (1.4 mi), with a maximum distance of 3.7 km (2.3 mi), to accomplish the data collection in a reasonable amount of time.

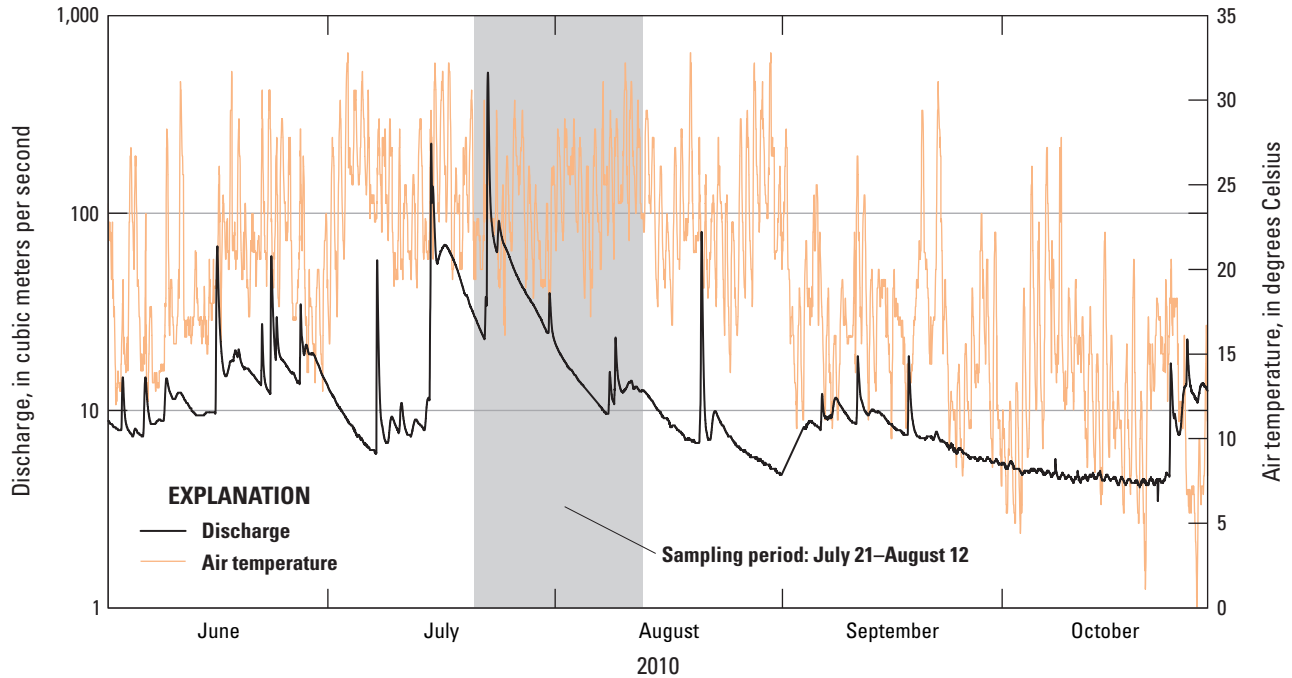


Figure 3. Air temperature measured at the General Mitchell International Airport in Milwaukee, Wisconsin, and the hydrograph from the Milwaukee River at Milwaukee, U.S. Geological Survey streamgage (04087000), showing the field sampling period of this study.

The Maumee River was sampled over a period of 5 days during August 2011 (fig. 5). Air temperatures recorded at the Toledo Express Airport in Toledo, Ohio (National Oceanic and Atmospheric Administration, 2012) and the hydrograph for the Maumee River at the USGS streamgage at Waterville, Ohio (04193500), are shown in figure 5. The largest daily averaged flow during the event was 78.2 m³/s (2,760 ft³/s), which is exceeded less than 30 percent of the time for the months of May–November at that streamgage (Straub, 2001). Figure 5 also includes the estimated maturation date for spawning based on the thermal load in Lake Erie from Kocovsky and others (2012). The distance between cross sections averaged 2.6 km (1.6 mi), if the two rapids reaches that were not sampled are excluded. The two rapids reaches, which are 10.7 km (6.7 mi) and 12.8 km (8 mi) long, were excluded from sampling for safety and access issues.

The Sandusky River was sampled over a period of 5 days during September 2012 (fig. 6). However, limited access to the river upstream of the Ballville Dam restricted data collection in this reach and, therefore, only data downstream of

the Ballville Dam (September 11 and 12, 2012) were used in this analysis. Currently (2013), Ballville Dam is impassible by migratory fish (though at the time of this publication (2013) it is being considered for removal). The sampled event occurred following a summer of drought conditions during a period of very low flow (base flows near 1 m³/s) and peaked at 33.3 m³/s on September 10, 2012, at the USGS streamgage at Fremont, Ohio (04198000) (fig. 6). The largest daily averaged flow during the event was 30.9 m³/s (1,090 ft³/s), which is exceeded approximately 21 percent of the time at that streamgage (U.S. Geological Survey, 2012c). Figure 6 also includes the estimated maturation date for Asian carp spawning based on the thermal load in Lake Erie from Kocovsky and others (2012). Water temperature at Fremont, Ohio, during the survey averaged about 21°C (and air temperatures varied between 17 and 27°C). The average distance between sampled cross sections was 1.7 km (1.1 mi), with a maximum distance of 2.25 km (1.4 mi), and data were collected continuously between cross sections in the lower 20 km of the river.

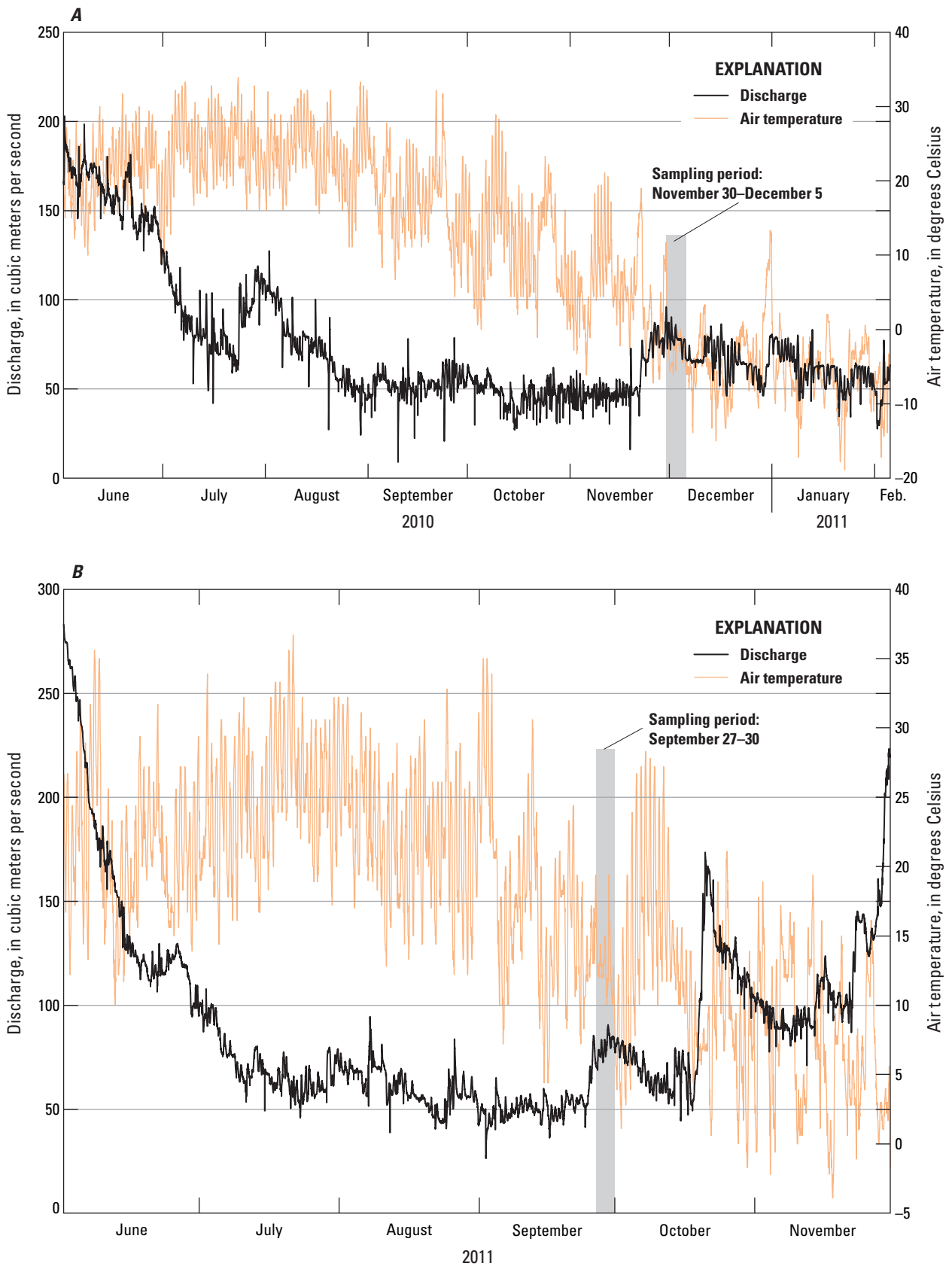


Figure 4. Air temperature measured at the South Bend Regional Airport in South Bend, Indiana, and the hydrographs from the St. Joseph River at Niles, U.S. Geological Survey streamgage (04101500), showing the two field sampling periods of this study. *A*, November 30–December 5, 2010. *B*, September 27–30, 2011.

10 Investigation of Great Lakes Tributaries, Asian Carp Spawning and Egg-Transport Suitability

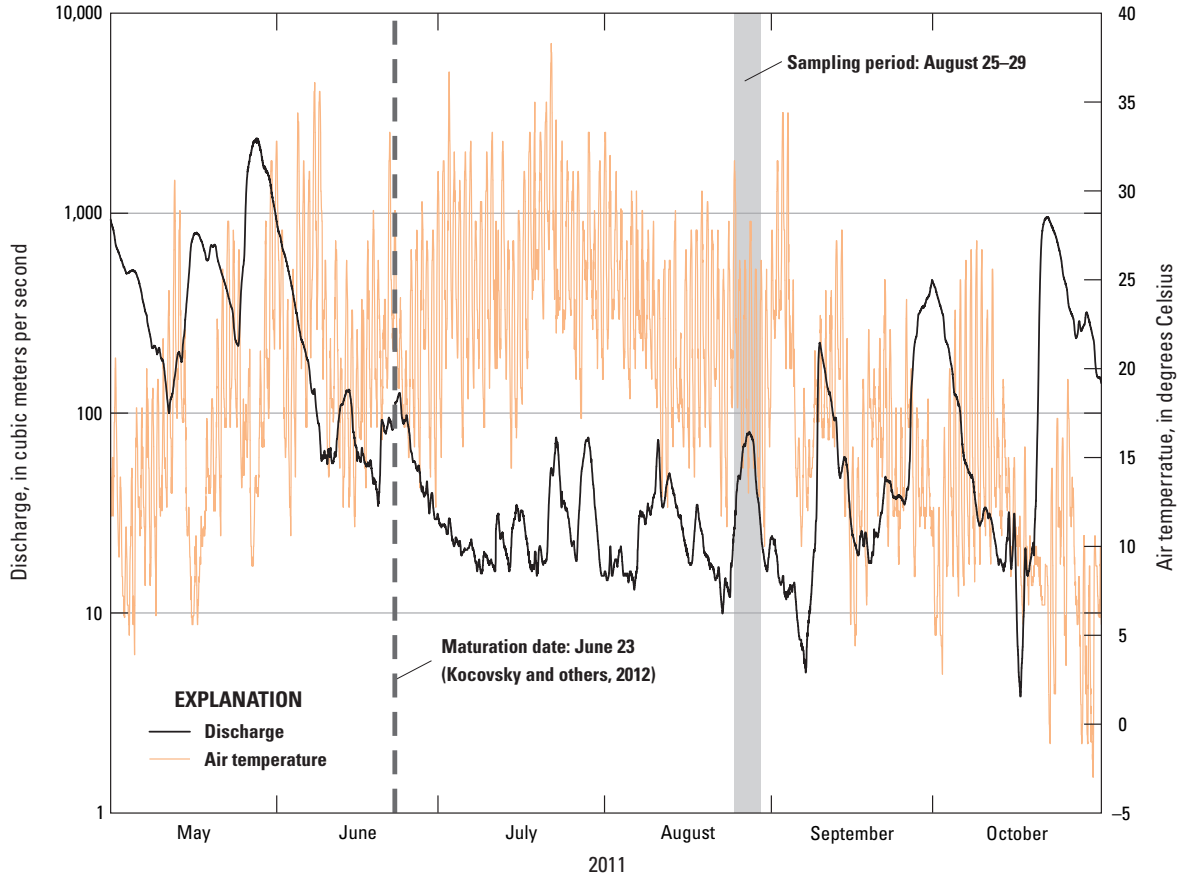


Figure 5. Air temperature measured at the Toledo Express Airport in Toledo, Ohio, and the hydrograph from the Maumee River at Waterville, U.S. Geological Survey streamgage (04193500), showing the field sampling period of this study.

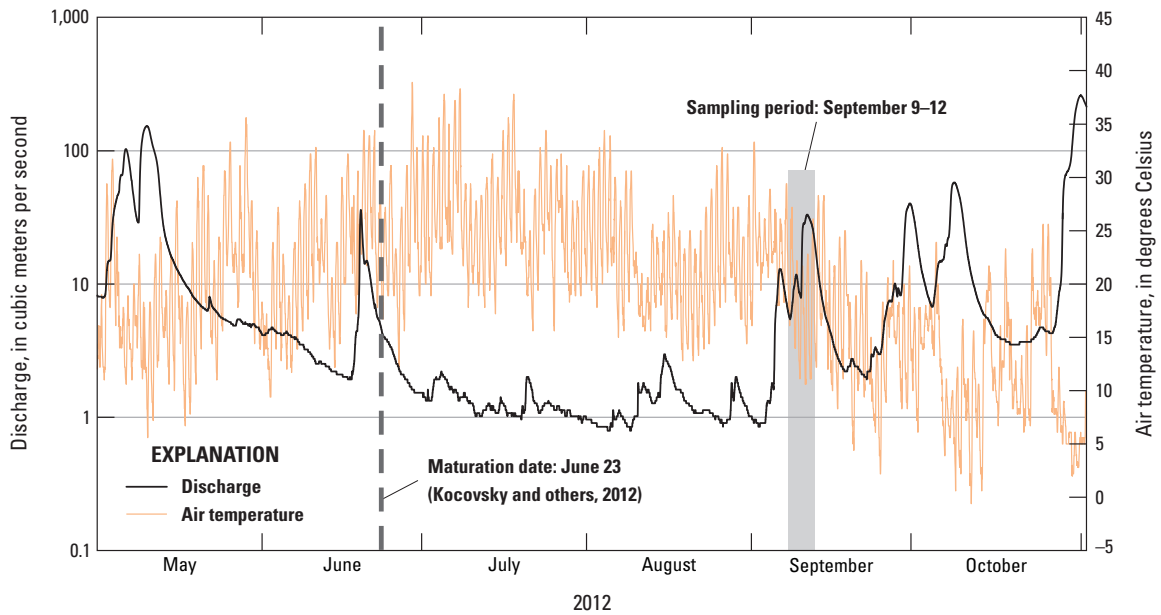


Figure 6. Air temperature measured at Toledo Metcalf Field in Toledo, Ohio, and the hydrograph from the Sandusky River at Fremont, Ohio, U.S. Geological Survey streamgage (04198000), showing the field sampling period of this study.

Data Processing

The ADCP data were processed using the Velocity Mapping Toolbox (Parsons and others, 2012). The ADCP data were processed to provide depth, discharge, depth-averaged velocity, vertical velocity, acoustic backscatter, and shear velocity, though not all of these parameters were used in this analysis.

The shear velocity (u^*) is a critical parameter to calculate when evaluating whether a particle (in this case, an Asian carp egg) will remain in the suspension or settle out of the water column. A particle will only remain in suspension when the turbulent vertical-velocity fluctuations in the flow overcome the settling velocity of the particle (Bagnold, 1966). The shear velocity of a flow is of the same magnitude as the maximum value of the turbulence intensity (Hinze, 1975), allowing one to define the initiation of suspension of a particle as when the shear velocity equals the settling velocity (van Rijn, 1984). Therefore, when the settling velocity of the particle exceeds the shear velocity, the particles (eggs) can no longer remain in suspension.

Shear velocity was calculated three different ways from the collected data. Several methods were chosen to (1) provide independent estimates of the shear velocity for comparison, (2) determine if one method is more suitable than another for these assessments, (3) determine what data are necessary for estimation of the shear velocity (different methods have different data requirements), and (4) provide continuity in data through reaches where one or more methods fail to produce reasonable estimates. In the first method, the stationary ADCP profiles were averaged and fit using a logarithmic profile to estimate the shear velocity at each cross section (Sime and others, 2007). The second method utilized moving-boat ADCP velocity profiles collected while moving between cross sections. These profiles were referenced to the bed, normalized by the water column depth, averaged over 120-second intervals to remove noise, and fit with a logarithmic velocity profile to estimate the shear velocity. Normalization of the profiles ensures that streamwise variations in depth are accounted for and observations of velocity from the same relative height above the bed are averaged together. The third method calculates an estimate of the shear velocity (u^*) from the Manning-Strickler power form of Keulegan's relation (1938)

$$U/u^* = 8.1(H/k_s)^{1/6} \text{ where } k_s \sim 2.5D_{50} \quad (1)$$

where

- U is mean velocity (meters per second),
- H is mean depth (meters), and
- k_s is the effective roughness height of the riverbed and is approximately equal to $2.5D_{50}$, where D_{50} is the median grain size (meters) of the riverbed sediment.

This approach assumes no bedforms or submerged vegetation are present on the bed and k_s is proportional to the median grain size of the bed substrate. For this study, substrate information was provided by assessments made by the

Wisconsin Department of Natural Resources, the U.S. Fish and Wildlife Service, consultants, and academics (St. Joseph River—Wesley and Duffy, 1999; Milwaukee River—Will Wawrzyn, Wisconsin Department of Natural Resources, written commun., 2012; Maumee River—Jim Boase, U.S. Fish and Wildlife Service, Habitat Assessment in the Maumee River, unpub. data, 2007; Sandusky River—Stantec Consulting Services, 2011; and Evans and others, 2002). Substrate data were used to estimate the median grain size for each reach within the survey area. Some adjustments to these values were required for reaches where equation 1 significantly underpredicted the shear velocity compared to the values determined from fitting (likely owing to unaccounted for bedforms, vegetation, and other roughness elements). Adjustments were made to the effective roughness height (k_s), guided by estimates of the roughness height determined in fitting velocity profiles collected with a stationary boat.

The water-quality data were downloaded from the water-quality sonde data loggers and georeferenced by interpolating the position of the instrument from the GPS navigation record (high resolution >1 hertz data) at the sampling times of each water-quality observation. The water-quality data then were reviewed as time series, outliers were marked and omitted from analysis, and the resulting dataset was used to create a GIS point shapefile for each river. Of the water-quality data collected, the most critical parameter is water temperature. Water temperature determines the development rate of the Asian carp eggs and the time elapsed between egg laying and hatching into larval fish. Specific conductance, dissolved oxygen, and pH are parameters that indicate general water quality, and higher turbidity reduces visibility in the water column and may aid in successful recruitment by decreasing predation on the eggs. While these synoptic surveys capture only a snapshot in time of the water-quality distributions and the observed distributions can have temporal effects included in the data, the distributions allow biologists to understand the overall range of water-quality conditions the fish and eggs may be subject to during a spawning event.

Settling Velocities and Hatch Times of Asian Carp Eggs

Settling velocities of fertilized eggs from silver and bighead carp were determined in laboratory experiments during 2010–11 at the USGS Columbia Environmental Research Center (Duane Chapman, U.S. Geological Survey, unpub. data, 2011). Four critical settling velocities were identified from the data based on elapsed time since fertilization. After the eggs are deposited in the water by the female, the egg membrane absorbs water and the density of the egg decreases in a process called water hardening. A fully water-hardened egg is almost neutrally buoyant, but the egg changes in density until approximately 18 hours after fertilization. As the density of the egg decreases, the settling velocity also decreases.

Table 2 presents the settling-velocity data of Chapman (Duane Chapman, U.S. Geological Survey, unpub. data, 2011) for bighead and silver carp eggs and the average settling velocity used in the present analysis. The settling velocity of the eggs within 2 hours of fertilization is approximately 2 centimeters per second (cm/s). From 2 to 3 hours post fertilization, the settling velocity of the eggs is approximately 0.85 cm/s. From 3 to 4 hours post fertilization, the settling velocity of the eggs is approximately 0.8 cm/s. From 18 to 20 hours, the settling velocity is approximately 0.75 cm/s. According to Chapman (Duane Chapman, U.S. Geological Survey, unpub. data, 2011), the egg diameter is relatively constant after 20 hours and therefore, there is likely little change in the settling velocity after 20 hours until the egg hatches. (As previously mentioned, if the shear velocity of the river falls below the settling velocity of the eggs, turbulence in the water can no longer hold the egg in suspension, and the eggs could settle to the riverbed where it is thought they would perish (Kolar and others, 2007)).

Table 2. Bighead and silver carp egg-settling velocities from Duane Chapman (U.S. Geological Survey, unpub. data, 2011), and approximate average settling velocities used in the 2013 analysis.

[cm/s, centimeter per second]

Developmental period (hours post fertilization)	Bighead egg-settling velocity (cm/s)	Silver egg-settling velocity (cm/s)	Average egg-settling velocity (cm/s)
0 to 2 hours	2.12	1.9	2
2 to 3 hours	.9	.79	.85
3 to 4 hours	.85	.77	.8
18 to 20 hours	.8	.69	.75

Hatching time varies widely with temperature (Chapman and George, 2011) (fig. 7). Higher temperatures drive faster development and earlier hatching. Figure 7 presents a compilation of hatching times available in the literature for silver and bighead carps. The silver carp egg-hatching time data have been fit to allow extrapolation over the spawning temperature range, and bighead carp egg-hatching times have been estimated using the silver carp empirical formula as a model along with the data of Chapman and George (2011). Silver carp eggs were observed to hatch in approximately 45 hours post fertilization at 19.6°C (Chapman and George, 2011) and in as short as 18.5 hours at approximately 28.5°C (Murty and others,

1986). Bighead carp hatching times have limited observations, but appear to follow a similar temperature dependence with slightly longer (approximately 3.7 hours greater at 22.3°C) hatching times (Chapman and George, 2011). The estimates of hatching times developed in figure 7 are based on limited data with poor temperature control in many of the studies. While the accuracy of the estimates should be sufficient for the purposes of this study, the estimates of hatching times developed herein should be used with caution.

Spawning and Egg-Transport Suitability Criteria

Several hydraulic and biologic factors must be assessed to determine if a river is capable of supporting successful Asian carp spawning and recruitment. The river must be accessible by mature Asian carps, the river must have sufficient water-quality and hydraulic characteristics to keep the egg alive and in suspension until hatching, and the river must have suitable nursery habitat for juvenile fish. While the nursery habitat assessment is beyond the scope of this study, the hydraulic and water-quality assessment is presented for each of the four study tributaries in the remainder of this section. Any tributary meeting the hydraulic qualifications for spawning would have to be assessed for nursery habitat to determine if successful recruitment is possible.

Of particular interest in the hydraulic assessment are the identification of three key pieces of information about each of the tributaries—likely spawning areas, potential settling zones, and advective traveltime. Spawning sites are critical and thought to be in areas of high turbulence (rock outcroppings, dam spillways, behind piers) (Kolar and others, 2007), probably because the additional turbulence aids in keeping the non-water-hardened eggs in suspension during that densest developmental stage. Datasets from field crews are unlikely to have thoroughly measured such flows since many of these turbulent areas present safety, access, and instrument-operation issues. Therefore, for the remainder of this analysis the assumption is that the carp will spawn in a location with sufficient turbulence to keep the eggs in suspension for the first 2 hours of development. Potential spawning locations can be identified in the datasets by looking at areas with the highest observed shear velocity. In contrast, potential egg-settling zones can be identified by determining where the estimates of shear velocity from each river fall below the settling velocities in table 2.

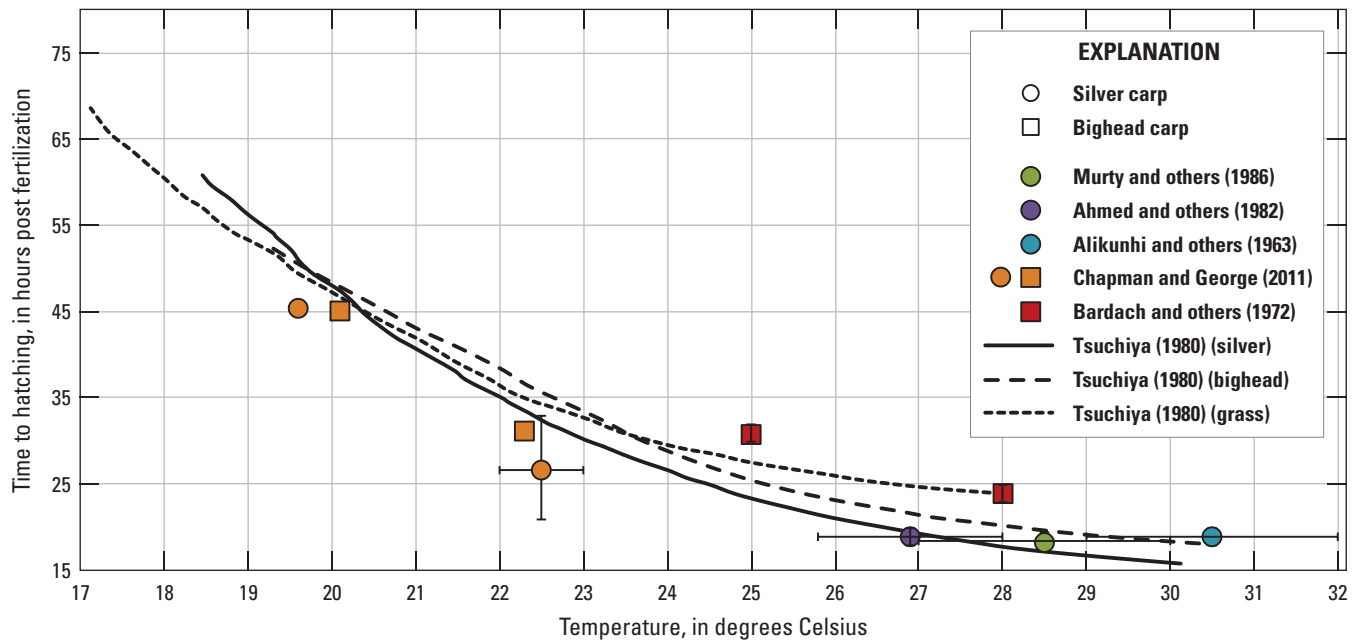


Figure 7. Observations of hatching times for silver and bighead carps from a range of studies and empirical estimates over a range of temperatures.

Although a river may have sufficient flow to keep eggs in suspension, the river also must have sufficient length to allow eggs to hatch before reaching the lake in order to be suitable for recruitment. Therefore, an estimate of traveltime is required for this assessment. Cumulative traveltime for the peak of an egg distribution can be estimated from the field data by computing the 120-second mean depth-averaged velocity from longitudinal ADCP data. Dividing the streamwise distance between observations by the mean velocity at each point and then summing the traveltime over the individual reaches yields the time required to travel from the top of the sampled reach to the mouth of the river. The traveltime of the peak concentration of eggs does not take into account how the plume of eggs would spread out due to dispersion. Therefore, the leading edge and trailing edge traveltimes are estimated using empirical equations and are included to represent the range of traveltimes for the plume. The leading edge and trailing edge (to 10 percent of peak concentration) traveltimes are estimated based on empirical relations developed by Jobson (1996). Traveltimes can be compared to hatching times documented in Chapman and George (2011) to determine if the eggs will hatch prior to reaching the river mouth or another settling zone where they likely will settle out and perish.

Results

The four study tributaries were analyzed for spawning suitability based on the criteria outlined in the previous section—likely spawning areas, potential settling zones, and

advective traveltime. This section presents the results from each of these case studies. In addition, this section presents a method for estimating the minimum velocity needed to keep water-hardened eggs in suspension based on the flow depth and substrate type.

Tributary Case Studies

Milwaukee River

The lower 100 km of the Milwaukee River generally is fast flowing and shallow, except for backwater areas behind the largest of the eight dams that occupied this reach at the time of the survey (two dams have since been removed) (fig. 8). Mean flow velocities observed upstream of Grafton Dam were approximately 45 cm/s, while those downstream of the dam were significantly higher, averaging approximately 70 cm/s, except within the estuary downstream of the former North Avenue Dam where the velocity abruptly decreased and pulsed in response to the lake seiche (fig. 9A). The highest velocities observed were downstream of dams, and the lowest velocities observed were in the impoundments upstream of the dams. The Grafton, Thiensville, and Estabrook Dams had the greatest impact on the flow both upstream and downstream of the dams. Vertical velocities measured with the ADCP, while noisy, were markedly smaller upstream of the Thiensville, Grafton, and Newburg Dams. The fluctuations in the vertical velocities are an indication of the amount of turbulence in the river.

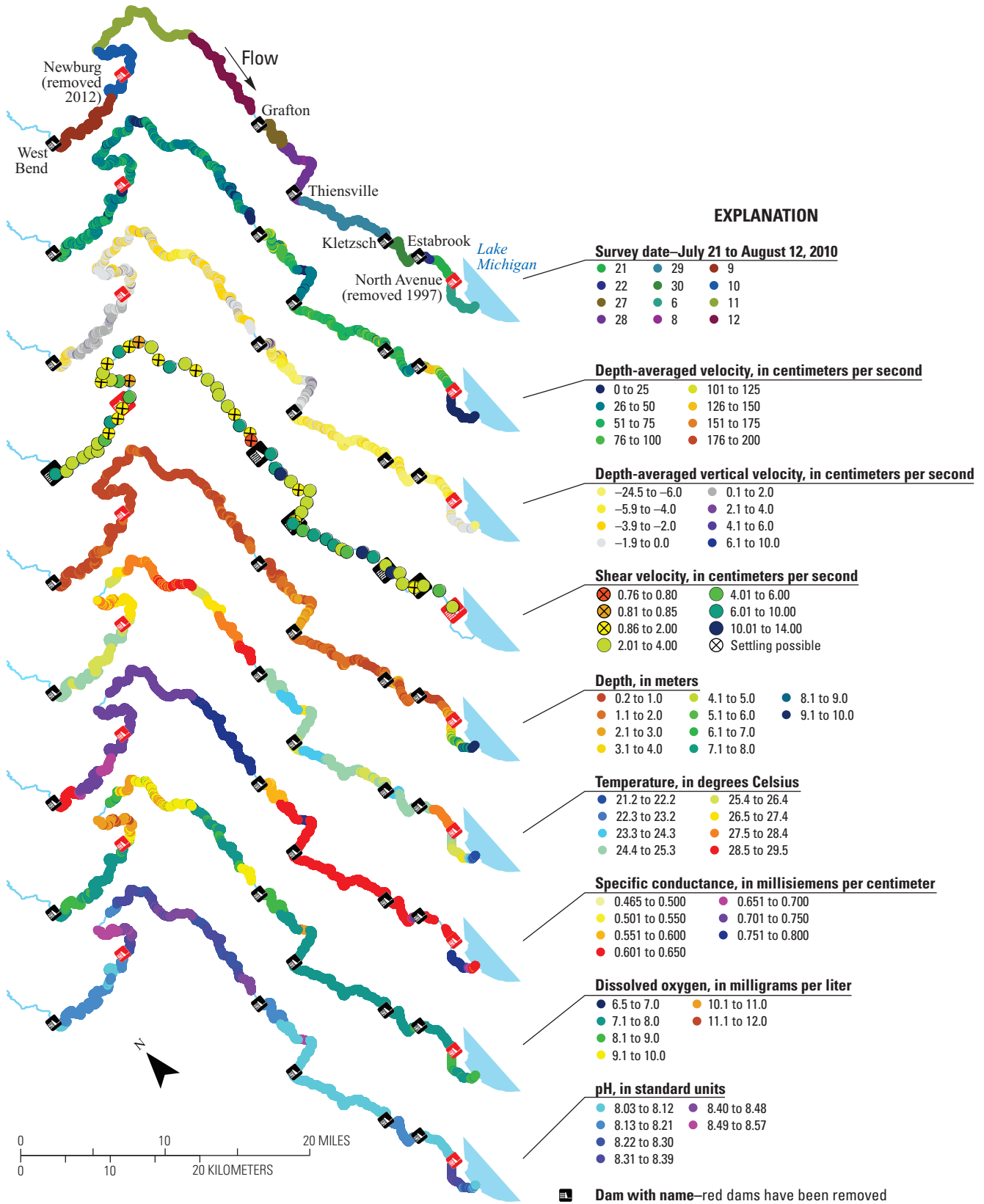


Figure 8. Hydraulic and water-quality data for the Milwaukee River, Wisconsin, July 21–August 12, 2010.

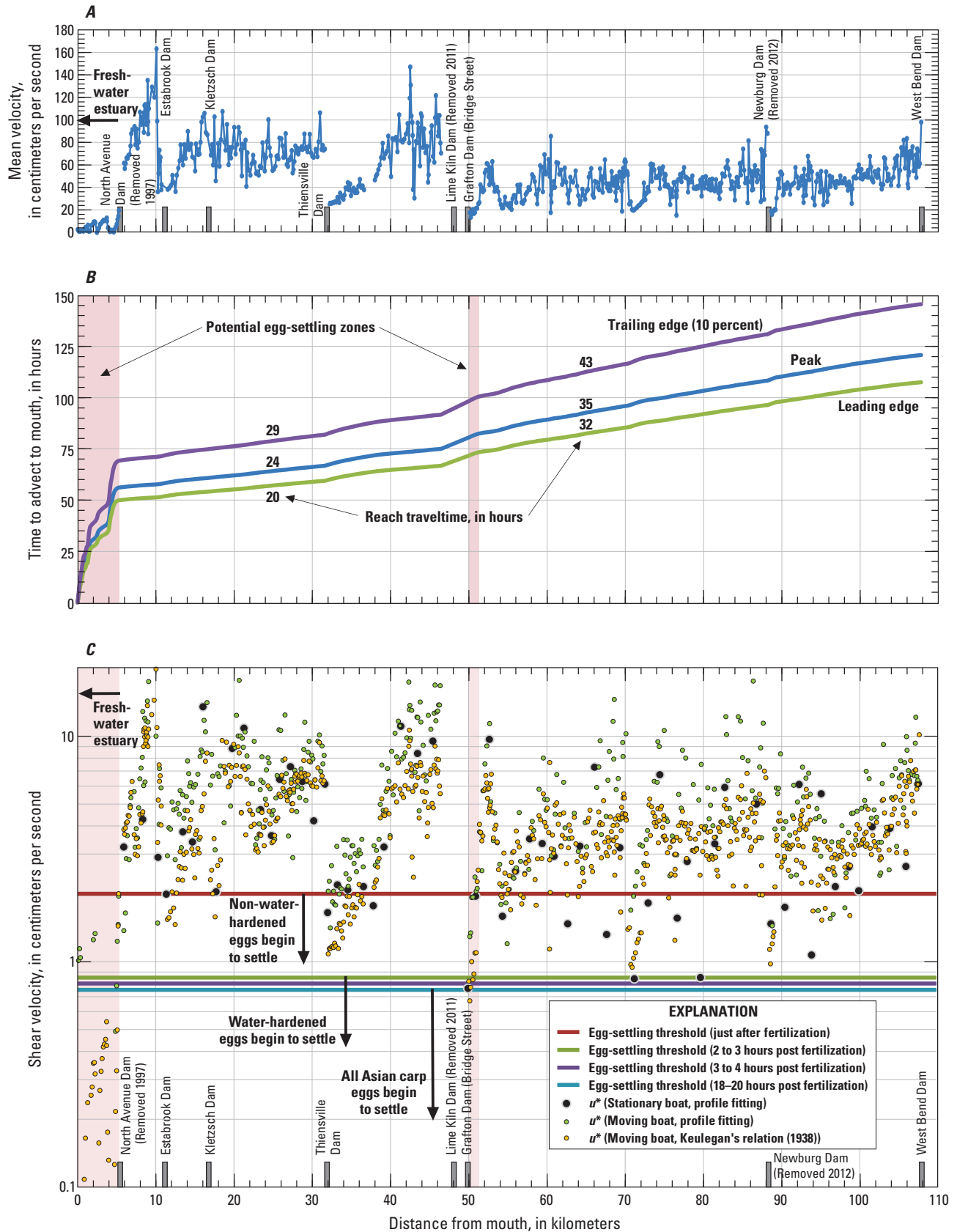


Figure 9. A, Mean velocity, B, estimated advection time, and C, shear velocity for the Milwaukee River, Wisconsin, July 21–August 12, 2010.

Water-quality distributions within the Milwaukee River were dominated by temporal (diurnal) changes and otherwise showed little variation (fig. 8). Observed water temperatures upstream of the river mouth ranged from 23 to 29°C, with a majority of the variation (up to 5°C) attributable to diurnal variations. Dissolved oxygen was relatively uniform with values from 7 to 9 milligrams per liter (mg/L) for most of the river, except for several reaches upstream of Grafton Dam where diurnal changes in water temperature are correlated with high dissolved oxygen (9 to 12 mg/L). The diurnal change in dissolved oxygen in these reaches may be indicative of oxygen production by aquatic vegetation during peak solar-radiation periods in the midday and afternoon, which also would lead to the observed increase in water temperatures. Survey crew notes and photos documented these reaches as having very abundant aquatic vegetation across the width of the channel. Areas with higher dissolved oxygen also exhibited higher values of pH (consistent with high rates of photosynthesis from vegetation) and otherwise showed little variation along the river. Specific conductance showed little variation in the river when accounting for temporal variation.

The lower Milwaukee River includes several zones that may allow settlement of Asian carp eggs; however, the potential settlement reaches are short and travel times between reaches appear to be sufficient for egg development to hatching prior to reaching these settlement zones (fig. 9B). Two potential egg-settling zones were identified in which the shear velocity was lower than the settling velocity of the eggs. A 2-km reach above Grafton Dam was determined to have a sufficiently low shear velocity to settle out water-hardened eggs. The second settling zone identified is the estuary where the Milwaukee River meets Lake Michigan. The estuary settling zone is approximately 5 km long. There also were several pools identified to have low shear velocities (fig. 9C), mostly areas upstream of dams. It is important to note that Newburg Dam, which is the source of one of these low shear velocity pools, was removed in 2012 and that likely changed the flow characteristics in this area to eliminate the pool. Advective travel times between the primary settling zones identified in figure 9B are 24 and 35 hours, respectively, for the peak of the egg distribution. The estimated times to hatching for silver and bighead carps at a water temperature of 26.0°C (mean water temperature during the survey) are approximately 20 and 23 hours, respectively. These travel times indicate that at the observed temperatures these reaches are sufficiently long to allow both silver and bighead carp eggs to develop to the hatching phase before reaching a settling zone.

The highest observed turbulence, as indicated by high shear velocities, were observed in the lower 50 km of the Milwaukee River, specifically just downstream of the Grafton, Thiensville, and Estabrook Dams. Additionally, the data indicate high shear velocities downstream of the West Bend Dam. The high-velocity, high-gradient portion of the lower 50 km of the Milwaukee River and areas immediately downstream of

the previously mentioned dams may present attractive spawning conditions for Asian carps. Grafton Dam currently (2013) has no fish ladder and it is considered the terminal point for upstream migration of most fish species (Will Wawrzyn, Senior Fisheries Biologist, Wisconsin Department of Natural Resources, written commun., 2012). The impedance of the Grafton Dam combined with the high turbulence downstream of the dam make this location a favorable spawning location for Asian carps.

St. Joseph River

Five dams located along the lower 100 km of the St. Joseph River heavily influence the hydraulics of the river (fig. 10). Mean velocities during the surveyed event ranged from 50 to 150 cm/s downstream of dams and within the free-flowing lower 40 km of the river, to less than 25 cm/s within the backwater pools upstream of the Berrien Springs, Buchanan, and South Bend Dams and within the estuary at the river mouth (fig. 11A). Like the observations from the Milwaukee River, a significant decrease in the vertical velocity was observed in the backwater areas behind the dams. Impoundments provided the greatest depths (3 to 8 m) while the remainder of the river exhibited depths that averaged from 1 to 3 m.

Variability in the water-quality distributions in the St. Joseph River appear to be influenced by a combination of anthropogenic sources and tributary inflows (fig. 10). Temperature variation within the lower 100 km is low (<1°C) accounting for temporal variations. Signatures of both anthropogenic and tributary inflows can be seen near river kilometer 66 where the Niles Wastewater Treatment Plant effluent and Dowagiac River both enter the river, slightly raising the local water temperature (fig. 10). In contrast, the cooler water observed above the South Bend Dam may be the effect of a local anomaly owing to inflows from Bowman Creek. While temperatures were low (approximately 16°C during this survey), the mean water temperature at the USGS streamgage at Niles, Mich. (04101500), was 26.5°C for the month of July based on data from July 2011 and July 2012. Dissolved oxygen, pH, and turbidity all decreased in impoundments and increased downstream of the dams (fig. 10). In contrast, the specific conductance increased slightly upstream of the Berrien Springs and Buchanan Dams, within the lower 30 km of the river, and just downstream of the South Bend Wastewater Treatment plant and Judy Creek inflow near river kilometer 81. The cause of the increase in specific conductance upstream of the dams is unclear, but the higher specific conductance from river kilometer 30 to the mouth may be owing to contribution from Lemon Creek, which also appears to have increased the turbidity concentrations in the St. Joseph River near the confluence (fig. 10).

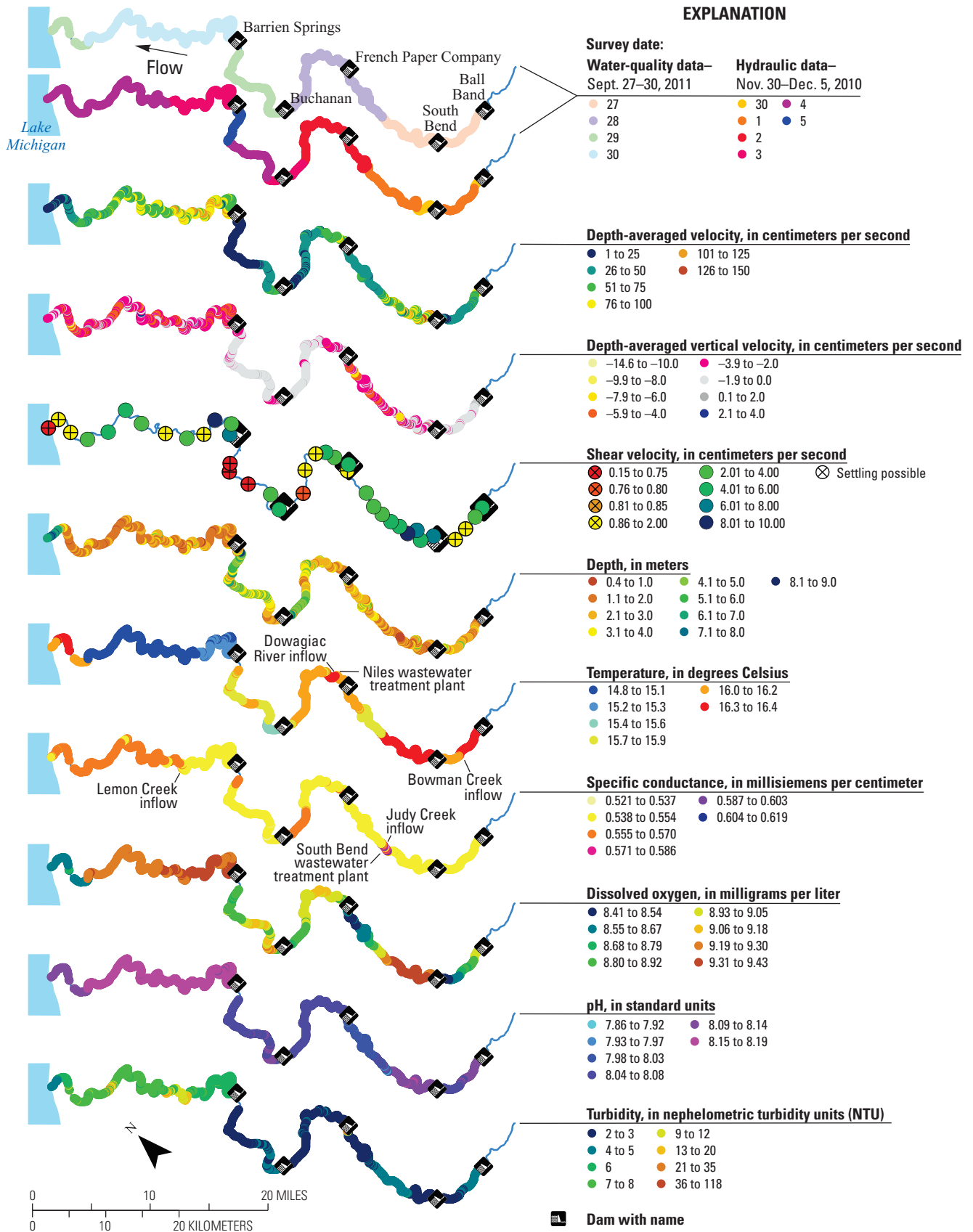


Figure 10. Hydraulic and water-quality data for the St. Joseph River, Michigan and Indiana, November 30–December 5, 2010 (hydraulic data), and September 27–30, 2011 (water-quality data).

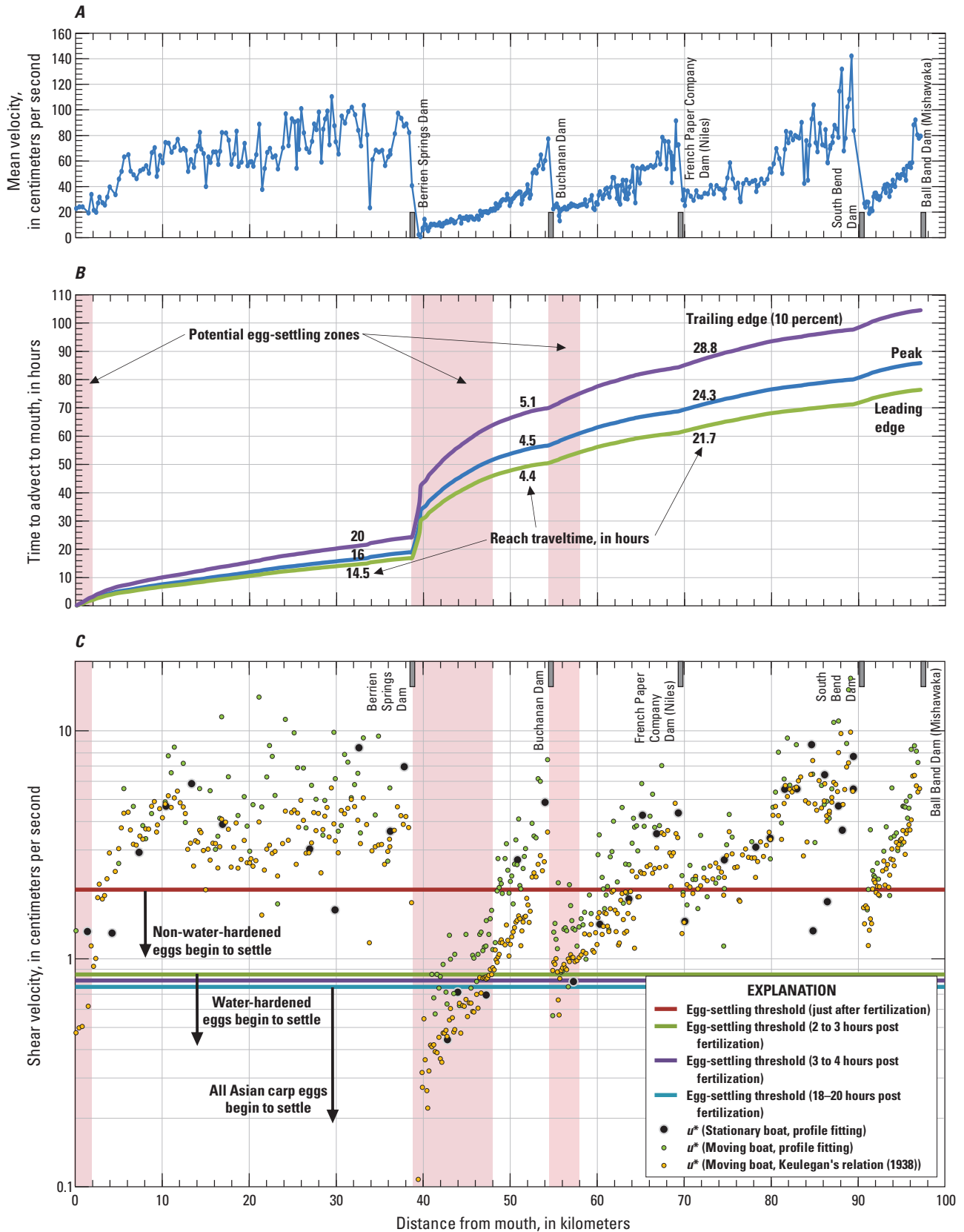


Figure 11. A, Mean velocity, B, estimated advection time, and C, shear velocity for the St. Joseph River, Michigan and Indiana, November 30–December 5, 2010 (hydraulic data), and September 27–30, 2011 (water-quality data).

Dams on the St. Joseph River create well-defined settling zones due to their significant deceleration of the flow (fig. 11A). Three potential egg-settling zones were identified from the shear velocity data. The Buchanan Dam forms an approximately 4 km long settling zone within the impoundment where some settling of eggs is likely to occur. The Berrien Springs Dam forms an approximately 9 km long settling zone where significant settling of water-hardened eggs is likely to occur. There also were pool areas behind the French Paper Company and South Bend Dams identified to have low shear velocities (fig. 11) where some egg settlement may occur, particularly of the more dense non-water-hardened eggs. Settling also is possible within about 2 km of the river mouth. In contrast, the highest shear velocities were observed within the lower 38 km of the river and downstream of the dams. The dam at South Bend appeared to generate the highest shear velocity (and turbulence) downstream of its spillway. The turbulence downstream of each of the major dams on the lower St. Joseph River may present attractive spawning conditions for Asian carps.

The peak transport time from the top of the sampling reach to the first potential settling zone upstream of Buchanan Dam is approximately 24 hours with leading and trailing edge transport times of 22 and 29 hours, respectively (fig. 11B). This length of time like would likely be sufficient under typical July water temperatures (26.5°C) for Asian carp eggs to develop to hatching (approximately 19 hours for silver carp and 22 hours for bighead carp at 26.5°C). The peak transport time between the Buchanan and Berrien Springs Dams is 4.5 hours with leading and trailing edge transport times of 4 and 5 hours, respectively. Eggs spawned in the reach between these two dams would be likely to settle to the bottom of the river and not hatch. The peak transport time from below Berrien Springs Dam to the settling zone where the St. Joseph River meets Lake Michigan is approximately 16 hours with leading and trailing edge transport times of 15 and 20 hours, respectively. It is likely that successful hatching may occur within this reach for peak summertime temperatures and lower flow rate events; however, based on the variability in hatching times observed in figure 7, only a fraction of the eggs may hatch before reaching the lake.

Maumee River

The lower 100 km of the Maumee River can be divided into three primary sections: (1) the upper reach between Independence and Providence Dams dominated by steady, slow flows; (2) the middle swift-water reach between Providence

Dam and Perrysburg, Ohio, dominated by rapids; and (3) the lower freshwater estuary starting about 24 km upstream of the mouth and dominated by highly variable flows due to backwater effects and lake seiches (fig. 12). The surveyed reach between Independence and Providence Dams exhibited little flow variability, had a gradual decrease in the flow velocity in the downstream direction (mean velocities ranged from 15 to 30 cm/s, fig. 13A), and had depths ranging from 2 to 5 m. The rapids section below Providence Dam generally was inaccessible by boat, resulting in little measured data. These rapids are comprised of sections of swift water with velocities greater than 1 m/s and short pools between bedrock and cobble riffles with velocities less than 20 cm/s. Downstream of Perrysburg, Ohio, the Maumee River is in backwater and becomes a freshwater estuary with highly variable velocities (mean velocities ranging from 0.25 to 30 cm/s), reversing flows, and depths up to 10 m. The highly variable velocities in this 24 km long estuary are due to periodic seiches on Lake Erie and wind-driven currents within the estuary and nearshore Lake Erie. The highly variable hydrodynamics observed within the Maumee River estuary are consistent with prior studies (Miller, 1968; Herdendorf and others, 1977; Kunkle and Wordelman, 1978).

The Maumee River exhibited less temporal variation in water quality than the other rivers in the study and several aspects of this dataset warrant further discussion (fig. 12). The mean water temperature for the lower 100 km of the Maumee River during the survey was approximately 26°C with slightly higher temperatures observed upstream of Providence Dam and the lowest temperatures just downstream of the swift-water rapids. Diurnal changes in water temperature ranged from 1 to 3°C. Consistent with other Great Lakes tributaries, the specific conductance in the river was significantly higher than Lake Erie water and concentrations dropped upon entering the estuary. Contrary to intuition, dissolved oxygen was higher in the pool upstream of Providence Dam (approximately 12 mg/L) as compared to the sections downstream of the rapids (6–10 mg/L) and within the estuary (5–10 mg/L). Values of pH were uniform (8.5–8.7) for most of the river, with slightly lower values near Lake Erie (8.1–8.4) and higher values just downstream of the town of Napoleon, Ohio (river kilometer 70), where pH values approached 9.4. An elevated temperature (near 30°C), a 15 percent decrease in specific conductance, and a large rise in dissolved oxygen (75 percent) also occurred just downstream of the town of Napoleon. Several outfalls to the Maumee River are present downstream of Napoleon including one from the Napoleon Waste Water Treatment Plant and nine outfalls from the Campbell's Soup plant.

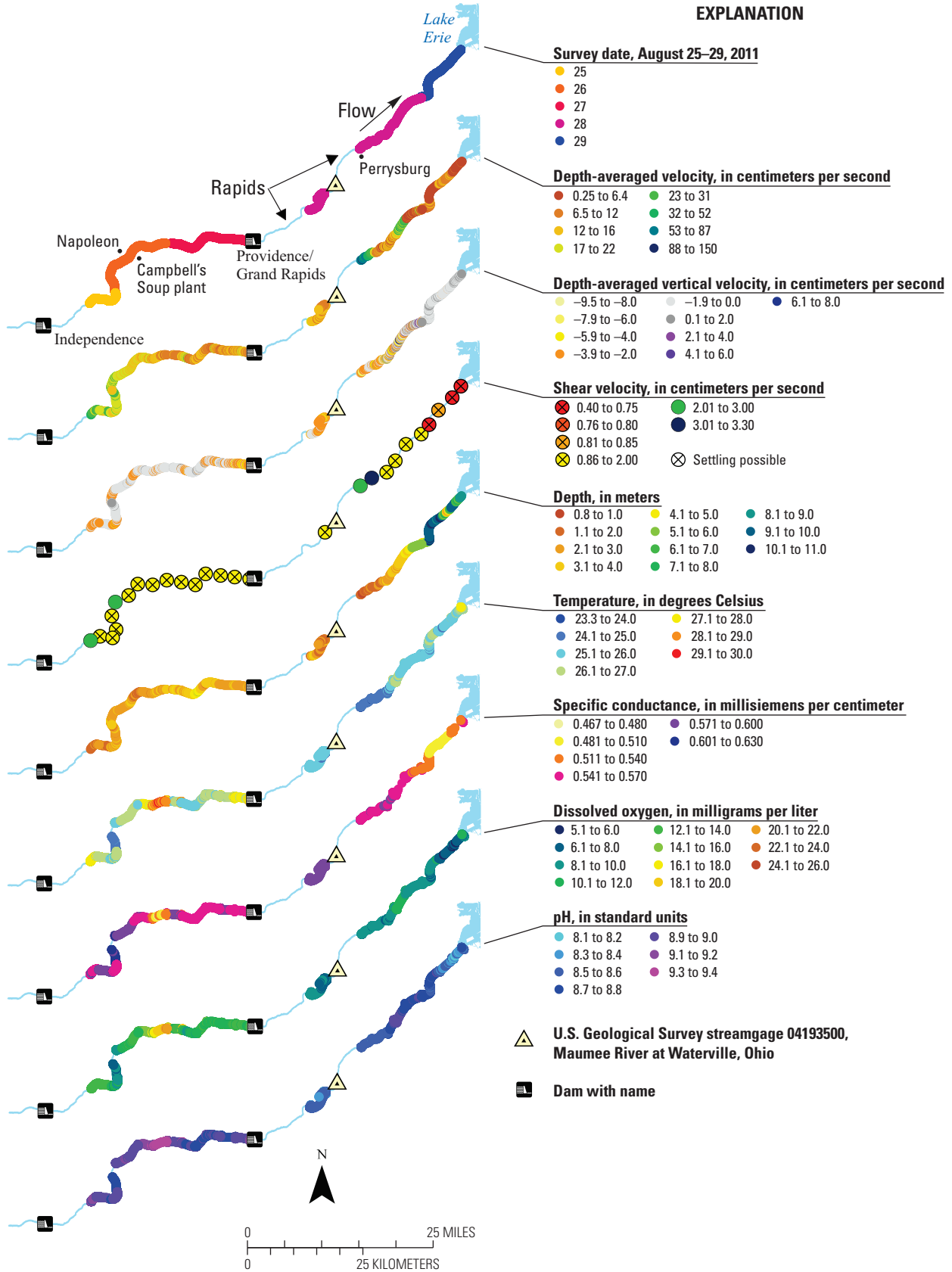


Figure 12. Hydraulic and water-quality data for the Maumee River, Ohio, August 25–29, 2011.

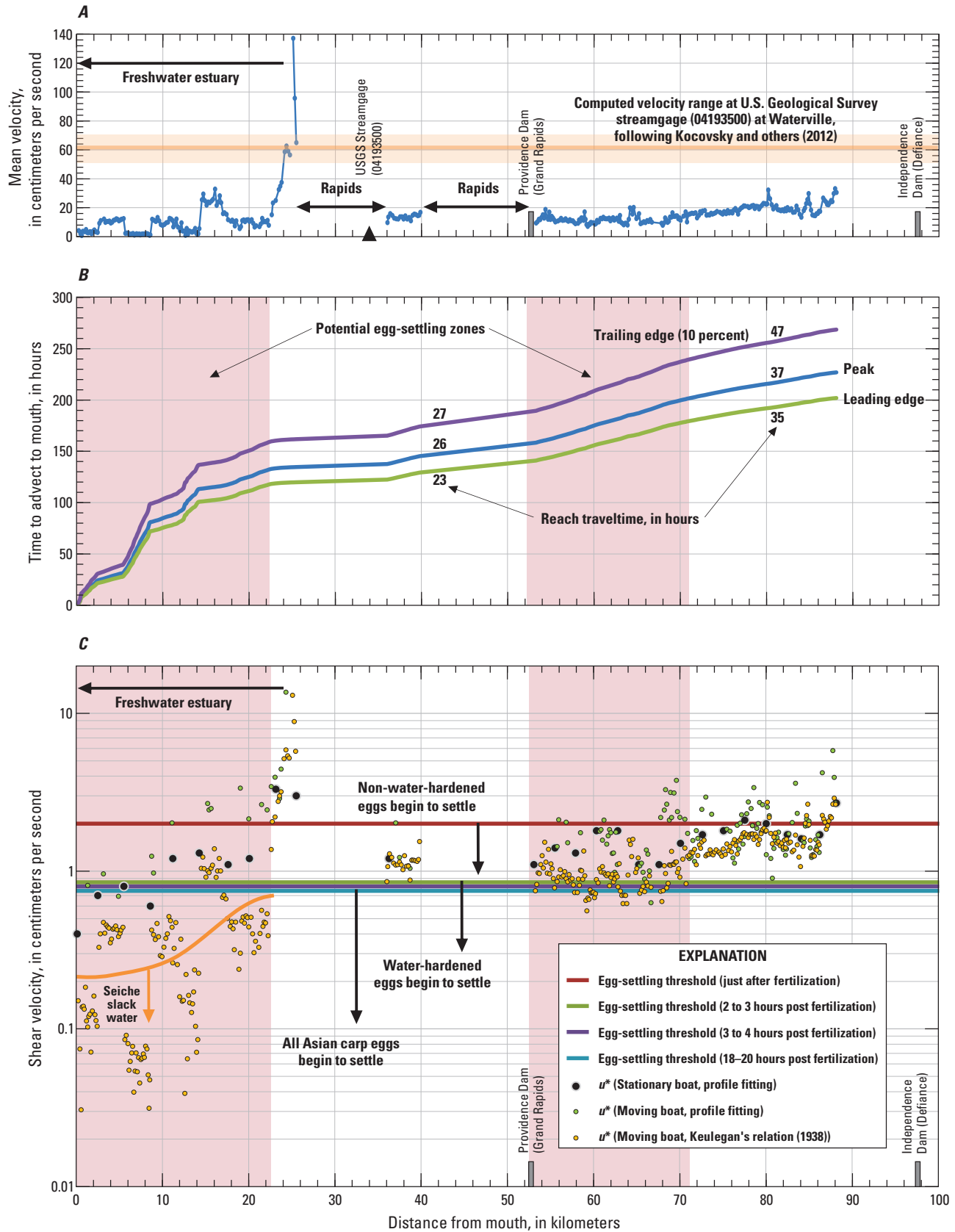


Figure 13. A, Mean velocity, B, estimated advection time, and C, shear velocity for the Maumee River, Ohio, August 25–29, 2011.

The hydraulics in the lower Maumee River dictate a largely varying capacity for Asian carp egg transport (fig. 13). Several long reaches are capable of egg transport, including the 30 km rapids section, and two large potential settling zones were identified. One of the settling zones is located upstream of the Providence Dam in Grand Rapids, 52 km upstream from the mouth and extends to approximately 71 km above the mouth. All three shear velocity calculation methods identified this area as potentially settling out eggs. While the Providence Dam does not decelerate the flow to the extent that was seen for the dams on the St. Joseph River, the low velocities in the pool between the Independence and Providence Dams result in potential settling well upstream of the dam. A second settling zone is located in the estuary upstream of the confluence with Lake Erie. This settling zone is approximately 22 km long and spans nearly the entire 24 km long extent of the estuary. Shear velocity calculation in this area was complicated by flow fluctuations created by seiche-driven pulses in water level and discharge within the estuary. The inconsistency in velocity data within the estuary made fitting the velocity profile more uncertain and led to a larger range of estimated shear velocities.

In spite of having large settling zones within the lower Maumee River, the advective transport times upstream of these settling zones are sufficiently long to allow Asian carp eggs to develop to hatching at the high temperatures in the Maumee River in late summer (fig. 13B). With a mean water temperature of 26°C, silver and bighead carps require approximately 20 and 23 hours, respectively, to hatch (fig. 7). The transport time for the peak concentration of an egg distribution is approximately 24 hours from the top of the study reach to the upstream end of the first identified settling zone behind the Providence Dam. The transport time for the leading and trailing edges is 22 and 30 hours, respectively. However, if the traveltime curve is extended with the same slope upstream of the study reach another 9 km to the Independence Dam at Defiance, Ohio, the peak transport time is 37 hours with leading and trailing edge transport times of 35 and 47 hours, respectively. Those traveltimes are sufficient for hatching, and the extension is reasonable considering there are no large obstructions in the channel upstream from where sampling began. The peak transport time between the Providence Dam and the estuary settling zone is estimated to be 26 hours with leading and trailing edge transport times of 23 and 27 hours, respectively. It is likely that some eggs would have sufficient development time to hatch in the reach of the Maumee River between the dam and the estuary.

Data collection was limited in the rapids reach because of safety concerns; therefore, some velocities in this reach were estimated using bed slope. The rapids section just downstream of the Providence Dam has an approximate mean slope of 5.7×10^{-4} , and the rapids reach, including the USGS

streamgage at Waterville, Ohio (04193500), has an approximate mean slope of 9.5×10^{-4} . Utilizing this information along with estimates of Manning's roughness coefficient (Chow, 1959) and hydraulic geometry within the reaches, Manning's equation was used to obtain approximate mean velocities throughout the rapids reaches. In this analysis, a weighted mean was applied to account for the percentage of riffles and pools (determined using aerial imagery) within each reach. Pools were given a lower velocity (0.15 cm/s) compared to the riffles (determined using Manning's equation). The final estimates of traveltimes through the rapids reaches were computed using a mean velocity in the upper, pool-dominated rapids reach of 28 cm/s and a mean velocity of 1.0 m/s in the lower, steeper rapids reach.

Kocovsky and others (2012) discussed the possibility of the Maumee River among others for Asian carp spawning. Citing the difficulty in obtaining data on the shear velocity in a river, linear (streamwise) velocity was used to determine whether eggs were likely to stay suspended. The mean velocity for the whole of the Maumee River was estimated from the discharge data at the USGS streamflow-gaging station at Waterville, Ohio (04193500), which is located in the lower, bedrock-riffle dominated rapids reach. This velocity estimated from the daily discharge data at the gage then was compared to a value of 70 cm/s, an estimate often cited as the velocity needed to keep the eggs in suspension. Kocovsky and others (2012) concluded that there was sufficient flow to keep eggs suspended based on this comparison. This approach for a tributary spawning assessment was proposed for rivers in which detailed hydraulic data are not available. However, while their conclusion that the Maumee River could support successful spawning is upheld by the current study, their approach is complicated by the fact, as figure 13 shows, that the gage is located in a section of rapids and therefore, is not representative of the velocity over the majority of the lower Maumee River.

Observations of high shear velocities in the Maumee River are limited for this study between the rapids reaches and the high flows downstream of dam spillways; however, the lower Maumee River should possess suitable spawning grounds for Asian carps (fig. 13). The most likely spawning grounds for the reach above Providence Dam is at the spillway of the Independence Dam, as this study documented low-turbulence flow in the remainder of the reach. The rapids below the Providence Dam are likely spawning grounds due to the high velocities, bedrock outcroppings, and turbulence generated by the flow over the Providence Dam spillway. In both reaches, if the carp spawn just downstream of either of the dams, there appears to be sufficient reach length and velocity downstream for the eggs to drift and hatch before settling out of the water column.

Sandusky River

The lower Sandusky River below Ballville Dam can be divided into five primary reaches based on channel and flow characteristics (Stantec Consulting Services, 2011; Evans and others, 2002) (fig. 14). The upper three reaches have shallow depths (<1 m, on average) and were not measured during this study owing to access and safety issues, but their characteristics are documented in the literature (Stantec Consulting Services, 2011; Evans and others, 2002). Extending about 0.6 km downstream of Ballville Dam is a relatively high gradient (6.2×10^{-3} meters per meter (m/m)) bedrock reach with swift (approximately 80 cm/s mean velocity for the discharge in this study), shallow flow. The dam spillway, bedrock substrate, and swift flows generate significant turbulence in this reach. Extending approximately 1.7 km downstream of the bedrock reach is the “habitat” reach (Stantec Consulting Services, 2011) with prevalent gravel and cobble substrate, a slope of 2.9×10^{-3} m/m, and mean velocities of about 60 cm/s at the study discharge. The third reach, called the “Levee” reach, extends 1.1 km downstream of the habitat reach and is bounded by floodwalls. The substrate varies substantially from bedrock to clay, with a predominance of sand and fine gravel (Stantec Consulting Services, 2011). The slope of this reach is 8.33×10^{-4} m/m, and approximate mean flow velocities are 50 cm/s for the study discharge. The fourth reach, extending 2.2 km downstream of the Levee reach, is the lake-affected transitional reach. Within this reach, the backwater from the lake begins affecting the hydrodynamics, and the substrate transitions to fine silts and clays. The slope is approximately 3.9×10^{-4} m/m in this reach with a mean velocity of less than 40 cm/s for the study discharge. The final reach of the lower Sandusky River is the estuary reach extending 20 km from the end of the transitional reach to Muddy Creek Bay (fig. 14). Dominated by backwater from Lake Erie, this reach has a mean velocity of less than 20 cm/s, and flows become highly variable with flow reversals due to lake-seiche activity and wind events near the bay. Depths in this reach vary significantly from 1 to 6 m. The lower portion of this reach has numerous backwater areas and resembles a marsh ecosystem (Stantec Consulting Services, 2011). This reach is the most likely settling zone, so measurements in this study were concentrated in this 20 km long estuary reach.

The lower Sandusky River exhibits significant variability in water quality as the water body transitions from river to estuary (fig. 14). The mean water temperature for the lower 25 km of the Sandusky River during the survey was approximately 22°C with diurnal changes in water temperature of 3°C. Higher temperatures of some backwater areas and tributary inflows produced anomalies in the water-temperature data collected in the main channel. Unlike other Great Lakes tributaries in the study, the specific conductance in the river increased in the estuary and approached a maximum for the survey at Muddy Creek Bay (an intermediate bay between the mouth of the river and Sandusky Bay). Dissolved oxygen was highest downstream of the Ballville Dam (approximately

9 mg/L at the most upstream point in the survey) and dropped steadily within the estuary (6–8 mg/L). Diurnal variations of dissolved oxygen appear to be about 1 to 2 mg/L, with the lowest values occurring in the morning (likely owing to consumption at night caused by respiration and production during the day by aquatic plants and algae). Values of pH were uniform (7.7–8.2) for most of the river. Finally, turbidity was highest at the top of the survey reach closest to Ballville Dam (77 nephelometric turbidity units (NTU)) and decreased steadily into the estuary (down to 33 NTU). However, midway through the estuary, the survey crews on September 12, 2012, observed higher turbidity values in the estuary (60–70 NTU), but this may be a diurnal effect or was caused by resampling of the slug of high turbidity water measured close to the dam on day 1 (traveltime is about 20–25 hours for this reach and the time between sampling ending on September 11, 2012, and resuming on September 12, 2012, was about 15 hours). Periodic fluctuations in turbidity are seen in the data near the mouth of the river at Muddy Creek Bay and may be due to turbulence and resuspension of sediment arising from seiche-induced flow reversals and wind-driven wave action. Overall, the turbidity for the lower Sandusky River was considerably higher than the turbidity measured on the St. Joseph River. The higher turbidity could contribute to more recruitment success in the lower Sandusky River.

Unlike the Maumee River in which nearly all of the 24-km long estuary reach is conducive to egg settling, the upper 9 km of the 20 km long estuary reach of the lower Sandusky River appears capable of transporting water-hardened Asian carp eggs (fig. 15). The primary settling zone observed in the current study was in the lower 11 km of the Sandusky River. Within this settling zone, the shear velocity was low enough to allow all Asian carp eggs to settle (water-hardened and non-water-hardened). Upstream of this settling zone, some settling of non-water-hardened eggs may occur, and these data indicate some settling of water-hardened eggs may occur near the top of the estuary reach. The unmeasured reach below Ballville Dam appears to be suitable for Asian carp spawning, and velocities are high enough to maintain non-water-hardened eggs in suspension. While the Sandusky and Maumee Rivers have similar length estuary reaches, the Sandusky River appears to be less affected by lake-seiche activity as flow reversals were only apparent near the mouth of the river at Muddy Creek Bay. This lack of flow variability in the upper portion of the Sandusky River estuary reach allows the flow to transport eggs farther into the estuary reach as compared to the Maumee River estuary. The likely cause for the lower flow variability in the Sandusky River is the dampening effect of Sandusky and Muddy Creek Bays on the lake-seiche activity. These bays are shallow with depths generally less than 1.6 m deep (Herdendorf and Lindsay, 1975). The shallow waters and large, 30 km length of these bays may allow for significant dampening of lake-induced fluctuations prior to reaching the mouth of the Sandusky River.

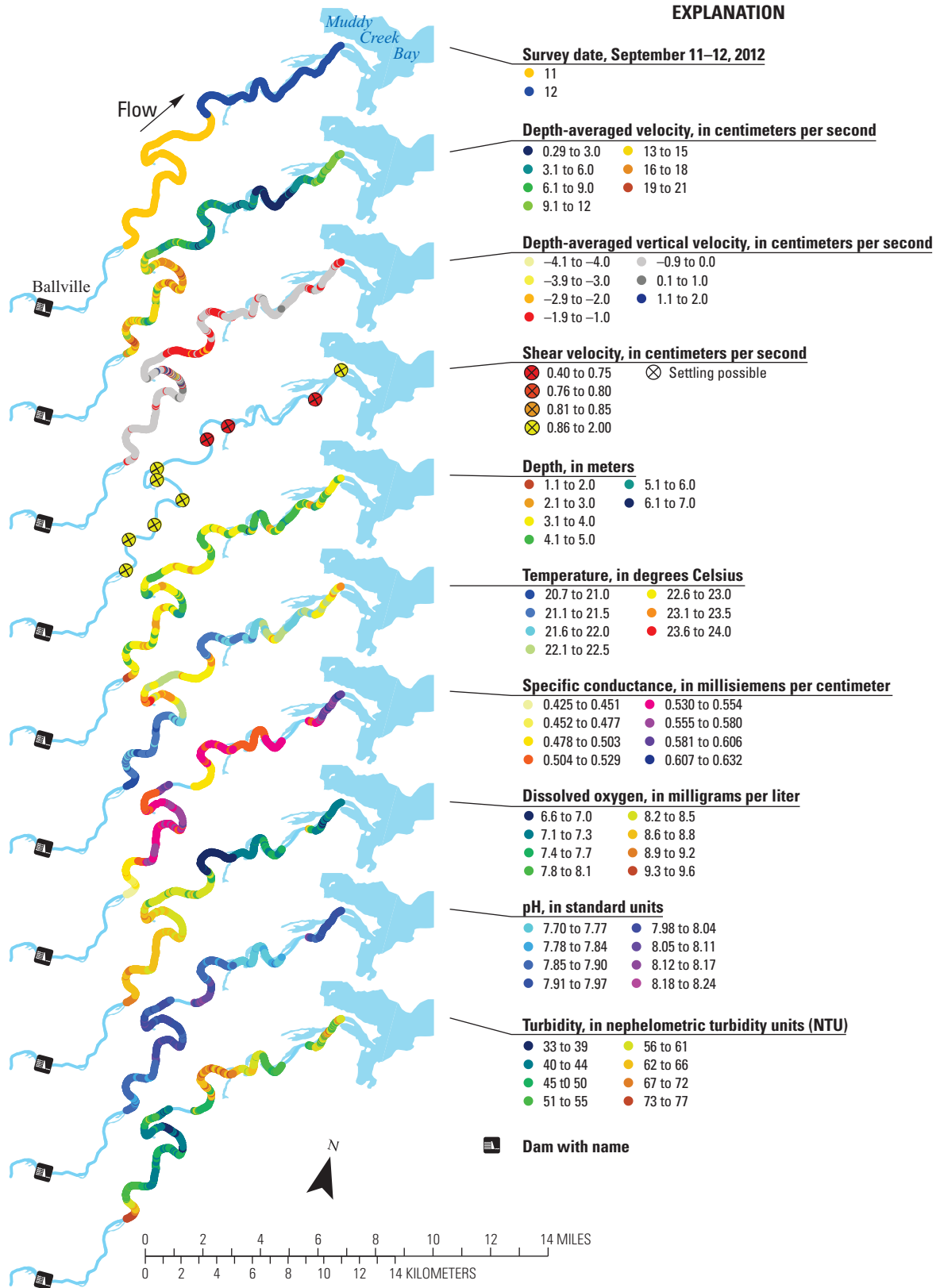


Figure 14. Hydraulic and water-quality data for the Sandusky River, Ohio, September 11 and 12, 2012.

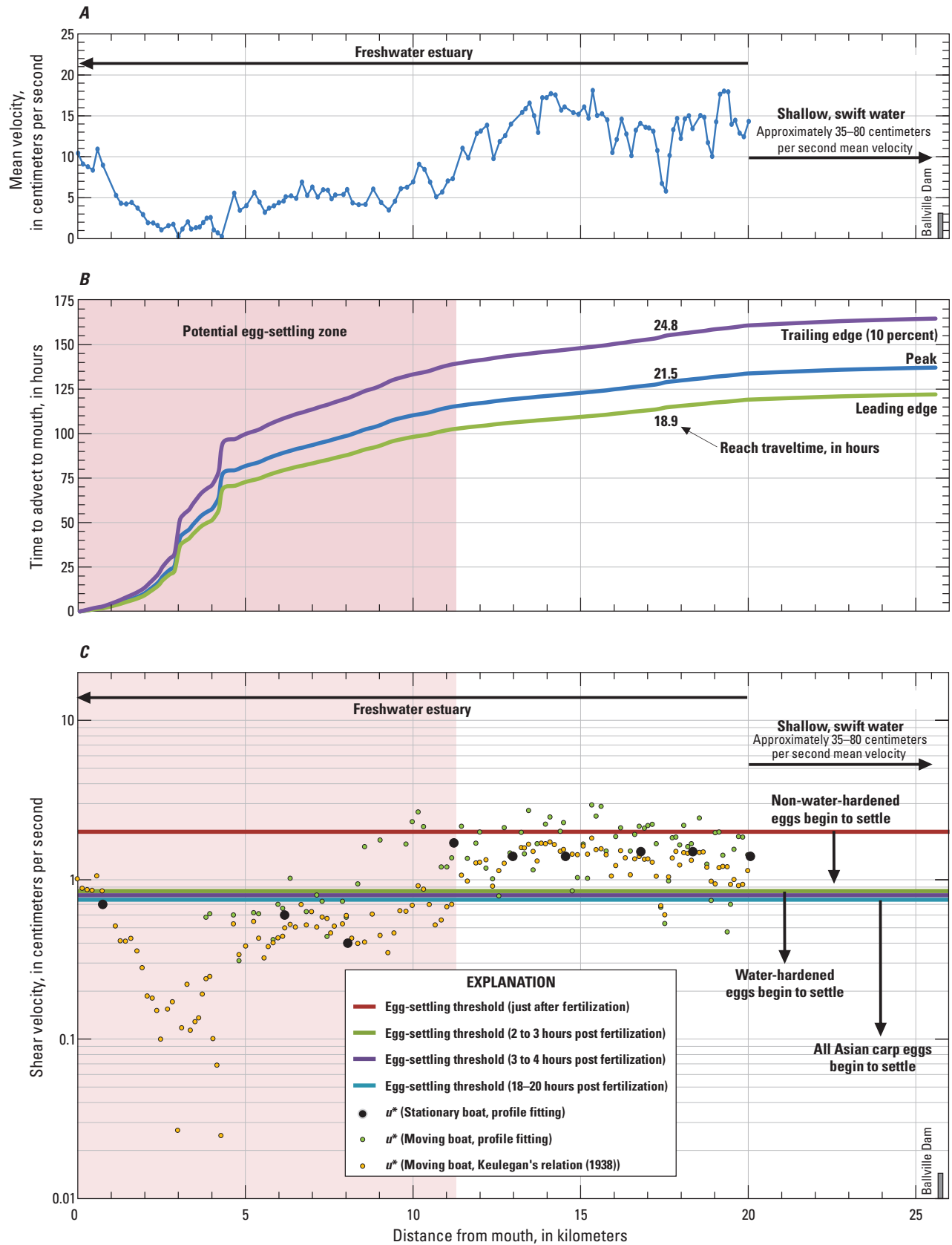


Figure 15. A, Mean velocity, B, estimated advection time, and C, shear velocity for the Sandusky River, Ohio, September 11 and 12, 2012.

The transport time from Ballville Dam to the top of the potential settling zone is approximately 22 hours for the peak of the egg distribution with leading and trailing edge transport times of 19 and 25 hours, respectively (fig. 15B). Kocovsky and others (2012) predicted a mean summer water temperature for the lower Sandusky River of greater than or equal to 24°C, and data from this study indicated a water temperature of 21 to 24°C for mid-September. Continuous water-temperature data record at the USGS streamgage on the Sandusky River near Fremont, Ohio (04198000), recorded a mean water temperature of 25.1°C for August 2012 (max = 33.1°C and min = 19.3°C). From figure 7, at 24°C, the hatch time for silver carp is approximately 25 hours and for bighead carp is approximately 27 hours with higher temperatures having shorter hatching times. Therefore, the traveltime of the eggs from Ballville Dam to the settling zone may be sufficiently long to allow hatching of at least a portion of the egg mass prior to reaching the settling zone during floods of a similar magnitude to the study event and average summer water temperatures. Additionally, velocity variability within the Sandusky River estuary reach due to lake-seiche activity that was not captured in this study likely will affect these results (flow variability can both hinder and aid the transport of eggs depending on the magnitude of the variations and direction of the currents).

Critical Velocity for Transport of Water-Hardened Asian Carp Eggs

Critical shear velocity determines at what point eggs will settle; however, mean velocity is generally more widely available and more easily calculated. Therefore, the current study data can be used to develop a relation between the two values and, as a result, determine critical mean velocity values for settlement of eggs. The current study data (figs. 9, 11, 13, and 15) show that the critical shear velocity at which eggs start to sink corresponds to mean depth-averaged velocities in the range of 15 to 25 cm/s. These velocities are significantly smaller than the 70 cm/s threshold that is commonly reported in the literature. The variability in this transport threshold is due to difference in the flow depth and substrates in the study

ivers. Using equation 1 and a shear velocity of 0.75 cm/s, the minimum transport velocity for water-hardened Asian carp eggs can be plotted as a function of the mean flow depth and the bed substrate (fig. 16). The relation derived to generate figure 16 assumes that the streambed is flat (no bedforms) and free of vegetation (both cause an increase in roughness that cannot be accounted for by the median grain size). Therefore, a first-order assessment of the transport capability of a river for Asian carp eggs can use the mean flow depth and substrate type to determine the required minimum flow velocity for transport. If mean velocity of a reach does not meet this criterion, it is likely that eggs would settle out of suspension. The results from this first-order approach then can be used to guide further investigation of hydrodynamics in potential settling reaches.

Suggested Future Studies

Although this study increases understanding of how hydraulic and water-quality characteristics of rivers contribute to their suitability for spawning and transport of Asian carp eggs, several areas were identified that warrant further study. This study was limited to Great Lakes tributaries without Asian carps. It would be valuable to repeat this type of evaluation in areas where Asian carps are spawning and recruiting. Comparing results from a spawning reach to the current study results would help to verify the developed methodology and analysis. An additional limitation of the study was the lack of an assessment for nursery habitat, which would be a factor in recruitment success. Assessments of rivers with both successful spawning and recruitment of Asian carps would contribute to understanding how important this habitat is and where it needs to be located to be accessible to the carps. A third limitation is the lack of research on the mortality of Asian carp eggs. Eggs settled on the bottom of a river generally are thought to perish; however, the mechanism of mortality is not understood. Further study of how eggs are affected by scour and deposition areas in a stream could lead to new control technologies.

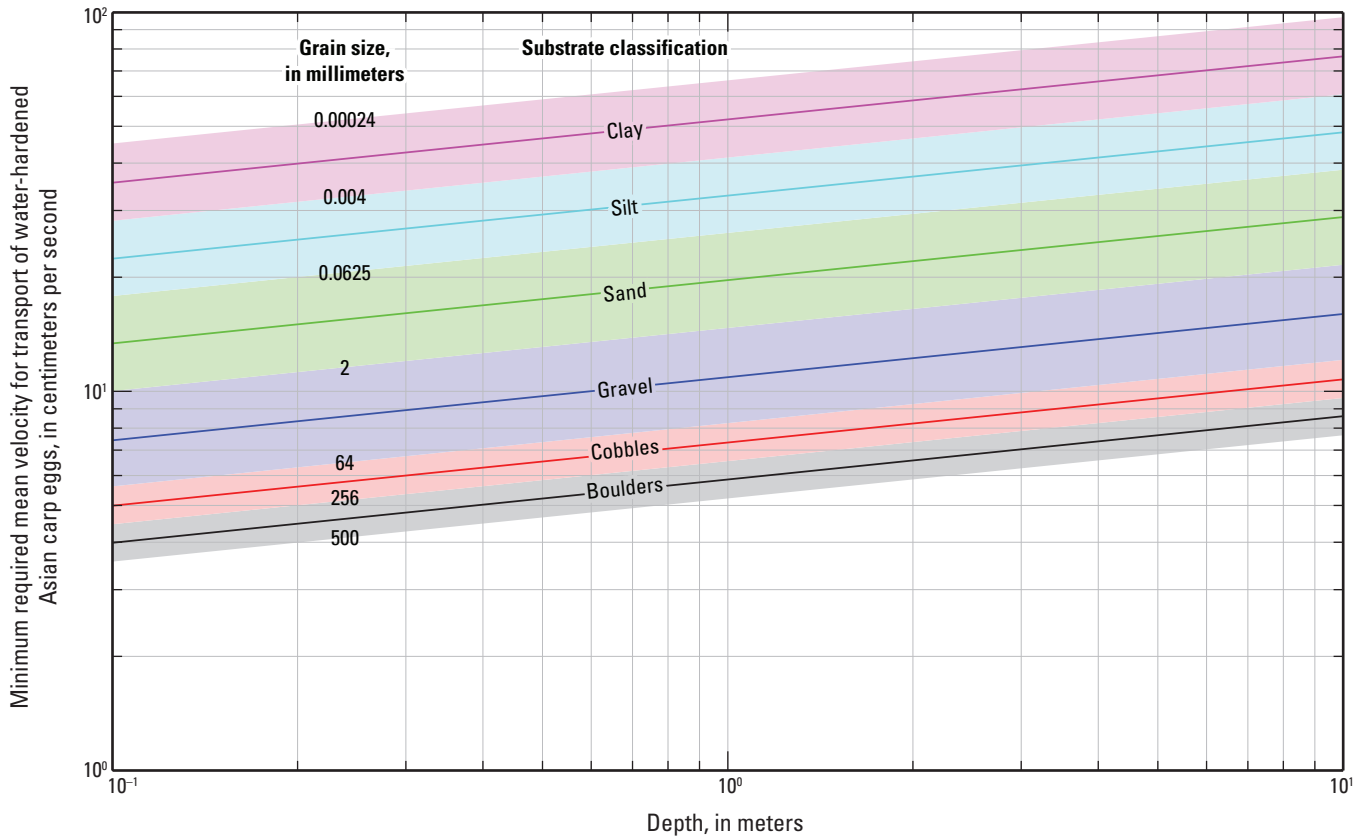


Figure 16. Theoretical curves for estimating the minimum transport velocity for water-hardened Asian carp eggs from observations of mean flow depth and substrate type. This relation assumes the bed contains no bedforms or aquatic vegetation.

Conclusions

If the invasive Asian carps (bighead carp *Hypophthalmichthys nobilis* and silver carp *Hypophthalmichthys molitrix*) migrate to the Great Lakes in spite of the efforts to stop their advancement, these species will require the fast flowing water of the Great Lakes tributaries for spawning and recruitment in order to establish a growing population. This report describes the hydraulic and water-quality data-collection effort by the U.S. Geological Survey (USGS), in cooperation with the Great Lakes Restoration Initiative as administered by the U.S. Environmental Protection Agency, on four Great Lakes tributaries and uses new information about egg-transport characteristics to provide insight into the spawning and recruitment suitability of these tributaries. As part of this study, two Lake Michigan tributaries (the Milwaukee and St. Joseph Rivers) and two Lake Erie tributaries (the Maumee and Sandusky River) were investigated to determine if these tributaries, deemed to be potential spawning grounds, possess the hydraulic and water-quality characteristics to allow successful spawning

and transport of Asian carp eggs. This study utilized standard USGS sampling protocols and instrumentation for hydraulic and water-quality measurements, together with differential global positioning system data for georeferencing. Non-standard data-processing techniques, combined with laboratory analysis of Asian carp egg characteristics, allowed a detailed assessment of the transport capabilities of each of these four tributaries. This assessment is based solely on analysis of observed data and did not utilize the collected data for detailed transport modeling (an ongoing, parallel aspect of this project).

All four tributaries exhibited potential settling zones for Asian carp eggs both within the estuaries and river mouths and within the lower 100 kilometers (km) of the river. Dams played a leading role in defining these settling zones, with the exception of dams on the Sandusky River. The impoundments created by many of the larger dams on these rivers acted to sufficiently decelerate the flows and allowed the shear velocity to drop below the settling velocity for Asian carp eggs, which allowed the eggs to fall out of suspension and settle on the bottom where it is thought the eggs would perish.

While three rivers exhibited these settling zones upstream of the larger dams, not all settling zones are likely to have such effects on egg transport. The Milwaukee River exhibited only a short settling zone upstream of the Grafton Dam, whereas the St. Joseph and Maumee Rivers both had extensive settling zones (>5 km) behind major dams. These longer settling zones are likely to capture more eggs than shorter reaches. In addition, all four tributaries exhibited settling zones at their river mouths. However, the Sandusky and Maumee Rivers both had large settling zones (11 and 22 km, respectively) that extended far up the rivers from the mouth, and the Lake Michigan tributaries exhibited much shorter estuary settling zones.

While hydraulic data from all four rivers indicated settling of eggs is possible, all four exhibited sufficient temperatures, water-quality characteristics, turbulence, and transport times outside of settling zones for successful suspension and development of Asian carp eggs to the hatching stage before the threat of settlement. This finding indicates that, based on observed data, these four Great Lakes tributaries have sufficient hydraulic and water-quality characteristics to support successful spawning and transport of Asian carp eggs. More generally, the findings indicate that under the right temperature and flow conditions, river reaches as short as 25 km may allow Asian carp eggs sufficient time to develop to hatching. Additionally, examining the relation between critical shear velocity and mean velocity, egg settling appears to take place at mean velocities in the range of 15–25 centimeters per second, a much lower value than generally is cited in the literature. Finally, curves are presented for a first-order approach to estimating the minimum transport velocity for Asian carp eggs from mean flow depth and river-substrate type in the absence of bedforms or vegetation. These conclusions would expand the number of possible tributaries suitable for Asian carp spawning and contribute to the understanding of how hydraulic and water-quality information could be used to evaluate additional rivers in the future. Future studies will be needed to verify the conclusions of this study in rivers where Asian carp are known to spawn and to further explore the mechanisms of mortality for the Asian carp eggs.

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