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Integrated Synoptic Surveys of the Hydrodynamics and Water-Quality Distributions in Two Lake Michigan Rivermouth Mixing Zones using an Autonomous Underwater Vehicle and a Manned Boat

Scientific Investigations Report 2014–5043

U.S. Department of the Interior
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Cover photograph: The autonomous underwater vehicle (foreground) parked on the surface awaiting recovery in outer Milwaukee Harbor, Wisconsin, with the Milwaukee skyline in the background.

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SALLY JEWELL, Secretary

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	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)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)

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

°F=(1.8×°C)+32

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

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L), micrograms per liter (µg/L), or cells per milliliter (cells/mL).

Abbreviations

ADCP	acoustic Doppler current profiler
AOC	area of concern
AUV	autonomous underwater vehicle
DVL	Doppler velocimetry log
fDOM	fluorescent dissolved organic material
GPS	global positioning system
MMSD	Milwaukee Metropolitan Sewerage District
NTU	nephelometric turbidity unit
ppb	parts per billion
USGS	U.S. Geological Survey
VMT	Velocity Mapping Toolbox
YSI	Yellow Springs Instrument
<	less than

Acknowledgments

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Integrated Synoptic Surveys of the Hydrodynamics and Water-Quality Distributions in Two Lake Michigan Rivermouth Mixing Zones using an Autonomous Underwater Vehicle and a Manned Boat

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Abstract

The U.S. Geological Survey (USGS), in cooperation with the National Monitoring Network for U.S. Coastal Waters and Tributaries, launched a pilot project in 2010 to determine the value of integrated synoptic surveys of rivermouths using autonomous underwater vehicle technology in response to a call for rivermouth research, which includes study domains that envelop both the fluvial and lacustrine boundaries of the rivermouth mixing zone. The pilot project was implemented at two Lake Michigan rivermouths with largely different scales, hydrodynamics, and settings, but employing primarily the same survey techniques and methods. The Milwaukee River Estuary Area of Concern (AOC) survey included measurements in the lower 2 to 3 miles of the Milwaukee, Menomonee, and Kinnickinnic Rivers and inner and outer Milwaukee Harbor. This estuary is situated in downtown Milwaukee, Wisconsin, and is the most populated basin that flows directly into Lake Michigan. In contrast, the Manitowoc rivermouth has a relatively small harbor separating the rivermouth from Lake Michigan, and the Manitowoc River Watershed is primarily agricultural. Both the Milwaukee and Manitowoc rivermouths are unregulated and allow free exchange of water with Lake Michigan.

This pilot study of the Milwaukee River Estuary and Manitowoc rivermouth using an autonomous underwater vehicle (AUV) paired with a manned survey boat resulted in high spatial and temporal resolution datasets of basic water-quality parameter distributions and hydrodynamics. The AUV performed well in these environments and was found primarily well-suited for harbor and nearshore surveys of three-dimensional water-quality distributions. Both case studies revealed that the use of a manned boat equipped with an acoustic Doppler current profiler (ADCP) and multiparameter sonde (and an optional flow-through water-quality sampling system) was the best option for riverine surveys. To ensure that the most accurate and highest resolution velocity data were collected concurrently with the AUV surveys, the pilot study used a manned boat equipped with an ADCP. Combining the AUV and manned boat datasets resulted in datasets that are essentially continuous from the fluvial through the lacustrine zones of a rivermouth. Whereas the pilot studies were completed during low flows on the tributaries, completion of surveys at higher flows using the same techniques is possible, but the use of the AUV would be limited to areas with relatively low velocities (less than 2 feet per second) such as the harbors and nearshore zones of Lake Michigan.

Overall, this pilot study aimed at evaluation of AUV technology for integrated synoptic surveys of rivermouth mixing zones was successful, and the techniques and methods employed in this pilot study should be transferrable to other sites with similar success. The use of the AUV provided significant time savings compared to traditional sampling techniques. For example, the survey of outer Milwaukee Harbor using the AUV required less than 7 hours for approximately 600 profiles compared to the 150 hours it would have taken using traditional methods in a manned boat (a 95 percent reduction in man-hours). The integrated datasets resulting from the AUV and manned survey boat are of high value and present a picture of the mixing and hydrodynamics of these highly dynamic, highly variable rivermouth mixing zones from the relatively well-mixed fluvial environment through the rivermouth to the stratified lacustrine receiving body of Lake Michigan. Such datasets not only allow researchers to understand more about the physical processes occurring in these rivermouths, but they provide high spatial resolution data required for interpretation of relations between disparate point samples and calibration and validation of numerical models.

Introduction

Rivermouths are mixing zones that lie at the interface of fluvial and lacustrine waters, where predictable physical and chemical attributes create spatial gradients and a mosaic of habitats, biotic assemblages, and related ecosystem services

(Larson and others, 2013). Rivermouths on the Laurentian Great Lakes lie at the interface of tributaries and the open water of the Great Lakes. In addition to the natural variability present in rivermouth mixing zones due to the interaction of fluvial and lacustrine waters, many rivermouths are located in populated areas and are the focal point of human interaction with the lake (Larson and others, 2013). As a result, anthropogenic influences in rivermouths are high and have resulted in serious degradation of many rivermouth ecosystems. A majority of the Great Lakes areas of concern (AOC) lie within or are associated with rivermouths (U.S. Environmental Protection Agency, 2013). From an ecosystem services standpoint, rivermouths must provide many services to humans including transportation, recreation, and attenuation of fluvial and wastewater inflows, but also have aesthetic, commercial, economic, political, and environmental value. Despite their recognized value, rivermouths are rarely the focus of system-scale research or management efforts (Larson and others, 2013).

Unfortunately, rivermouths lie within the grey area between research focused on the open waters of the Great Lakes and research focused on the upland watersheds (Pebbles and others, 2013; Larson and others, 2013). The complex hydrodynamics and mixing taking place within rivermouths and the impacts of those processes on ecosystem services provided by these rivermouths is not well understood (Larson and others, 2013). System-scale studies of rivermouths require collaboration between agencies and organizations that often draw their boundaries within the rivermouth domain. Such studies require researchers to venture into both the fluvial- and lacustrine-dominated portions of the rivermouth and all areas in between. Of particular need, according to Larson and others (2013), are studies focused on (1) rivermouth hydrodynamics and mixing processes, (2) rivermouth biogeochemical processing and its effect on nearshore nutrient dynamics and harmful algal blooms, and (3) the scales of influence of individual rivermouths on the adjacent Great Lake.

This report documents the methods and instrumentation used to perform integrated synoptic surveys of two Lake Michigan rivermouths and presents results from these surveys. During the integrated surveys, hydrodynamic data are collected, in conjunction with water-quality data within the fluvial and lacustrine portions of the rivermouth mixing zones, including harbors, over short periods of time (days). These surveys are designed to overlap both fluvial continuous streamgaging stations and repeated sampling locations within the rivermouths, harbors, and nearshore zones. The primary objective of this work is not only to test the techniques and methods employed in these surveys and assess their usefulness for rivermouth research, but to provide some understanding about the hydrodynamics and spatial distributions of basic water-quality parameters within the rivermouth. Such information may assist researchers from a range of organizations (for example, the National Monitoring Network, the Great Lakes Rivermouth Collaboratory, and municipal wastewater-treatment districts) during interpretation of point data collected at disparate points within the rivermouth, harbors, and nearshore zone.

Integrated Synoptic Survey Methods

Integrated synoptic surveys of bathymetry, basic water-quality parameters, water velocity, and side-scan sonar were performed using a combination of an autonomous underwater vehicle (AUV) and a manned boat. The AUV was used to perform synoptic surveys of the spatial distributions of basic water-quality parameters, bathymetry, and water velocity. In addition, side-scan sonar imagery was collected by the vehicle along the primary transects of the survey (not presented in this report). The basic water-quality parameters collected by the instrument include temperature, specific conductance, pH, dissolved oxygen, turbidity, total chlorophyll, and blue-green algae concentrations. The manned boat was used to deploy and recover the AUV, collect independent water-velocity and water-quality data, and perform general observations of nearshore mixing. Manned boat survey lines coincided with the programmed AUV mission lines where possible. In addition, the manned boat was used to survey the tributaries leading to the harbors as the lower parts of the rivers surveyed are not suitable for the AUV due to nautical traffic, currents, moorings, and other obstructions.

To yield three-dimensional water-quality data, the AUV was operated in an undulating survey mode. The undulating dive pattern consists of continuous undulations between the water surface and 6 feet (ft) above the lake bed as the AUV executes its mission. The undulating dive pattern used a 15 degree dive angle and resulted in approximately 28–38 profiles of the water column over a 3,700 ft transect (or sample spacing at a given depth of about 100 to 140 ft). In all surveys, the manned boat followed behind the AUV, keeping a distance of about 200 ft while collecting independent water-velocity and water-quality data.

Description of the Autonomous Underwater Vehicle

The AUV used in the surveys is 63.6 inches (in.) in length, 5.8 in. in diameter, weighs approximately 60 pounds (lb) in air (fig. 1), and is built by Yellow Springs Instrument (YSI), Inc. and OceanServer Technology, Inc. (EcoMapper® AUV). It is comprised of a carbon-fiber hull with aluminum nose and tail sections. The nose of the AUV houses a 6600 V2-4 YSI sonde bulkhead with four optical ports and temperature/conductivity and pH ports. A pressure sensor also is integrated into the sonde bulkhead for measurement of the sample depth. Aft of the sensor suite (on the nose of the vehicle) is the Doppler velocimetry log (DVL) instrument. The DVL is a six-beam system for underwater navigation (bottom tracking) and includes vertical beams (uplooking and downlooking) for altitude and depth measurement. Additionally, the DVL provides current-profiling capabilities below the instrument. Located on the top of the vehicle (near the tail section) is the antennae mast, which houses the differential global positioning system (GPS) antenna (Wide Area Augmentation System corrected), the 2.4 gigahertz 802.11g wireless radio antenna, navigation lights, and an external power plug for vehicle charging. Directly below the antennae mast on both sides of the vehicle are the side-scan sonar transducers. The tail comprises four independent control fins and a three-blade propeller. More detailed information on the DVL and side-scan sonar systems, calibration procedures for the AUV, instrument operation, handling of data files, and data-processing routines can be found in Jackson (2013).

The water-quality sensor suite comprises a YSI 6600 V2-4 bulkhead equipped with a YSI 6560FR fast response temperature/conductivity probe, a YSI 6589FR fast response pH sensor, a YSI 6150FR fast response ROX optical dissolved oxygen sensor, a YSI 6136 turbidity sensor, a YSI 6025 chlorophyll sensor, and a YSI 6131 BGA-PC Phycocyanin (blue-green algae) sensor. Manufacturer's specifications for each of the probes are shown in table 1. All water-quality sensors are sampled at a rate of 1 hertz.

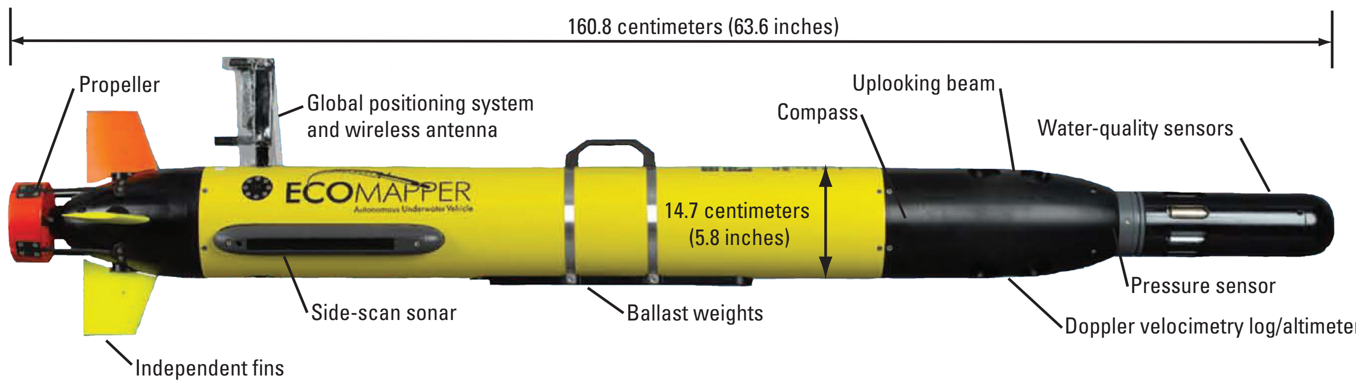


Figure 1. Schematic of the autonomous underwater vehicle.

Table 1. Manufacturer's specifications for the water-quality sensors aboard the autonomous underwater vehicle.

[mS/cm, millisiemens per centimeter; °C, degrees Celsius; m, meter; ppt, parts per thousand; mg/L, milligrams per liter; NTU, nephelometric turbidity units; µg/L, micrograms per liter; cells/mL, cells per millliter; %, percent; ft, foot; —, not specified; R^2, coefficient of determination]

Sensor	Range	Detection limit	Resolution	Accuracy	Linearity	Estimated lag, in seconds
Conductivity	0 to 100 mS/cm	—	0.001 to 0.1 mS/cm	±0.5% + 0.001 mS/cm	—	0.5
Temperature	−5 to 50º C	—	0.01º C	±0.15º C	—	2.1
Depth	0 to 656 ft (200 m)	—	0.001 ft (0.001 m)	±1 ft (±0.3 m)	—	—
Salinity	0 to 70 ppt	—	0.01 ppt	±1% or 0.1 ppt	—	—
pH	0 to 14 units	—	0.01 units	±0.2 units	—	*7.1
Dissolved oxygen	0 to 50 mg/L	—	0.01 mg/L	±0.1mg/L or 1%	—	5.5
Turbidity	0 to 1,000 NTU	—	0.01 NTU	±2% or 0.3 NTU	—	2.1
Chlorophyll	0 to 400 µg/L	0.1 µg/L	0.1 µg/L	—	R2 > 0.9999	2.1
Blue-green algae (phycocyanin)	0 to 280,000 cells/mL	220 cells/mL	1 cell/mL	—	R2 > 0.9999	2.1

*Can vary with age of sensor.

Manned Boat Deployments

Two manned boats were used in the synoptic surveys: the 19-ft M/V Sangamon aluminum workboat from Kann Manufacturing for the Milwaukee Estuary, and a 16-ft SeaArk jon boat for the Manitowoc River. Both boats were equipped with a Teledyne RDI 600 kilohertz Rio Grande® acoustic Doppler current profiler (ADCP) mounted on a rigid mount near the bow of the vessel (fig. 2). A Hemisphere Crescent® A100 Smart Antennae differential GPS receiver mounted directly over the ADCP was used to georeference the ADCP data. In addition, the GPS feed was used in conjunction with the HYPACK® software suite (HYPACK, Inc., 2011) for precise navigation along plan lines during the survey. Boat speeds were optimized during the survey to allow enough time to complete the survey without compromising data quality. When time allowed, repeat transects were obtained along survey lines to reduce the noise in the data. The ADCP data were post-processed and visualized using the Velocity Mapping Toolbox (VMT) (Parsons and others, 2013). Independent water-quality point measurements and profiles were made throughout the survey using a YSI 6920 multiparameter sonde equipped with a suite of sensors including temperature, specific conductance, pH, and dissolved oxygen. A turbidity

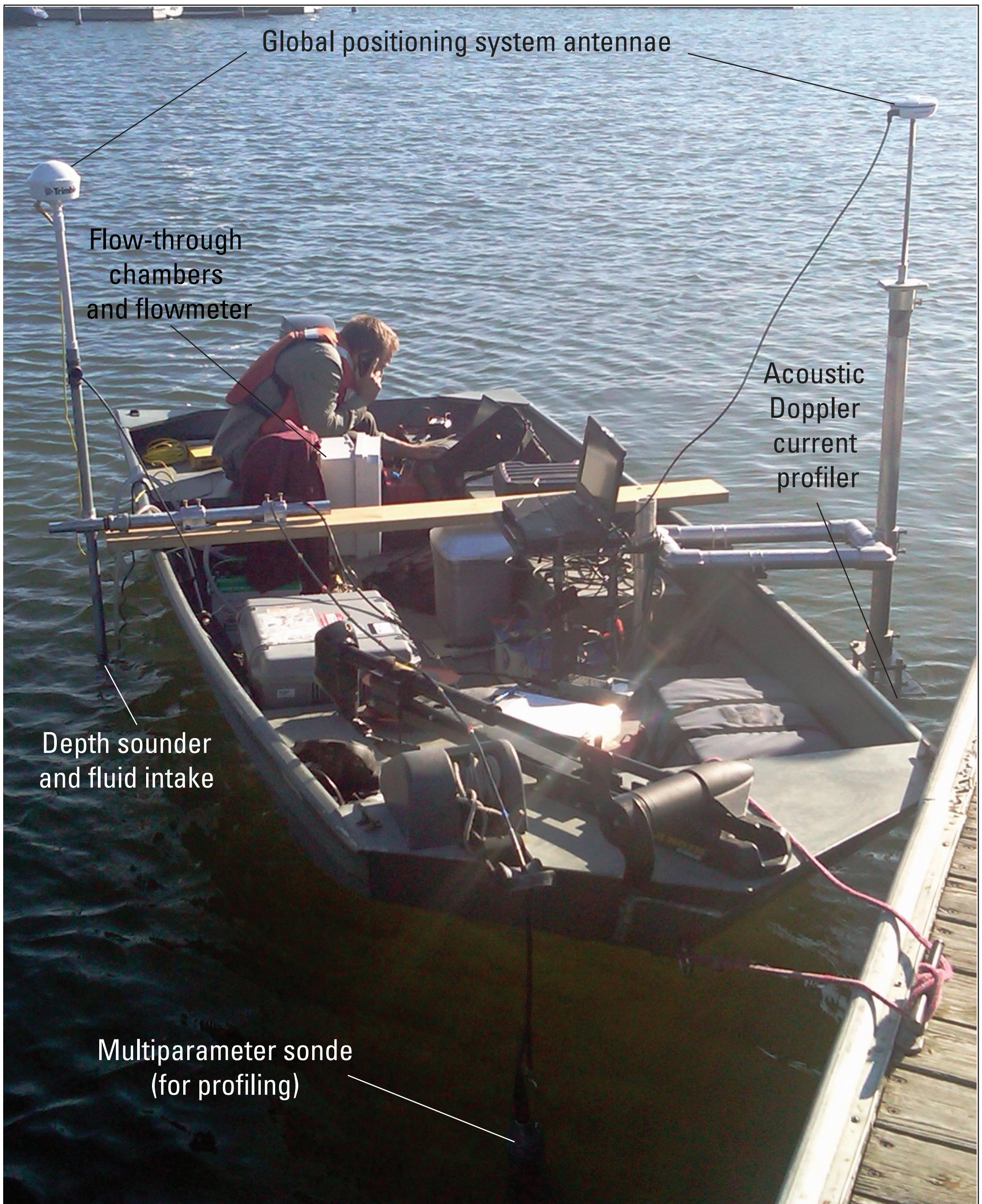


Figure 2. Manned boat and onboard equipment used in the Manitowoc rivermouth survey, Manitowoc, Wisconsin.

sensor was installed for the Milwaukee survey, but was not available for the Manitowoc survey owing to sensor circuit board failure; however, near-surface turbidity data were collected using the flow-through system described in the next section.

For the Manitowoc survey, the manned boat also was equipped with a flow-through water-quality sampling apparatus (fig. 2). The flow-through system included a YSI 6920 multiparameter sonde and a Turner C6, both of which had independent flow-through cells. The water intake for the systems was located approximately 1.5 ft below the water surface, and water was pushed through the system using a centrifugal pump at flow rates from 1 to 1.8 gallons per minute (gal/min). The centrifugal pump used in this system can affect dissolved oxygen readings; therefore, the dissolved oxygen data from this system were not used during data analysis. A flowmeter outputting data in real-time was used along with the known volume of the system to calculate the lag time between sample extraction and the time the sample reaches the sensors. Location of every sample was determined using a Trimble AG132 differential GPS. Dissolved oxygen, turbidity, conductivity, temperature, pH, fluorescent dissolved organic material (fDOM), system flow rate, and location were recorded at a rate of 1 hertz.

Data Processing

Processing of the manned-boat ADCP data was accomplished using the VMT by Parsons and others (2013). This software suite allows for transect averaging in addition to spatial averaging of the data to reduce noise in the velocity data. In addition, the suite allows for visualization of the velocity data in both plan view and for each cross section.

Processing of the AUV data is discussed in detail in Jackson (2013). Output from data-processing routines was further refined in ArcGIS® and graphics design software to generate the figures in this report. Jackson (2013) also discusses the method used to compute water density from measurements of temperature and specific conductance.

Case Studies of Two Lake Michigan Rivermouths

Integrated synoptic surveys of two Lake Michigan rivermouths are presented in this section. The two sites—Manitowoc and Milwaukee, Wisconsin—represent very different hydrodynamic settings, scales, and challenges. Nearly identical methods were employed in both surveys, using the AUV for harbor and nearshore surveying and manned boats for riverine surveys. However, the Milwaukee survey did not have the additional boat-mounted flow-through water-quality sampling instrumentation and relied on profiling with a multiparameter sonde for water-quality data in the rivers.

Milwaukee River Estuary, Milwaukee, Wisconsin

The Milwaukee River Basin includes the Milwaukee, Menomonee, and Kinnickinnic Rivers and has a drainage area of 850 square miles (mi^2). The three tributaries converge in the Milwaukee River Estuary in Milwaukee, Wisconsin (fig. 3). The Milwaukee River Basin, with a population of over 1.5 million people, is the most populated basin that flows directly into Lake Michigan (Great Lakes Commission, 2000). With the Milwaukee River Estuary located within the most densely populated part of the basin, the estuary has a disproportionately high level of pollution and was designated as an AOC by the International Joint Commission in 1987 (International Joint Commission, 1987). The AOC extends from approximately 2.9 miles (mi) upstream in the Milwaukee River, 2.6 mi upstream in the Menomonee River, and 1.5 mi upstream in the Kinnickinnic River through the inner and outer harbors and into coastal Lake Michigan to about 1.2 mi offshore from the harbor entrance (fig. 3). The AOC includes two major point sources: (1) a thermal input from the Valley Power Plant on the Menomonee River (approximately 250 cubic feet per second (ft^3/s) is withdrawn from the Menomonee River for cooling water and returned to the South Menomonee Canal; We Energies, 2012) and (2) discharge of effluent from the Jones Island Wastewater Treatment Plant into the outer harbor (approximately 230 ft^3/s average daily discharge; Henning and others, 2005) (fig. 3). The major concern within the Milwaukee River Estuary AOC is from both conventional contaminants (phosphorous and suspended solids) and toxic contaminants (metals and organic chemicals) (Great Lakes Commission, 2000). The main priorities for the AOC include remediation of contaminated sediments, control of nonpoint-source pollution, improvement of beach water quality, enhancement of fish and wildlife populations, and habitat enhancement (U.S. Environmental Protection Agency, 2013).

The U.S. Geological Survey (USGS) operates two streamgages within the AOC domain including one on the Menomonee River at 16th Street (04087142; 2.2 mi upstream of the mouth of the Milwaukee River) and one at the mouth of the Milwaukee River near the Hoan Bridge and the Jones Island Wastewater Treatment Plant (04087170). Two additional USGS streamgages are located just outside of the AOC including the Milwaukee River at Milwaukee, Wisconsin (04087000; 6.7 mi upstream of the mouth) and the Kinnickinnic River at South 11th Street (04087159; 3.5 mi upstream of the mouth). At the time of the survey (September 2010), the only streamgage continually collecting water-quality data was the Menomonee River streamgage as a part of the National Monitoring Network (Advisory Committee on Water Information and the National Water Quality Monitoring Council, 2006). All other streamgages were limited to continuous measurements of stage and discharge, with no water-quality observations. Point sampling of water quality is completed by the Milwaukee Metropolitan Sewerage District (MMSD) at

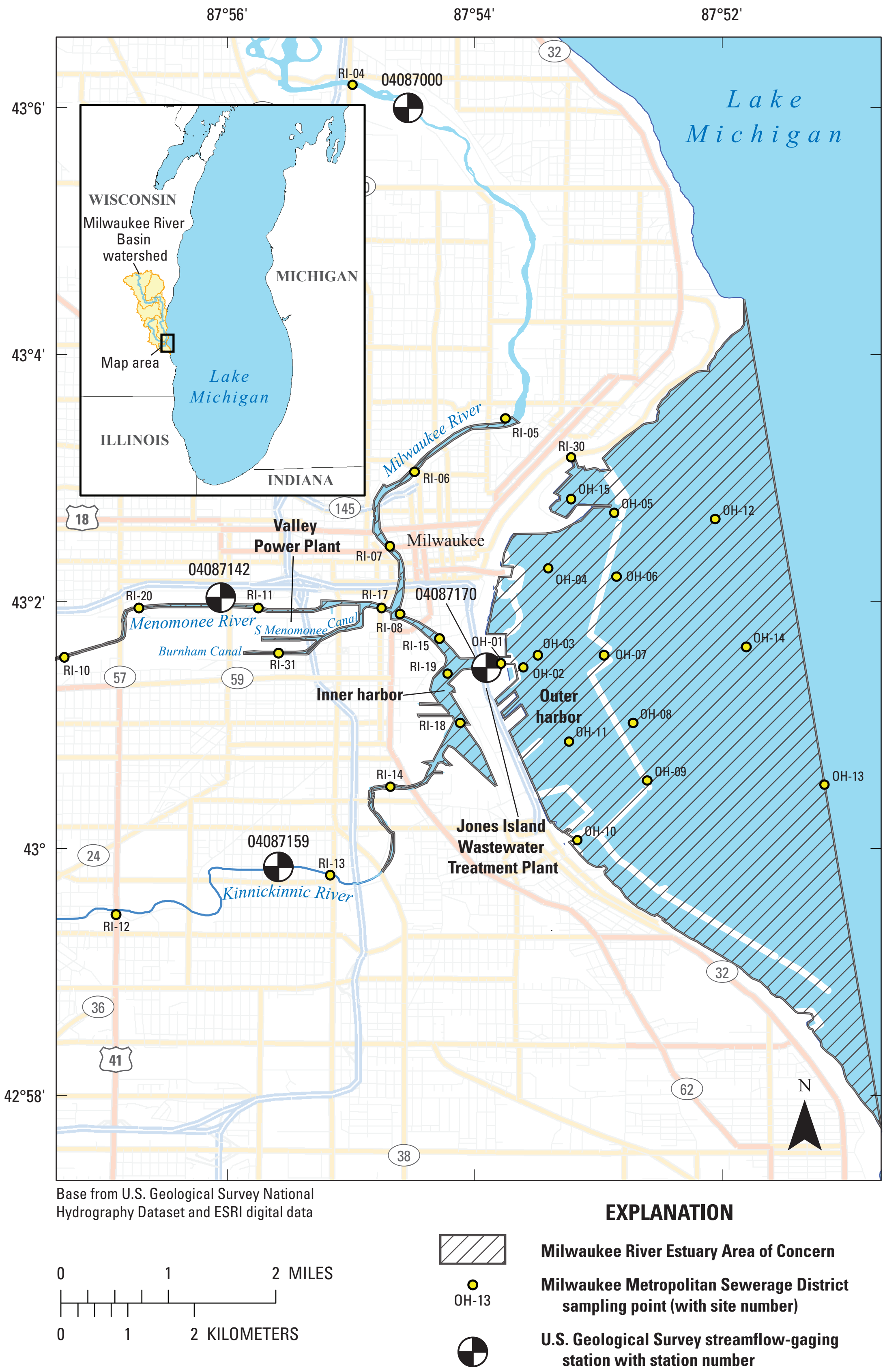


Figure 3. Milwaukee River Estuary and surrounding area including the mouths of the Milwaukee, Menomonee, and Kinnickinnic Rivers in Milwaukee, Wisconsin.

18 points within the outer harbor and nearshore parts of the AOC on a bi-weekly basis (Milwaukee Metropolitan Sewerage District, 2010). Additional point sampling is completed by the MMSD in the rivers and inner harbor at approximately 15 points in the AOC (bi-weekly) and at 16 points over an approximately 300 mi^2 area of nearshore Lake Michigan on a monthly basis. At sites greater than 4 meters (m) in depth, three samples are generally collected (1 m below the surface, 1 m above the bottom, and at mid-depth). Sites less than 4 m in depth are generally sampled at two depths (1 m below the surface and 1 m above the bottom) or at one depth (mid-depth) depending on site conditions. In rivers, samples are collected at mid-channel or where the predominance of flow is occurring.

To help interpret these data and understand observed variability between sampling points, a synoptic water-quality and water-velocity survey was performed during September 7–9, 2010, in the Milwaukee River Estuary AOC using a manned boat and AUV (fig. 4). The AUV was used to survey the inner and outer harbors, whereas the manned boat was used to complete velocity mapping in the outer harbor and discharge measurements, velocity mapping, and water-quality profiling at 16 points in the three tributaries (fig. 4). This survey coincided with point sampling efforts by the MMSD. Interpreting point samples of water-quality parameters in the Milwaukee River Estuary AOC requires an understanding of the mixing zones and hydrodynamics of the system. While this synoptic survey represents only one possible scenario for the system, it provides insight into the dynamics of the system and may aide in interpretation of continuous and periodic monitoring data collected at sampling sites within the rivers, harbors, and lake by the USGS and the MMSD.

Outer Harbor Profiles

Profiles of basic water-quality parameters were constructed from data collected during the AUV survey on September 9, 2010, in the outer Milwaukee Harbor (fig. 5). These profiles represent the median parameter values observed for a given depth and have been separated into two regions: north of the rivermouth and south of the rivermouth. The profiles show a weak thermocline at depths of about 12 to 13 ft, though the total change in temperature over the water column is only about 3 degrees Celsius (°C) (approximately 10.4 to 13.4 °C in the southern harbor). The water in the south part of the harbor is generally 1–2 degrees warmer, has a slightly higher specific conductance (0.01 millisiemens per centimeter (mS/cm)), and a lower density (0.1 kilograms per cubic meter (kg/ m^3)) at all depths than water in the north part of the harbor. The outer harbor has relatively high dissolved oxygen values (10.5 to 11.7 milligrams per liter (mg/L)), with the greatest dissolved oxygen occurring near the surface and decreasing below the thermocline. While dissolved oxygen values were generally equal in the north and sound ends of the outer harbor for the surface mixed layer, the hypolimnetic water on the south end of the harbor had a slightly higher (0.5 mg/L) dissolved oxygen compared to the north part of the harbor. Turbidity in the harbor was low (less than (<) 4 nephelometric turbidity units (NTU)) and slightly higher in the south end of the harbor. Both total chlorophyll and blue-green algae had maxima near the base of the mixed surface layer (top of the thermocline)—approximately 6 to 9 micrograms per liter (µg/L) and 750 to 1,100 cells per milliliter (cells/mL), respectively—and showed higher concentrations in the southern part of the harbor as compared to the northern part.

Figure 4. Study domain including the Milwaukee, Menomonee, and Kinnickinnic Rivers, and inner and outer Milwaukee Harbors in Milwaukee, Wisconsin.

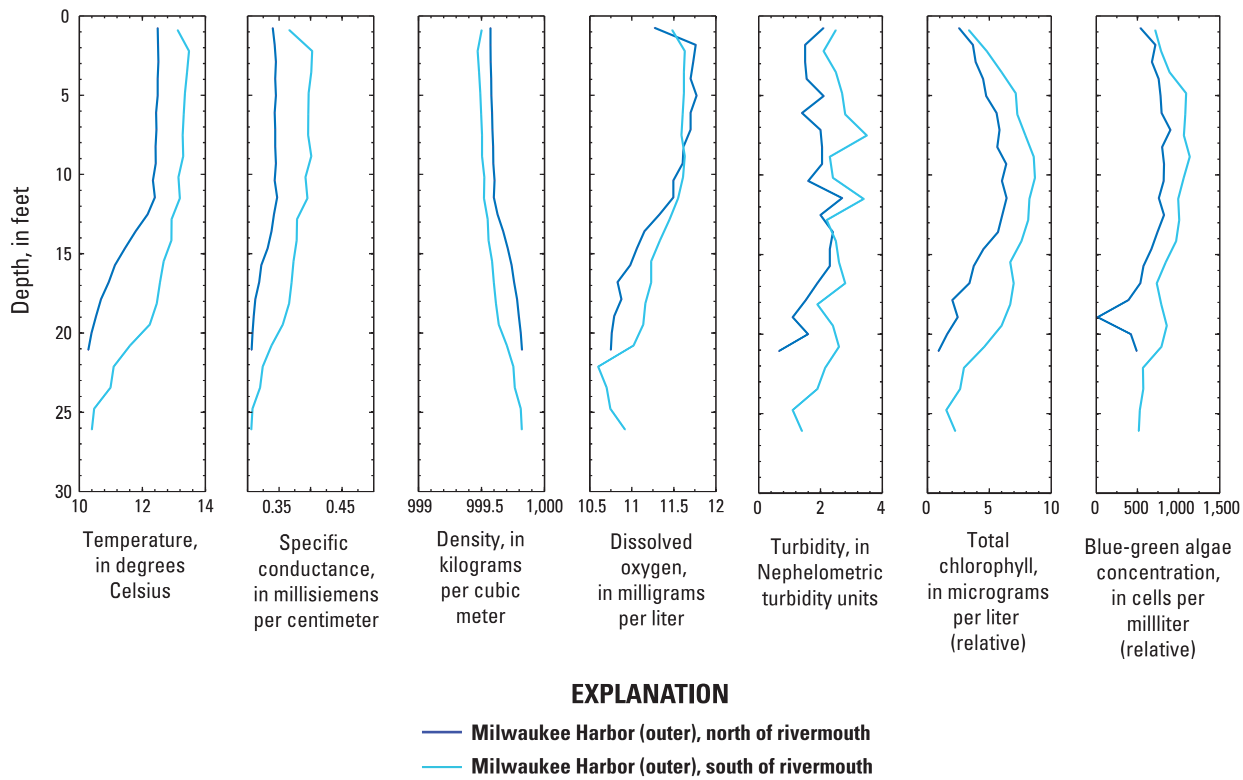


Figure 5. Profiles of water-quality parameters compiled from the autonomous underwater vehicle survey on September 9, 2010, in outer Milwaukee Harbor. These profiles represent the median parameter values observed for a given depth and have been separated into two domains: one domain north of the rivermouth and one domain south of the rivermouth.

Gradients and Mixing in the Milwaukee, Menomonee, and Kinnickinnic Rivers

The Milwaukee, Menomonee, and Kinnickinnic Rivers were in low-flow conditions at the time of this survey (2 weeks after last major high-flow event) (USGS National Water Information System; *http://waterdata.usgs.gov/nwis*), and no storm events were captured in this dataset (table 2). However, strong winds were present from the west-southwest at 15–25 miles per hour (mi/h) with gusts to 45 mi/h on September 7, 2010, during the survey of the rivers (observations from NOAA WBAN14839, Milwaukee Mitchell International Airport, located 5 miles south of the Inner Harbor). In general, the Milwaukee, Menomonee, and Kinnickinnic Rivers were warmer, had a higher specific conductance (with the exception of the Kinnickinnic River), lower dissolved oxygen, and higher turbidity than Lake Michigan water in the outer Milwaukee Harbor. The density of water in the three tributaries was less than lake water at the time of the survey resulting in an overflow and surface plume as the combined river water reaches the inner and outer harbors (fig. 6). Denser Lake Michigan water can be seen pushing upstream along the bed into the three tributaries approximately 1 mi up the Milwaukee and Menomonee Rivers and 1.5 mi up the Kinnickinnic River (fig. 6). The thermal plume from the discharge of the Valley Power Plant located approximately 1.2 mi upstream of the mouth creates a distinct increase in temperature and associated decrease in density. Any time isopycnals (lines of equal density) are tilted, as in the case of the interface between the lake water “wedge” and river water (fig. 6*A* and *B*), density-driven currents can develop and mixing will take place (Turner, 1973). The substantial decrease in density due to the Valley Power Plant outfall strengthens the density gradient locally and reinforces density-driven flows in the Menomonee and lower Milwaukee Rivers.

While substantial gradients in basic water-quality parameters and density developed in the inner harbor and the lower 2 mi of both the Milwaukee and Menomonee Rivers, the profiles furthest upstream in all three rivers, and the profile at the USGS streamgage on the Menomonee River (04087142) were relatively uniform and did not contain substantial vertical stratification.

Discharge and velocities in the Milwaukee River Estuary, which includes the lower Milwaukee, Menomonee, and Kinnickinnic Rivers, were highly variable during the survey. All three rivers are affected by backwater from Lake Michigan within the estuary and had measured negative discharges (upstream flow) as far upriver as 1.9 mi on the Kinnickinnic and 2.5 mi on the Milwaukee and Menomonee Rivers. Discharge measurements followed standard USGS protocol at the time of the survey (Mueller and Wagner, 2009), except for completing only four transects at each cross section regardless of the percent difference in the measured discharge. On September 7, 2010, a total of five discharge measurements were made on each of the Milwaukee and Menomonee Rivers over 120 and 95 minutes, respectively, whereas three measurements were made on the Kinnickinnic River over 60 minutes. All three rivers showed substantial variation in the discharge over these measurement periods with the changes from positive to negative discharge (or vice-versa) approximately every 30 minutes. The Milwaukee River had measured discharges ranging from −780 to 3,030 ft^3/s and only 30 minutes

Table 2. Characteristics (daily averages) of the Milwaukee, Menomonee, and Kinnickinnic Rivers, Wisconsin, for September 7–9, 2010.

[USGS, U.S. Geological Survey; —, not available]

USGS streamgage	River	Date	Discharge, in cubic feet per second	Temperature, in degrees Celsius	Specific conductance, in millisiemens per centimeter	Dissolved oxygen, in milligrams per liter	Turbidity, in formazin nephelometric units
04087000	Milwaukee	September 7, 2010.	328	—	—	—	—
		September 8, 2010.	393	—	—	—	—
		September 9, 2010.	352	—	—	—	—
04087142	Menomonee	September 7, 2010.	56	19.1	0.745	6.5	12
		September 8, 2010.	34	21.2	0.732	6.5	8.3
		September 9, 2010.	30	21.6	0.738	6.4	7.1
04087159	Kinnickinnic	September 7, 2010.	6.1	—	—	—	—
		September 8, 2010.	5.7	—	—	—	—
		September 9, 2010.	5.6	—	—	—	—

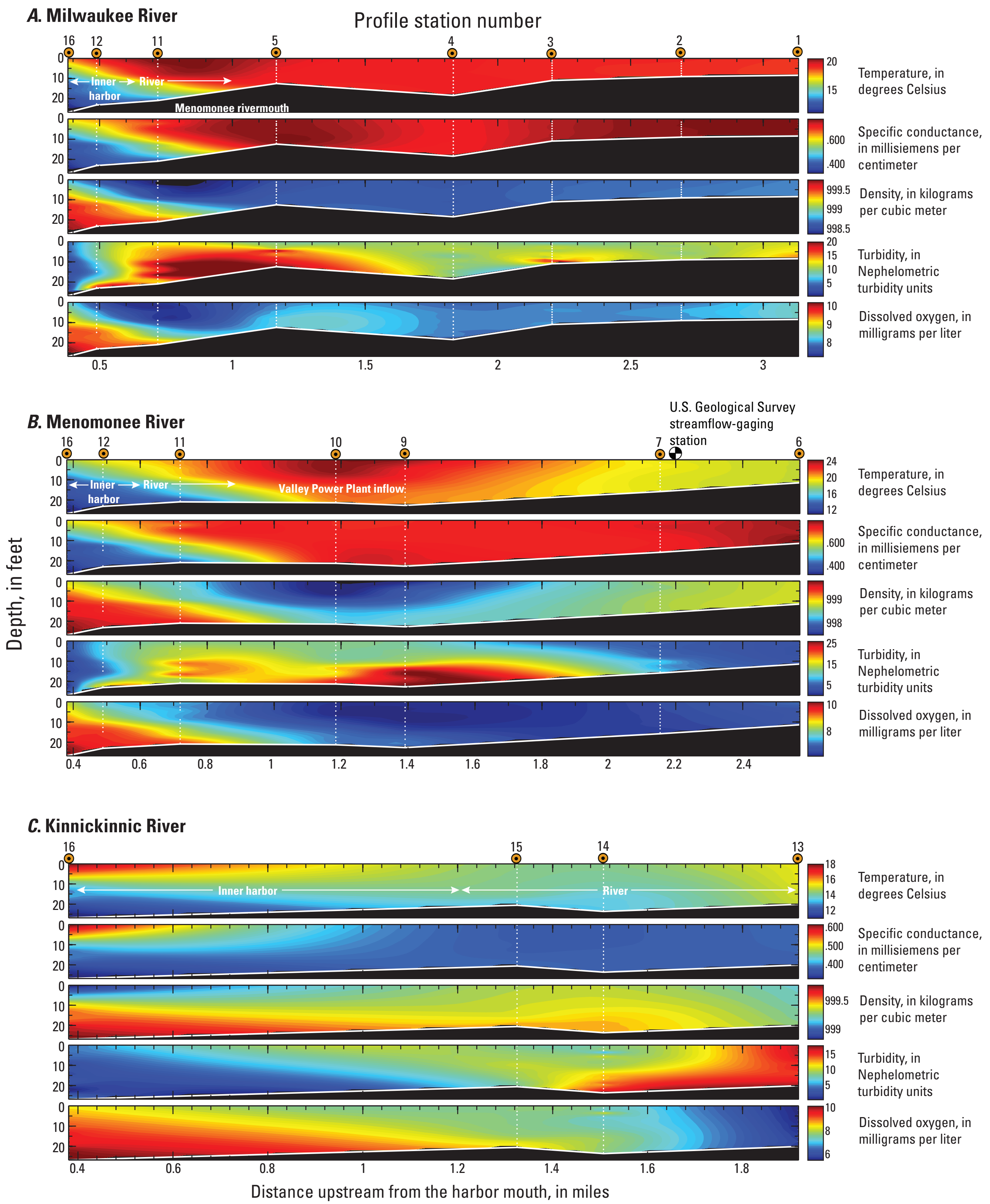


Figure 6. Streamwise sections of measured water-quality parameters developed from 16 profile stations in Wisconsin. *A*, Milwaukee River. *B*, Menomonee River. *C*, Kinnickinnic River. For reference, profile station numbers are shown at the top of each figure along with the location of the U.S. Geological Survey streamgage on the Menomonee River. Data were collected September 7, 2010.

separated these two extremes. The Menomonee River had measured discharges ranging from −350 to 1,100 ft^3/s with only 25 minutes separating these two extremes. The Kinnickinnic River had measured discharges ranging from −1,935 to 231 ft^3/s with only 23 minutes separating these two extremes. For reference, upstream of the estuary, the daily average discharges of the Milwaukee, Menomonee, and Kinnickinnic Rivers were 328, 56, and 6.1 ft^3/s, respectively (table 2). The highly variable flows in the lower reaches of these three tributaries not only indicates the flows in the estuary vary with lake seiche activity and wind-driven waves and currents (recall the high offshore winds observed on September 7, 2010), but such variability can lead to significant mixing in the estuary and difficulty in predicting water-quality distributions.

The highly variable flows observed in the estuary are consistent with the results from the unsteady flow model of House (1987) who found that lake seiche oscillations are responsible for upstream flows throughout the estuary, and major flow reversals can occur within 1 hour. The House (1987) model also showed that upstream and downstream flows driven by these oscillations within the estuary can exceed the average daily discharge by four times. Our observations of flow oscillations which exceed four times the daily average may be owing to the high winds present during the survey. While House (1987) did not include wind forcing in the final model, early model runs incorporated wind effects and showed little difference in the results with and without wind forcing. House (1987) does not give the details of the magnitude and direction of the wind forcing used in early model runs and attributes the lack of response to wind to the shelter of the estuary from tall buildings. Field observations from September 7, 2010, include observations of significant wind forcing all through the estuary and little shelter provided by the buildings. In fact, the buildings channeled the winds along the rivers creating significant difficulty controlling the sampling boat and occasional gusts and down-bursts so strong that river water was entrained into the wind to create fine droplets that “sprayed” the boat and its occupants (even in the absence of any significant waves).

Circulation in Outer Milwaukee Harbor

Outer Milwaukee Harbor is the receiving body for the three tributaries that enter the inner harbor. It also is the receiving body for effluent from the Jones Island Wastewater Treatment Plant. The outer harbor is approximately 0.75 mi wide, 3 mi long, and has three primary exchange points with Lake Michigan proper (one at the north end, one at the south end, and one in the middle) (fig. 7). In addition, the outer harbor exchanges water with marinas to the north and south of the harbor. The inner harbor connects with the outer harbor in the center of the harbor (from a north-south perspective) near the Jones Island Wastewater Treatment Plant (fig. 3).

Water circulation within the surface mixed layer (0 to 13 ft deep) in the outer harbor is primarily from north to south, consistent with the 8–10 mi/h northeasterly winds observed on September 9, 2010, (fig. 7*A*). Layer-averaged velocities are low (generally less than 0.2 foot per second (ft/s)) with the greatest magnitudes observed near the central part of the harbor where the river water enters the harbor and where the harbor exchanges with the lake. Higher magnitudes also were observed in the surface-layer near the southern exit of the harbor. Numerous low-velocity eddies were present in the outer harbor, primarily along the breakwater walls and along the western boundary of the harbor. While flow was primarily observed to be exiting the southern harbor exit, the central harbor exit had bidirectional flow in the surface water with water entering the harbor to the south and exiting to the north (fig. 7*A*).

In contrast to the surface layer, the near-bed layer (0 to 10 ft above the bed) exhibited recirculation as a primary feature and had substantially higher velocities than the surface layer, primarily near the rivermouth (fig. 7*B*). The near-bed water in the northern part of the harbor exhibited a counterclockwise rotation with near-bed water moving in opposite direction to the surface water, primarily near the eastern half of the harbor. A similar counterclockwise rotation occurred in the near-bed water in the southern part of the harbor; however, to the south of the rivermouth, the primary surface and near-bed currents are both aligned to the south-southeast (fig. 7*B*). Near-bed water at the central harbor exit was primarily to the west (indicating deeper lake water is entering the harbor) and a bi-directional flow was observed near the rivermouth with near-bed water flowing into the inner harbor along the south bank and near-bed water exiting the inner harbor along the north bank.

The two-fold increase in velocity magnitude of near-bed water over surface water near the rivermouth is due to two factors. First, the outfall of the Jones Island Wastewater Treatment Plant is located approximately 600 ft south of the rivermouth. This subsurface outfall located approximately 12 ft below the surface at average lake levels discharges effluent to the harbor at a daily average rate of approximately 230 ft^3/s and is clearly influencing the near-bed water velocity distribution. Layer-averaged velocities of 0.4 ft/s are seen just south of the outfall in the near-bed layer and such velocities should not be associated with the river plume, which is buoyant and primarily contained in the surface layer at this location (see later sections). Second, the near-bed velocity can exceed 0.5 ft/s in the rivermouth as dense lake water pushes into the inner harbor and up the rivers. The ebb and flow associated with lake seiche activity, wave action, inertial oscillations, wind forcing, and density variations drive these deep currents back and forth through this narrow opening between the inner and outer harbors, which accelerates the flow in this locale.

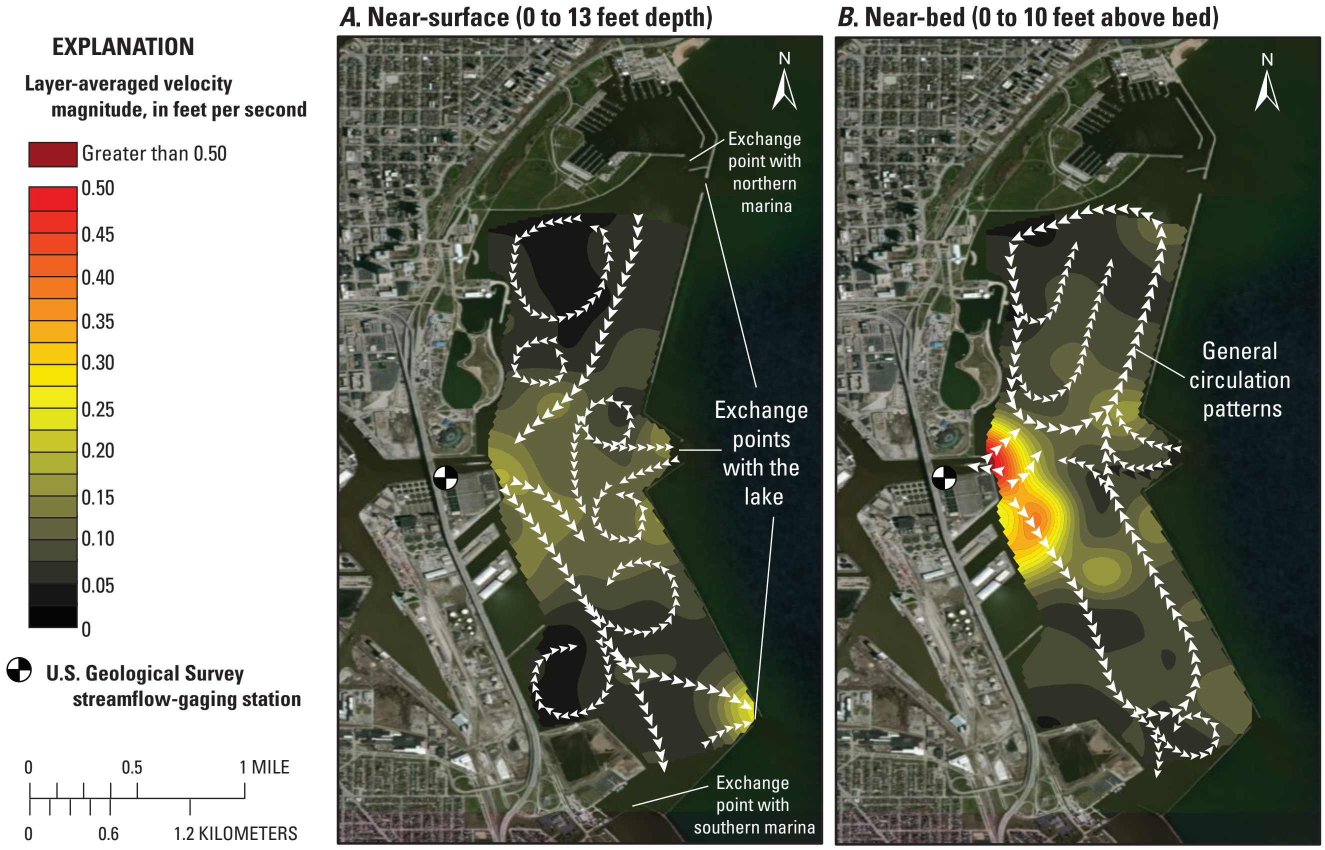


Figure 7. Distributions of layer-averaged velocity magnitude for the outer Milwaukee Harbor on September 9, 2010. *A*, Surface layer (0 to 13 feet depth). *B*, Near-bed layer (0 to 10 feet above bed). General circulation patterns derived from velocity vector fields from the same dataset are shown for reference.

Gradients and Mixing within the Milwaukee Estuary AOC

Based on the September 2010 observations, the highest gradients in water quality occur in the lower Milwaukee River between the confluence with the Menomonee River and the inner harbor, between the inner and outer harbor, and around the rivermouth and effluent outfall in the outer harbor (figs. 8 and 9). During the survey, the Milwaukee and Menomonee Rivers were the primary contributors to the thermal and specific conductance loading to the estuary, with the thermal load from the Valley Power Plant on the Menomonee River raising the temperature of the surface water by as much as 5 °C just prior to the confluence with the Milwaukee River (fig. 8). In spite of having specific conductance values nearly three time higher than Lake Michigan water (approximately 0.3 ± 0.015 mS/cm), the density of the water in the Milwaukee and Menomonee Rivers is controlled by temperature and the 10–15 degree higher temperatures in the Milwaukee and Menomonee Rivers compared to Lake Michigan (approximately 10–12 °C) results in a buoyant surface plume from the two rivers that reaches the inner harbor and mixes. Some of the river water mixes into the inner harbor and some moves out into the outer harbor (fig. 8). Unlike the Milwaukee and Menomonee Rivers, the lower Kinnickinnic River has a relatively low temperature and specific conductance and high density and takes on the characteristics of the inner harbor.

In all three tributaries, dissolved oxygen is low (less than 8 mg/L) relative to the outer harbor and Lake Michigan water (generally greater than 10 mg/L) (figs. 8 and 9). The surface plume carrying low dissolved oxygen water fills the inner harbor and spills out into the outer harbor where it combines with the plume from the Jones Island Wastewater Treatment Plant effluent outfall (fig. 8). By the time it reaches the outer harbor, the surface layer dissolved oxygen has only increased to about 9 mg/L through mixing with lake water. In contrast, the dissolved oxygen of the near-bed water (within 10 ft of the bed) exhibits more mixing with lake water in the inner harbor and up the lower Milwaukee River to the confluence with the Menomonee River and has concentrations approaching 11 mg/L by the time it reaches the outer harbor (fig. 9).

Distributions of near-bed water show evidence of cold, low specific conductance, and dense Lake Michigan water entering the outer harbor through the north and central

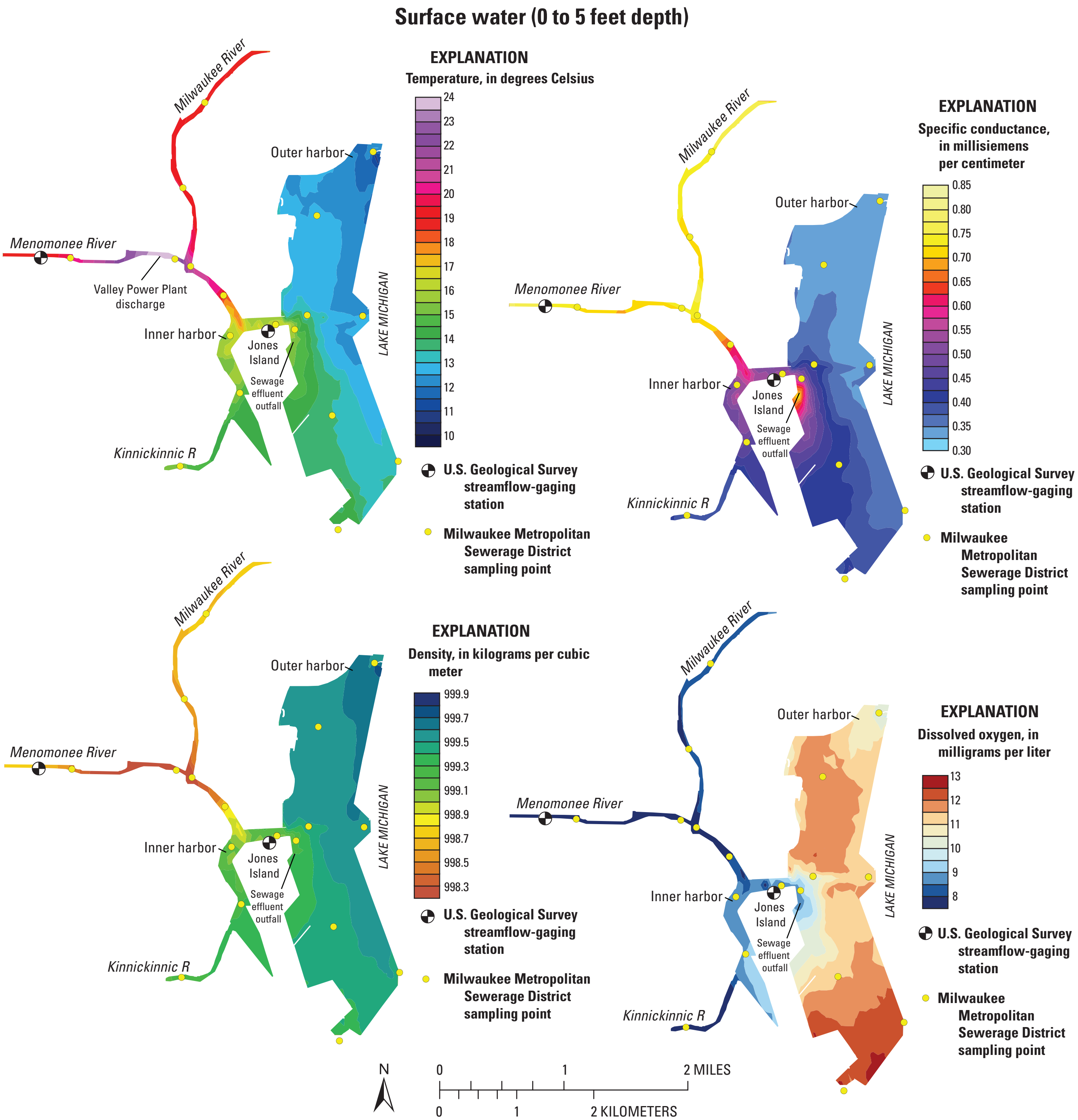


Figure 8. Distribution of basic water-quality parameters for the surface water (averaged over 0 to 5 feet depth) for the Milwaukee, Menomonee, and Kinnickinnic Rivers and inner and outer Milwaukee Harbor, Wisconsin, on September 7–9, 2010. The rivers were surveyed on September 7, 2010, while the inner and outer harbors were surveyed on September 8 and 9, 2010, respectively.

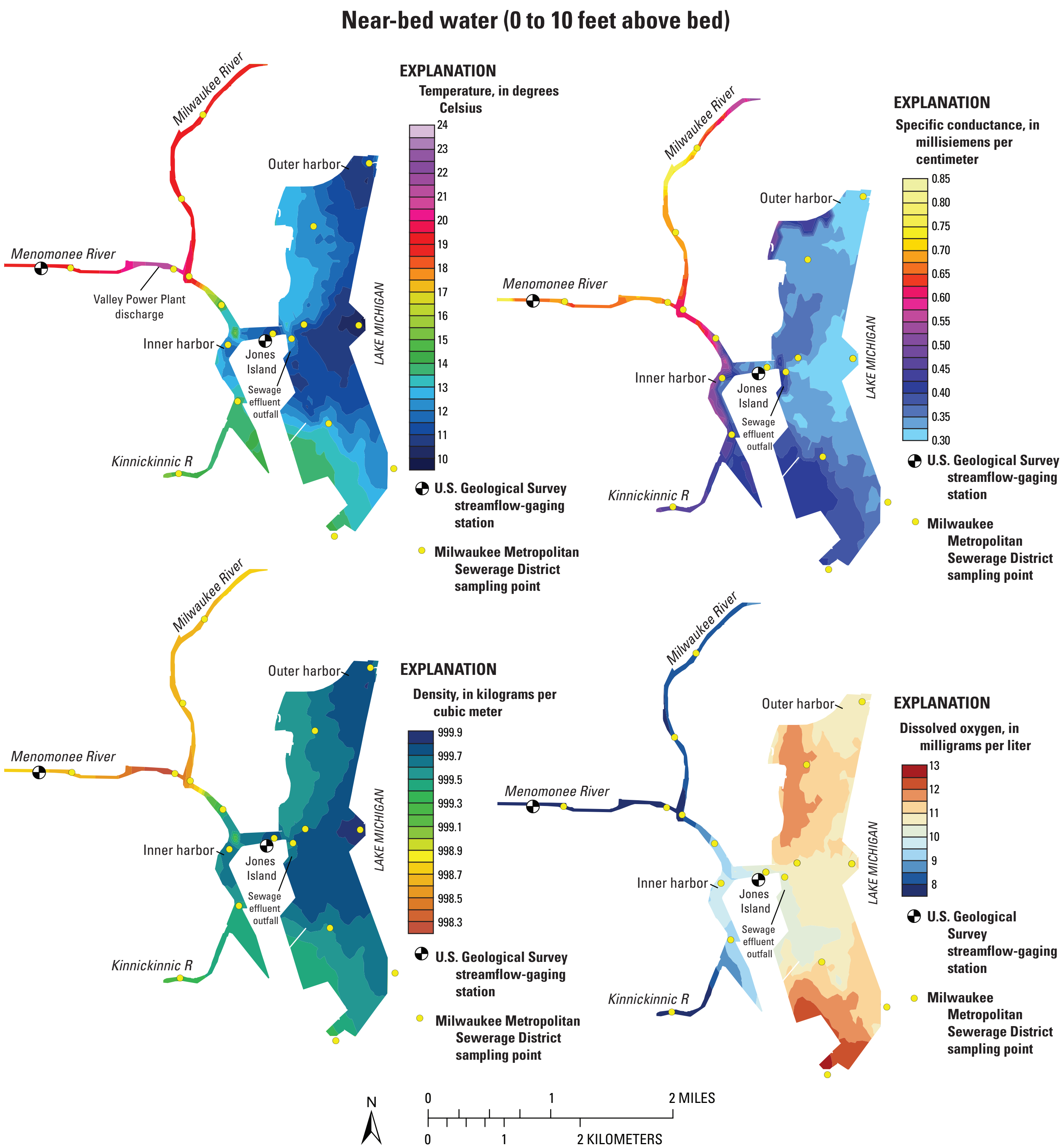


Figure 9. Distribution of basic water-quality parameters for the near-bed water (averaged over 0 to 10 feet above bed) for the Milwaukee, Menomonee, and Kinnickinnic Rivers and inner and outer Milwaukee Harbor, Wisconsin, on September 7–9, 2010. The rivers were surveyed on September 7, 2010, while the inner and outer harbors were surveyed on September 8 and 9, 2010, respectively.

exchange points and pushing into the inner harbor and up the tributaries approximately 1 mi (fig. 9). This intrusion of lake water into the Kinnickinnic, Milwaukee, and Menomonee Rivers is consistent with the streamwise profiles presented in figure 6. The substantially lower discharge of the Kinnickinnic River (5.6 to 6.1 ft^3/s; see table 2) as compared to the combined discharge of the Milwaukee and Menomonee Rivers (382 to 427 ft^3/s; see table 2) appears to not only substantially reduce the loading and influence of this tributary on the water quality in the inner harbor, but it allows the inner harbor and lake water to protrude further up the Kinnickinnic River beyond the domain of this survey. In spite of the highly oscillatory flows in the Milwaukee River Estuary, the wedge of lake water that was observed protruding up the Milwaukee River is arrested near the confluence with the Menomonee River (figs. 9 and 6). The upstream extent of the lake water influence is highly dependent on flow in the rivers, density differences between the rivers and the lake, bed slopes in the rivers, and lake seiche activity. These observations serve as one example of the mixing regime in the Milwaukee River Estuary, and in addition to understanding the hydrodynamics and mixing in the estuary, the data can provide a valuable dataset for modelers in need of data for model calibration and validation.

Mixing and dispersion of the river plume in the outer harbor is complicated by the effluent outfall from the Jones Island Wastewater Treatment Plant, which has a similar signature in terms of water quality to the river plume (high temperature, high specific conductance, low dissolved oxygen, and low density) (fig. 10). It is clear from the specific conductance

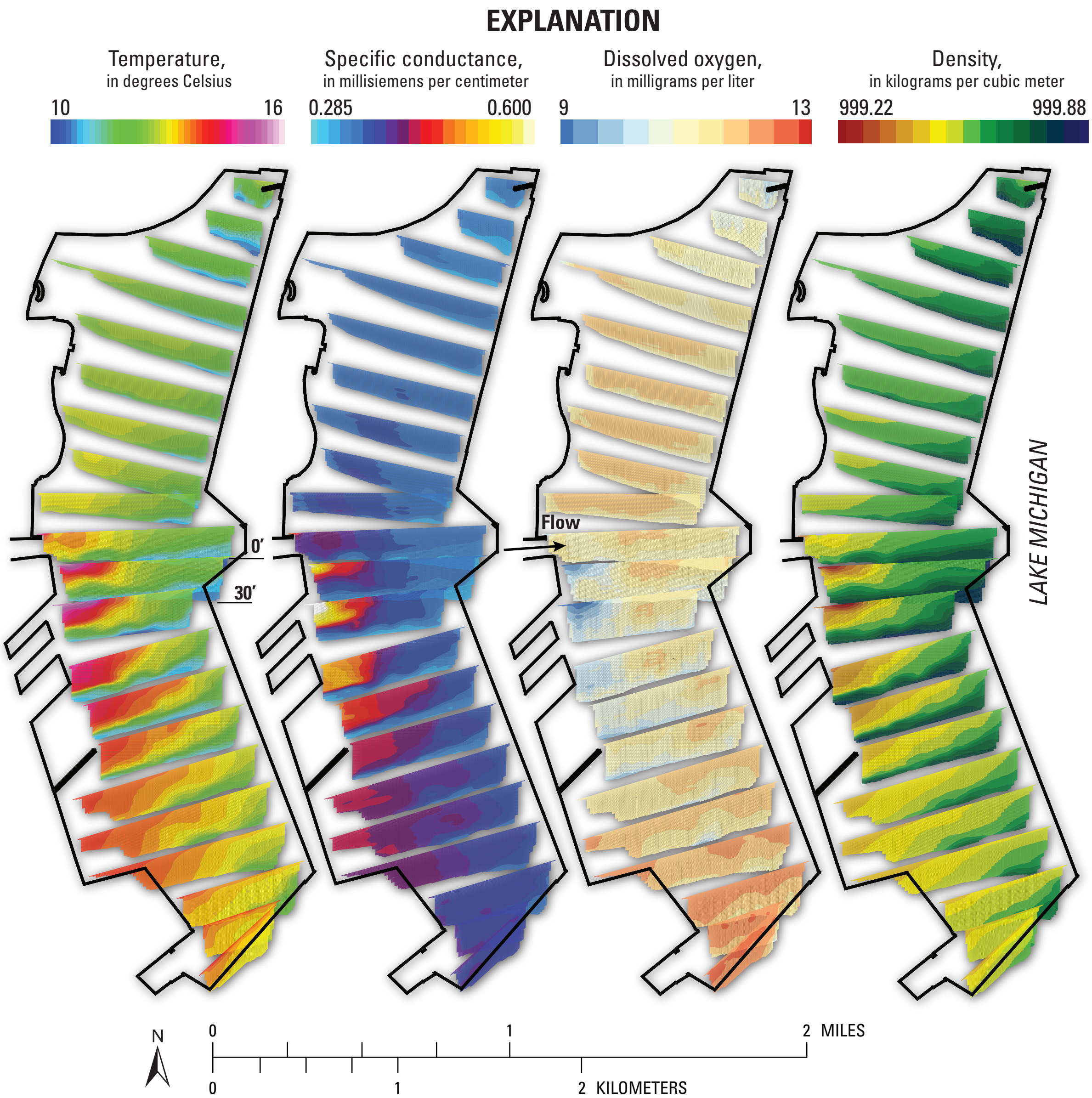
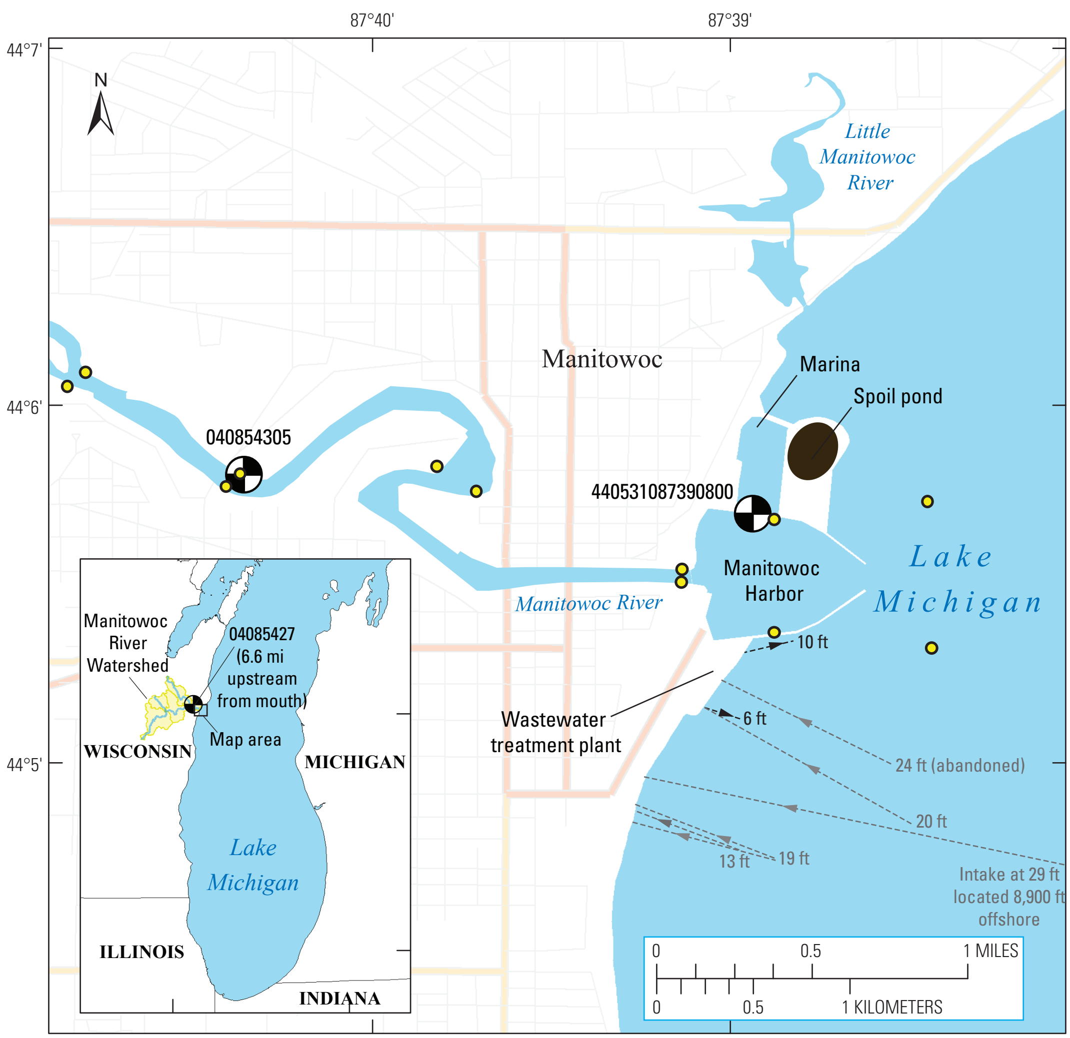


Figure 10. Three-dimensional distribution of basic water-quality parameters for the outer Milwaukee Harbor, Wisconsin, on September 9, 2010.

distribution in figure 8 that the effluent outfall is present and influencing the water quality in the outer harbor. Consistent with the circulation patterns observed in the outer harbor (fig. 7), the river plume coalesces with the outfall plume and moves south in the harbor primarily along the western half of the basin (fig. 10). As the plume moves south, it mixes deeper into the water column and dilutes considerably. For example, specific conductance in the center of the plume near the mouth of the river and outfall exceeds 0.6 mS/cm, yet by the time the plume reaches the southern boundary of the inner harbor, the plume has mixed across the full cross section and has a nearly uniform concentration of less than 0.4 mS/cm. While the river and outfall plume are mostly contained to the southern part of the outer harbor, there is some evidence of the plume north of the rivermouth (figs. 8, 9, and 10). A tongue of river and outfall water can be seen moving north in distributions of specific conductance in figures 8, 9, and 10. This tongue appears to be forming in response to primarily deep, near-bed currents that are advecting water to the north along the bed (fig. 7). Some of the river and outfall water is getting trapped in these currents and advecting north in the harbor, but mixing created by the opposing surface currents quickly disperses the northward plume before it can travel less than 1 mi (fig. 10).

Manitowoc Rivermouth, Manitowoc, Wisconsin

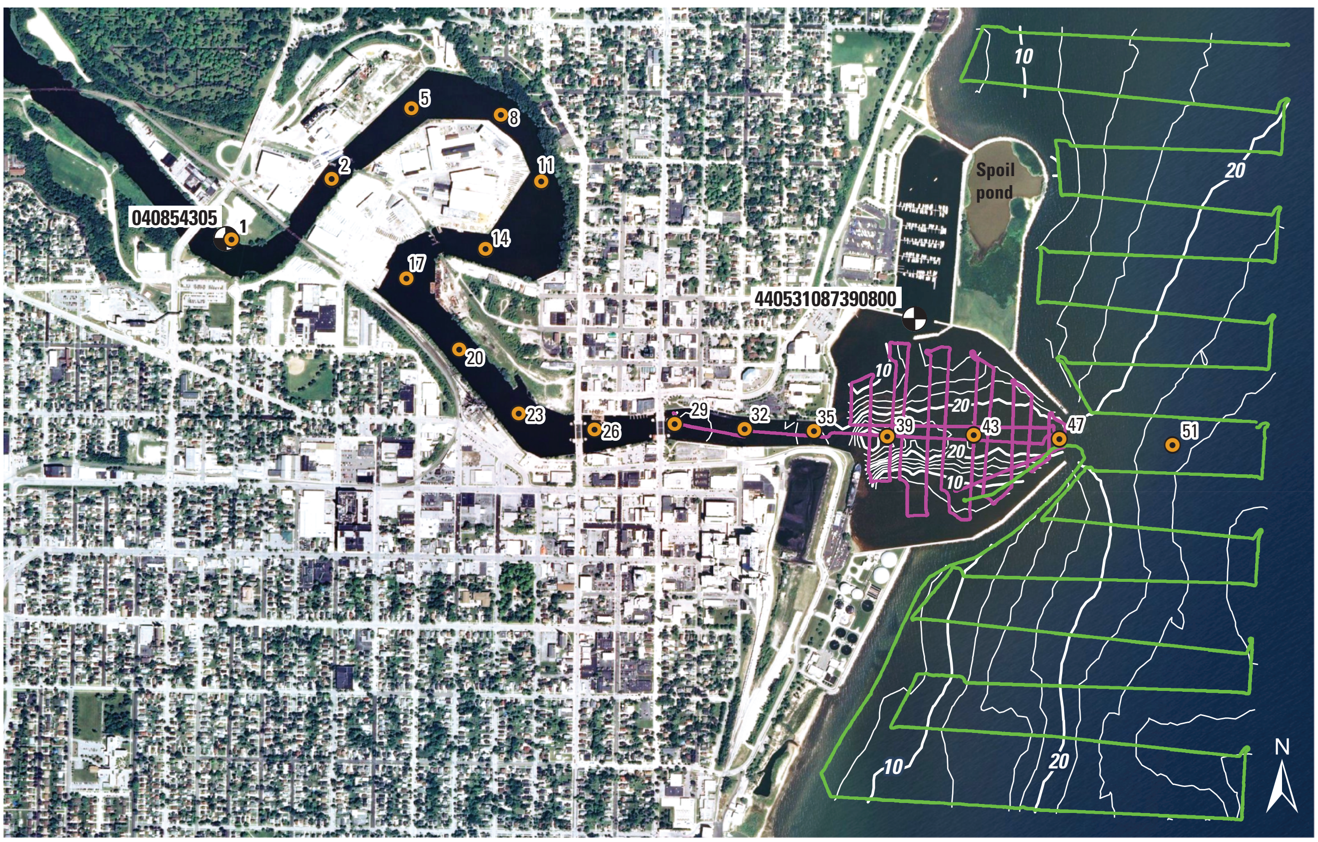
The Manitowoc River is a tributary to Lake Michigan and has a drainage area of 526 mi^2. Phosphorus, sediment, and coliform bacteria loadings from cropland and dairy waste runoff and point sources have impaired uses in the Manitowoc Watershed and nearshore waters (Gale and others, 1993). The lower 2 mi of the river are dredged to maintain a navigation channel for industry located in the lower reach (fig. 11). The Manitowoc River empties into the 80-acre Manitowoc Harbor before reaching Lake Michigan. North of the harbor are a 20-acre inner harbor and marina and a 24-acre spoil area with a 9-acre pond. One mi north of the harbor is the mouth of the Little Manitowoc River, a small 10 mi long stream that drains coastal lands (fig. 11). To the south of the harbor are two offshore sewer outfalls servicing a wastewater-treatment plant located just south of the harbor and six offshore water intakes servicing the wastewater-treatment plant and the Manitowoc Public Utilities of Manitowoc, Wisconsin.



Base from U.S. Geological Survey National Hydrography Dataset and ESRI digital data

Figure 11. Manitowoc Rivermouth, Manitowoc, Wisconsin, and surrounding area.

The USGS streamgage located 2.2 mi upstream of the mouth of the Manitowoc River (040854305) is part of the National Monitoring Network (fig. 11). As part of this program, continuous water-quality monitoring is performed at this streamgage. In addition, continuous water-quality data were collected at a USGS streamgage (440531087390800) at the south end of the marina during this survey and periodic point sampling is performed in nearshore Lake Michigan, in Manitowoc Harbor, and in the lower Manitowoc River by the Great Lakes Rivermouth Collaboratory (Pebbles and others, 2013) (fig. 11). To help interpret these data and understand observed variability between streamgages and sampling points, a synoptic water-quality and water-velocity survey was performed on September 19–20, 2011, in the lower Manitowoc River, Manitowoc Harbor, and nearshore Lake Michigan using a manned boat and an AUV (fig. 12). This survey coincided with sampling efforts by other research groups studying this rivermouth (members of the Great Lakes Rivermouth Collaboratory, unpub. data, 2010). Interpreting relations between observations at streamgages and disparate point samples of water-quality parameters in the lower Manitowoc River, Manitowoc Harbor, and nearshore Lake Michigan requires an understanding of the mixing zones and general circulation of the system. While this synoptic survey represents only one possible scenario for the system, it will provide insight into the dynamics of the system and aide in interpretation of continuous monitoring data collected by the USGS as part of the National Monitoring Network.



Base image from ESRI World Imagery Layer (http://goto.arcgisonline.com/maps/World_Imagery)

0 0.2 0.40 0.6 MILES
0 0.25 0.5 0.75 KILOMETERS

EXPLANATION

- Automomous underwater vehicle (AUV) survey path, September 19, 2011
- AUV survey path, September 20, 2011
- U.S. Geological Survey streamflow-gaging station with station number
- 8 Vertical profiling station with station number
- 20 Bathymetric contour, in feet (2.5 foot interval)

Figure 12. Survey lines, profiling locations, and bathymetry for the Manitowoc Rivermouth, Manitowoc, Wisconsin, and surrounding area. Bathymetric contours derived from depth soundings were collected by the autonomous underwater vehicle during the survey.

Nearshore Lake Profiles

Profiles of basic water-quality parameters were constructed from data collected during the AUV survey on September 19, 2011, in coastal Lake Michigan (fig. 13). These profiles represent the median parameter values observed for a given depth. The profiles show a very weak thermocline at a depth of about 10 ft, though the total change in temperature over the water column is less than 1 °C (approximately 16.5–17.1 °C). Hypolimnetic water is characterized by lower specific conductance, lower turbidity, and near equal pH and dissolved oxygen concentrations compared to hyperlimnetic (surface) water. Dissolved oxygen and pH both show a maximum at about 10 ft depth on the day of this survey. Chlorophyll and blue-green algae concentrations were generally uniform through the water column with elevated values near the surface (though some contamination from air bubbles is suspected in the surface data; note that both sensors were zeroed using deionized water during the one-point calibration process).

Gradients and Mixing in the Manitowoc River

The Manitowoc River was in low-flow conditions at the time of this survey and no storm events were captured in this dataset (last substantial high-flow event occurred 14 days prior to the survey on September 5, 2011) (USGS National Water Information System; http://waterdata.usgs.gov/nwis). Manitowoc River characteristics are shown in table 3 for two locations upstream of the mouth at USGS streamgages 040854305 (water quality) and 04085427 (discharge). In general, Manitowoc River water was slightly warmer, had a higher specific conductance, a higher pH, and higher dissolved oxygen than nearshore Lake Michigan water in the vicinity of Manitowoc Harbor. The density of Manitowoc River water was slightly less than lake water at the time of the survey, resulting in an overflow and surface plume as it enters the lake (fig. 14). Throughout the river survey, strong winds persisted from the south-southeast at 15–25 mi/h resulting in wind-driven (and possibly seiche-driven) surface currents in the upstream direction. In contrast, near-bed currents were primarily oriented downstream.

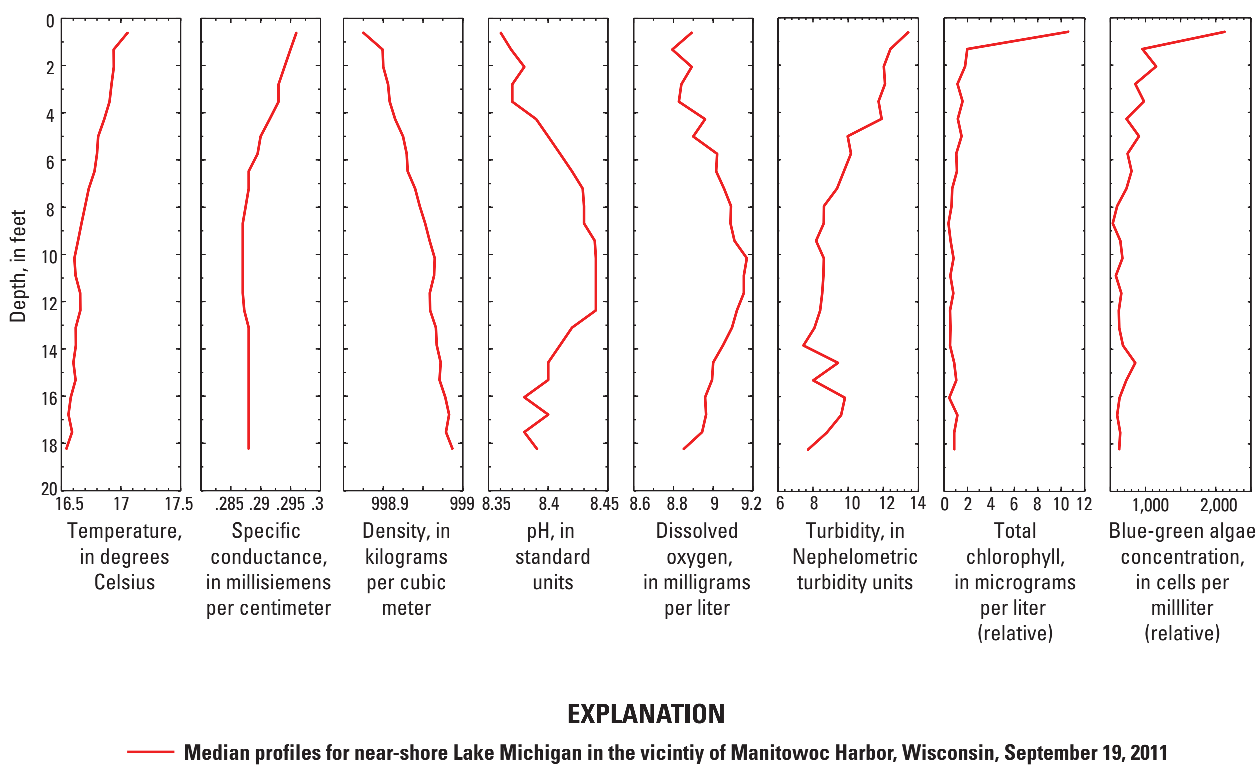


Figure 13. Profiles of water-quality parameters compiled from the autonomous underwater vehicle survey on September 19, 2011, in nearshore Lake Michigan. These profiles represent the median parameter values observed for a given depth.

Table 3. Characteristics of Manitowoc River water upstream of the mouth at Lake Michigan.

[USGS, U.S. Geological Survey; —, not applicable]

USGS streamgage	Date / time	Discharge, in cubic feet per second	Temperature, in degrees Celsius	Specific conductance, in millisiemens per centimeter	pH, in standard units	Dissolved oxygen, in milligrams per liter	Comments
040854305	9-20-2011 / 1450	—	17.8	0.659	8.65	10.59	On left bank at gage sensors, 2.2 miles upstream of mouth.
04085427	9-19-2011	37	—	—	—	—	6.6 miles upstream of mouth.
	9-20-2011	34	—	—	—	—	
	9-21-2011	40	—	—	—	—	

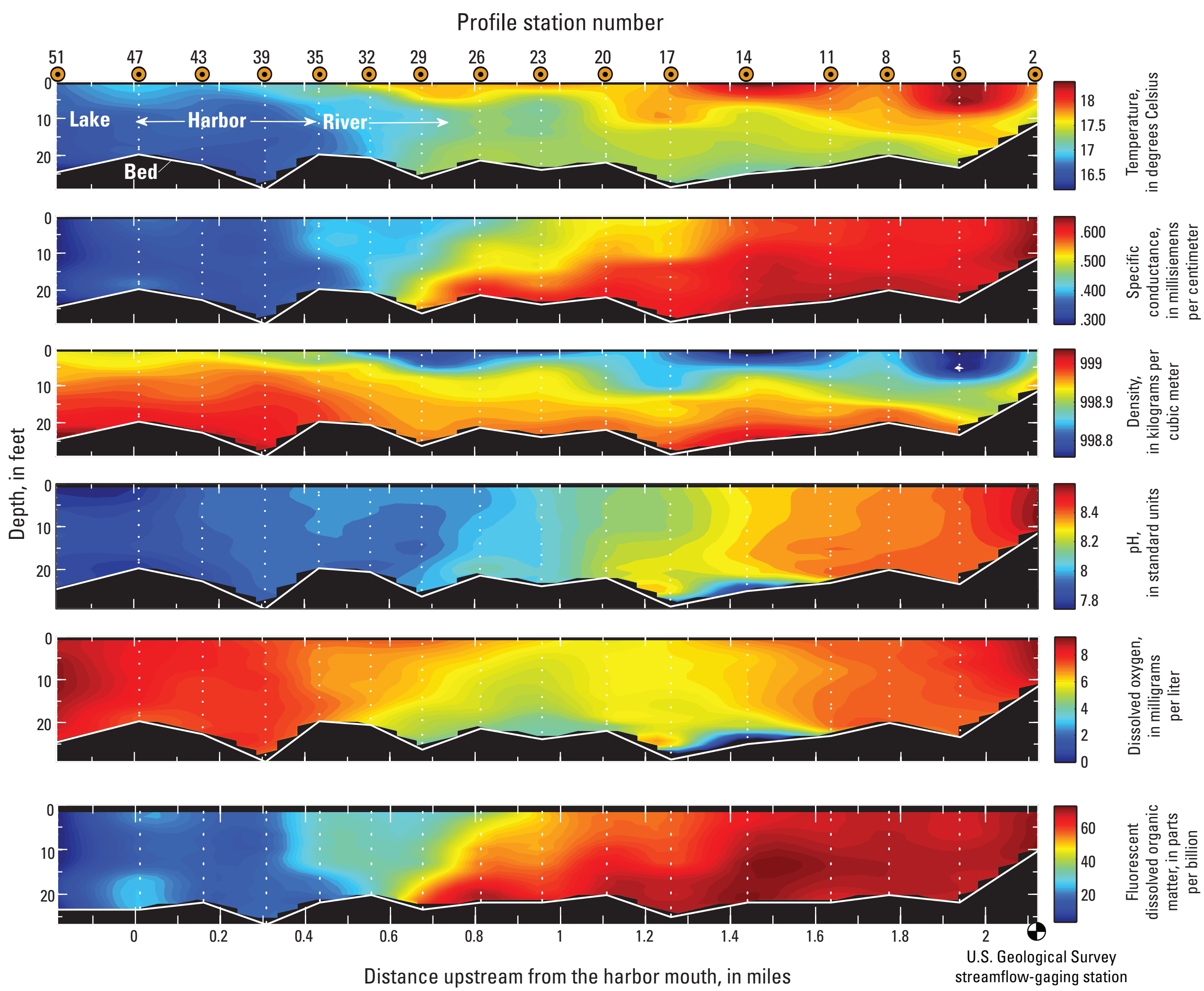
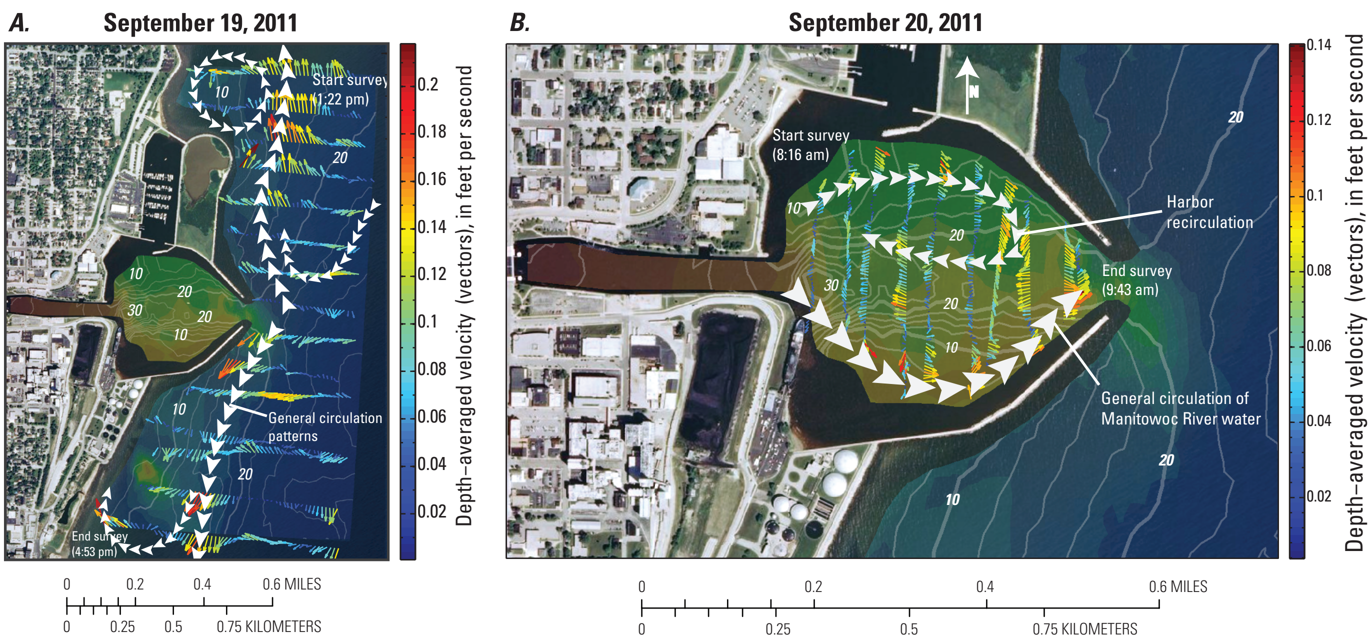


Figure 14. Streamwise sections of measured water-quality parameters developed from 16 profile stations along the lower 2.2 miles of the Manitowoc River, Manitowoc Wisconsin. For reference, profile station numbers are shown at the top of the figure, and the location of the U.S. Geological Survey streamgage on the Manitowoc River is shown at the bottom of the figure. Data were collected September 20, 2011.

The mixing in the mouth of the Manitowoc River, as visualized by the synoptic data from the September 19 and 20 surveys, has several noteworthy characteristics. First, water entering the artificially deepened navigation channel from the Manitowoc River extending approximately 2 mi upstream of the harbor mouth undergoes a sudden deceleration due to the larger channel cross-sectional area and increases in temperature (fig. 14). The increase in temperature is likely owing to anthropogenic sources (several outfalls were noted in the reach), but some effect of solar heating cannot be ruled out. Water with a density characteristic of lake water is seen as far as 2 mi upstream where the navigation channel ends, though the water mass appears to have undergone significant mixing to reach this point as the specific conductance of the water mass is close to that of river water (fig. 14). On September 20, 2011, the primary mixing zone in the river was between stations 14 and 35 (fig. 14). Within this region there is a significant change in temperature, specific conductance, pH, dissolved oxygen, and fDOM as the river water is diluted by lake water. The fDOM and specific conductance distributions in the river are highly correlated and display very similar distributions (fig. 14). Of particular interest is the formation of a low dissolved oxygen zone within the mixing zone with concentrations approaching 0 mg/L near the bed at stations 14 and 17. It is not clear what is causing this low dissolved oxygen zone, but it appears that the stratified conditions of the river mouth are sufficiently strong to inhibit mixing of oxygen to the riverbed at stations 14 and 17.

Circulation in Manitowoc Harbor and Nearshore Lake Michigan

Observations of circulation patterns in the Manitowoc Harbor and nearshore Lake Michigan in the vicinity of Manitowoc Harbor are limited to the conditions present on September 19 and 20, 2011 (fig. 15*A* and *B*, respectively). Therefore, these circulation patterns will likely not persist under different conditions (discharge, winds, and water quality). In addition, it is important to remember that temporal variability present during the survey will be captured in these circulation patterns, so care must be taken when interpreting these data. Nevertheless, these synoptic measurements provide insight into the mixing processes present in Manitowoc Harbor and nearshore Lake Michigan and may shed light on variability observed in routine point samples of water quality.



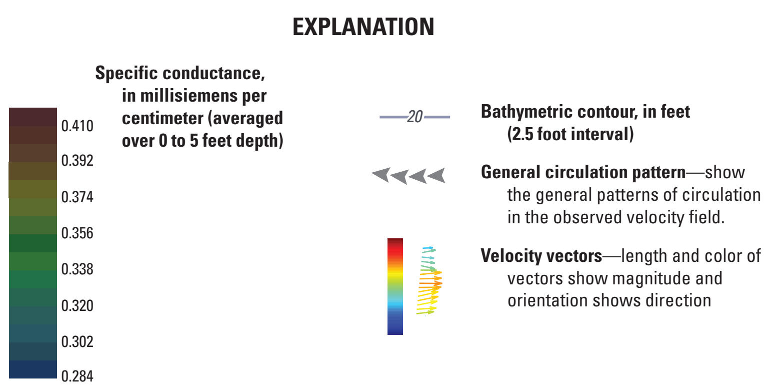


Figure 15. Depth-averaged velocity distributions (vectors). *A*, Coastal Lake Michigan near the mouth of the Manitowoc River, Manitowoc, Wisconsin, on September 19, 2011. *B*, Manitowoc Harbor on September 20, 2011. Specific conductance of the surface water (0 to 5 feet depth) measured over the same 2 days is shown as color gradations for reference.

A strong clockwise circulation cell was observed in the northern half of Manitowoc Harbor spanning nearly the full length of the harbor (fig. 15*B*). This recirculation was strongest near the bed, (fig. 16), yet persisted to the surface. Manitowoc River water enters the harbor with little momentum and circulates through the shallow water on the south end of the basin before exiting the harbor. Prior to exiting the harbor, the water near the surface accelerates through the contraction at the harbor mouth. The distribution of specific conductance near the surface shows good correlation with the observed circulation patterns (figs. 15 and 16) and displays signs of mixing in the harbor at the shear layer formed between the eastward river flow and the westward recirculation in the harbor.

In general, nearshore Lake Michigan in the vicinity of Manitowoc Harbor has variable circulation patterns. Depth-averaged velocities show a flow divide at the mouth of Manitowoc Harbor with alongshore currents to the north for regions north of the harbor mouth and southward currents to the south of the harbor (fig. 15*A*). Recirculating flow is observed to the north and south of the harbor resulting in the potential for trapping of contaminants within the recirculations near the shore. Decomposing the velocities into near-surface and near-bed layers (fig. 16) shows a southward alongshore current at the surface (likely driven by the observed west-northwest winds) and a relatively strong current flowing to the north near the bed (in opposition the surface current) north of the harbor mouth. Deep currents to the south of the harbor mouth are variable, perhaps resulting from interaction with the numerous outfall and intake pipes along the bed. Two nearshore (< 500 ft offshore) sewage effluent outfalls discharge in less than 10 ft of water and six water intake pipelines extend from 1,600 to 8,900 ft offshore and collect water from 13 to 29 ft below the surface (fig. 11). The northward deep current may be an artifact of the persistently strong (10–20 mi/h) winds from the southeast observed on September 18, 2010. The flow divide observed at the mouth of Manitowoc Harbor has the potential for transporting contaminants from the river both northward and southward along the lakeshore in spite of the primarily southward surface current observed in the lake.

Gradients and Mixing in the Manitowoc Rivermouth and Nearshore Lake Michigan

Water-quality distributions within the Manitowoc Rivermouth are presented in this section. Three dimensional distributions are presented in two dimensions by extracting data by layers (near-surface and near bed). Near-surface data are defined as any observations within 5 ft of the surface and near-bed data refers to observations within 10 ft of the bed (note that by this definition, observations in water less than 10 ft deep are considered to be part of both the surface and near-bed layers). Data visualizations also are shown with and without the inclusion of the river profile data to highlight subtle anomalies and mixing zones. Like the circulation data, temporal variability in the water-quality parameters over the course of the 2-day survey is present in these data. This is perhaps most apparent in temperature data which have relatively substantial diurnal variability most likely resulting from solar heating.

As the Manitowoc River approaches Lake Michigan, the near-bed water gradually cools as it mixes with cooler lake water while the surface water warms slightly as it enters the deeper navigation channel before cooling as it nears the lake (figs. 14 and fig. 17). The warming of the surface water may be associated with anthropogenic point sources (several outfalls were observed in this reach), but solar heating cannot be ruled out. As the river enters the harbor, the higher temperature river water hugs the southern wall of the harbor before exiting into the cooler lake water through the harbor mouth (figs. 17 and 15). Note that the high temperature anomaly at the mouth of the harbor is most likely an artifact of diurnal heating (the harbor was surveyed on the morning of September 20, 2011, whereas the lake was surveyed in the afternoon of September 19, 2011, resulting in a temperature discontinuity at the harbor mouth).

The thermal plume from the harbor dissipates quickly upon entering the lake (fig. 17), but appears to mix into deeper water as is evident by the persistence of the plume in near-bed water. An offshore sewer outfall formed a large anomaly and plume to the south of the harbor over the entire water column (fig. 17). The location of the anomaly is consistent with a sewer outfall marked on nautical charts of the area (fig. 11). The thermal distributions also reveal anomalies in shallow areas due to more efficient solar heating and an anomaly near the northeast corner of the seawall separating the spoil area from the lake. Visual inspection of aerial photos of the wall at this point revealed what appeared to be a permeable wall feature perhaps designed to allow for exchange of water between the spoil pond and the lake (visual observations in the field confirmed the apparent exchange of water through this part of the wall). The thermal anomaly detected indicates that higher temperature water from the spoil pond is entering the lake through the wall at this point.

Perhaps the best tracer for Manitowoc River water (and associated contaminants) is specific conductance owing to its conservative nature and relatively high concentration compared to lake water (recall Manitowoc River water had a specific conductance of 0.659 mS/cm compared to the lake, which had a mean value of about 0.290 mS/cm). As Manitowoc River water approaches the lake, the specific conductance decreases through dilution (figs. 14 and 18). The surface water is diluted faster than the near-bed water, which maintains a higher specific conductance as it approaches the harbor (figs. 14 and fig. 18). By the time the river water reaches the harbor, it has been diluted to about 60 percent of its original concentration at the USGS streamgage (040854305), 1.7 mi upstream of the harbor. As the river water enters the harbor, it hugs the southern end of the basin (consistent with velocity and temperature observations) and dilutes by another 10 percent as it mixes across the harbor (fig. 18). Both surface- and near-bed water exhibit similar distributions in the harbor indicating rather efficient vertical mixing in the harbor. In contrast, the recirculation cell in the northern part of the harbor seems to be sufficiently strong to maintain lower specific conductance within the cell and a horizontal gradient from north to south across the harbor. Mixing can be observed as tongues of higher specific conductance water are entrained into the recirculation (fig. 15).

As the diluted river water exits the harbor into the relatively uniform, low specific conductance lake water, it spreads as a plume primarily to the south (fig. 18). The plume mixes rapidly and overall concentrations are reduced by 15 percent within 0.25 mi of the mouth of the harbor. As the plume spreads south, it deepens and coalesces with the plume from the offshore sewer outfall and continues to spread south offshore. A weak secondary plume is evident in the data to the north of the harbor mouth. While this plume is connected with the harbor mouth by a thin band along the shoreline, it may have a secondary source including the leakage from the spoil pond or perhaps the Little Manitowoc River, a stream that enters the lake about 1 mi north of the mouth of the Manitowoc River.

The distribution of pH was similar to that of specific conductance with a few important differences. A diurnal variation of about 0.5 pH units in the lake at sampling station 51 caused slightly differing results between figures 14 and 19. On the morning of September 20, 2011, the lake had a pH of about 7.9 at site 51, whereas the AUV data from the afternoon of September 19, 2011, had a pH of about 8.4 for this same location. Therefore, the longitudinal profiles displayed in figure 14 show a steady decrease in pH as the river water enters the lake, whereas figure 19 shows a decrease in pH from the river into the harbor and then an increase in pH as the river enters the lake. The two instruments used in these measurements were checked against one another in the field on September 20, 2011, and found to be within 0.03 pH units of one another. Therefore, the variation in lake water pH at site 51 is assumed to be real and owing to diurnal variations resulting from biological production or contamination of site 51 by effluent from the offshore outfalls south of the harbor.

Unlike specific conductance, pH in the harbor is relatively uniform (fig. 19). The data do not show the circulation of river water along the south end of the harbor as was seen with temperature and specific conductance. In contrast, the pH distribution in the lake clearly visualizes the plume from the mouth of the harbor and the plume from the offshore outfall south of the harbor. The pH data also exhibit a low pH plume, of similar magnitude as the Manitowoc plume, emanating from the permeable part of the seawall separating the spoil area from the lake. This plume is visible in both the surface water and near-bed water (fig. 19). Finally, additional low pH zones are evident south of the harbor at the location of the sewage effluent outfall and north of the offshore outfall near the shoreline. North of the harbor, the pH decreases slightly near the spoil pond exchange point with the lake (fig. 19) and along the shoreline to the north.

As Manitowoc River water enters the deep navigation channel about 0.2 mi downstream of USGS streamgage (040854305), the dissolved oxygen level drops rapidly (figs. 14 and 20). Dissolved oxygen levels reach a minimum value at station 14 near the bed (observed values dropped below 1 mg/L and surface values about 5.8 mg/L, or about one-half the concentration observed at the streamgage 0.9 mi upstream) and then increase again approaching the harbor. Dissolved oxygen distribution in the harbor is relatively uniform over the depths, but shows lower levels on the south end of the harbor. This distribution is consistent with temperature, specific conductance, and the observed circulation pattern in the harbor. The dissolved oxygen plume emitted from the mouth of the harbor quickly bends to the south and dissipates within 0.25 mi from the harbor mouth. Nearshore waters both south of the harbor and north of the harbor exhibit lower dissolved oxygen values compared to offshore waters. The anomalies to the south of the harbor are in the vicinity of the sewage effluent outfall and nearshore areas adjacent to the wastewater-treatment plant where a visible discoloration of the water was observed during the survey (dark, biological sludge in the water). This may be a result of decomposing organic matter, which would be consistent with the sag in dissolved oxygen in this area. Lastly, the linear gradient in dissolved oxygen at the north end of the coastal Lake Michigan survey is likely owing to diurnal variations in dissolved oxygen brought on by biological production (photosynthesis). The morning of September 19, 2011, was overcast with light rain, followed by a clearing sky in the afternoon, resulting in a prolonged dissolved oxygen sag in the morning and a rise in the afternoon brought about by the increased solar radiation.

The distribution of turbidity was relatively uniform throughout the lower reach of the river, harbor, and lake with slightly higher turbidity values observed nearshore (fig. 21). In general, turbidity values were observed to be less than 20 NTU throughout the survey area except south of the harbor near the wastewater-treatment plant where turbidity values of up to 60 NTU were observed. The location of this anomaly in turbidity coincides with a low dissolved oxygen anomaly, low pH anomaly, and visual observations of water discoloration along the shoreline (biosludge). No significant turbidity anomaly was detected from the Manitowoc River, though no turbidity data were collected upstream of station 29.

Distributions of total chlorophyll and blue-green algae concentration in Manitowoc Harbor were uniformly low with an increase in concentration of both parameters at the mouth of the harbor (fig. 22). However, entrainment of air bubbles is suspected of causing contamination of some of the data when the AUV was on the surface. This contamination is apparent in the repeatedly high concentrations observed at the limits of the lake survey extent where the AUV surfaced to make turns. Therefore, care must be taken when interpreting these data, especially data collected on the surface. It also is important to remind the reader that these concentrations are relative and not absolute. One-point calibrations were performed on these sensors (zeroed in deionized water) (see Jackson, 2013).

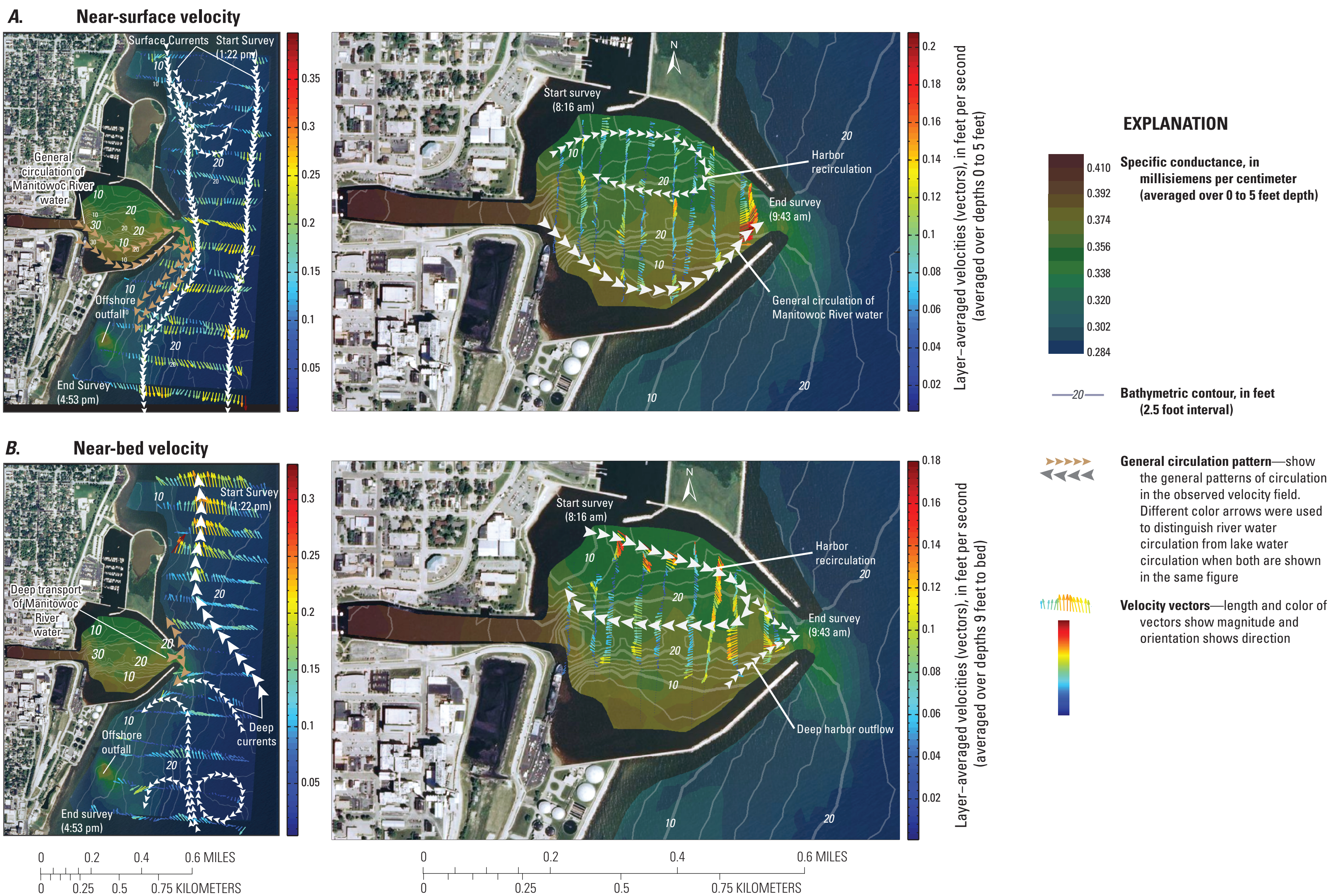


Figure 16. Layer-averaged velocity distributions (vectors). *A*, Near-surface layer (0 to 5 feet depth) in coastal Lake Michigan near the mouth of the Manitowoc River and Manitowoc Harbor, Wisconsin, on September 19 and 20, 2011. *B*, Near-bed layer (below 9 feet depth) in coastal Lake Michigan near the mouth of the Manitowoc River and Manitowoc Harbor on September 19 and 20, 2011. Specific conductance of the surface water (0 to 5 feet depth) measured over the same 2 days is shown as gradations for reference.

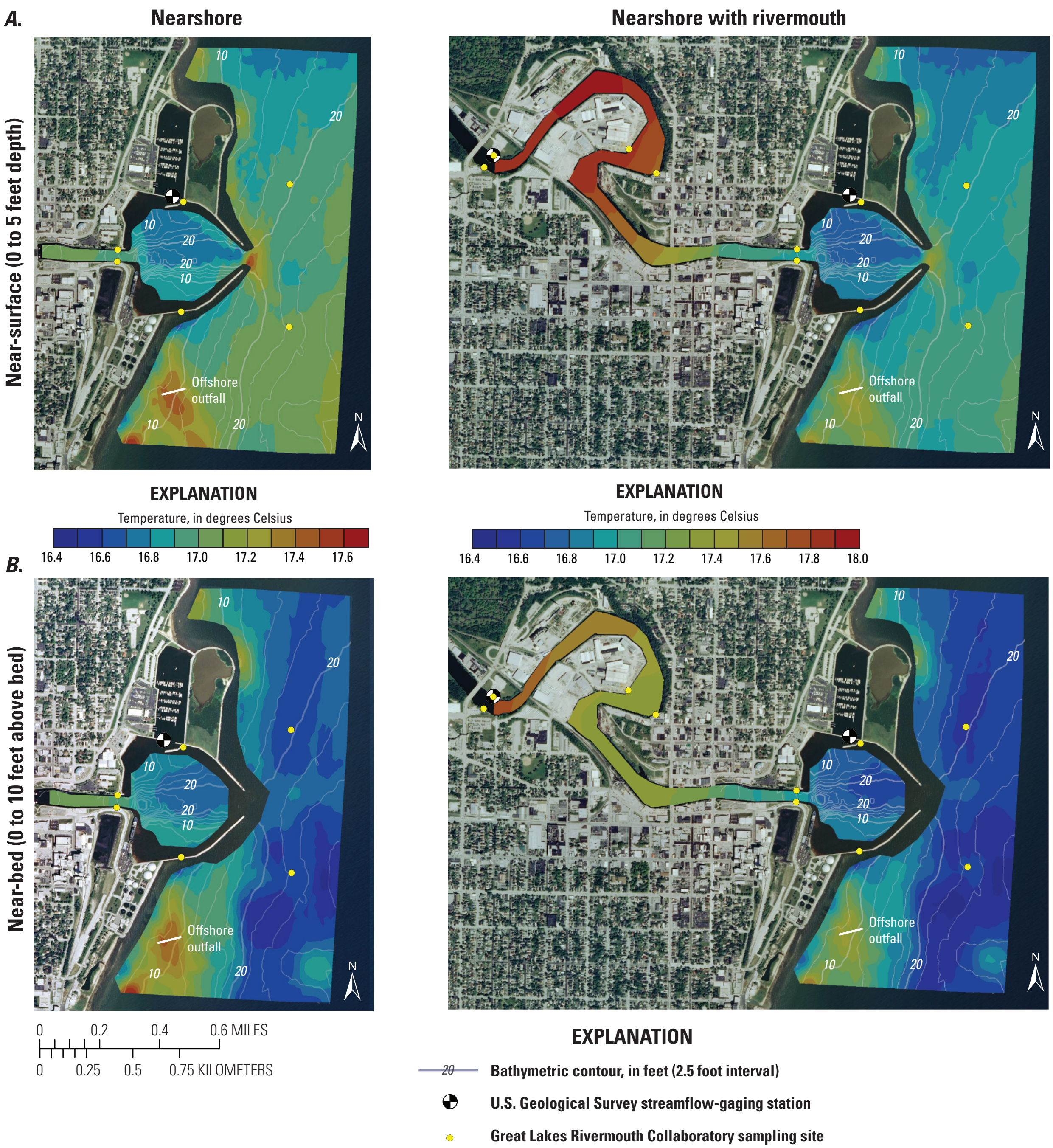


Figure 17. Layer-averaged distributions of water temperature in the Lower Manitowoc River, Manitowoc Harbor, and nearshore mixing zone as compiled from measurements on September 19 and 20, 2011. *A*, Near-surface layer (0 to 5 feet depth). *B*, Near-bed layer (0 to 10 feet above bed).

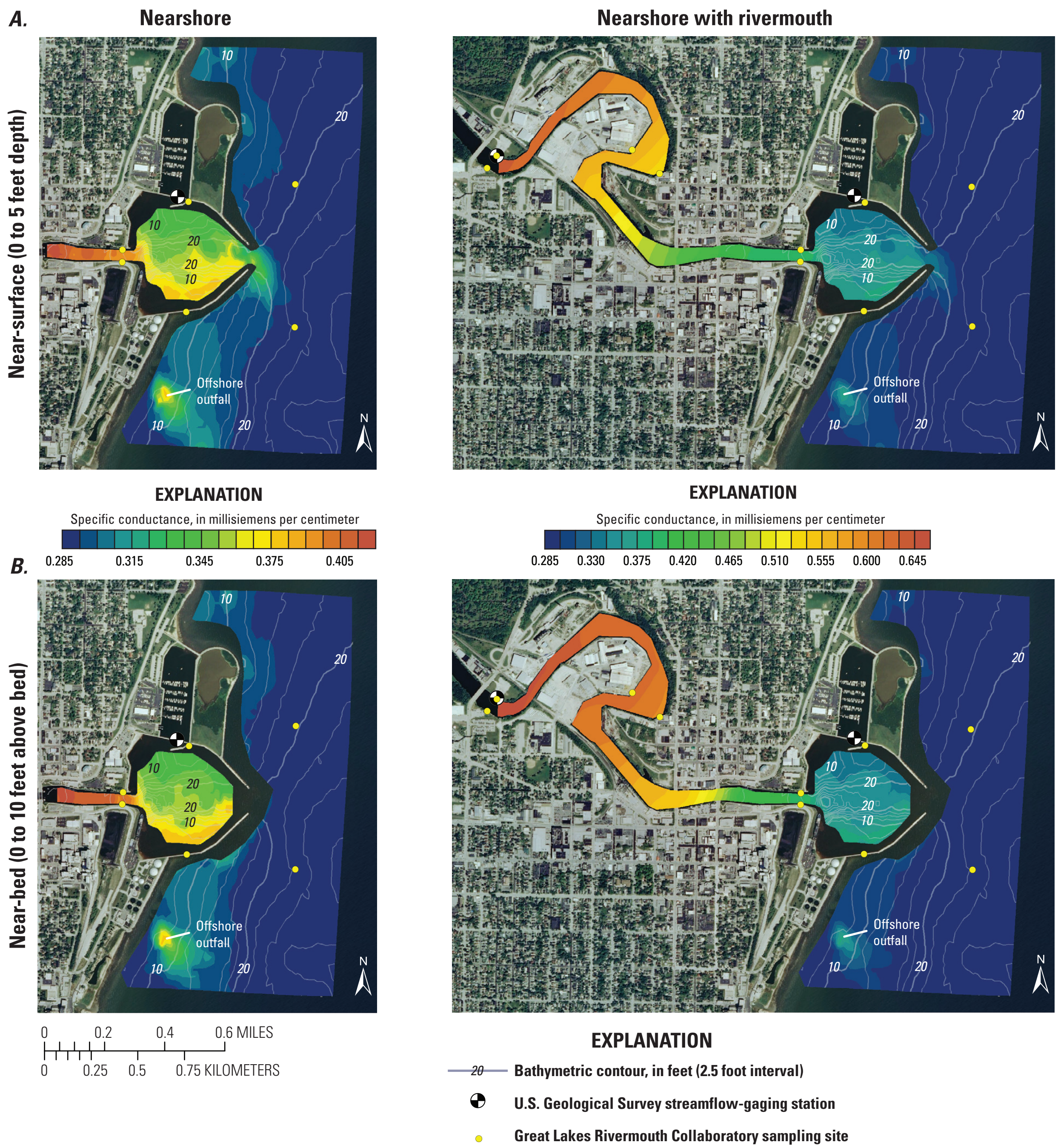


Figure 18. Layer-averaged distributions of specific conductance in the Lower Manitowoc River, Manitowoc Harbor, and nearshore mixing zone as compiled from measurements on September 19 and 20, 2011. *A*, Near-surface layer (0 to 5 feet depth). *B*, Near-bed layer (0 to 10 feet above bed).

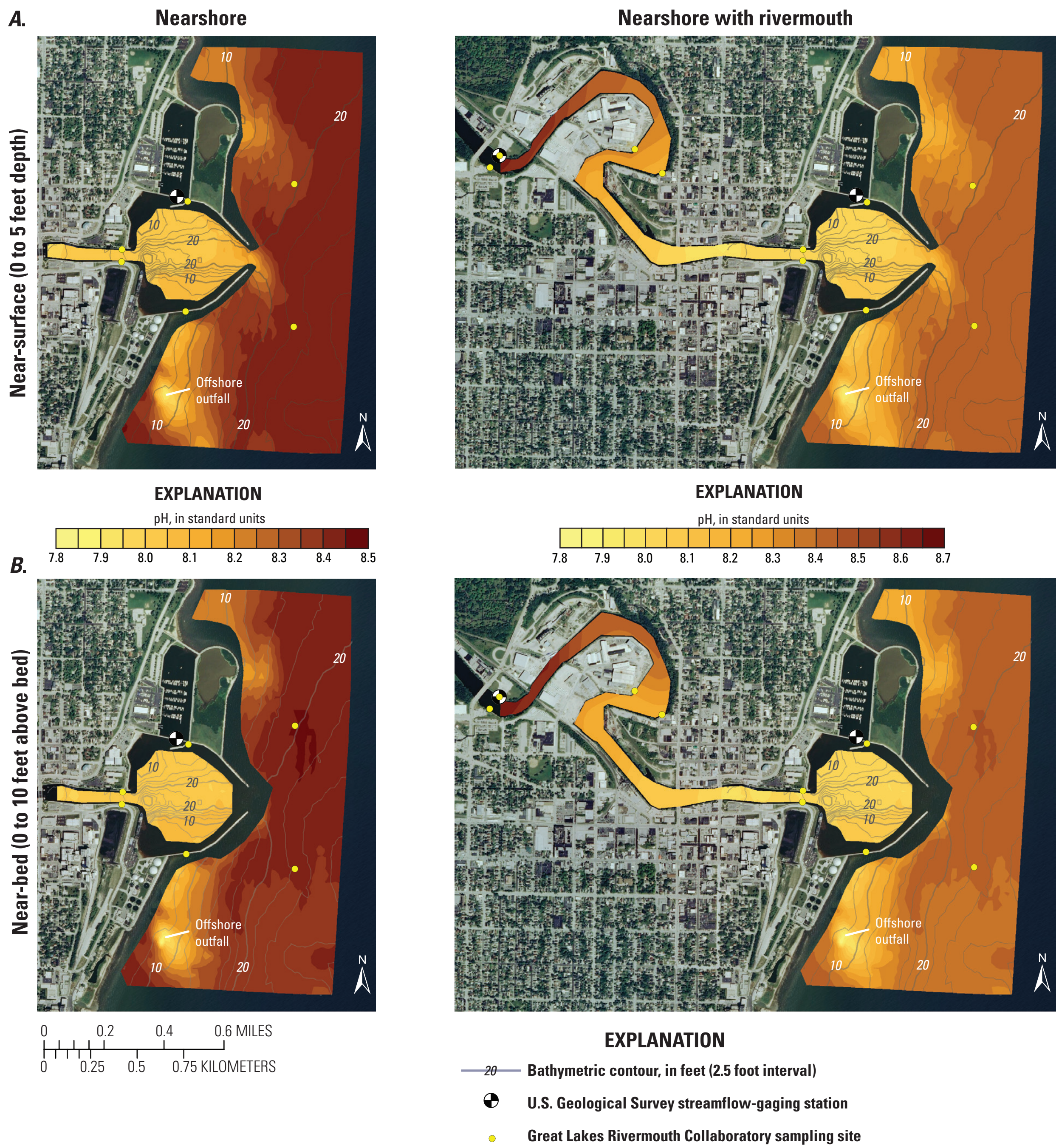


Figure 19. Layer-averaged distributions of pH in the Lower Manitowoc River, Manitowoc Harbor, and nearshore mixing as compiled from measurements on September 19 and 20, 2011. *A*, Near-surface layer (0 to 5 feet depth. *B*, Near-bed layer (0 to 10 feet above bed).

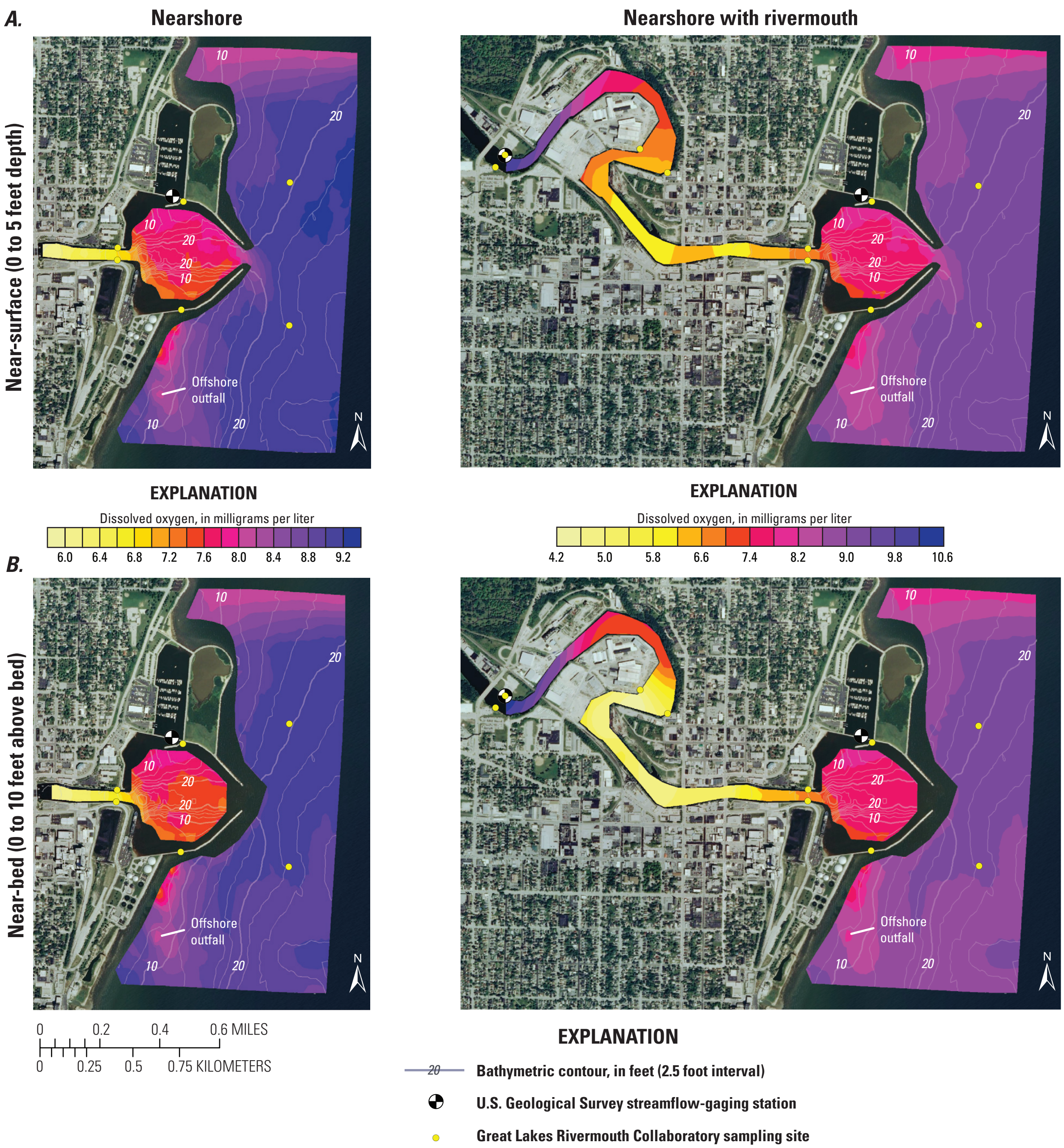


Figure 20. Layer-averaged distributions of dissolved oxygen in the Lower Manitowoc River, Manitowoc Harbor, and nearshore mixing zone as compiled from measurements on September 19 and 20, 2011. *A*, Near-surface layer (0 to 5 feet depth). *B*, Near-bed layer (0 to 10 feet above bed).

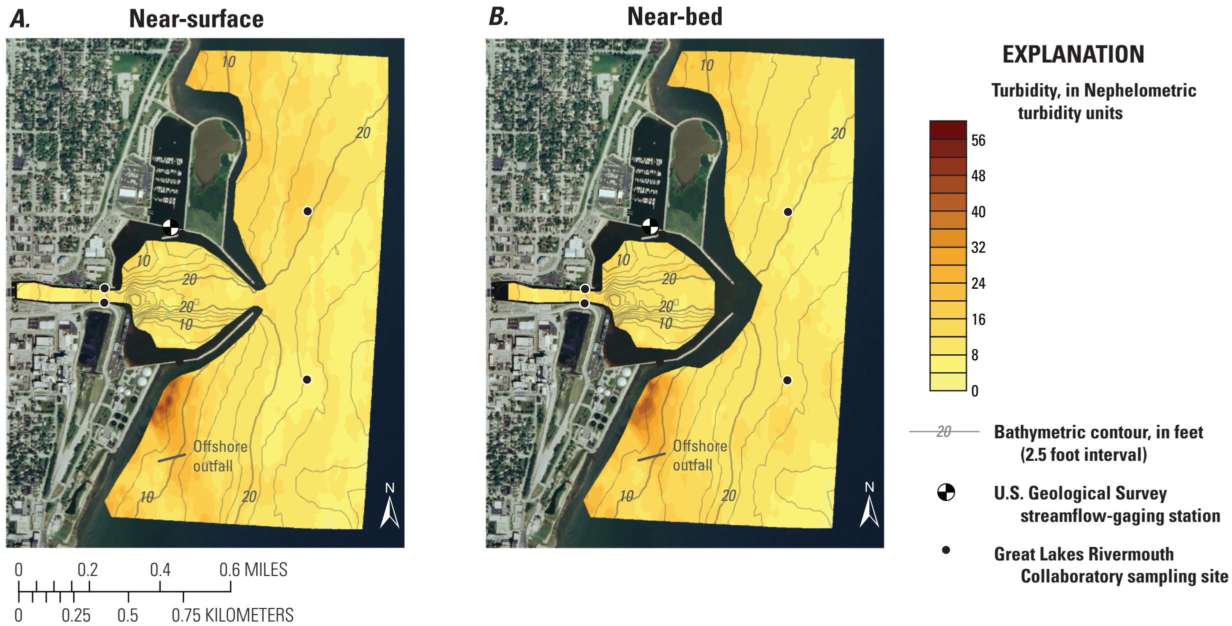


Figure 21. Layer-averaged distributions of turbidity in the Lower Manitowoc River, Manitowoc Harbor, and nearshore mixing zone as compiled from measurements on September 19 and 20, 2011. *A*, Near-surface layer (0 to 5 feet depth). *B*, Near-bed layer (0 to 10 feet above bed).

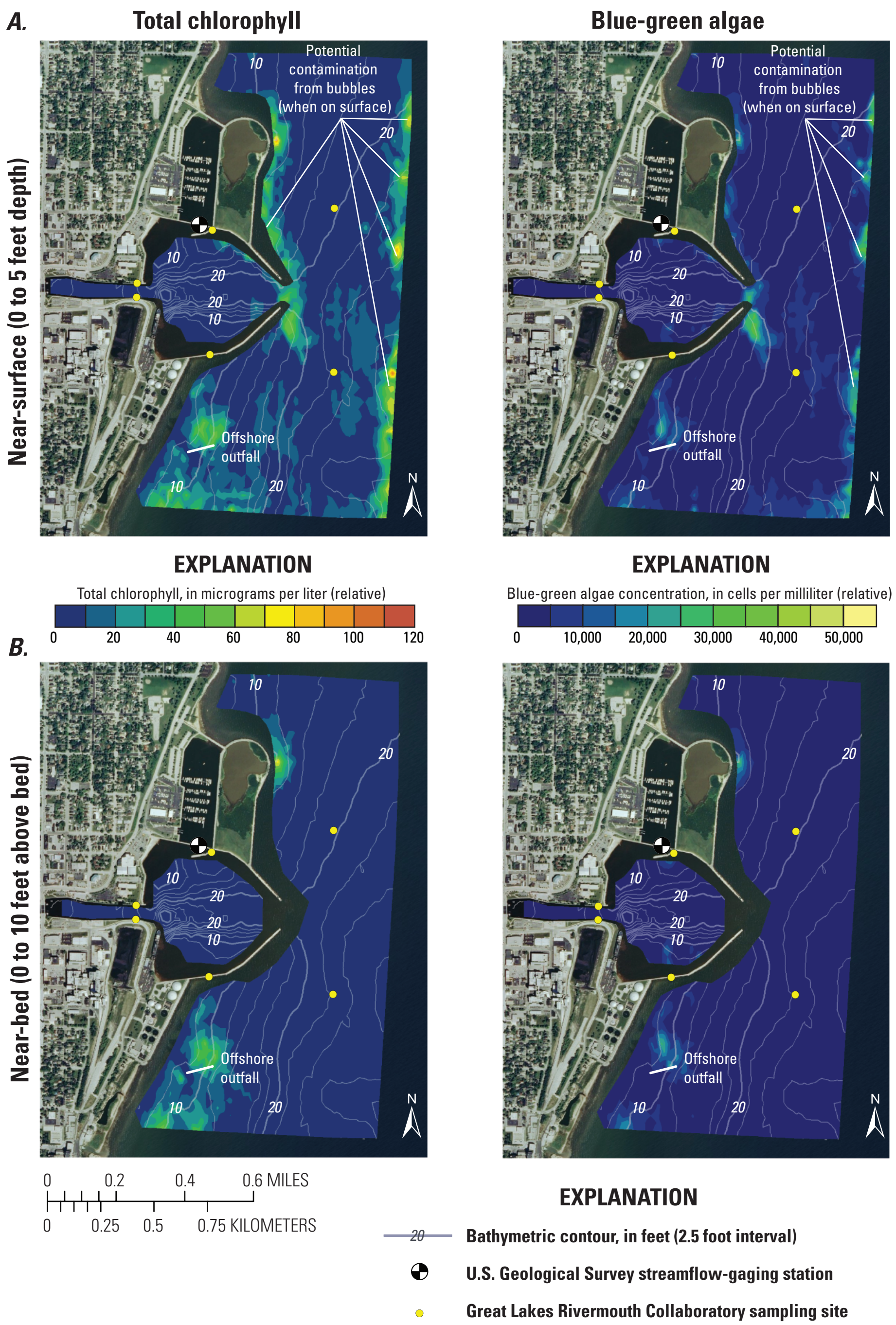


Figure 22. Layer-averaged distributions of total chlorophyll and blue-green algae concentrations in the Lower Manitowoc River, Manitowoc Harbor, and nearshore mixing zone as compiled from measurements on September 19 and 20, 2011. *A*, Near-surface layer (0 to 5 feet depth). *B*, Near-bed layer (0 to 10 feet above bed). Concentrations are relative to deionized water (one-point calibration) and are not absolute.

The distributions of chlorophyll and blue-green algae concentrations in the lake reveal several potential zones of higher concentration (neglecting those data believed to be contaminated by bubbles by primarily concentrating on near-bed distributions). The first zone is south of the harbor near the offshore outfall (fig. 22). Concentrations were higher in this area relative to the rest of the survey domain and this correlates well with visual observations of discolored water and measured higher turbidity values in this area. In addition, this distribution makes sense from a biological standpoint as the nutrient-rich water surrounding a sewer outfall is a likely place for biological activity (Canadian Council of Ministers of the Environment, 2006). The second zone of high concentration is near the permeable seawall separating the spoil area from the lake. This location showed an anomaly in nearly all water-quality parameters measured.

Distributions of fDOM in Manitowoc Harbor followed a similar distribution to specific conductance (fig. 23). The concentration of fDOM dropped rapidly from about 0.5 mi upstream of the harbor (50 parts per billion (ppb)) to less than 5 ppb in the lake. The harbor acted as a dilution basin, and a plume in fDOM can be seen emerging from the mouth of the harbor and turning south with the surface currents (fig. 23). Like many of the other parameters, fDOM concentrations were higher nearshore than in the open lake, and the fDOM values increased substantially near the wastewater-effluent outfall south of the harbor and, to a lesser extent, near the spoil pond exchange point north of the harbor.

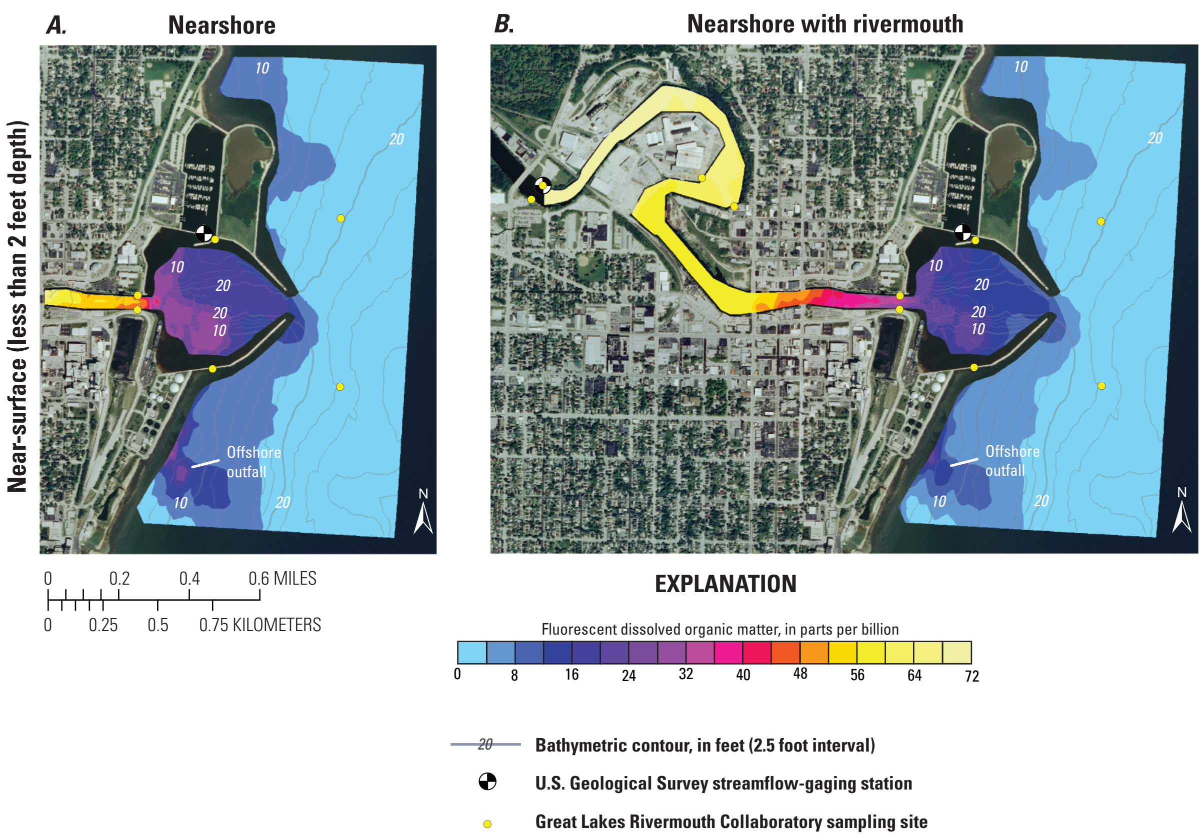


Figure 23. Near-surface distributions of fluorescent dissolved organic material in the lower Manitowoc River, Manitowoc Harbor, and nearshore mixing zone as compiled from measurements on September 19 and 21, 2011.

Limitations of the Study

Whereas the pilot studies were completed during low flows on the tributaries, completion of surveys at higher flows using the same techniques is possible. Once programmed, the AUV survey missions can be stored on the vehicle and a repeat survey of the same survey lines can be initiated in minutes once onsite. In addition, the AUV can be deployed and recovered from shore with only a minor modification to the mission program in the event a manned boat is unavailable or conditions are deemed unsafe for manned boats (wave action, night time, polluted water). Such methods have been employed on studies in Lake Erie when necessary (Jackson, 2013). However, higher flows will result in higher velocities, and one must ensure that the velocities the AUV will be exposed to will not overcome the vehicle's propulsion system (approximately 4 knots maximum).

To ensure that the most accurate and highest resolution velocity data were collected concurrently with the AUV surveys, this pilot study used a manned boat equipped with an ADCP. While the AUV has a DVL system capable of water-column profiling, the velocities have been found to be noisy and are uncorrected for heading, pitch, roll, vehicle depth, and vehicle speed. Not only must one make these corrections, but during undulating missions in which the vehicle is constantly diving at angles up to 25 degrees, a significant amount of the water column is not sampled by a down-looking DVL system. Therefore, to ensure that the greatest portion of the water column is sampled for velocity over the AUV survey domain, the AUV tender boat should be equipped with an ADCP, and data should be collected simultaneously during the AUV survey along the same lines the AUV is surveying. This is good practice in general in harbors and near rivermouths where vessel traffic can be high and numerous hazards exist as the tender boat is never far from the AUV and can oversee its completion of the mission and intervene if necessary.

Conclusions

In response to a call for rivermouth research, which includes study domains that envelop both the fluvial and lacustrine boundaries of the rivermouth mixing zone, the U.S. Geological Survey, in cooperation with the National Monitoring Network for U.S. Coastal Waters and Tributaries, launched a pilot project to determine the value of integrated synoptic surveys of rivermouths using autonomous vehicle technology. The pilot project was implemented at two Lake Michigan rivermouths with largely different scales, hydrodynamics, and settings, but employing primarily the same survey techniques and methods. The Milwaukee River Estuary area of concern (AOC) survey included surveys of the lower 2 to 3 mi of the three tributaries that empty into the estuary (Milwaukee, Menomonee, and Kinnickinnic Rivers) and inner and outer Milwaukee Harbor. This estuary is situated in downtown Milwaukee, Wisconsin, and is the most populated basin that flows directly into Lake Michigan. The major concerns within the Milwaukee River Estuary AOC are conventional (such as phosphorous and suspended solids) and toxic contaminants (metals and organic chemicals). In contrast, the Manitowoc River enters Lake Michigan at Manitowoc, Wisconsin, and has a relatively small harbor separating the rivermouth from Lake Michigan. The Manitowoc River Watershed is primarily agricultural; phosphorus, sediment, and coliform bacteria loadings from cropland and dairy-waste runoff and point sources have impaired the waters of the lower Manitowoc and rivermouth mixing zone.

This pilot study of the Milwaukee River Estuary and Manitowoc rivermouth using an autonomous underwater vehicle (AUV) paired with a manned survey boat resulted in high spatial and temporal resolution datasets of basic water-quality parameter distributions and hydrodynamics with considerable savings in time. The AUV performed well in these environments and was found to be primarily well-suited for harbor and nearshore surveys of three-dimensional water-quality distributions. The use of the AUV showed exceptional savings in time compared to traditional surveys. For example, the AUV completed the approximately 14-mile, 600 profile survey of the outer Milwaukee Harbor in just under 7 hours. Completing such a survey using a manned boat with traditional profiling techniques in 30 feet of water would have taken approximately 150 hours (6.25 days) to complete based on typical profiling speeds with a multiparameter sonde. While the AUV was deployed in the more confined lower reach of the Manitowoc and Milwaukee Rivers and performed adequately, the influence of steel sheet pile walls and other magnetic fields did appear to affect the compass, which resulted in drift offline during dives. In addition, large structures (buildings and bridges) can affect the global positioning system signal received by the AUV and cause it to navigate offline. These factors, combined with hazards from navigation traffic, currents, and confined space, make it more risky to deploy the AUV in rivers. Both case studies found that use of a manned boat equipped with an acoustic Doppler current profiler (ADCP) and multiparameter sonde (and optionally a flow-through water-quality sampling system) was the best option for riverine surveys. Combining the AUV and manned boat datasets was relatively straightforward within the geographic information system environment and resulted in datasets that are essentially continuous from the fluvial through the lacustrine zones of a rivermouth.

Overall, this pilot study aimed at evaluation of AUV technology for integrated synoptic surveys of rivermouth mixing zones was successful, and the techniques and methods employed in this pilot study should be transferrable to other sites with similar success. The integrated datasets resulting from the AUV and manned survey boat are of high value and present a snapshot of the mixing and hydrodynamics of these highly dynamic, highly variable rivermouth mixing zones from the relatively well-mixed fluvial environment through the rivermouth to the stratified lacustrine receiving body of Lake Michigan. Such datasets will not only allow researchers to understand more about the physical processes occurring in these rivermouths, but they provide high spatial-resolution data required for interpretation of relations between disparate point samples and calibration and validation of numerical models.

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