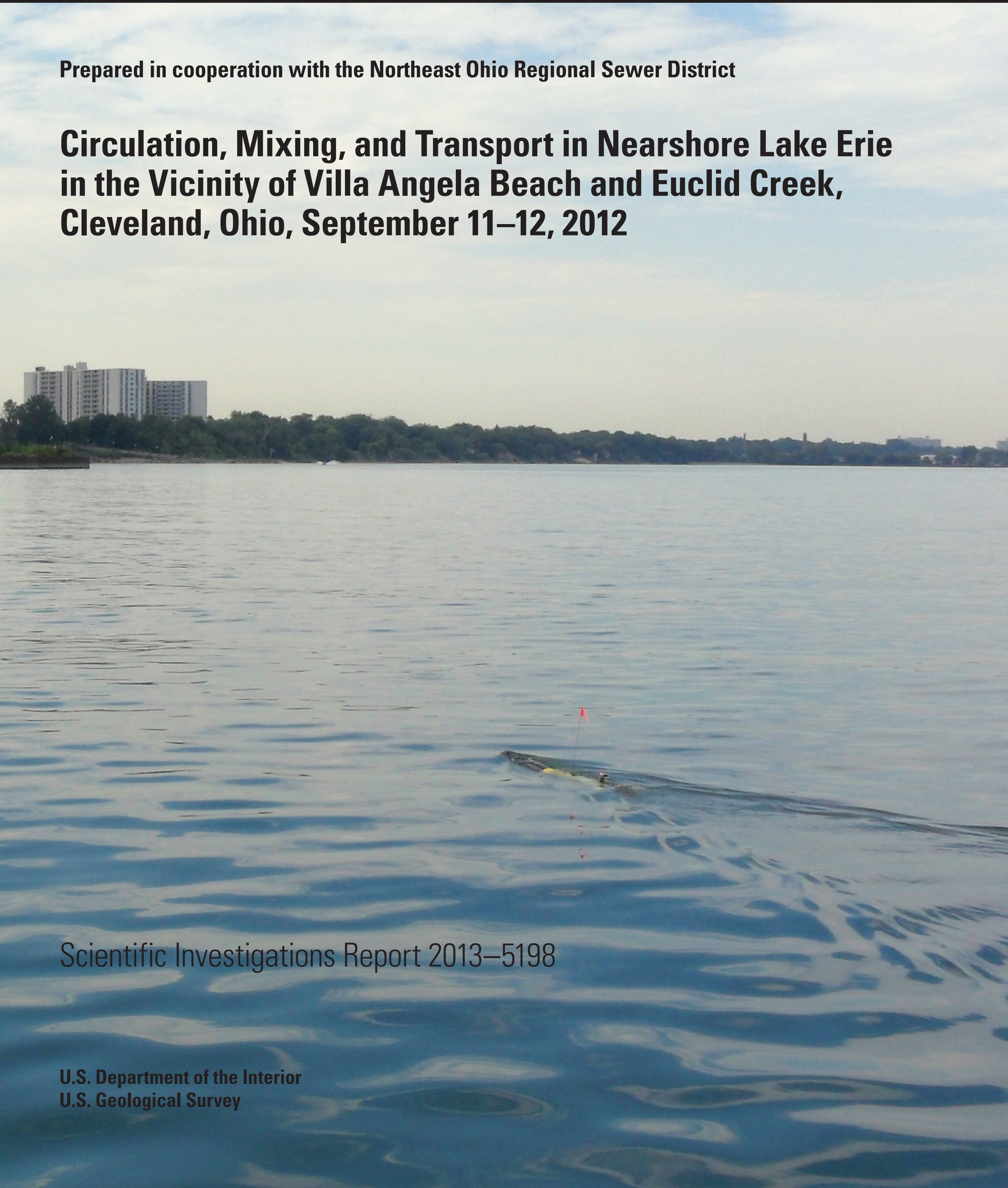
Prepared in cooperation with the Northeast Ohio Regional Sewer District

Circulation, Mixing, and Transport in Nearshore Lake Erie in the Vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 11–12, 2012



Scientific Investigations Report 2013–5198

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

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SALLY JEWELL, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2013

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Conversion Factors and Abbreviations

Inch/Pound to SI

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)
	Volume	
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	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)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
knots	0.51444	meter per second (m/s)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
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

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

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 used in this report

ADCP	acoustic Doppler current profiler
ADVM	acoustic Doppler velocity meter
AUV	autonomous underwater vehicle
CSO	combined sewer overflows
DVL	Doppler velocimetry log
E. coli	*Escherichia coli*
ENE	east-northeast
EPA	U.S. Environmental Protection Agency
GIS	geographic information system
GPS	global positioning system
NEORSD	Northeast Ohio Regional Sewer District
NRDC	National Resources Defense Council
NTU	Nephelometric turbidity unit
SSE	south-southeast
SSW	south-southwest
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
VMT	Velocity Mapping Toolbox
WSE	water-surface elevation
WWTP	wastewater treatment plant

Acknowledgments

The author acknowledges the Northeast Ohio Regional Sewer District for funding this study in 2012 and the pilot studies in 2007 and 2011. The author also acknowledges Dennis Kumfer and Jim Mangus of the U.S. Geological Survey Ohio Water Science Center for their assistance in organizing and conducting the field work. Lastly, the author acknowledges the Wildwood Marina for providing a slip for the survey vessel during the 2011–12 field campaigns.

Circulation, Mixing, and Transport in Nearshore Lake Erie in the Vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 11–12, 2012

By P.R. Jackson

Abstract

Villa Angela Beach, on the Lake Erie lakeshore near Cleveland, Ohio, is adjacent to the mouth of Euclid Creek, a small, flashy stream draining approximately 23 square miles and susceptible to periodic contamination from combined sewer overflows (CSOs) (97 and 163 CSO events in 2010 and 2011, respectively). Concerns over high concentrations of *Escherichia coli (E. coli)* in water samples taken along this beach and frequent beach closures led to the collection of synoptic data in the nearshore area in an attempt to gain insights into mixing processes, circulation, and the potential for transport of bacteria and other CSO-related pollutants from various sources in Euclid Creek and along the lakefront. An integrated synoptic survey was completed by the U.S. Geological Survey on September 11–12, 2012, during low-flow conditions on Euclid Creek, which followed rain-induced high flows in the creek on September 8–9, 2012. Data-collection methods included deployment of an autonomous underwater vehicle and use of a manned boat equipped with an acoustic Doppler current profiler. Spatial distributions of water-quality measures and nearshore currents indicated that the mixing zone encompassing the mouth of Euclid Creek and Villa Angela Beach is dynamic and highly variable in extent, but can exhibit a large zone of recirculation that can, at times, be decoupled from local wind forcing. Observed circulation patterns during September 2012 indicated that pollutants from CSOs in Euclid Creek and water discharged from three shoreline CSO points within 2,000 feet of the beach could be trapped along Villa Angela Beach by interaction of nearshore currents and shoreline structures. In spite of observed coastal downwelling, denser water from Euclid Creek is shown to mix to the surface via offshore turbulent structures that span the full depth of flow. While the southwesterly longshore currents driving the recirculation pattern along the beach front were observed during the 2011–12 synoptic surveys, longshore currents with a southwesterly component capable of establishing the recirculation only occurred about 30 percent of the time from June 7 to October 6, 2012, based on continuous velocity data collected near Villa Angela Beach.

Introduction

Frequent high *Escherichia coli (E. coli)* concentrations have been found in water samples collected in Lake Erie at Villa Angela Beach (Bushon and others, 2009). Villa Angela Beach is one of 13 beaches in the country, and the only in Ohio, to be listed on the National Resources Defense Council (NRDC) repeat offenders list in which more than 25 percent of water samples received exceeded the U.S. Environmental Protection Agency's (EPA) applicable single-sample maximum bacteria standard for designated beach areas each year from 2006 to 2010 (Dorfman and others, 2011). Microbial source tracking indicated both humans and gulls as the sources of the *E. coli* (Bushon and others, 2009). The highest *E. coli* concentrations detected in the study were collected in Euclid Creek following recent rainfall; the markers were specific to humans and not gulls. These results are consistent with bacterial contamination of Euclid Creek by combined sewer overflow (CSO) discharges during rainfall events. According to Northeast Ohio Regional Sewer District (NEORSD) records, Euclid Creek received 97 CSO discharges in 2010 and 163 CSO discharges in 2011. From 2002 to 2007, Villa Angela Beach was closed for approximately 60 percent of the recreational season because of high bacteria levels (Cuyahoga County Soil and Water Conservation District, 2007). More recently, from 2008 to 2012, the beach was closed on average about 40 percent of the recreational season because of high bacteria levels (Ohio Department of Health, 2013). Of the 204 closure days during the 2008–12 swimming seasons, only 1 closure was classified as due to a CSO; the remainder have unknown causes for the bacterial contamination. In 2010, NEORSD monitored *E. coli* concentrations at Villa Angela Beach (east and west ends) and at two points in Euclid Creek within 0.5 miles (mi) of the mouth and determined that (1) the east end of Villa Angela Beach had significantly higher *E. coli* on average than the west end of the beach, and (2) illicit discharges and CSOs along Euclid Creek directly impact the water quality at Villa Angela Beach (Ohio Department of Health, 2010).

To better understand potential sources of bacteria on and near the beach and transport mechanisms, the NEORSD requires information on flow patterns in Lake Erie near the beach under a variety of conditions. With multiple potential sources surrounding Villa Angela Beach—including Euclid Creek and three Lakefront CSO discharge points—understanding the circulation, mixing, and transport in the nearshore in the vicinity of Villa Angela Beach is a critical component in improving beach health.

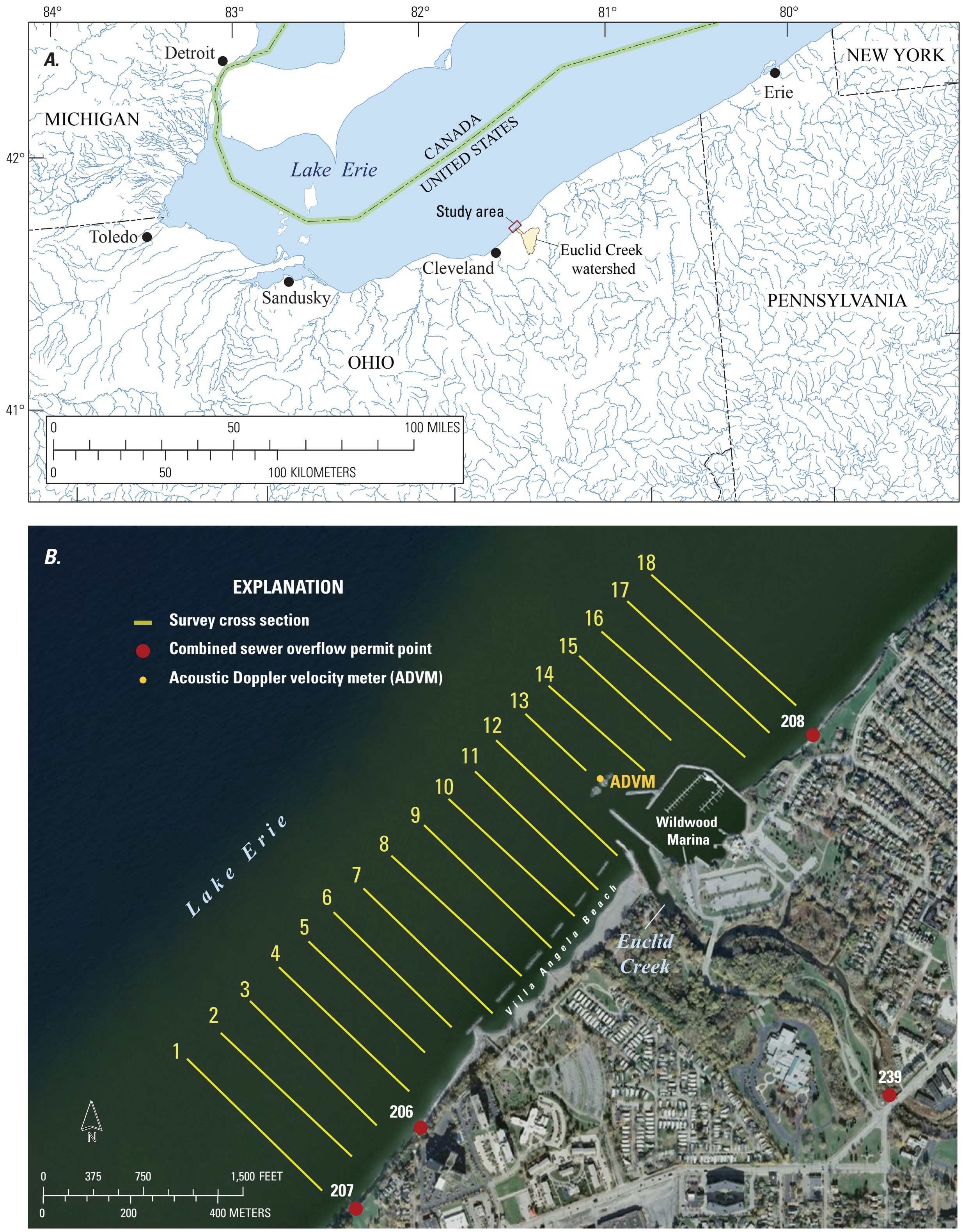
Purpose and Scope

The purpose of this report is to present the results of synoptic surveys performed in 2012 of nearshore Lake Erie in the vicinity of Euclid Creek and Villa Angela Beach, to identify circulation, mixing, and transport patterns in this area, and to provide information about potential pathways for CSO-related pollutants between Euclid Creek and several lakefront CSO discharge points and Villa Angela Beach. The scope of this report does not include any attempt to qualify bacterial concentrations as is done in predictive beach water-quality models, but rather examines pathways for transport between potential sources in the area and Villa Angela Beach. Potential sources in this study are limited to Euclid Creek and three lakefront CSO discharge points surrounding Villa Angela Beach (fig. 1). Recognizing that a synoptic survey represents only one instance in time and circulation patterns change, the results of the synoptic surveys are compared to continuous current and wind data measured near Villa Angela Beach during summer 2012.

Study Site

Villa Angela Beach, on the Lake Erie lakeshore, 8.8 mi northeast of Cleveland, Ohio, is adjacent to the mouth of Euclid Creek, which is a small, flashy stream draining approximately 23 square miles (mi^2) and susceptible to periodic contamination from CSOs (fig. 1). The shoreline in the study reach is oriented southwest to northeast. The beach is partially protected by six breakwaters approximately 200 feet (ft) offshore and oriented parallel to the beach. These breakwaters reduce the open water connection to the lake to approximately 44 percent of its original, unaltered state. The portion of the beach behind the western-most two breakwaters also is called Euclid Beach by locals. For simplicity, we will not make this distinction in this study and instead use the term “Villa Angela Beach” to refer to the entire reach protected by breakwaters (fig. 1*B*). A CSO discharge point (fig. 1*B*, point 239) is located on Euclid Creek about 2,300 ft upstream of the mouth. In addition, three other CSO discharge points are along the lakefront within 1,600 ft of the beach (two to the southwest and one to the northeast). The NEORSD Easterly Wastewater Treatment Plant (WWTP), which treats up to 94 million gallons per day (Mgal/d) of wastewater, is approximately 1 mi to the southwest of Villa Angela Beach. Lake Erie is the effluent discharge point for the Easterly WWTP.

The mouth of Euclid Creek is bordered by Villa Angela Beach to the southwest and Wildwood Marina to the northeast. A short jetty separates the mouth of the creek from the beach and extends just beyond the breakwaters protecting the beach (about 250 ft offshore). Wildwood Marina, to the northeast of the mouth of Euclid Creek, is protected by a sea wall and two large caissons near the harbor entrance (fig. 1*B*). The marina sea wall and harbor entrance protection protrude out into the lake approximately 800 ft from the natural shoreline. The caissons protecting the entrance to Wildwood Marina serve as platforms for instrumentation for continuous monitoring of nearshore currents using an acoustic Doppler velocity meter (ADVM) operated by the U.S. Geological Survey (USGS) and a meteorological station operated by NEORSD.



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

Figure 1. Coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 2012. *A*, Overview of the study location and Euclid Creek watershed. *B*, Survey domain with designated survey lines and combined sewer overflow permitted discharge points.

Combined Sewer Overflows

Villa Angela Beach, near Cleveland, Ohio, is surrounded by four CSO discharge points, three on the lakefront and one on Euclid Creek just upstream of the mouth (fig. 1*B*). These discharge points are managed by the NEORSD. To aide in the interpretation of the synoptic data presented in this report, the NEORSD provided the USGS with CSO discharges to Euclid Creek for 2010–11 and for all the metered outfalls for the 10-day period leading up to the synoptic survey in 2012.

Euclid Creek is subject to a large number of CSO events, with most events occurring in the spring, late summer, and fall (fig. 2). Euclid Creek received approximately 56 million gallons (Mgal) of CSO in 2010 (97 events) and 221.6 Mgal of CSO in 2011 (163 events). These numbers account only for the CSO discharge at the Euclid Creek at Lakeshore Boulevard permitted discharge point (fig. 1, CSO 239).

In the 10 days prior to the 2012 synoptic survey, Euclid Creek received four CSO events (Sept. 1–3 and 8) totaling approximately 13 Mgal of CSO (table 1). In addition, the 156th Street lakefront CSO discharge station (206) had two CSO events (September 3 and 8) totaling approximately 15.4 Mgal of CSO.

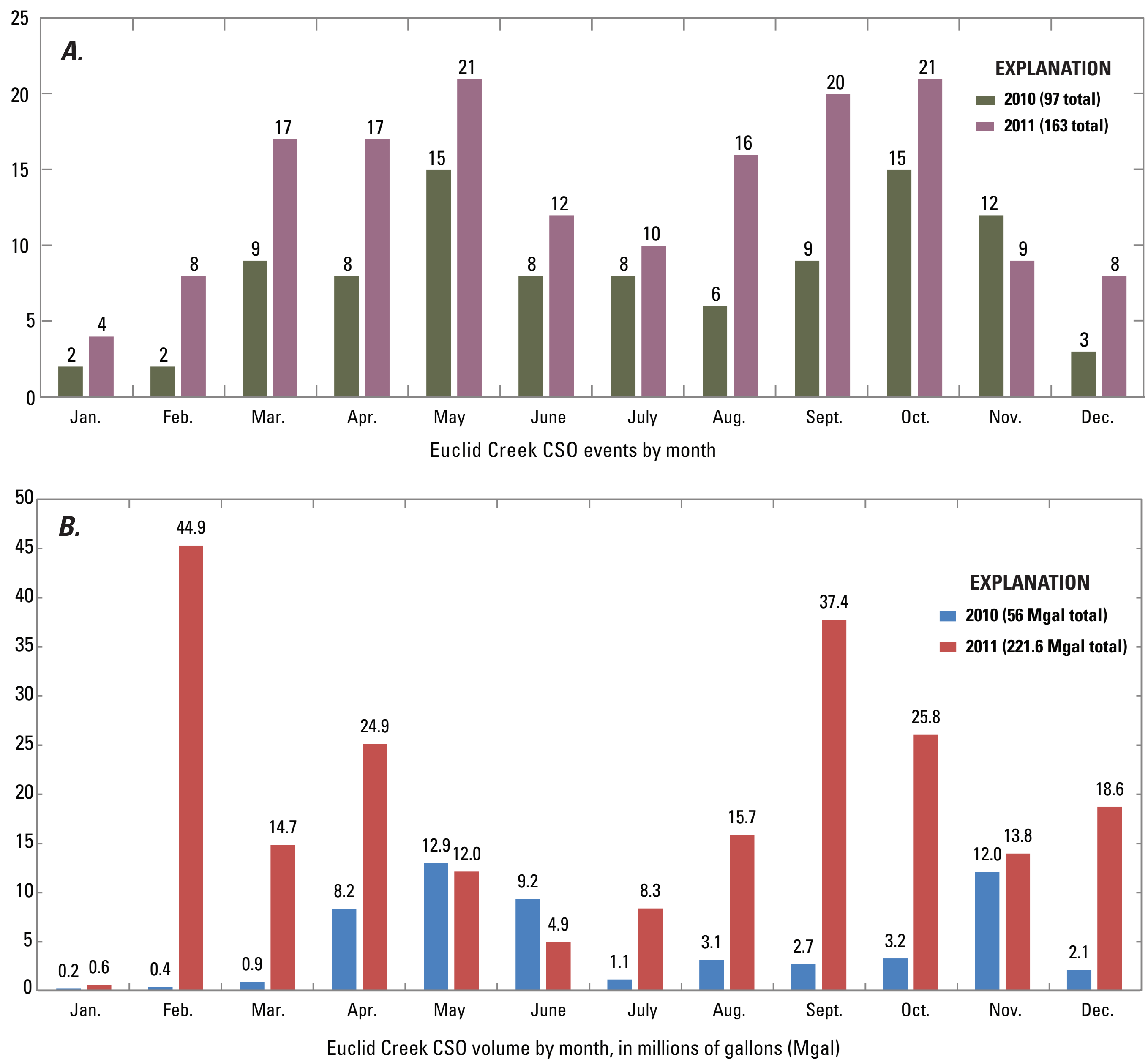


Figure 2. Combined sewer overflows to Euclid Creek at Lakeshore Boulevard, Cleveland, Ohio (discharge point 239), for 2010–11 (data provided by the Northeast Ohio Regional Sewer District) *A*, number of events by month and *B*, CSO volume by month.

Table 1. Combined sewer overflows near Villa Angela Beach, Cleveland, Ohio, September 1–12, 2012 (data provided by the Northeast Ohio Regional Sewer District).

Discharge location (name and number)	Receiving body	Date	Duration, in hours	Volume,[1] in millions of gallons	Average discharge, in cubic feet per second
Euclid Creek at Lakeshore Blvd. (239)	Euclid Creek	Sept. 1, 2012	1	0.087	3.24
Euclid Creek at Lakeshore Blvd. (239)	Euclid Creek	Sept. 2, 2012	2.67	0.84	11.71
Euclid Creek at Lakeshore Blvd. (239)	Euclid Creek	Sept. 3, 2012	4.5	3.601	29.79
156th Street and Lakefront (206)	Lake Erie	Sept. 3, 2012	1.67	6.191	137.99
Euclid Creek at Lakeshore Blvd. (239)	Euclid Creek	Sept. 8, 2012	11.08	8.522	28.63
156th Street and Lakefront (206)	Lake Erie	Sept. 8, 2012	4	9.165	85.29

[1]Approximate volume.

Previous Work

The USGS performed an initial study in 2007 to measure and map nearshore currents in the vicinity of Villa Angela Beach. Georeferenced velocity profiles were measured in Lake Erie in 2007 by use of an acoustic Doppler current profiler (ADCP) outfitted with a global positioning system (GPS). Measurements were made along several transects extending from the shoreline out into the lake. The transects started from west of the beach and ended east of the marina near the mouth of Euclid Creek. Measurements also were made along transects oriented parallel to the breakwaters off Villa Angela Beach (both on the lake and the beach sides of the breakwaters) and across the mouth of Euclid Creek. The transect lines along with vectors indicating mean velocity magnitudes and directions were plotted on a base map to help visualize velocity patterns in the lake. In spite of calm conditions on the lake during the 2007 measurements, significant noise in the data led to uncertain results.

A second effort to map the nearshore circulation and mixing off Villa Angela Beach was performed in late August 2011 by the USGS, in cooperation with the NEORSD. The multi-day survey was completed under calm conditions, much like the conditions in 2007, yet measurement techniques and advances in data-processing techniques led to enhanced capabilities and more consistent results. In addition to the use of a manned boat equipped with water-quality sensors and an ADCP, the USGS also deployed an autonomous underwater vehicle (AUV) to map bathymetry and the spatial distribution of selected water-quality parameters. The general onshore-offshore-oriented transect survey method used in 2007 was adopted for the 2011 survey, though the same survey lines were not used. Variable nearshore currents and the spatial distributions of water-quality parameters observed in August 2011 indicated that nearshore mixing was primarily wind-driven during low flows on Euclid Creek. In addition, observed circulation patterns in 2011 indicated that Euclid Creek water, and the CSO-related pollutants therein, can be mixed along Villa Angela Beach by interaction of nearshore currents with local bathymetry. Density differences between the denser Euclid Creek water and the lake surface water indicated that Euclid Creek water may form density currents that are transported out into the lake along the lakebed before being mixed to the surface by local turbulence. The higher specific conductance of Euclid Creek water provided contrast with the lower conductivity lake water, which allowed it to be used as a tracer. Specific conductance data supported the density current hypothesis, but did not provide the only explanation for the observed mixing patterns. In addition, observations of multiple water-quality parameters indicated that in late August 2011, at least one anomaly in water quality was present along Villa Angela Beach, near the west end of the beach behind the second breakwater. This anomaly indicated the possibility of groundwater discharge to the lake.

Data Collection

This section describes the methods and instrumentation used to collect the meteorological data, continuous observations of nearshore currents, water-velocity distributions, and water-quality distributions in the vicinity of Villa Angela Beach.

Meteorological Data

Local meteorological data are collected during the summer months by the NEORSD by using a weather station mounted on the northern caisson at the entrance to Wildwood Marina (fig. 1*B*). The NEORSD began operation of a meteorological station at the Wildwood Marina near Villa Angela Beach in May 2012. The NEORSD provided hourly data for the period of record (May 17 to September 17, 2012) to the USGS for analysis of dominant wind characteristics. Additional meteorological data for the survey period are available from the National Climatic Data Center for WBAN station 04853, which is located at the Burke Lakefront Airport, approximately 7 mi southwest of the study area.

Continuous Monitoring of Nearshore Currents

In May 2012, the USGS began operation of an ADVM near the entrance of the Wildwood Marina, just northeast of Villa Angela Beach. The ADVM is mounted to the northwest side of the northern caisson near the harbor entrance and is programmed to measure currents out about 300 ft into Lake Erie (fig. 1). The ADVM is mounted about 8 ft above the bed and measures the currents parallel and perpendicular to the face of the meter (which is approximately parallel with the shoreline) with a sampling volume northwest of the caisson and discretized in bins of 30 ft width (10 bins total with a 5-ft blanking zone). The ADVM averages 5 minutes of data in each bin during every 15-minute period and records the values. An obstruction approximately 65 ft from the transducer along the path of the acoustic beams corrupted data from bins 3–10; therefore, only data from the first two bins are available for analysis (5–35 ft and 35–65 ft from the caisson). Based on the broad acoustic return signal, the obstruction is likely the lake bed. The fact that the acoustic signal is striking the bed indicates that the caisson may be sitting in a local depression (possibly caused by scour around the caisson), and the measured mounting height of 8 ft above the bed is not representative of bed elevations 65 ft from the transducer. It is believed that the true height of the transducer above the bed is closer to 3–5 ft when considering bed elevations away from the face of the caisson (based on the beam angle, pitch of the instrument, and obstruction distance).

Integrated Synoptic Surveys

Integrated synoptic surveys of bathymetry, basic water-quality parameters, water velocity, and side-scan sonar were performed by using a combination of an AUV and a manned boat. Surveys were conducted on September 11–12, 2012, by using both the manned boat and the AUV simultaneously in the mornings and only the manned boat for velocity surveys in the afternoons. 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, 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 and are shown in figure 1*B*.

A total of six synoptic surveys were completed during September 11–12, 2012. Four of the surveys were simultaneous AUV and manned boat surveys, and the remaining two surveys were velocity surveys with only the manned boat. With the exception of two longshore surveys, all surveys were carried out following the onshore-offshore transects depicted in figure 1*B*. Longshore surveys followed three survey lines that paralleled the shoreline at Villa Angela Beach, one line inside the breakwaters and two lines outside the breakwaters (these surveys yielded little additional information and are not discussed further in this document). The onshore-offshore surveys were completed by using an undulating dive pattern (between 6 ft above bottom and the surface) for the AUV, and the longshore surveys were completed with the AUV at the surface. The undulating dive pattern used a 15 degree dive angle and resulted in approximately 14–15 profiles of the water column over a 1,500 ft transect (or sample spacing at a given depth of about 150 ft). In all simultaneous surveys, the manned boat followed behind the AUV, keeping a distance of about 200 ft. The velocity-only surveys were comprised of repeat transects on each of the survey lines (one offshore transect and one onshore transect). Repeat transect surveys provide additional data to permit averaging, thereby reducing variability in the measurements.

Description of the Autonomous Underwater Vehicle

The AUV used in the 2011–12 surveys is 63.6 in. in length, 5.8 in. in diameter, weighs approximately 60 pounds (lb) in air (fig. 3), and is built by YSI, 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

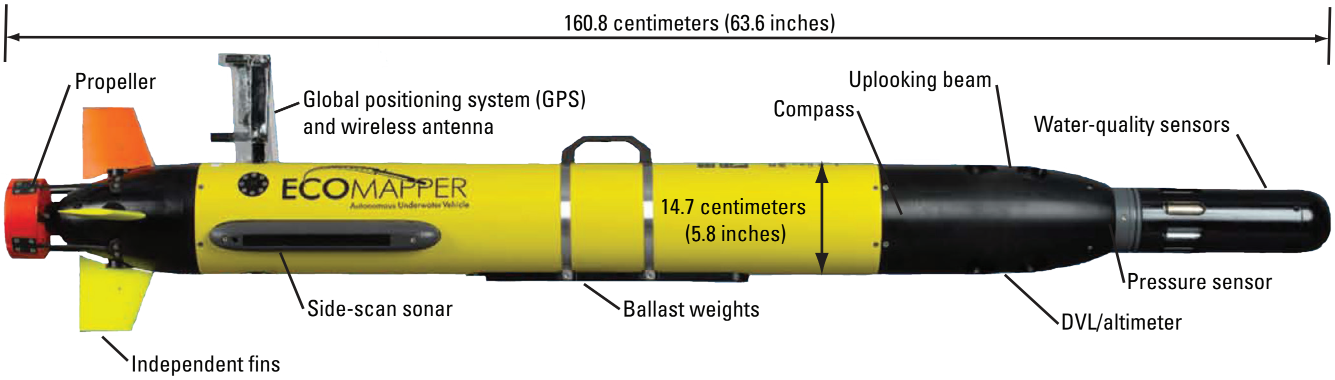


Figure 3. Schematic of the autonomous underwater vehicle.

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. The tail is comprised of four independent control fins and a three-blade propeller. Atop the vehicle near the tail section is the antennae mast, which houses the differential 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. All communication with the vehicle is through the wireless Ethernet radio link. Onboard electronics include an embedded computer running Windows XP and an 80 gigabyte hard drive for data storage. The aft section of the body also houses the integrated Imagenex side-scan sonar transducers, mounted on the port and starboard sides of the vehicle just forward of the tail section. The calibration procedures for the AUV, instrument operation, handling of data files, and data-processing routines are described in detail in appendix 1.

The water-quality sensor suite is comprised of 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 (not operational for this survey), and a YSI 6131 BGA-PC Phycocyanin (blue-green algae) sensor. Manufacturer's specifications for each of the probes are given in table 2. All water-quality sensors are sampled at a rate of 1 hertz (Hz).

Table 2. Manufacturer's specifications for the water-quality sensors aboard the autonomous underwater vehicle.

[mS/cm, millisiemens per centimeter; %, percent; °C, degrees Celsius; foot, ft; m, meter; ppt, parts per thousand; mg/L, milligrams per liter; NTU, Nephelometric turbidity units; µg/L, micrograms per liter; cells/mL, cells per milliliter; >, greater than; --, not specified]

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 50ºC	—	0.01ºC	±0.15ºC	—	2.1
Depth	0 to 656 ft (200 m)	—	0.001 ft	±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	—	$R^2 > 0.9999$	2.1
Blue-green algae (phycocyanin)	0 to 280,000 cells/mL	220 cells/mL	1 cell/mL	—	$R^2 > 0.9999$	2.1

*Can vary with age of sensor.

The 6-beam DVL system aboard the AUV is comprised of four 1 megahertz (MHz) beams oriented at a 25-degree slant angle from the vertical with acoustic beam widths of 3.5 degrees. The additional two 500 kHz beams are oriented vertically, one uplooking and one downlooking, for range-to-surface and range-to-bed measurements, respectively. The vertical beams have a beam width of 5 degrees, a range of 0.82 ft (0.25 meters (m)) to 197 ft (60 m), an accuracy of 1 percent of measured range, and a resolution of 0.01 m. The DVL has an internal sampling rate of up to 70 Hz depending on the configuration, but DVL data are averaged and reported at 1 Hz to the AUV onboard computer. Manufacturer's specifications report the bottom-tracking range of the DVL to be 0.16 ft (0.05 m) to 98 ft (30 m), the current profiling velocity range of ±32.8 feet per second (ft/s) (±10 meters per second (m/s)) with an accuracy of ±0.0066 ft/s (±0.2 centimeter per second (cm/s)) or 0.25 percent of measured profile velocity, and a resolution of 0.032 ft/s (0.01 m/s). The minimum cell size for the DVL profiling is 0.82 ft (0.25 m), and the maximum number of cells is 128.

In addition to the DVL, the AUV has several other integrated sensors to aid in navigation. A three-axis digital compass is integrated into the vehicle as is a second pressure sensor. The compass is required for underwater navigation with the DVL and when using dead reckoning. Additionally, the compass is required for proper alignment of velocity data from the DVL. The second pressure sensor is used for navigation of the vehicle and provides depth measurements redundant to the YSI bulkhead pressure sensor and the uplooking vertical beam. According to the manufacturer, the vehicle pressure sensor has a range of 200 ft (61 m), accuracy of ±0.02 ft (0.006 m), and resolution of 0.001 ft. Finally, the AUV is equipped with a 75 kilohertz (kHz) acoustic pinger for location of the vehicle from a manned boat by using a hydrophone.

Acoustic images of the bed are obtained by using the integrated Imagenex 330/800 kHz side-scan sonar. Two dual-frequency transducers are mounted on the vehicle near the tail (one on each side) and are angled down at 20 degrees. The range of the sonar is 49 ft (15 m) to 394 ft (120 m) and is user configurable. Resolution of the sonar is computed as the range scale divided by 250 (or 500 if only operating one transducer).

Manned Boat Deployments

The manned boat used in the synoptic surveys was the M/V Sangamon, a 19-ft aluminum workboat from Kann Manufacturing. The boat was equipped with a Teledyne RDI 600 kHz Rio Grande® ADCP mounted on the starboard side of the vessel near the bow. 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 for precise navigation along plan lines during the survey (fig. 1*B*). Boat speeds were optimized during the survey to allow enough time to complete the survey without compromising the quality of the data. When time allowed, repeat transects were obtained along survey lines to reduce the noise in the data. The depth of the transducers was set to 1.5 ft below the water surface, and the ADCP was operated in water mode 12 with 1.64 ft (50 cm) bins because of wave action. ADCP data were post-processed and visualized by using the Velocity Mapping Toolbox (VMT) (Parsons and others, 2013). Independent water-quality point measurements were made throughout the survey by using a YSI 6920 multiparameter sonde equipped with a suite of sensors including temperature, specific conductance, pH, and dissolved oxygen.

Data Processing

This section describes the techniques used for processing the meteorological, ADVM, ADCP, and AUV data. Where possible, computer scripts were used to process the data for efficiency and consistency.

Meteorological Data

All meteorological data were processed by using custom scripts written in Matlab®. The NEORSD data were processed by developing histograms of wind direction (10-degree bins) and wind speed (5 mile per hour (mi/h) bins). The number of observations in each bin was divided by the total number of hourly observations in the period of record (n = 2,744) to compute a percentage of the record corresponding to each wind direction and speed. Wind directions are referenced to the direction (in heading from true north) from which the wind is originating (that is, the direction facing into the wind). This is an opposite convention to water currents, which are referenced to the direction the current is flowing.

One-minute wind speed, wind direction, and air temperature data from the NEORSD weather station at Wildwood Marina were averaged over 15-minute intervals and compared with hourly data from the Burke Lakefront Airport (WBAN 04853) for the period September 1–13, 2012. Wind direction from the NEORSD weather station was referenced to magnetic north and required a transformation to true north by using a magnetic declination of −8.37 degrees prior to comparison with data from Burke.

Acoustic Doppler Current Meter Data

Data from the ADVM for June 7 to October 6, 2012, were analyzed to aide in the interpretation of the synoptic data and provide insight into the repeatability of nearshore current patterns. Data processing consisted of rotating the velocity data from a local X-Y coordinate system (X is parallel and Y is perpendicular to the face of the instrument) to a geographic coordinate system. This was required because the onboard compass in the unit was greatly affected by the sheet pilings of the caisson; therefore, it did not provide accurate headings. A projection angle of 309 degrees from true north was used for computation as the orientation of the Y-axis of the ADVM. The rotated east and north components of velocity were then used to compute the magnitude and direction (in geographic coordinates) of the velocity vector for every sample in each of the two good bins. The magnitude of the rotated vector was compared to that reported by the ADVM to ensure no errors were made in the rotation. Lastly, histograms were generated for all the data with respect to current speed (by using 0.05 ft/s bins) and direction (by using 10-degree bins), as well as for each month of data (to determine if the direction of the currents varies by month). The histograms were used to develop frequency plots showing the percentage of the period of record (or month) that the currents displayed a particular speed or direction.

Acoustic Doppler Current Profiler Data

Processing of the manned boat ADCP data was accomplished by using the VMT by Parsons and others (2013). This software suite allows for transect averaging in addition to spatial averaging of the data to allow for reduction of 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.

Autonomous Underwater Vehicle Data

Processing of the AUV data is discussed in detail in appendix 1 of this report. Output from data-processing routines was further refined in ArcGIS® and graphics design software to generate the figures in this report.

Observations

This section is dedicated to presentation and discussion of the observed meteorological, hydrodynamic, and water-quality conditions present near Villa Angela Beach on September 11–12, 2012. Distributions of individual parameters in time and space are compared and used to interpret interactions between atmospheric forcing, local lake circulation, and water-quality distributions in the vicinity of Villa Angela Beach and the mouth of Euclid Creek, Ohio.

Meteorological Data

Local Wind Patterns for Summer 2012

At the Lake Erie lakefront near Villa Angela Beach, winds during summer 2012 were dominantly out of the east to east-northeast (ENE) (40 to 60 degrees) (fig. 4). There is a secondary, broad peak in wind direction at 140–210 degrees

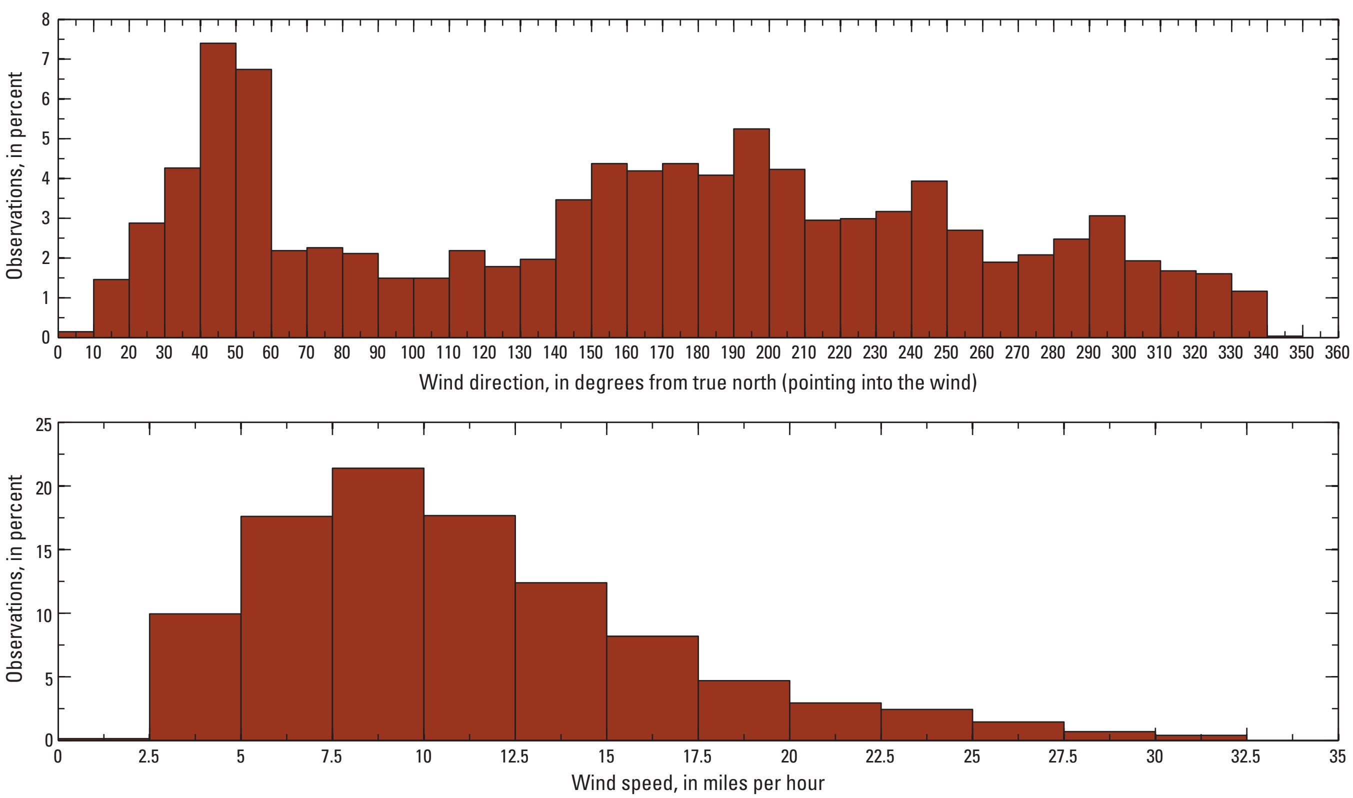


Figure 4. Wind direction and wind speed characteristics observed at the Wildwood Marina near Villa Angela Beach, Cleveland, Ohio, for the period May 17 to September 17, 2012 (based on hourly data provided by the Northeast Ohio Regional Sewer District).

(south-southeast (SSE) to south-southwest (SSW)). Wind speed ranges from 0 to 35 mi/h with a typical wind speed of about 10 mi/h. Based on the orientation of the shoreline (about 42 degrees from true north), the data indicate that offshore winds were present about 64 percent of the time, and onshore winds occurred about 36 percent of the time during summer 2012.

Local Climatic Conditions During the September 2012 Synoptic Survey

With the exception of a large storm event on September 8, 2012, that disrupted the pattern for several days, the 10 days leading up to the surveys on September 11–12, 2012, had relatively consistent and repeatable wind patterns (fig. 5). Prior to the September 8 storm, the winds tended to be onshore during the day and offshore at night. Wind speeds generally peaked in the mid-afternoon period at 10–20 mi/h and became calm overnight (0–10 mi/h). High winds on September 8, 2012, accompanied a large precipitation event. Winds were sustained from the northwest at 20–30 mi/h for an 18 hour period during the storm. Following the storm, winds were persistently out of the north for 2 days, but began to regain the offshore-onshore pattern on September 11, 2012. The wind patterns on September 11 and 12, 2012, were nearly identical. The pattern consisted of south winds at 5–10 mi/h before dawn (offshore) followed by a clockwise rotation of the wind direction (south to west to north) through the afternoon. This rotation began each day just after sunrise. Wind speeds peaked around noon on September 11 and near mid-morning on September 12. After sunset each day, the wind speeds decreased and winds abruptly changed direction from the north (onshore) to the south (offshore). The air temperature ranged from 15 to 27 degrees Celsius (°C) at the Wildwood Marina near Villa Angela Beach over the 12-day period and changed only 5–10 °C over the course of a day. Wind speed and direction and temperature were relatively consistent between the observations at Wildwood Marina and Burke Lakefront Airport (7.7 mi to the southwest; fig. 5).

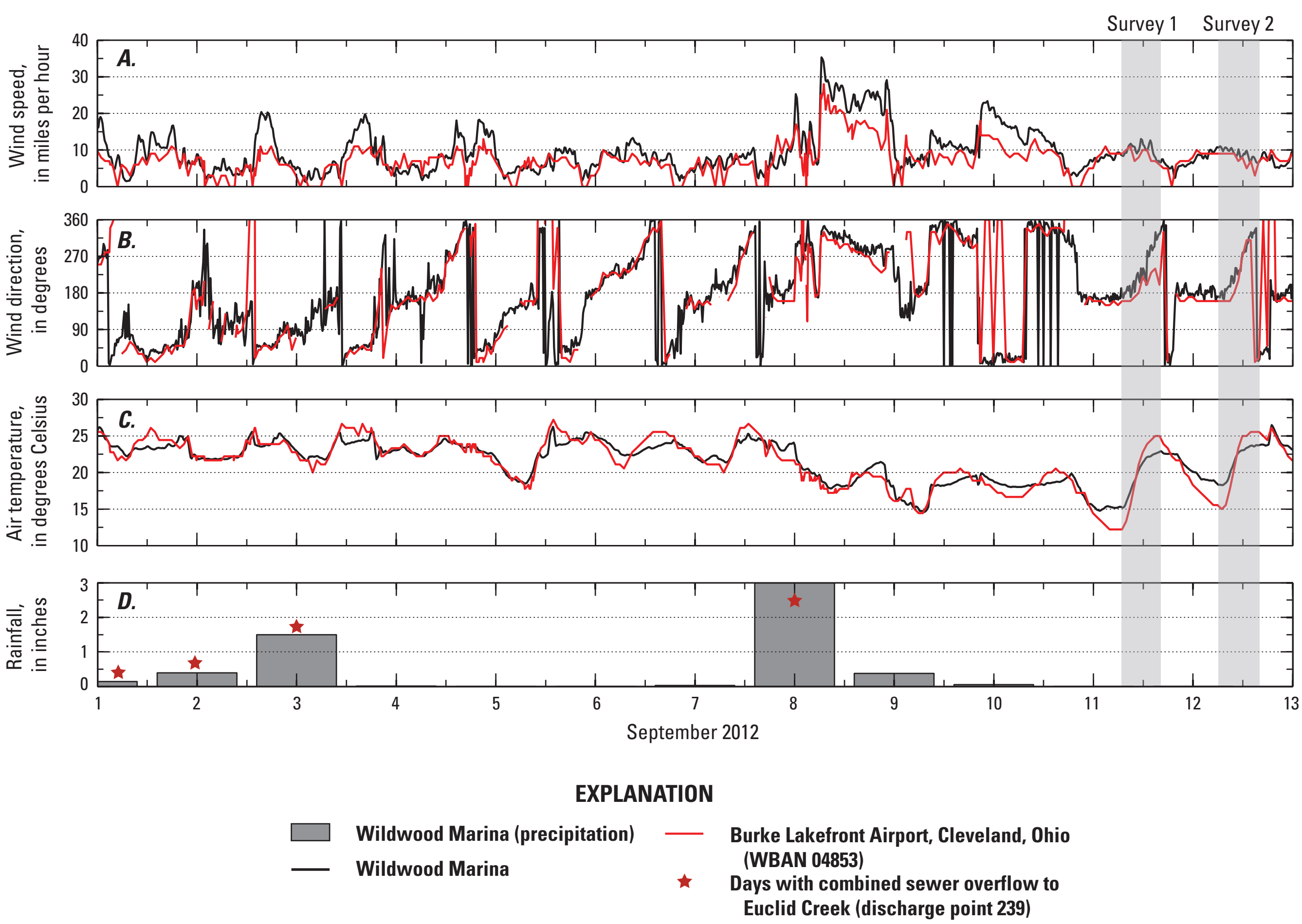


Figure 5. Observations for a 12-day period in September 2012 at Wildwood Marina near Villa Angela Beach, Cleveland, Ohio (data provided by the Northeast Ohio Regional Sewer District), and at Burke Lakefront Airport, Cleveland, Ohio (data provided by the National Climatic Data Center). *A*, Wind speed. *B*, Wind direction (pointing into the wind). *C*, Air temperature. *D*, Daily rainfall.

Precipitation measured at Wildwood Marina shows two large rainfall events occurred in the 10 days prior to the surveys. Daily rainfall totals on September 3 and 8, 2012, measured 1.5 and 3.0 in., respectively. Less than 0.5 in. of rain was recorded on the days just prior to and following these two events. The CSOs to Euclid Creek (point 239) were documented on September 1, 2, 3 and 8, 2012 (see table 1). The flashy nature of Euclid Creek allowed it to return to low-flow conditions prior to the start of the surveys on September 11, 2012. CSO discharges also were reported for the 156th Street and lakefront discharge point (206) on September 3 and 8, 2012 (table 1). CSO discharge points 207 and 208 (fig. 1*B*) are not gaged, so it is not clear if they had CSO discharges during any of these events.

Euclid Creek Inflow

Euclid Creek was at low-flow conditions during these surveys (8–10 ft^3/s; USGS streamgage 04208700). However, the high-flow events on September 3 and 8, 2012 (approximately 900–1,200 ft^3/s), and associated CSO discharges were likely to deliver bacteria to the creek and river mouth that could leach out into the lake over time. Recall that when studying Villa Angela Beach bacteria sources, Bushon and others (2009) found the highest *E. coli* concentrations within Euclid Creek following recent rainfall. Euclid Creek water-quality characteristics measured on September 12, 2012, are given in table 3 for two sampling depths within the creek, 1,000 ft upstream from the mouth. Euclid Creek water was colder, had a higher specific conductance, and a lower pH than nearshore Lake Erie water in the vicinity of Villa Angela Beach. The specific conductance in Euclid Creek was nearly three times higher than that observed in the lake, providing the opportunity to use specific conductance as a tracer to track Euclid Creek water into the lake. Specific conductance is relatively high in raw sewage and septic water compared to lake water and is nearly conservative in this environment making it an excellent candidate for a tracer (Lalor and Pitt, 1999). Lastly, Euclid Creek water is denser than lake water and may form an underflow (or density current) as it enters the lake.

Water in the Wildwood Marina had limited exchange with the lake because of the surrounding jetties; therefore, the water-mass characteristics of the marina also were documented. The marina water was of equal temperature, slightly higher specific conductance, nearly equal pH, and much higher dissolved oxygen as compared to the nearshore Lake Erie water mass (table 3). In addition, significant aquatic vegetation was present within the marina, while little vegetation was observed outside of the marina. This may explain the elevated dissolved oxygen (produced during photosynthesis).

Nearshore Circulation

Circulation within Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Ohio, is influenced by the interaction of the longshore currents—which are primarily driven by regional wind patterns and influenced by seiche activity and inertial waves—with shoreline structures and the outflow from Euclid Creek. This section examines the observed currents for summer 2012 by using ADVM data and highly resolved circulation patterns from synoptic surveys for 2 days in September 2012. Circulation patterns are compared with observations from August 2011.

Table 3. Water-quality characteristics of Euclid Creek and Wildwood Marina water masses, Cleveland, Ohio, September 11–12, 2012.

Site	Sample time (Eastern Daylight Time)	Sampling depth, in feet	Temperature, in degrees Celsius	Specific conductance, in millisiemens per centimeter	pH, in standard units	Dissolved oxygen, in milligrams per liter	Turbidity, in Nephelometric turbidity units	Density, in kilograms per cubic meter
Marina	9/11/2012 13:08	2.1	22.4	0.301	8.43	9.38	0.4	997.788
Marina	9/12/2012 12:16	2.5	22.3	0.3	8.41	10.09	0.1	997.82
Euclid Creek	9/12/2012 12:23	1.3	19	0.851	7.93	7.88	17.5	998.728
Euclid Creek	9/12/2012 12:24	4.4	17.7	0.894	7.86	7.85	36.6	999.001

Magnitude and Direction of Observed Currents near Villa Angela Beach, Ohio, for Summer 2012

Based on the entire period of record (June–October 2012), the currents near Villa Angela Beach are oriented to the east-northeast (75 degrees) 15–20 percent of the time (fig. 6). This is an onshore orientation with a longshore component to the northeast and does not align with the shoreline orientation (about 42 degrees). This misalignment may be due to the local flow disturbance by the caissons, as bin 2 (35–65 ft from the caisson) shows better alignment with the shoreline (65 degrees) than bin 1 (5–35 ft from the caisson; 80 degrees) (fig. 6). A second dominant direction in currents is to the southwest at a heading of about 220 degrees, approximately aligned with the shoreline and consistent with the synoptic observations presented in this report (fig. 6). The magnitude of these currents is small, with a majority of the currents less than 0.2 ft/s and a range of 0–1.4 ft/s. Currents in bin 1 (5–35 ft from the meter) are generally less than currents in bin 2 (35–65 ft from the meter), indicating that flow disturbance around the caisson is occurring (recall the meter is mounted to the north caisson at the marina entrance and points out into the lake; fig. 1*B*). Overall, dividing these data into two groups based on the longshore current component, these data indicate that currents with a longshore component to the northeast occur 67.3 percent of the time in bin 1 and 71.7 percent of the time in bin 2 (table 4). In contrast, currents with a longshore component to the southwest occur 32.7 percent of the time in bin 1 and 28.3 percent of the time in bin 2 (table 4). Therefore, longshore currents in similar directions to those associated with the observed recirculation patterns off Villa Angela Beach occurred approximately 30 percent of the time during summer 2012. It should be noted, however, that not all southwest longshore currents will produce a recirculation, and some northeast longshore currents also may induce flow separation and recirculation off Villa Angela Beach because of flow disturbance caused by the marina jetties and other structures.

While all summer months show a similar trend in current direction (dominant to the ENE), longshore currents to the northeast occurred more often in early summer (June), and the percentage of southwest longshore currents was highest toward the end of summer (August) (fig. 7 and table 4). It is not known whether the observed trends are characteristic of typical conditions because only one summer of data was collected.

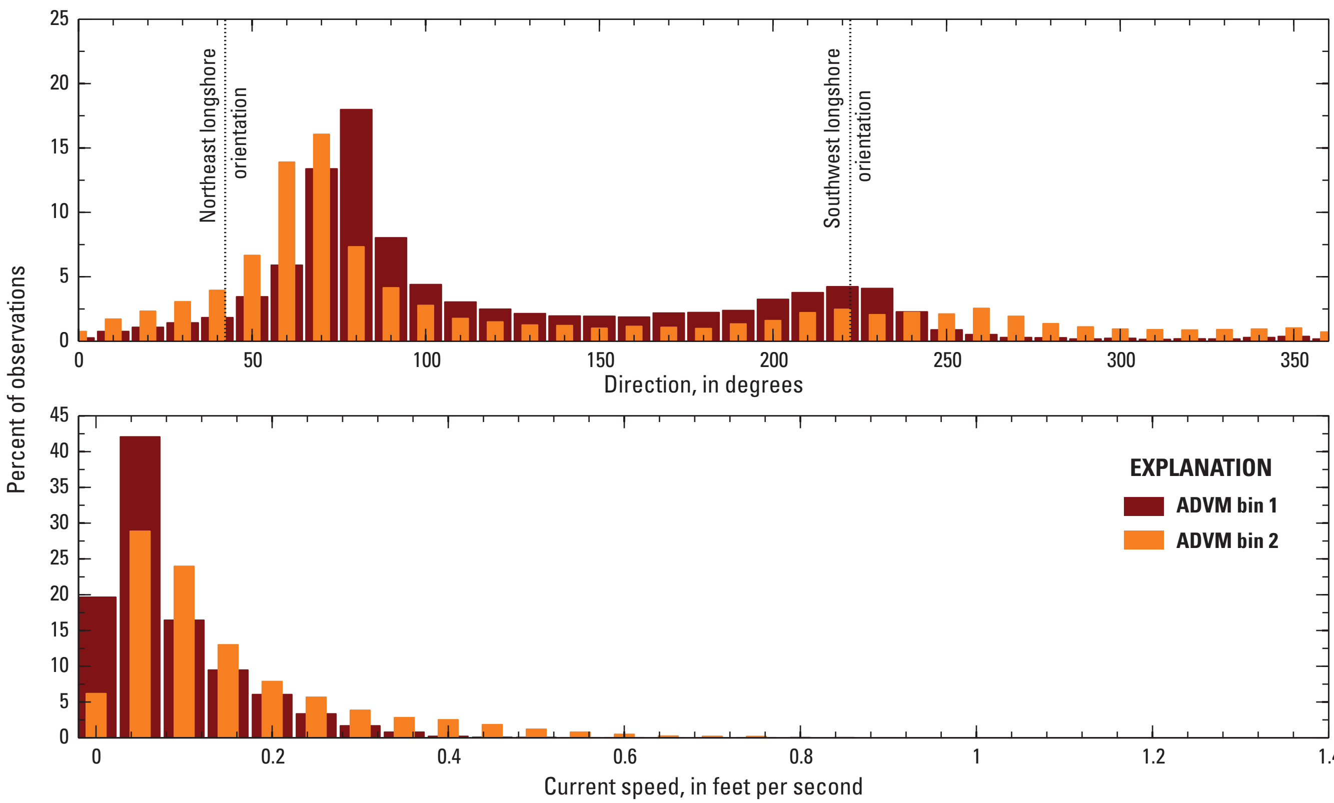


Figure 6. Characteristics of nearshore currents measured by the acoustic Doppler current meter (ADVM) mounted to the northern caisson in front of the Wildwood Marina near Villa Angela Beach, Cleveland, Ohio. Currents were measured lakeside of the caisson from June 7 to October 6, 2012, at a height above bottom of approximately 8 feet. Bin 1 is located 5–35 feet from the instrument, and bin 2 is located 35–65 feet from the instrument.

Table 4. Prevalence of the orientation of the longshore current component of observed currents measured by the acoustic Doppler velocity meter (ADVM), sorted by month, near Villa Angela Beach, Cleveland, Ohio, for June 7 to October 6, 2012, at a height above bottom of approximately 8 feet.

Month	ADVM Bin	Northeast longshore current component (percent of observations)	Southwest longshore current component (percent of observations)
June	1	77.84	22.16
June	2	81.13	18.87
July	1	69.62	30.38
July	2	74.66	25.34
August	1	59.14	40.86
August	2	63.75	36.25
September	1	64.38	35.63
September	2	67.89	32.11
All	1	67.33	32.67
All	2	71.71	28.29

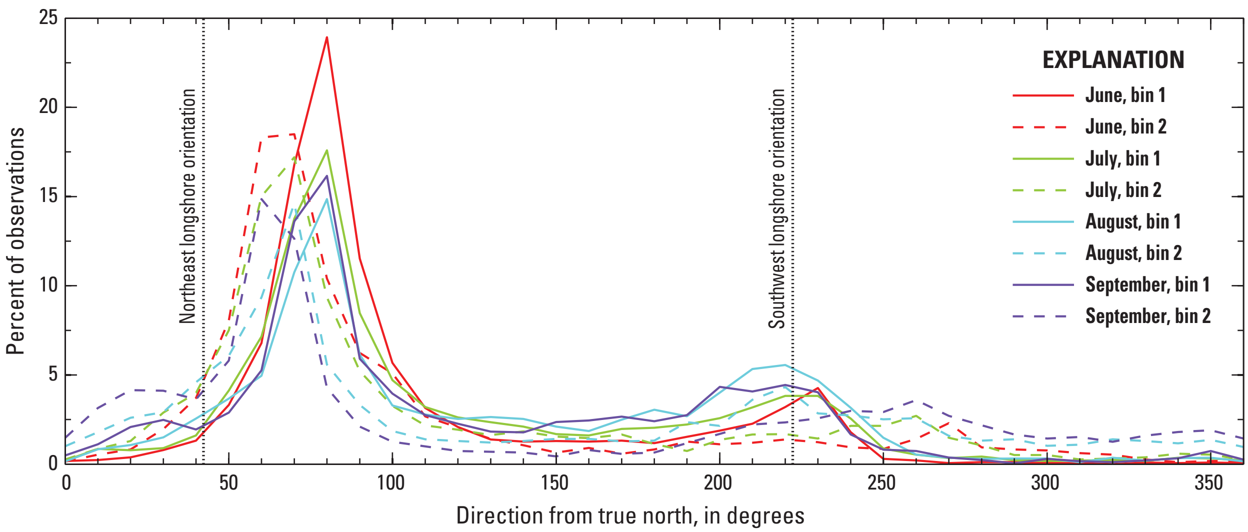


Figure 7. Monthly characteristics of nearshore currents measured by the acoustic Doppler velocity meter mounted to the northern caisson in front of the Wildwood Marina near Villa Angela Beach, Cleveland, Ohio. Currents were measured lakeside of the caisson from June 7 to October 6, 2012, at a height above bottom of approximately 8 feet. Histogram data are presented as a line plot (by connecting the top, center of each bin with a line) to improve clarity. Bin 1 is located 5–35 feet from the instrument, and bin 2 is located 35–65 feet from the instrument.

Longshore Currents

Throughout the entire synoptic survey period, longshore currents were oriented southwest at a heading of approximately 220 degrees (figs. 8–10). The magnitude of the depth-averaged longshore currents generally ranged from 0.2 to 0.4 ft/s. Near-surface currents were generally larger than near-bed currents for most of the survey area, with the exception of the southwest portion of the survey area, which exhibited near-bed velocities that were equal to, or larger than, near-surface velocities (fig. 10). These longshore currents persisted throughout the survey in spite of the opposing midday winds that were out of the southwest, west, and northwest. These currents were likely a result of a regional circulation setup by the strong northwesterly winds observed on September 8, 2012 (fig. 5). Due to the rotation of the earth and the Coriolis effect, northwesterly winds (at 310 degrees) will produce a net transport of water 90 degrees to the right of the wind or at a heading of 220 degrees. This is consistent with the observations of longshore currents in the southwesterly direction.

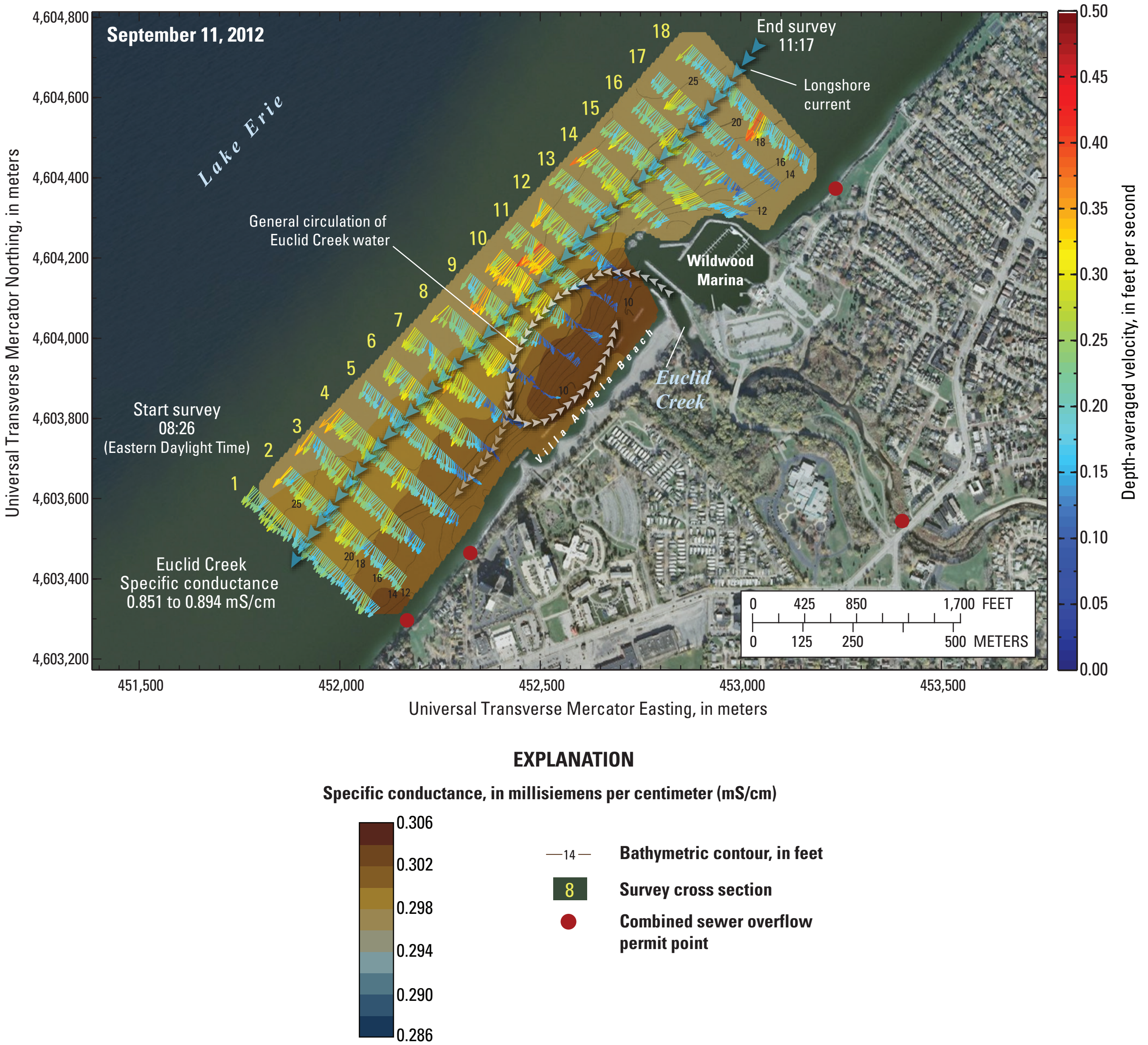


Figure 8. Depth-averaged currents and distribution of near-surface specific conductance in coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 11, 2012.

Villa Angela Beach Recirculation Zone

Longshore currents flowing to the southwest interact with the jetties surrounding Wildwood Marina and Euclid Creek to form a persistent eddy or zone of recirculation on the leeward side of the marina just off Villa Angela Beach (figs. 8–10). This recirculation impedes the ability of nearshore currents to dilute Euclid Creek water and leads to steering of Euclid Creek waters (and CSO-related pollutants such as bacteria) into Villa Angela Beach, as evidenced by the persistence of higher specific conductance water along the beachfront (figs. 8 and 9). Such a zone of recirculation also was documented in synoptic surveys in August 2011 by the USGS indicating it is a repeatable circulation pattern for this site. The maximum specific conductance observed in the survey domain over the 2 days of data collection occurred on September 12, 2012, on the eastern end of Villa Angela Beach behind the easternmost breakwater and the beach (fig. 9) and is consistent with the 2009–10 NEORSD data, which showed significantly higher *E. coli* concentrations on the east end of Villa Angela Beach as compared to the west end (Ohio Department of Health, 2010).

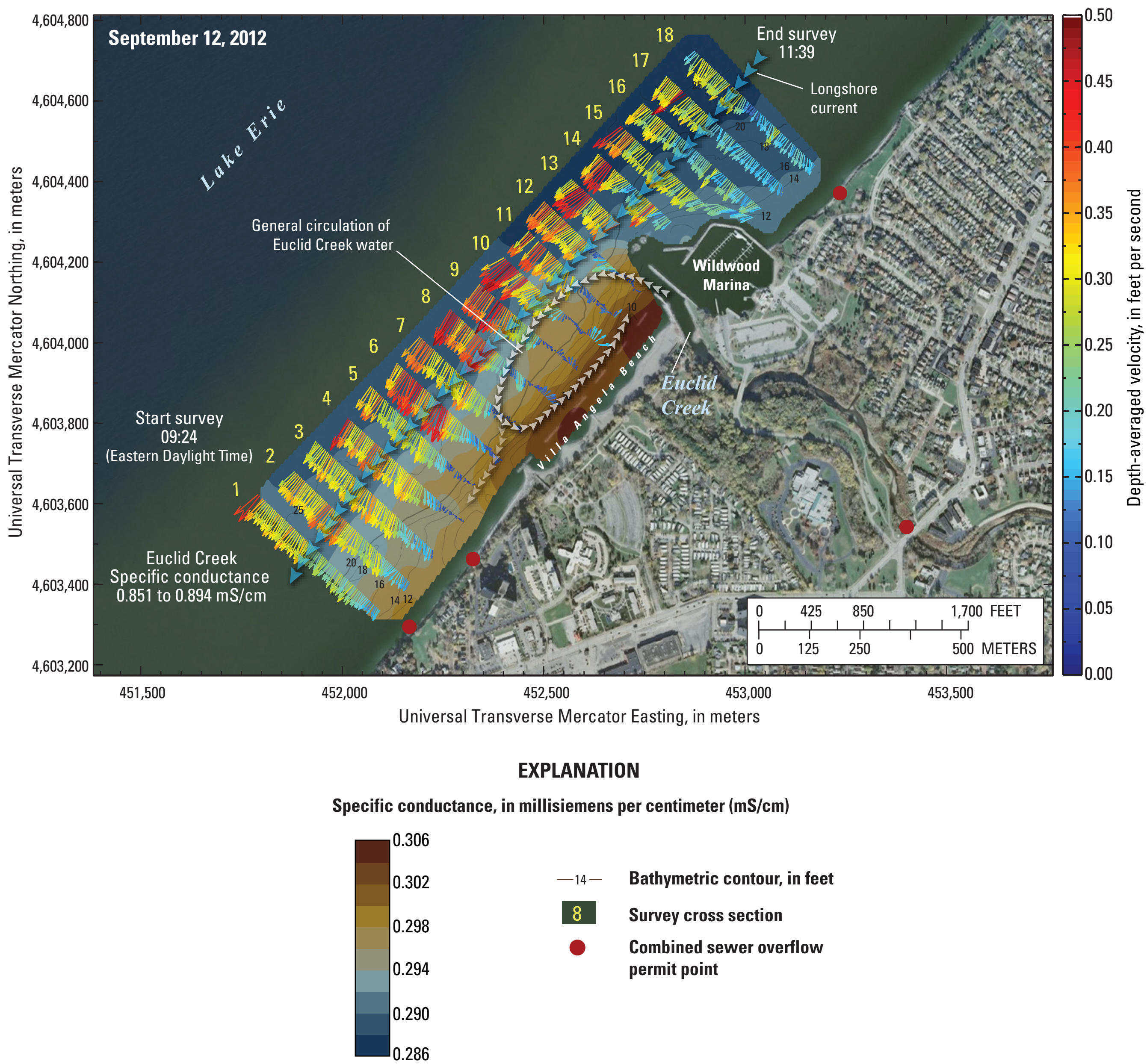


Figure 9. Depth-averaged currents and distribution of near-surface specific conductance in coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 12, 2012.

The extent of the recirculation varies in time and space, with significant differences in extent between the surface layer and near-bed layer (fig. 10). On the afternoon of September 11, 2012, the recirculation cell was relatively tight and covered the extent of Villa Angela Beach. The near-bed extent of the recirculation was nearly twice the extent of the recirculation at the surface. A similar pattern was observed on the afternoon of September 12, 2012, but with a much larger extent of the near-bed recirculation that extends well beyond the southwestern end of Villa Angela Beach and envelops the two CSO discharge points to the southwest of the beach (fig. 10). This is important to note because this deep recirculation provides a mechanism for CSO discharge water to be transported to the beachfront and recirculated along with Euclid Creek water for an extended period of time in spite of longshore currents to the southwest. The growth of the zone of recirculation on September 12, 2012, may have been caused by a weakening of the longshore currents in the afternoon combined with a change in the nearshore lake water mass (discussed in the water-quality section).

In general, September 11–12, 2012, was a period of onshore surface flows and offshore near-bed flows (figs. 10 and 11). Combined with the longshore current and neglecting the zone of recirculation, these patterns can be characterized as a helical flow trajectory in which surface water is pushed ashore as it moves southwest along the lakefront, followed by downwelling (plunging) near the shoreline and offshore transport near the lake bed. This pattern is best visualized in figure 11 in which the velocity data from cross section 9 have been plotted in a manner that shows both longshore and onshore-offshore velocity components over the full depth of flow. To better see the opposing bidirectional flow present within the zone of recirculation, the color scale has been set to show southwesterly longshore currents in warm colors (red, orange, and yellow) and northeasterly currents in cool colors (blues). While the nearshore downwelling is present both days, the circulation patterns for the afternoon surveys are markedly different. Large-scale eddies present on the afternoon of September 11, 2012 (fig. 11*A*), drive mixing offshore and allow near-bed water to be mixed to the surface. The recirculation (blue) is pinned nearshore and does not extend beyond about 700 ft offshore (consistent with the edge of the recirculation and specific conductance plume in fig. 8). However, on the afternoon of September 12, 2012, the longshore currents are weaker (as are the onshore-offshore currents), no large-scale eddies are present (primarily downwelling), and the near-bed zone of recirculation (blue) spreads more than 1,500 ft offshore. It should be noted that velocity data from the morning of September 12, 2012 (not shown), exhibit large-scale, full-depth eddies (similar to those in fig. 11*A*) with vertical velocities of up to 0.2 ft/s and widths of 300 ft creating mixing off Villa Angela Beach (approximately 500–1,200 ft offshore). The presence of such eddies on the morning of September 12, 2012, indicates that upwelling was occurring earlier in the day on September 12, 2012, and may have continued from the previous day.

Onshore-offshore circulation patterns exhibited in figure 11 may allow bacteria from Euclid Creek or other CSO points near Villa Angela Beach to be pushed onshore by surface currents, taken offshore by near-bed currents, and mixed between the two layers by large-scale turbulent eddies, all while recirculating counterclockwise just offshore of Villa Angela Beach.

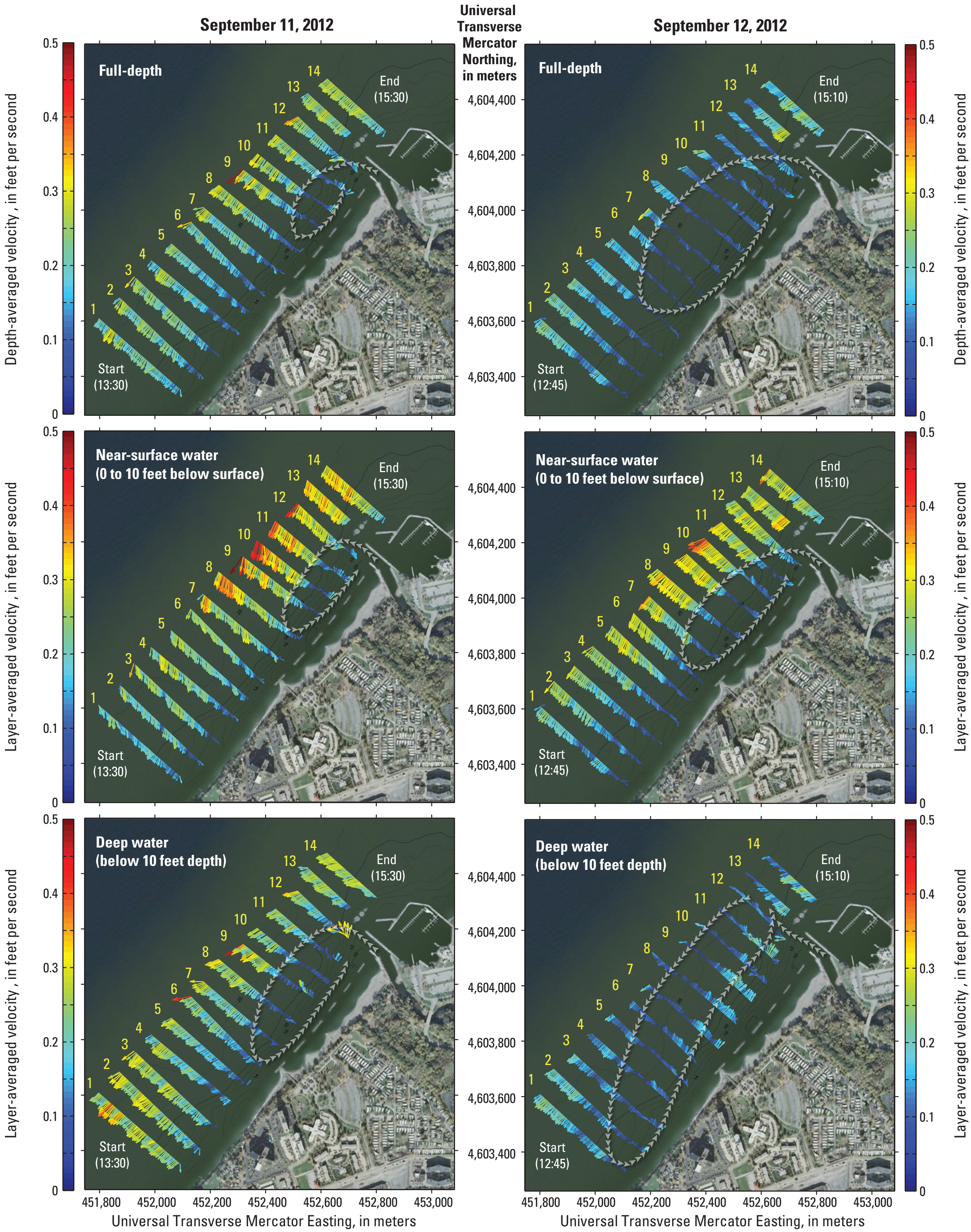


Figure 10. Depth- and layer-averaged currents in coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, on the afternoons of September 11 and 12, 2012. Repeat transects (one offshore and one onshore) were averaged at each cross section to compute velocity field for each section (averaged independently from adjacent sections). All survey start and end times are in Eastern Daylight Time.

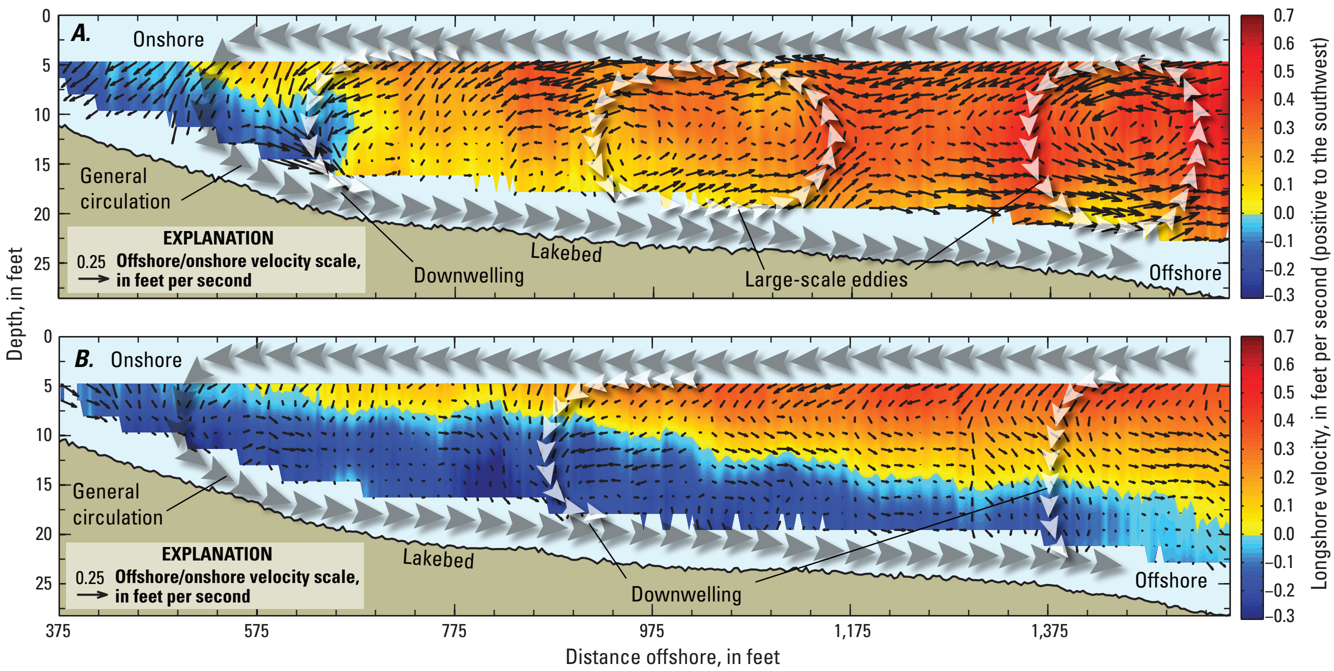


Figure 11. Distribution of currents in cross-section 9 (XS9) in coastal Lake Erie in the vicinity of Villa Angela Beach, Cleveland, Ohio. *A*, Afternoon of September 11, 2012. *B*, Afternoon of September 12, 2012.

Water-Quality Distributions

This section discusses the observed water-quality distributions for September 11–12, 2012, near Villa Angela Beach. Data are presented in both plan view and as cross sections through the survey area so as to provide the reader with a full three-dimensional picture of the distribution of basic water-quality parameters near the mouth of Euclid Creek and Villa Angela Beach.

Density Distribution

On September 11–12, 2012, there existed a relatively large difference in density between the water in Euclid Creek and Lake Erie water in the vicinity of Villa Angela Beach. The overall change in density over depth in nearshore Lake Erie within the survey area was 0.12 kilograms per cubic meter (kg/m^3), while the difference in density between Euclid Creek water and Lake Erie water was over 10 times greater with a density difference of 1.241 kg/m^3. Therefore, there is sufficient density difference between the creek water and the lake water to drive a density current consisting of mainly river water offshore along the lake bed from the mouth of the creek. The excess density, defined as the difference in density between the two water masses divided by the density of the ambient lake water, is 0.124 percent and is nearly three times greater than the excess density of density currents measured on the Chicago River (Jackson and others, 2008). The greater the excess density, the greater the driving force of the density current. The weaker Chicago River density currents are capable of flowing 1.6 mi upstream along the bed against the flow of the river before being arrested by the Chicago Lock at Lake Michigan. Consistent with the conclusions from the 2011 USGS survey, data indicate that Euclid Creek water can form density currents as it enters Lake Erie.

On September 11, 2012, distributions of density in nearshore water are consistent with the formation of density currents from Euclid Creek and the subsequent mixing of this dense water into the water column through the action of turbulence and wave action (figs. 12 and 13). Dense water can be seen entering the lake from Euclid Creek (fig. 13) and forming tilted isopycnals (surfaces of equal density). For such tilted density surfaces, gravity drives density currents out into the lake while attempting to restore these surfaces to equilibrium (horizontal). As the dense water moves out into the lake, large turbulent eddies like those seen in figure 11*A* mix the dense water up into the water column, diluting the current, thus reducing its driving force, and generating a local anomaly in water density near the mouth of Euclid Creek (fig. 12). Nearshore surface water is significantly denser than offshore water (fig. 12) and a zone of upwelling (likely caused by a large eddy) can be seen both in the near-surface distribution (fig. 12, line 11) and in the near-bed density distribution (fig. 12, line 10). This upwelling is accurately captured in figure 13, line 11 (September 11, 2012). Offshore vertical mixing of the dense Euclid Creek water will help dilute the concentrations of any CSO-related pollutants that may be present in this water mass, but it also may allow resuspension and transport of near-bed water. If the lakebed off Villa Angela Beach contains any contaminated sediment and (or) bacteria potentially deposited on the bed during higher flow events on Euclid Creek or CSO discharges directly to the lake, then this upwelling and vertical mixing may provide a mechanism for transport to the beach. Once in the water column, any resuspended bacteria may be trapped in the recirculating zone off Villa Angela Beach or re-deposited along the beachfront.

As compared to September 11, 2012, the density distribution on September 12, 2012, is relatively uniform off Villa Angela Beach and generally more stratified northeast of the marina (figs. 12 and 13). While a density current signature is not visible in these data, the relative uniformity of the density distribution within the recirculation (transects 1–12) may reflect stronger mixing in the water off Villa Angela Beach as compared to the stratified water northeast of the marina (transects 13–18). The significantly larger zone of recirculation and stronger near-bed recirculating currents seen on September 12, 2012 (fig. 10), may be responsible for the enhanced mixing. In addition, velocity distributions on the morning of September 12, 2012, showed large-scale eddies (similar to those in fig. 11*A*) creating upwelling and mixing in the water column.

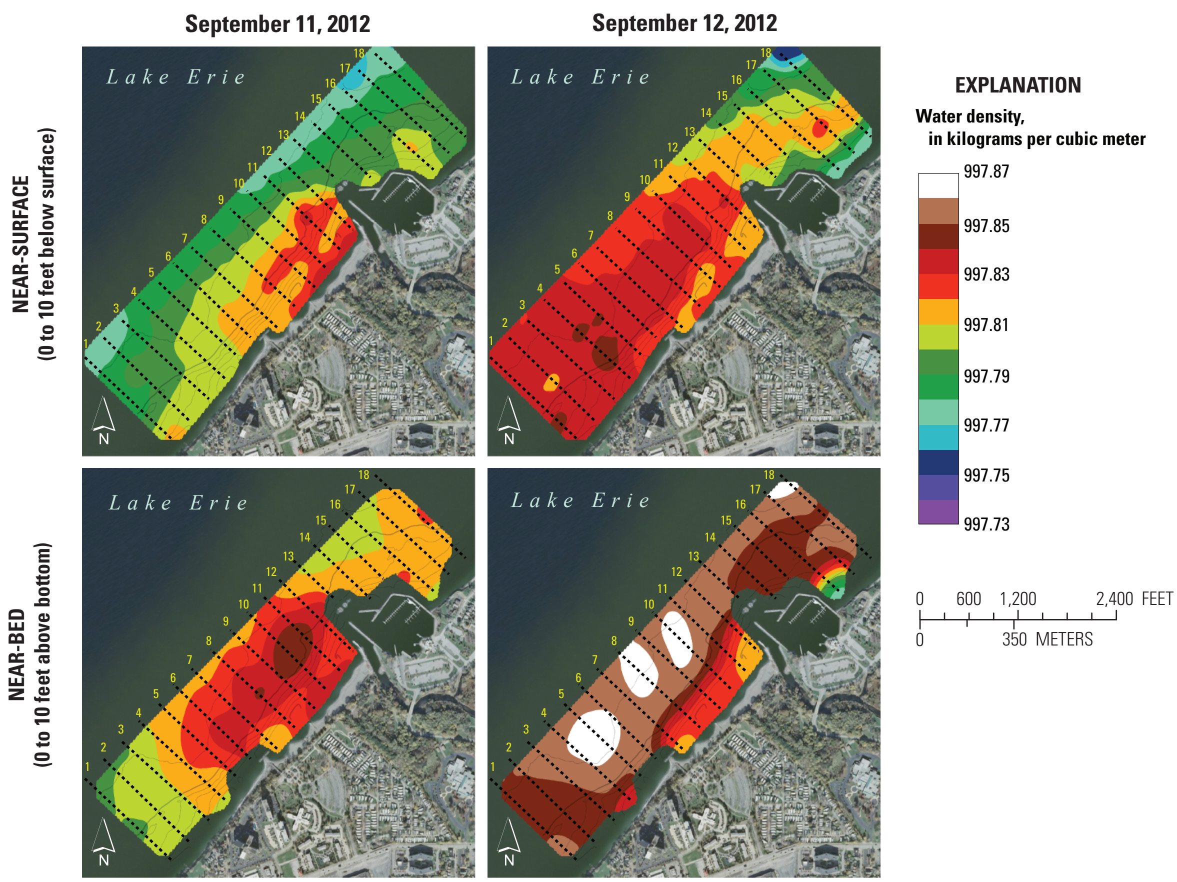


Figure 12. Maps showing distributions of water density for coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio. Survey lines and bathymetric contours are shown for reference (see figure 8 for contour labels).

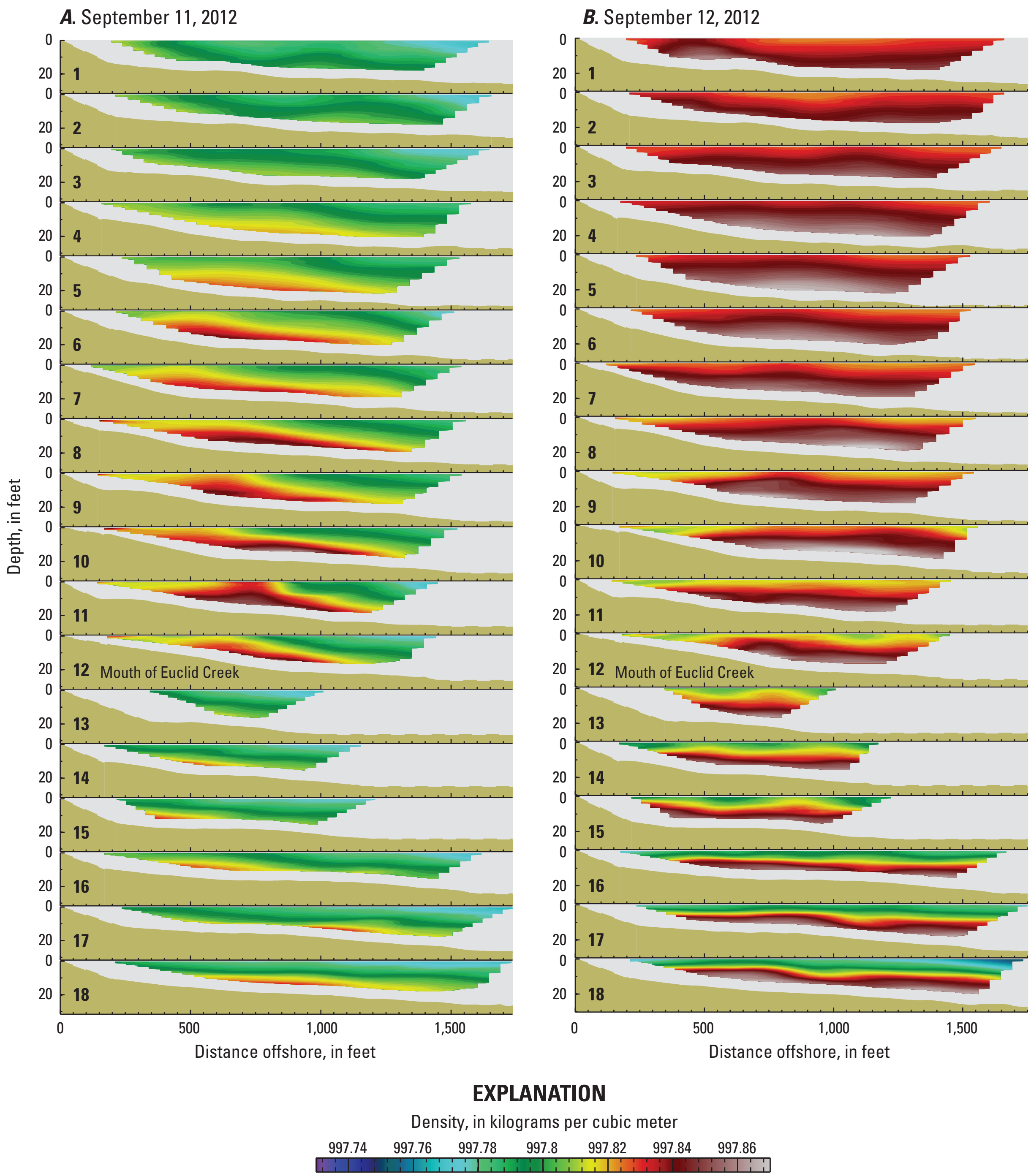


Figure 13. Cross sections of water density for 18 sections of coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio. *A*, September 11, 2012. *B*, September 12, 2012.

Temperature Distribution

A lower temperature thermal plume, characteristic of Euclid Creek water, was evident within Lake Erie surrounding the mouth of Euclid Creek and Villa Angela Beach on September 11, 2012, while a much more complex thermal distribution was present on September 12, 2012 (figs. 14–17). The extent of the September 11 thermal plume matches that of the specific conductance plume presented in figures 8 and 14–16, lending validity to the conclusion that this plume was created primarily by Euclid Creek water and not by upwelling of colder hypolimnetic water. However, offshore upwelling was occurring on September 11, 2012, due to large-scale eddies (see fig. 11*A*) and is evident in the anomalous cold water spot in figure 14 (line 11) and more clearly in figure 15 (line 10) and figure 16 (line 11). The upwelling cell captured in these data shows colder water from near the bed being advected up to the surface in an area several hundred feet in diameter. This upwelling cell occurred within the shear layer along the outer boundary of the river plume.

The temperature distributions from September 12, 2012, do not show a clearly defined river plume, but instead show relative uniform temperatures offshore of Villa Angela Beach and much greater variability northeast of the marina (figs. 14–17). As previously discussed in the density section, the uniformity of the temperature distribution off Villa Angela Beach is evidence for significant vertical mixing and upwelling of hypolimnetic water, both of which are consistent with the velocity distributions observed on the morning of September 12, 2012. Unlike the survey on the preceding day, data from September 12, 2012, show a temperature distribution that is decoupled from the specific conductance distribution providing further evidence for a thermal distribution dominated by upwelling and solar radiation. The water temperature gradually increased from the start of the survey to the end of the survey (fig. 14) indicating that solar radiation played a larger role in defining water temperatures on September 12, 2012, compared to the previous day. Finally, there is some evidence that the temperature distribution on September 12, 2012, was influenced by advection of a colder water mass from the northeast as a ‘river’ of colder surface water is seen moving southwest in lines 13–18 (fig. 14). However, this distribution also could arise from more localized upwelling northeast of the marina. Because water temperature varies during the day due to solar radiation and seasonally from air and surface-temperature variations, and because the lake is not thermally uniform, use of spatial variations in temperature needs to be substantiated with other water-quality data to determine the extent of river plumes in nearshore areas of Lake Erie.

Specific Conductance Distribution

With specific conductance in Euclid Creek nearly three times higher than Lake Erie water (which was relatively uniform away from the creek), specific conductance proved to be an excellent tracer to track the plume from Euclid Creek into Lake Erie. Both survey days exhibit a specific conductance distribution that clearly defines the river plume within the surface water (fig. 14), the near-bed water (fig. 15), and throughout the full depth of the water column (figs. 16 and 17). Data from September 11, 2012, show specific conductance highest within the center of the recirculation zone just offshore of Villa Angela Beach (figs. 14 and 8). On September 12, 2012, the region of highest specific conductance occurs nearshore and covers the extent of Villa Angela Beach (with the highest concentration on the east end of the beach). The shift in the position of this high concentration zone is likely related to the change in the character and extent of the nearshore zone of recirculation between the 2 days. This has important implications for the health of Villa Angela Beach because CSO-related pollutants, such as bacteria, which may be present in Euclid Creek water, will likely exhibit similar distributions and mixing patterns as specific conductance.

The extent of the near-bed specific conductance plume (fig. 15) is larger than the surface plume (fig. 14) because of plunging of the Euclid Creek water and formation of density currents driving near-bed flow offshore. Unfortunately, because of the safety requirement to keep the AUV 6 ft above the bed at all times, the full extent of the near-bed specific conductance plume was not captured and is likely more extensive than that displayed in figure 15. Nevertheless, the plunging is evident in the velocity (fig. 11) and the specific conductance data (figs. 16 and 17). Sections 8 and 10 appear to have more consistent and significant plunging and density-current formation as compared to other sections because both sections exhibit the formation of near-bed protrusions of higher specific conductance water, characteristic of a density current, on both September 11 and 12, 2012. This may be caused by a combination of favorable hydrodynamics (lower opposing currents and (or) greater aiding currents) and bathymetry (topographic lows) within these sections that allow the currents to form.

pH and Dissolved Oxygen Distributions

Based on the data collected in this study, distributions of pH and dissolved oxygen in the vicinity of Euclid Creek and Villa Angela Beach do not appear to be greatly influenced by the inflowing river water (the zone of greatest influence may have been confined to the river channel and not captured in the nearshore survey); however, the distributions may be affected in an indirect manner as Euclid Creek supplies nutrients to algae and macrophytes, which in turn affect the pH and dissolved oxygen of the aquatic environment. Sunny days like those during the survey can trigger photosynthesis in the nearshore aquatic populations and the plants produce oxygen (thus increasing dissolved oxygen) and use up hydrogen molecules causing a local rise in pH. Data from September 11, 2012, show relatively high pH and dissolved oxygen values along the shoreline with the greatest concentrations northeast of the marina and near the mouth of Euclid Creek (figs. 14–17). However, Euclid Creek had pH values of about 7.9 standard units and a dissolved oxygen concentration of about

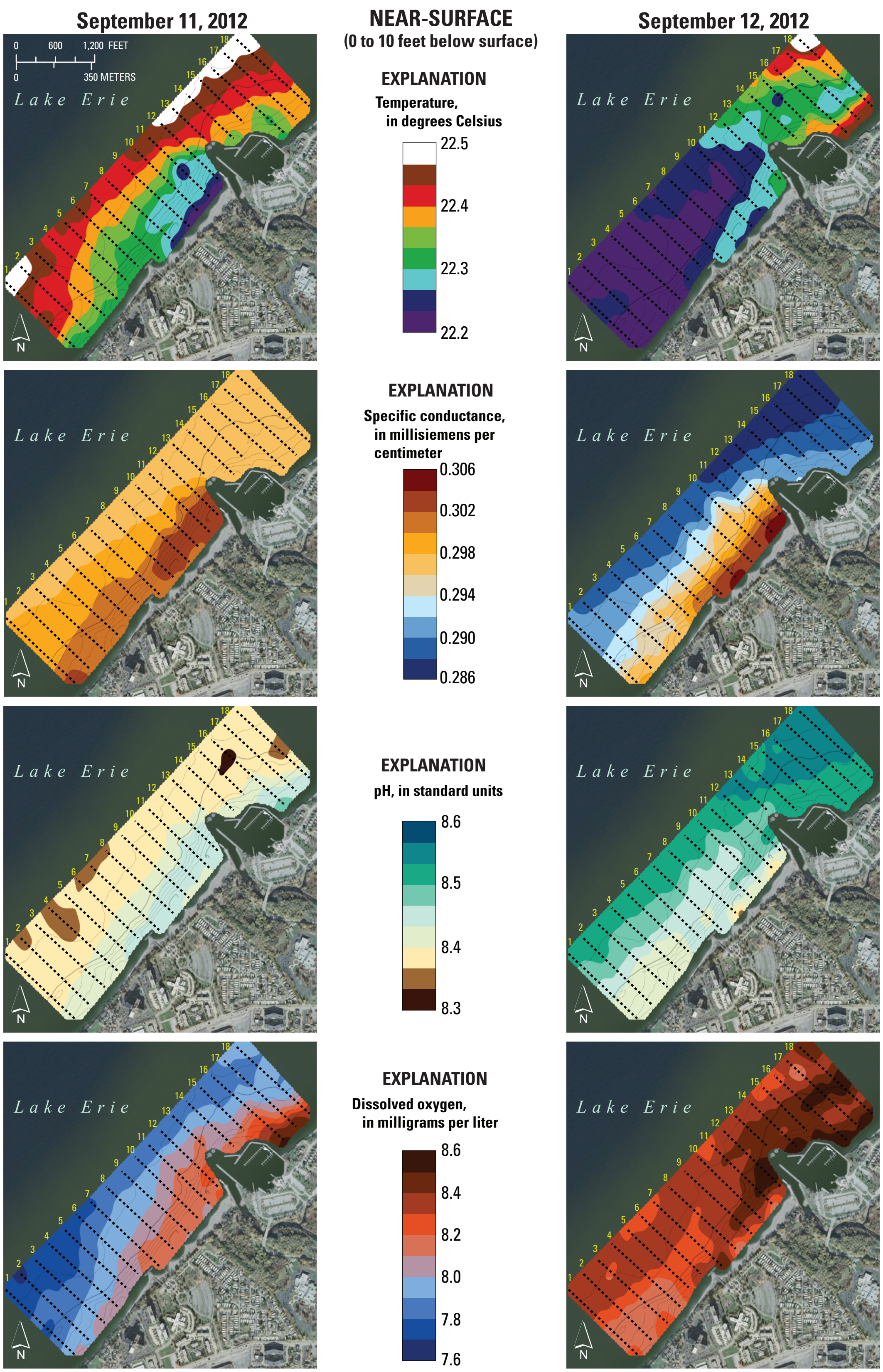


Figure 14. Maps showing distributions of near-surface (0–10 feet depth) basic water-quality parameters for coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 11–12, 2012. Survey lines and bathymetric contours are shown for reference (see figure 8 for contour labels).

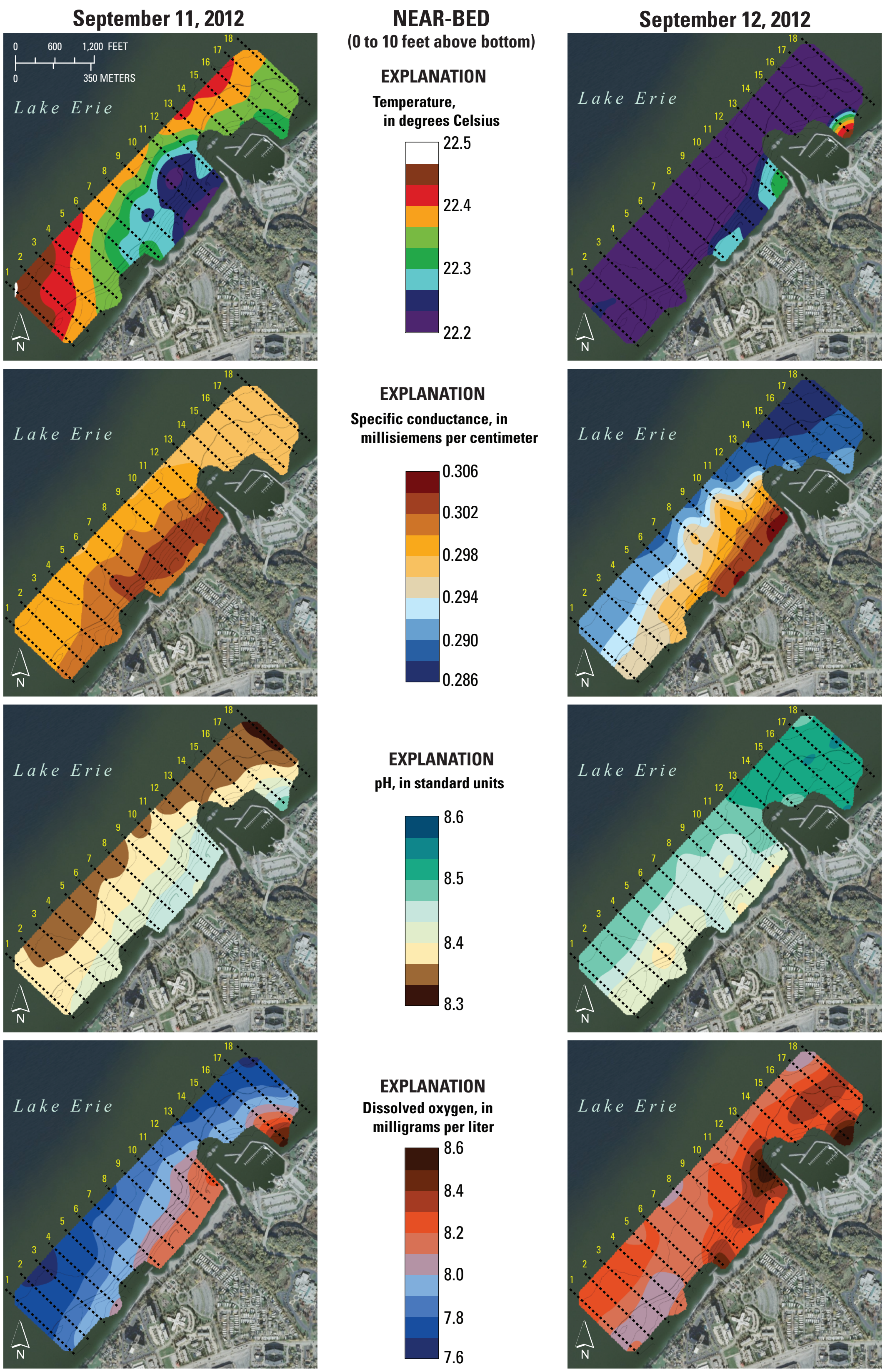
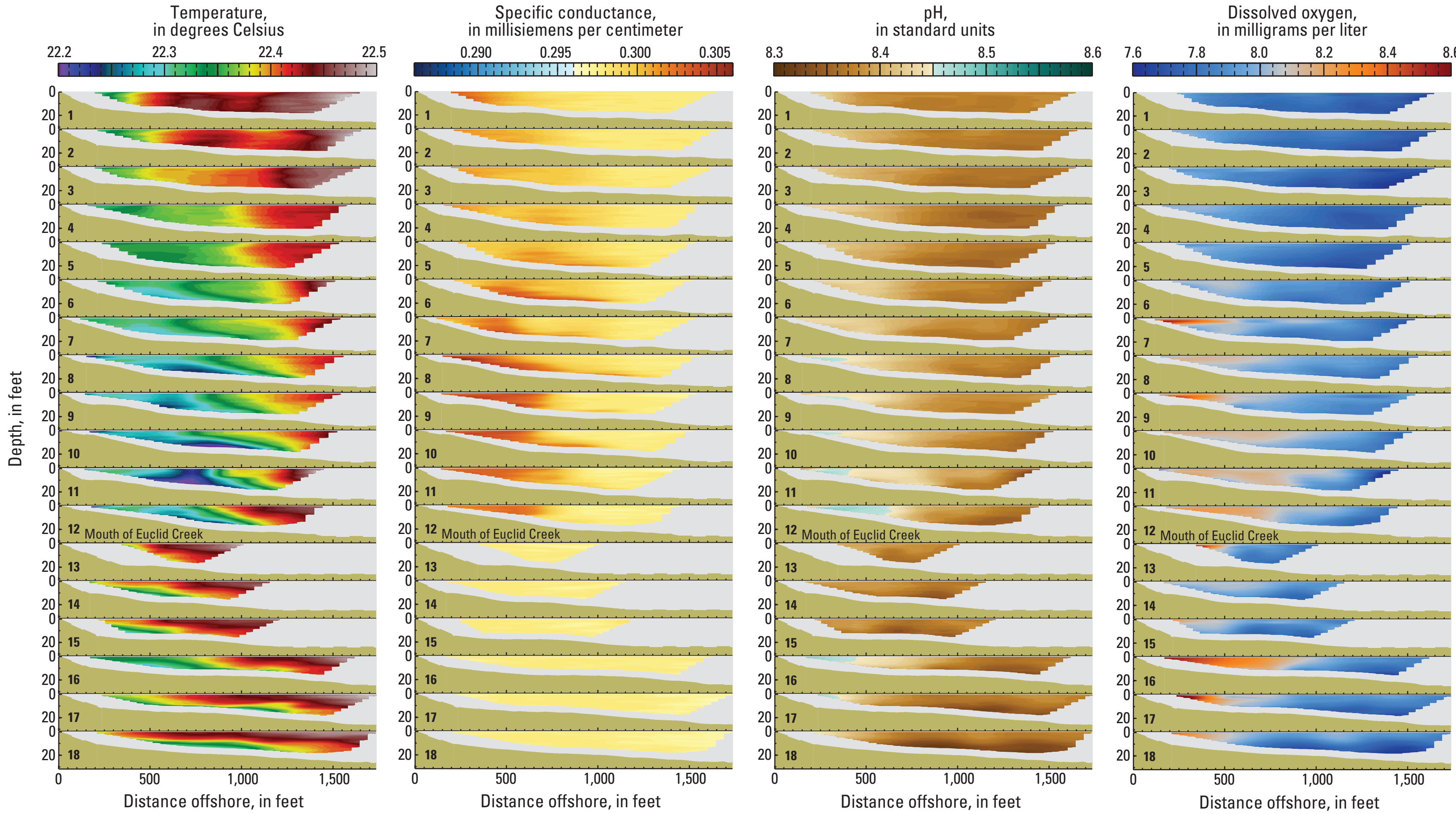


Figure 15. Distributions of near-bed (0–10 feet above bed) basic water-quality parameters for coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 11–12, 2012. Survey lines and bathymetric contours are shown for reference (see figure 8 for contour labels).



September 11, 2012

Figure 16. Cross sections of basic water-quality parameters for 18 sections of coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 11, 2012.

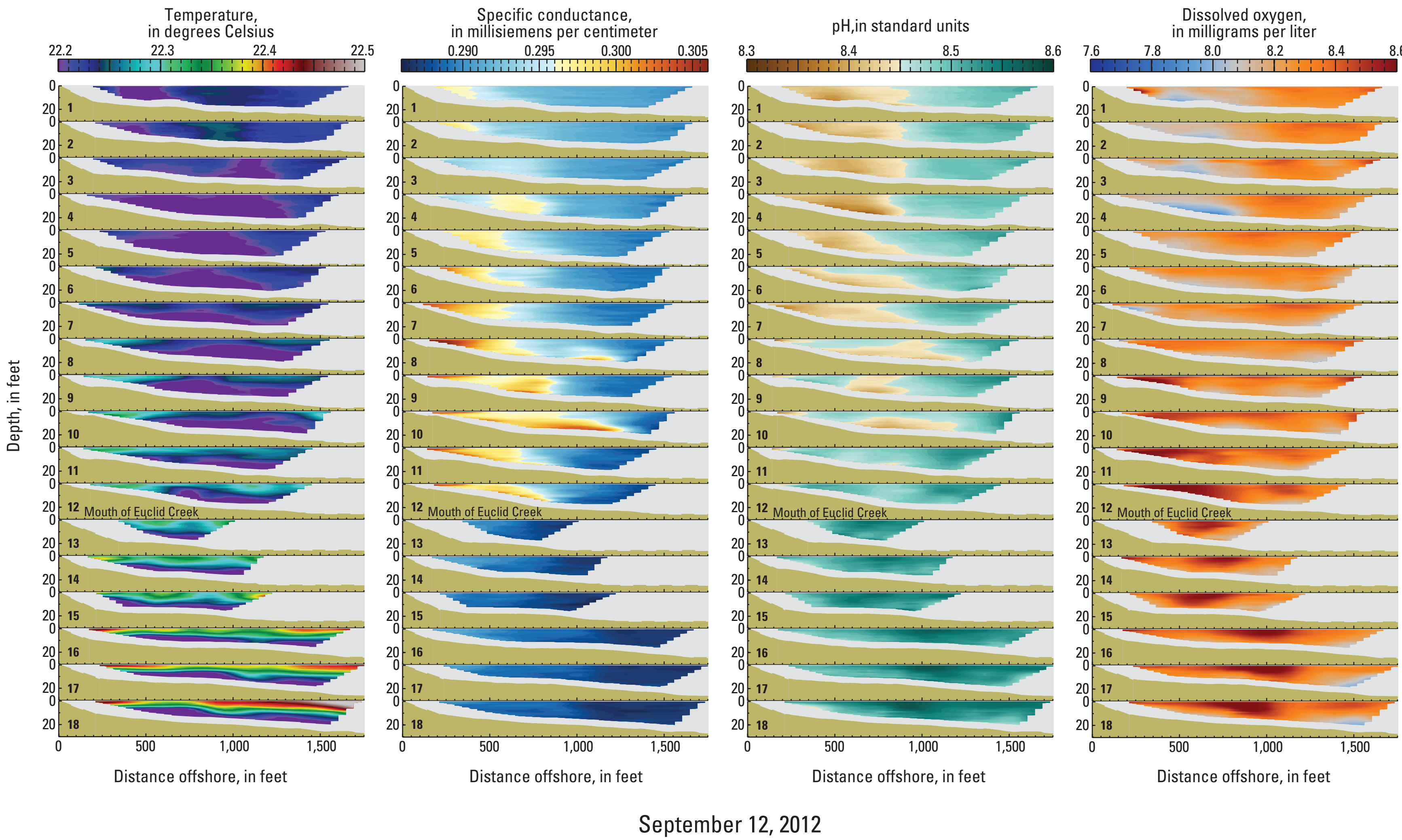


Figure 17. Cross sections of basic water-quality parameters for 18 sections of coastal Lake Erie in the vicinity of Villa Angela Beach and Euclid Creek, Cleveland, Ohio, September 12, 2012.

7.9 milligrams per liter (mg/L) (table 3), both of which were lower than the observed nearshore values on Lake Erie (figs. 14 and 15). In addition, the marina had pH values of about 8.4 standard units and a dissolved oxygen concentration of about 9.4 mg/L (table 3) and had dense populations of macrophytes and algae present during the survey. Therefore, it is likely that the marina is a partial source of the local anomalies in pH and dissolved oxygen and contributes to the local affect from Euclid Creek. The distributions also are potentially affected by macrophytes and algae populations present along the protected beach and within dead zones just northeast of the marina.

The distributions of pH and dissolved oxygen on September 12, 2012, were less conclusive and dominated by a higher dissolved oxygen and higher pH water mass that moved into the area from the northeast. Like the temperature distribution on September 12, 2012, the distributions of pH and dissolved oxygen show a similar ‘river’ of high pH and high dissolved oxygen entering the survey domain from the northeast (figs. 14 and 17, lines 13–18). The source of this water mass is unknown because it is not fully contained within the study domain; therefore, these interpretations should be used with caution. In contrast to the previous day, this change in Lake Erie water mass traps lower pH and lower dissolved oxygen water nearshore along the southwestern portion of Villa Angela Beach, but the area surrounding the mouth of Euclid Creek and the marina continues to have the highest dissolved oxygen (figs. 14–17), lending some validity to the theory that the marina may contribute to the local anomaly in pH and dissolved oxygen near the mouth of Euclid Creek. It should be noted that interpretation of these data are complicated by the limited exchange of water between the marina and the lake, the lack of data in the mouth of Euclid Creek, the number of potential sources and sinks of dissolved oxygen in the study area, the proximity of the marina to the mouth of Euclid Creek, and the lack of water-quality data outside the study domain.

Turbidity and Blue-Green Algae Distributions

Distributions of turbidity in the nearshore in the vicinity of Euclid Creek were relatively uniform with turbidity values generally less than 10 Nephelometric turbidity units (NTUs) (no figure shown). However, the September 12, 2012, survey did show slightly elevated turbidity values near the mouth of Euclid Creek (up to 20 NTUs) and along the northeast portion of Villa Angela Beach directly adjacent to the mouth of Euclid Creek. No signature of Euclid Creek water was detected in turbidity during the survey on September 11, 2012. Turbidity values in Euclid Creek upstream from the mouth were 17.5–36.6 NTUs on September 12, 2012 (table 3).

Relative blue-green algae concentrations in the nearshore in the vicinity of Euclid Creek were highly variable (surface sampling can introduce more noise in the optical probes due to air entrainment), but indicated elevated relative concentrations (6,000–10,000 cells per milliliter (cells/mL)) near the beachfront adjacent to the mouth of Euclid Creek and in the corner where the shoreline meets the jetty just northeast of the marina on September 11, 2012 (no figure shown). This distribution is consistent with the elevated nearshore pH and dissolved oxygen concentrations on September 11, 2012 (figs. 14 and 15). The distribution of blue-green algae on September 12, 2012, showed elevated concentrations (8,000–14,000 cells/mL) only along the beachfront adjacent to the mouth of Euclid Creek. Note that these concentrations are relative because the sensor was calibrated only in deionized water (0 cells/mL), a one-point calibration. For comparison, the lake water away from the marina and the beachfront had relative blue-green algae concentrations of 3,000–4,000 cells/mL.

Summary and Conclusions

Villa Angela Beach, along the Lake Erie lakeshore in Cleveland, Ohio, is adjacent to the mouth of Euclid Creek, a small, flashy stream in which approximately 100–200 combined sewer overflows (CSOs) have occurred per year, in recent years. Concerns over high concentrations of *Escherichia coli (E. coli)* in water samples taken along this beach and a high number of beach closures during the recreational season have led to synoptic sampling of the nearshore mixing zone in an attempt to gain insight into mixing processes, circulation, and potential for transport of CSO-related pollutants, such as bacteria, from nearby sources to the beach. An integrated synoptic survey of the nearshore mixing zone was performed on September 11–12, 2012, by the U.S. Geological Survey (USGS), following a high-flow event and a CSO discharge in Euclid Creek on September 8–9, 2012. Sampling methods included deployment of an autonomous underwater vehicle (AUV) and use of a manned boat equipped with an acoustic Doppler current profiler to measure currents and basic water-quality distributions (temperature, specific conductance, pH, dissolved oxygen, turbidity, and blue-green algae concentrations).

Spatial distributions of specific conductance and temperature and nearshore currents indicate the mixing zone in the vicinity of Euclid Creek and Villa Angela Beach is dynamic and highly variable, but can exhibit large and persistent coherent structures such as eddies that, at least for short periods of time, can be decoupled from local wind forcing. The observation of currents that are decoupled from local wind forcing contradicts the observations from the 2011 USGS study in which local currents appeared to be primarily driven by local winds. These conflicting results indicate that large-scale circulation patterns within Lake Erie generated by regional wind patterns, inertial waves, and seiche activity, can, at times, oppose local wind patterns for at least a period of days.

Therefore, any prediction of nearshore currents near Villa Angela Beach based on local wind observations also must take into account recent regional wind patterns and the associated large-scale circulation patterns within the entire Lake Erie Basin.

The high specific conductance of Euclid Creek water relative to Lake Erie water provided an excellent tracer for visualization of the transport and fate of Euclid Creek water in the nearshore environment. Other parameters such as temperature, pH, dissolved oxygen, and turbidity proved less useful for tracking Euclid Creek water. Unlike the 2011 USGS survey, which detected a persistent anomaly in water quality along the southwestern end of Villa Angela Beach inside of the breakwater (possibly indicating groundwater inflow), no persistent anomaly was detected in the same location (or anywhere else along the beach) in the 2012 survey.

Observed circulation patterns indicate that Euclid Creek water and water discharged from nearby CSO discharge points along the shoreline, and the bacteria therein, may be mixed along Villa Angela Beach by interaction of nearshore currents and shoreline structures. A large, persistent zone of recirculation observed off Villa Angela Beach created by southwesterly longshore currents can act as a pathway for transport of bacteria from multiple sources to Villa Angela Beach and can trap these pollutants along the beachfront for a period of days. In spite of observed coastal downwelling, denser, near-bed water from Euclid Creek is shown to mix to the surface of Lake Erie by way of turbulent eddies and upwelling cells spanning the full depth of flow. Analysis of continuous current measurements near the Wildwood Marina entrance show that currents with a southwesterly longshore component occurred nearly 33 percent of the time during summer 2012, with slightly higher percentages in August and September. Given the high frequency of longshore currents in the summer similar to those observed during the surveys and the observed persistence of recirculation, it is possible that similar occurrences of recirculation are not uncommon along Villa Angela Beach during summer months. This recirculation can prolong the exposure of Villa Angela Beach to CSO-related pollutants, such as bacteria, from Euclid Creek by trapping the Euclid Creek plume along the beachfront. Because currents with a northeasterly longshore component were dominant during summer 2012, a mechanism exists for longshore transport of bacteria to Villa Angela Beach from sources to the southwest including effluent from the Northeast Ohio Regional Sewer District Easterly Wastewater Treatment Plant (WWTP) and lakefront CSO discharge points. While the 2011–12 synoptic surveys did not include the Easterly WWTP outfall within the survey area, understanding the fate and transport of this effluent and how it may impact Villa Angela Beach is suggested for possible future work.

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Appendix 1. Autonomous Underwater Vehicle Calibration, Operation, Data Management, and Data Processing

Instrument Calibration

Calibration of water-quality sensors adhere to procedures outlined by YSI and the U.S. Geological Survey (USGS) Field Manual. All sensors were calibrated prior to deployment, and calibrations were checked for drift following each survey. When possible, all calibrations are done in the laboratory, and thus are done in a controlled environment. The autonomous underwater vehicle (AUV) thermistor is not user calibrated, but rather is periodically checked for accuracy against a National Institute of Standards and Technology-certified thermometer, in a thermal bath over a range of temperatures. Typically, the chlorophyll and blue-green algae sensors are calibrated (zeroed) in deionized water by using a one-point calibration method. The one-point calibration method results in relative chlorophyll and blue-green algae distributions rather than absolute concentrations. If absolute concentrations are required by the project, the sensors are post-calibrated with a second point by using samples collected in the field in close proximity to the AUV during data collection and analyzed by a qualified laboratory. The chlorophyll sensor was not operational during this survey because of a faulty circuit board inside the sensor.

Calibration of the vehicle compass was achieved by running an in-water compass calibration mission comprised of four survey sweeps. Each sweep consisted of six 400-foot (ft) underwater legs (three in each direction) at a depth of 7 ft below the surface. Each of the four sweeps was run at a different orientation (north-south, east-west, northeast-southwest, and northwest-southeast). Navigational errors between the actual and computed position of the vehicle were monitored and used to generate a compass-deviation table. This deviation table was comprised of compass errors at different headings and was used in real-time during subsequent missions to correct the compass heading on-the-fly. According to the manufacturer, a properly calibrated compass can reduce underwater offline drift (drift equals accumulated error) to 0.5 percent of the underwater run length (5 ft drift for 1,000 ft underwater run). Based on past experience, field calibrations have produced drift errors of approximately 1 percent of the underwater run.

Instrument Operation

The *EcoMapper*® AUV performs autonomous surveys of water bodies and when properly programmed requires no assistance during execution of the survey. Programming a survey involves obtaining a high-resolution georeferenced aerial photo of the water body (typically a USGS digital ortho quarter-quadrangle) and locations of any potential obstructions (from initial reconnaissance). The aerial imagery and obstructions are then imported into *Vector Map*®, the primary programming software for the AUV, and used as a background for survey planning. Within *Vector Map*®, the user creates missions (surveys) by generating a field of numbered waypoints for the AUV to visit. The points are numbered sequentially, and the AUV will follow the set order, executing commands at each waypoint. Each waypoint has a set of associated commands including dive mode, speed, dive angle, depth or height above bottom, sonar settings, and park commands. Dive mode options include (1) constant depth, where the AUV will achieve and maintain a specific depth below the surface by using its redundant-pressure sensors and vertical uplooking beam; (2) constant height above bottom, where the AUV will maintain a specified height above the bed by using its vertical downlooking beam; and (3) undulate, where the vehicle will undulate between two depths (or a combination of a depth and height above bottom) at a specified dive angle. The speed command sets the speed over ground of the AUV and is limited to 2.5 knots at the surface and 4 knots underwater. Sonar settings can be adjusted for each waypoint and include the range, gain, frequency, and transducer configuration (single-side or both sides). Lastly, park commands can be issued at any waypoint to force the vehicle to park on the surface at a waypoint and actively maintain that position for a specified period of time. Park commands generally are issued at the end of a mission, at a specified meeting point with the manned boat, for recovery of the AUV. The AUV executes the waypoint commands of the destination waypoint and transitions to the next set of commands after entering the waypoint success radius (user defined) of the destination waypoint. Once the mission is programmed in *Vector Map*®, it is transferred to the AUV via the wireless connection as a text-based mission file (*.mis).

Execution of a mission begins with the loading of a mission into the UVC, the onboard control program of the AUV. The UVC decodes the mission command file and controls the AUV sensors, navigation, and propulsion to execute each of the sequential commands. Prior to deployment, the user sets the safety settings within UVC (settings that allow the AUV to abort a mission if necessary) and loads a 'safe return path' or SRP file if necessary (the SRP is a mission file that will execute only upon abortion of the survey mission). The goal of the SRP is to bring the AUV back to land safely in the event of a system malfunction.

Deployment of the AUV usually is accomplished, by hand, by placing the AUV into the water, though deployment lines may be required on vessels with high freeboard. The AUV is checked for proper ballasting (and adjustments are made if necessary) after it is placed into the water, and the pressure sensors are zeroed. Internal checks of the global positioning system (GPS) receiver, altimeter, and compass also are completed in addition to response checks of all water-quality sensors, Doppler velocimetry log (DVL) system, and the navigation and propulsion systems. If all systems are functional, the mission is started in UVC, via the wireless connection, with a remote computer aboard the vessel. The AUV then begins to navigate to each of the programmed waypoints, in sequential order, executing the waypoint commands along the way. All data are recorded to files and stored on the internal hard drive aboard the AUV. Upon mission completion, the AUV is met at the meeting point, disabled remotely, and then recovered by hand. Once onboard, data files are recovered via the Wi-Fi connection, and a new mission is loaded (if necessary). Should the AUV fail to arrive at the meeting point at the scheduled time, the operators should check the 'beaching point' in the SRP to determine if the AUV aborted the mission and returned to shore. If the AUV aborts the mission for any reason, the data files contain a set of error codes that explain the reason.

Data Files

Raw data files from the AUV include a LOG file (*.log) consisting of georeferenced and time-stamped data from the AUV and onboard sensors in a semicolon-delimited data format. Data include navigation data (waypoint number, speed, heading, depth, altitude, latitude, longitude), vehicle data (pitch, roll, yaw, prop speed, fin settings, dive angle), bathymetry data (water column depth), and water-quality data (temperature, specific conductance, pH, dissolved oxygen, turbidity) from the installed sensors. All data in the LOG file are recorded at a sampling rate of 1 hertz.

In addition to the LOG file, the AUV creates DVL (*.dvl) and PFD (*.pfd) data files. The DVL file contains time-stamped series of vehicle position and DVL output. The DVL outputs in this file are related to distance traveled, speed, and range to bottom. In addition, this file contains bottom-track quality indicators to assess quality of the bottom-track data. The PFD data files contain water-velocity profile data as measured by the DVL below the instrument. The velocities contained in this file are organized by cell, or range from the transducers, and have not been corrected for depth or speed of the instrument, heading, pitch, or roll. Therefore, these files contain a very basic form of the velocity-profile data and must be post-processed to obtain meaningful, georeferenced, water-velocity data.

Data Processing

All data are post-processed by using a suite of custom *Matlab*® scripts. This process is detailed in figure 1–1. The processing begins with applying several corrections to position and depth. Corrections to the positional data include correction of the vehicle track for drift during dives. Drift generally is induced by compass error or improper calibration. Drift is identified by screening the vehicle track for jumps in position greater than 5 meters in 1 second. Jumps generally will occur when the vehicle surfaces and corrects its position based on GPS data in its track log. Any identified drift is corrected by applying a linear correction between the dive point and the surface point assuming a constant heading and speed. Following the drift correction, a depth correction is applied to the total water column depth to account for the offset of the downlooking vertical beam from the water surface. The data are then screened manually to identify outliers and remove them from the dataset. This is accomplished by plotting the time-series data and manually selecting any outliers for removal. Outliers are identified as individual 1 second samples that have large deviations from the surrounding points (spikes) that are uncharacteristic of a natural system in which shape gradients are normally smoothed by turbulence and diffusion. Once all outliers have been removed, the user has the option to smooth the time-series data for each variable independently. This process generally is applied only to turbidity, chlorophyll, and blue-green algae data, as these data tend to be noisy. During smoothing, a moving average is applied to the data with a user-defined window size. The user chooses the window size such that noise is minimized, yet true oscillations of the dataset are maintained (an iterative process).

The final step (if required) in this processing routine is to apply temporal lags to each parameter to account for lags in the sensor response time. Standard lag times have been provided by YSI based on laboratory tests of response time; however, the processing code also determines an empirical lag for each parameter when vertical profile data are available from diving missions. To determine these lag constants, the data for each parameter is plotted as a function of depth and the variance of the data cloud is computed. Because a lag in the sensor response time will lead to larger variance in a parameter for a given depth, the code seeks to minimize the variance in the parameter by applying a range of lag times to the data and recomputing the variance at each step. The lag time that produces the minimum variance in the vertical profile of each parameter is chosen as the suggested lag time. The user can then override the lag times with manual entries (standard values) if necessary. Once lag times are determined, each parameter is shifted in time by the appropriate lag time. Standard lag times for each of the sensors are given in table 2 of the report. The corrected dataset is then saved as a *Matlab*® data structure, which can be used as input for additional processing and visualization scripts.

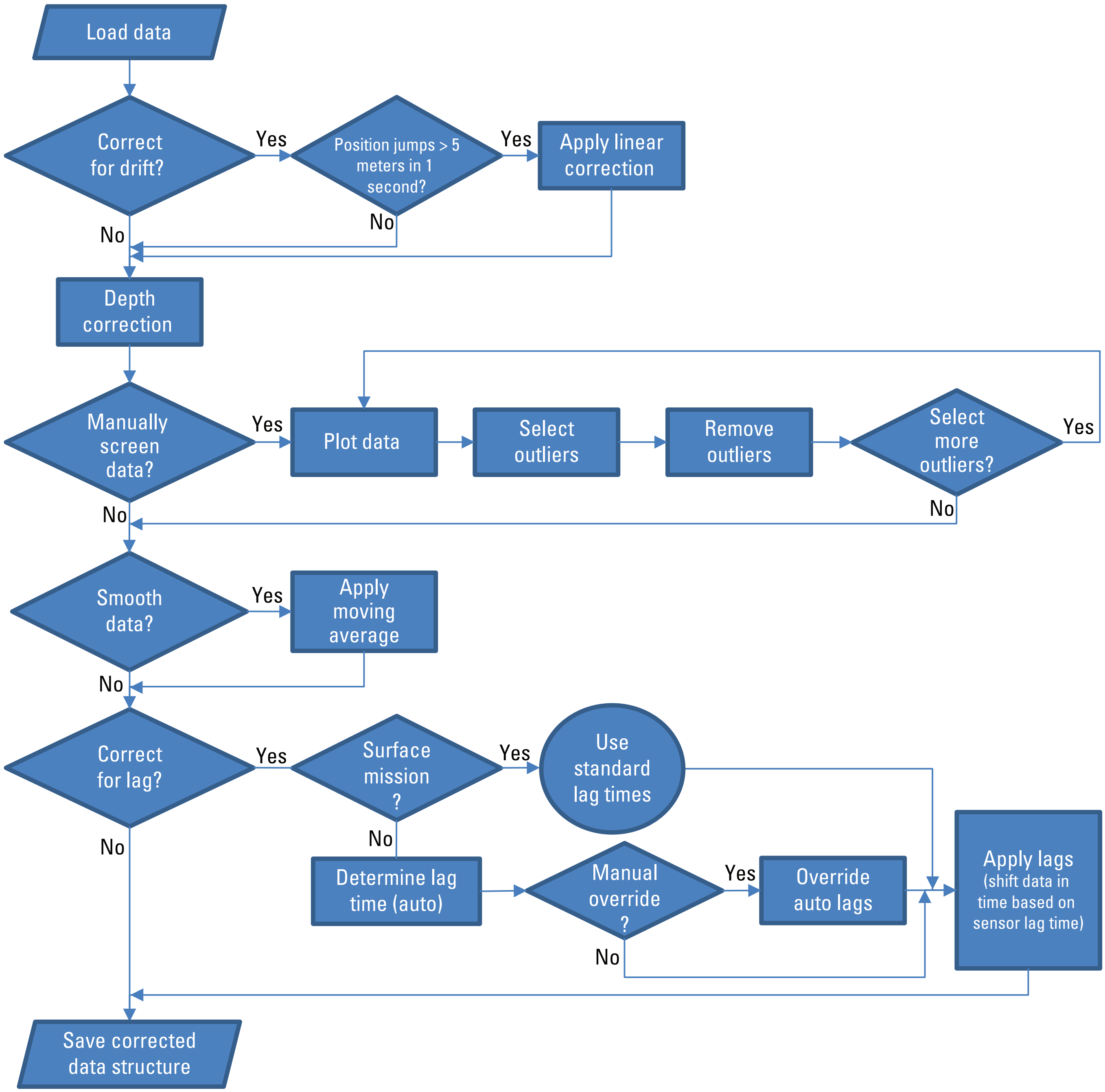

Figure 1–1. Data-processing algorithm for LOG files from the autonomous underwater vehicle. (>, greater than)

The corrected data structure is used to generate geographic information system (GIS)-compatible water-quality data files by using the processing steps defined in figure 1–2. When generating the water-quality data file for GIS import, computation of parameter anomalies are performed. This process starts by computing the median value of the parameter for the entire dataset for surface missions or the median vertical profile of each parameter for diving missions. The median profile is computed by dividing the extent of the vertical-profile data into discrete bins and computing the median value of all the data points in each bin. Anomalies are then computed by taking the difference between an observed value at a specific point and the median value for that sample depth. This process will identify any observed data that are inconsistent with the median value for that depth in the water body being surveyed. The benefit of this method is that it effectively eliminates the depth-dependence of the data and aides in identification of anomalous data. For surface missions in which all the data are collected on the surface, the computed anomalies are simply the difference between the observed value at a point and the median value for the entire dataset.

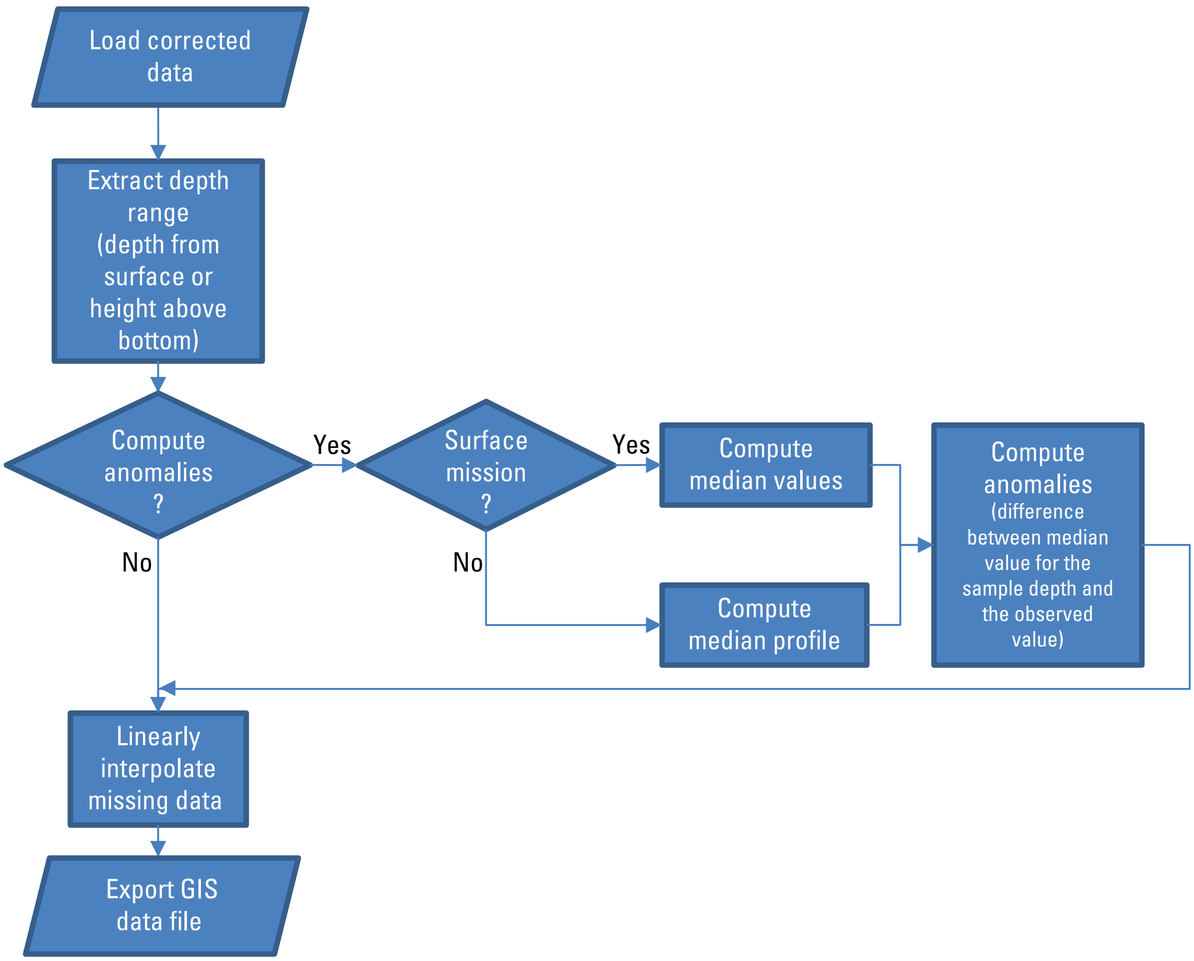

Figure 1–2. Data-processing algorithm for generation of geographic information system (GIS)-compatible water-quality data files from the corrected autonomous underwater vehicle LOG files.

A GIS-compatible bathymetry-data file is generated from the corrected LOG data by using the processing steps defined in figure 1–3. The process begins with application of known water-surface elevation (WSE) data to transform depths to bed elevations. Constant values or times-series data can be applied depending upon the availability of the data and variations in WSE for the duration of the survey. In a method similar to the water-quality outlier screening, the bed-elevation data are manually screened to remove outliers. The user can then choose to smooth all or part of the data with an iterative routine and user-defined window. Following smoothing, the user can then elect to perform more outlier removal if necessary. The process concludes with the generation of XYZ files that are compatible with ArcGIS® and TecPlot®. Water-quality and bathymetry data are gridded in ArcGIS® by using ordinary kriging (bathymetry) and diffusion interpolation with barriers (water quality) routines in the Geostatistical Analyst Toolbox®.

Density is computed from water temperature and specific conductance following the United Nations Educational, Scientific, and Cultural Organization (UNESCO) 1983 equation of state for seawater that is valid for the observed temperatures and salinities (Fofonoff and Millard, 1983). A low salinity correction is applied following Clesceri and others (1999). All density computations were completed for every sample prior to subsampling and visualization.

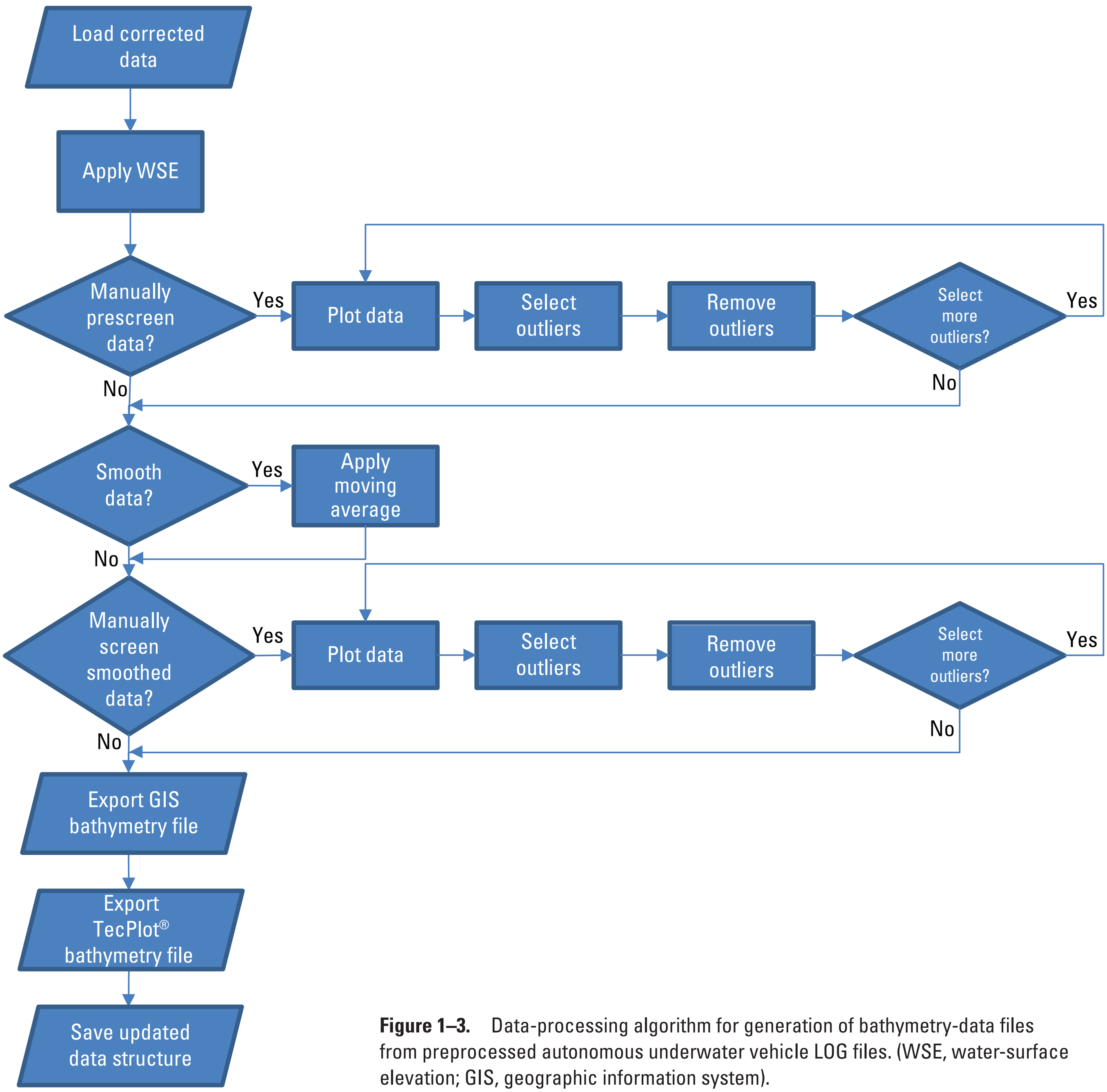

Figure 1–3. Data-processing algorithm for generation of bathymetry-data files from preprocessed autonomous underwater vehicle LOG files. (WSE, water-surface elevation; GIS, geographic information system).

Jackson—**Circulation, Mixing, and Transport in Nearshore Lake Erie in the Vicinity of Villa Angela Beach and Euclid Creek**—SIR 2013-5198

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