Prepared in cooperation with the Pennsylvania Sea Grant

Longshore Water-Current Velocity and the Potential for Transport of Contaminants: A Pilot Study in Lake Erie from Walnut Creek to Presque Isle State Park Beaches, Erie, Pennsylvania, June and August 2015

Open-File Report 2016–1206

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

Cover. Photo of watercraft used to measure longshore water-current velocity magnitude and direction on Lake Erie, Pennsylvania. Photo by Lowell Abbadini, U.S. Geological Survey.

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By Elizabeth Hittle

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Volume	
cubic meter (m^3)	35.31	cubic foot (ft^3)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

Datum

Vertical coordinate information is referenced to the [insert datum name (and abbreviation)]; For example, North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the [insert datum name (and abbreviation)]; For example, North American Datum of 1983 (NAD 83).

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

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

Abbreviations

ADCP	Acoustic Doppler Current Profiler
dGPS	Differential Global Positioning System
GIS	Geographic Information System
GPS	Global Positioning System
PISP	Presque Isle State Park
RSC	Regional Science Consortium
T(1)	Transect (1)
USGS	U.S. Geological Survey
VMT	Velocity Mapping Toolbox

Longshore Water-Current Velocity and the Potential for Transport of Contaminants: A Pilot Study in Lake Erie from Walnut Creek to Presque Isle State Park Beaches, Erie, Pennsylvania, June and August 2015

By Elizabeth Hittle

Abstract

Bacteria-driven restrictions and (or) advisories on swimming at beaches in Presque Isle State Park (PISP), Erie, Pennsylvania, can occur during the summer months. One of the suspected sources of bacteria is sediment. A terrestrial sediment source to the west of PISP is Walnut Creek, which discharges to Lake Erie about 8.5 kilometers southwest of PISP Beach 1. On June 24, June 25, August 18, and August 19, 2015, synoptic surveys were conducted by the U.S. Geological Survey, in cooperation with the Pennsylvania Sea Grant, in Lake Erie between Walnut Creek and PISP Beach 1 to characterize the water-current velocity and direction to determine whether sediment from Walnut Creek could be affecting the PISP beaches. Water-quality data (temperature, specific conductance, and turbidity) were collected in conjunction with the synoptic surveys in June. Water-quality data (*Escherichia coli* [*E. coli*] bacteria, temperature, and turbidity) were collected about a meter from the shore (nearshore) on June 24, August 19, and after a precipitation event on August 11, 2015. Additionally, suspended sediment was collected nearshore on June 24 and August 11, 2015. Samples collected near Walnut Creek during all three bacterial sampling events contained higher counts than other samples. Counts steadily decreased from west to east, then increased about 1–2 kilometers from PISP Beach 1; however, this study was not focused on examining other potential sources of bacteria.

The Velocity Mapping Toolbox (VMT) was used to process the water-current synoptic surveys, and the results were visualized within ArcMap. For the survey accomplished on June 24, 2015, potential paths a particle could take between Walnut Creek and PSIP Beach 1 if conditions remained steady over a number of hours were visualized. However, the water-current velocity and direction were variable from one day to the other, indicating this was likely an unrealistic assumption for the study area. This analysis was not accomplished for the other surveys due to unsteady lake conditions encountered on June 25 and August 18, and reduced quality of the survey on August 19.

Introduction

Owing to high levels of bacteria, restrictions and (or) advisories on swimming at beaches at Presque Isle State Park (PISP), Erie, Pennsylvania, can occur during the summer months. High concentrations of bacteria in nearshore waters make beaches unsafe for swimming because of their negative effects on human health. Consequently, the restrictions and advisories have a negative effect on tourism in the region. One of the suspected sources of bacteria is sediment. A terrestrial sediment source to the west of PISP is Walnut Creek (Pennsylvania Department of Environmental Protection, 2008), which discharges to Lake Erie about 8.5 kilometers southwest of PISP Beach 1 (fig. 1). Previous exploratory work has been done by the U.S. Geological Survey (USGS) to determine the suspended sediment and bacteria concentrations discharging from Walnut Creek into Lake Erie, but little is known about the transport of those contaminants once they enter the lake. The USGS, in cooperation with the Pennsylvania Sea Grant, conducted synoptic surveys during June and August 2015 to provide new information designed to guide future research in determining whether transport of contaminants from Walnut Creek to PISP beaches occurs. During the synoptic surveys, water temperature, specific conductance, and turbidity were measured from a boat. *Escherichia coli* (*E. coli*) bacteria, temperature, turbidity, and suspended sediment were obtained from nearshore samples collected by wading into the lake. The magnitude of velocity and direction of water current in the lake were also measured.

Purpose and Scope

The purpose of this report is to provide snapshots of lake conditions from nearshore to about a kilometer off shore from synoptic surveys conducted at the Lake Erie study area during June and August 2015. Synoptic surveys were conducted to determine whether longshore water-current velocity has the potential to transport contaminants in Lake Erie from Walnut

Figure 1. Lake Erie study area, Pennsylvania, from Walnut Creek to Presque Isle State Park.

Creek to PISP. Study area lake conditions are presented by using measured longshore water-current velocity magnitude and direction, and water-quality data. Water temperature, specific conductance, and turbidity data were collected from a boat; bacteria, water temperature, turbidity, and suspended sediment data were collected about a meter (m) from shore. These snapshots will be used to better inform future work in the study area. This report does not include any suspended sediment and bacteria loading computations.

Study Area

The Lake Erie study area extends from just west of Walnut Creek to Presque Isle State Park (PISP) Beach 1 (fig. 1) and extends approximately 1,000 m from shore. The direction of longshore water currents in this area is generally from west to east, but is highly dependent on wind direction and magnitude. Within this approximately 8.75-kilometer reach, four streams discharge into Lake Erie with Walnut Creek being the largest. The Walnut Creek watershed includes 134.2 stream kilometers and has a drainage area of 98.9 square kilometers. In 2007, the predominant land use in the watershed was open/wooded (56.7%), followed by low density residential (21.5%), agriculture (11.3%) and other land uses composing the other 10.5% (Pennsylvania Department of Environmental Protection, 2007).

Pilot Study Data Collection

Five synoptic surveys were conducted during 2 weeks in 2015. Four surveys were conducted when Lake Erie was relatively calm (waves less than 1 m and winds less than 24 kilometers per hour). One synoptic survey was conducted exclusively nearshore when sampling by boat was not possible. This section describes the methods and equipment used to collect the synoptic survey data in Lake Erie from Walnut Creek to PISP during June and August 2015.

Longshore water-current velocity magnitude and direction of flow were measured, and water-quality data (water temperature, specific conductance, and turbidity) were collected, from a boat along 25 transects (survey lines that extended out 1,000 m into the lake perpendicular to the shoreline) established starting just west of Walnut Creek to PISP Beach 1 (fig. 2*A*, *B*). Samples along transects were not always collected from west to east (numerical order) nor was velocity on each transect measured during every survey. Data were collected using the best scheme to achieve the objective for each survey. Nearshore samples were collected at points about a meter offshore coinciding with each of the same 25 transects for *E. coli* bacteria, water temperature, turbidity, and suspended sediment. A summary of data collection dates and activities is presented in table 1.

Table 1. Summary of synoptic survey dates and activities performed in the Lake Erie study area, Pennsylvania, during June and August 2015.

Date	Velocity transects[1]	Water-quality transects	Nearshore bacteria collected?	Suspended sediment collected?
6/24/2015	1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 17, 20, 24	1, 2, 4, 6, 8, 12, 17, 24	Yes	Yes
6/25/2015	25, 24, 22, 20, 18, 16, 14, 1, 2, 4, 8, 12, 6	25, 22, 18, 14, 2, 1	No	No
8/11/2015	None	None	Yes	Yes
8/18/2015	1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 19, 15, 13, 11, 5, 2	None	No	No
8/19/2015	1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	1, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24	Yes	No

[1]Velocity transects are listed in the order in which they were collected.

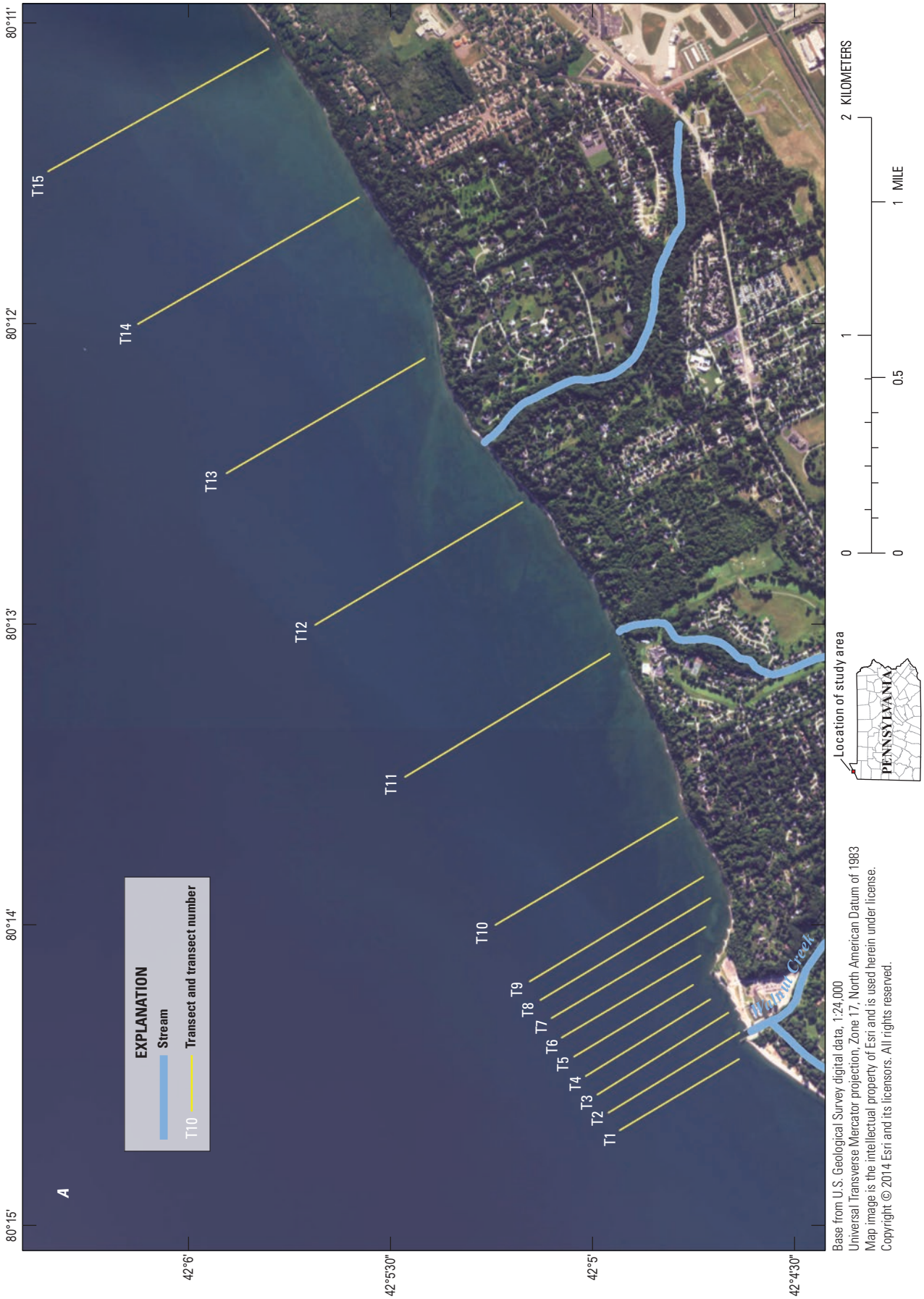


Figure 2. Location of *A*, transects 1–15 and *B*, transects 15–25 relative to the Lake Erie study area shoreline, Pennsylvania. Transect 15 is repeated in each figure.

Figure 2. Location of *A*, transects 1–15 and *B*, transects 15–25 relative to the Lake Erie study area shoreline, Pennsylvania. Transect 15 is repeated in each figure.—Continued

Longshore Water-Current Velocity Magnitude and Direction

Longshore water-current velocity magnitude and direction data were collected from a manned boat. The boat used was a SAFE Boat International 25 Full Cabin (U.S. Coast Guard Defender Class; http://www.safeboats.com/boats/full-cabin-25) equipped with twin 250-horsepower engines with a Teledyne RDI 600-kHz Rio Grande® Acoustic Doppler Current Profiler (ADCP) mounted on the starboard side of the vessel near the stern. A Hemisphere Crescent® A100 Smart Antenna differential Global Positioning System (dGPS) receiver mounted directly over the ADCP was used to georeference the ADCP data. An additional Global Positioning System (GPS) was used in conjunction with the HYPACK® software suite for precise navigation along plan lines during the survey. Because of the large study area and highly dynamic nature of lake conditions, fewer than the full number of transects (for example, every other transect or every 3 transects) were measured over the entire length of the study area in 1 day instead of sequentially measuring all 25 transects over 2 days to cover the entire length of the study area. Boat speeds were optimized during the survey to allow enough time to complete the survey without compromising the quality of the data; speeds ranged from 0.9 to 1.6 meters per second (m/s). Repeat transects (one pass from nearshore out 1,000 m into the lake perpendicular to the shoreline and one pass back) were obtained along survey lines to reduce the noise in the data and minimize directional bias, with the exception of surveys performed August 19 when only one transect was used for velocity visualization in order to have more time to gather water-quality data. The depth of the transducers was set to 33 centimeters (cm) below the water surface, and the ADCP was operated in water mode 12 with 15-cm bins in an attempt to get as close to shore as possible. For this bin size, the horizontal velocity standard deviation is 0.09 m/s, indicating velocities less than this may be interpreted as noise. ADCP data were post-processed within the vendor software WinRiver II, then processed and visualized by using the Velocity Mapping Toolbox (VMT) (Parsons and others, 2013). The VMT has been used by USGS personnel for the visualization of current in river systems (Jackson, 2013). The VMT software suite allows for transect averaging, custom visualization, data smoothing, and spatial averaging of the data to filter out noise in the velocity data. The spatial averaging aids in seeing the true signal through the noise in the velocity measurements.

The VMT allows for visualization of the velocity data in both plan view and cross-section view. An example of a typical VMT plan view, with velocity averaged over the entire depth, for transect (T) 5 completed on June 24, 2015, is shown in figure 3. In VMT, the size of the arrows indicates the relative velocity magnitude (the longer the arrow, the faster the water speed). There is no way in VMT to set a constant size to correspond to a particular velocity. Thus, for visualization herein the graphics from VMT were duplicated in Geographic information systems (GIS) where better control of the arrow sizes could be achieved. The color of the arrows indicates the velocity magnitude as seen on the color scale on the right y-axis. The arrow direction indicates the velocity direction based on true north. VMT processed data for transects collected on June 24, 25, and August 18, 2015, are published in Hittle (2016a, http://dx.doi.org/10.5066/F7KP808D).

Transect 5 in cross-sectional view is shown in figure 4. The distance depicted on the x-axis is relative to where the transect itself started (as close to the shore as possible) not the distance from shore. Depth is referenced relative to the lake surface. Streamwise velocity refers to the velocity magnitude that is perpendicular to the transect direction. The transects extend out into the lake approximately perpendicular to the shoreline; therefore, streamwise velocity can be interpreted as the velocity of the water that is running parallel to the shore. Focusing on the area at a distance of 500–600 m (fig. 4) and about 4 m from the water surface, the velocity is reversed from the top as shown with the dark blue velocities that are around -2 centimeters per second (cm/s). The black arrows within the cross-section are the secondary flow vectors in the transverse and vertical direction. In figure 4, the size of the arrow is indicative of absolute velocity as referenced to the arrow shown at 300 m. For consistency, the color bar to the right and this arrow reference value are uniform for all subsequent graphics. The cross-sectional views of all transects are presented in Appendix 1.

Water Quality Along Transects

Water quality was measured at selected transects by sampling water temperature, specific conductance, and turbidity from collection points at approximately 10 verticals along the transect (fig. 5). The water-quality monitoring was completed every 75 m on a pass across the selected transect that was separate from the longshore water-current velocity collection. For each vertical, a YSI EXO water-quality sonde was lowered from the boat, and data were collected every 1 or 5 seconds from just below the water surface to about 0.75 m from the lake bottom.

Nearshore Water Quality

Water-quality samples were collected about a meter from shore and coincide with the 25 longshore water-current velocity transects (fig. 2) as closely as conditions would allow. The samples were collected during 2 of the 4 longshore water-current velocity surveys and once after a storm when it was not possible to collect any data from the lake by boat (table 1). Samples were collected by Erie County Department of Health

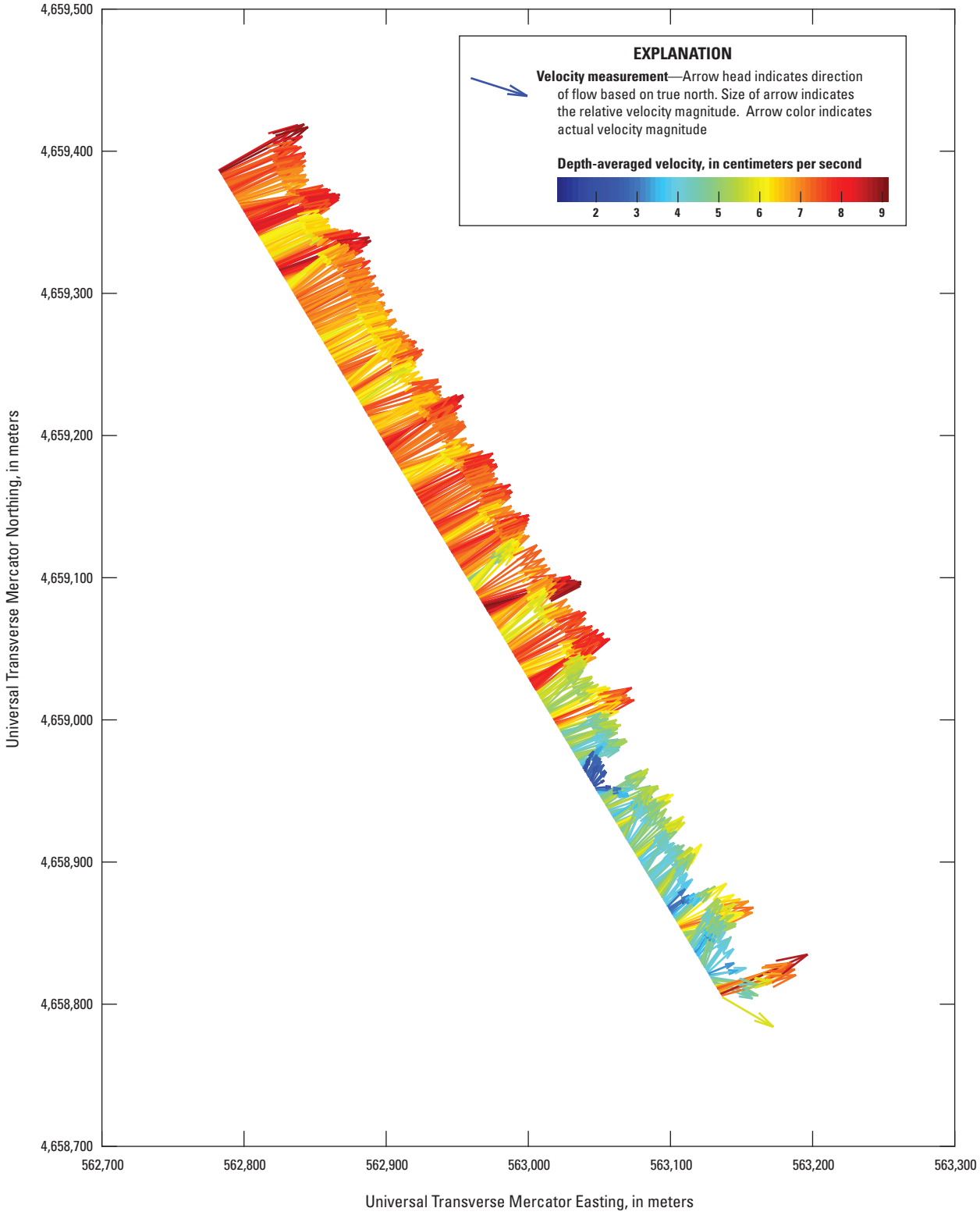


Figure 3. Plan view renderings of depth-averaged velocities for transect 5, from the Velocity Mapping Toolbox, Lake Erie study area, Pennsylvania, June 24, 2015.

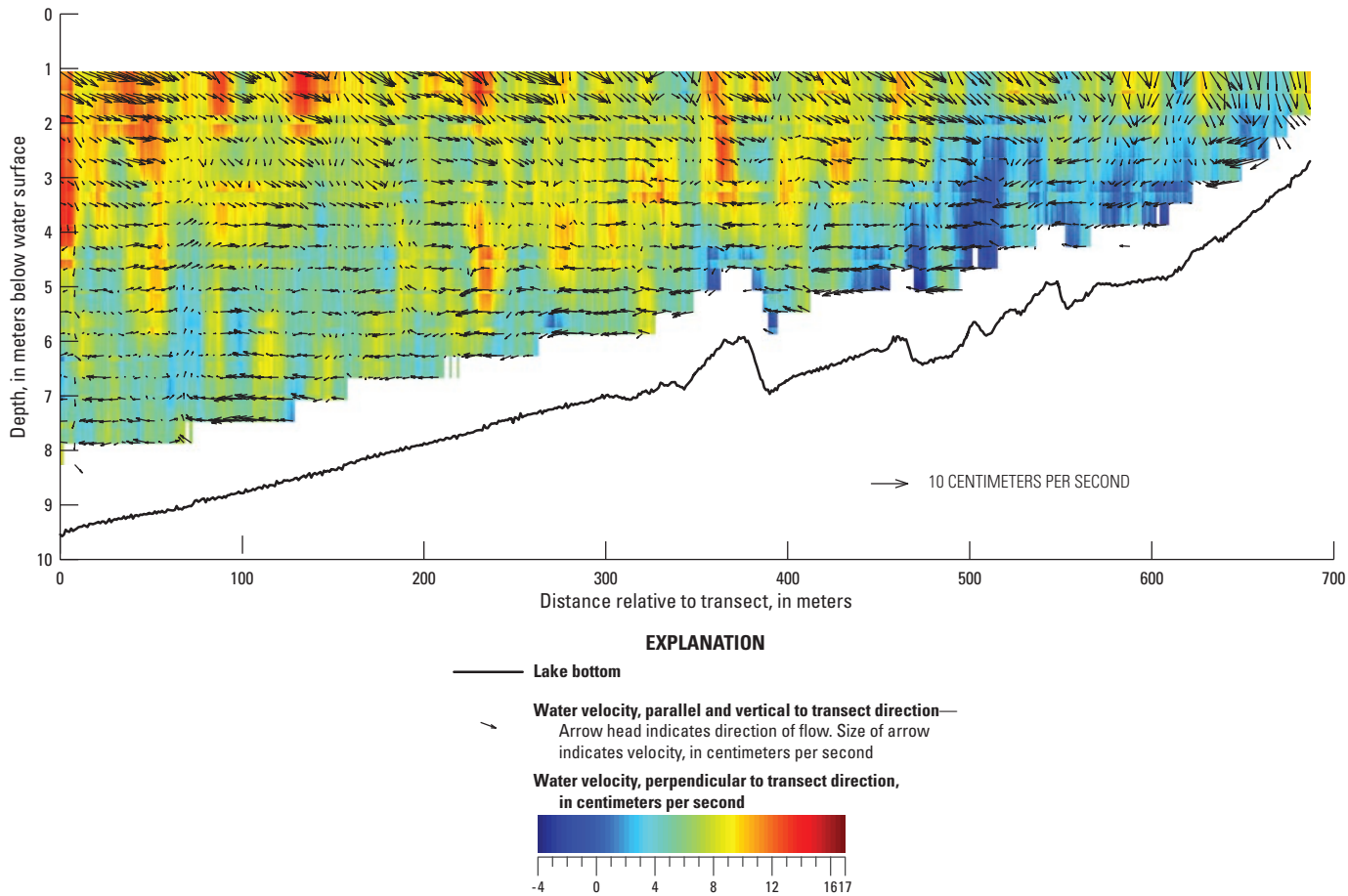


Figure 4. Cross-section view rendering of transect 5, from the Velocity Mapping Toolbox, Lake Erie study area, Pennsylvania, June 24, 2015.

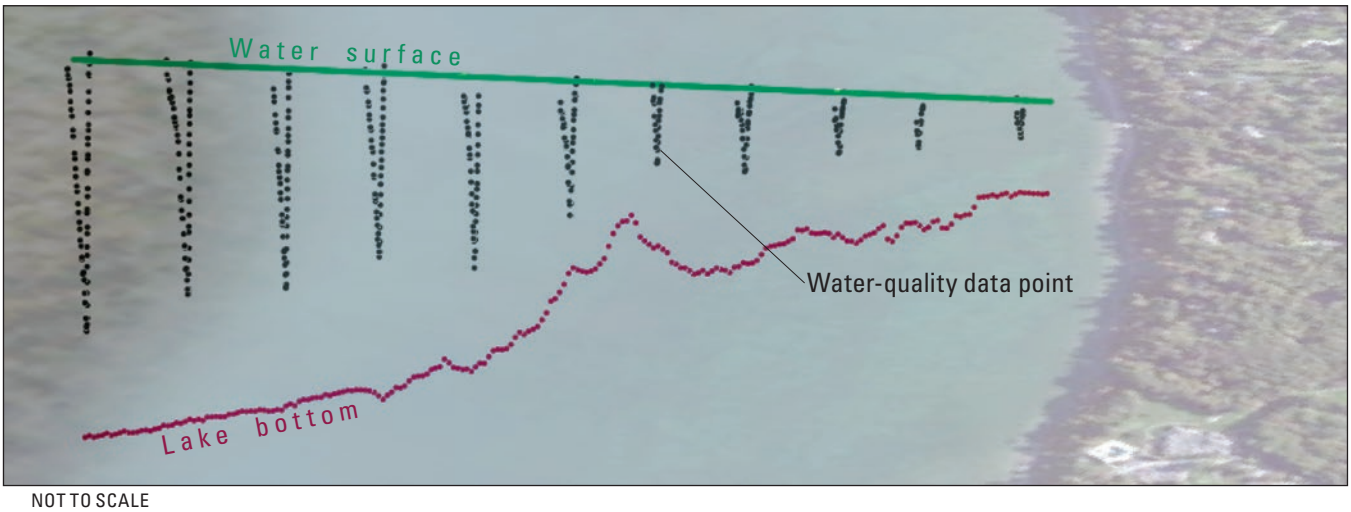


Figure 5. Water-quality data-collection verticals within Lake Erie study area, Pennsylvania, along the transects.

and Human Services employees and Regional Science Consortium (RSC) interns. The nearshore water-quality samples were collected using grab-sample techniques described in Myers and others (2007). To maintain sterile conditions, grab samples were collected in at least 1 m of water at approximately 0.3 m below the water surface, being careful not to stir up bottom sediments. Water samples for bacteria analysis (June 24, August 11, and August 19, 2015) were collected in pre-sterilized 500-milliliter (mL) polypropylene bottles, allowing about 6 cm of head space for proper mixing, and were kept on ice prior to processing. Bacteria samples were analyzed for *E. coli* using modified membrane-thermotolerant *E. coli* (mTEC) membrane-filtration techniques (U.S. Environmental Protection Agency, 2009) and were processed by RSC staff in the RSC laboratory within 6 hours of sample collection.

Water samples for suspended sediment analysis (June 24 and August 11, 2015) were collected in pre-tared 1,000-mL polypropylene bottles by tilting the bottle at about a 45-degree angle away from the sampler and moving it steadily from just under the surface (where the bottle was uncapped) to just above the lake bed and back in a smooth vertical motion to get as close to a depth-integrated, single-vertical grab sample as possible (Edwards and Glysson, 1999). There is no need to chill bottles for sediment analysis. Sediment samples were prepared for shipping and sent to the USGS sediment laboratory at the USGS Kentucky Water Science Center where they were analyzed for total suspended sediment concentration; sand/fine break (percent of sediment less than 4 millimeters [mm]); and fine components, including percent fines less than 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and silt/clay break at less than 0.0625mm.

In addition to collection of nearshore samples for bacteria and suspended sediment analysis, ancillary data, such as weather conditions, water temperature, and a physical description of the collection area (including whether any algae or other debris was present in the water) were recorded at each site at the time of sampling. Turbidity also was measured for each sampling site from two aliquots drawn from each of the 500-mL sample bottles collected for bacteria and analyzed in the RSC laboratory using a Hach Model 2100P turbidity meter. Results for all nearshore water-quality samples are stored in the USGS National Water Information System (NWIS) database and were published in Hittle (2016d; http://dx.doi.org/10.5066/F7KP808D).

Observations

This section is dedicated to presentation and discussion of the observed meteorological, hydrodynamic, and water-quality conditions present from Walnut Creek to PISP during the four synoptic surveys (June 24, June 25, August 18, August 19, 2015) and during one nearshore storm synoptic sampling (August 11, 2015) when sampling by boat was not possible (table 1).

Local Climatic Conditions During Sampling

Wind direction and speed (including maximum speed during a specified period), wave direction, and precipitation are shown for the week before each synoptic survey and for 2 days before the storm synoptic sampling (figs. 6, 7). Precipitation data were measured at Erie International Airport (fig. 1). All other climatic data were collected at the RSC Nearshore Buoy about 4.5 km off shore from the Presque Isle peninsula (fig. 8). This buoy operates generally from May to September, and data may be accessed at http://www.PALakeErieBuoy.com during that time frame.

June 24–25, 2015

From the morning of June 21 until noon on June 22, 2015, the wind blew generally from the west-southwest, and winds were variable after noon on June 22. Overnight from June 22 to June 23, the wind blew steadily from the south at 24–40 kilometers per hour (kph). A small craft advisory was issued on June 23 at Walnut Creek because of high wave and gusty wind conditions. On June 24, as the survey was starting, the wind blew from northwest to southwest at less than 16 kph. On June 25, the wind continued to change from south to east throughout the survey period; the wind went calm then picked up towards the end of the survey. Wave direction was generally to the west starting on June 21. During the survey on June 25, the wave direction was from the northwest to north and eventually to the northeast by the end of the 2-day survey.

August 11, 2015

On August 10, 2015, a storm was recorded that spanned approximately 4 hours; a total of 0.94 cm. of rain was recorded (fig. 7). The wind conditions directly before the sampling period were different from those measured during the synoptic surveys in June or August 2015; winds came steadily from the east the day before (August 9), then came from the northwest during sampling. In the beginning of the day (August 11), the wave direction was from the north and eventually from the west by the end of August 11.

August 18–19, 2015

From mid-morning on August 13 through the morning of August 18, 2015, the wind was generally from the southwest and oscillated between south and northwest on August 16 and 17 (fig. 7). On August 18, as the synoptic surveys were beginning, a large thunderstorm was noted to the east of Walnut Creek, but it did not affect Walnut Creek where the surveys for that day began. During the survey period, the wind started from the west, then changed direction from west to east, and eventually came from the north. By the end of the day on August 18, the wind came from the south-southwest and stayed that way during the entire survey on August 19. The wave direction lagged the wind direction by almost 12 hours, and after the August 18 survey ended, the wave direction changed from west to northeast.

Longshore Water-Current Velocity Magnitude and Direction

The longshore current velocity magnitude and direction were visualized through use of VMT. Data were vertically smoothed to obtain the best representation of longshore currents by spatially and temporally averaging over the noise. The VMT allows the user to select certain depth ranges over which to average velocity. This allows differentiation between different parts of the water column. For the June synoptic surveys, velocity was layer-averaged from surface to 2 m, 2 m to 4 m, and 4 m to the bottom. For the August 18 synoptic survey, velocity was layer-averaged from surface to 5 m, and 5 m to the bottom. The August 19 synoptic survey is of reduced quality, thus results are not presented within the report.

June 24, 2015

Winds were generally from the west during the synoptic survey on June 24, 2015 (fig. 9*A*–*F*). In general, the direction of the longshore current was from west to east; variations were noticed at transects 8 and 24 near the shore. The longshore current moving towards the west at transect 8 indicates an eddy may have been present in this vicinity as a result of the shape of the shore just west of the transect (fig. 9*A*). Transect 24 shows variation inside the breaker, indicating the breakers affect flow in the area (fig. 10). In figure 9*B*, the one vector arrow pointing toward the west at T12 is an example of measurement noise that was not eliminated in VMT processing.

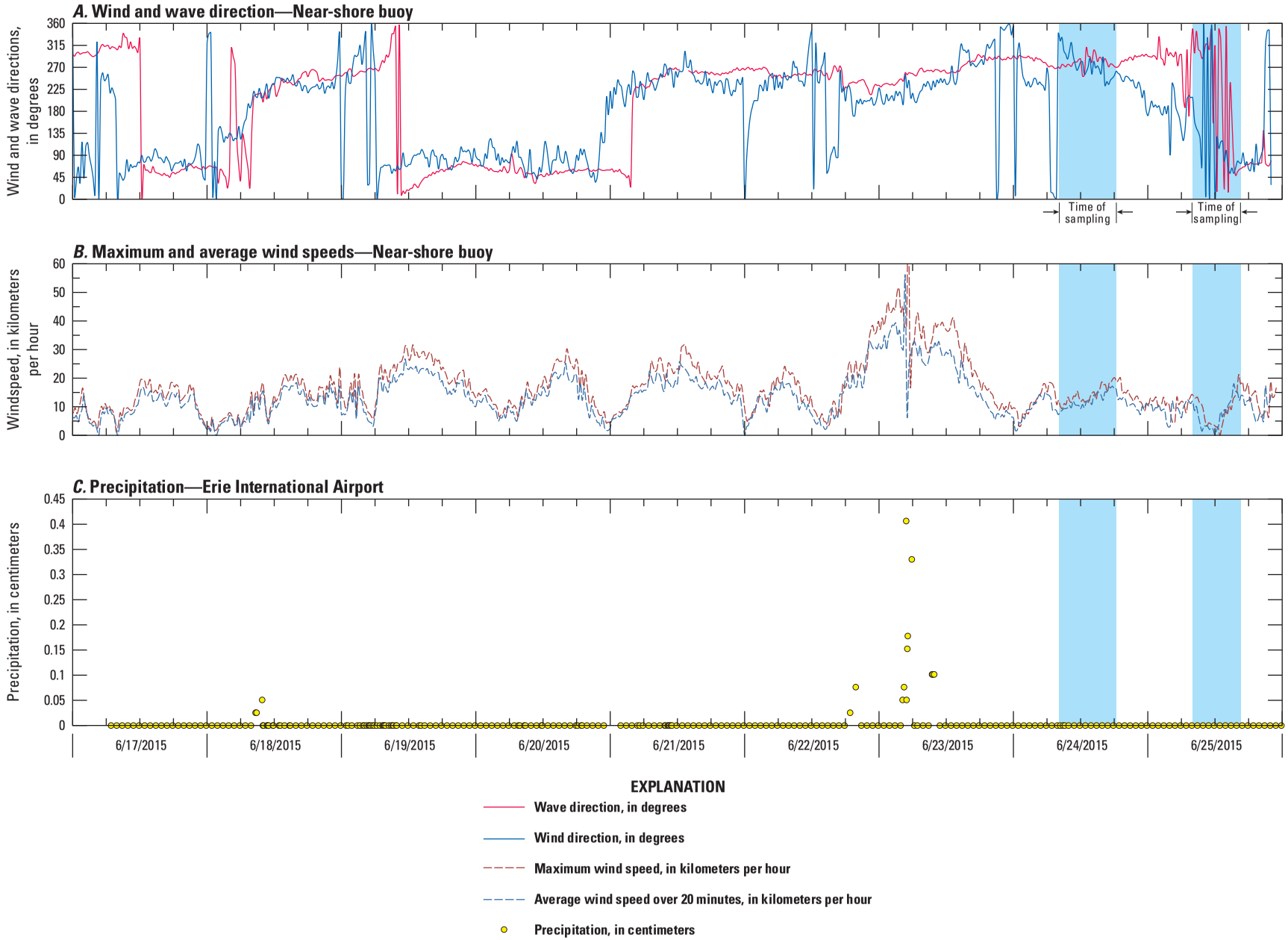


Figure 6. *A*, Wind and wave direction measured at the Nearshore Buoy, Lake Erie study area, Pennsylvania, during June 17–25, 2015, *B*, average and maximum wind speed at the Nearshore Buoy, and *C*, precipitation measured at Erie International Airport, Pennsylvania.

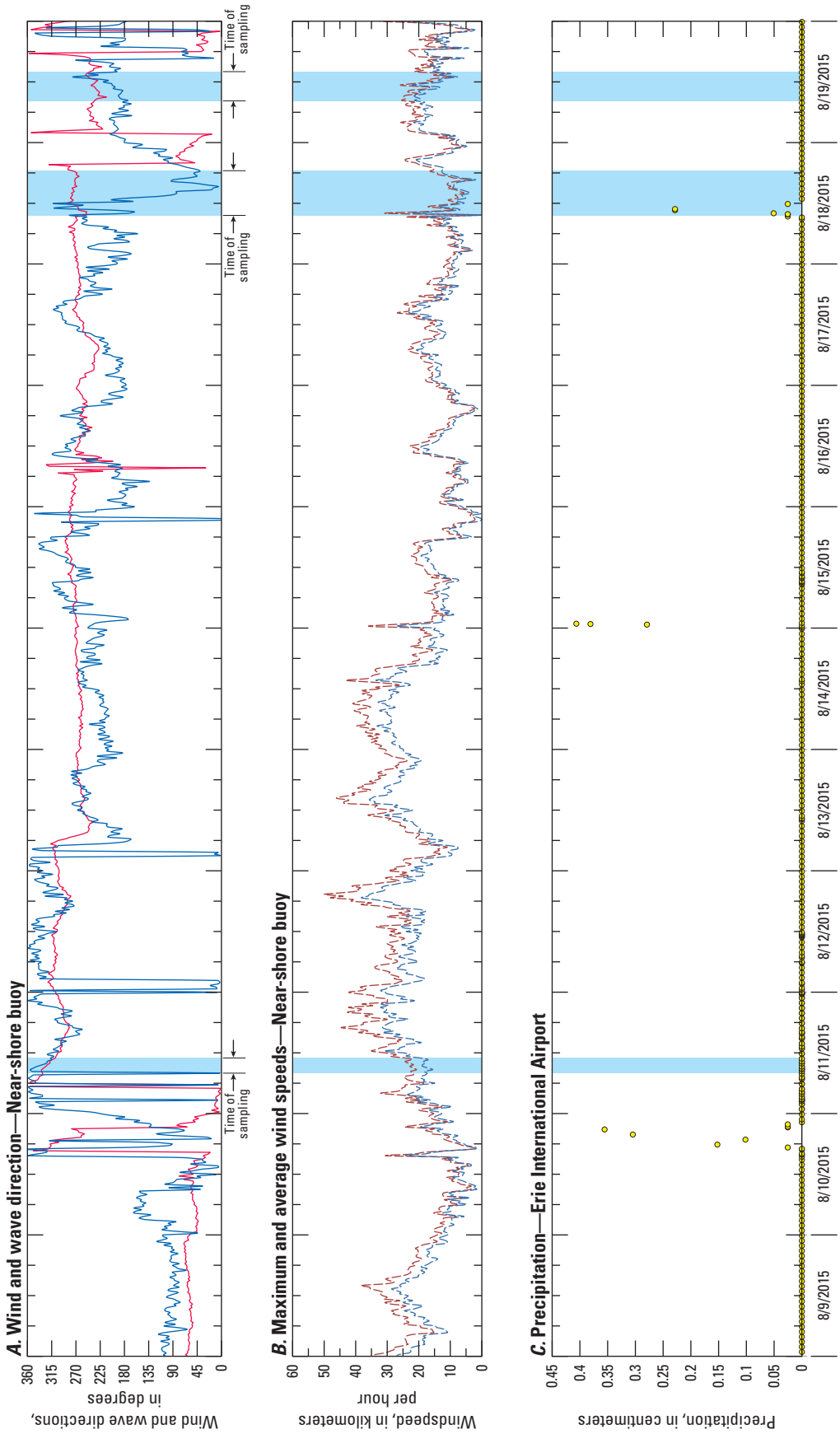


Figure 7. *A*, Wind and wave direction measured at the Nearshore Buoy, Lake Erie study area, Pennsylvania, during August 9–19, 2015, *B*, average and maximum wind speed, and *C*, precipitation measured at Erie International Airport, Pennsylvania.

Figure 8. Location of the Regional Science Consortium Nearshore Buoy in relation to the Lake Erie study area, Pennsylvania.

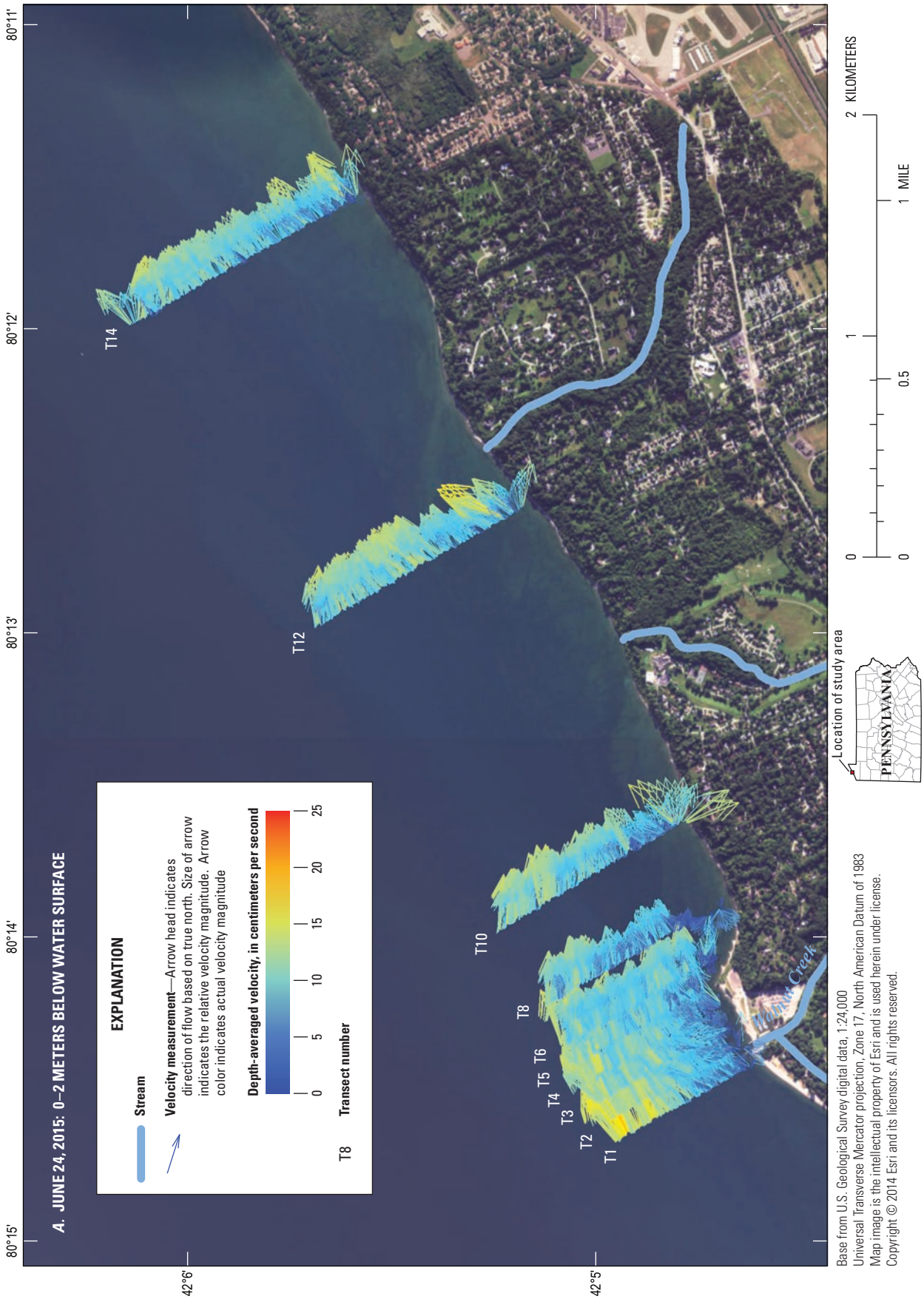
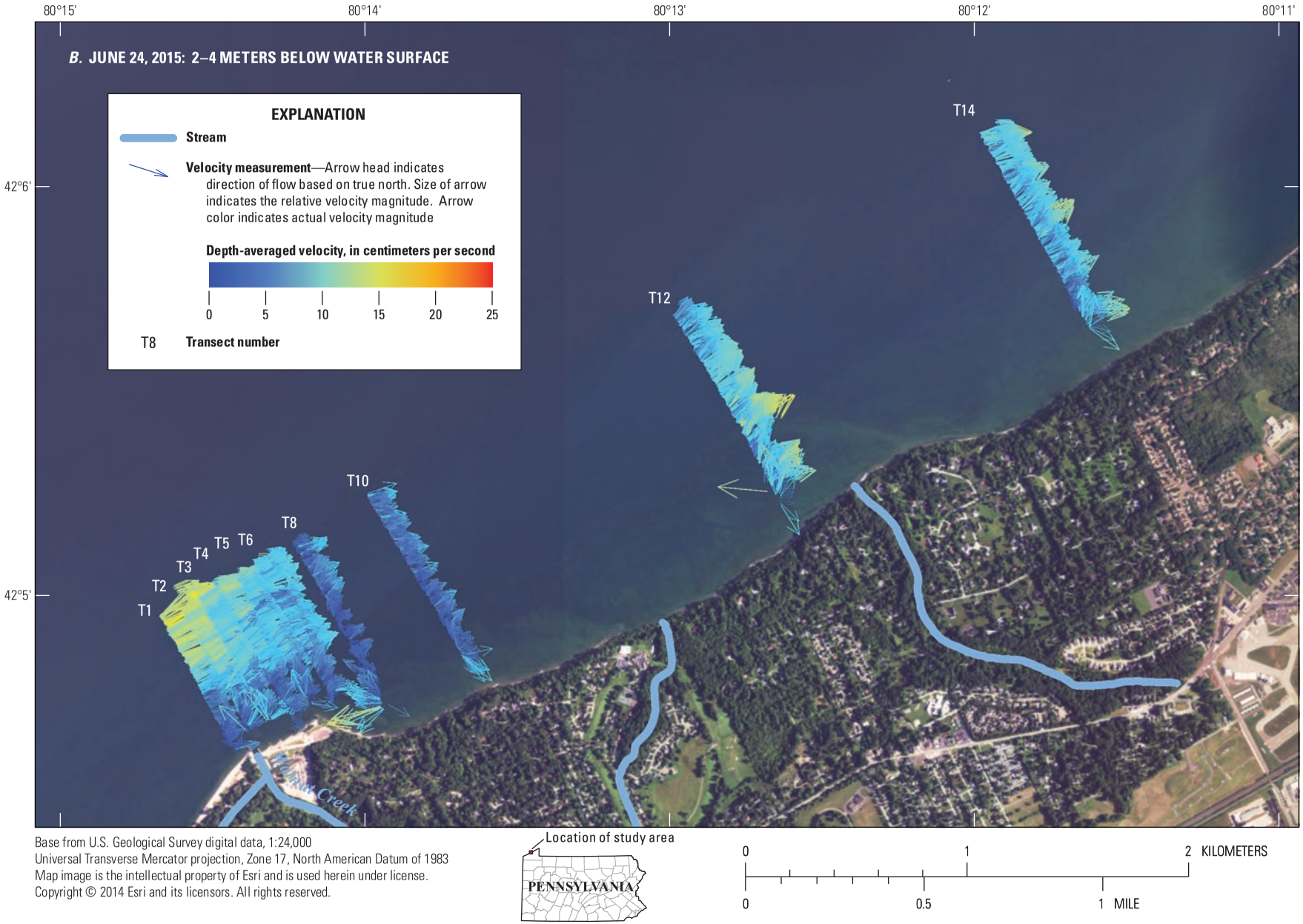


Figure 9. Longshore current velocity magnitude and direction *A*, averaged over a depth of 0 to 2 meters (m) at transects 1–6, 8, 10, 12, and 14, Lake Erie study area, Pennsylvania, June 24, 2015, *B*, averaged over a depth of 2 to 4 m at transects 1–6, 8, 10, 12, and 14, *C*, averaged over a depth of 4 m to the lake bottom at transects 1–6, 8, 10, 12, and 14, *D*, averaged over a depth of 0 to 2 m at transects 17, 20, and 24, *E*, averaged over a depth of 2 to 4 m at transects 17, 20, and 24, and *F*, averaged over a depth of 4 m to the lake bottom at transects 17, 20, and 24.



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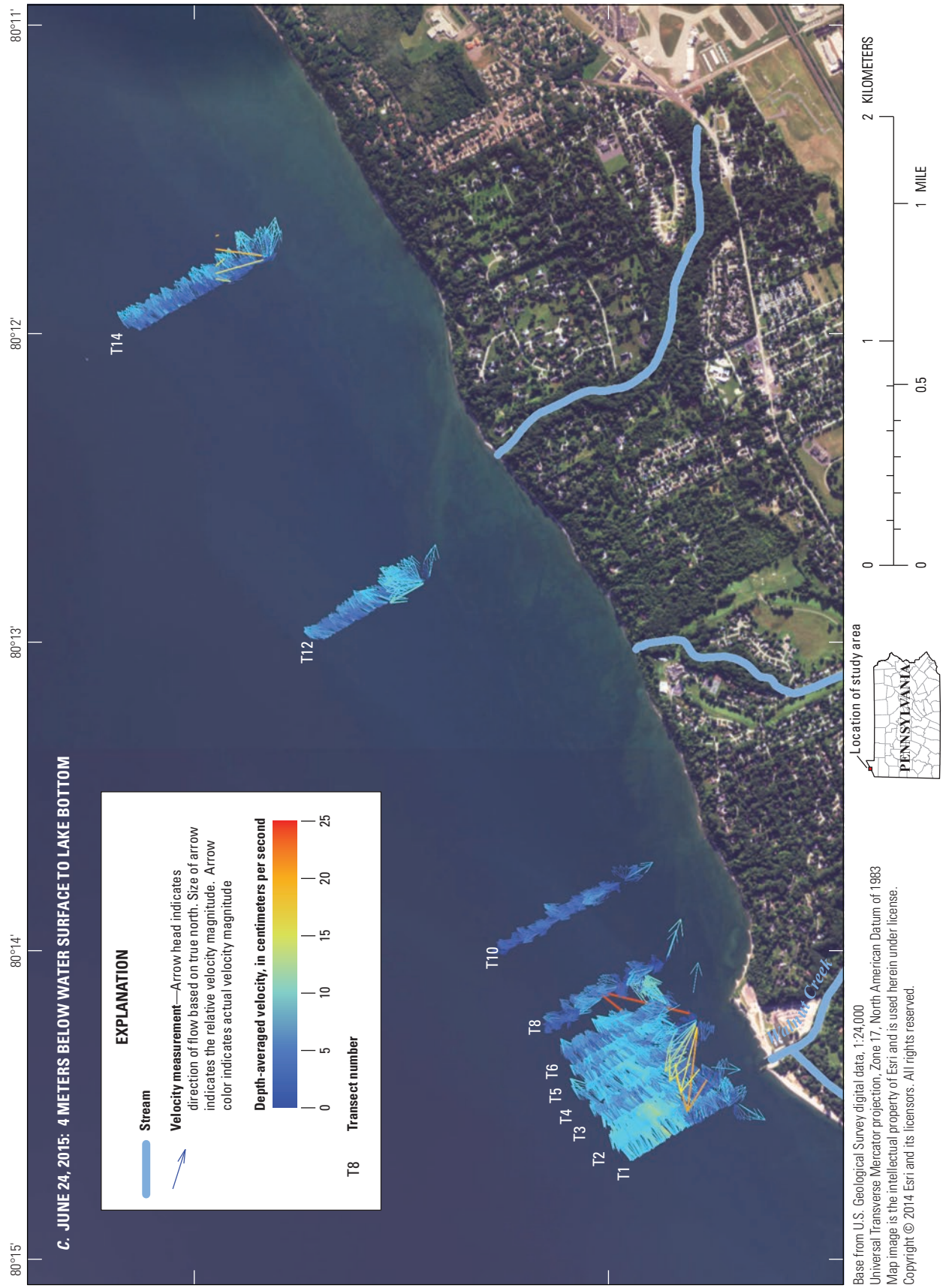

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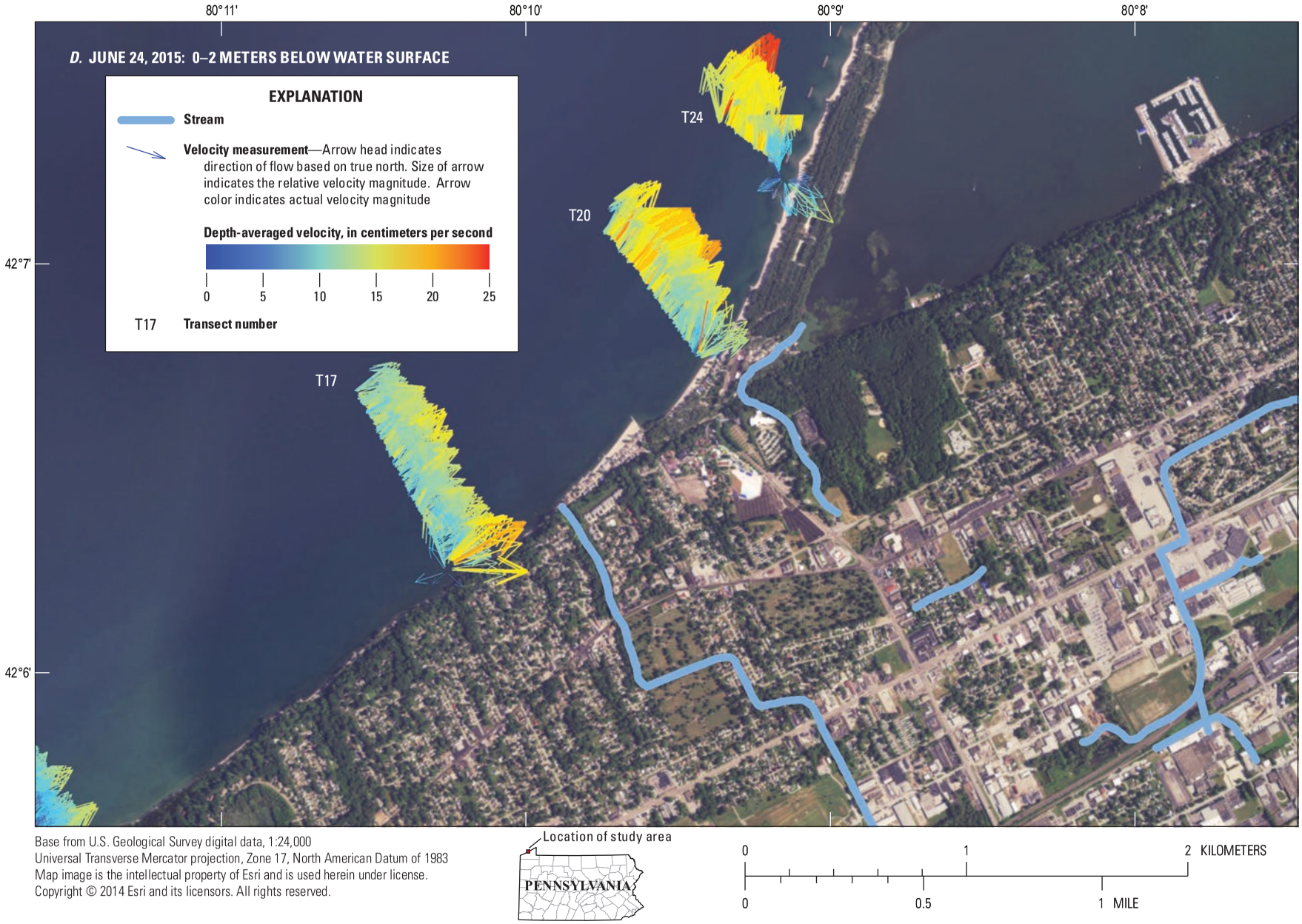

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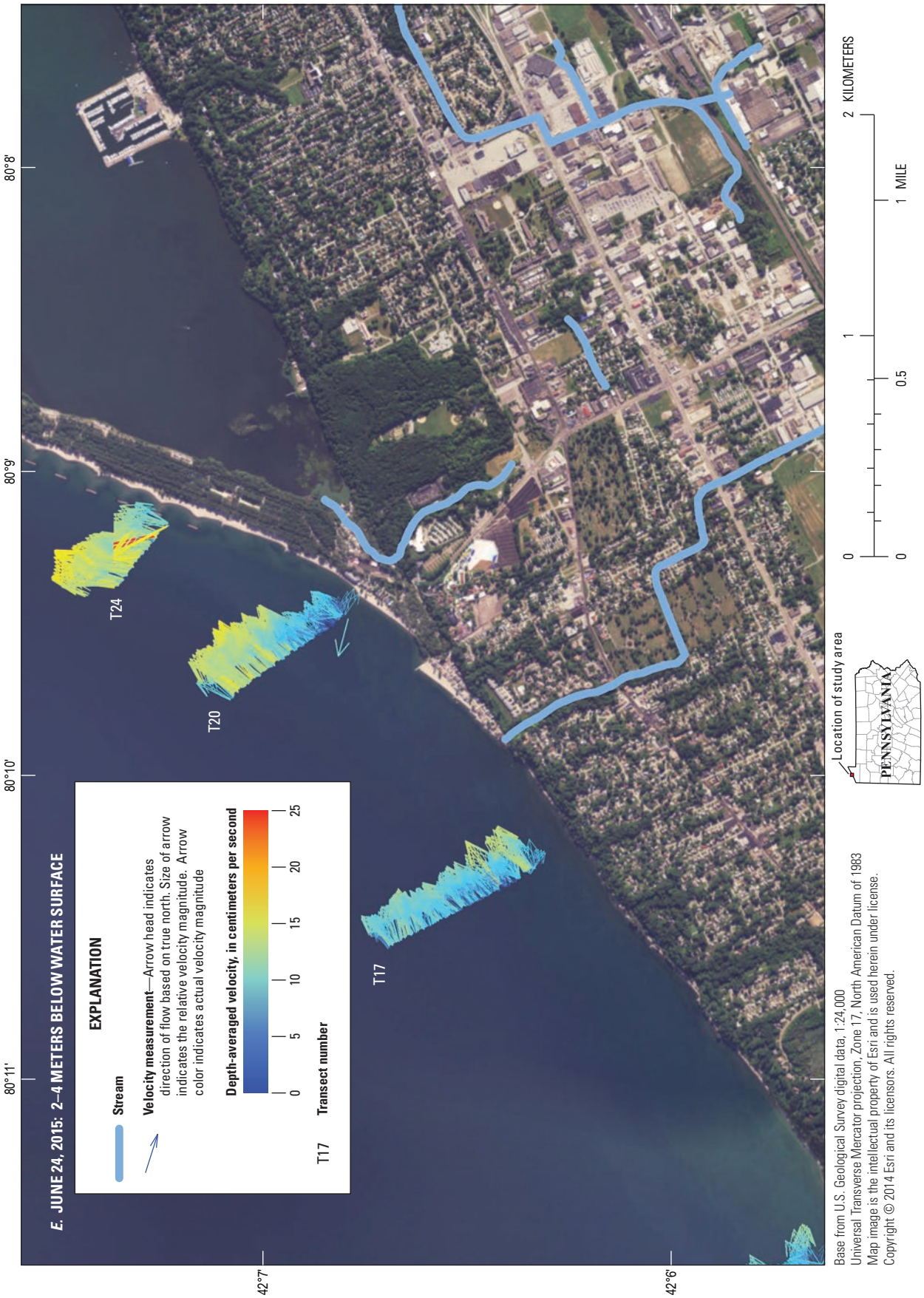

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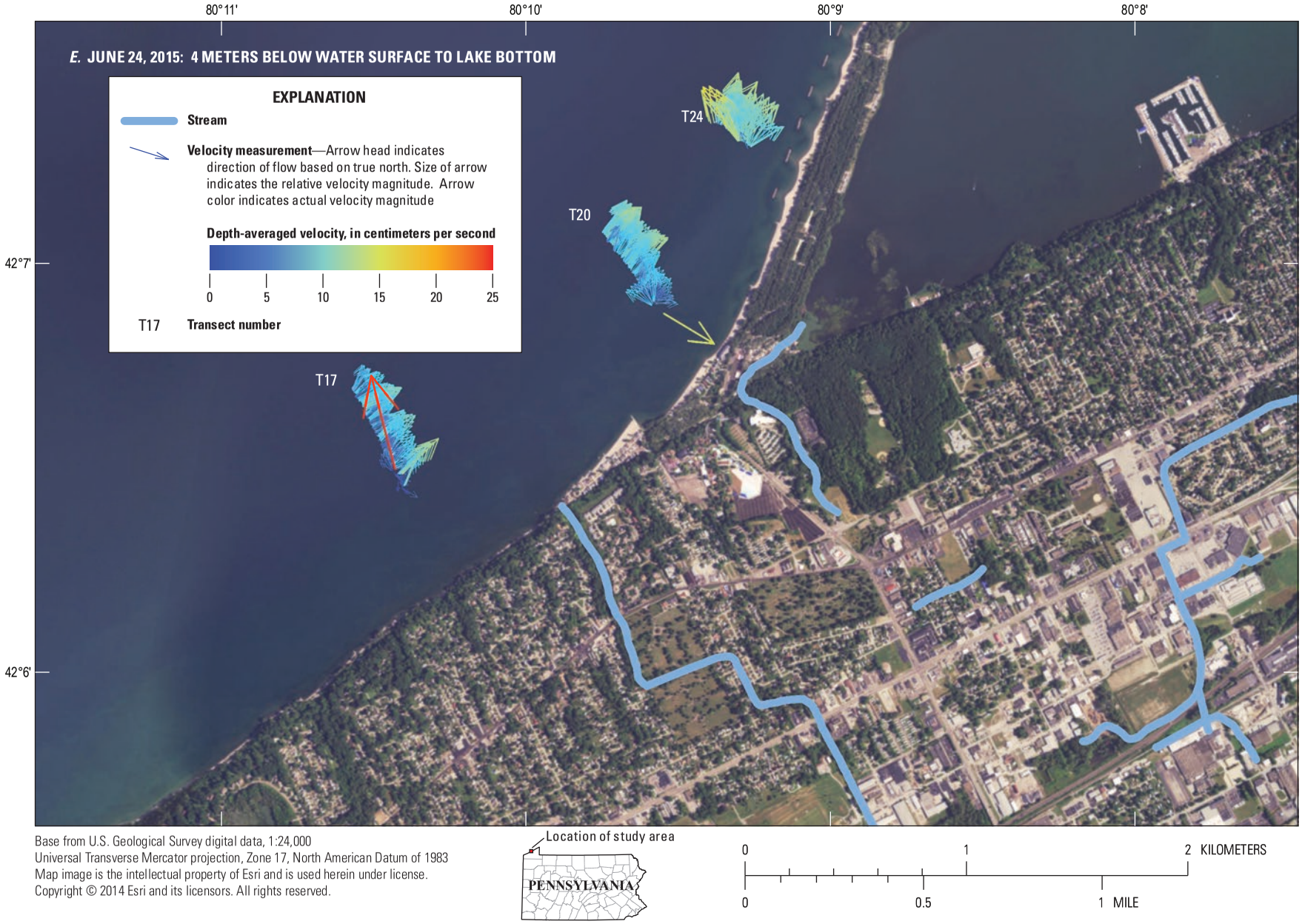

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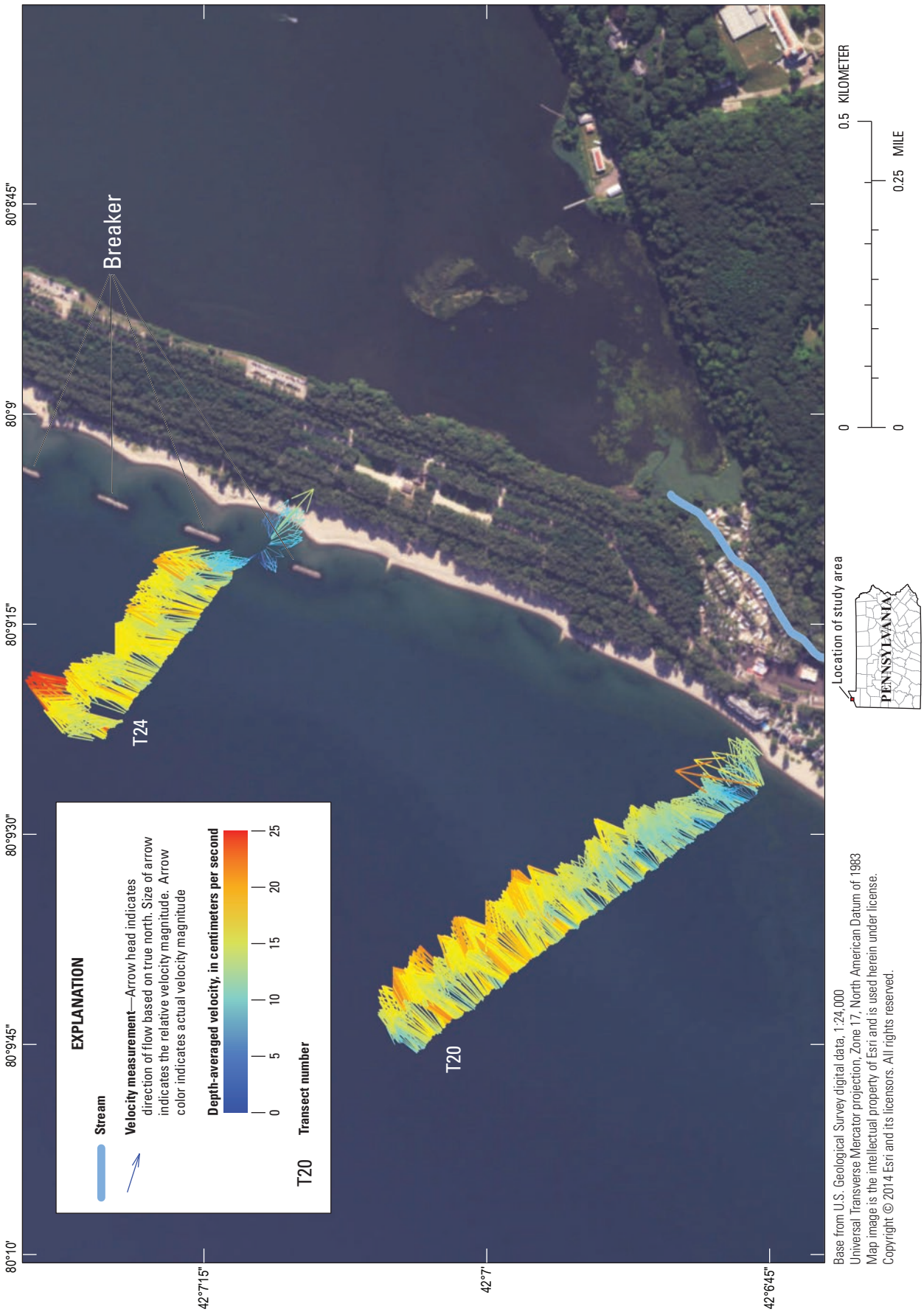

Figure 10. Longshore water-current velocity magnitude and direction averaged over a depth of 0 to 2 meters at transects 20 and 24, Lake Erie study area, Pennsylvania, June 24, 2015, illustrating the effect of a breaker on flow velocity direction and magnitude.

June 25, 2015

The synoptic survey on June 25, 2015, (fig. 11*A*–*F*) was conducted as the wind was changing direction from south to east. Direct comparisons of June 24 and June 25 velocity and direction data are shown in figures 12A–C for transects 1, 2, 12, and 20. Data were averaged over the entire depth to see the variation in longshore current velocity magnitude and direction over just 1 day (fig. 12*A*–*C*).

August 18, 2015

Wind and wave variation that occurred in June 2015 over 2 days caused the August synoptic survey strategy to be modified. The longshore water-current velocity survey was conducted by measuring transects 1 and 2, skipping every other transect, and going back to measure the skipped transects, as time allowed. The result was a snapshot of changes in longshore current velocity magnitude and direction that occurred over 1 day (fig. 13*A*, *B*).

Before noon, velocity and direction at transects 1, 2, 4, 6, 8, 10, and 12 were measured. The current direction was reversed from that of the June 2015 synoptic surveys with the general direction being from east to west (fig. 13*A*, *B*). When the top 5 m of depth was averaged, the longshore water-current velocity magnitude was generally in the 3–5 cm/s range. Closer to shore, the longshore current velocity direction and magnitude were variable with velocities ranging from 12 to 18 cm/s. This could be a result of high turbulence in shallow depths. The water velocity averaged from 5 m to the bottom was generally faster.

After noon, velocity and direction of current at transects 14, 16, 18, 20, 22, 24, 19, 15, 13, 11, 5, and 2 (in that order) were measured (fig. 14). For these transects, the direction of longshore current velocity was generally from east to west, a reverse of the direction in the morning To highlight this difference, figure 15 shows the western part of the study area with the morning transects colored in turquoise and the afternoon transects colored in magenta. Transect 2 was surveyed in the morning and afternoon. The change that can occur over 6 hours with the velocities generally slower in the afternoon and even reversing in the middle of the transect is shown in figure 16.

The averaging scheme for data display was adjusted on August 18 to obtain better water-current velocity and direction data. As evidenced from the changes seen between the morning and afternoon transects, conditions in the lake were not stable, and many small variations in velocity and direction were measured within a single transect. Averaging out the small variations allows a general trend to be shown. When the scheme of averaging the data over 2 m was attempted, no clear trend was seen in the current velocity and direction, thus the scheme of averaging over 5 m was implemented.

August 19, 2015

The synoptic survey on August 19, 2015, was processed in VMT for one pass only instead of one pass across and one pass back as in the other surveys. In order to get a complete picture of water quality, at one transect the first pass was dedicated to the current velocity survey, and the reciprocal pass was dedicated to water quality. This was to assure that the entire study area was measured in as short a time as possible to avoid the changing conditions that were seen the day before. It was not possible to average the water-quality data from the two passes because the pass strayed off the transect line when the boat was idling. The results for this synoptic survey are presented in the Appendix 1, but they are of reduced quality because only one pass was used for the VMT processing.

Nearshore Water Quality

Water-quality samples were collected within about 1 m of shore three times during the study. On August 11, nearshore water-quality samples only were collected after a precipitation event occurred the night before. Data that were collected at Walnut Creek are also presented.

Walnut Creek

The USGS seasonally (late spring–fall) operates a continuous water-quality monitor at USGS streamgage 04213152 just upstream from the mouth of Walnut Creek (fig. 1). Data on turbidity, specific conductance, dissolved oxygen, and temperature are collected every 15 minutes. A graph of specific conductance data for Walnut Creek collected during the June synoptic surveys is shown in figure 17.

Lake Erie

Data from all nearshore water-quality samples are stored in the USGS NWIS database and were published by Hittle (2016d; http://dx.doi.org/10.5066/F7KP808D). The data include *E. coli* bacteria, water temperature, and turbidity for all sampling dates. Samples were collected on June 24, 2015, and August 11, 2015, for suspended sediment concentration (SSC) and sediment particle size. Results of the nearshore bacteria sampling are shown in figure 18 for the three sampling dates. Discharge from Walnut Creek is a suspected source of bacteria to the lake and no attempt to identify other potential sources was made during the study. The highest discharge within 24 hours of sample collection and the mean daily discharge for the day before sample collection are given in table 2.

Longshore Water-Quality Surveys

Water-quality data along transects in the lake were collected on a pass separate from that of the longshore current velocity. In June 2015, some transects were selected for water-quality data collection (water temperature, specific conductance, and turbidity) to get an idea of conditions and to plan for the collection effort in August. Visualization of this data was accomplished using ArcScene (http://www.esri.com/software/arcgis/extensions/3danalyst/technical-information) because it allows depth visualization on a two-dimensional surface. The orientation of the transects was chosen as the best compromise for seeing the depth of the samples and the distance along shore. The orientations of the east and west views are different because the transects are oriented differently in order to remain perpendicular to the shore.

Data for the June 2015 water-quality surveys were published by Hittle (2016 b, c; http://dx.doi.org/10.5066/F7KP808D). Visualizations of the temperature, specific conductance, and turbidity for June 24, 2015, and June 25, 2015, are presented in figures 19*A*–*F* and 20*A*–*F*. For all characteristics, only the data that were collected by moving the water-quality sonde from the lake bottom to the water surface were determined to be appropriate; the data that were collected from the surface to the lake bottom were removed because of interference from the boat wake, as evidenced by the consistently higher turbidity and water temperature at the surface that did not occur when the probe went from bottom to top. On June 24, 2015, water-quality surveys were concentrated in the western part of the study area, except for transects 17 and 24, which are in the eastern part (table 1). Data were collected every 5 seconds on June 24, except at transects 17 and 24 where data were collected every 1 second. Depth data are not available for transects 4 and 6 as a result of an error in the depth sensor setup, but depth data are available for all other transects where water-quality data were collected. On June 25, water-quality surveys were concentrated in the eastern part of the study area, except for transects 1 and 2, which are in the western part of the study area (table 1). The water-quality data collected in August along transects were determined to be unusable as a result of instrument failure.

Table 2. Maximum discharge reported at Walnut Creek within 24 hours of the nearshore sample collection and the mean daily discharge, Lake Erie study area, Pennsylvania, June and August 2015.

[m^3/s, cubic meter per second, ft^3/s, cubic foot per second]

Date	Maximum discharge within 24 hours of sample collection (time)	Mean daily discharge
6/23/2015	1.90 m^3/s (67 ft^3/s) (12:00 p.m.)	0.96 m^3/s (34 ft^3/s)
8/11/2015	1.13 m^3/s (40 ft^3/s) (4:30 a.m.)	0.51 m^3/s (18 ft^3/s)
8/18/2015	2.32 m^3/s (82 ft^3/s) (4:30 p.m.)	0.51 m^3/s (18 ft^3/s)

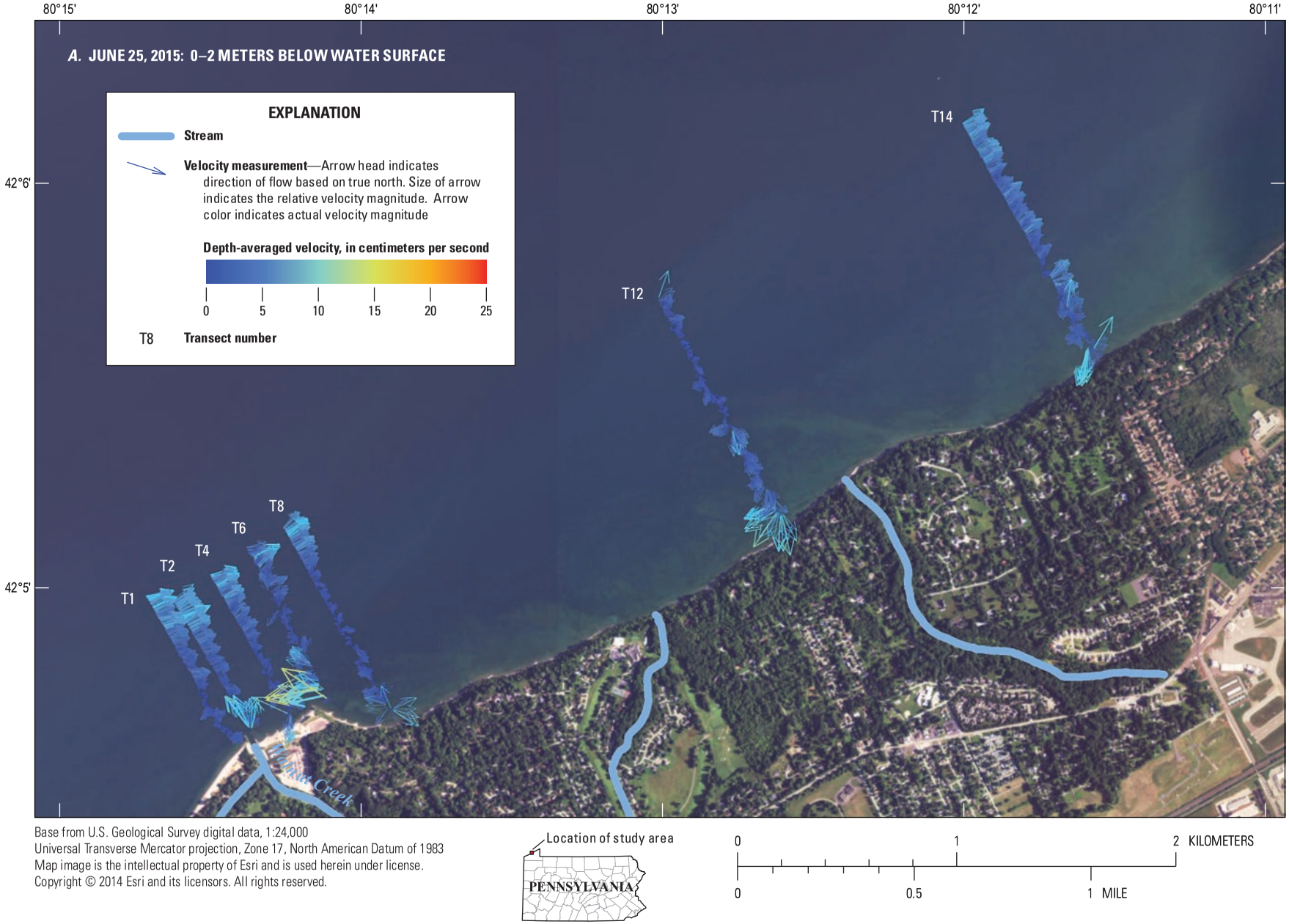

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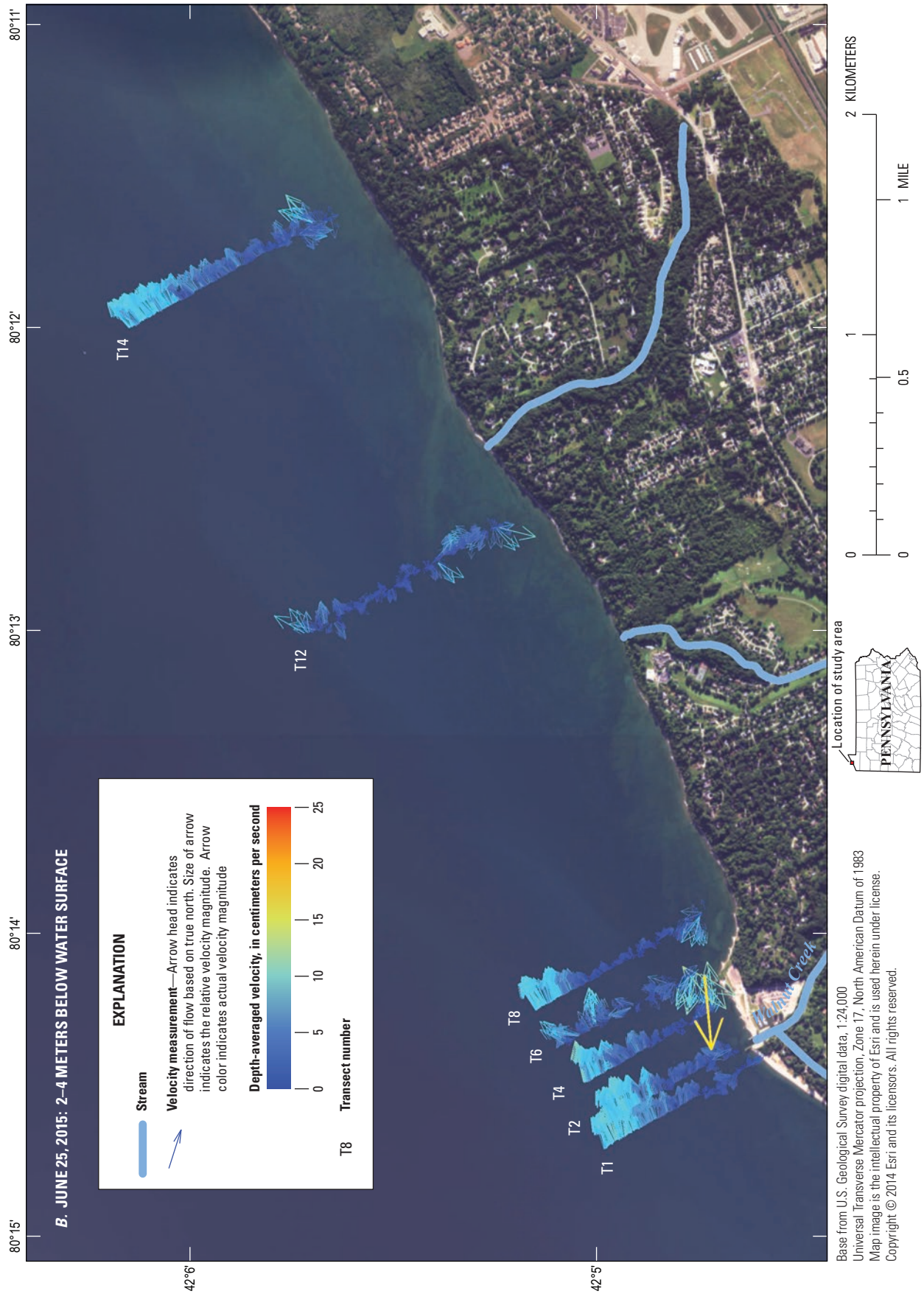
Figure 11. Longshore current velocity magnitude and direction *A*, averaged over a depth of 0–2 meters (m) at transects 1, 2, 4, 6, 8, 12, and 14, Lake Erie study area, Pennsylvania, June 25, 2015, *B*, averaged over a depth of 2–4 m at transects 1, 2, 4, 6, 8, 12, and 14, *C*, averaged over a depth of 4 m to the lake bottom at transects 1, 2, 4, 6, 8, 12, and 14, *D*, averaged over a depth of 0–2 m at transects 16, 19, 20, 22, 24, and 25, *E*, averaged over a depth of 2–4 m at transects 16, 19, 20, 22, 24, and 25, and *F*, averaged over a depth of 4 m to the lake bottom at transects 16, 19, 20, 22, 24, and 25.



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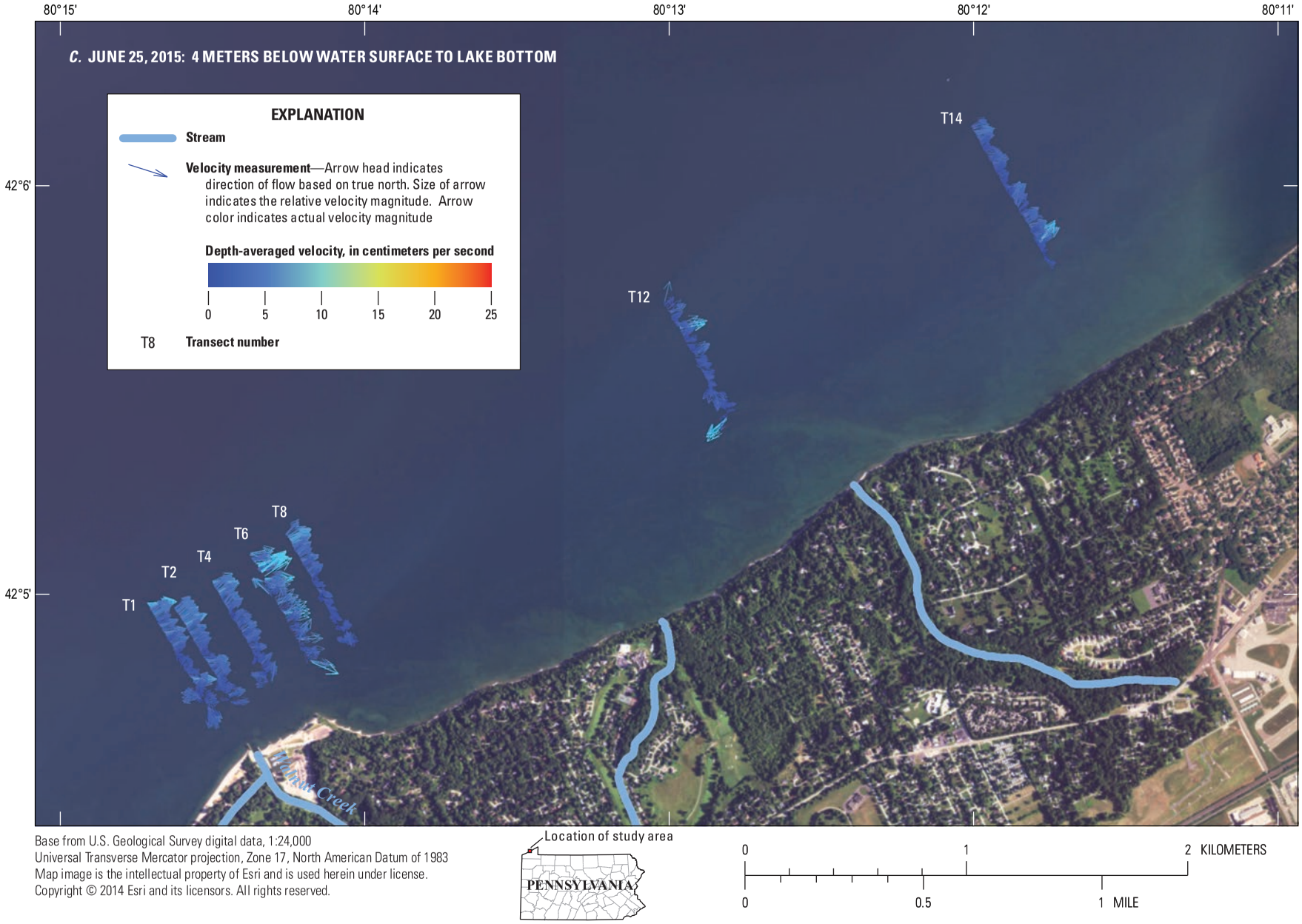

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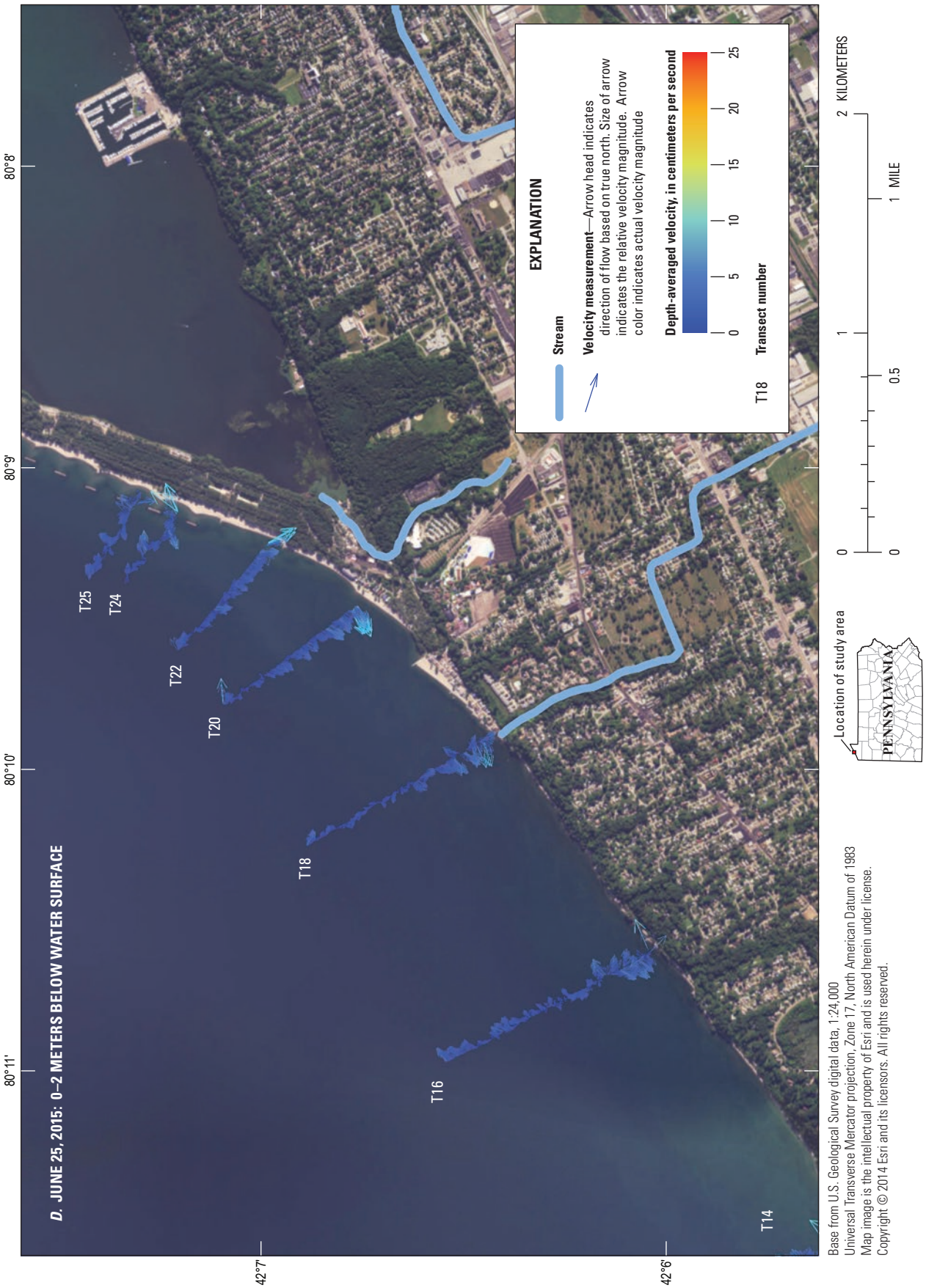

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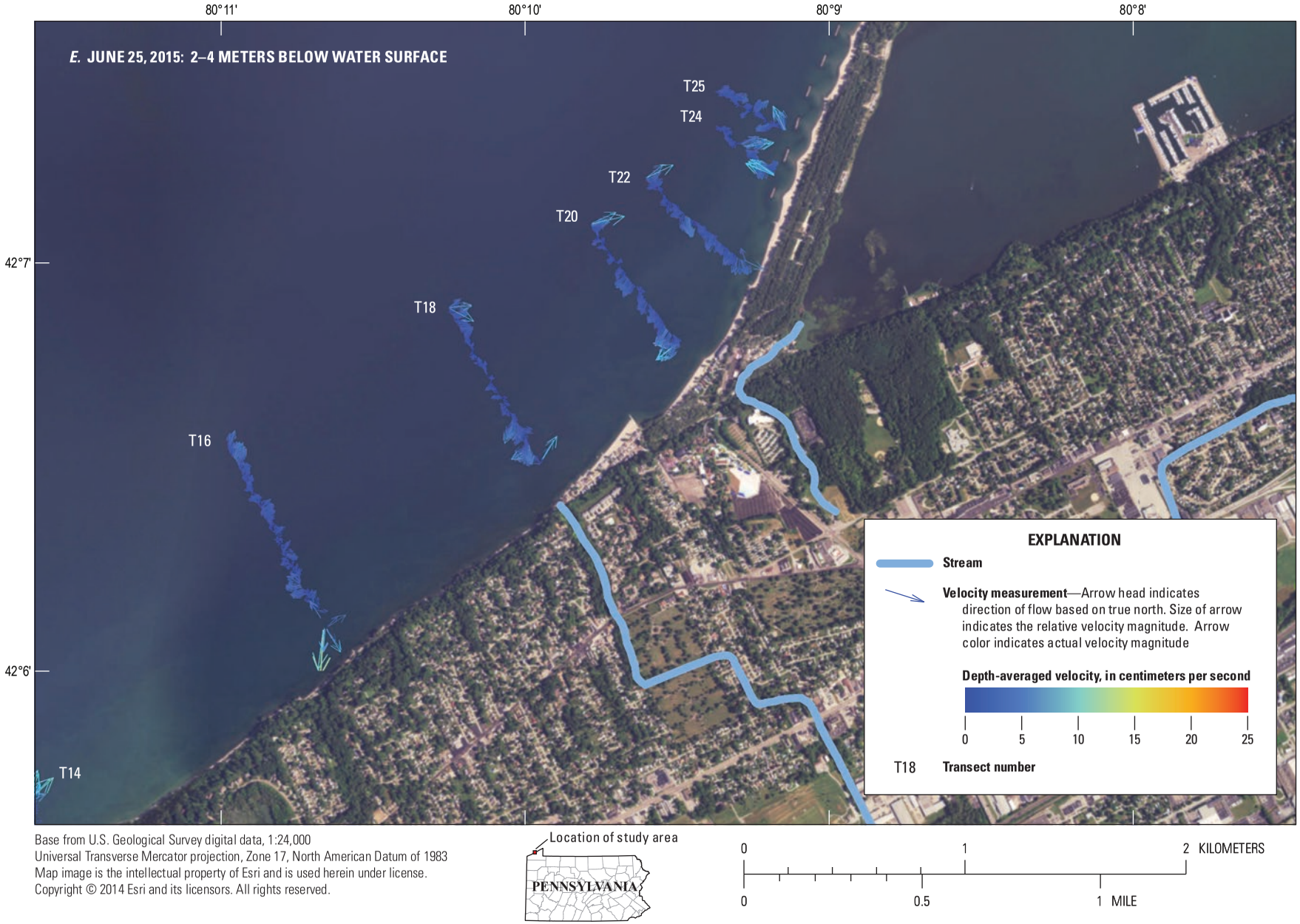

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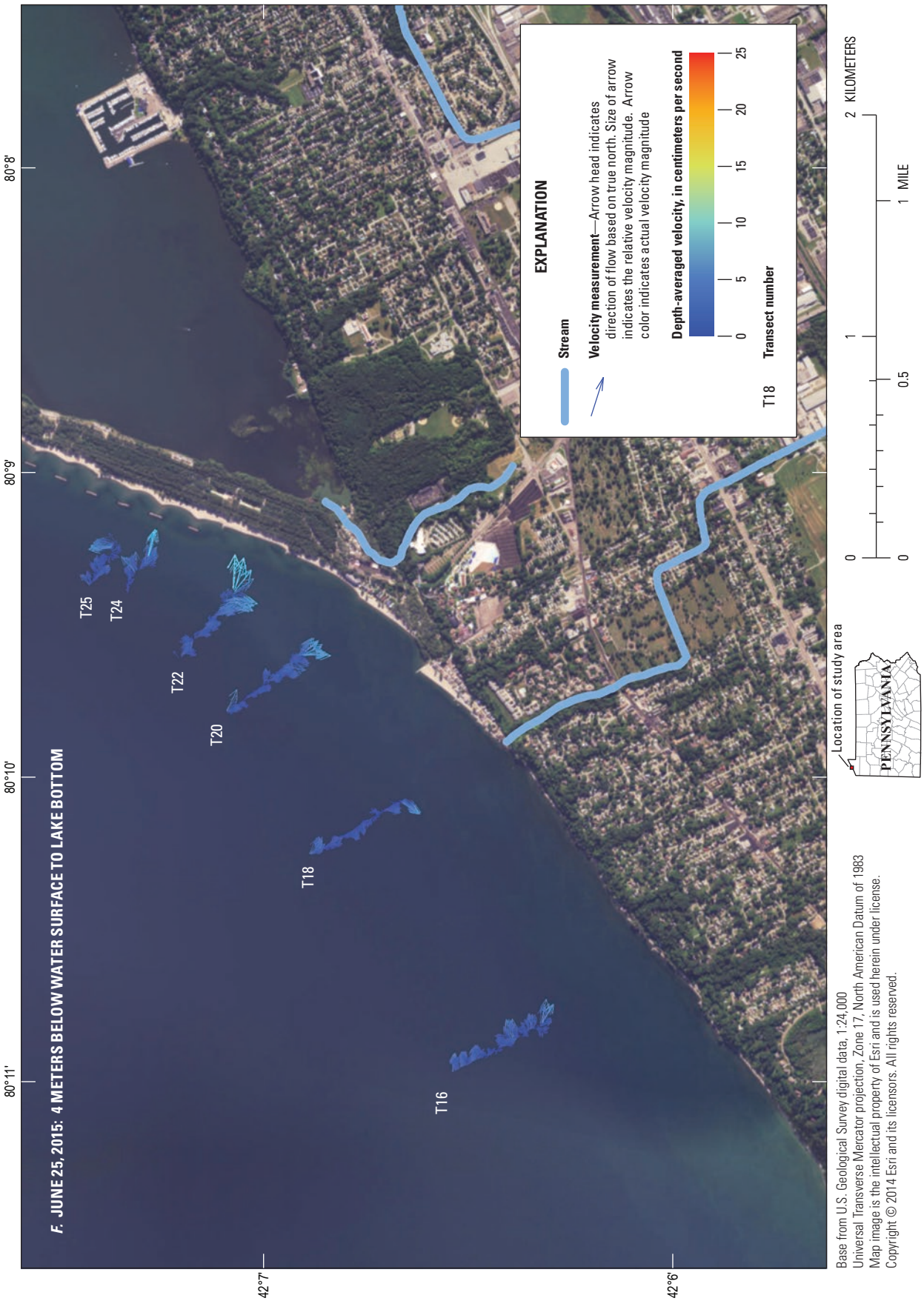

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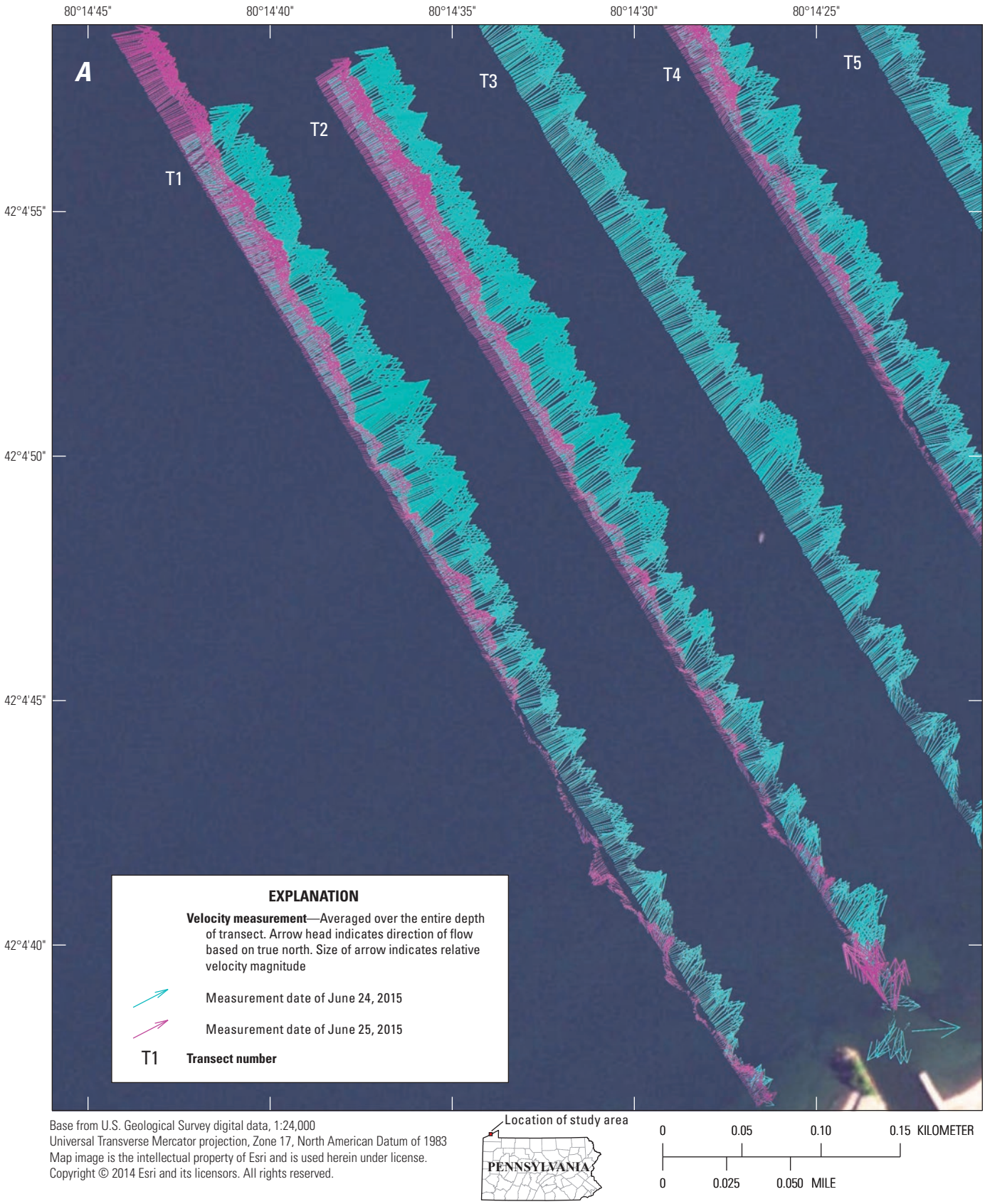

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Figure 12. Variation in longshore current velocity magnitude and direction averaged over the entire depth, Lake Erie study area, Pennsylvania, June 24–25, 2015, for *A*, transects 1 and 2, *B*, transect 12, and *C*, transect 20. Vector scaling is the same for both dates.

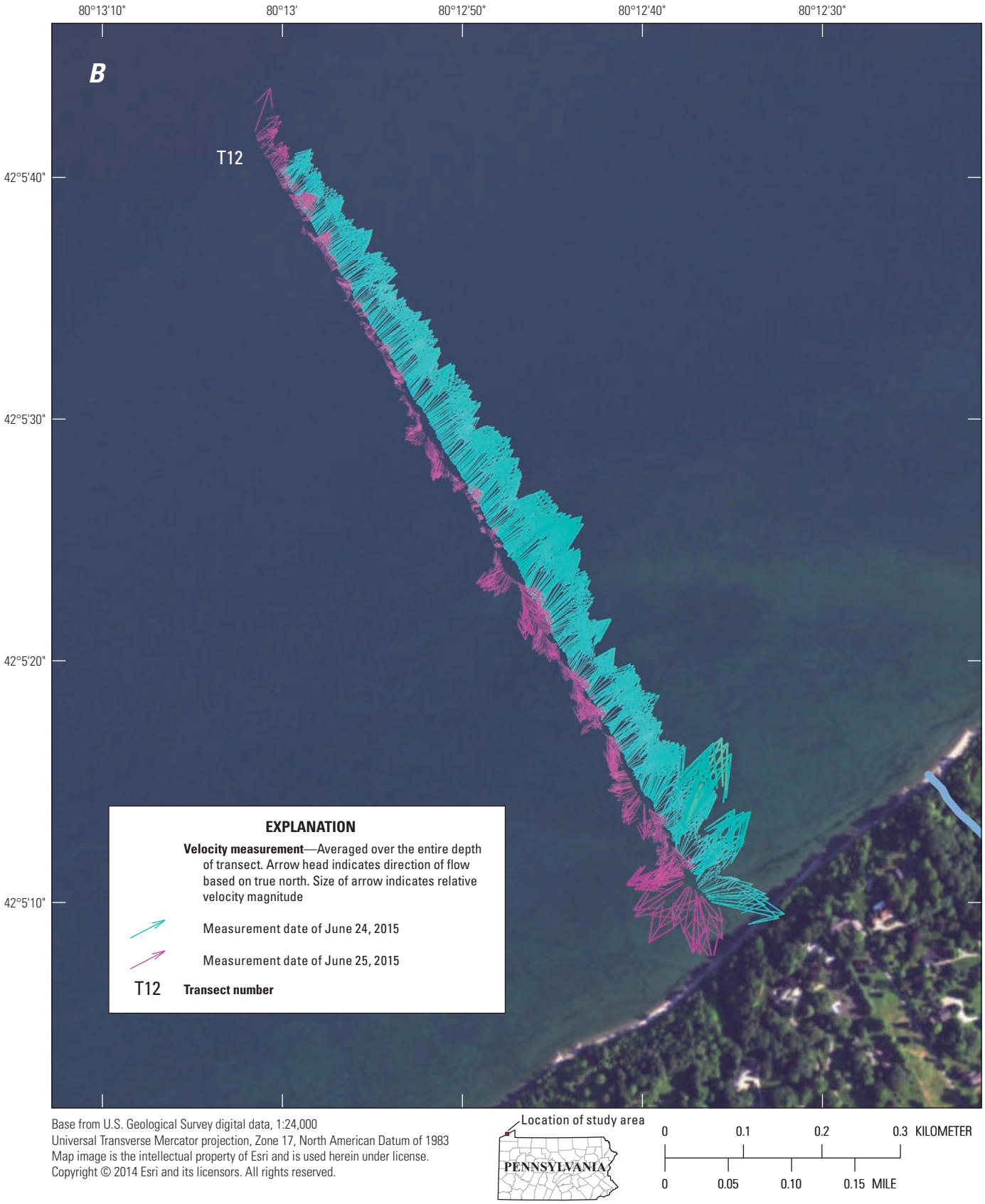

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Figure 12. Variation in longshore current velocity magnitude and direction averaged over the entire depth, Lake Erie study area, Pennsylvania, June 24–25, 2015, for *A*, transects 1 and 2, *B*, transect 12, and *C*, transect 20. Vector scaling is the same for both dates. —Continued

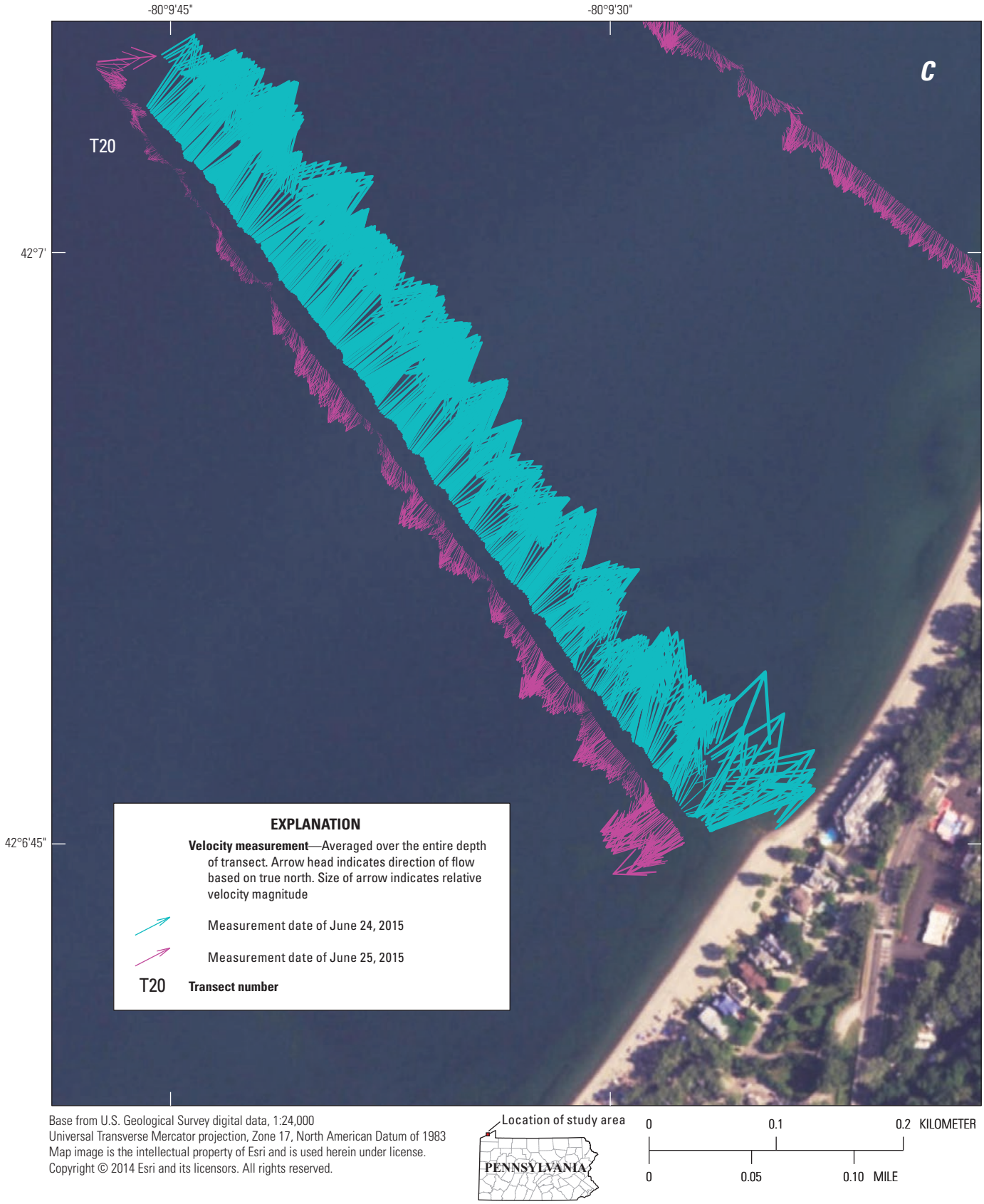

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Figure 12. Variation in longshore current velocity magnitude and direction averaged over the entire depth, Lake Erie study area, Pennsylvania, June 24–25, 2015, for *A*, transects 1 and 2, *B*, transect 12, and *C*, transect 20. Vector scaling is the same for both dates. —Continued

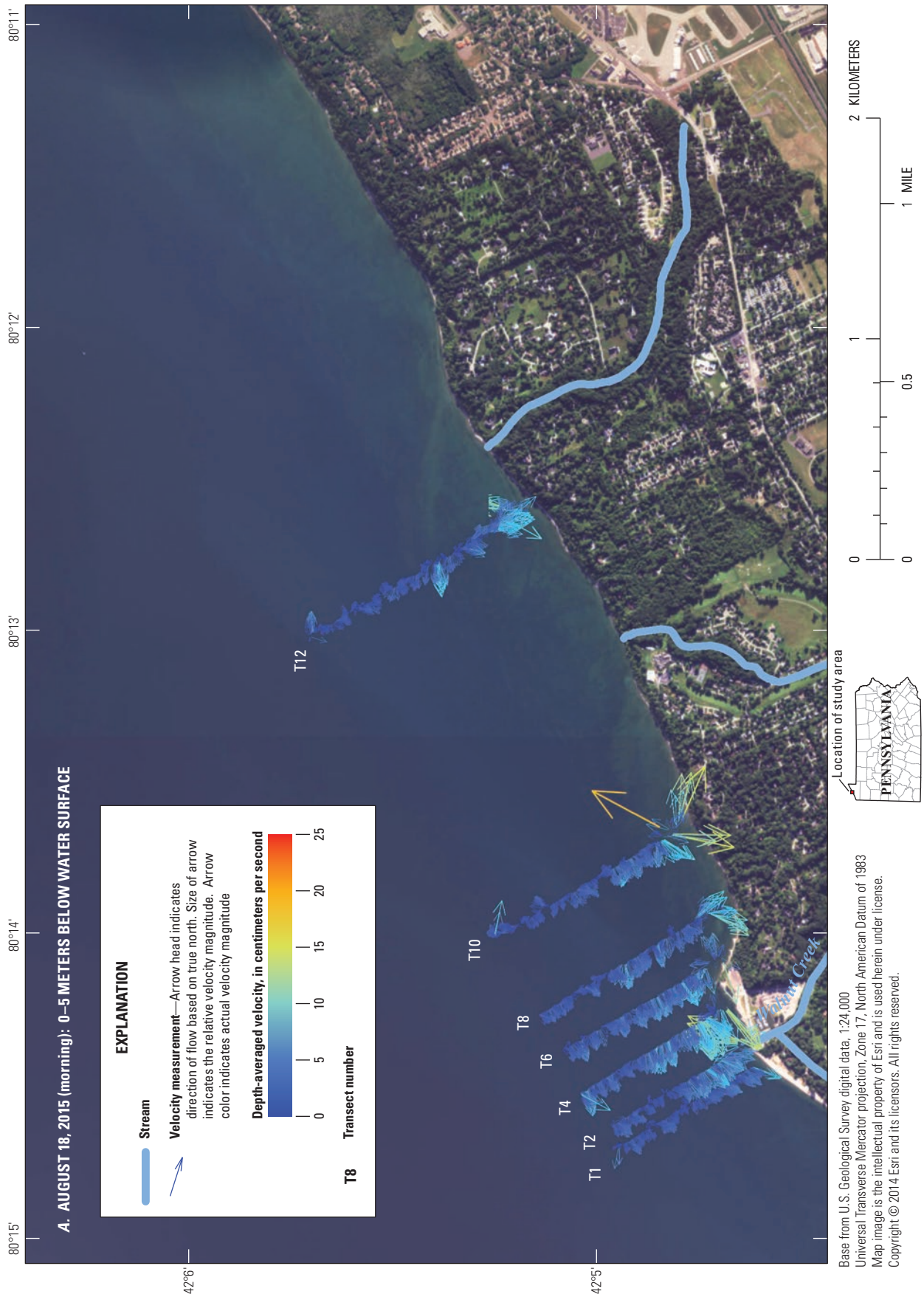

Figure 13. Longshore current velocity magnitude and direction, Lake Erie study area, Pennsylvania, August 18, 2015, *A*, at transects 1, 2, 4, 6, 8, 10, and 12 averaged over a depth of 0–5 meters (m), *B*, at transects 1, 2, 4, 6, 8,10, and 12 averaged over a depth of 5 m to the lake bottom.

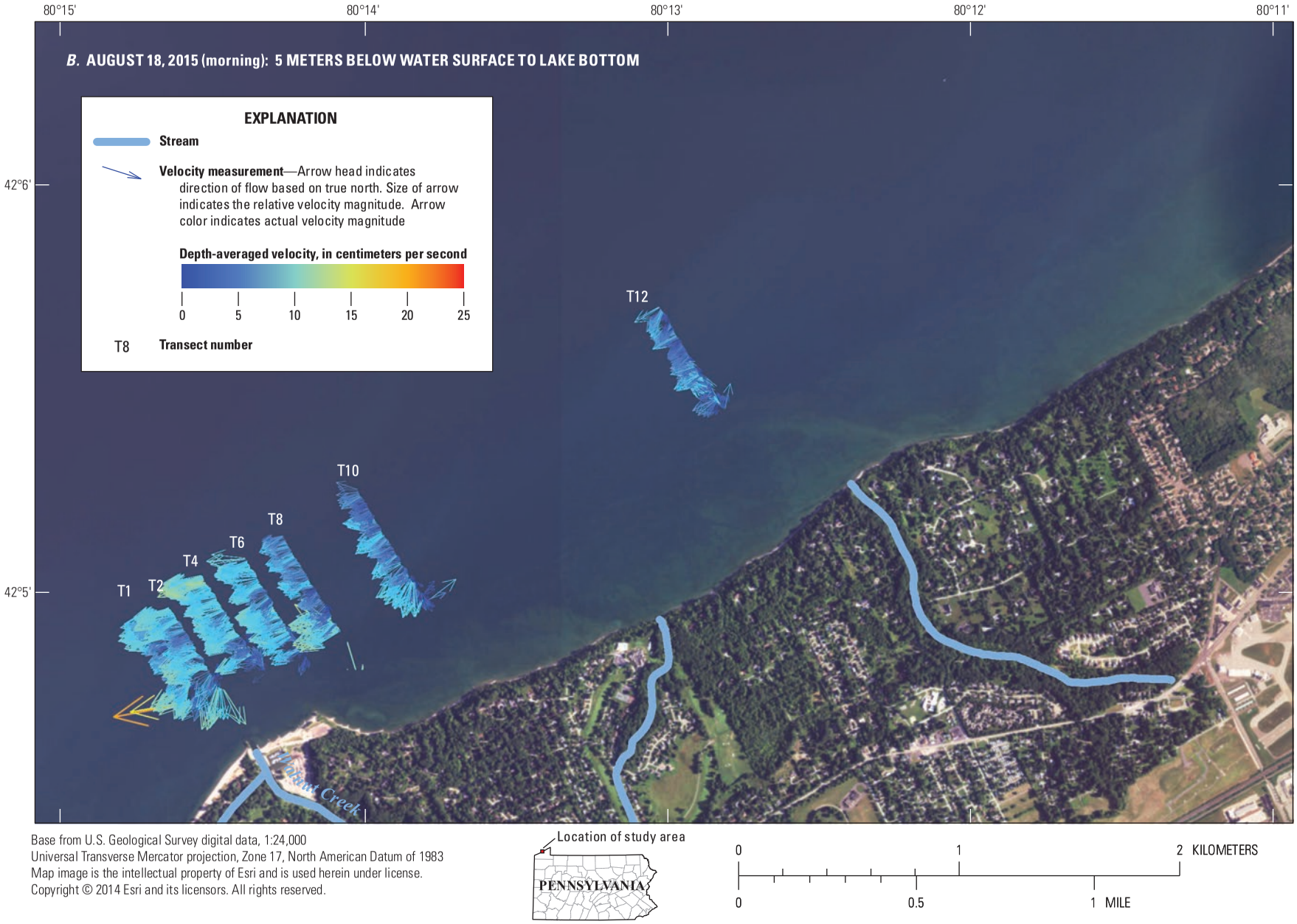

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Figure 13. Longshore current velocity magnitude and direction, Lake Erie study area, Pennsylvania, August 18, 2015, *A*, at transects 1, 2, 4, 6, 8, 10, and 12 averaged over a depth of 0–5 meters (m), *B*, at transects 1, 2, 4, 6, 8,10, and 12 averaged over a depth of 5 m to the lake bottom.—Continued

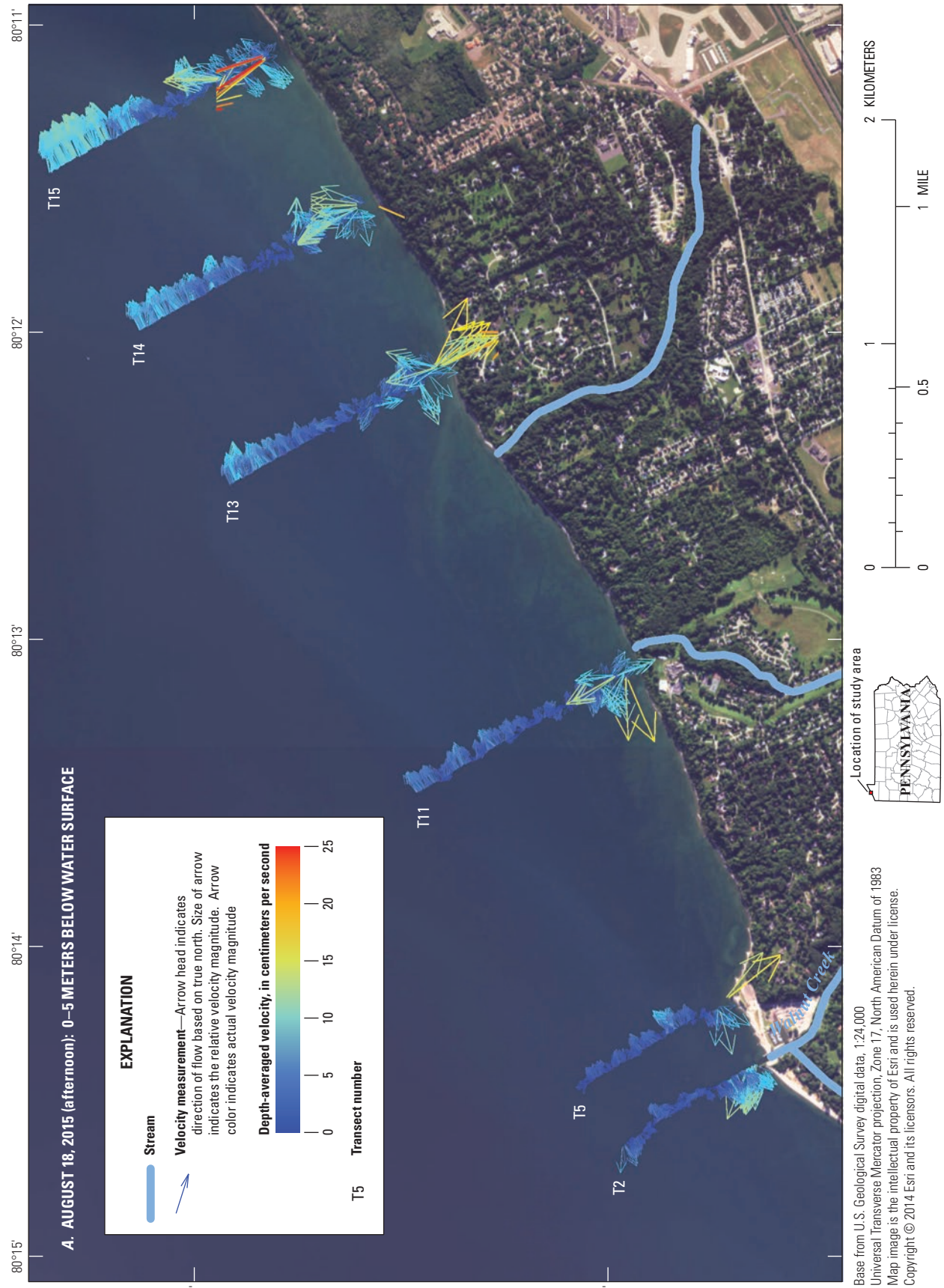

Figure 14. Longshore current velocity magnitude and direction, Lake Erie study area, Pennsylvania, August 18, 2015, *A*, at transects 2, 5, 11, 13, 14, and 15 averaged over a depth of 0–5 meters (m), *B*, at transects 2, 5, 11, 13, 14, and 15 averaged over a depth of 5 m to the lake bottom, *C*, at transects 15, 16, 18, 19, 20, 22, and 24 averaged over a depth of 0–5 m, and *D*, at transects 15, 16, 18, 19, 20, 22, and 24 averaged over a depth of 5 m to the lake bottom.

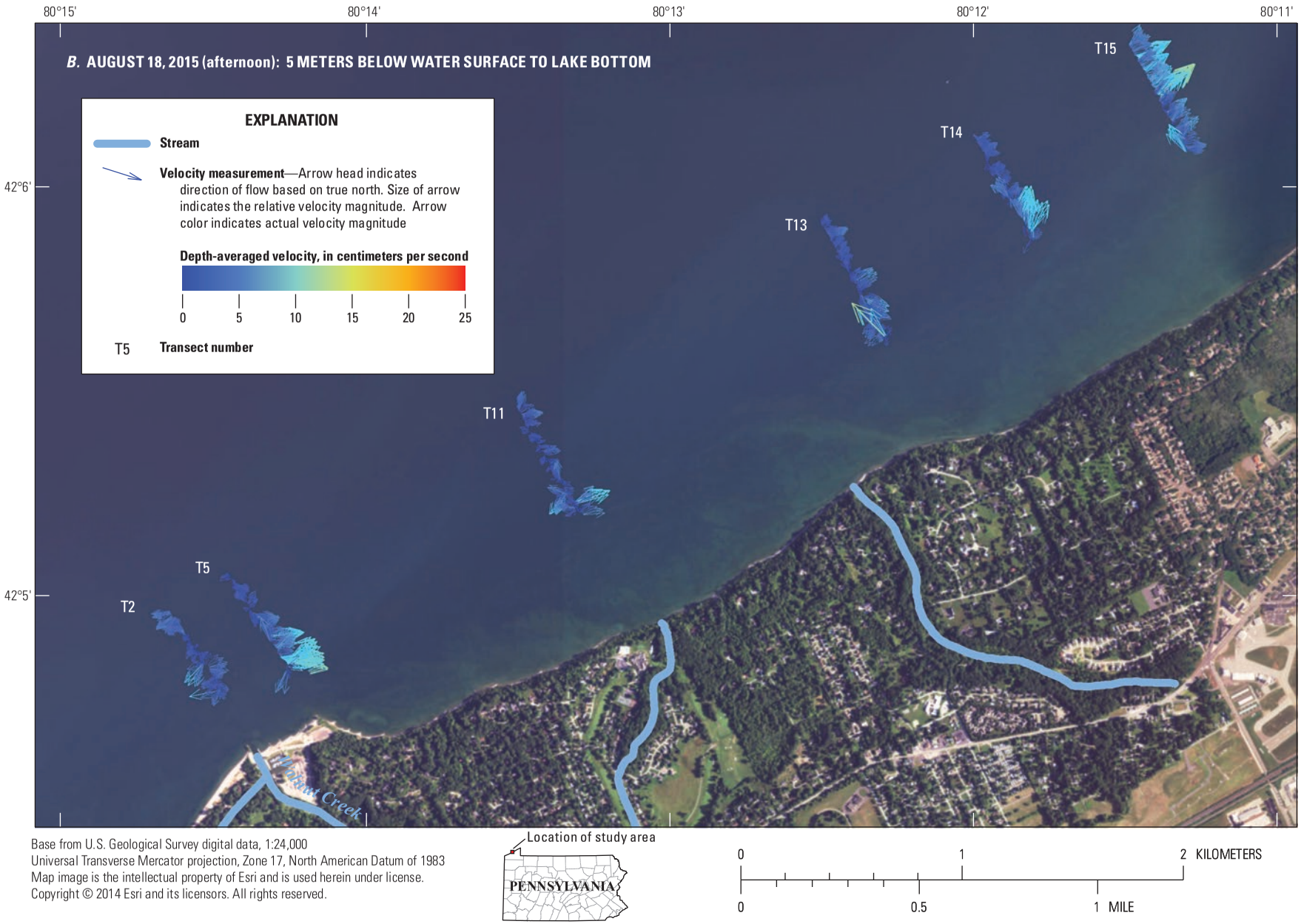

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Figure 14. Longshore current velocity magnitude and direction, Lake Erie study area, Pennsylvania, August 18, 2015, *A*, at transects 2, 5, 11, 13, 14, and 15 averaged over a depth of 0–5 meters (m), *B*, at transects 2, 5, 11, 13, 14, and 15 averaged over a depth of 5 m to the lake bottom, *C*, at transects 15, 16, 18, 19, 20, 22, and 24 averaged over a depth of 0–5 m, and *D*, at transects 15, 16, 18, 19, 20, 22, and 24 averaged over a depth of 5 m to the lake bottom.—Continued

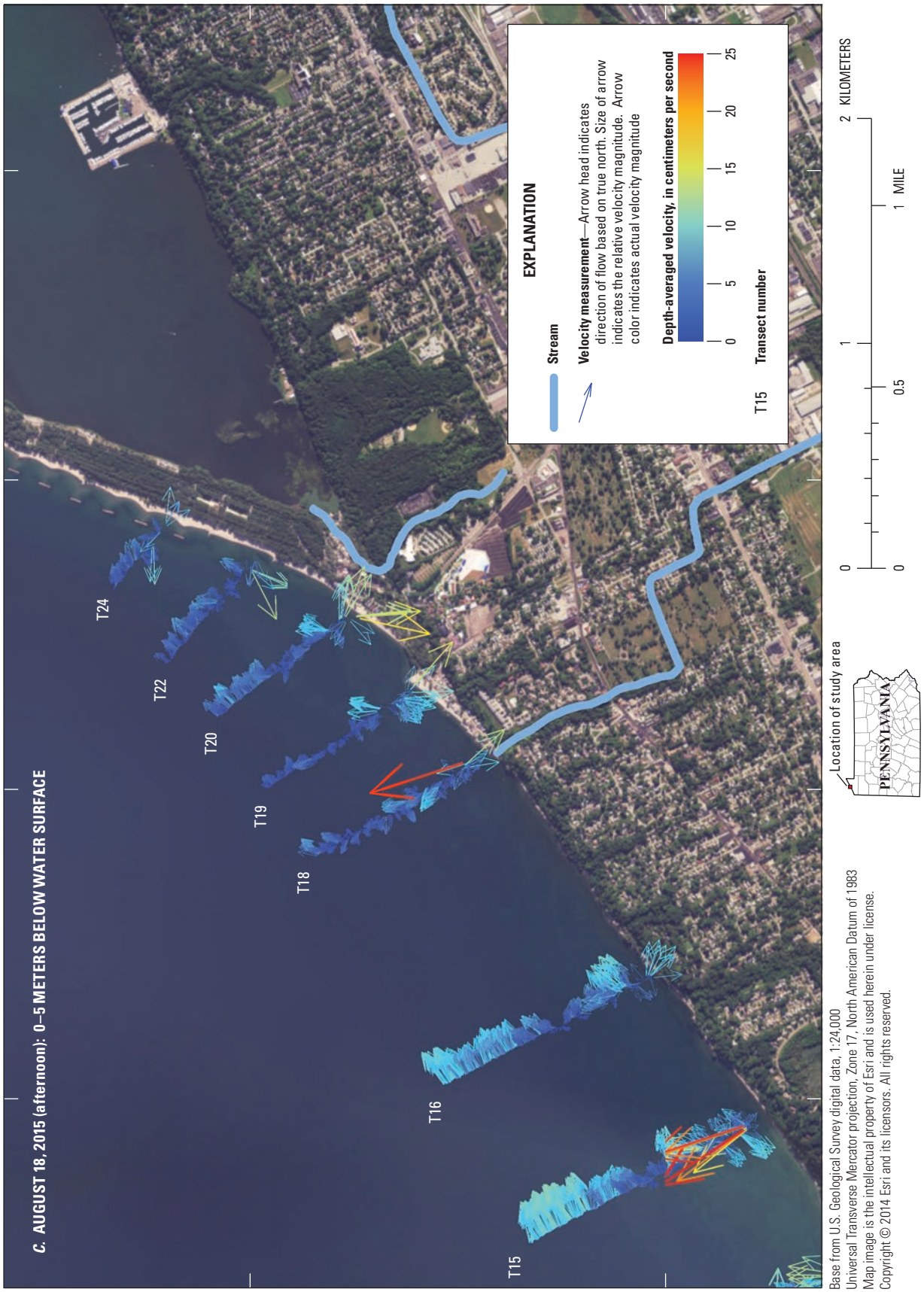

Figure 14. Longshore current velocity magnitude and direction, Lake Erie study area, Pennsylvania, August 18, 2015, *A*, at transects 2, 5, 11, 13, 14, and 15 averaged over a depth of 0–5 meters (m), *B*, at transects 2, 5, 11, 13, 14, and 15 averaged over a depth of 5 m to the lake bottom, *C*, at transects 15, 16, 18, 19, 20, 22, and 24 averaged over a depth of 0–5 m, and *D*, at transects 15, 16, 18, 19, 20, 22, and 24 averaged over a depth of 5 m to the lake bottom.—Continued

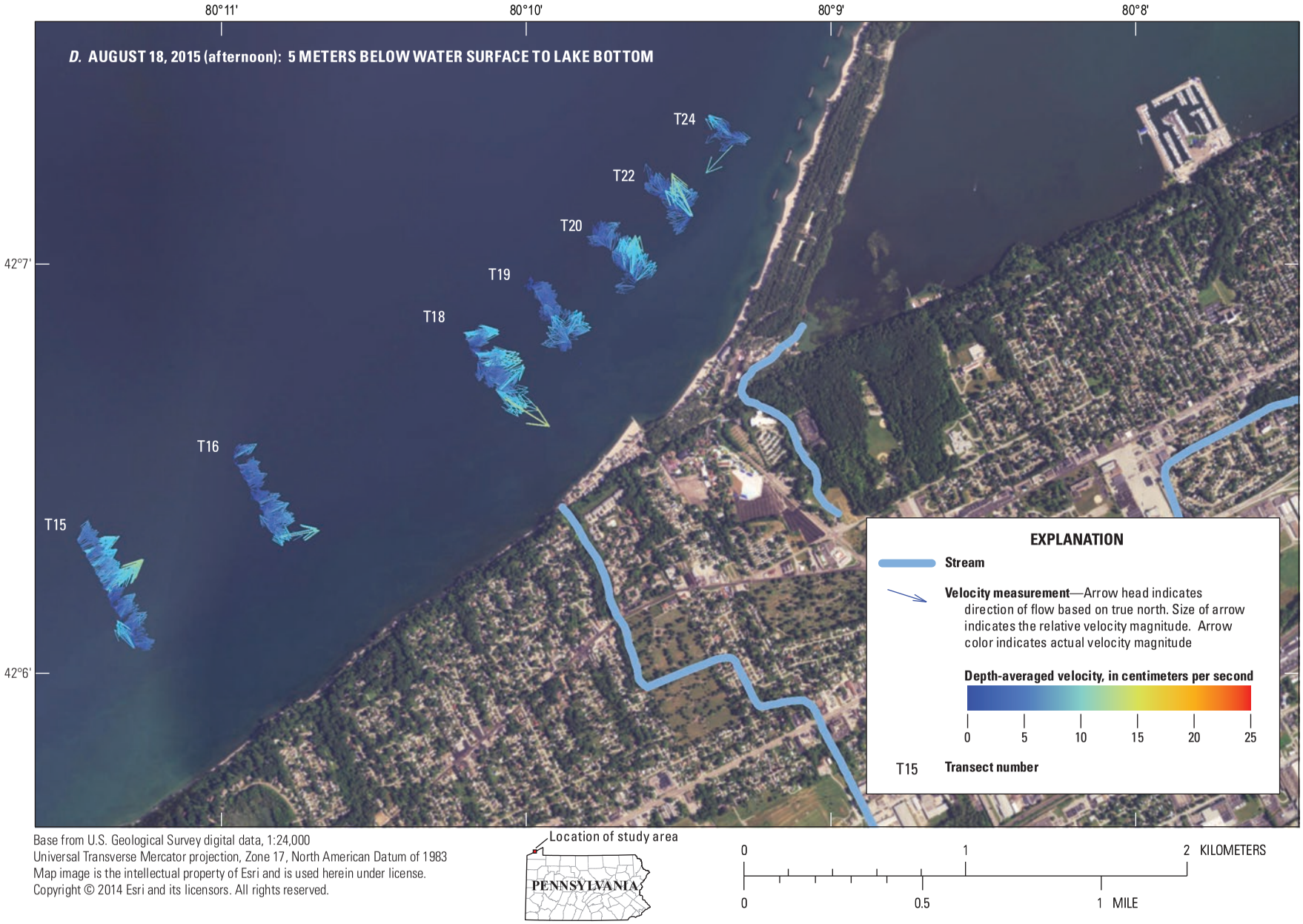

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Figure 14. Longshore current velocity magnitude and direction, Lake Erie study area, Pennsylvania, August 18, 2015, *A*, at transects 2, 5, 11, 13, 14, and 15 averaged over a depth of 0–5 meters (m), *B*, at transects 2, 5, 11, 13, 14, and 15 averaged over a depth of 5 m to the lake bottom, *C*, at transects 15, 16, 18, 19, 20, 22, and 24 averaged over a depth of 0–5 m, and *D*, at transects 15, 16, 18, 19, 20, 22, and 24 averaged over a depth of 5 m to the lake bottom.—Continued

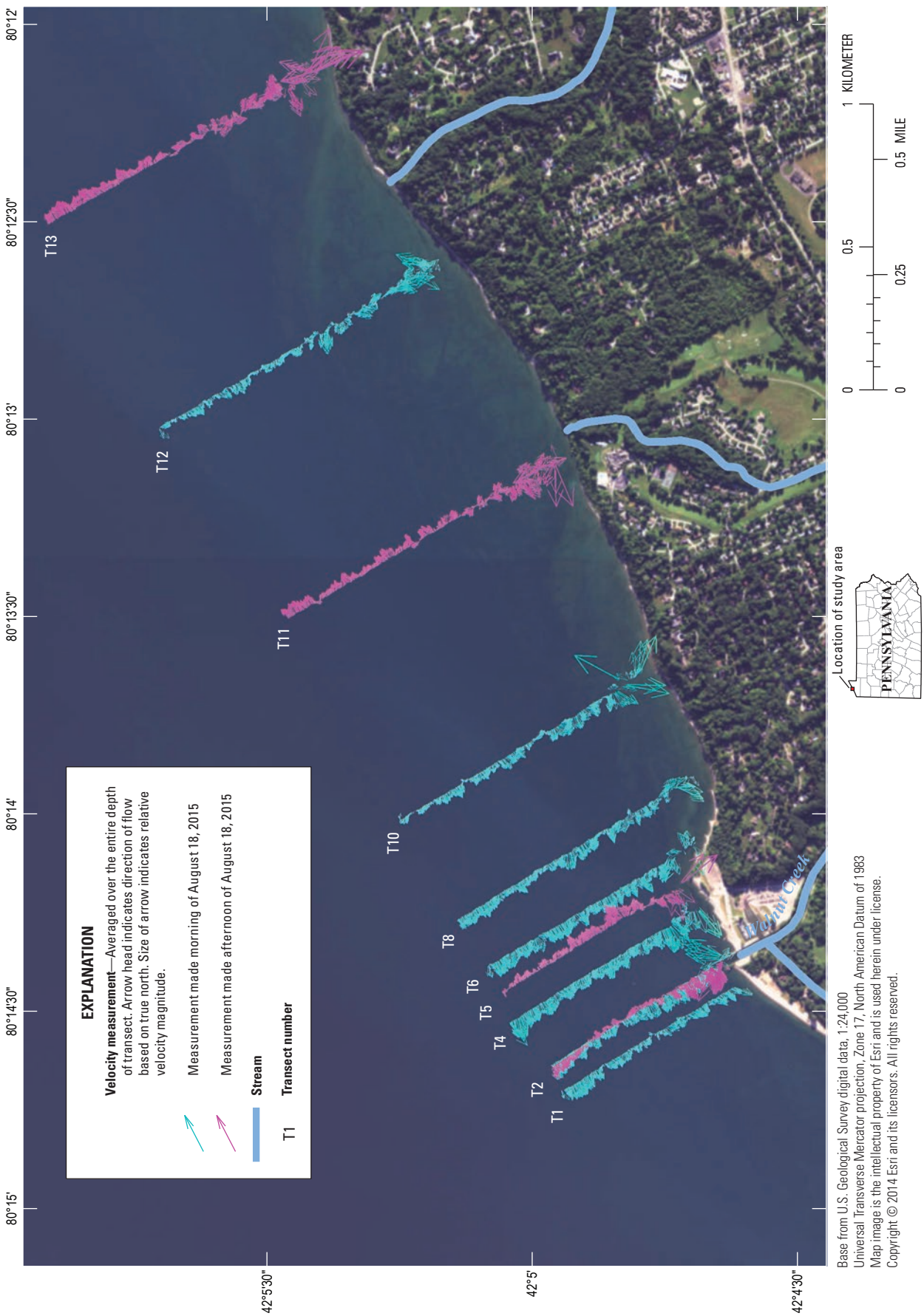

Figure 15. Longshore water-current velocity magnitude and direction, Lake Erie study area, Pennsylvania, August 18, 2015, at transects 1, 2, 4, 5, 6, 8, 10, 12, 14, and 16 averaged over the entire depth.

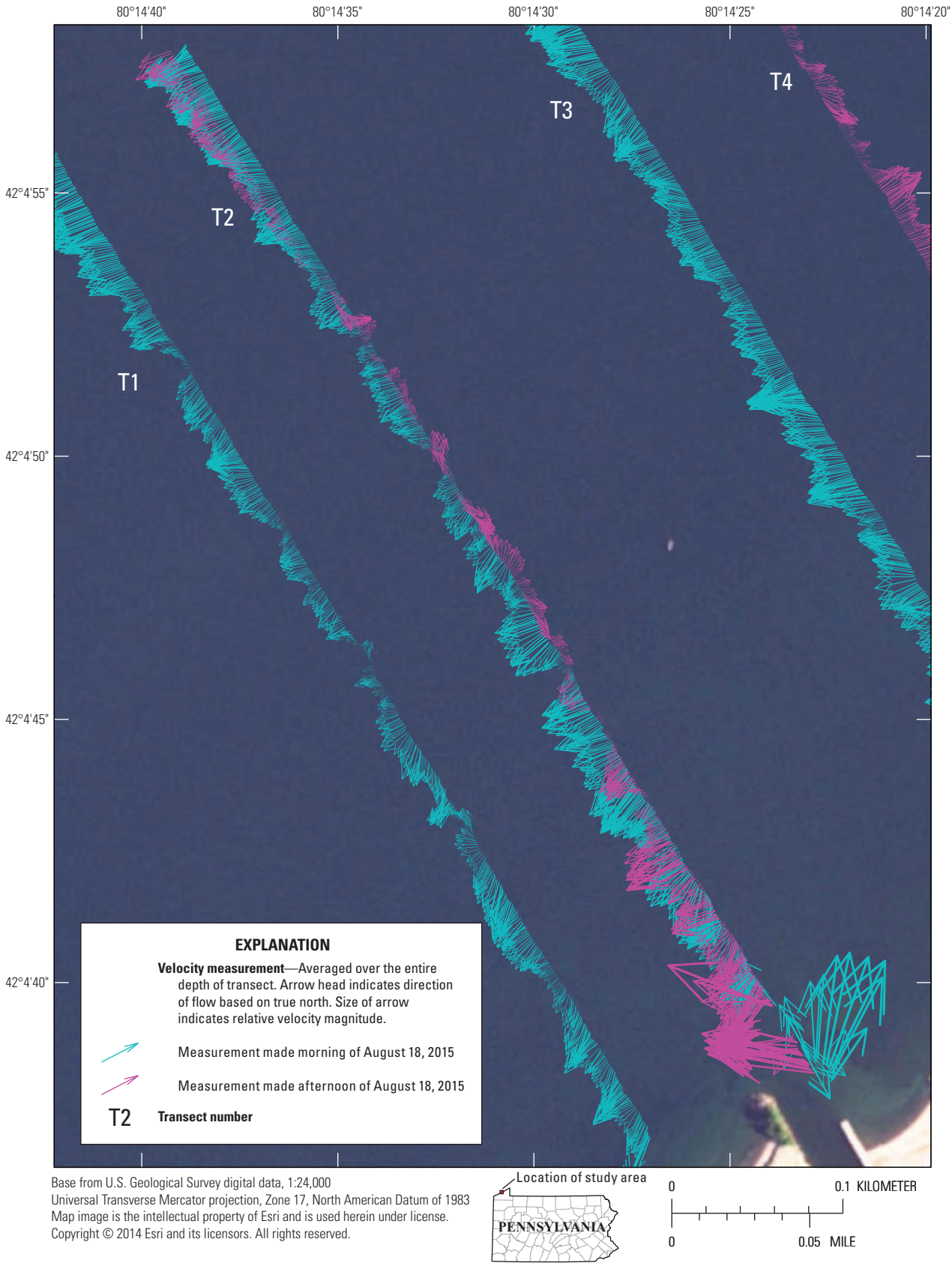

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Figure 16. Longshore water-current velocity magnitude and direction, Lake Erie study area, Pennsylvania, August 18, 2015, at transect 2.

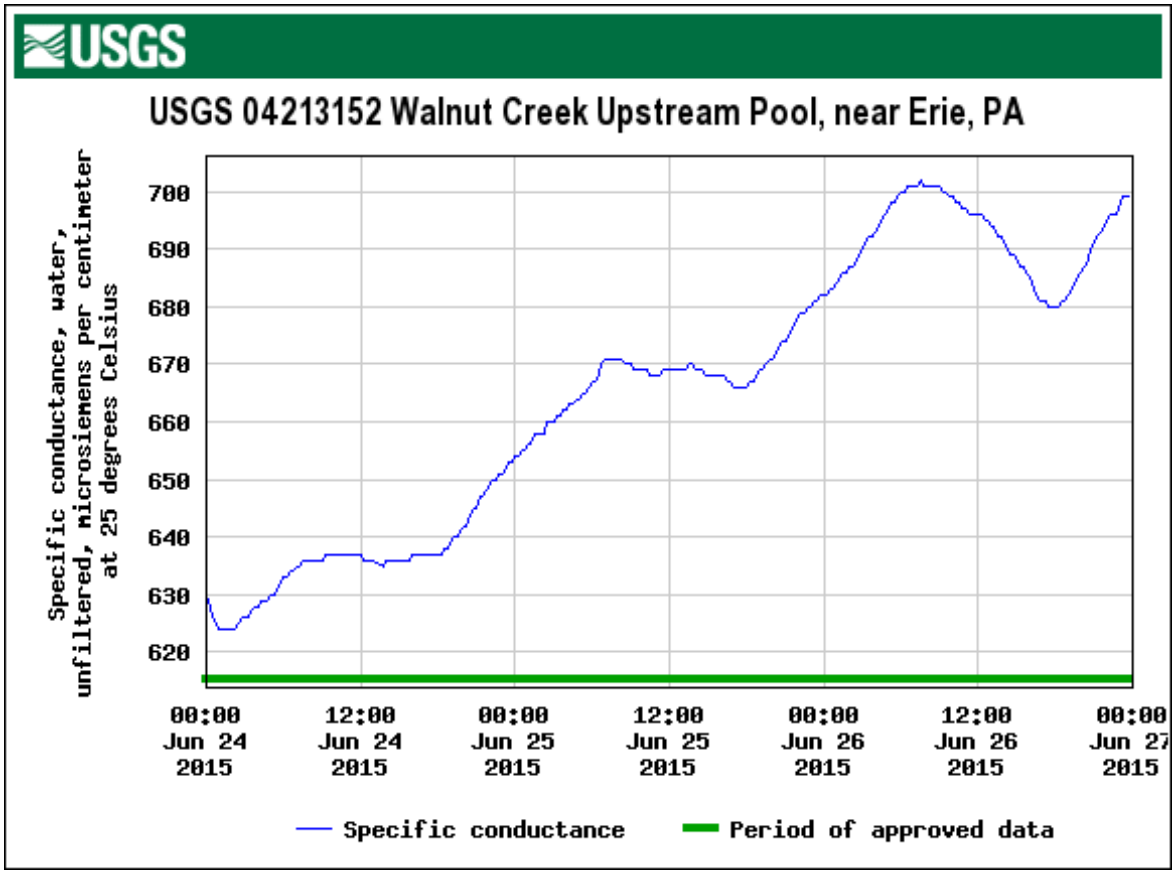

Figure 17. Specific conductance at U.S. Geological Survey streamgage 04213152, Lake Erie study area, Pennsylvania, during June 24–26, 2015.

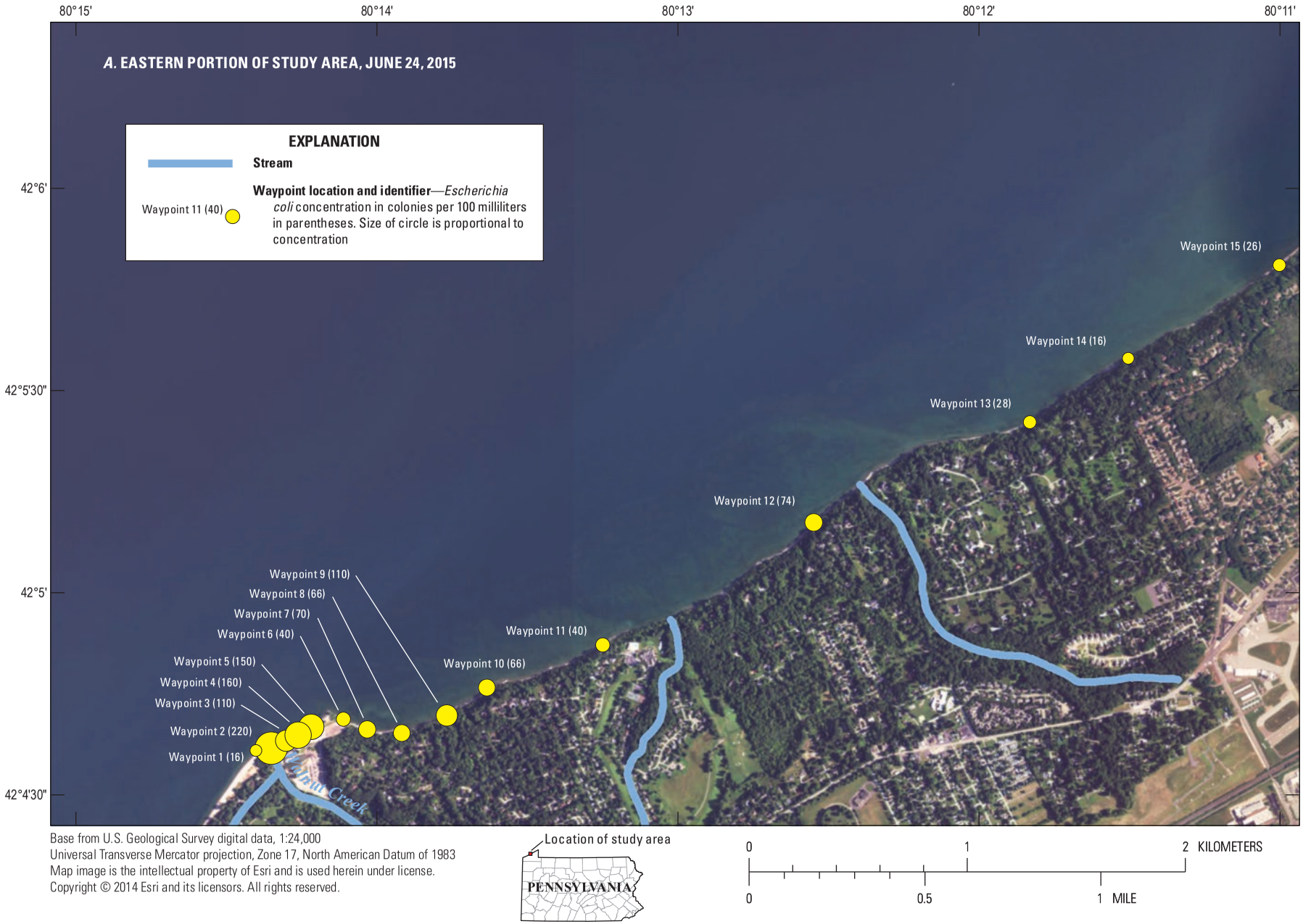

Figure 18. Bacteria counts for *Escherichia coli* in samples collected at nearshore sampling points, Lake Erie study area, Pennsylvania, at *A*, waypoints 1–15, June 24, 2015, *B*, waypoints 15–25, June 24, 2015, *C*, waypoints 1–15, August 11, 2015, *D*, waypoints 15–25, August 11, 2015, *E*, waypoints 1–15, August 19, 2015, and *F*, waypoints 15–25, August 19, 2015.

Figure 18. Bacteria counts for *Escherichia coli* in samples collected at nearshore sampling points, Lake Erie study area, Pennsylvania, at *A*, waypoints 1–15, June 24, 2015, *B*, waypoints 15–25, June 24, 2015, *C*, waypoints 1–15, August 11, 2015, *D*, waypoints 15–25, August 11, 2015, *E*, waypoints 1–15, August 19, 2015, and *F*, waypoints 15–25, August 19, 2015.—Continued

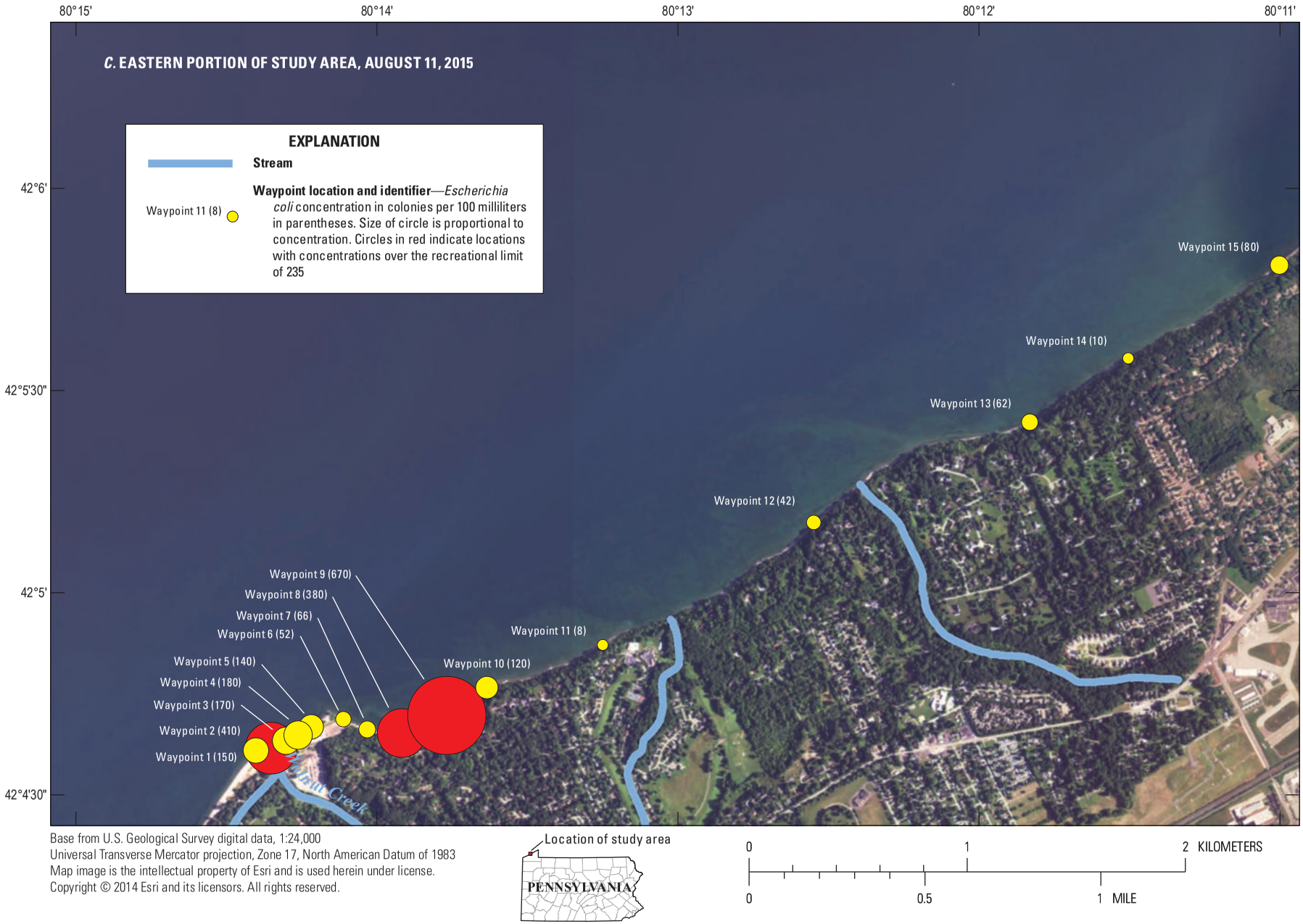

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Figure 18. Bacteria counts for *Escherichia coli* in samples collected at nearshore sampling points, Lake Erie study area, Pennsylvania, at *A*, waypoints 1–15, June 24, 2015, *B*, waypoints 15–25, June 24, 2015, *C*, waypoints 1–15, August 11, 2015, *D*, waypoints 15–25, August 11, 2015, *E*, waypoints 1–15, August 19, 2015, and *F*, waypoints 15–25, August 19, 2015.—Continued

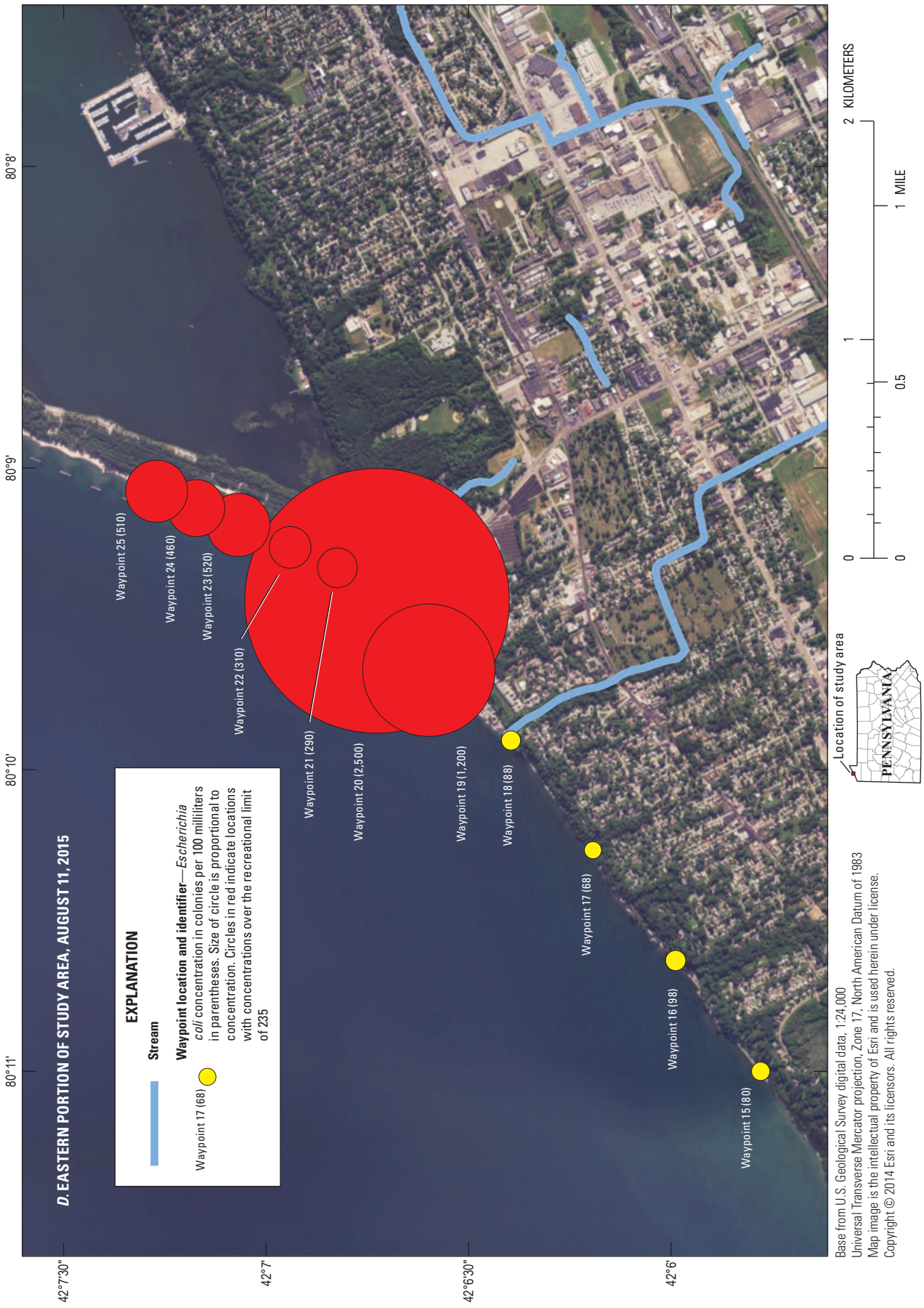
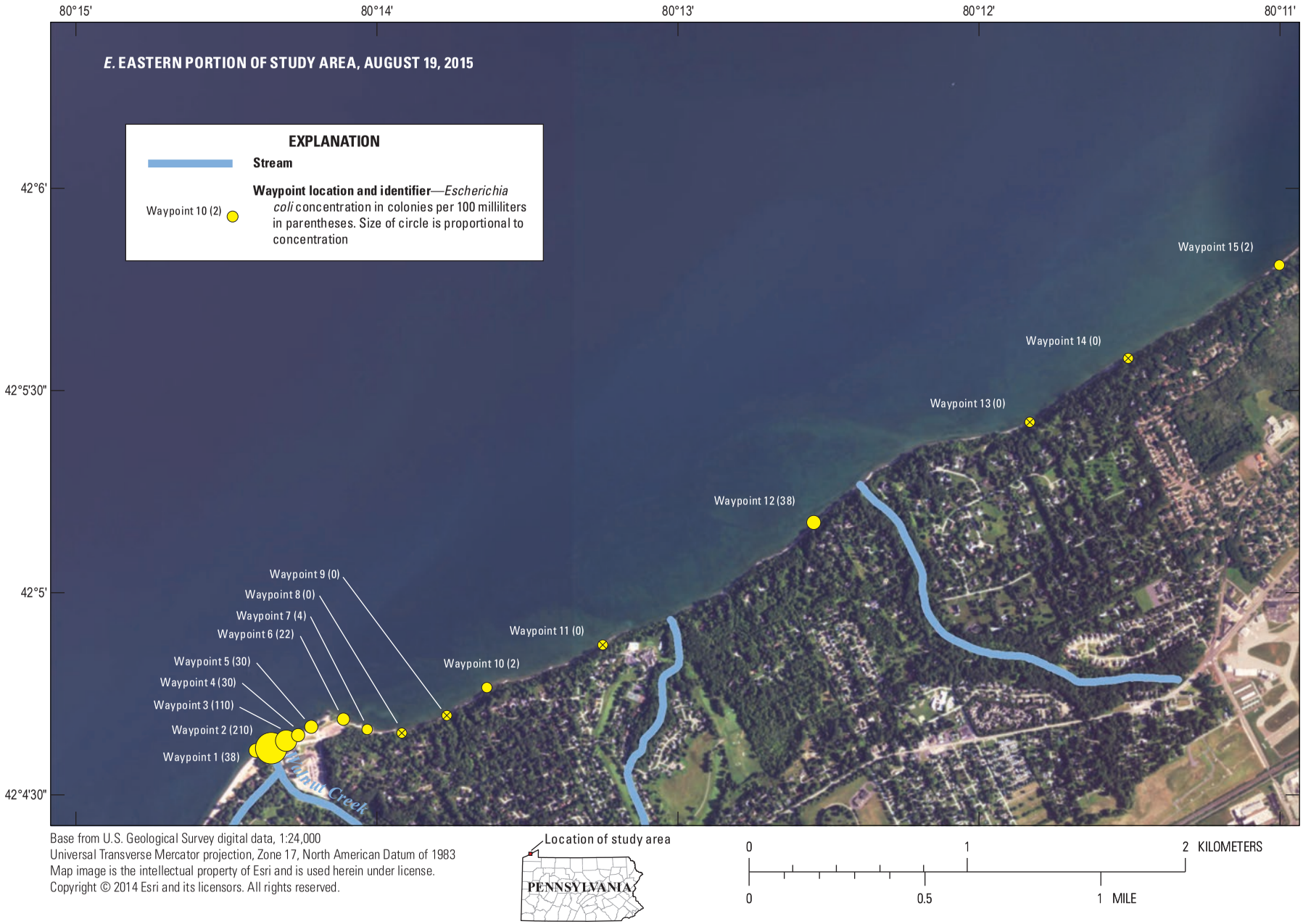


Figure 18. Bacteria counts for *Escherichia coli* in samples collected at nearshore sampling points, Lake Erie study area, Pennsylvania, at *A*, waypoints 1–15, June 24, 2015, *B*, waypoints 15–25, June 24, 2015, *C*, waypoints 1–15, August 11, 2015, *D*, waypoints 15–25, August 11, 2015, *E*, waypoints 1–15, August 19, 2015, and *F*, waypoints 15–25, August 19, 2015.—Continued



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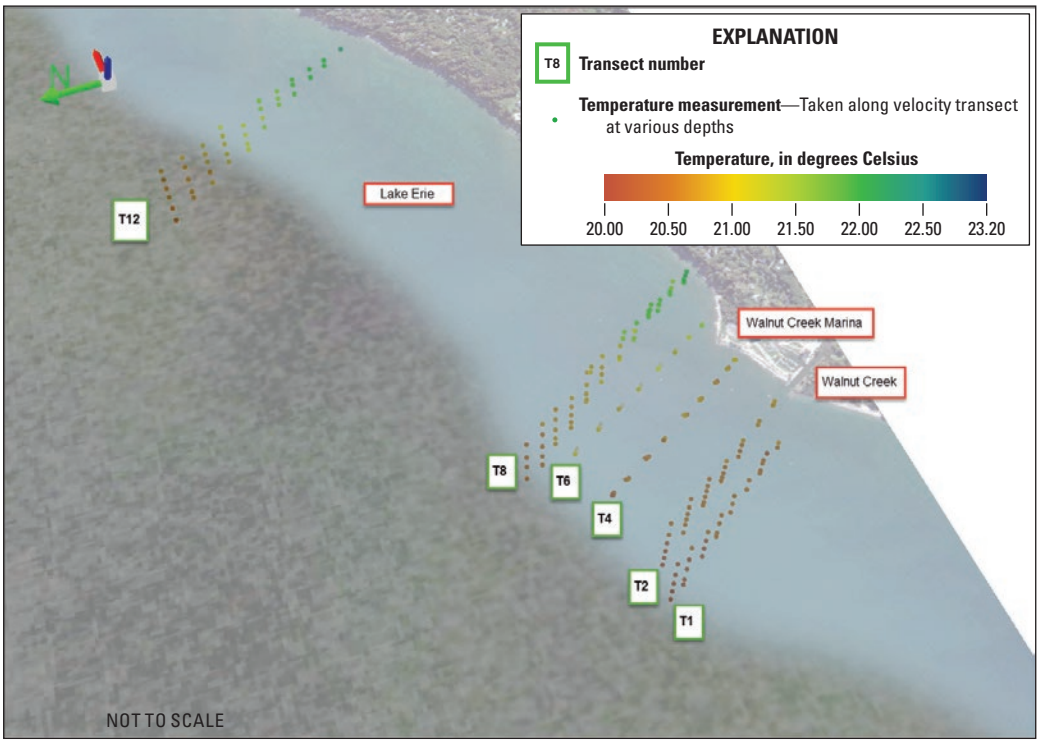
A. **WATER TEMPERATURE ON JUNE 24, 2015, FOR TRANSECTS 1, 2, 4, 6, 8, AND 12**



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B. **WATER TEMPERATURE ON JUNE 24, 2015, FOR TRANSECTS 12, 17, AND 24**

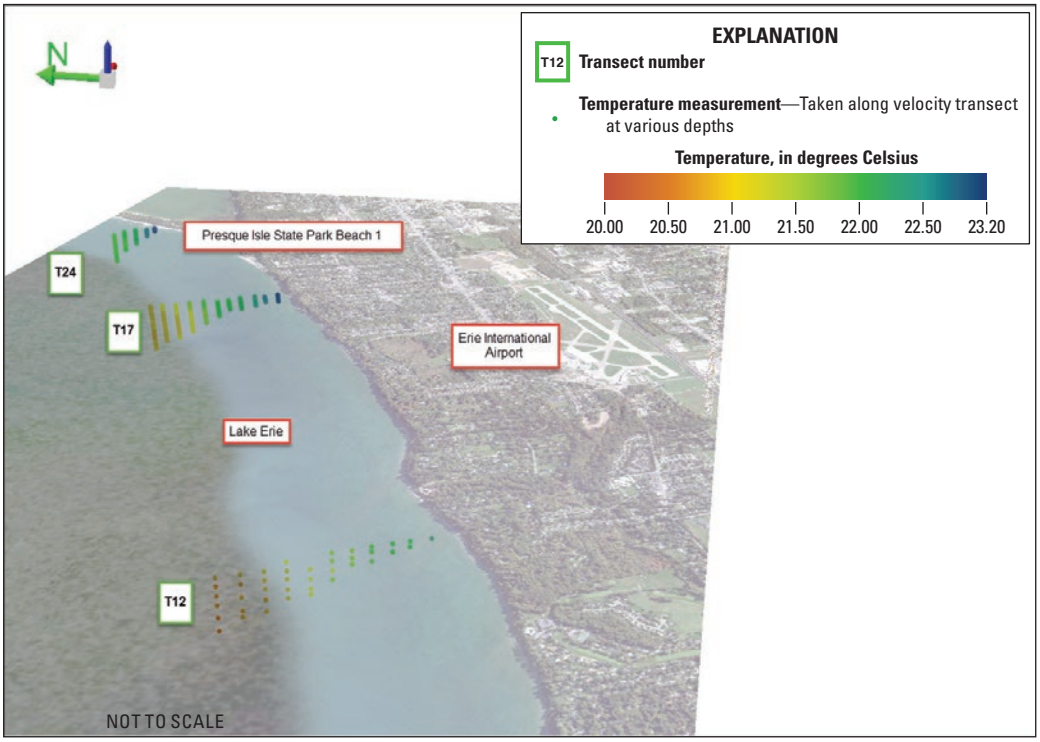

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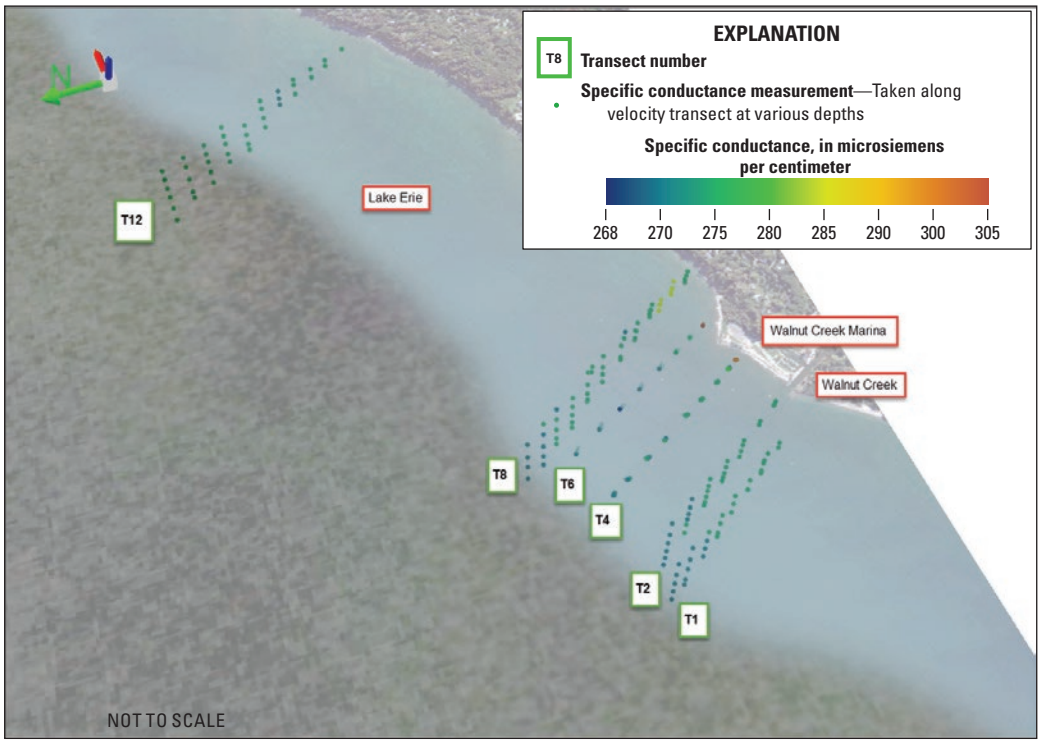
Figure 19. Water-quality surveys along the velocity transects, Lake Erie study area, Pennsylvania, June 24, 2015: *A*, water temperature at transects 1, 2, 4, 6, 8, and 12, *B*, water temperature at transects 12, 17, and 24, *C*, specific conductance at transects 1, 2, 4, 6, 8, and 12, *D*, specific conductance at transects 12, 17, and 24, *E*, turbidity at transects 1, 2, 4, 6, 8,and 12, and *F*, turbidity at transects 12, 17, and 24.

C. **SPECIFIC CONDUCTANCE ON JUNE 24, 2015, FOR TRANSECTS 1, 2, 4, 6, 8, AND 12**



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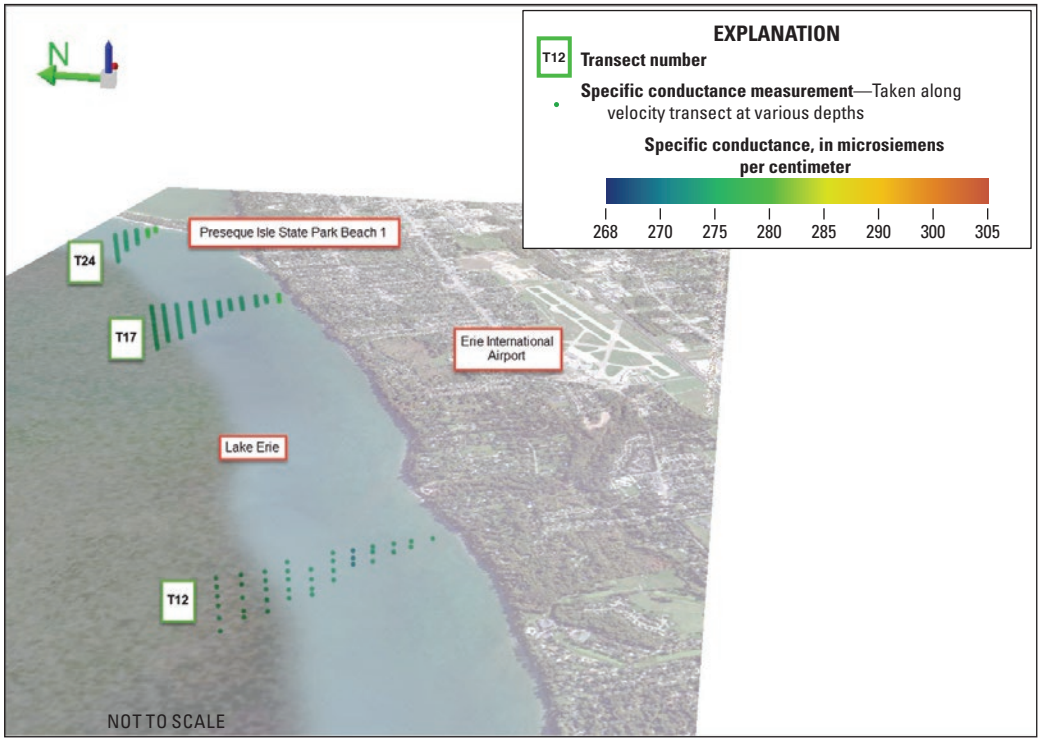
D. **SPECIFIC CONDUCTANCE ON JUNE 24, 2015, FOR TRANSECTS 12, 17, AND 24**



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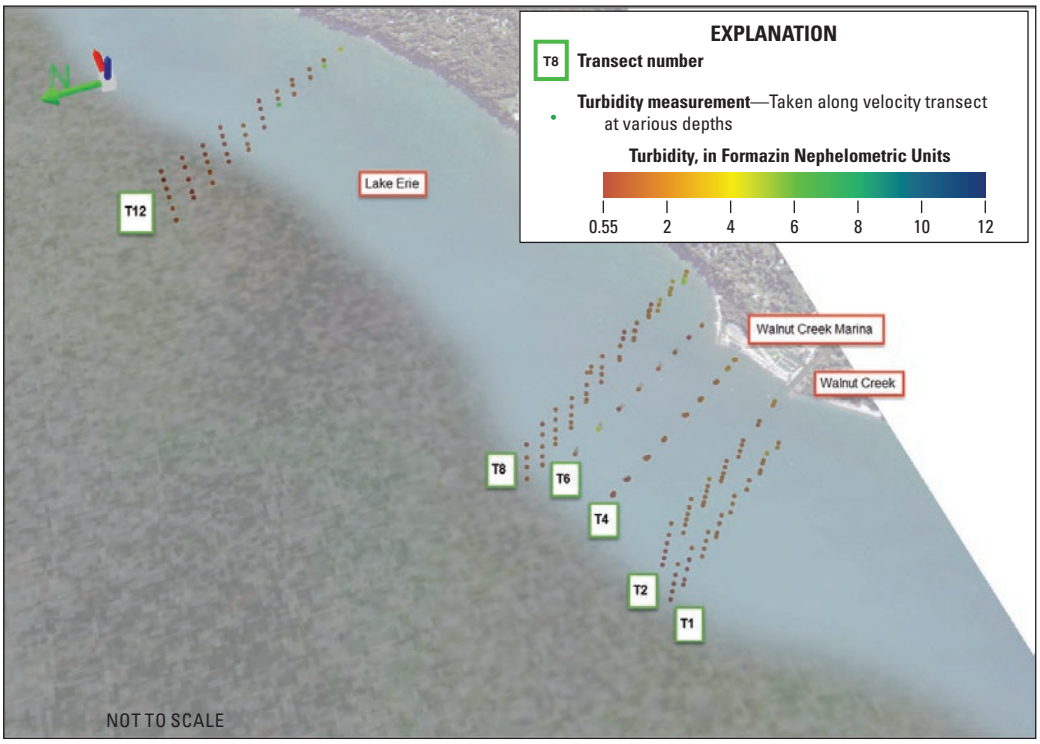
E. **TURBIDITY ON JUNE 24, 2015, FOR TRANSECTS 1, 2, 4, 6, 8, AND 12**



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F. **TURBIDITY ON JUNE 24, 2015, FOR TRANSECTS 12, 17, AND 24**

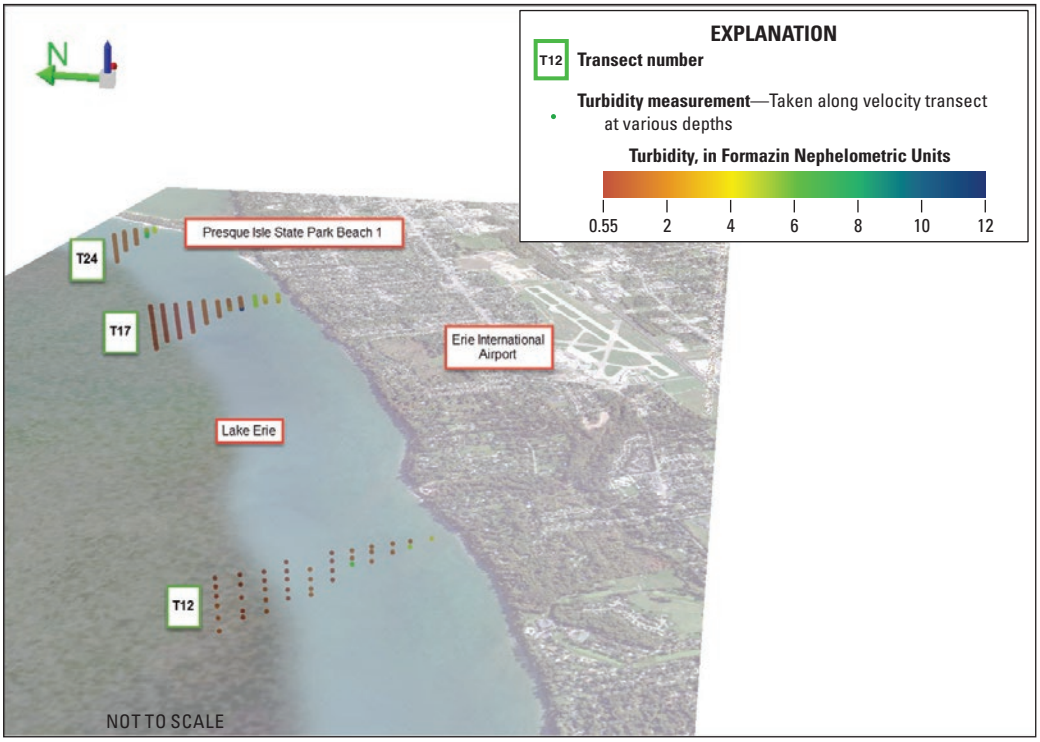

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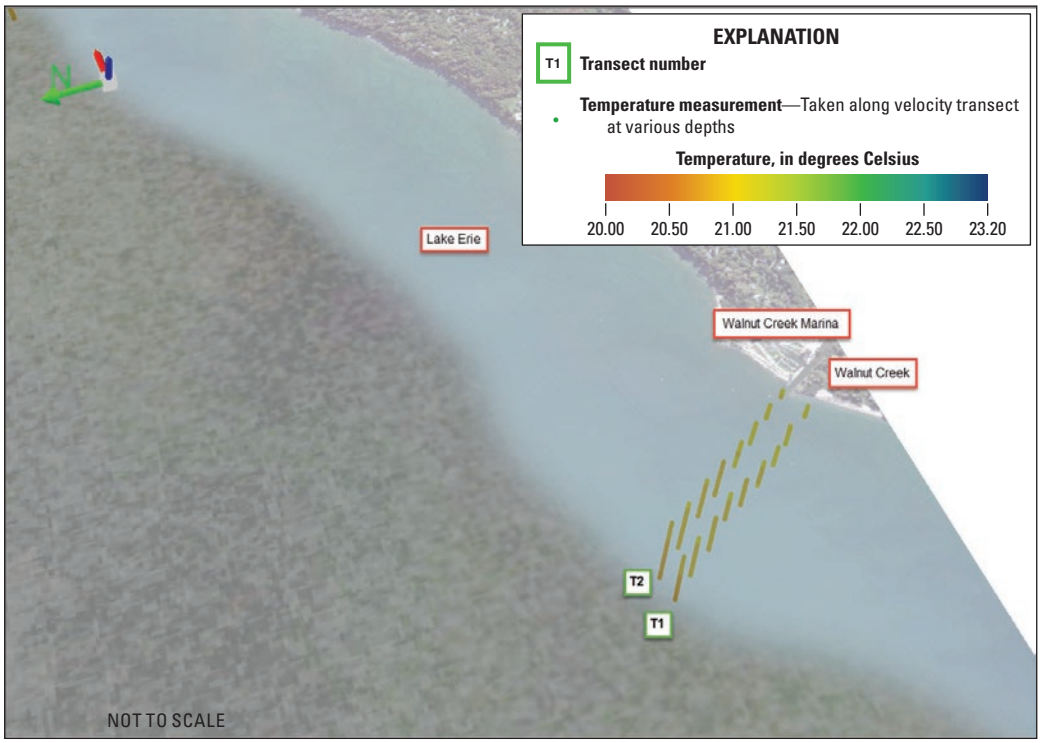
Figure 19. Water-quality surveys along the velocity transects, Lake Erie study area, Pennsylvania, June 24, 2015: *A*, water temperature at transects 1, 2, 4, 6, 8, and 12, *B*, water temperature at transects 12, 17, and 24, *C*, specific conductance at transects 1, 2, 4, 6, 8, and 12, *D*, specific conductance at transects 12, 17, and 24, *E*, turbidity at transects 1, 2, 4, 6, 8,and 12, and *F*, turbidity at transects 12, 17, and 24. —Continued

A. **WATER TEMPERATURE ON JUNE 25, 2015, FOR TRANSECTS 1 AND 2**



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B. **WATER TEMPERATURE ON JUNE 25, 2015, FOR TRANSECTS 14, 18, 22, AND 25**

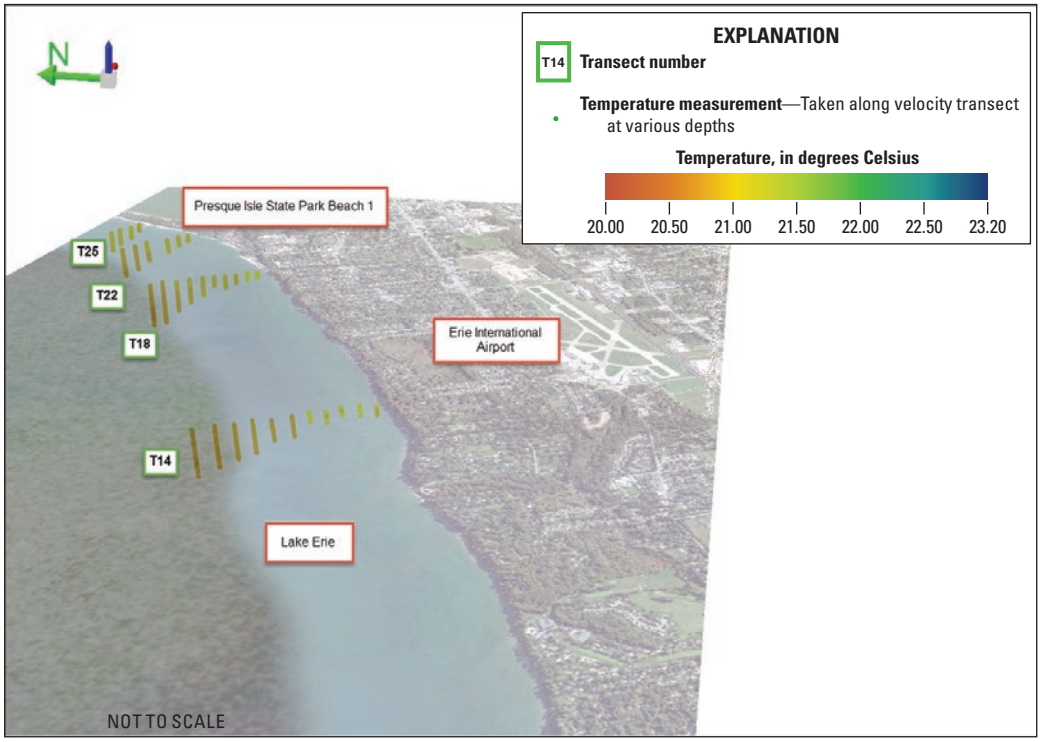

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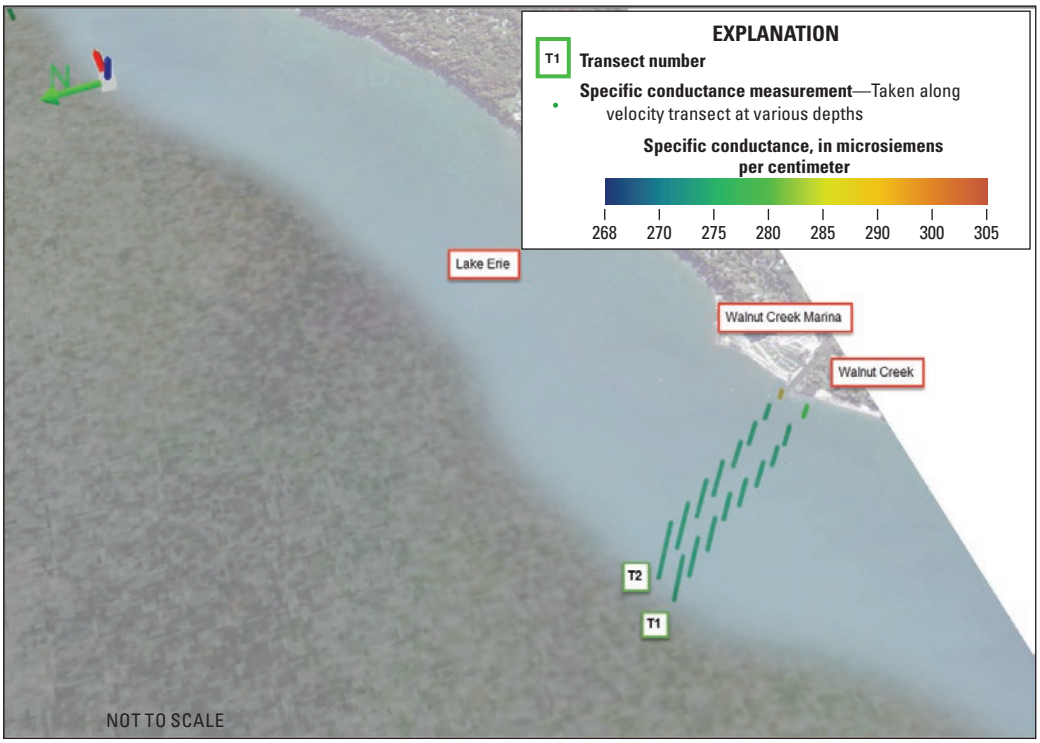
Figure 20. Water-quality surveys along the velocity transects, Lake Erie study area, Pennsylvania, June 25, 2015: *A*, water temperature at transects 1 and 2, *B*, water temperature at transects 14, 18, 22, and 25, *C*, specific conductance at transects 1 and 2, *D*, specific conductance at transects 14, 18, 22, and 25, *E*, turbidity at transects 1 and 2, and *F*, turbidity at transects 14, 18, 22, and 25.

C. **SPECIFIC CONDUCTANCE ON JUNE 25, 2015, FOR TRANSECTS 1 AND 2**



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D. **SPECIFIC CONDUCTANCE ON JUNE 25, 2015, FOR TRANSECTS 14, 18, 22, AND 25**

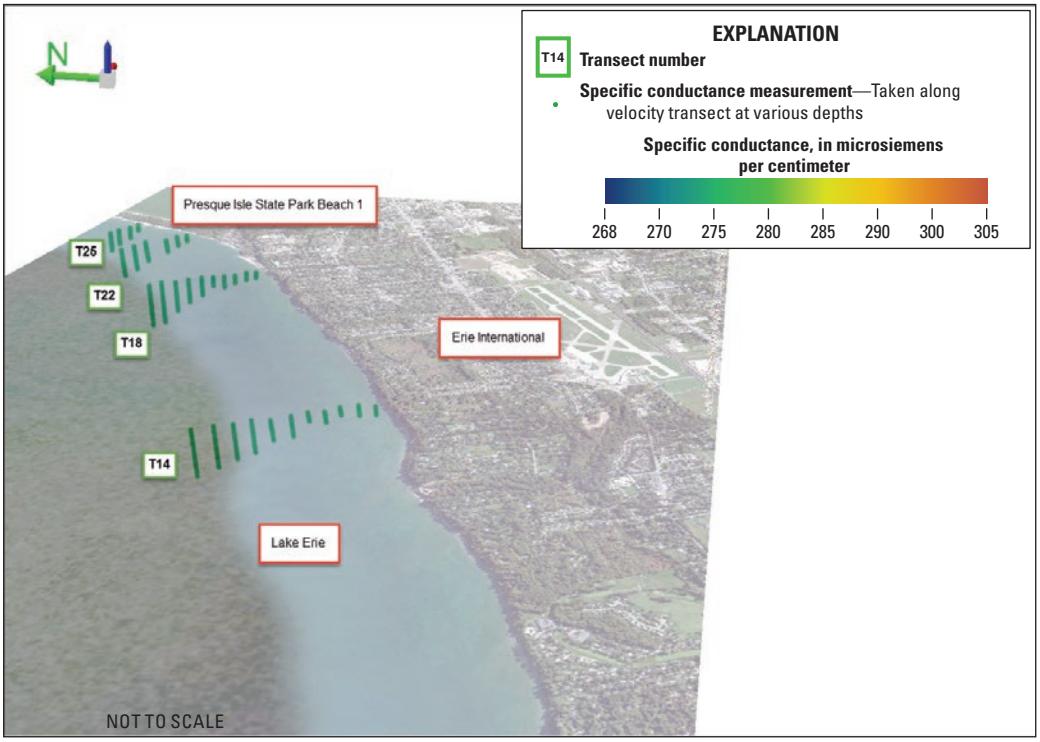

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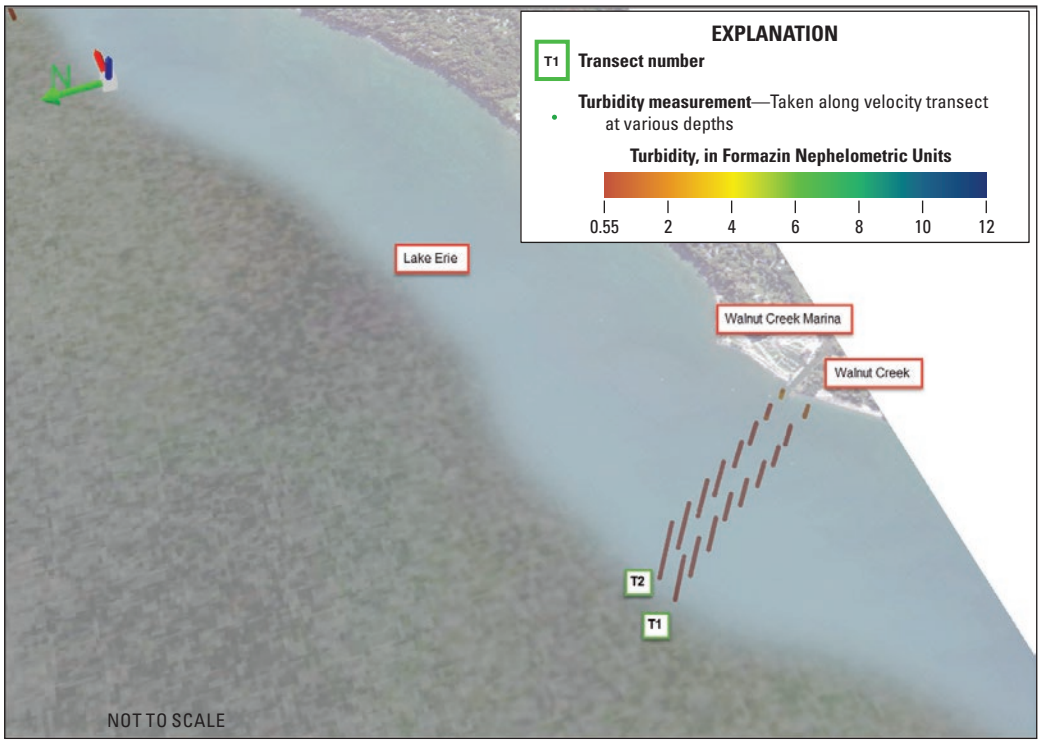
Figure 20. Water-quality surveys along the velocity transects, Lake Erie study area, Pennsylvania, June 25, 2015: *A*, water temperature at transects 1 and 2, *B*, water temperature at transects 14, 18, 22, and 25, *C*, specific conductance at transects 1 and 2, *D*, specific conductance at transects 14, 18, 22, and 25, *E*, turbidity at transects 1 and 2, and *F*, turbidity at transects 14, 18, 22, and 25.—Continued

E. **TURBIDITY ON JUNE 25, 2015, FOR TRANSECTS 1 AND 2**



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F. **TURBIDITY ON JUNE 25, 2015, FOR TRANSECTS 14, 18, 22, AND 25**

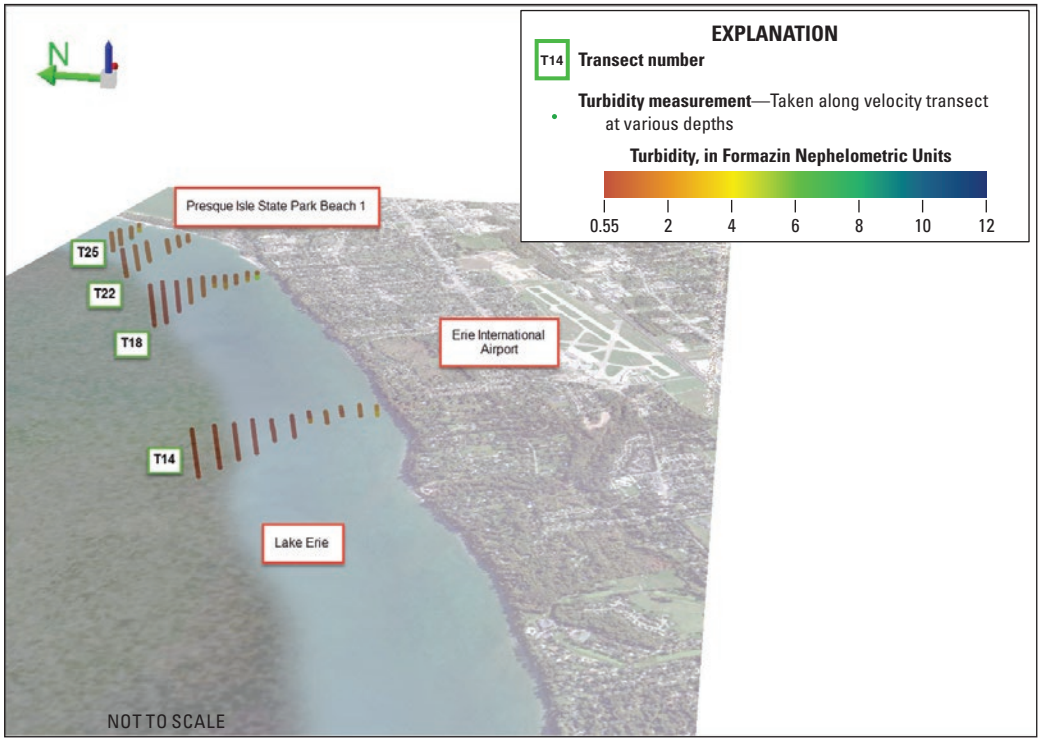

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Figure 20. Water-quality surveys along the velocity transects, Lake Erie study area, Pennsylvania, June 25, 2015: *A*, water temperature at transects 1 and 2, *B*, water temperature at transects 14, 18, 22, and 25, *C*, specific conductance at transects 1 and 2, *D*, specific conductance at transects 14, 18, 22, and 25, *E*, turbidity at transects 1 and 2, and *F*, turbidity at transects 14, 18, 22, and 25.—Continued

Potential for Transport of Contaminants

The potential for transport of contaminants is discussed with a focus on circulation patterns and time of particle travel observed in the lake during the June 24, 2015, synoptic survey (longshore water-current velocity and water-quality data collected); the Walnut Creek water-quality signature; and nearshore bacteria sample results.

Flow Patterns of Discharge from Walnut Creek to Lake Erie

Analysis of flow patterns and time of travel of discharge from Walnut Creek to Lake Erie was focused on the synoptic survey conducted on June 24, 2015, because of the general stability of wind conditions on that date. Similar discussions for the other three synoptic surveys for the 2015 study are not possible because of the amount of change observed in the wind conditions on the other dates.

Development of Flow Path Maps

Visualization of the path a particle can take starting at a particular spot, and the time it takes to complete the path, was accomplished using the ArcMap Spatial Analyst Tool–Groundwater–Particle Track (http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/how-particle-track-works.htm). The particle-tracking algorithm used by the particle track tool employs a predictor–corrector scheme for predicting the future location of a particle on the basis of the local velocity field, as interpolated from the nearest raster cell centers, which is similar to that employed by Konikow and Bredehoeft (1978). The successive locations of the particles are not tied to the resolution or location of the raster cells, so they are free to float through the velocity field. The velocity magnitude and direction rasters were developed from the June 24, 2015, VMT processed transects using the Inverse Distance Weighted (IDW) interpolation technique in ArcMap (http://pro.arcgis.com/en/pro-app/tool-reference/3d-analyst/idw.htm). An IDW interpolation could be problematic when the direction is oriented north and varies between 0 and 360 degrees. However, because the flow is generally to the east, use of this method with this particular dataset was appropriate.

When analyzing the results of the particle tracking tool, some limitations of the results should be considered. Two assumptions are made by the tool when computing the particle tracks. The first assumption is that the particle does not move vertically in the water column, but stays in that part of water where it started. The second assumption is that the conditions within the lake do not change the entire time the particle is moving throughout the path. These assumptions are not necessarily true when analyzing the field data. In addition, velocity direction and magnitude greatly affect the boundaries of the raster map. This implies less confidence can be placed in the particle path near the shore than farther out.

Circulation Patterns

Two maps were created to examine possible flow paths of water from Walnut Creek to Lake Erie on the basis of longshore water-current velocity patterns observed on June 24, 2015. Water that flows from Walnut Creek and stays in the upper 2 m of the lake may go toward the east and be pulled toward shore. The water that stays closest to shore will likely go into the bay east of Walnut Creek and circulate there, as evidenced by the negative velocities seen in transect 8 and the particle path that begins to curve back to the west (fig. 21*A*). If the particle tracking is started before transect number 12, the particle will likely flow toward the east and could eventually reach shore beyond transect 20 (fig. 21*B*). The maps depicting particle tracks in the 2–4 m range provide further evidence for a recirculation just east of Walnut Creek (fig. 22*A*). As the water goes farther from shore, it continues to the east, and unlike the water in the 0–2 m range, it continues past transect 8 until it reaches shore before transect 20 (fig. 22*B*). The bacteria samples collected on June 24, 2015, support the concept of water from Walnut Creek circulating in the area just north of the Walnut Creek Marina (fig. 21). The bacteria counts were much higher in this area than in other areas and consistently decreased in samples collected progressively to the east.

Regarding PISP Beach 1, the flow path of most interest is the one that starts by transect 2 and continues past transect 20 (fig. 21*B*). The total length of this path is 7.1 km, and the time to complete it is 30 hours. The assumption here is that the lake condition does not change over those 30 hours. For the June 24 survey, this is unlikely because the conditions that were measured on June 25 were not the same. Additionally, it is assumed that the particles do not move vertically within the water column. The cross-sectional plots shown in Appendix 1 do show secondary currents implying that this assumption is violated to some degree.

Walnut Creek Water-Quality Signature

An expected outcome of the water-quality surveys was the determination of a water-quality signature of discharge from Walnut Creek to the lake. The specific conductance readings at the Walnut Creek gage were about three times that of the lake water. However, there are two factors that may prevent this signature from being seen in the lake. The first is the approximately 400-m long area in the Walnut Creek Marina where Walnut Creek discharge and Lake Erie water mix. The discharge from Walnut Creek during the survey on June 24, 2015, was approximately 1.42 cubic meter per second (m^3/s). Specific conductance data for transect 2 (just east of Walnut Creek) was not elevated above background values (fig. 19*C*), possibly because measurements were not made close enough to the shore. However, elevated specific conductance values were measured in transects 4 and 6. The circulation pattern described above could allow water from Walnut Creek to circulate in this area north of the Walnut Creek Marina, although potential effects from the marina itself could not be discerned.

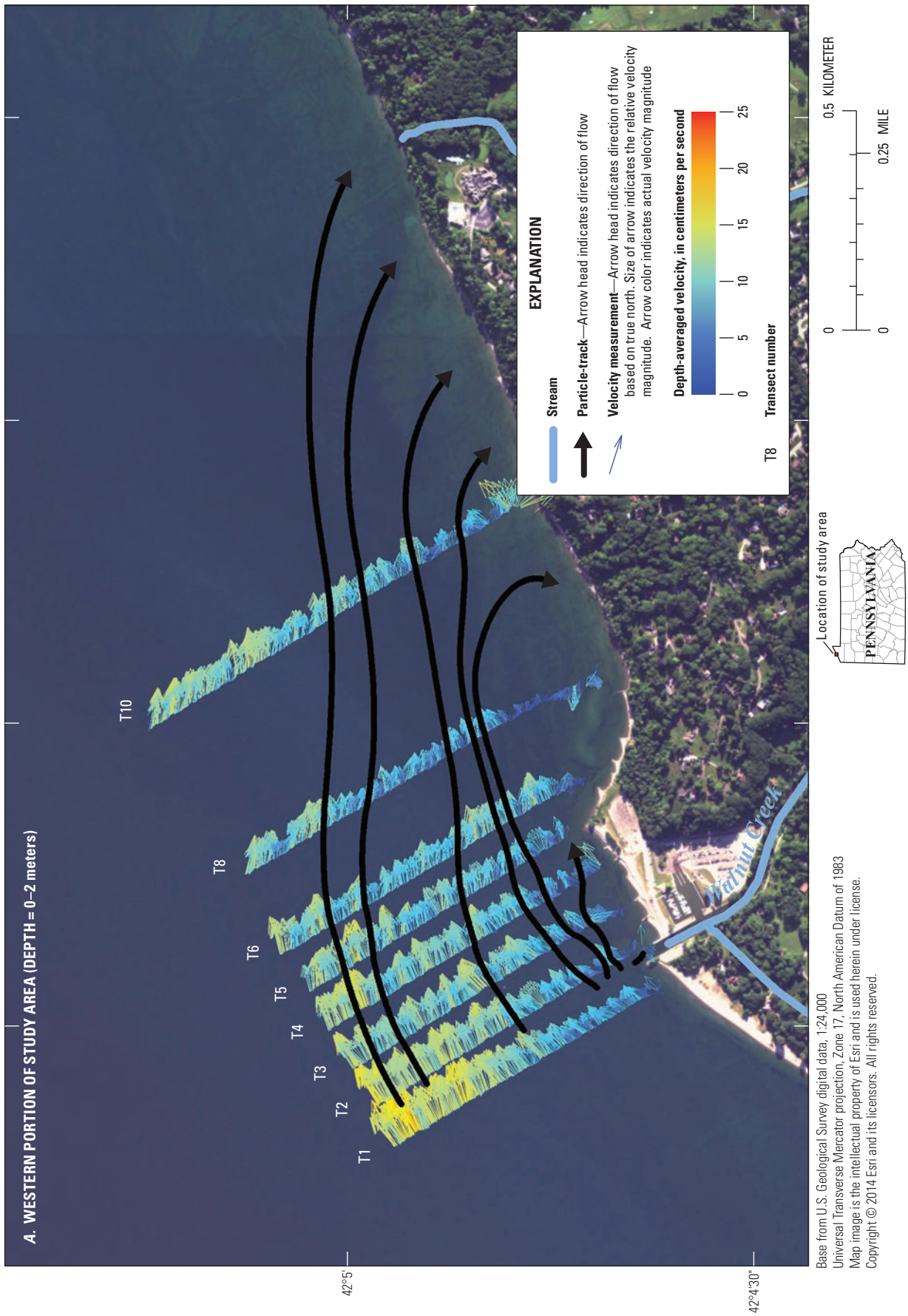
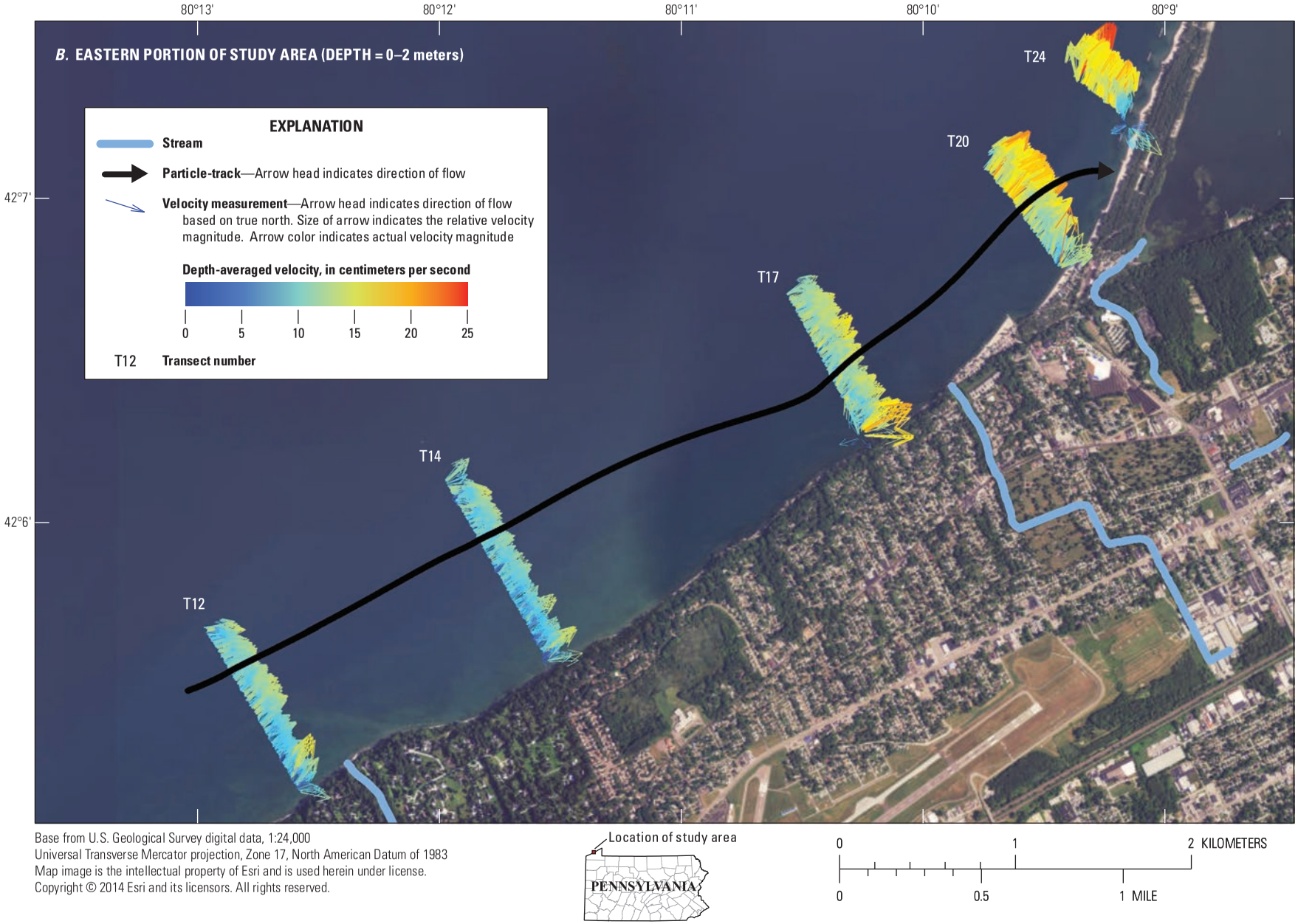


Figure 21. Longshore water velocity and direction from Walnut Creek to Lake Erie study area, Pennsylvania, June and August 2015, *A*, averaged 0–2 meters (m) with particle tracking path overlaid for the western part of the study area, including transects 1–10 and *B*, averaged 0–2 m with particle tracking path overlaid for the eastern part of the study area including transects 12–24.



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 17, North American Datum of 1983
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Figure 21. Longshore water velocity and direction from Walnut Creek to Lake Erie study area, Pennsylvania, June and August 2015, *A*, averaged 0–2 meters (m) with particle tracking path overlaid for the western part of the study area, including transects 1–10 and *B*, averaged 0–2 m with particle tracking path overlaid for the eastern part of the study area including transects 12–24.—Continued

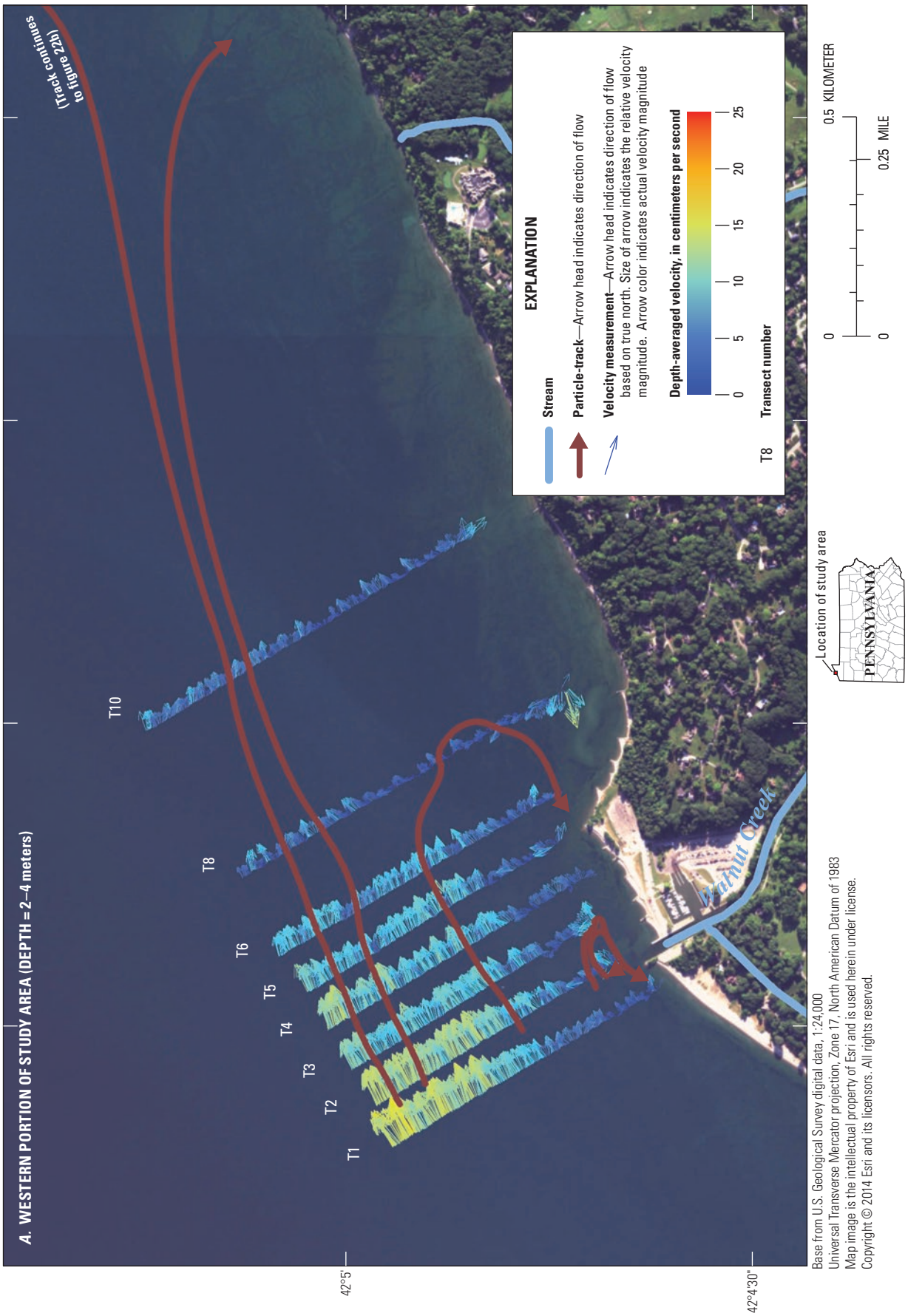
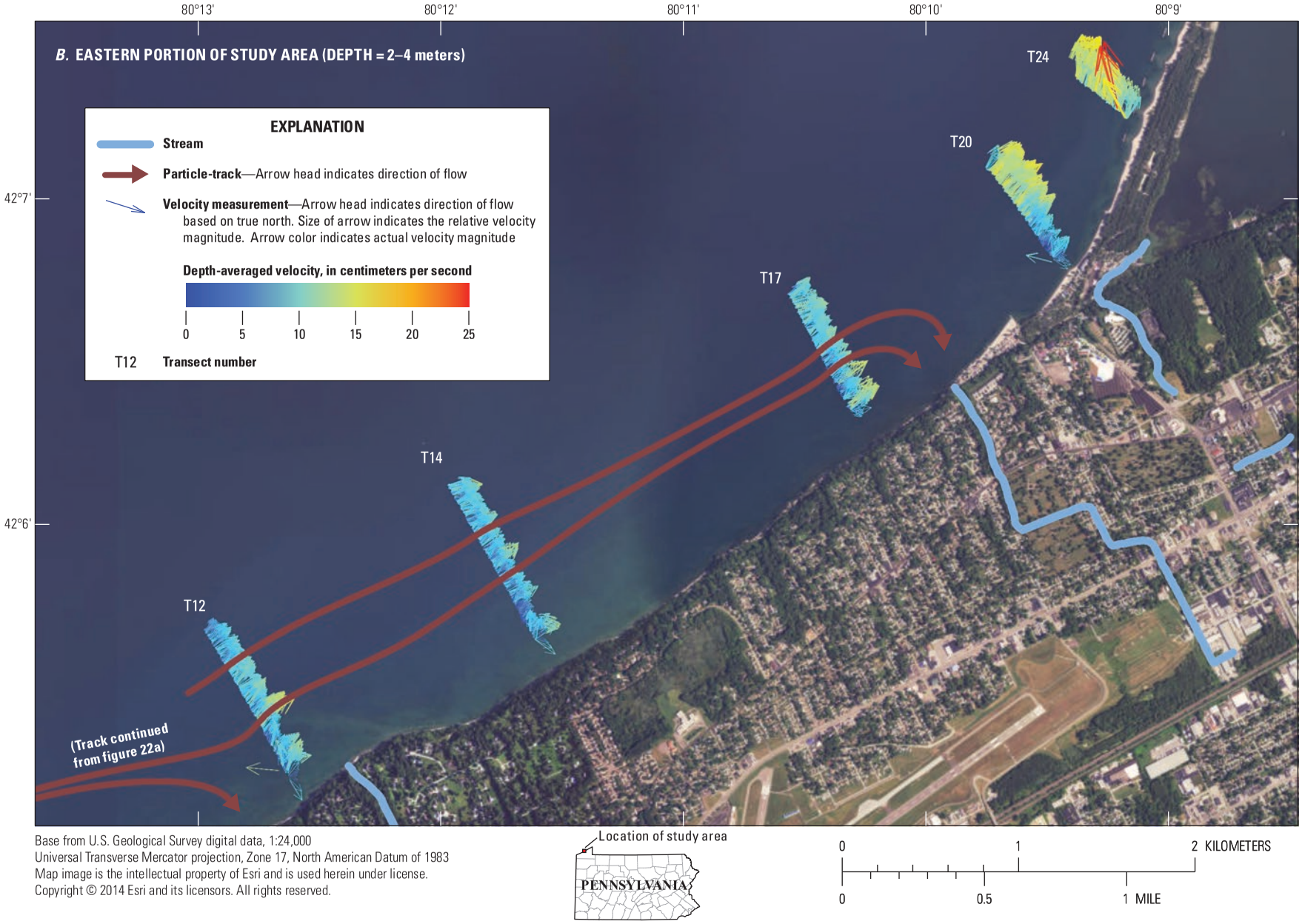


Figure 22. Longshore water velocity and direction from Walnut Creek to Lake Erie study area, Pennsylvania, June and August 2015, *A*, averaged 2–4 meters (m) with particle tracking path overlaid for the western part of the study area, including transects 1–10 and *B*, averaged 2–4 m with particle tracking path overlaid for the eastern part of the study area, including transect 12–24.



Base from U.S. Geological Survey digital data, 1:24,000
Universal Transverse Mercator projection, Zone 17, North American Datum of 1983
Map image is the intellectual property of Esri and is used herein under license.
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Figure 22. Longshore water velocity and direction from Walnut Creek to Lake Erie study area, Pennsylvania, June and August 2015, *A*, averaged 2–4 meters (m) with particle tracking path overlaid for the western part of the study area, including transects 1–10 and *B*, averaged 2–4 m with particle tracking path overlaid for the eastern part of the study area, including transect 12–24.—Continued

Nearshore Water-Quality Samples

Results from the nearshore water-quality samples collected during two of the synoptic surveys and during one storm are described in this section. Samples were collected for *E. coli* bacteria, water temperature, turbidity and suspended sediment (June 24, 2015, and August 11, 2015, only) at points nearshore that coincide with each of the 25 transects. All nearshore sample locations are designated as "waypoints" hereafter.

June 24, 2015

Nearshore water-quality samples were collected on June 24, 2015, after a light rainfall the day before (fig. 6). No sample had *E. coli* bacteria concentrations greater than 235 colony forming units per 100 milliliters (CFU/100 mL), the water-quality threshold for recreational waters; however, the sample collected directly east of Walnut Creek (waypoint 2, fig. 18A) was close to the threshold (220 CFU/100 mL; Hittle, 2016d, http://dx.doi.org/10.5066/F7KP808D). Bacteria concentrations decreased from waypoint 2 to waypoint 9, after which an increase was observed. Turbidity was measured along with the bacteria, and a linear regression for turbidity in relation to bacteria was generated for June 24 (fig. 23). Four outliers were identified at waypoints 2–5 immediately east of Walnut Creek and were not included in the regression. These waypoints are closest to Walnut Creek and could be affected directly by the small event the day before. The other waypoints (1, 6–25) included in the regression may not be directly affected by Walnut Creek owing to the small amount of discharge and circulation patterns observed. Waypoint 13 was included in the regression but identified as a potential outlier, although the reason for this outlier could not be determined (fig. 23). This analysis is confirmation of past research at Presque Isle State Park that has shown a strong relation between turbidity and *E. coli* (Zimmerman, 2006, 2008; Francy and others, 2013).

A similar analysis was conducted using the SSC data instead of turbidity (fig. 24). A relation between *E. coli* count and SSC with grain size less than 0.125 micrometers (µm) was determined, but there were four outliers. Two of the outliers represent points immediately east and west of Walnut Creek (waypoints 1 and 2). The other two outliers represent waypoints 13 and 18. For waypoint 18, the SSC was at least twice as high as that for the other samples, and the relation between SSC and turbidity was much different than that for other samples (fig. 25). No explanation as to why waypoint 13 is an outlier could be determined from available data. Regression statistics are presented in Appendix 2.

August 11, 2015

Nearshore water-quality samples were scheduled for collection on August 11, 2015, because a large storm was predicted to hit the area on August 10, 2015. The storm did materialize but with less precipitation than anticipated. The maximum discharge from Walnut Creek was 1.13 m^3/s (40 ft^3/s), but it occurred just 5 hours before sampling started. The result was high bacteria concentrations (> 235 CFU/100mL) in samples collected just east of Walnut Creek. Concentrations decreased until waypoints 8 and 9 (fig. 18C). The next high concentration (> 235 CFU/100mL) occurred at waypoints 19 and 20. All waypoints to the east (waypoints 21–25) had bacteria concentrations greater than 235 CFU/100 mL (fig. 18D).

The wind conditions that occurred before and during the nearshore water-quality sampling were not observed on the 4 days when velocity magnitude and direction data were collected by boat during the transect surveys, thus there is no indication of lake circulation on August 11, 2015, except for the wave direction recorded at the Nearshore Buoy (fig. 8). Observations made by the collectors include comments about wave heights of 1–2 feet higher than had been experienced on June 24, 2015. Considering the low bacteria concentrations (<235 CFU/100mL) measured west of waypoint 19, and the higher counts at waypoint 19 and further west, further investigation is needed to examine the bacteria loads at these sites and the effects on the beaches in the area.

E. coli bacteria, turbidity, and suspended sediment data were analyzed for this day. No relation between these variables could be determined from the available data. This could be due to high waves that prevented sampling at the same distance from shore at all sampling points and contributed to the generally higher amount of sand in the samples collected on August 11 than on June 24.

August 19, 2015

Bacteria samples were collected on August, 19, 2015, the day after a rainfall occurred in the area. As on June 24, the only sample to come back with *E. coli* concentrations near 235 CFU/100 mL was the waypoint directly east of Walnut Creek (waypoint 2). Concentrations of *E. coli* bacteria steadily decreased eastward. An anomalously high bacteria count was observed at waypoint 20 (140 CFU/100 mL), but the count was well below the recreational limit of 235 CFU/100 mL. Circulation, based upon transect 2, measured in the afternoon indicates that most of the water from Walnut Creek was forced to the east, whereas the water farthest from shore continued in a west to east direction (Appendix 1, fig. 1-44).

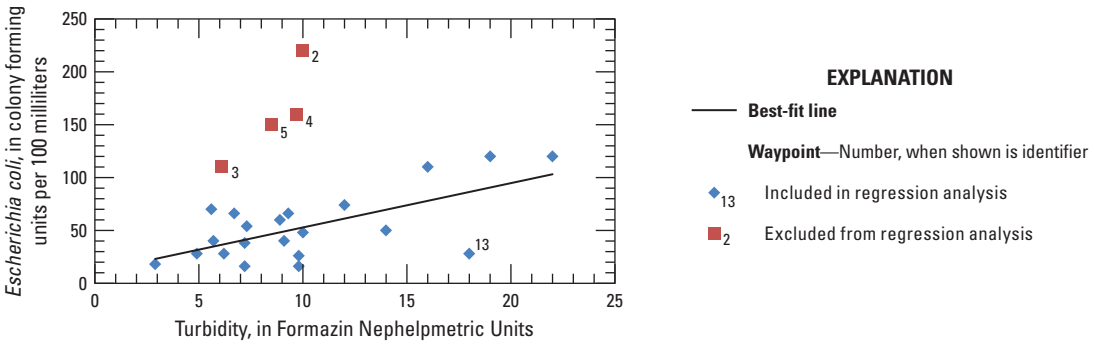

Figure 23. Relation between turbidity and *Escherichia coli* bacteria in samples collected from Lake Erie study area, Pennsylvania, June 24, 2015, excluding the four samples closest to Walnut Creek. Waypoint 13 is included in the regression but labeled for reference.

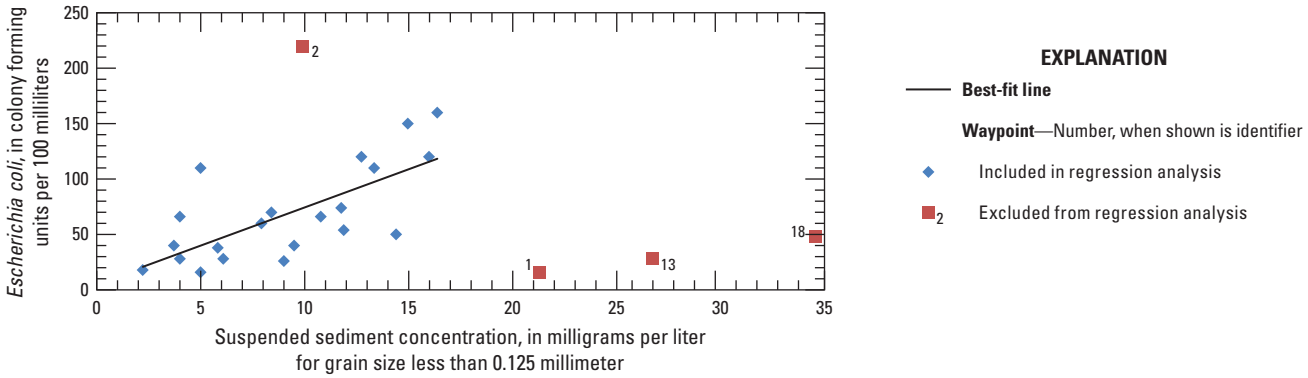

Figure 24. Relation between suspended sediment concentration less than 0.125 millimeter and *Escherichia coli* bacteria in samples collected from Lake Erie study area, Pennsylvania, June 24, 2015, with waypoints 1, 2, 13, and 18 excluded from the regression.

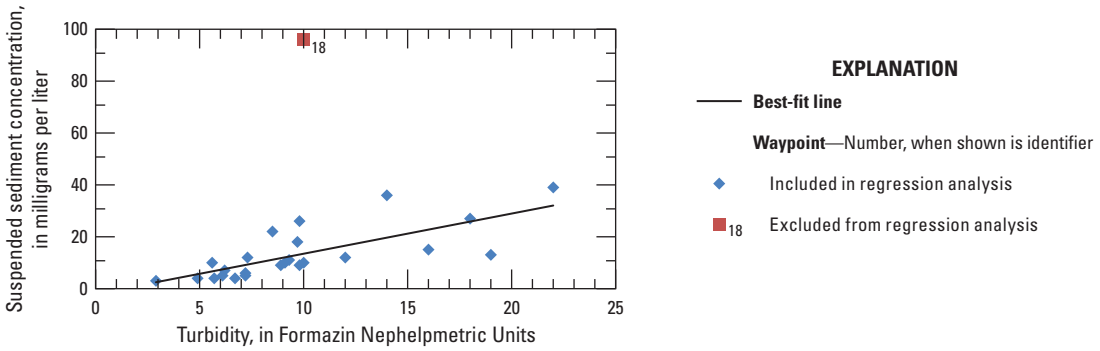

Figure 25. Relation between turbidity and suspended sediment in samples collected from Lake Erie study area, Pennsylvania, June 24, 2015, with waypoint 18 excluded from the regression.

Future Studies

When further work is done in this area, some changes could be made to the sampling strategy to decrease the amount of noise seen in the low velocity transects. The setup of the Acoustic Doppler Current Profiler (ADCP) could be changed to use a 1,200-kilohertz (kHz) ADCP in the shallow depths and continue to use a 600 kHz ADCP in the deeper water. This would allow the bin size to be increased, decreasing the standard deviation but getting closer to nearshore. Additionally, a smaller boat is needed to gather data closer to shore in shallow depths. The large boat used for the velocity surveys prevented data collection in depths less than 2.5 m. Data on velocity magnitude and direction for water currents collected from a small boat could confirm eddies seen in some areas and provide more information on the currents affecting the distribution of bacteria.

As evidenced by the rapidly changing conditions observed during the surveys, any future work in the area is best accomplished in as small an area as possible, or multiple boats may be needed to cover a large area in short time. Instrumentation that collects not only surface wave direction but velocity in the entire water column would be useful in the study area to quantify the changing conditions. Water velocity and direction surveys like those described herein could be accomplished while the instrumentation is collecting data. A relation between the instrument collected data and the survey data could be developed so the data at one point could provide an idea of the conditions in the entire study area. Models have been developed that can predict changing conditions, but the models are only available up to 3 days beforehand. Performing this work during steady conditions could improve the overall quality of the results.

Summary and Conclusions

The U.S. Geological Survey conducted synoptic surveys in cooperation with Pennsylvania Sea Grant to determine the potential for contaminant transport in Lake Erie from Walnut Creek to Presque Isle, Pennsylvania. Data were collected in Lake Erie to obtain a snapshot of the direction and velocity magnitude of nearshore water currents, nearshore water quality, and shoreline bacteria on June 24, June 25, August 11, August 18, and August 19, 2015. All data collection efforts were not accomplished each day. These snapshots do not tell the complete story of the lake, as evidenced by the changing velocity magnitude and direction seen on two consecutive days (June 24 and June 25) and between the surveys conducted in June and August. On the basis of the wind and wave data before and during the survey on June 24, the flow from Walnut Creek into the lake can be described. Using the spatial analysis tool, particle track, within ArcMap, potential flow paths were developed for a particle starting out in various positions within the lake. Most particle tracks show that a particle starting out from Walnut Creek will circulate in the area just east of the Walnut Creek Marina. One track shows it is possible for a particle to travel from Walnut Creek to Presque Isle State Park (PISP) Beach 1 in about 30 hours. However, the assumption incorporated into the tool is that the circulation pattern does not change over the 30 hours. This is unrealistic given the water velocity and direction measured the next day. However, changing weather conditions before and during the other surveys prevents any conclusions for the other survey days.

Water-quality sampling on June 24, 2015, provides evidence of circulation on this day. Specific conductance elevated above background conditions east of Walnut Creek indicates that water from Walnut Creek could be recirculating there. Additionally, the nearshore bacteria samples collected on June 24 support the hypothesis that water from Walnut Creek is recirculating in the area just north of the Walnut Creek Marina. The *Escherichia coli* (*E. coli*) bacteria counts were much higher in this area than at waypoints to the east.

The nearshore water-quality samples collected in August show a consistent pattern of higher *E. coli* counts close to Walnut Creek and lower counts farther east. A relatively high concentration of *E. coli* bacteria concentration (140 colony forming units per 100 milliliters) was measured at waypoint 20 close to Presque Isle State Park Beach 1, but this study does not attempt to address other potential sources of bacteria that may affect the Presque Isle beaches.

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Appendixes 1–2

Appendix 1. Velocity Mapping Toolbox Depictions of Transect Cross-Sections Showing Velocity Magnitude and Direction of Water Currents

Figures 1-1 to 1-58 show screenshots of the Velocity Mapping Toolbox (VMT) cross-section view renderings of transects measured on June 24, 25, August 18, and 19, 2015. The vertical axis is depth below water surface, in meters, and the horizontal axis is distance, in meters, in the cross-section. The distances shown are relative to the transect itself, not the shoreline. Velocity magnitude is measured perpendicular to the cross-section and is represented by the color scale. The arrow within the figures represents the velocity magnitude and direction of the water parallel to the cross-section and in the vertical direction. An arrow representing 10 centimeters per second is shown as a reference. (m, meter; cm/s, centimeters per second)

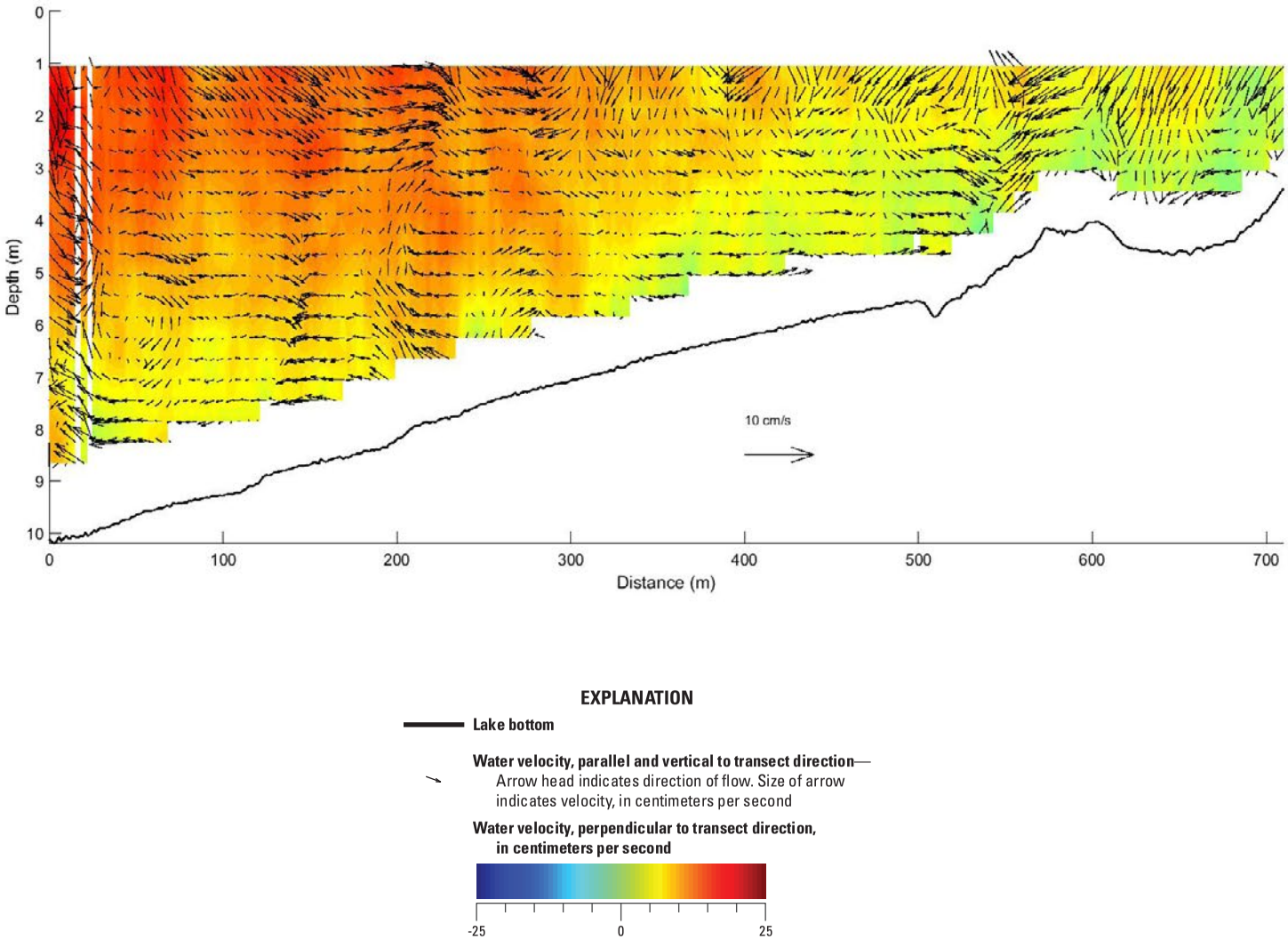


Figure 1-1. Transect 1, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

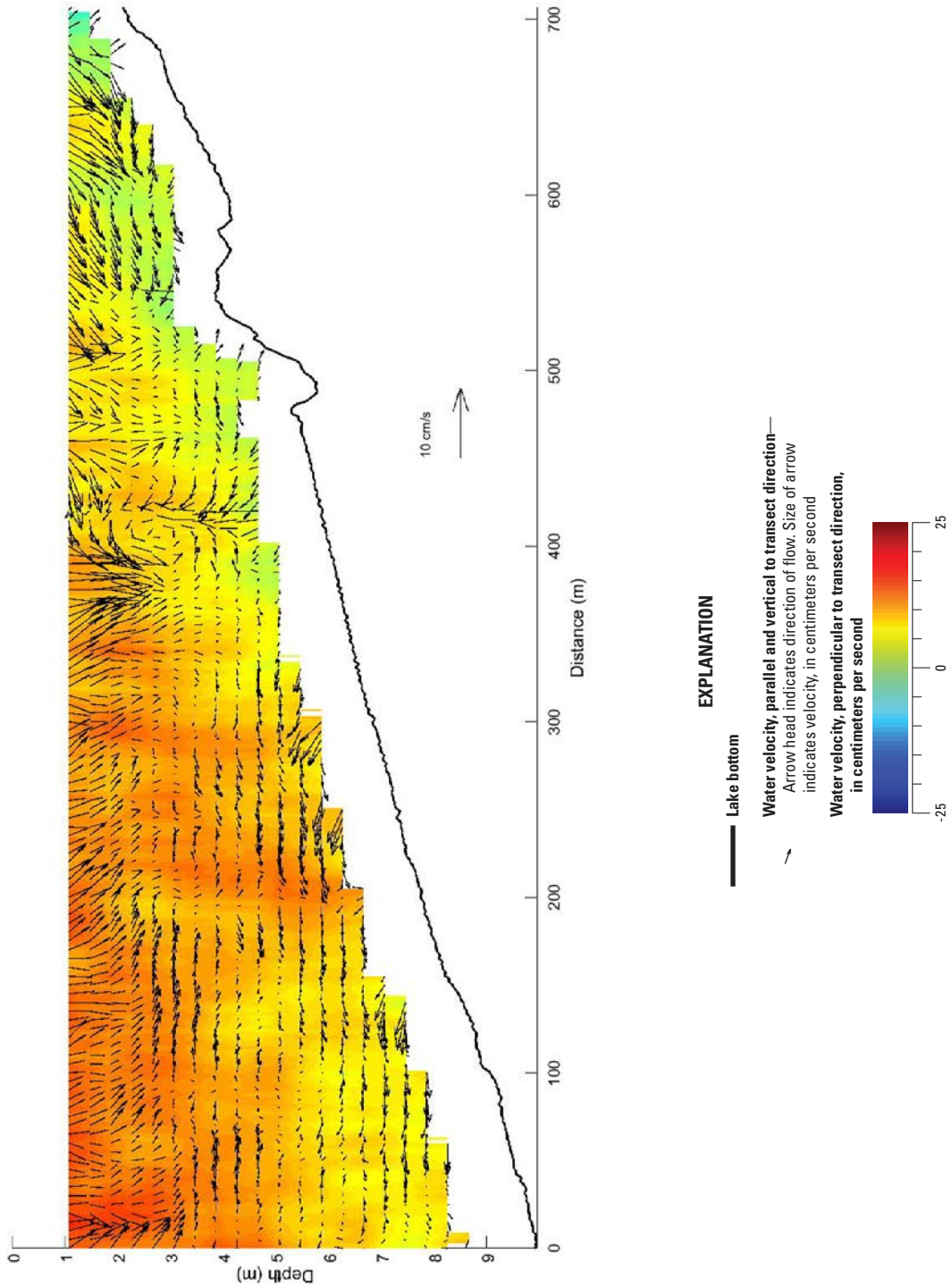
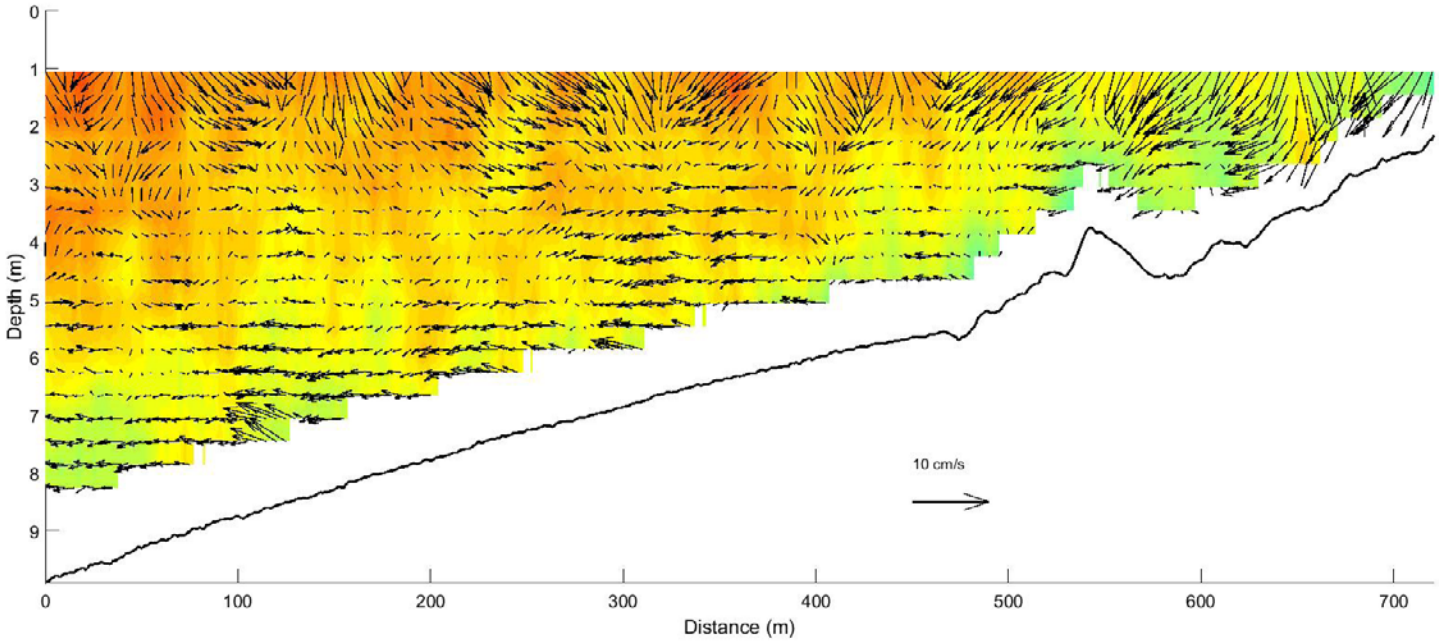


Figure 1-2. Transect 2, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

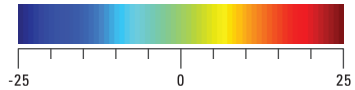


Figure 1-3. Transect 3, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

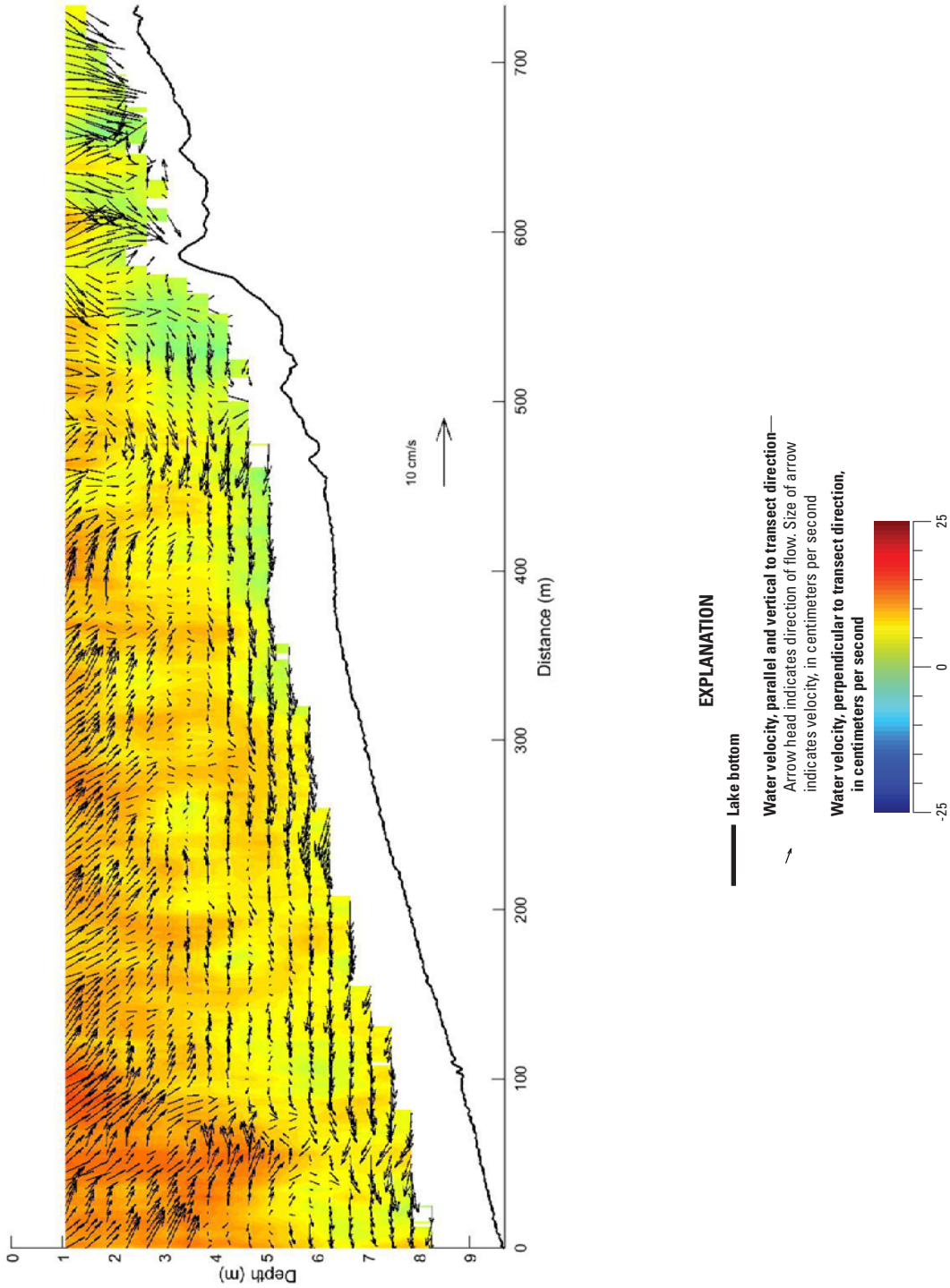


Figure 1-4. Transect 4, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

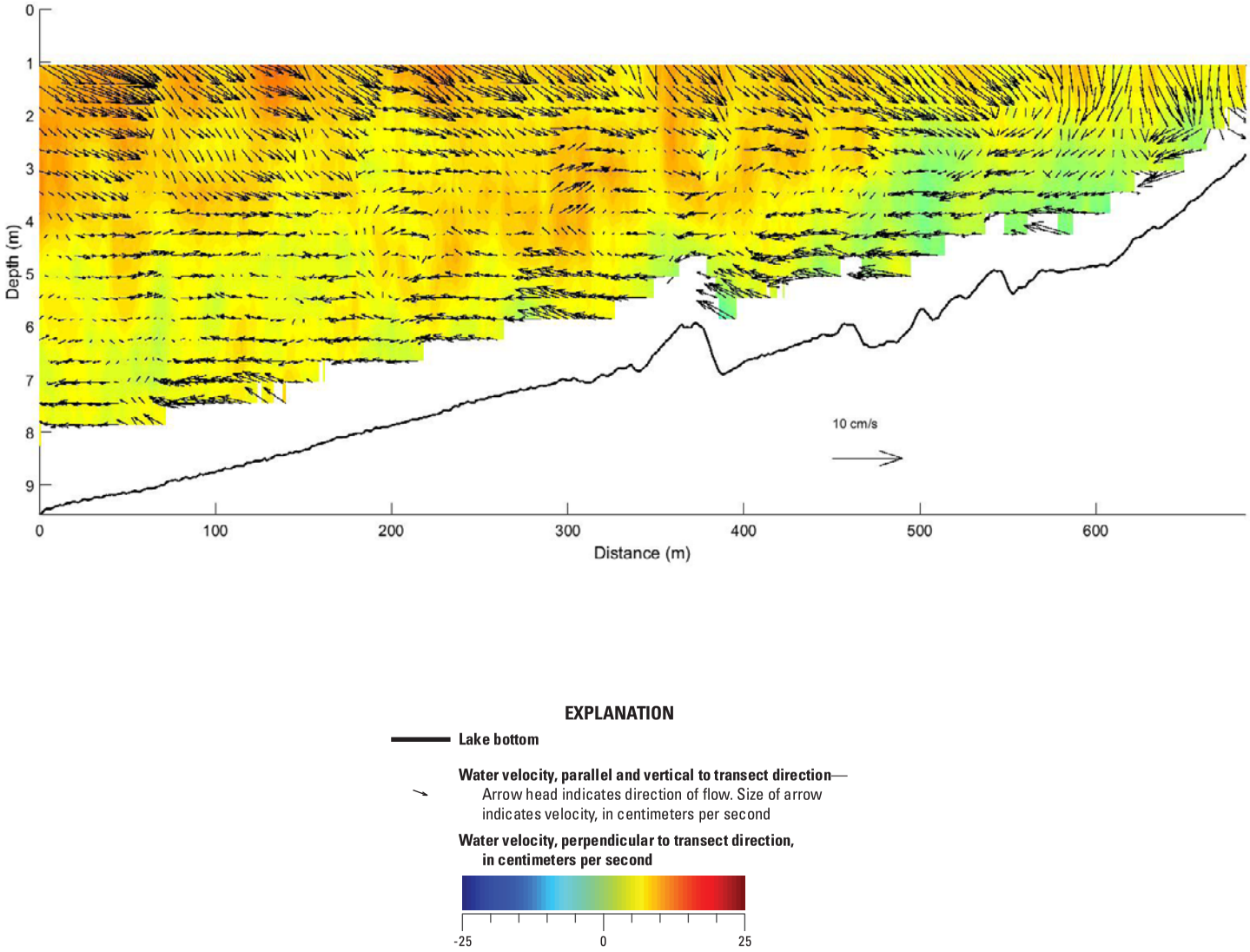


Figure 1-5. Transect 5, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

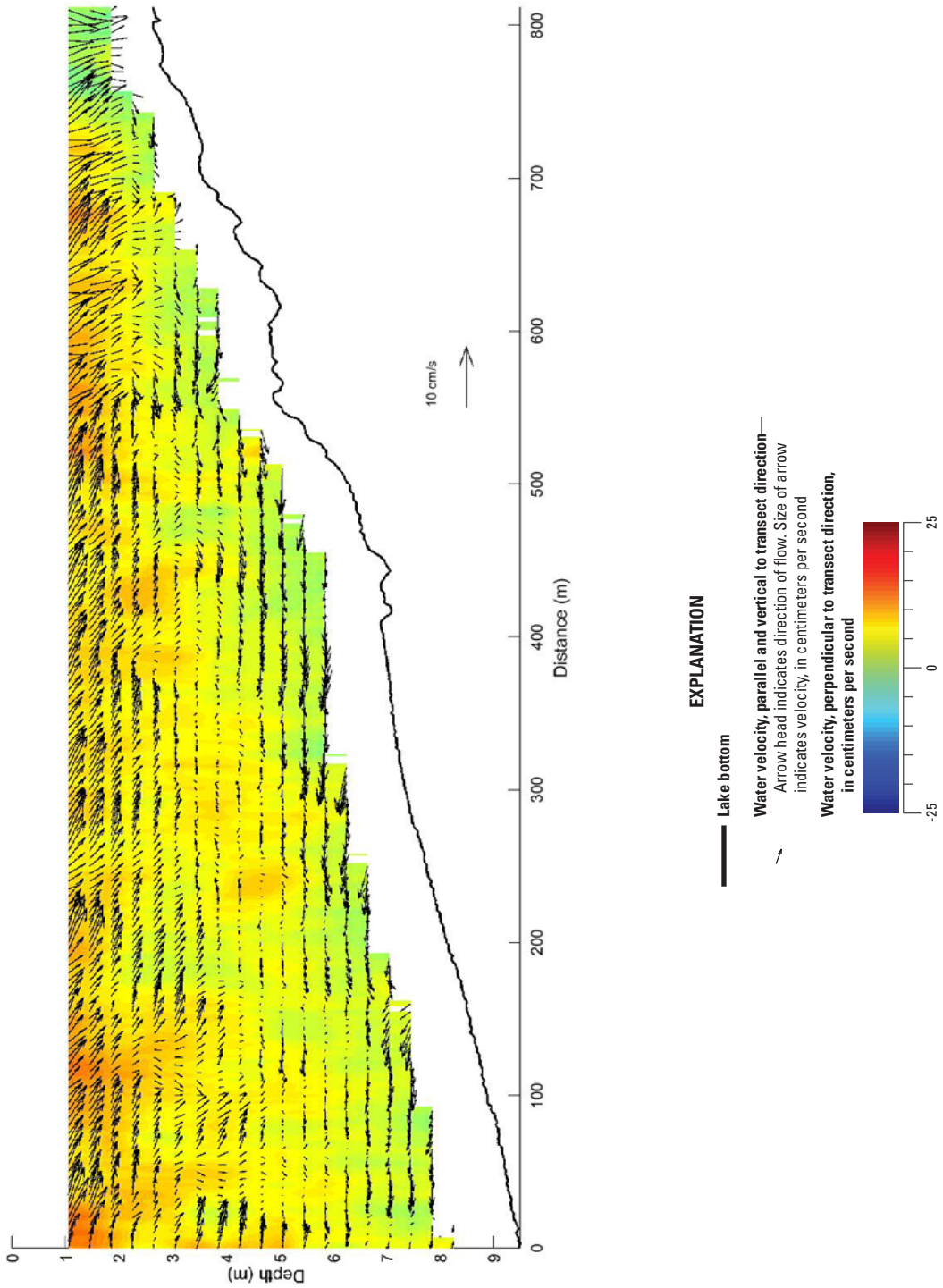


Figure 1-6. Transect 6, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

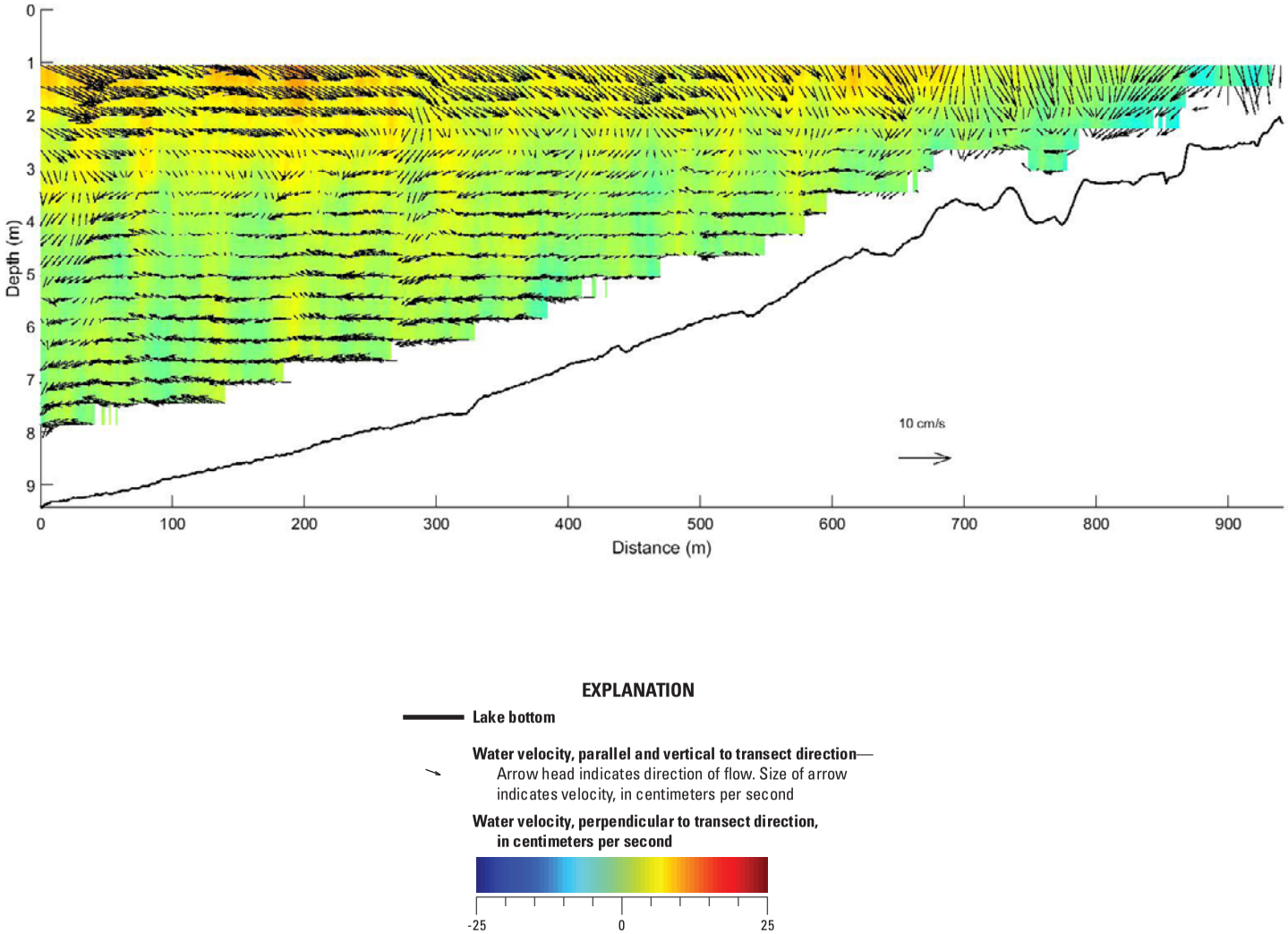


Figure 1-7. Transect 8, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

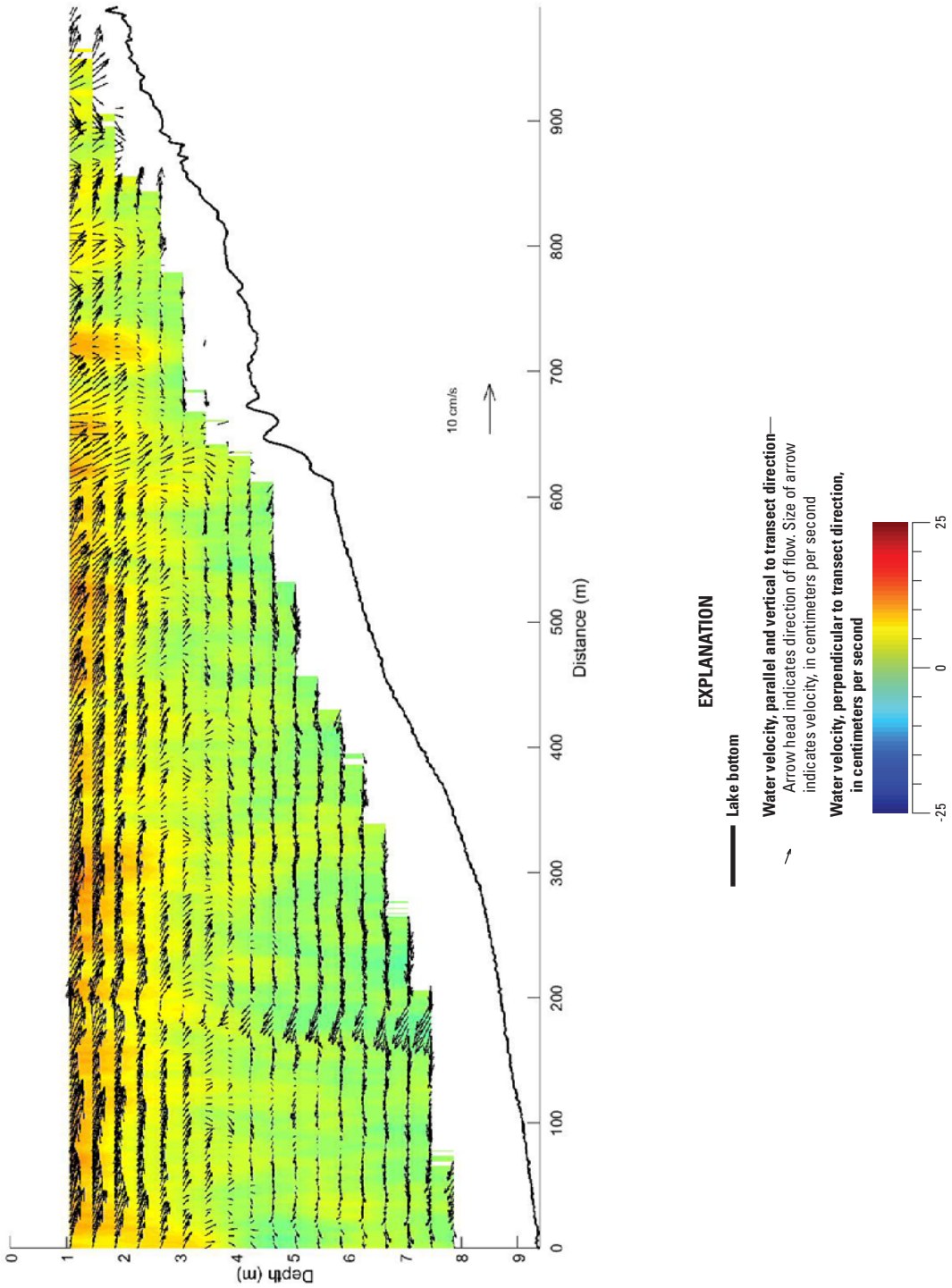


Figure 1-8. Transect 10, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

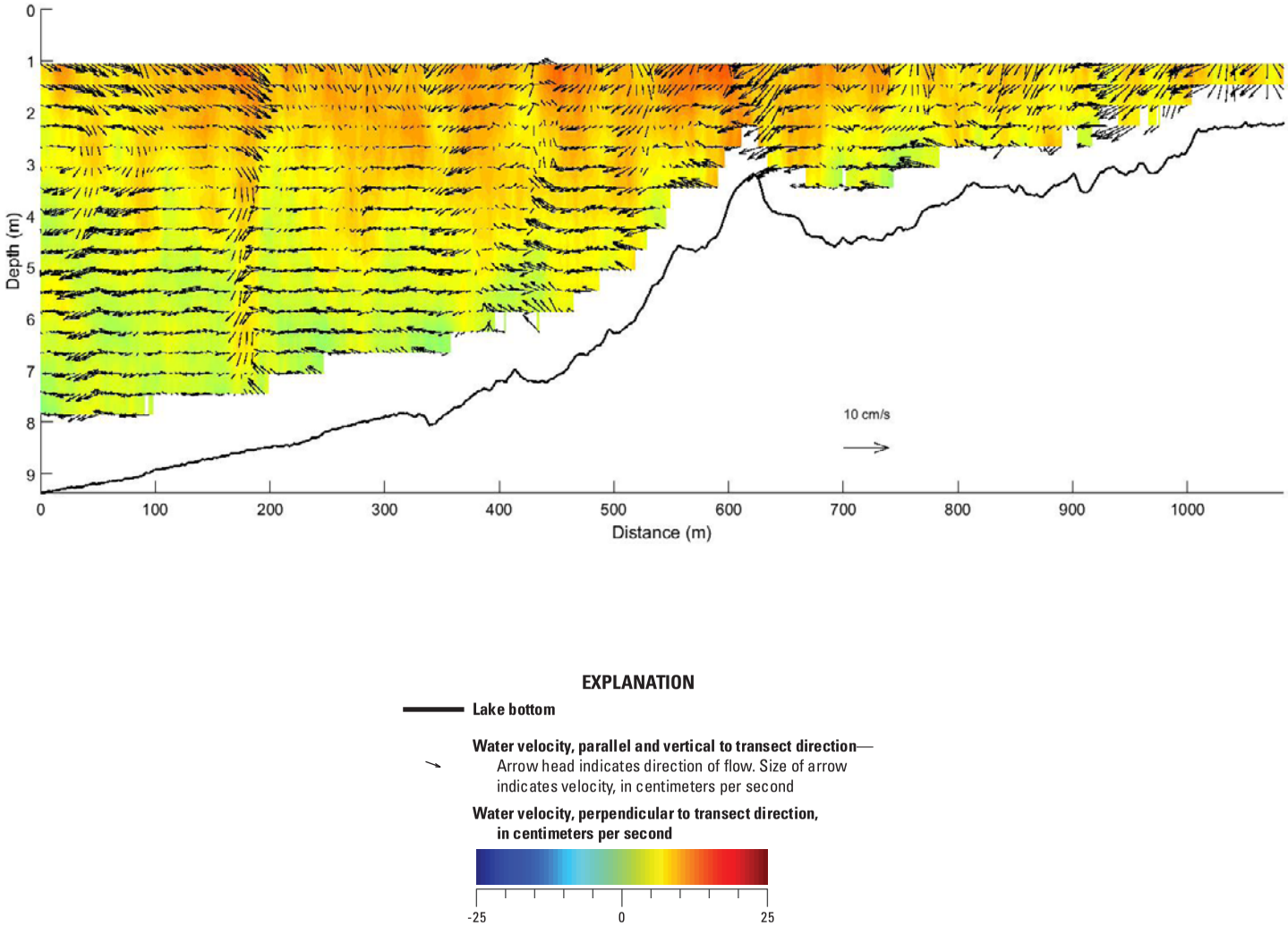


Figure 1-9. Transect 12, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

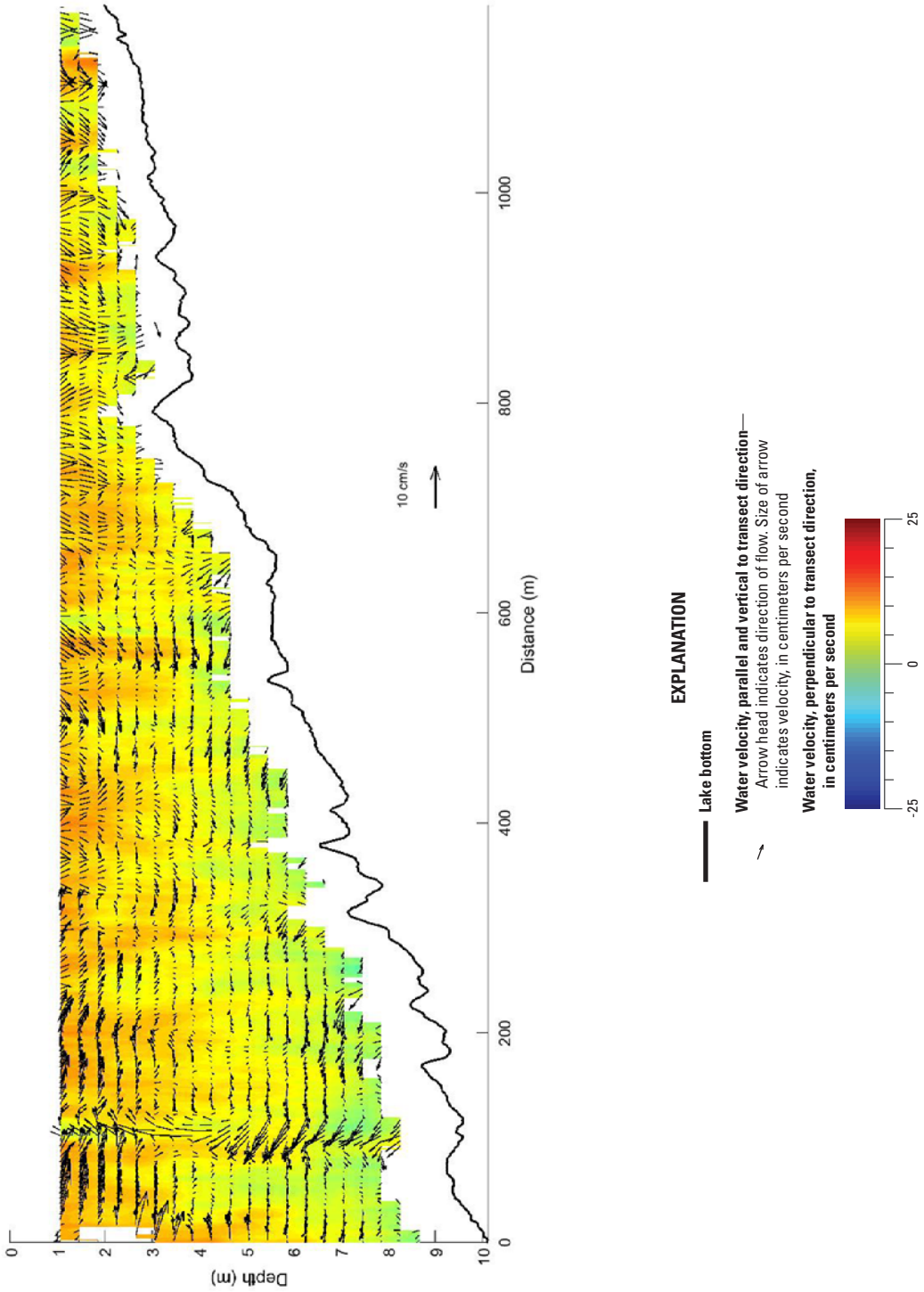
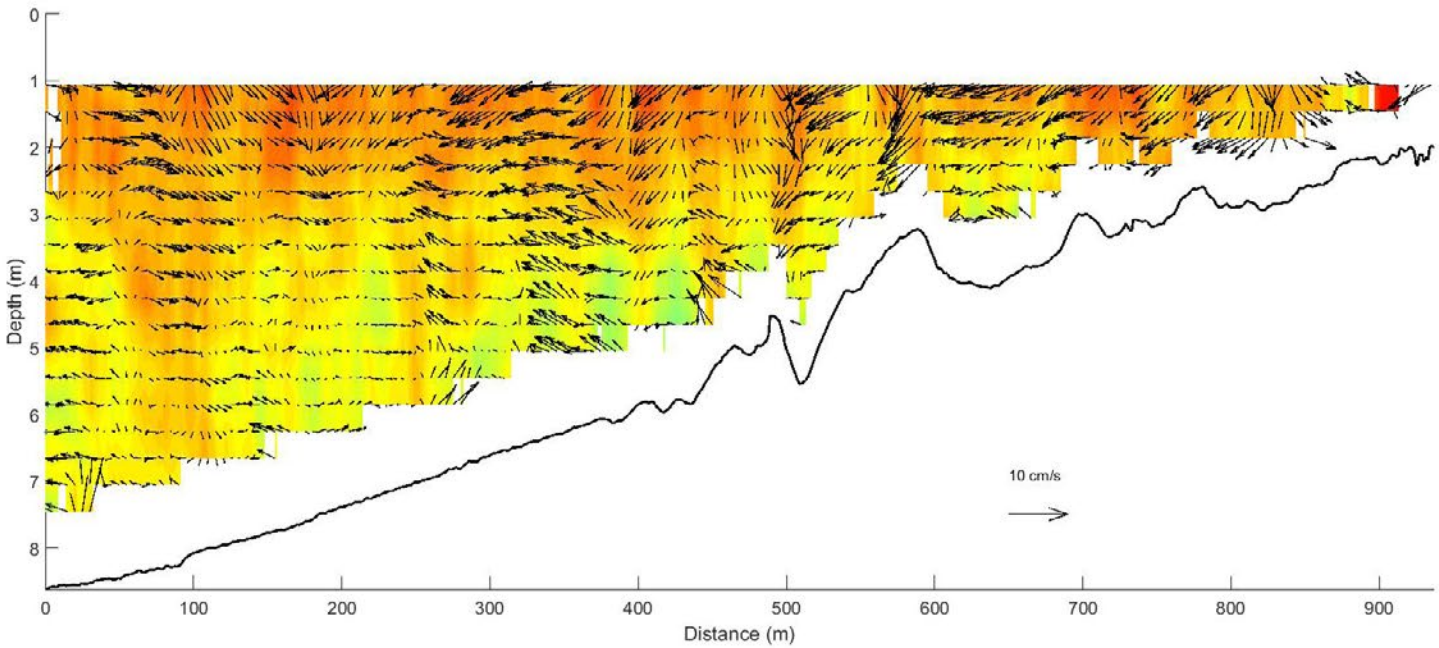


Figure 1-10. Transect 14, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)



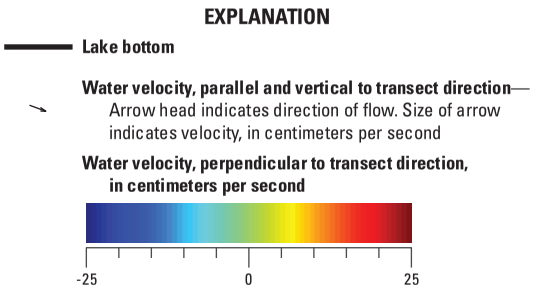


Figure 1-11. Transect 17, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

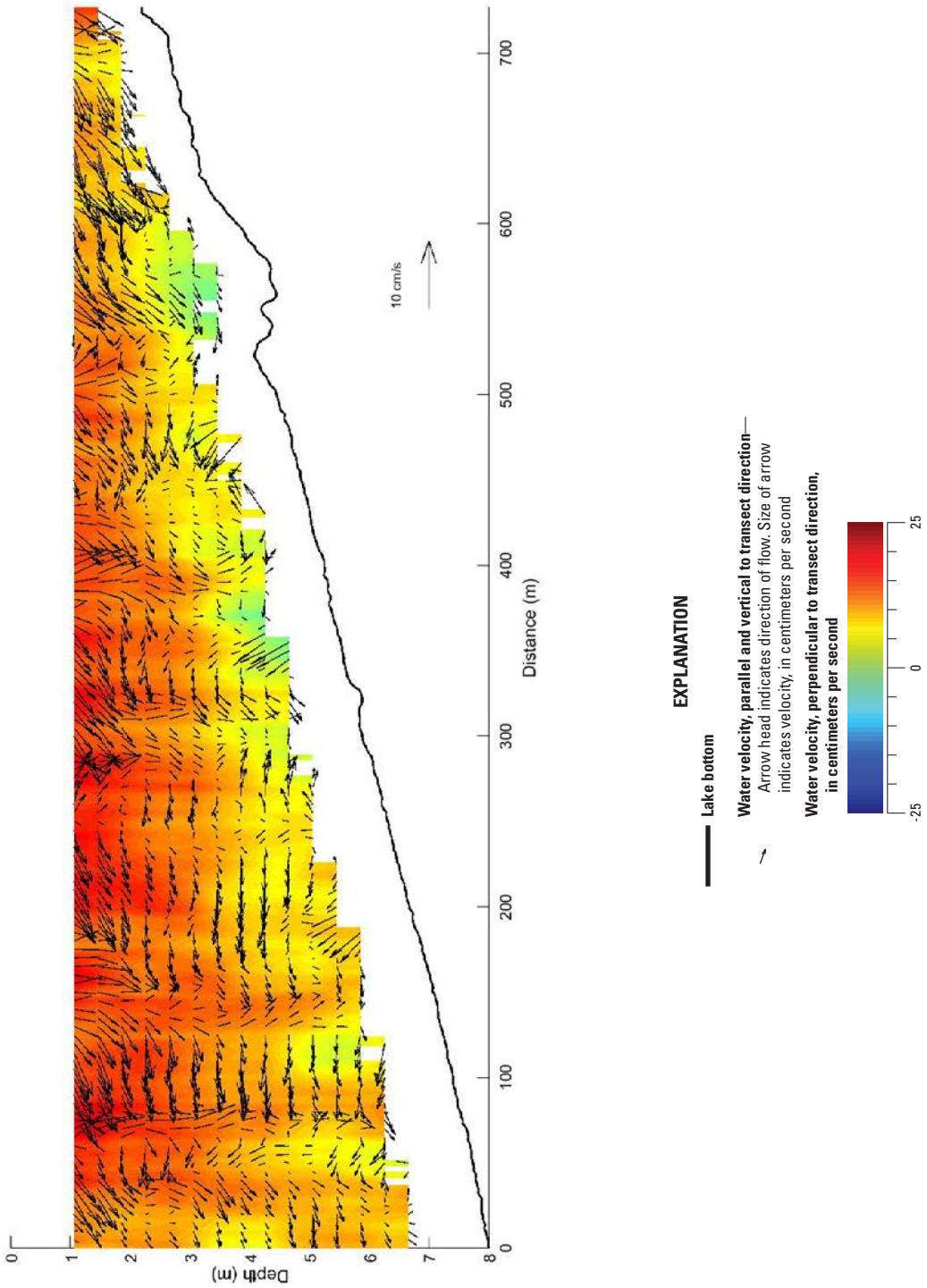


Figure 1-12. Transect 20, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

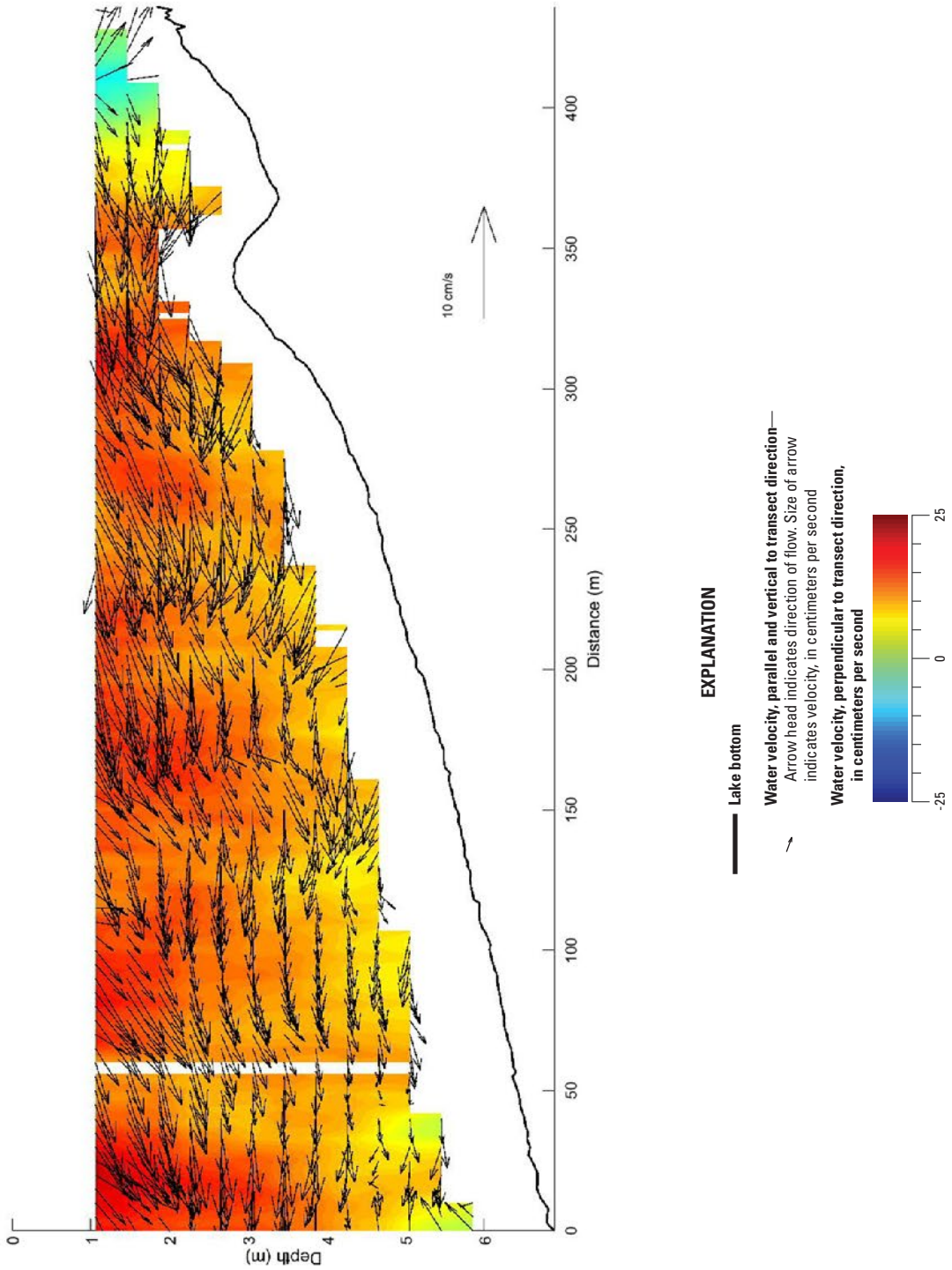


Figure 1-13. Transect 24, measured on June 24, 2015. (m, meter; cm/s, centimeters per second)

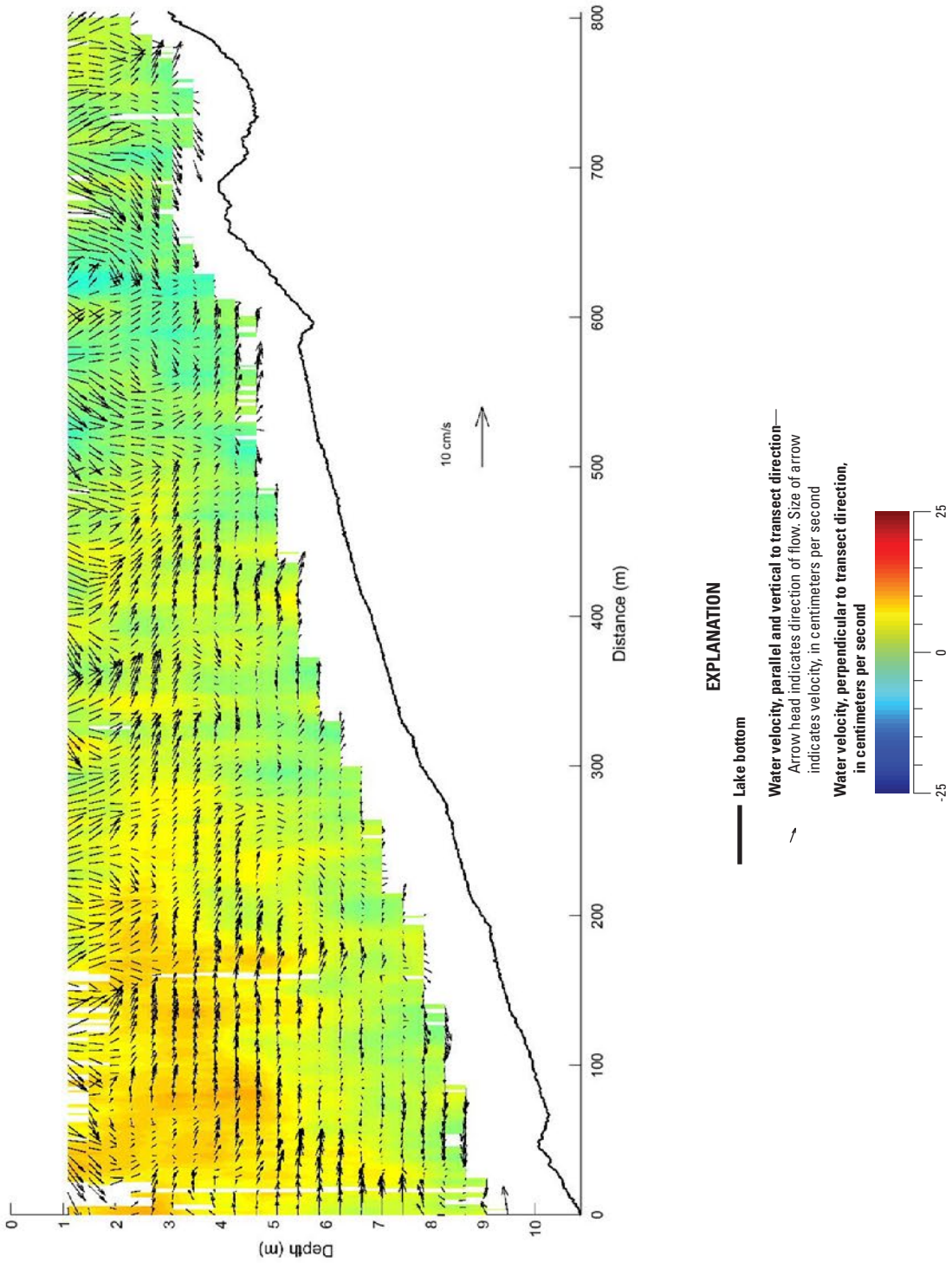
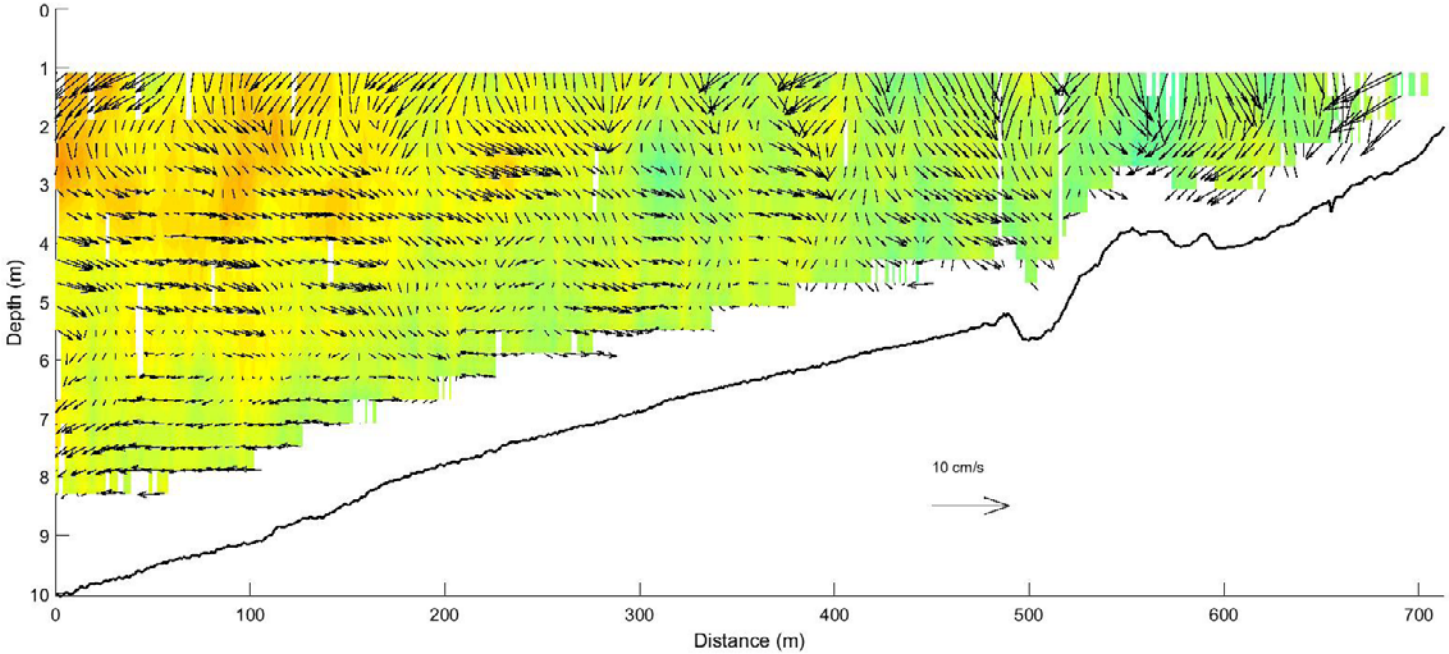


Figure 1-14. Transect 1, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

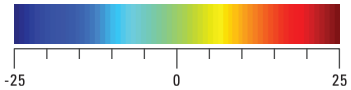


Figure 1-15. Transect 2, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

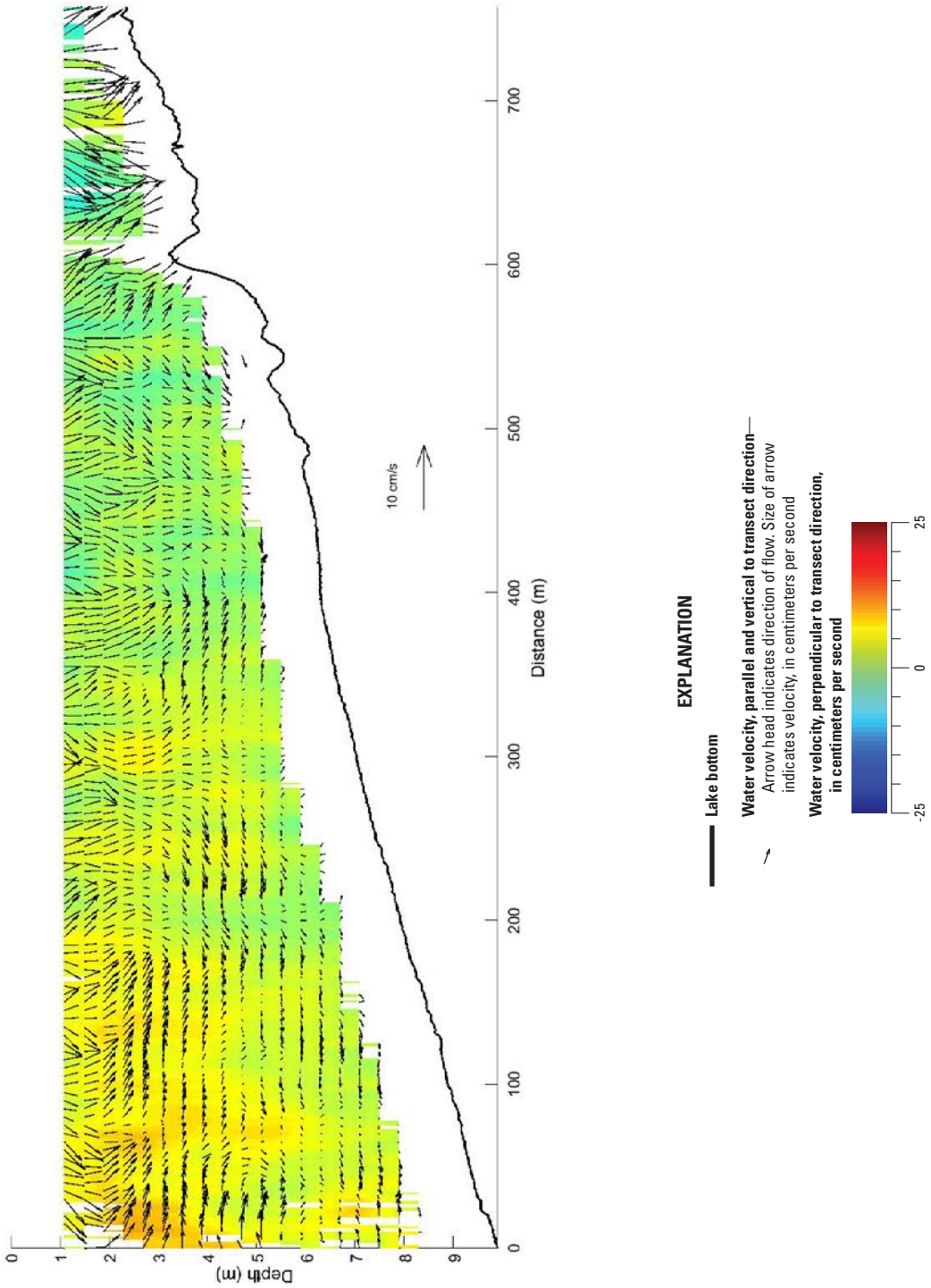


Figure 1-16. Transect 4, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

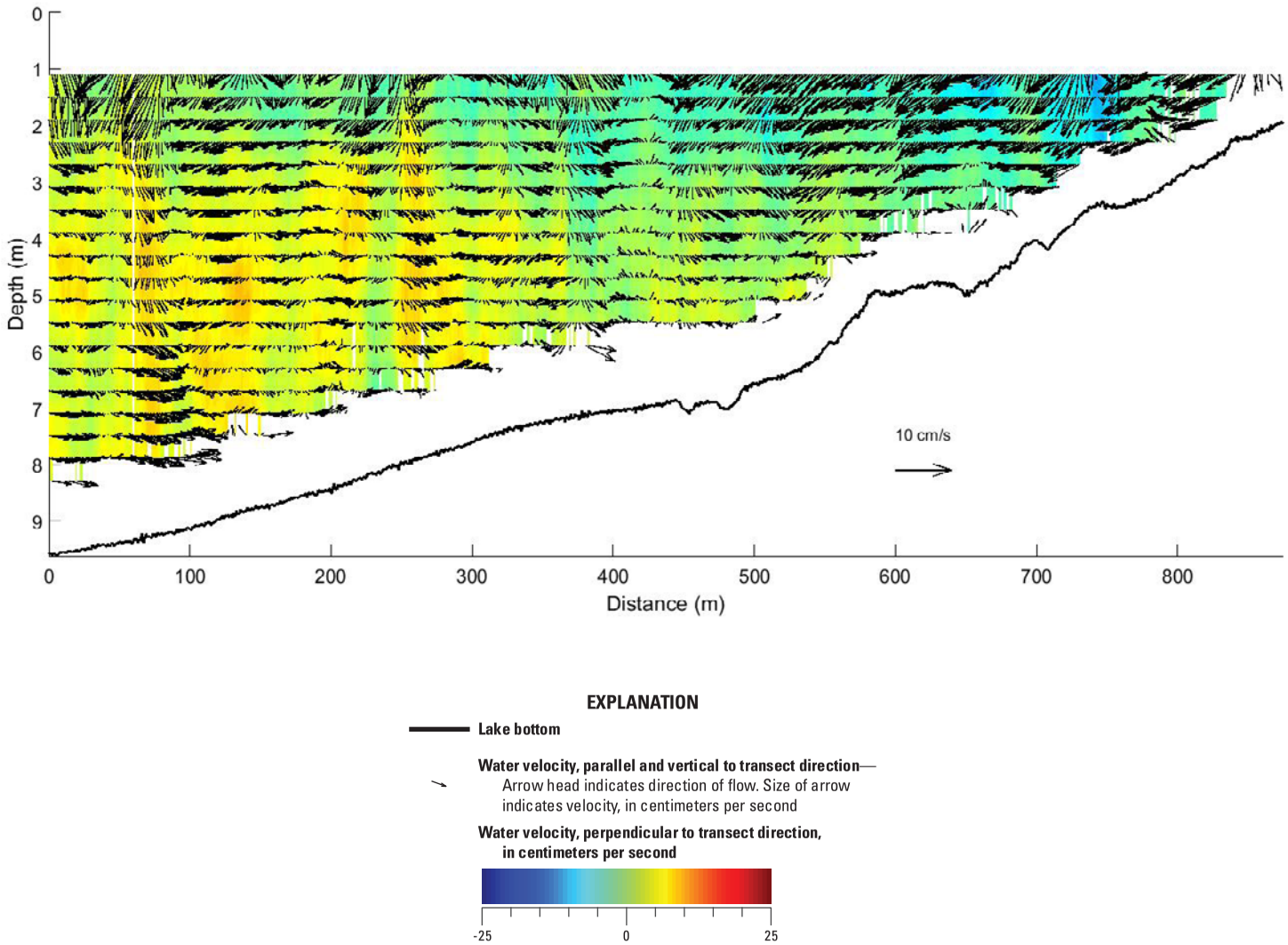


Figure 1-17. Transect 6, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

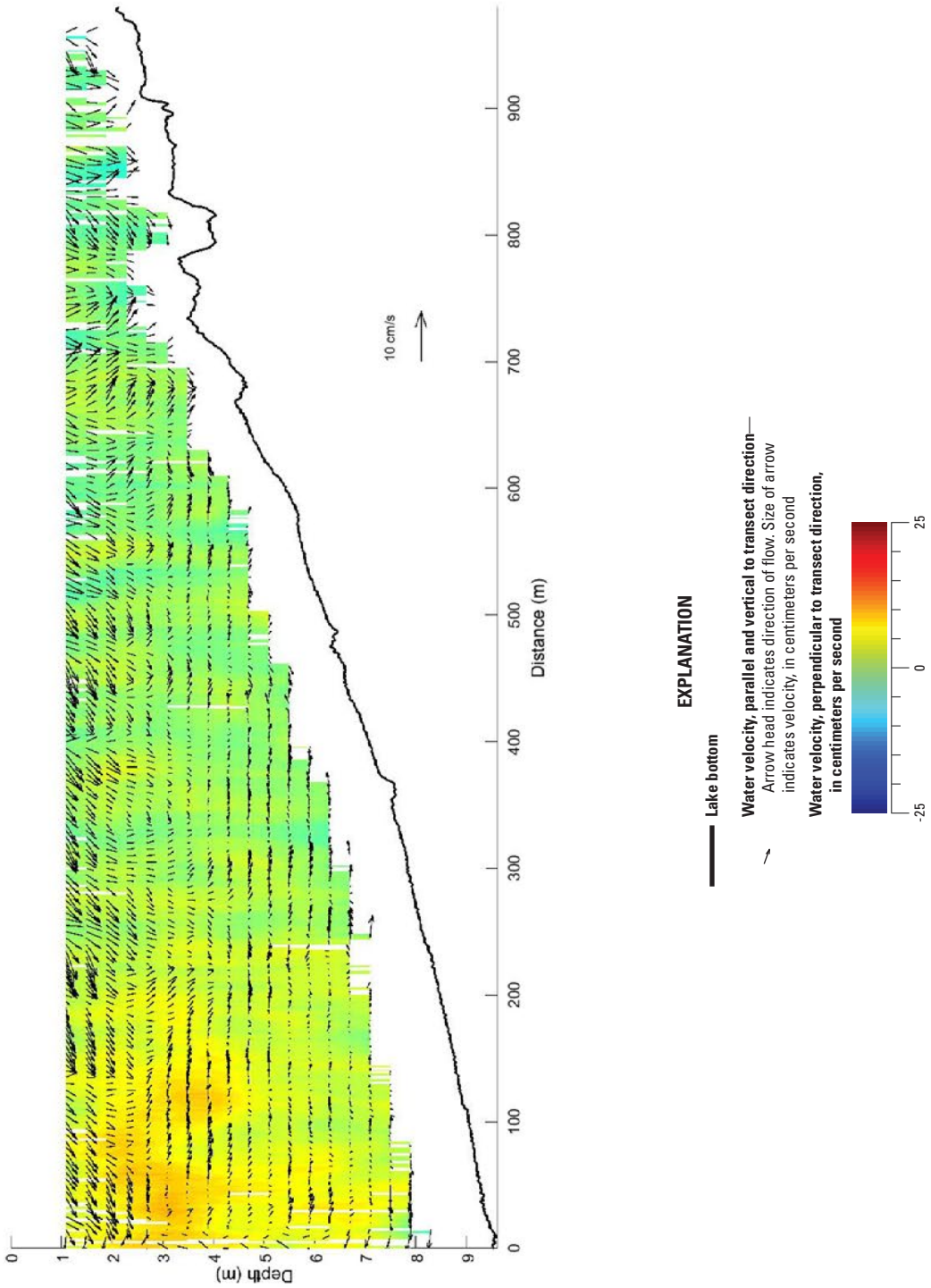


Figure 1-18. Transect 8, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

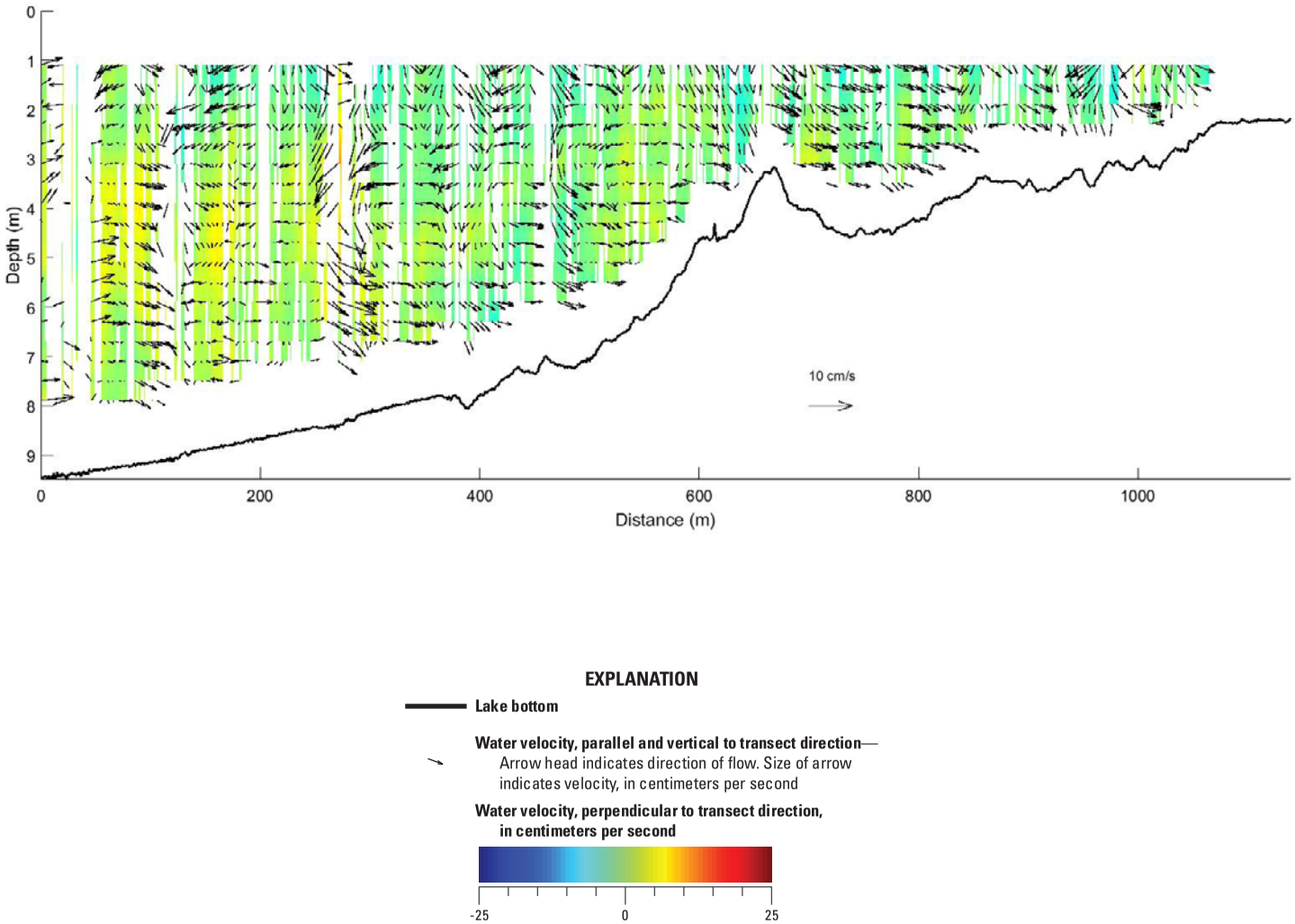


Figure 1-19. Transect 12, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

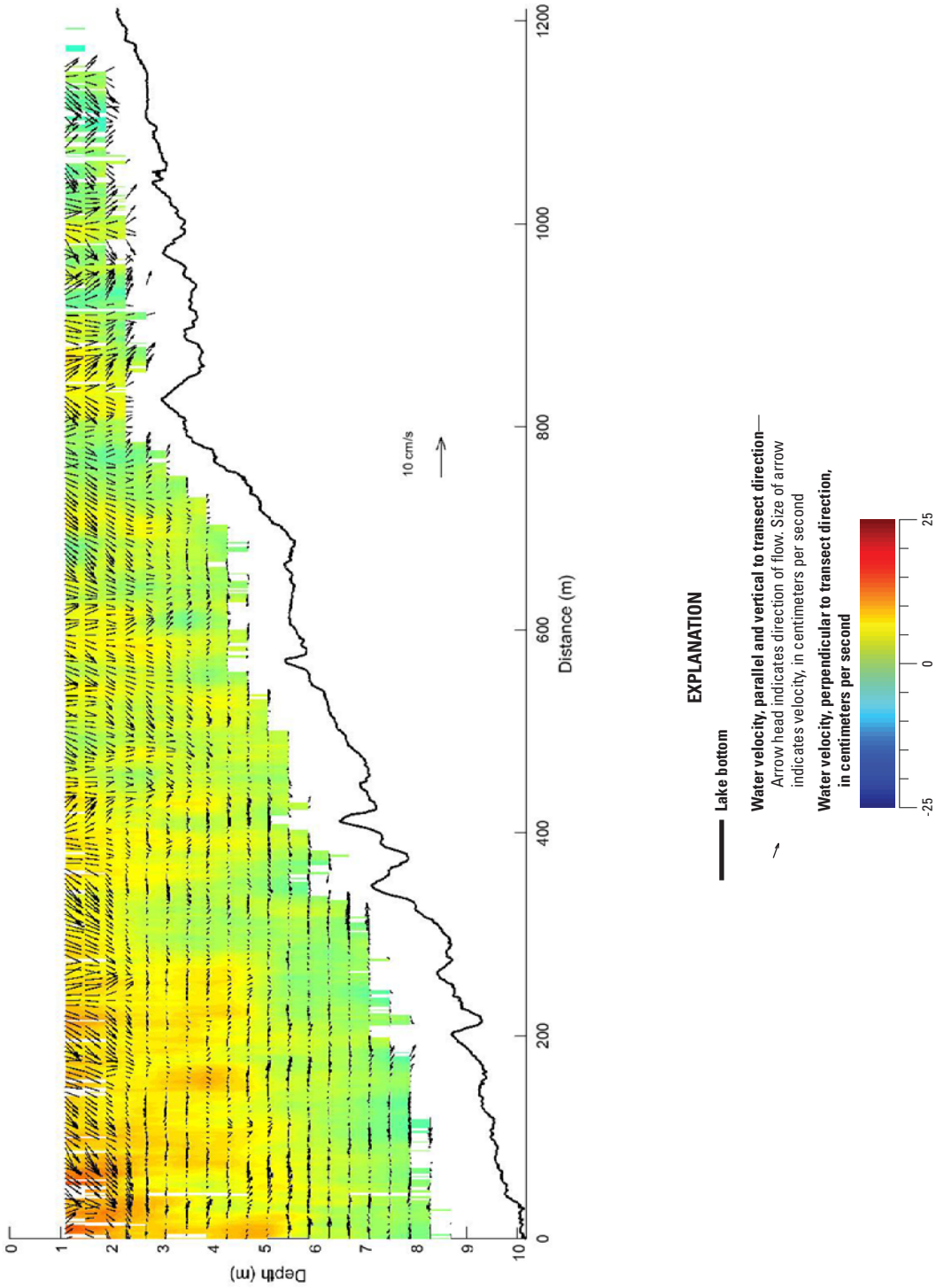
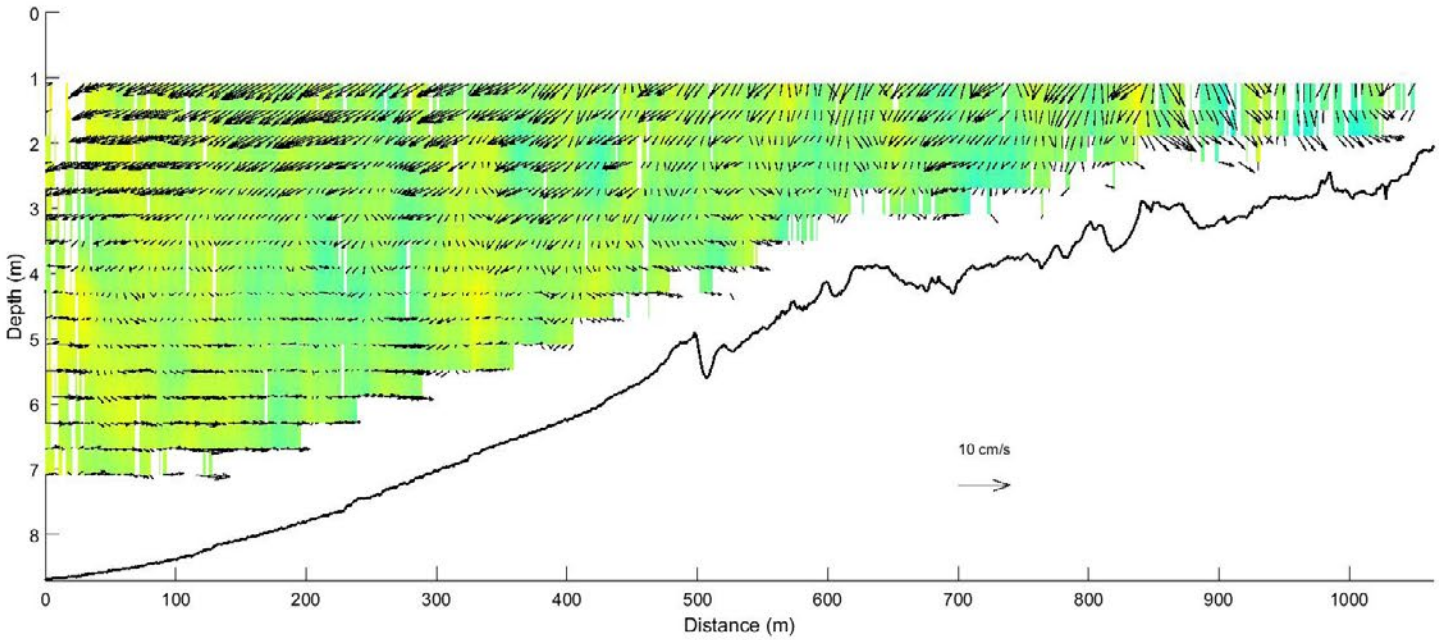


Figure 1-20. Transect 14, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

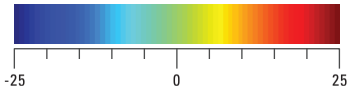


Figure 1-21. Transect 16, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

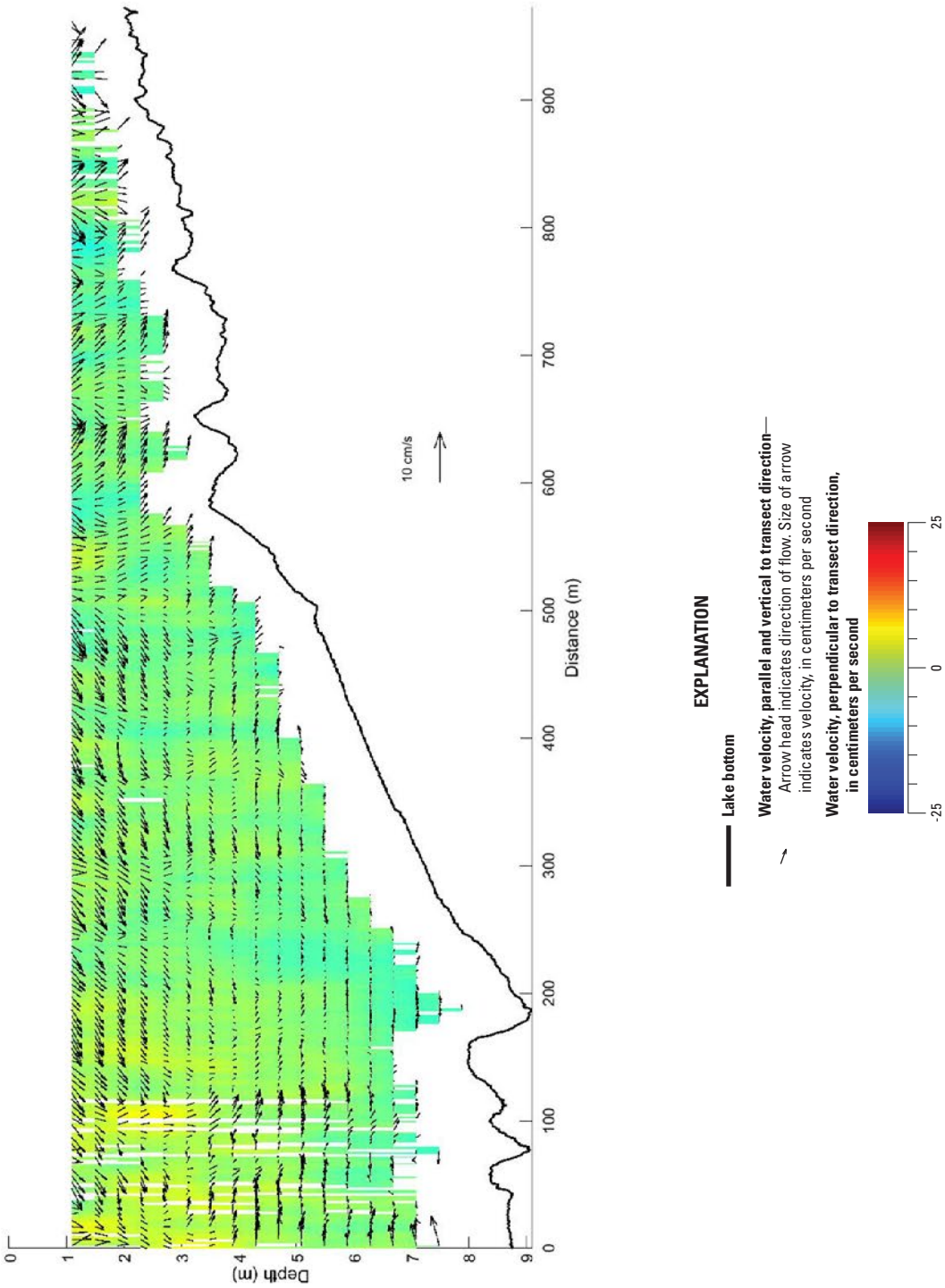
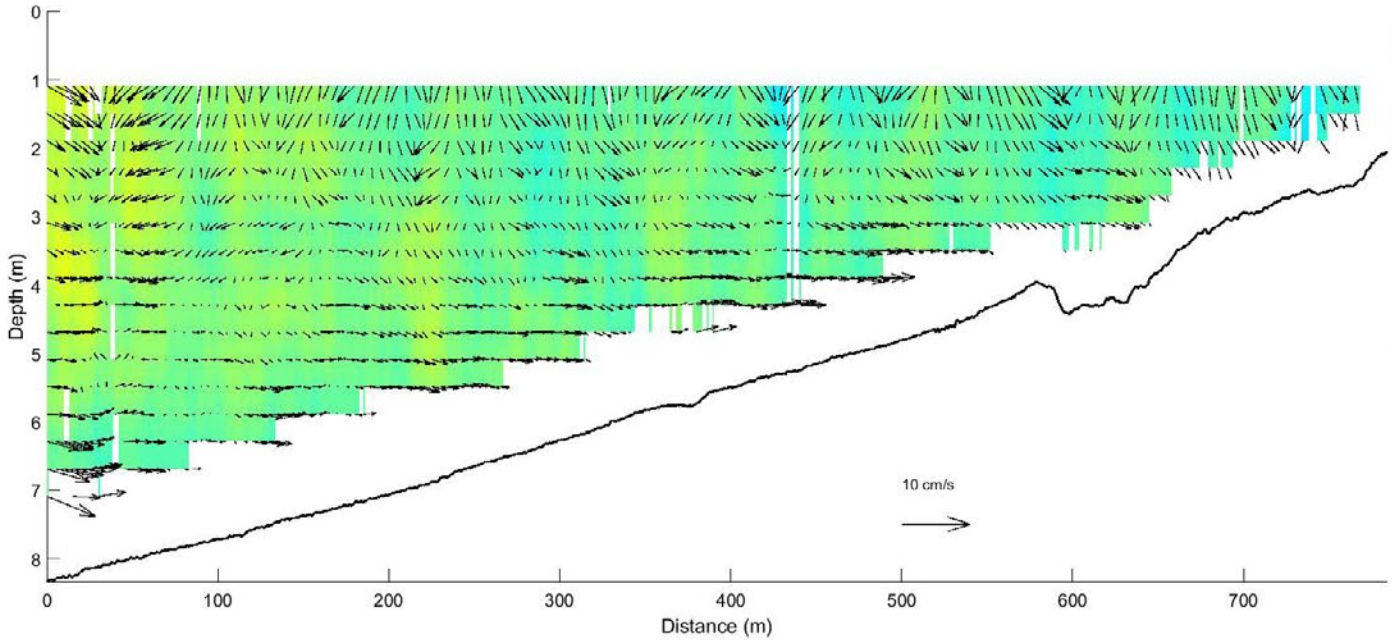


Figure 1-22. Transect 18, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)



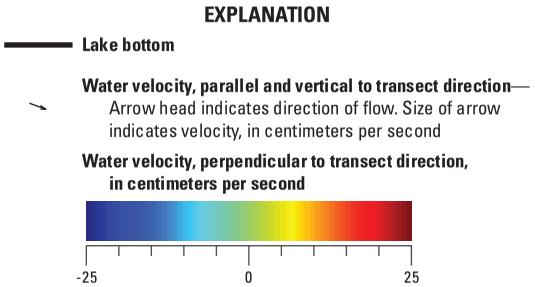


Figure 1-23. Transect 20, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

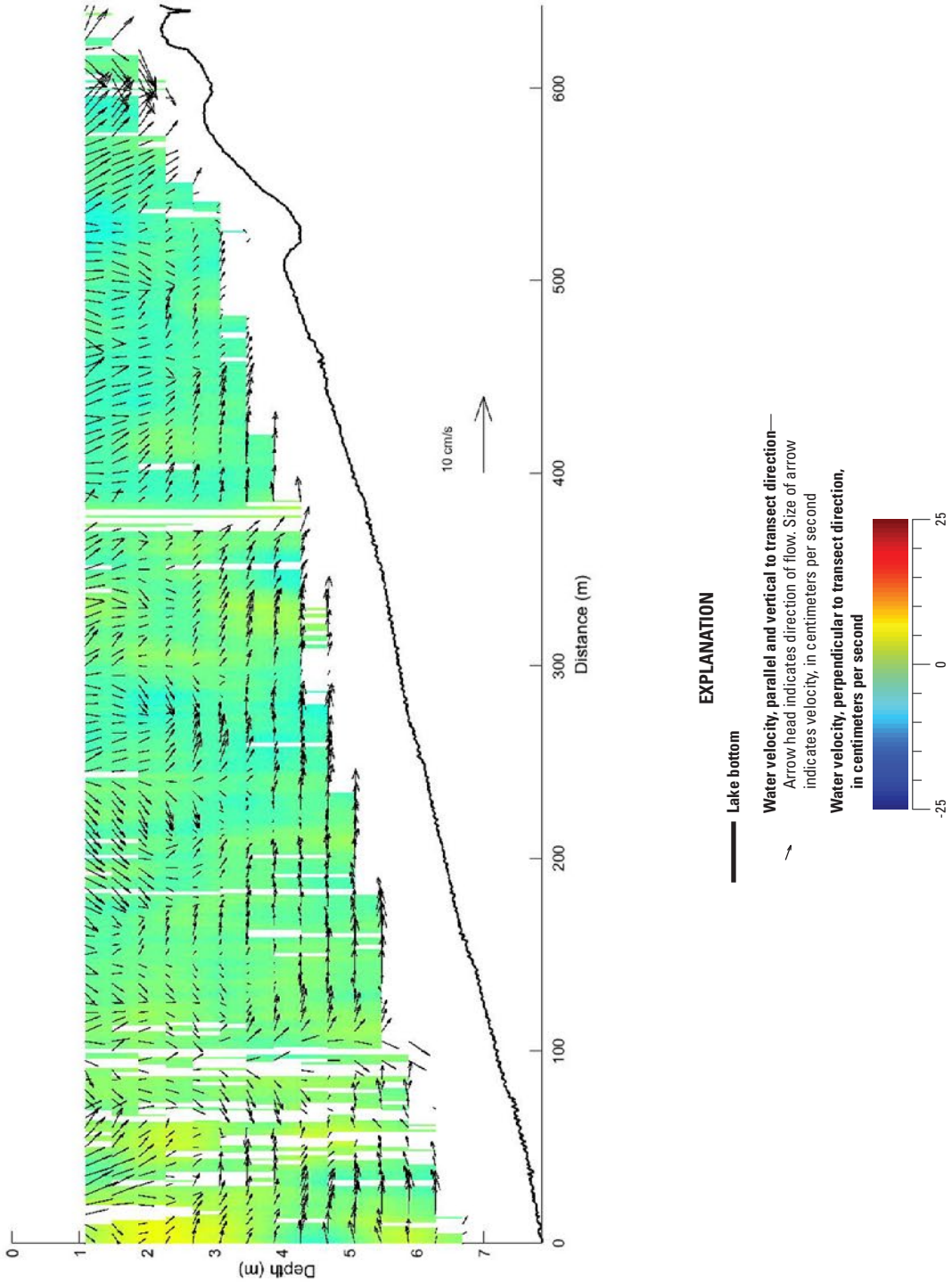


Figure 1-24. Transect 22, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

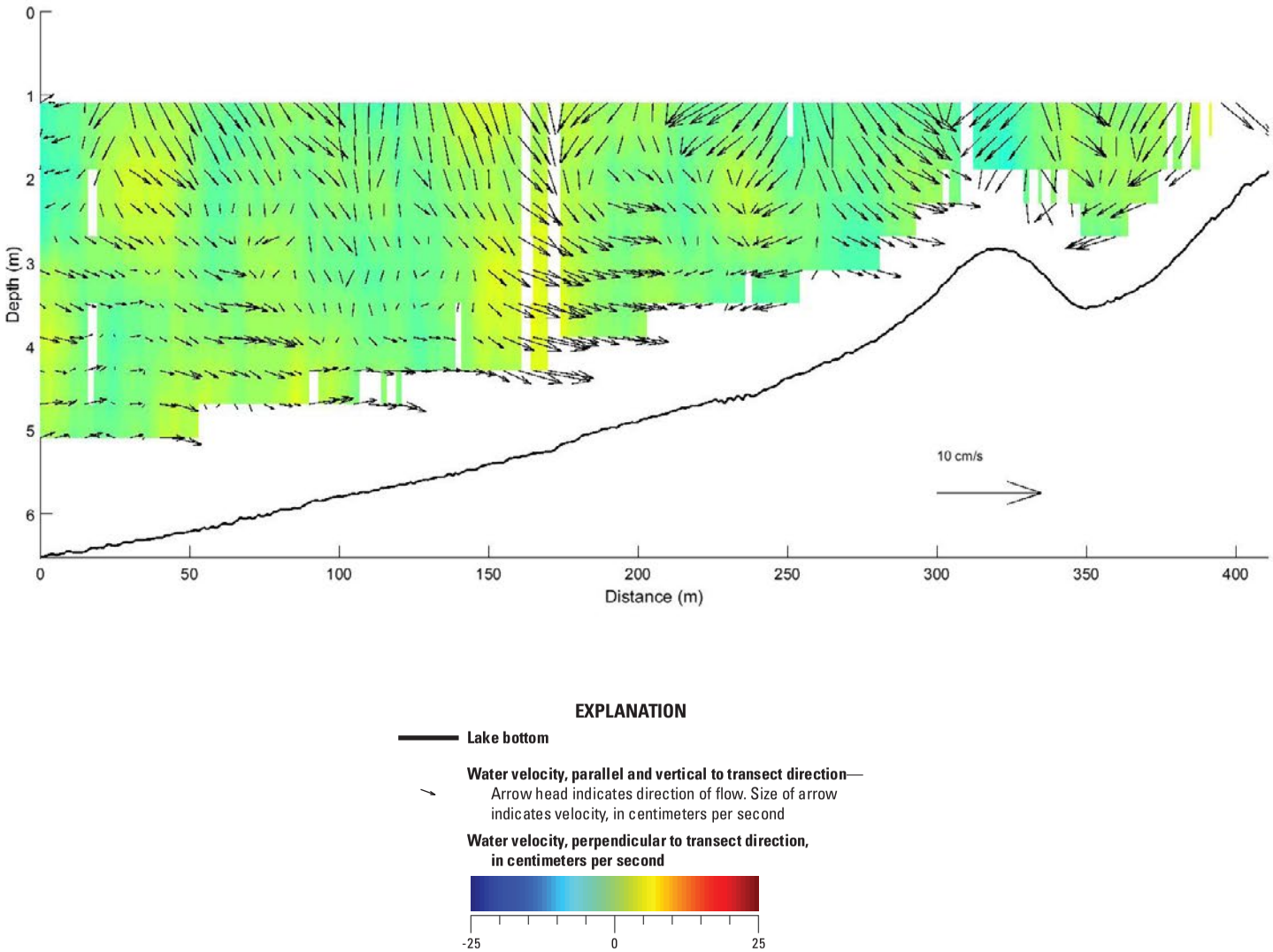


Figure 1-25. Transect 24, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

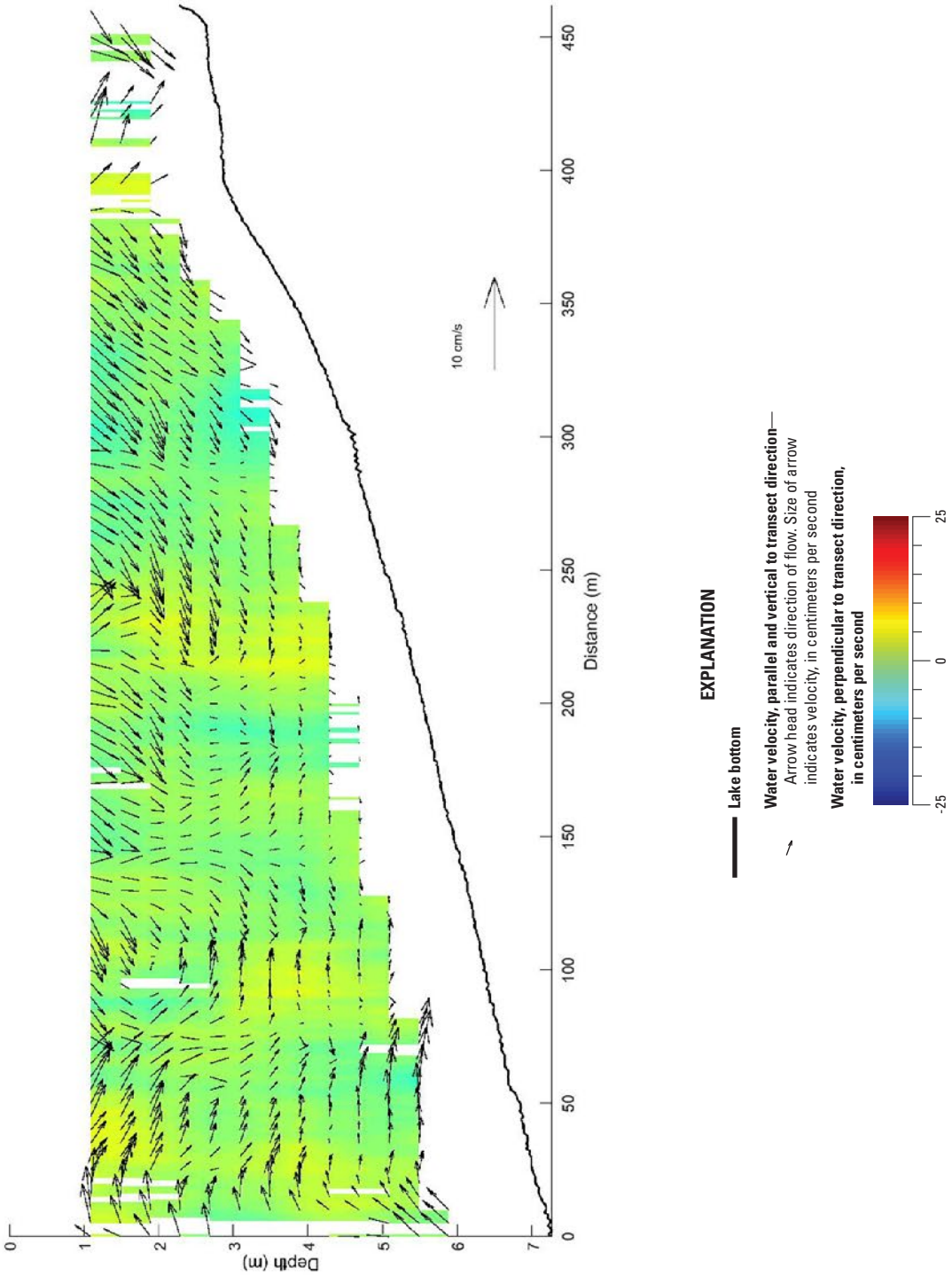


Figure 1-26. Transect 25, measured on June 25, 2015. (m, meter; cm/s, centimeters per second)

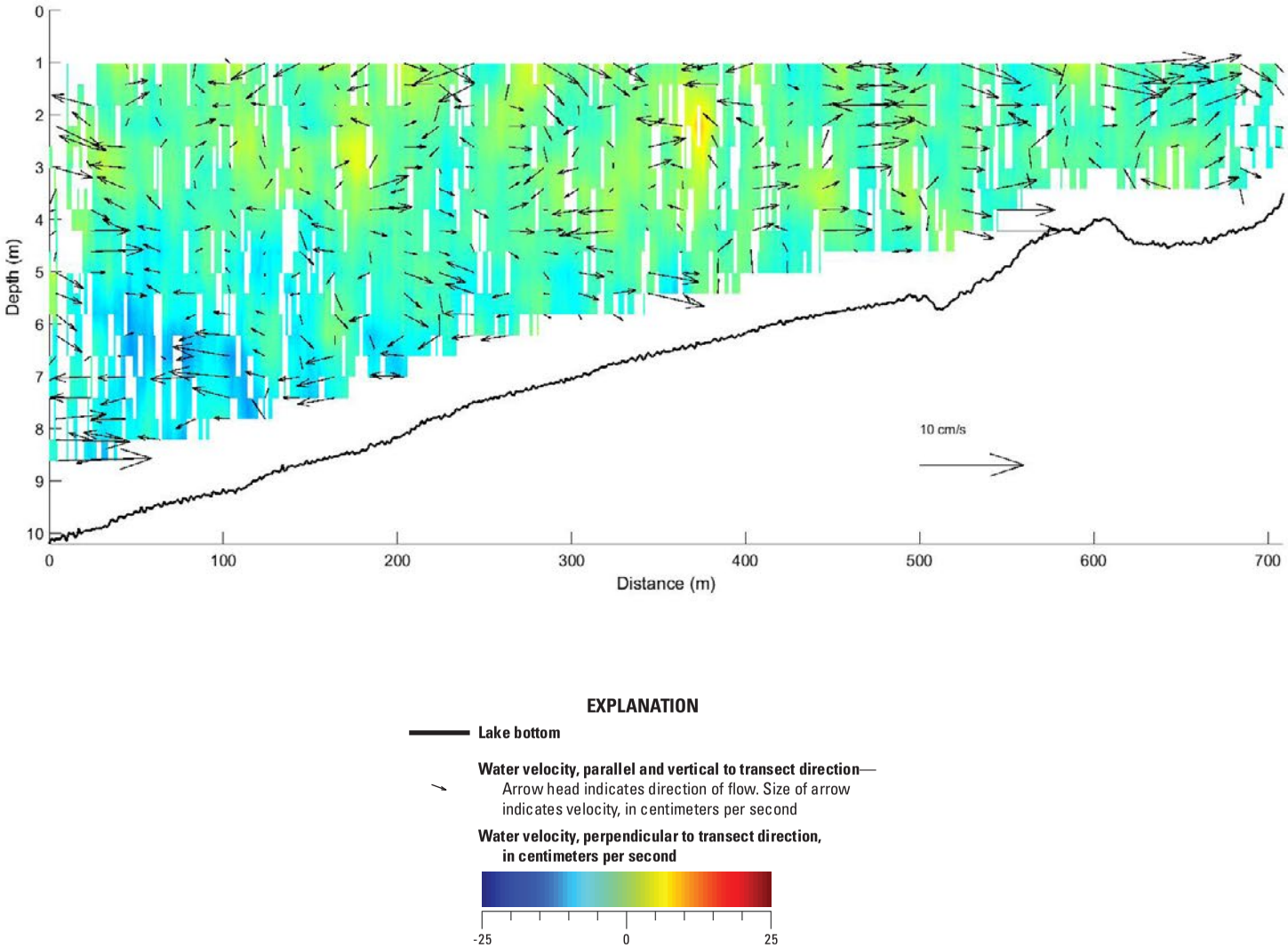


Figure 1-27. Transect 1, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

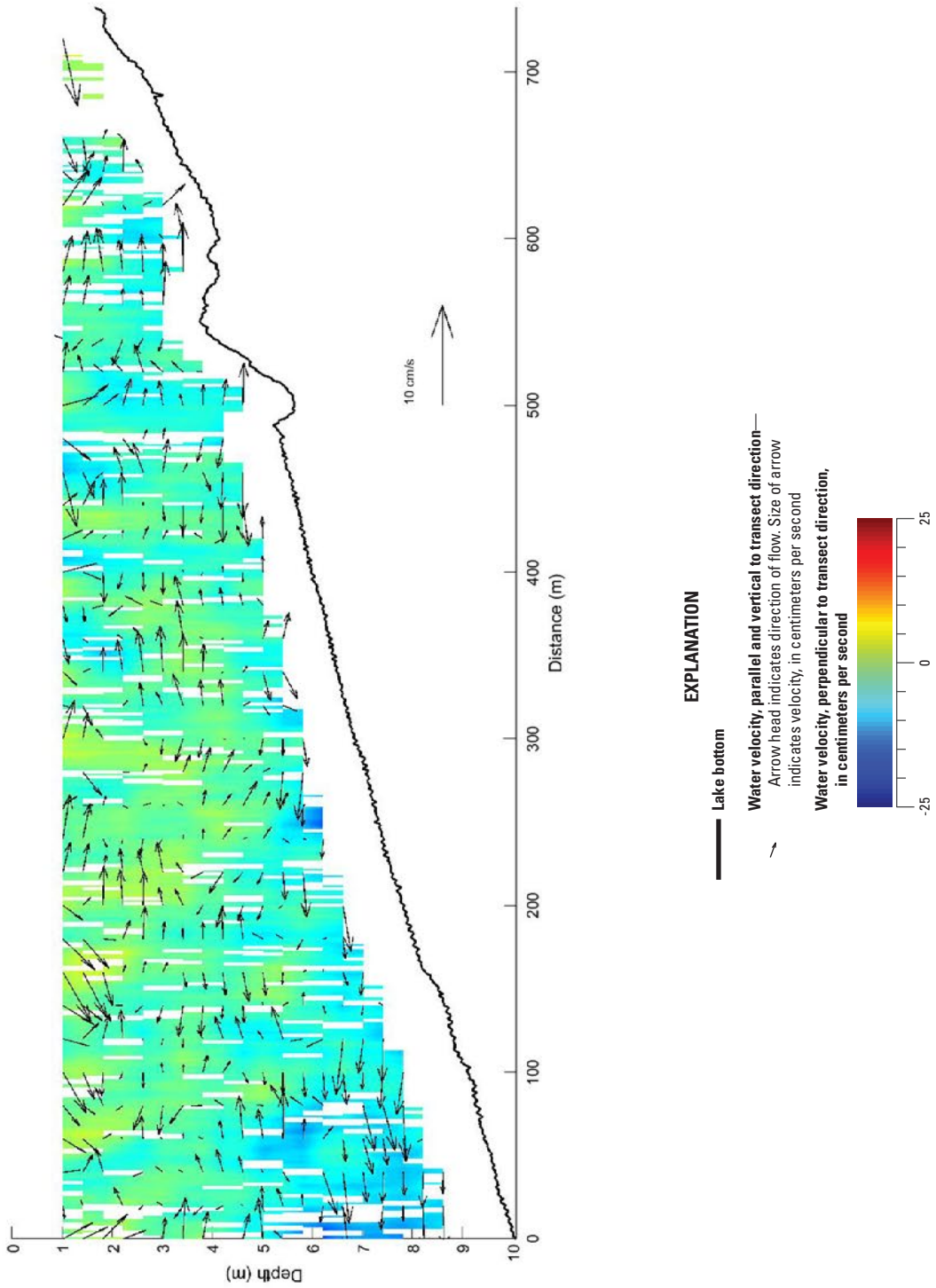
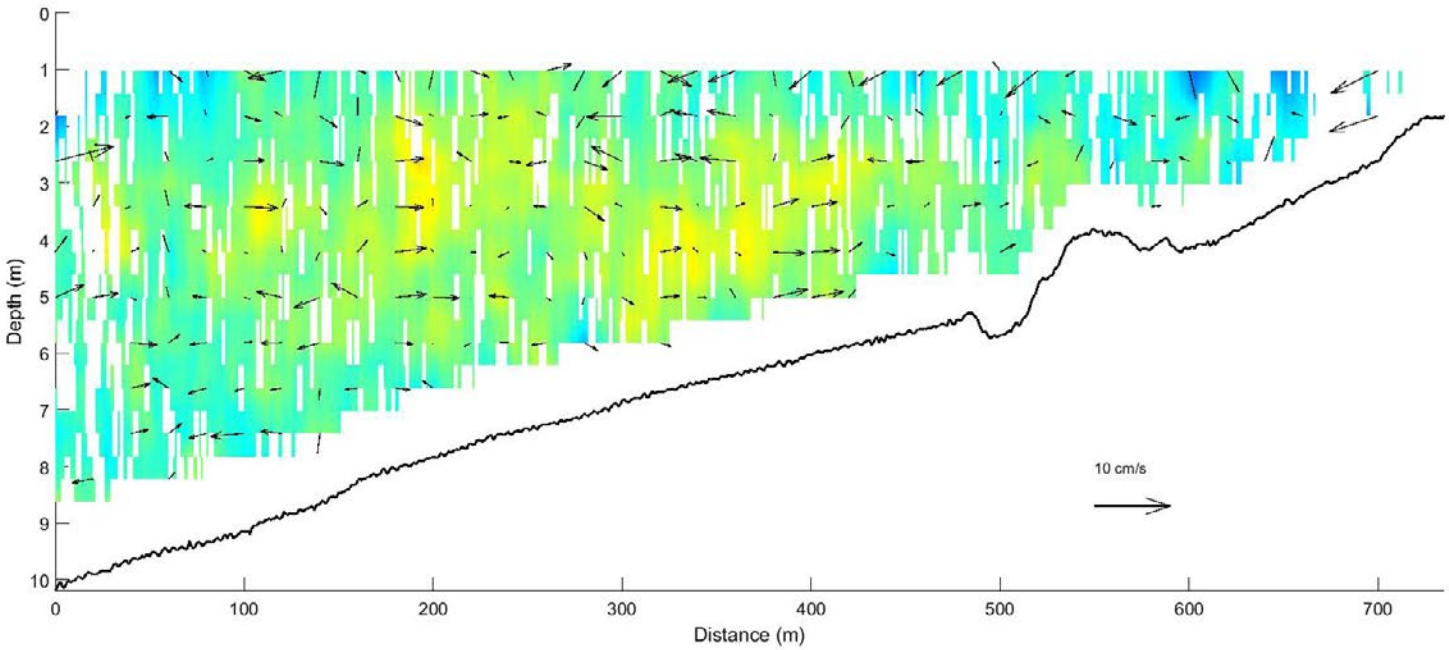


Figure 1-28. Transect 2, measured on the morning of August 18, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

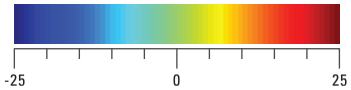


Figure 1-29. Transect 2, measured on the afternoon of August 18, 2015. (m, meter; cm/s, centimeters per second)

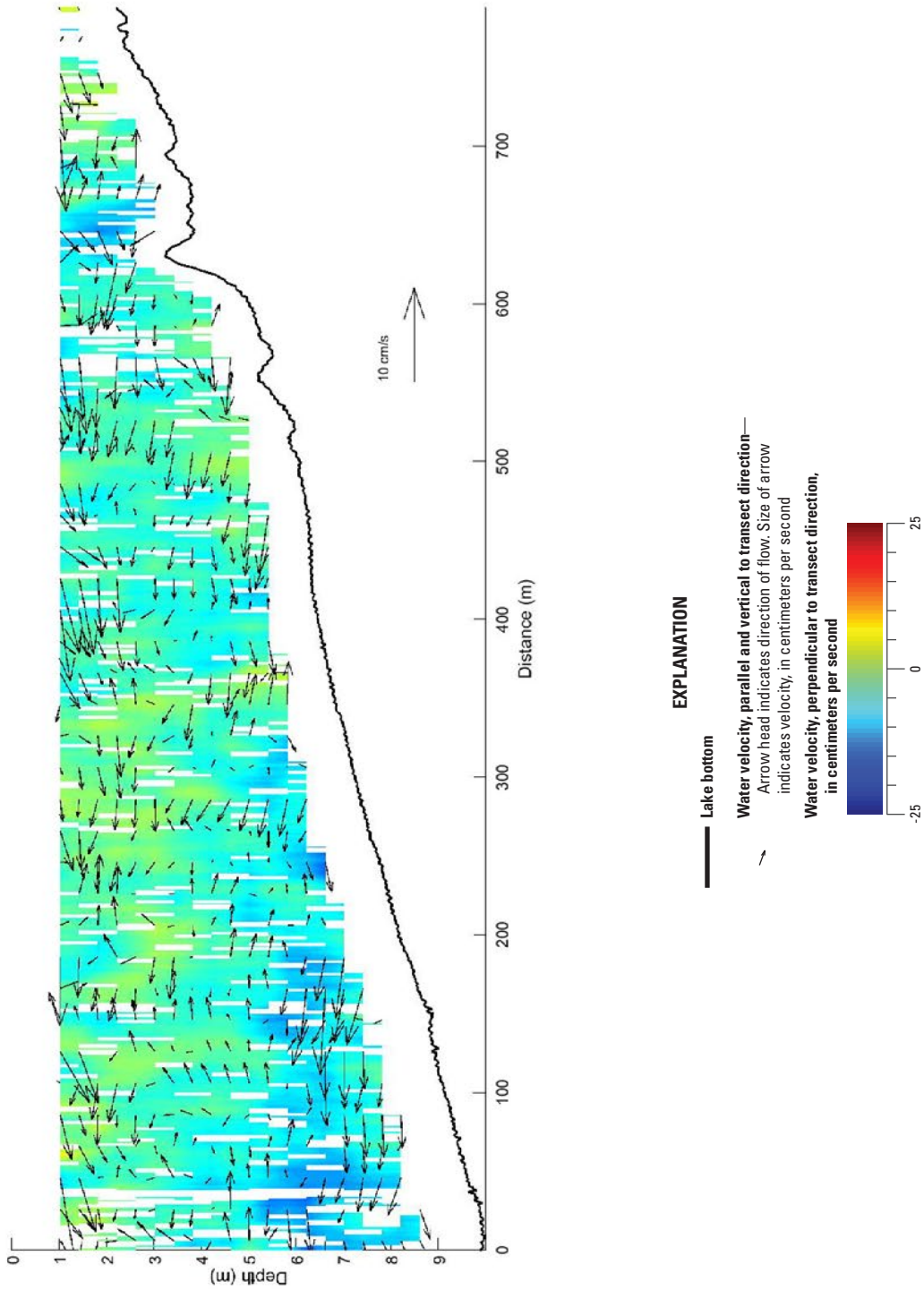
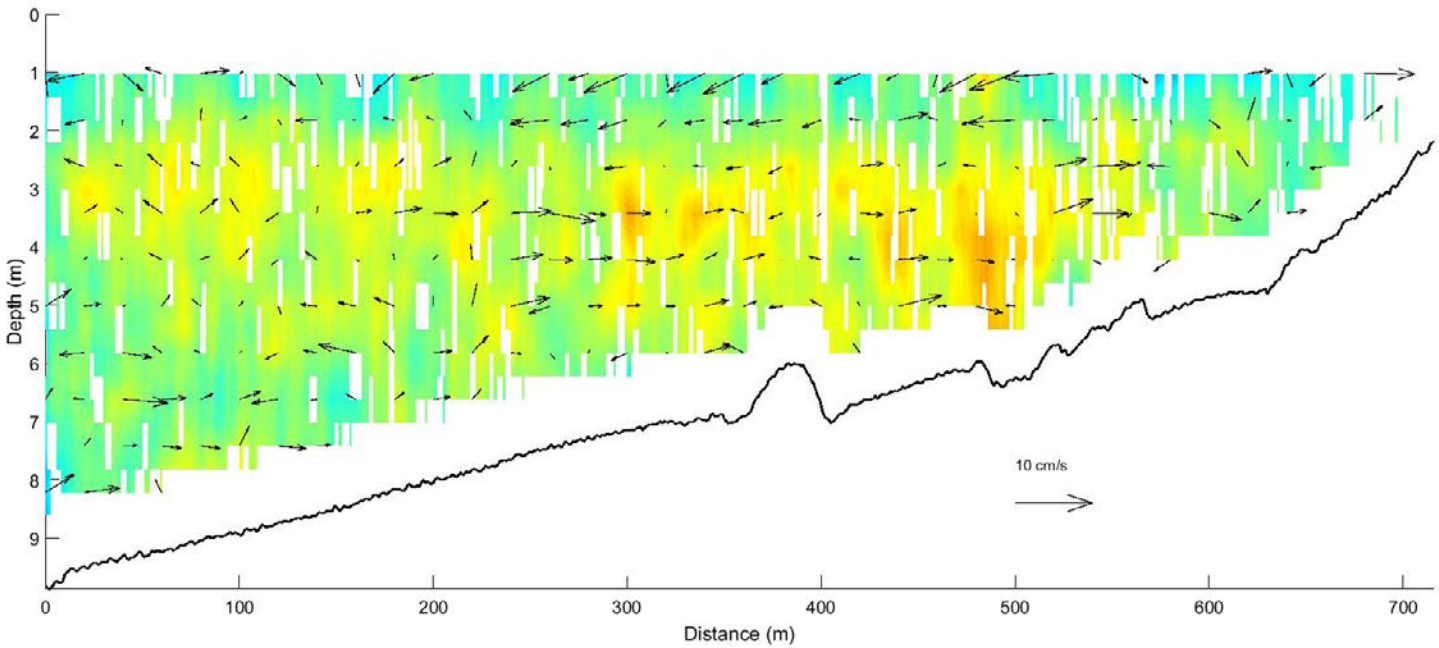


Figure 1-30. Transect 4, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

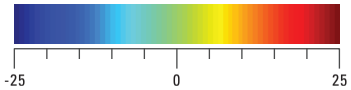


Figure 1-31. Transect 5, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

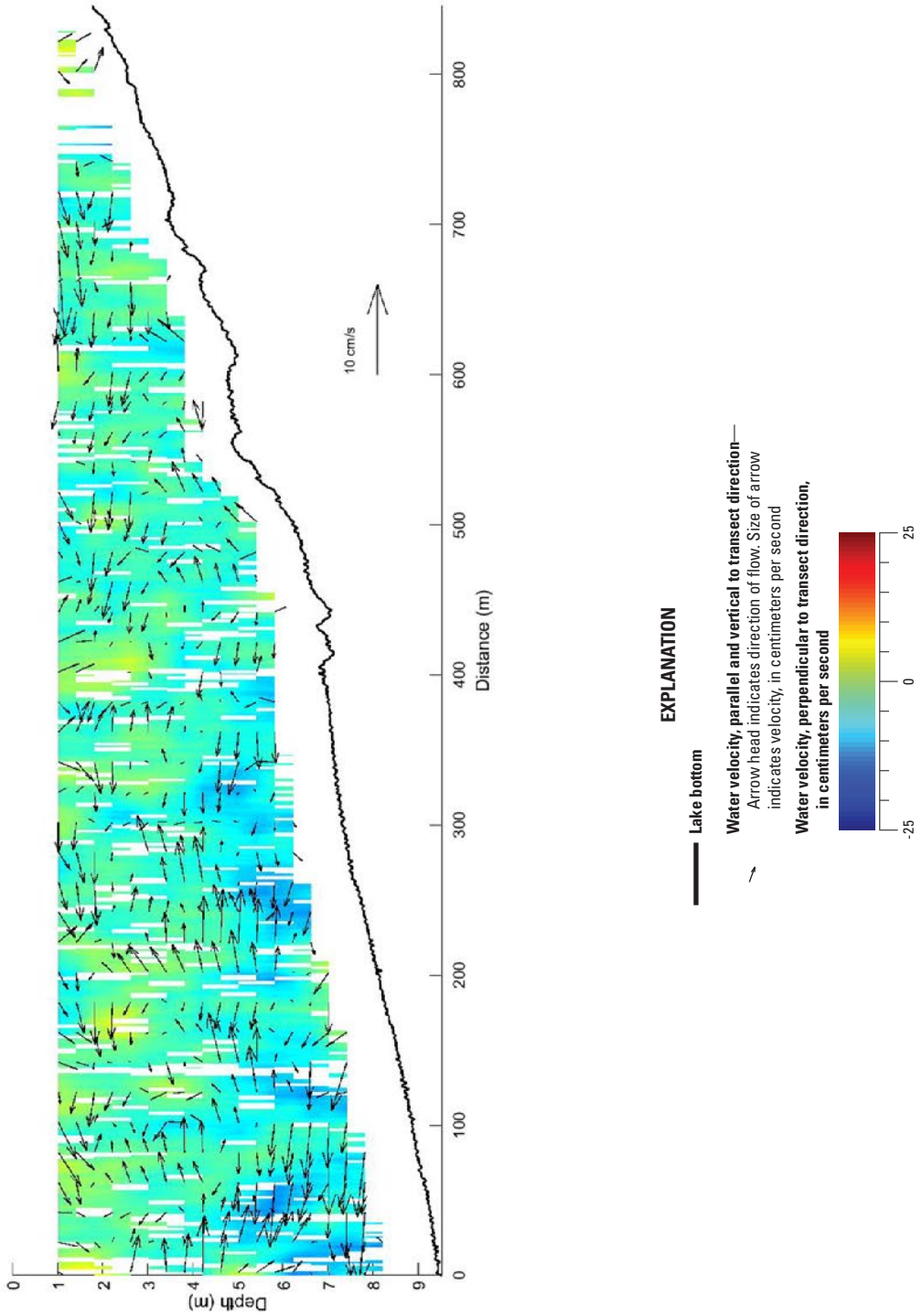
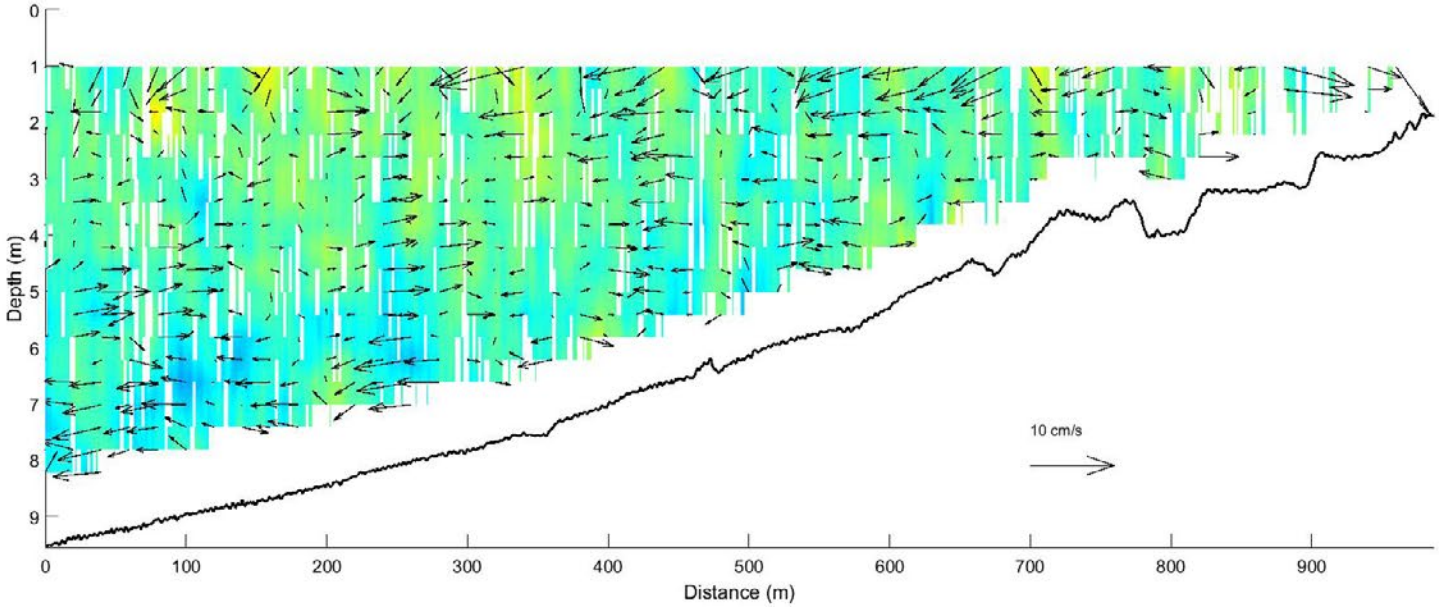


Figure 1-32. Transect 6, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

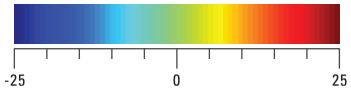


Figure 1-33. Transect 8, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

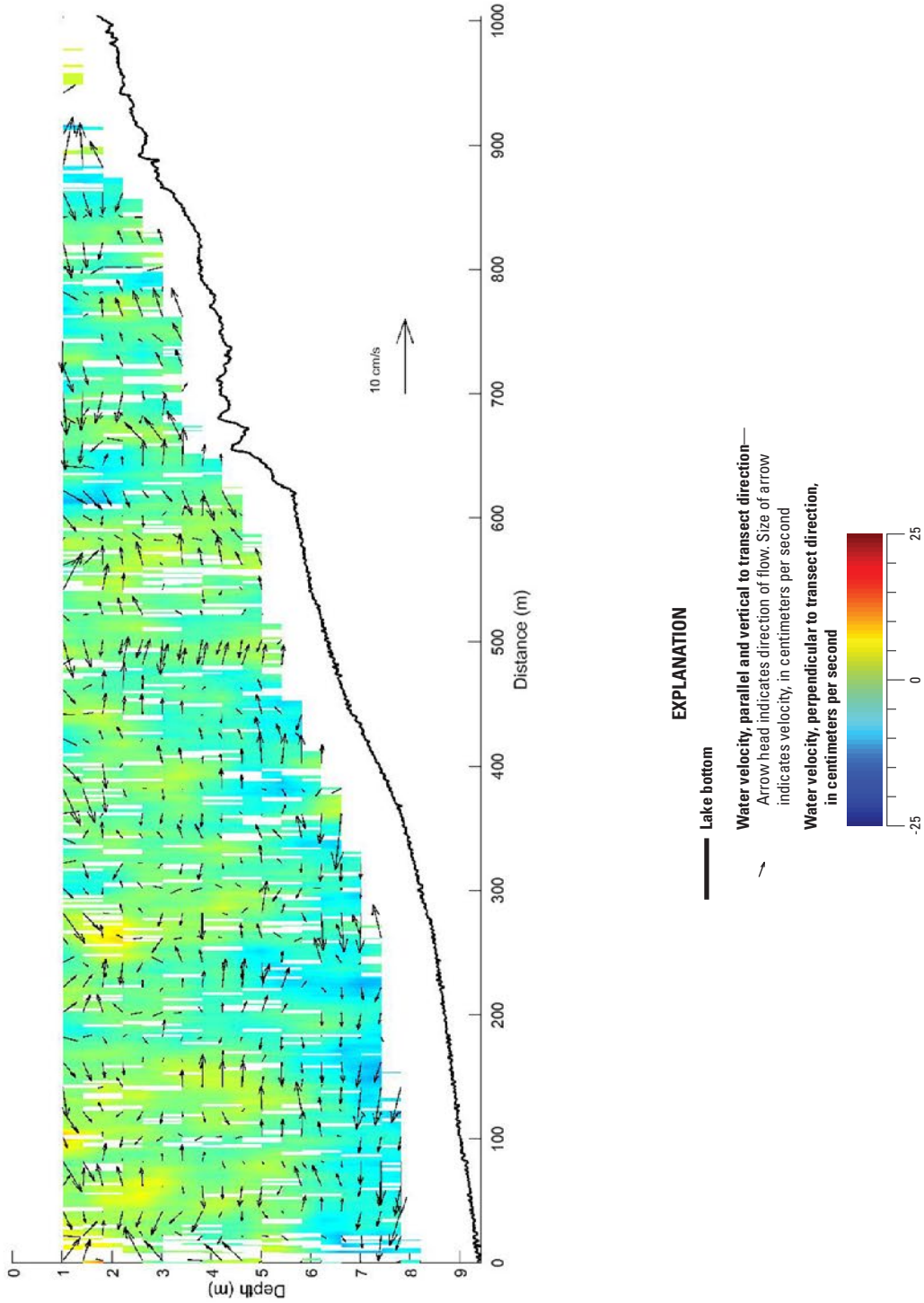
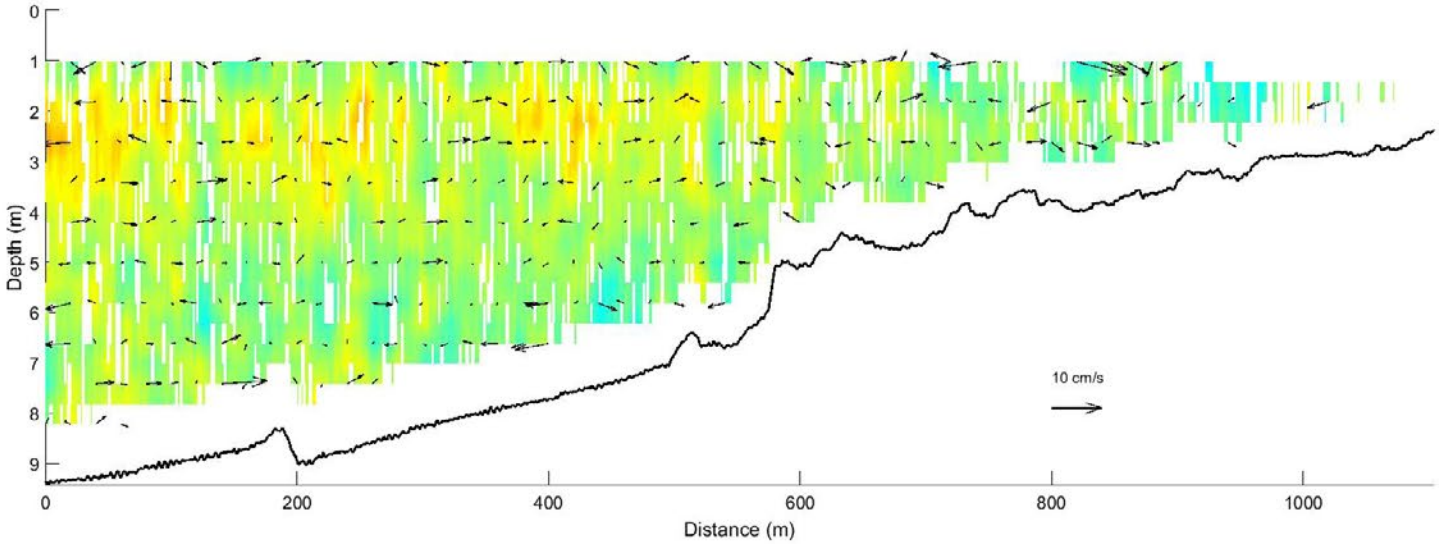


Figure 1-34. Transect 10, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

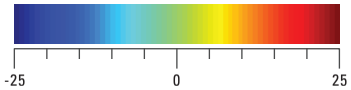


Figure 1-35. Transect 11, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

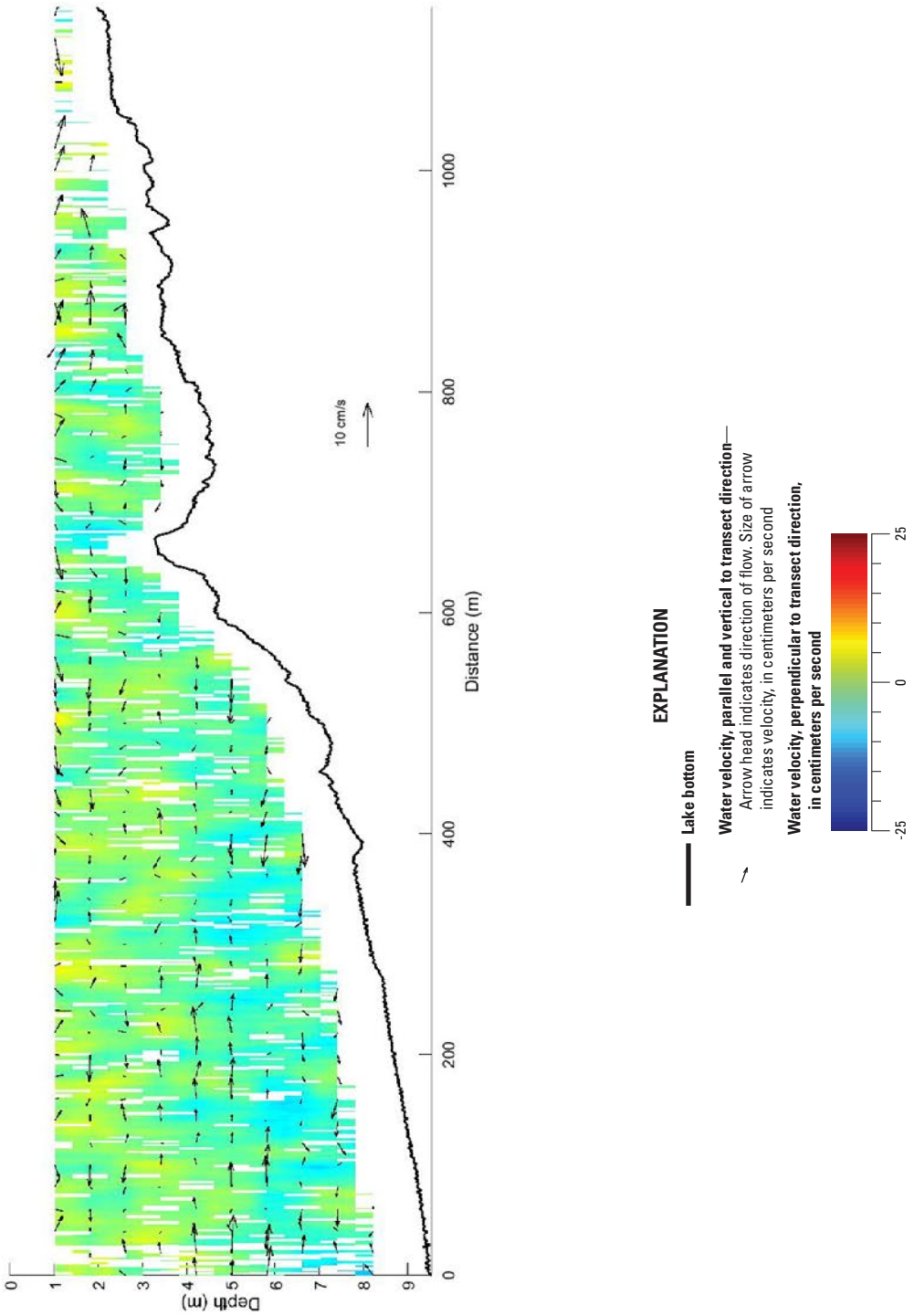


Figure 1-36. Transect 12, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

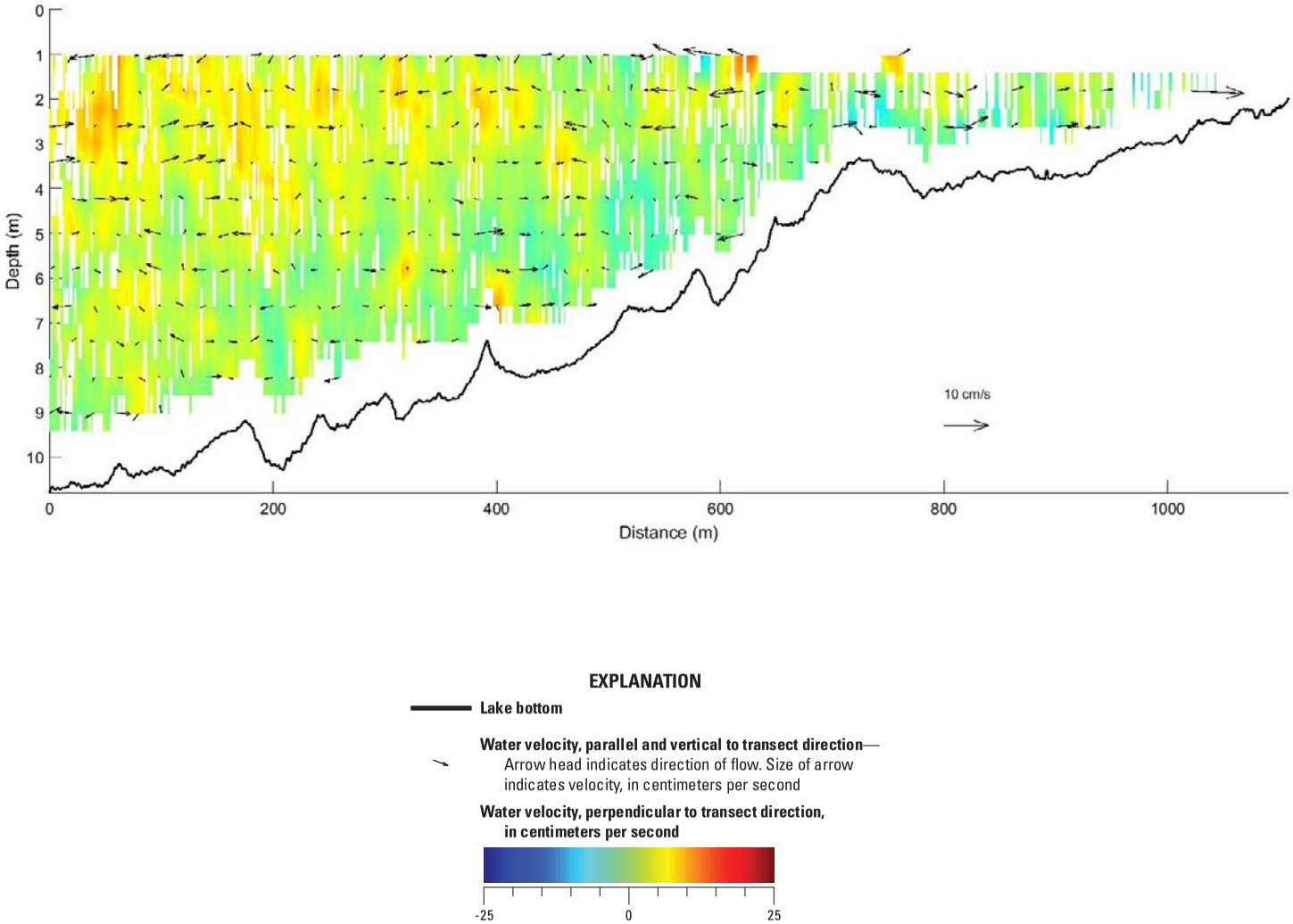


Figure 1-37. Transect 13, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

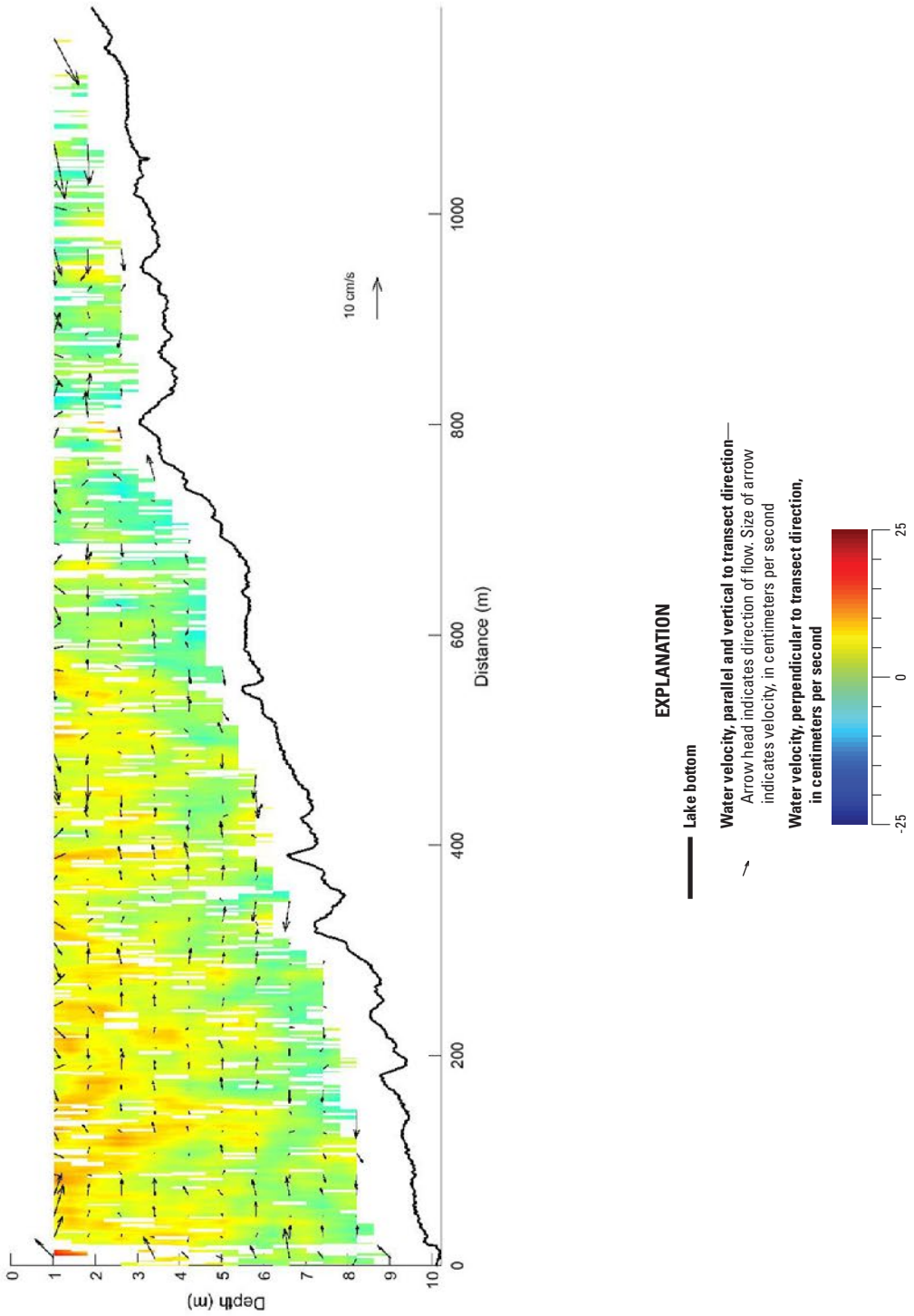
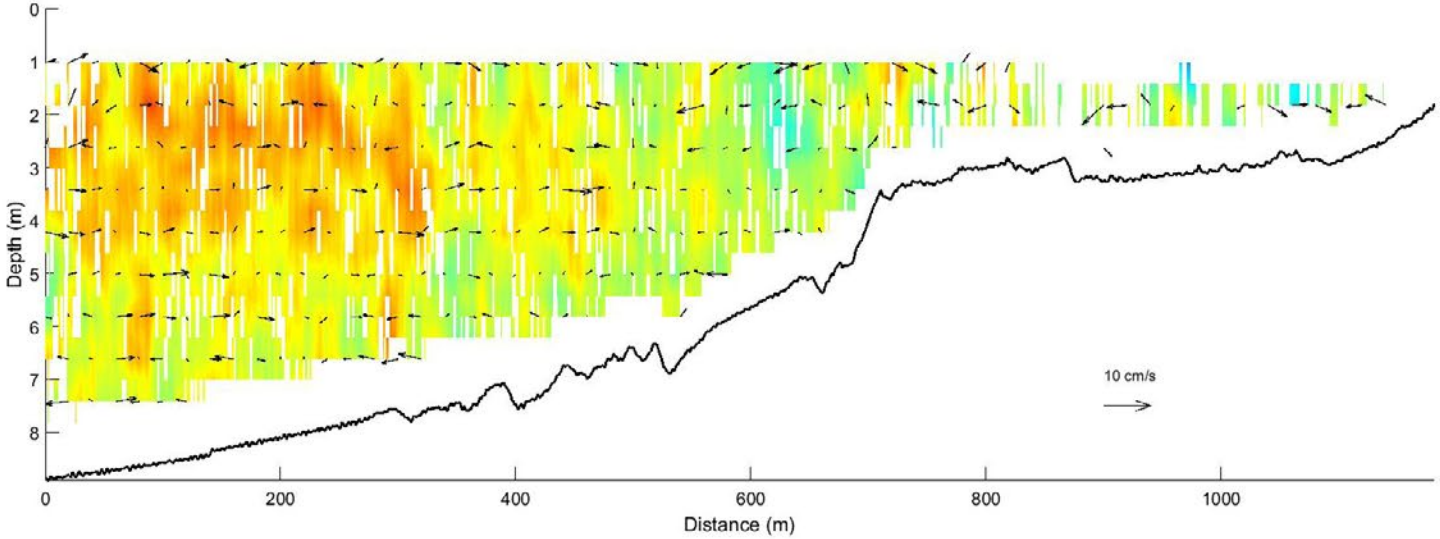


Figure 1-38. Transect 14, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)



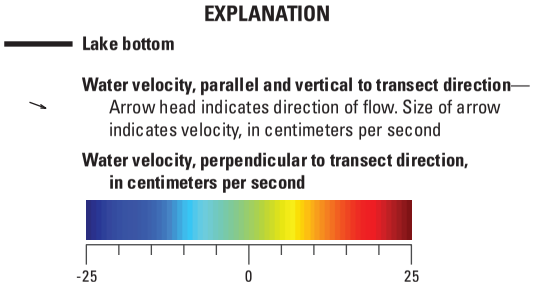


Figure 1-39. Transect 15, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

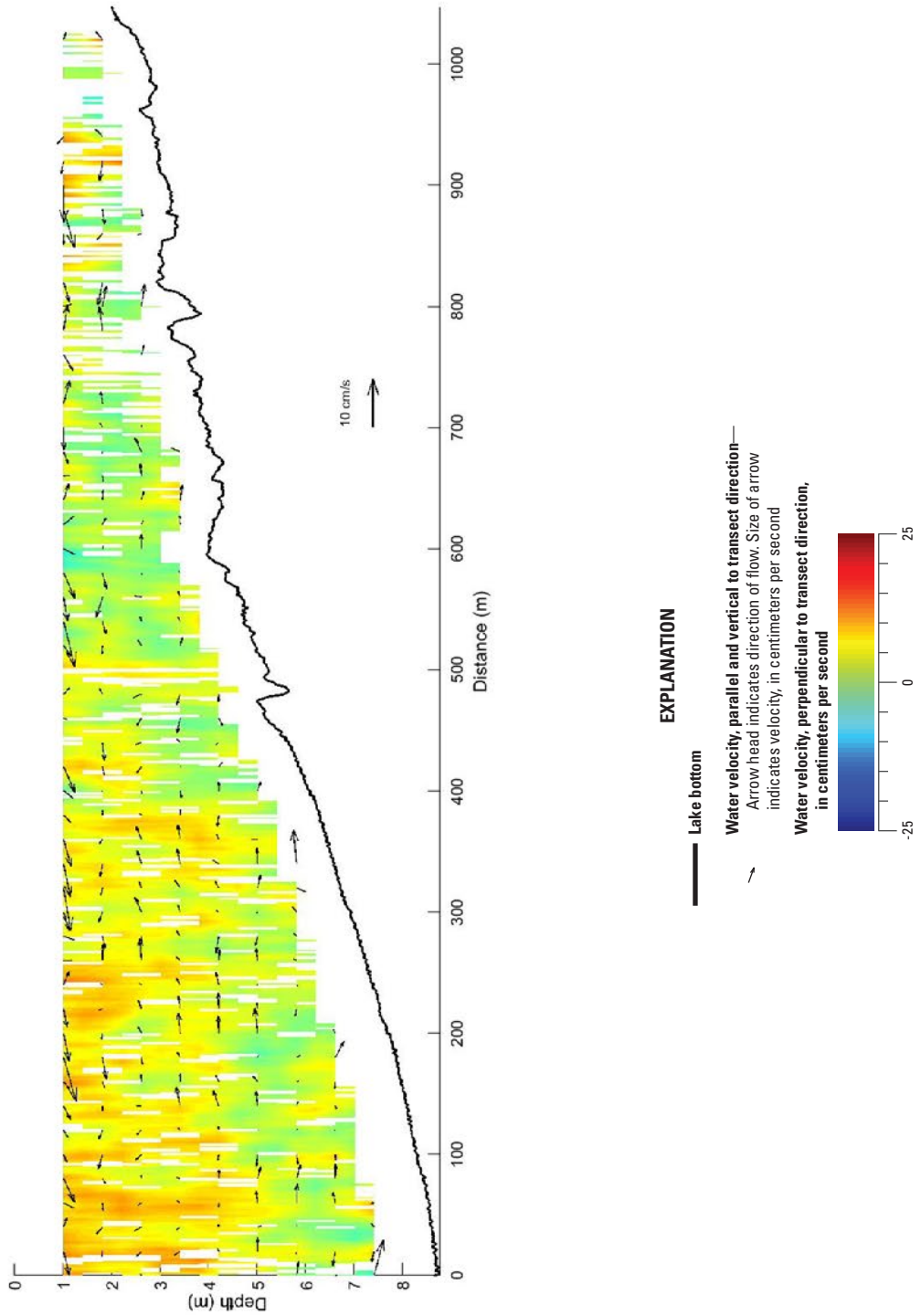
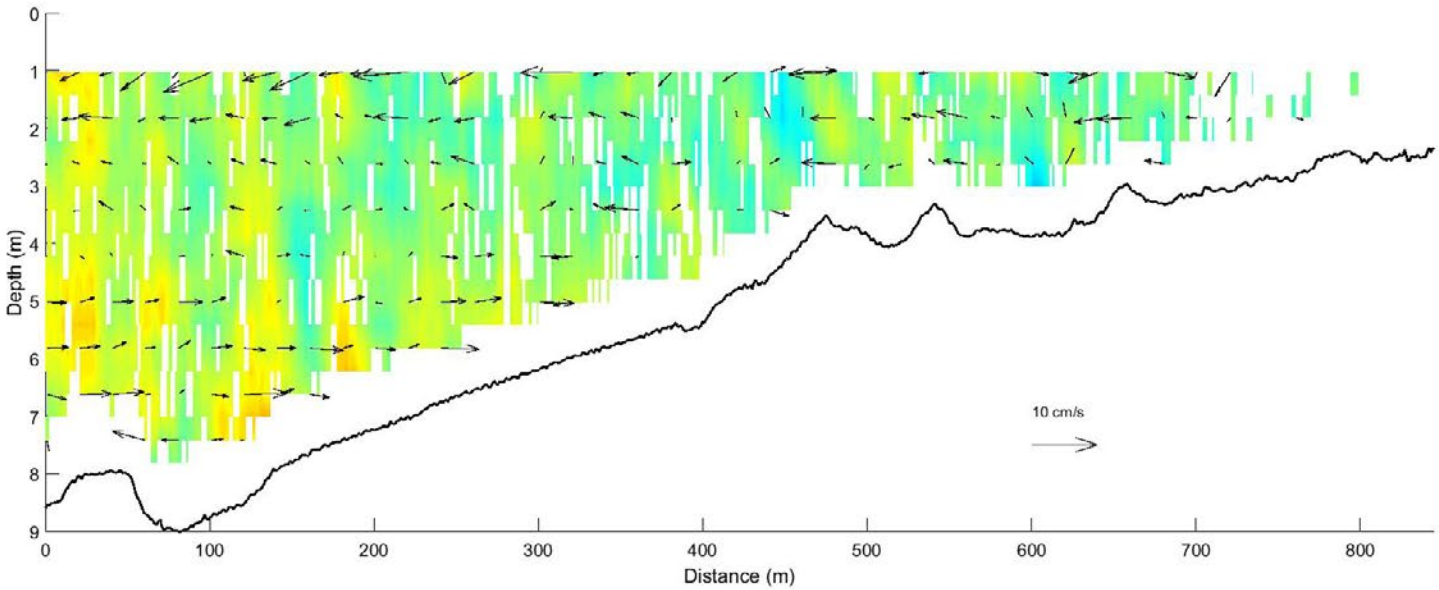


Figure 1-40. Transect 16, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)



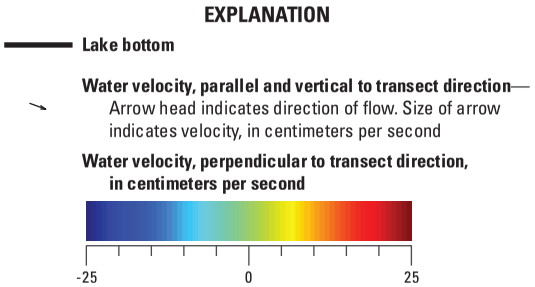


Figure 1-41. Transect 16, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

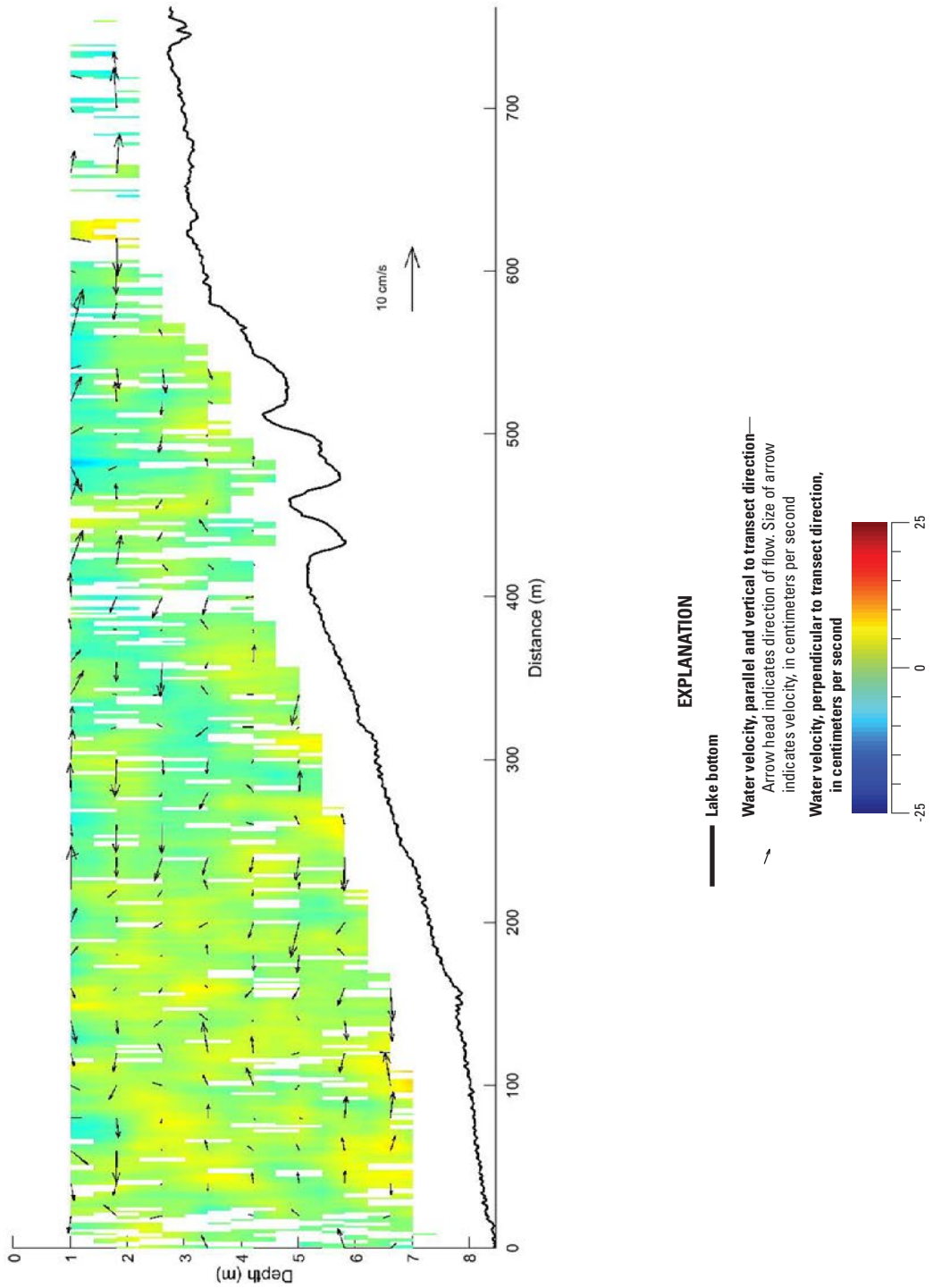
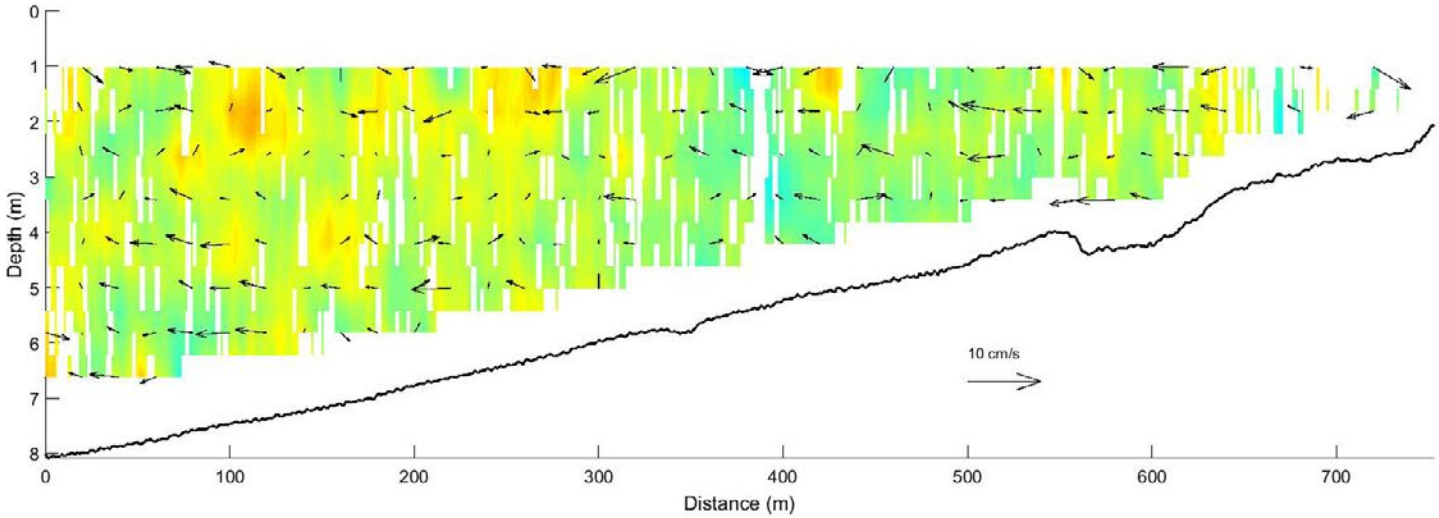


Figure 1-42. Transect 19, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)



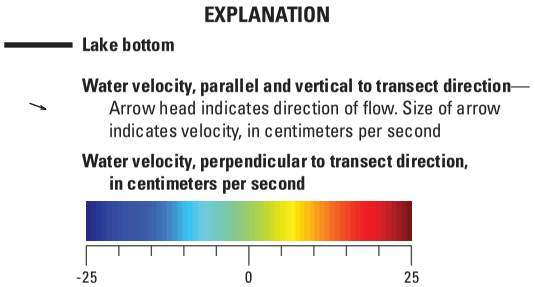


Figure 1-43. Transect 20, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

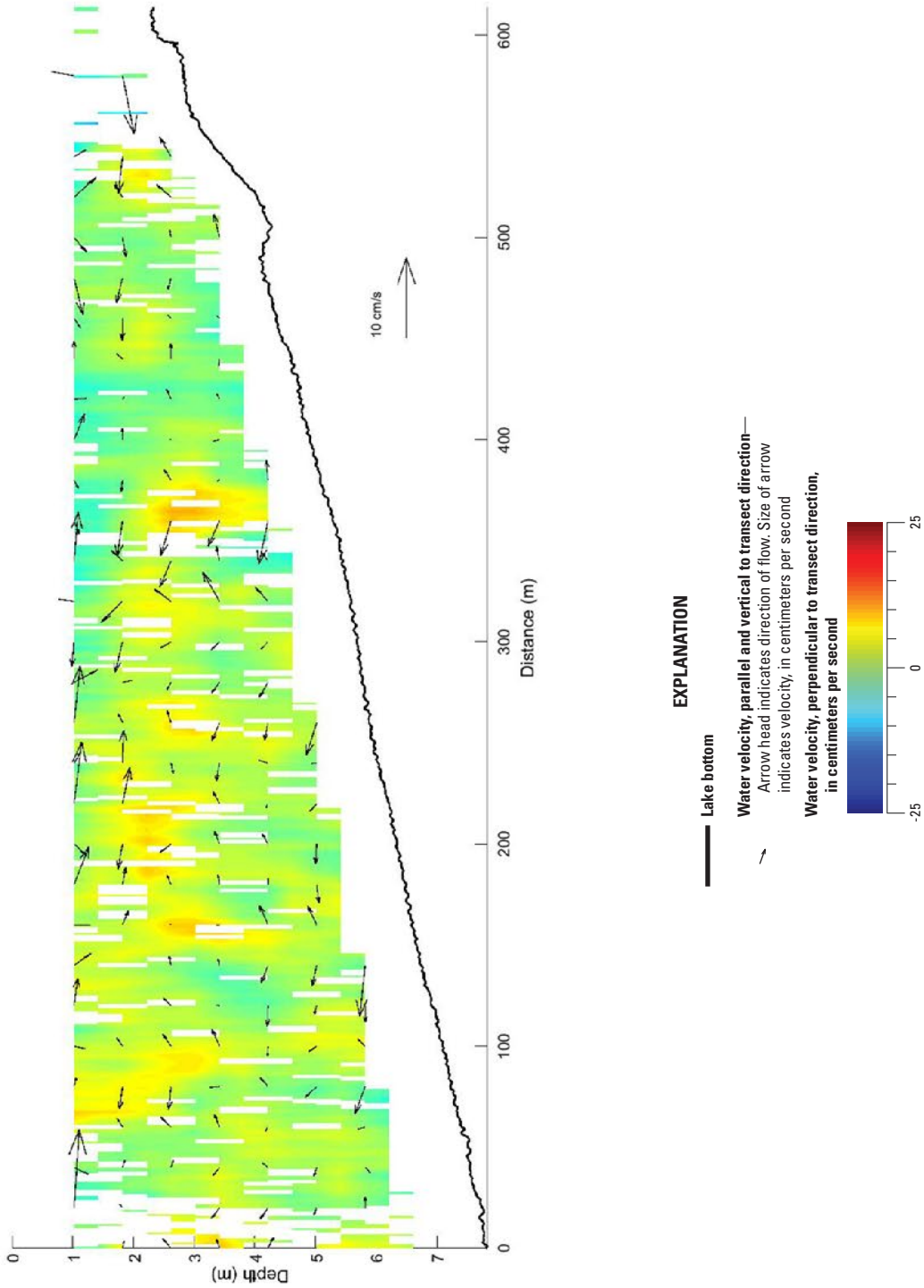
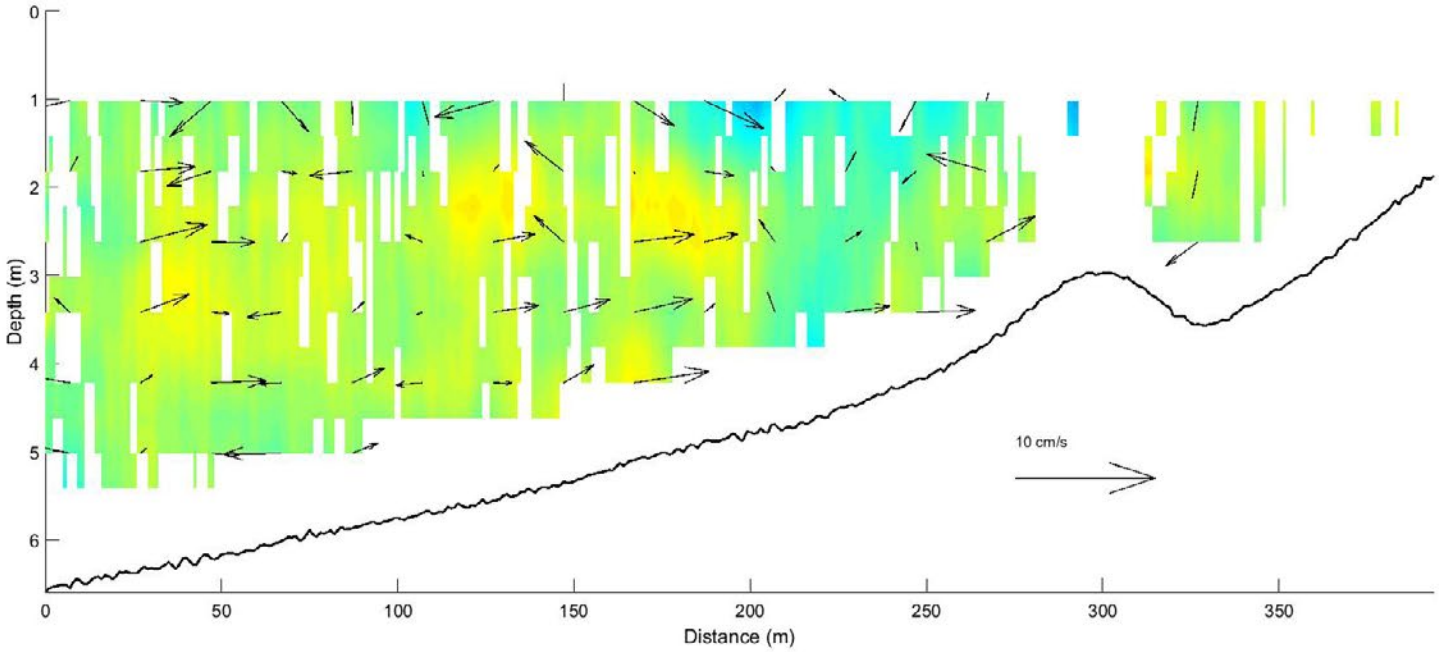


Figure 1-44. Transect 22, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

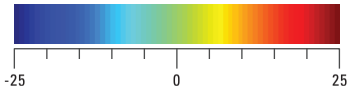


Figure 1-45. Transect 24, measured on August 18, 2015. (m, meter; cm/s, centimeters per second)

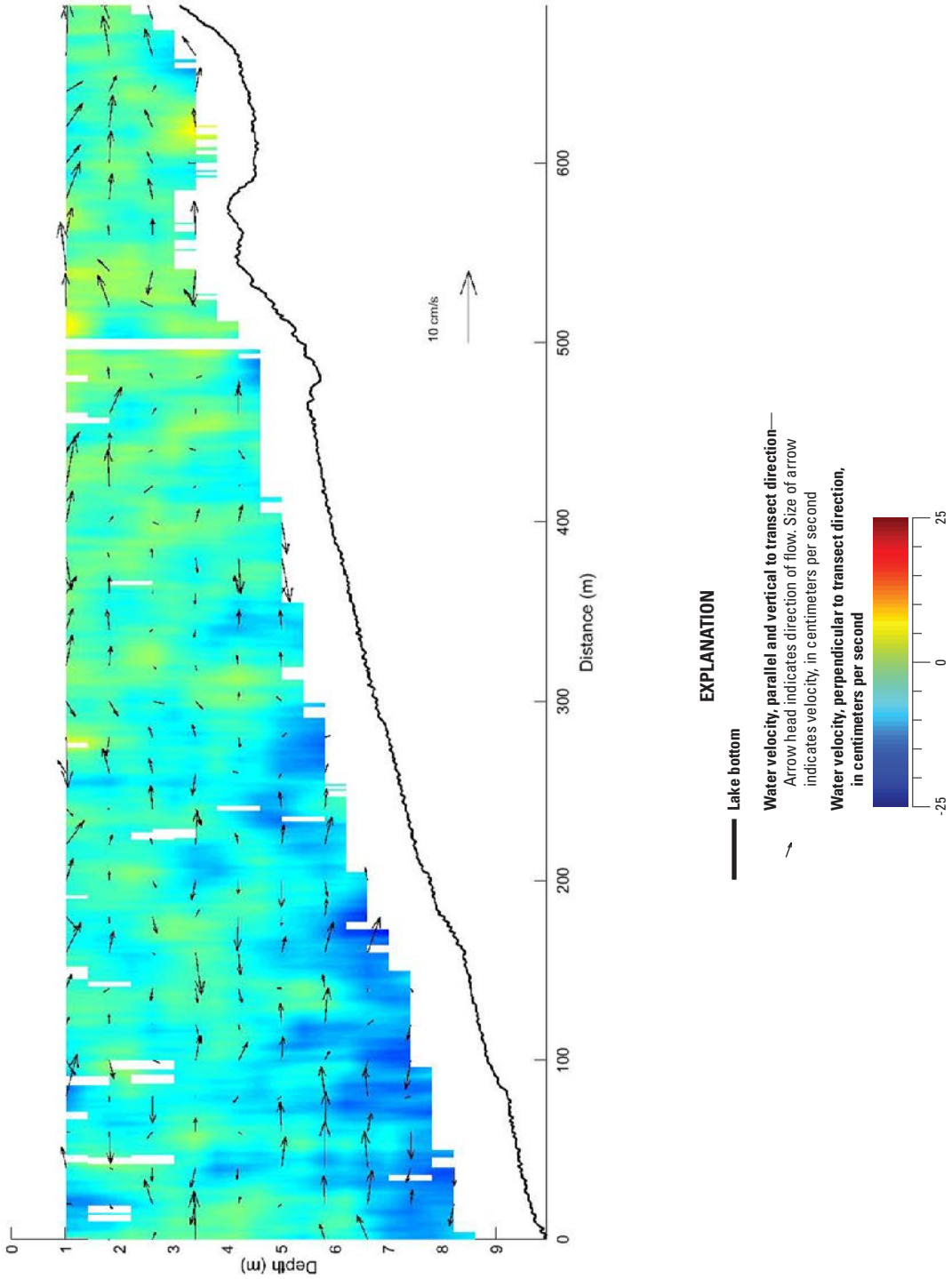
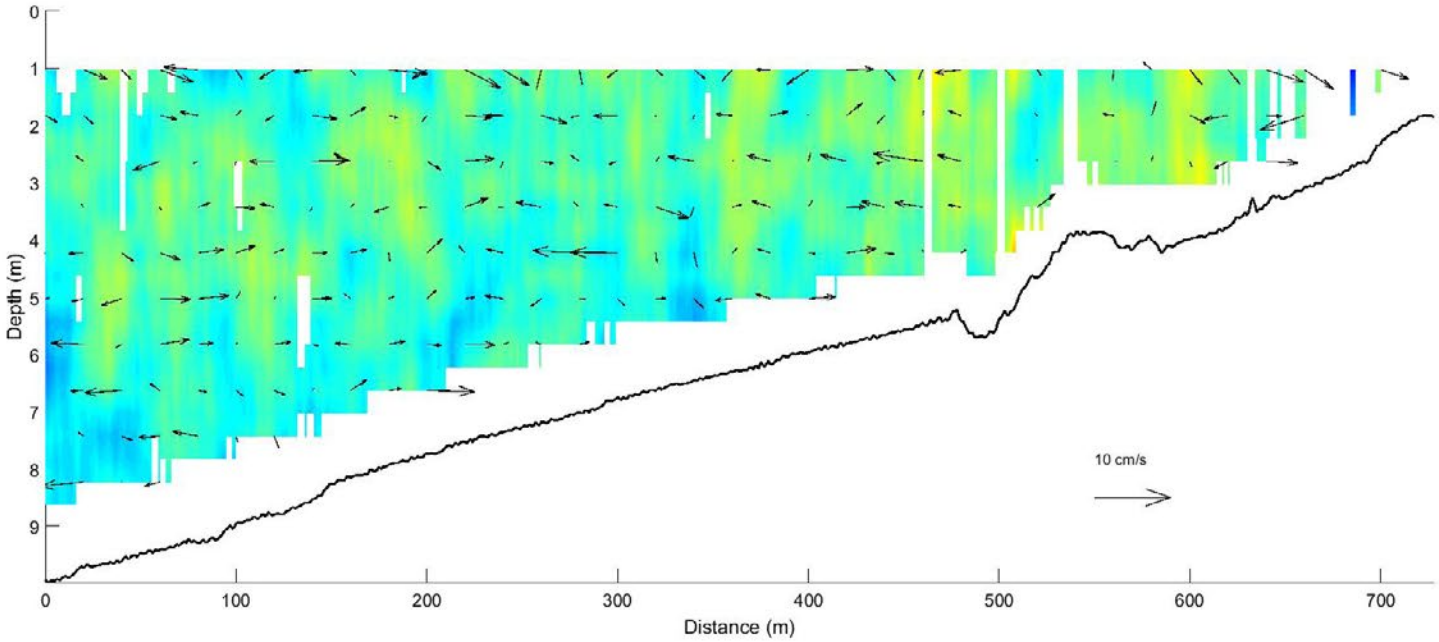


Figure 1-46. Transect 1, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

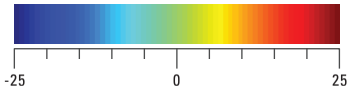


Figure 1-47. Transect 2, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

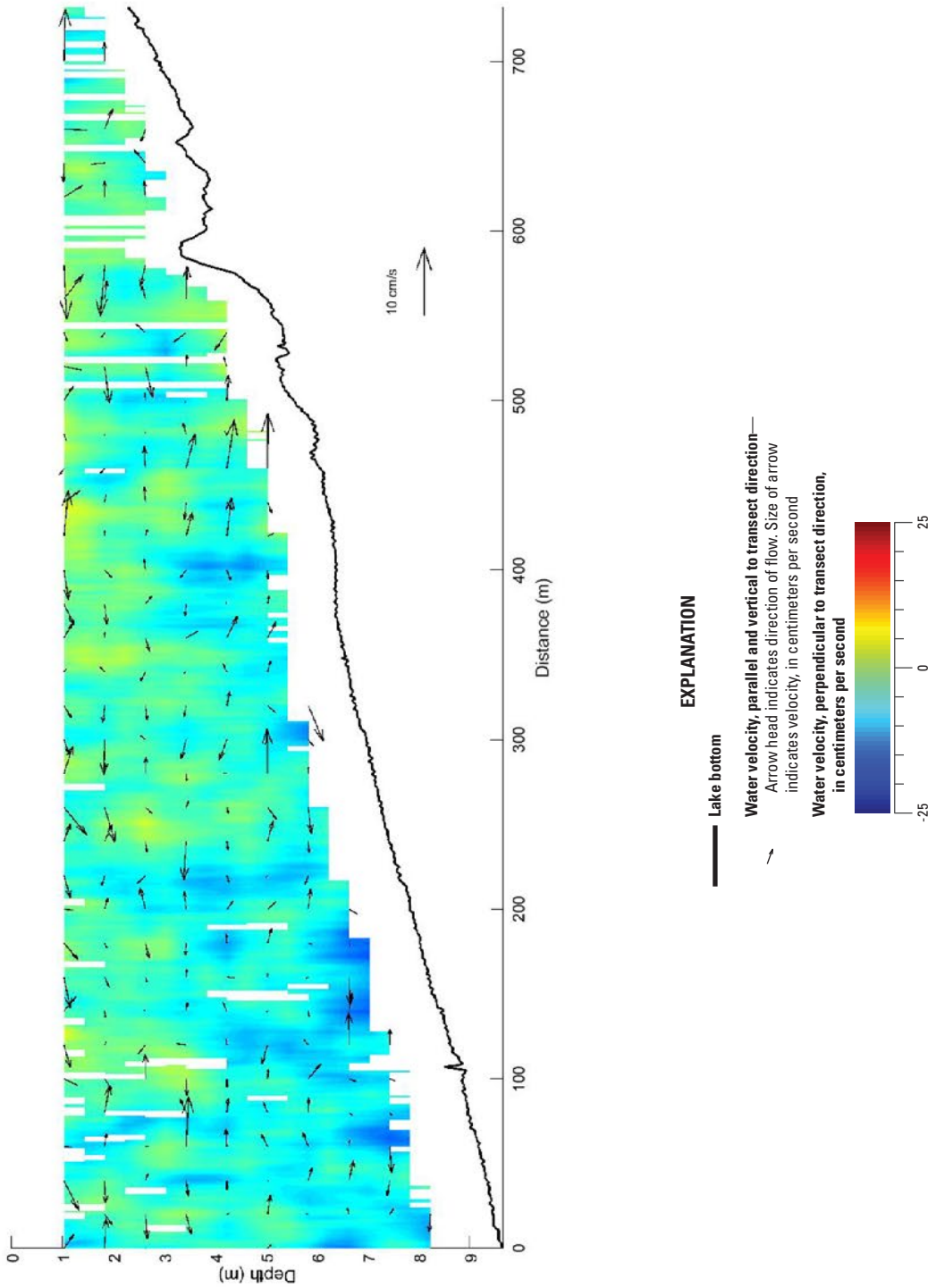


Figure 1-48. Transect 4, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

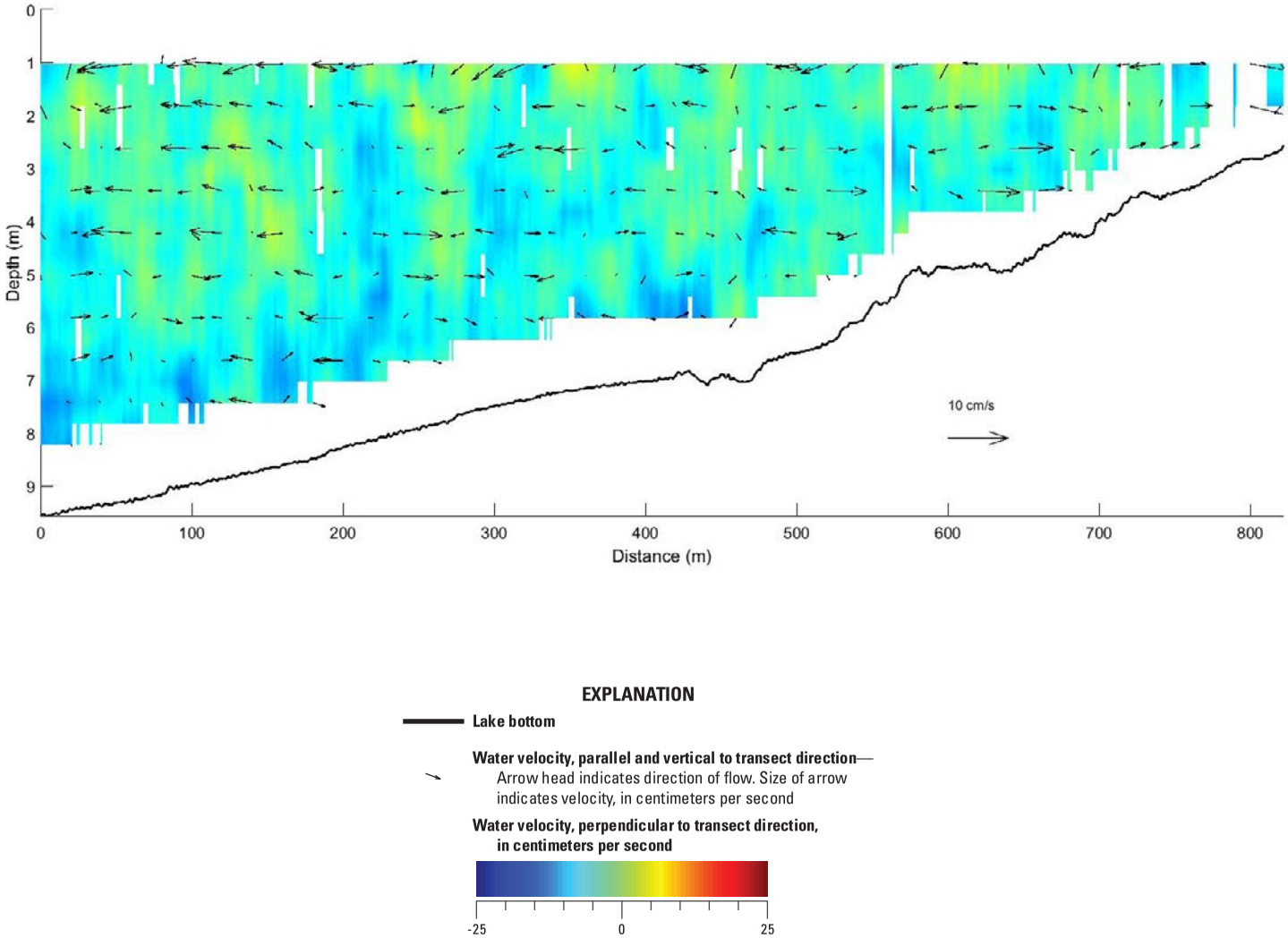


Figure 1-49. Transect 6, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

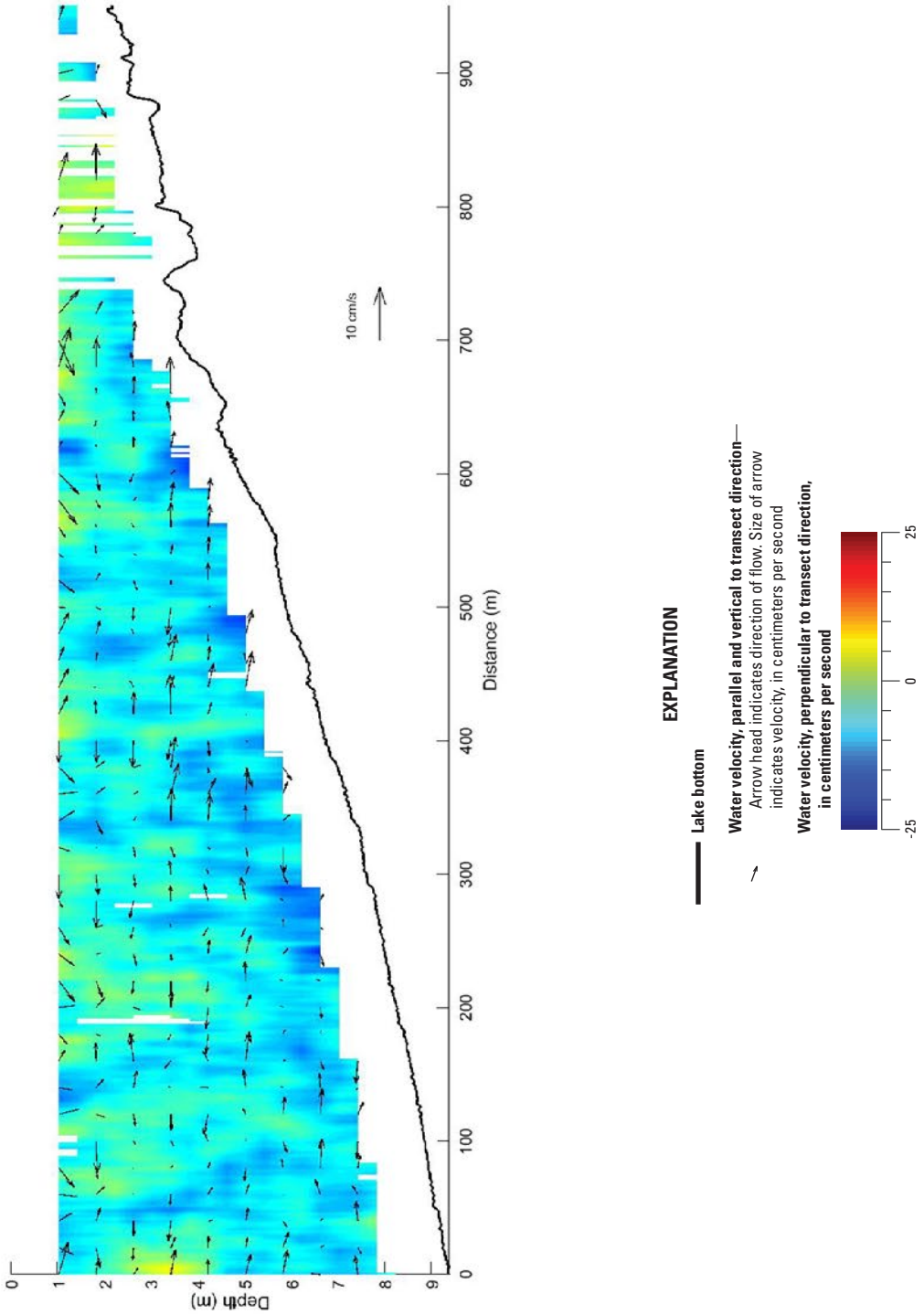


Figure 1-50. Transect 8, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

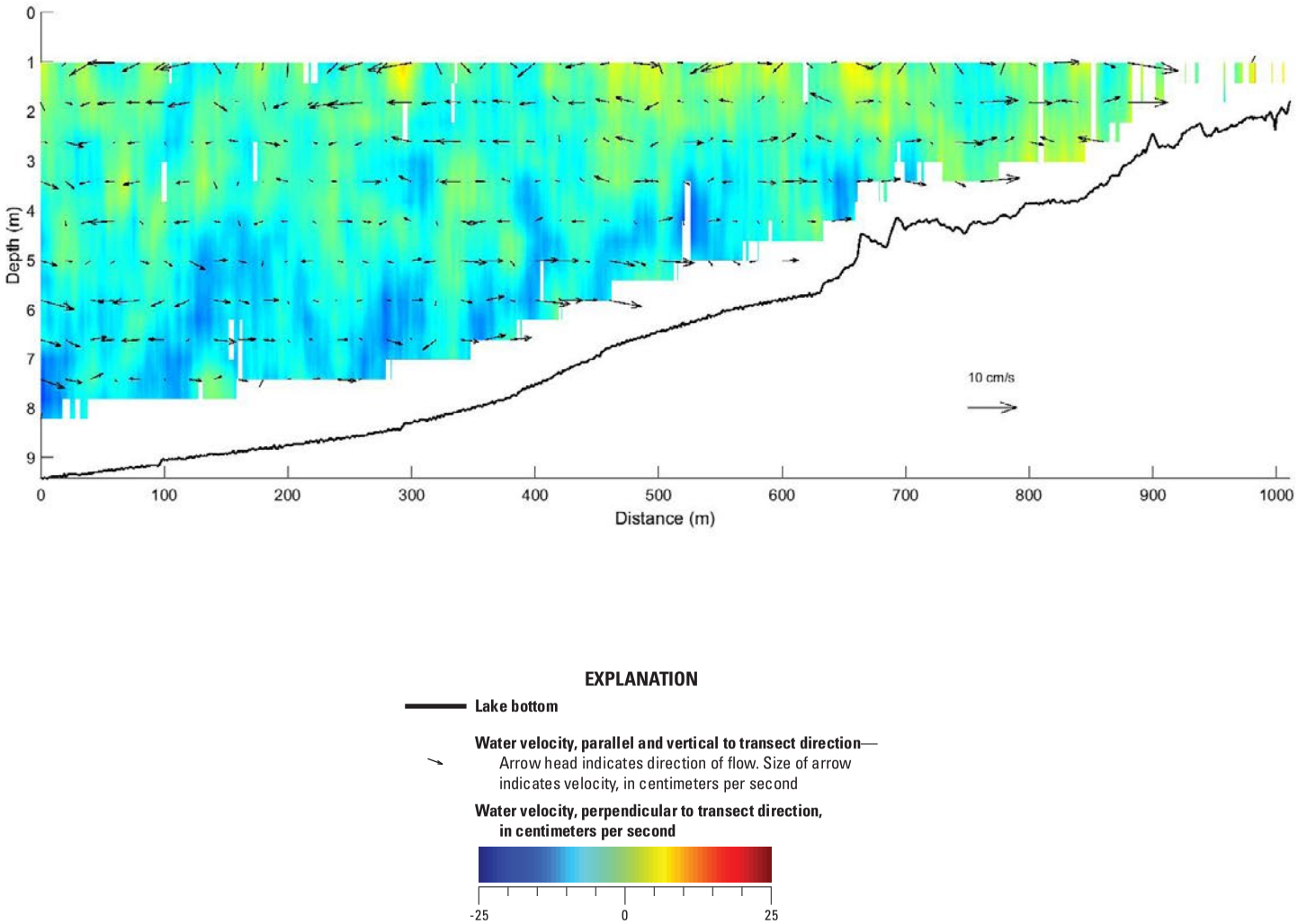


Figure 1-51. Transect 10, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

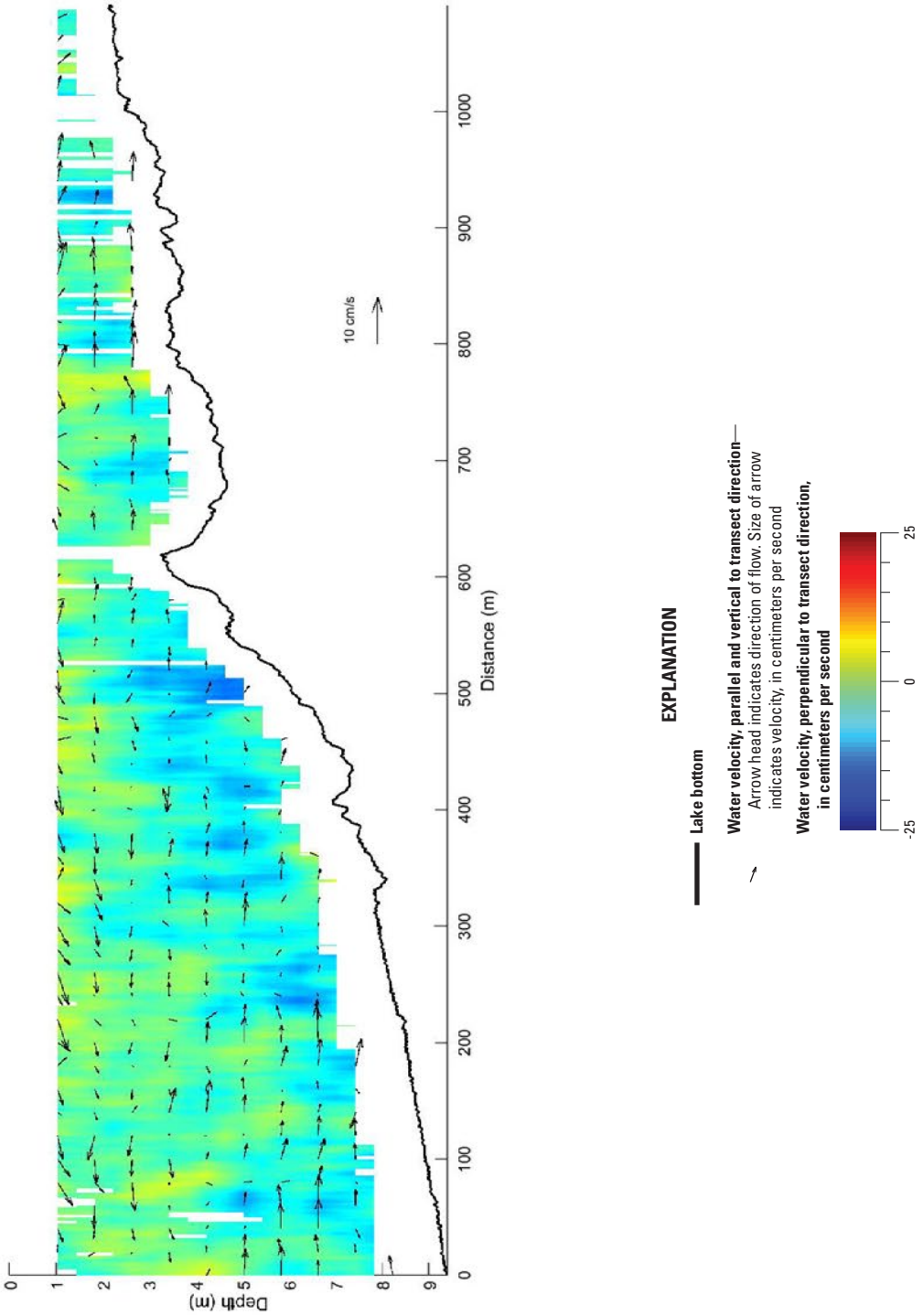
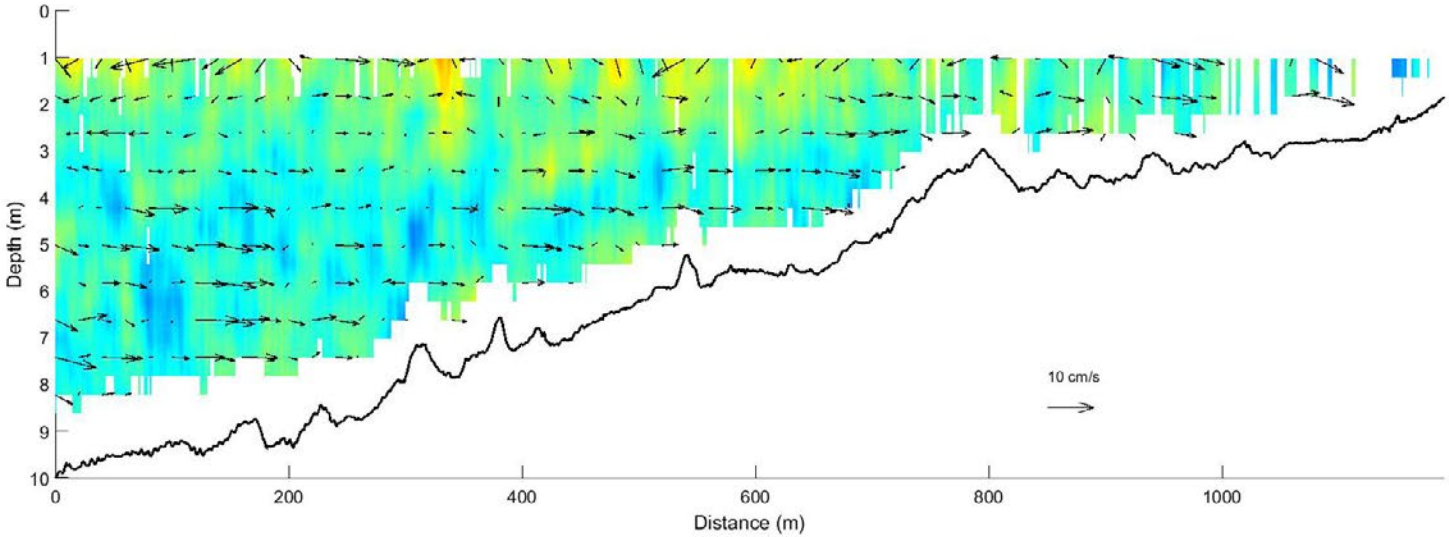


Figure 1-52. Transect 12, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

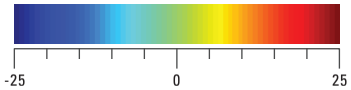


Figure 1-53. Transect 14, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

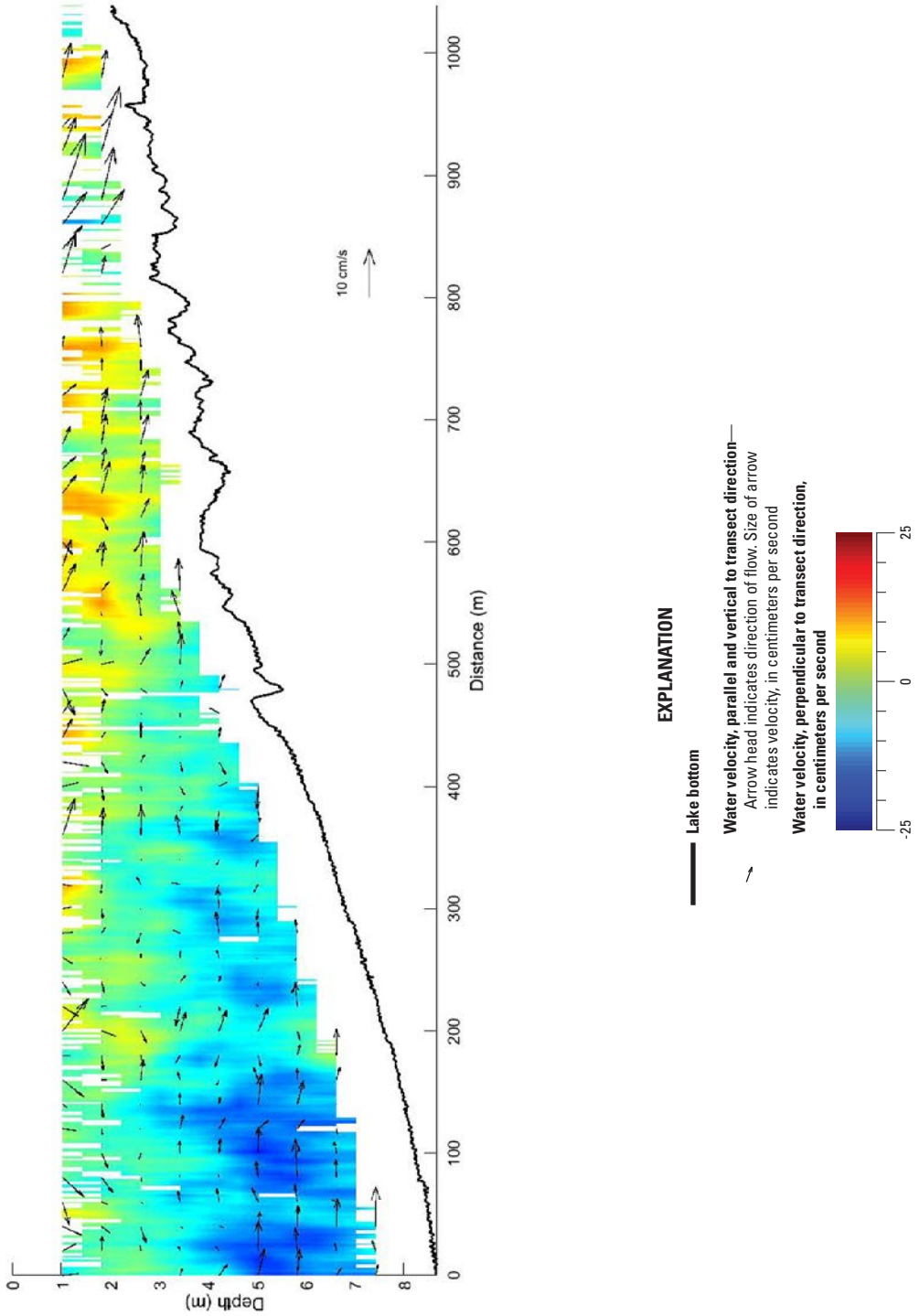
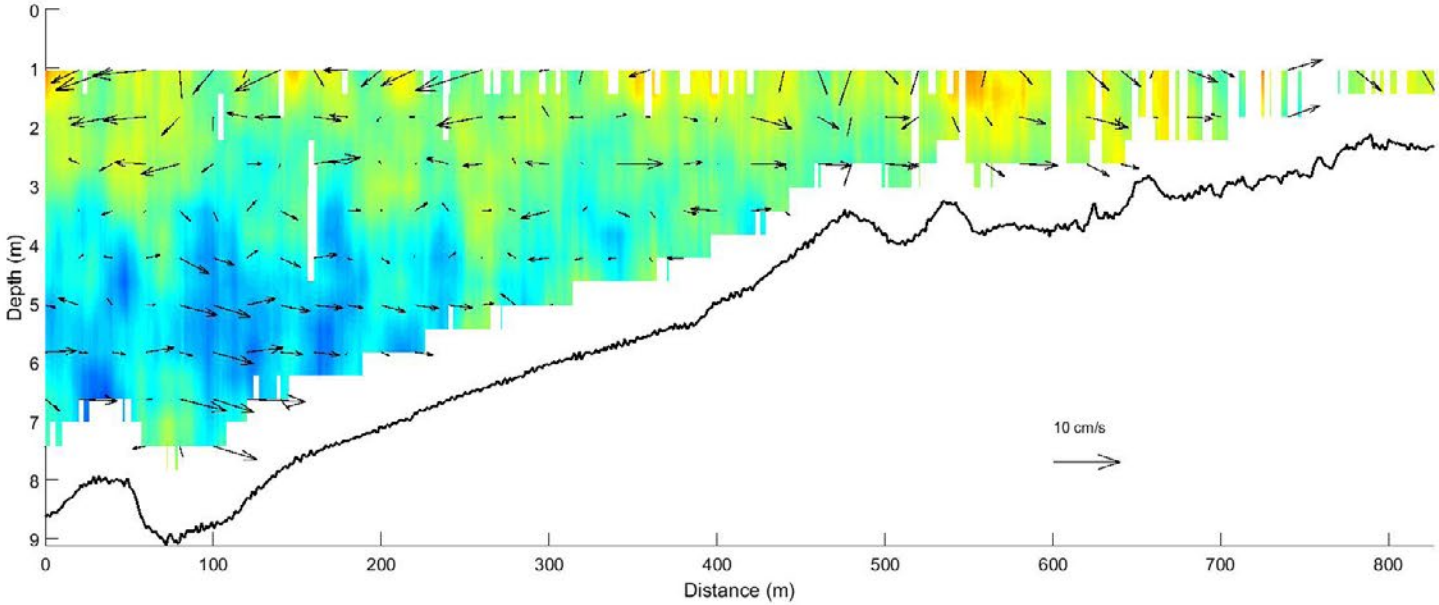


Figure 1-54. Transect 16, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)



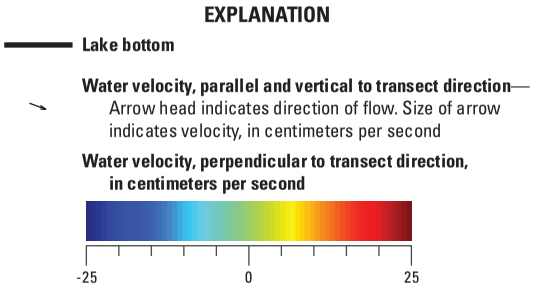


Figure 1-55. Transect 18, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

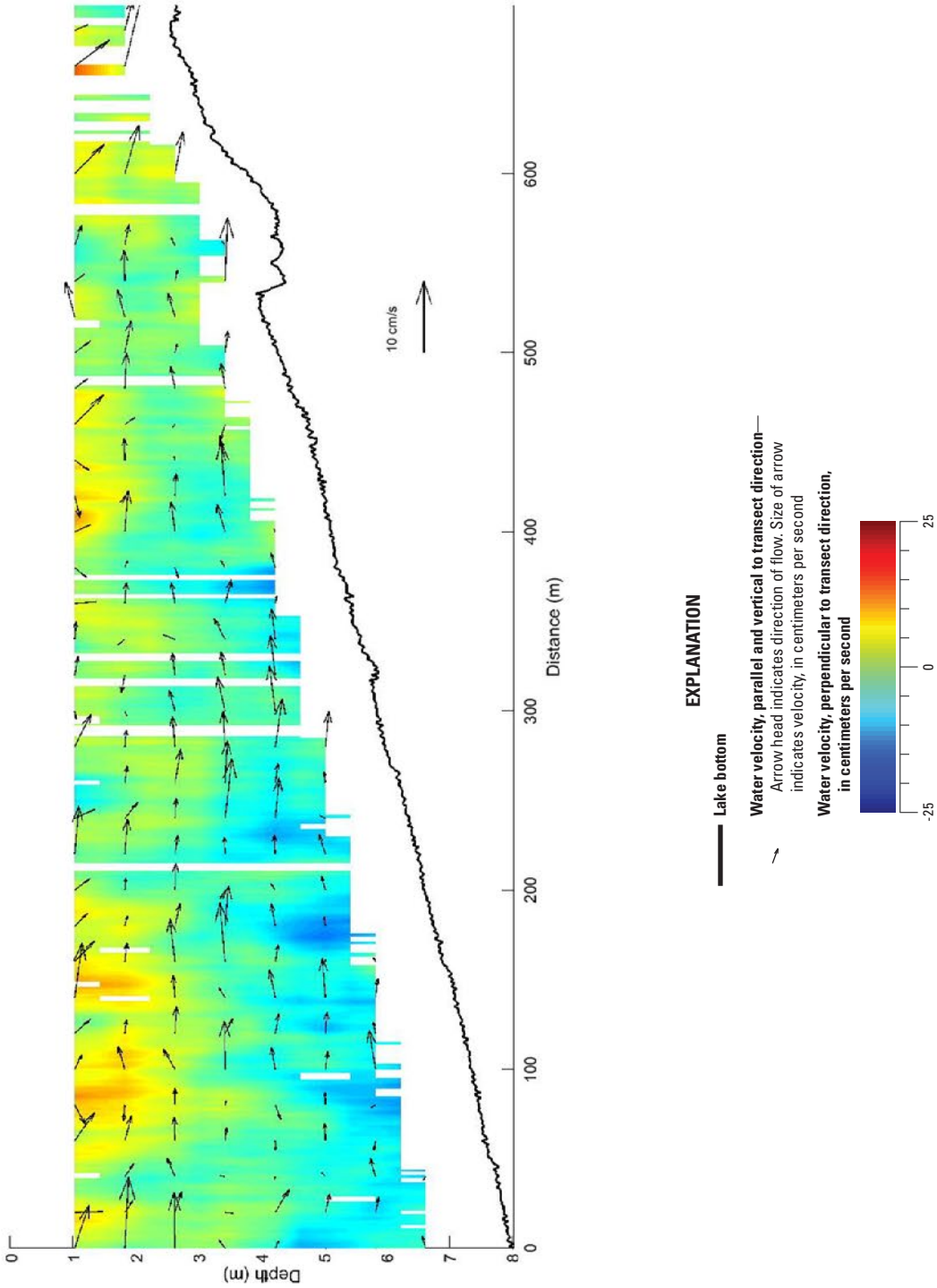
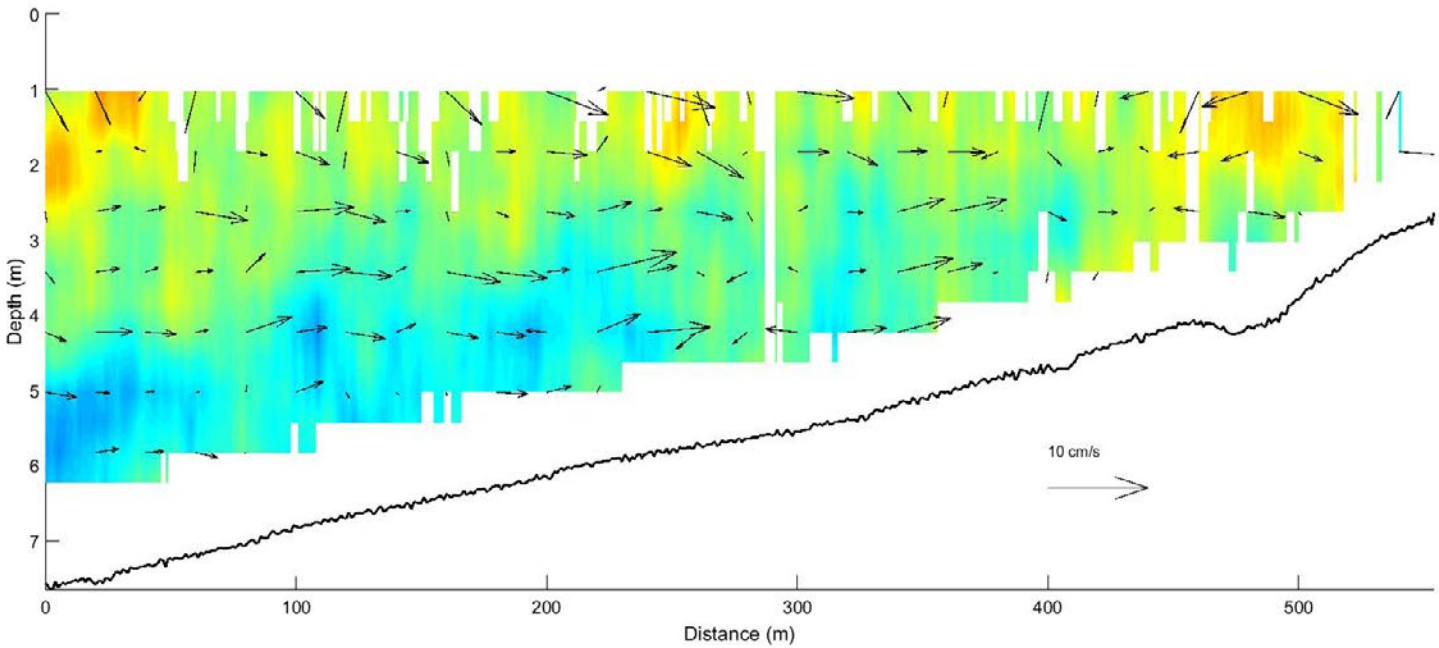


Figure 1-56. Transect 20, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)



EXPLANATION

Lake bottom

Water velocity, parallel and vertical to transect direction—Arrow head indicates direction of flow. Size of arrow indicates velocity, in centimeters per second

Water velocity, perpendicular to transect direction, in centimeters per second

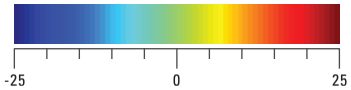


Figure 1-57. Transect 22, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

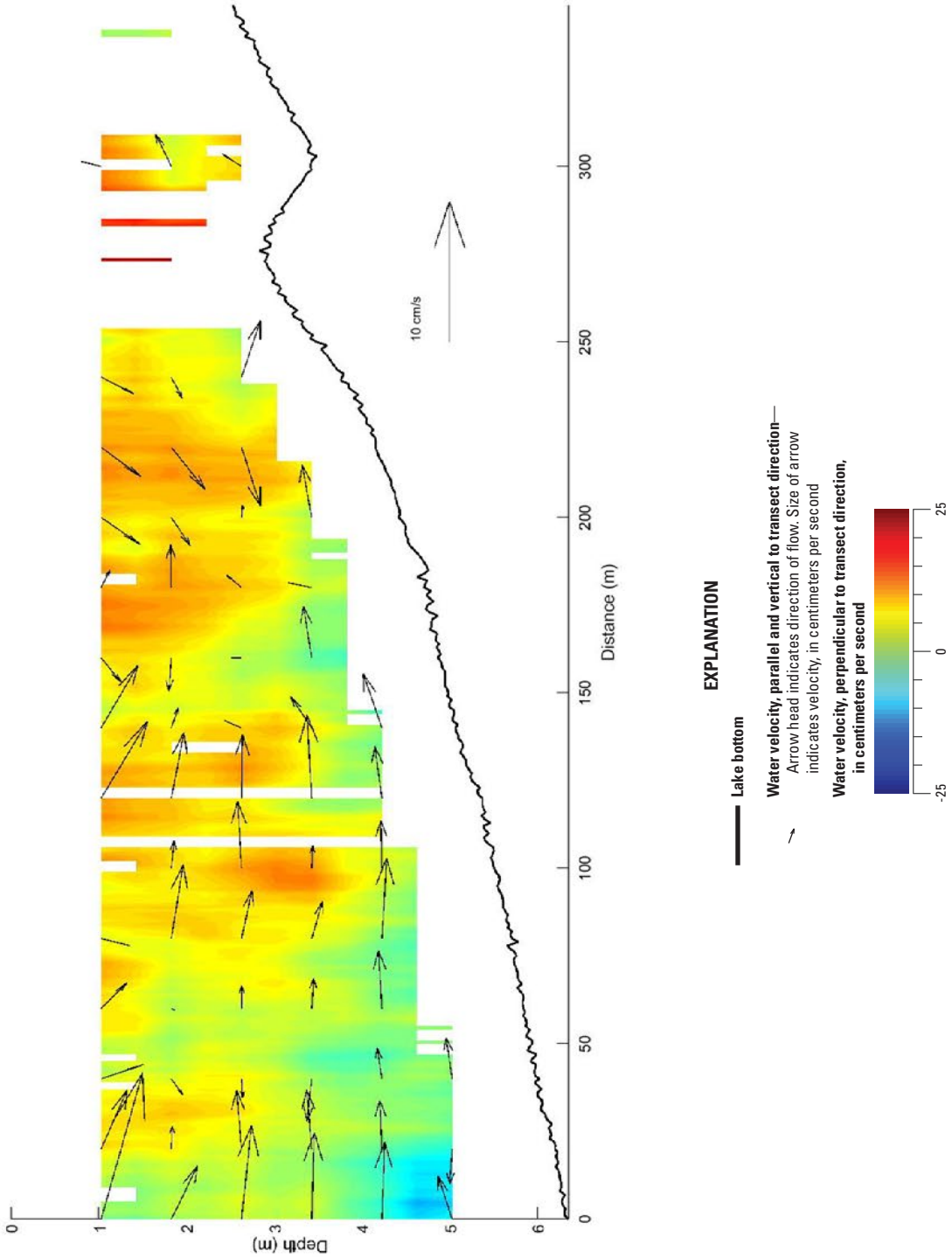


Figure 1-58. Transect 24, measured on August 19, 2015. (m, meter; cm/s, centimeters per second)

Appendix 2. Regression Statistics for Figures 23–25

Three tables which show the regression statistics in support of the regression lines in figures 23–25 are also available at https://doi.org/10.3133/ofr20161206.

- Table 2-1.csv—Statistics for regression between turbidity and *Escherichia coli* bacteria, excluding the four samples collected closest to Walnut Creek for figure 23. Waypoint 13 is included in the regression and labeled for reference.
- Table 2-2.csv—Statistics for regression between suspended sediment less than 0.125 millimeter and *Escherichia coli* bacteria, excluding waypoints 1, 2, 13, and 18, for figure 24.
- Table 2-3.csv—Statistics for regression between turbidity and suspended sediment, excluding waypoint 18 for figure 25.

Table 2-1. Statistics for regression between turbidity and *Escherichia coli* bacteria, excluding the four samples collected closest to Walnut Creek for figure 23. Waypoint 13 is included in the regression and labeled for reference.

[%, percent]

Regression statistics as output from EXCEL

Multiple R	= 0.661
R Square	= 0.437
Adjusted R Square	= 0.408
Standard error	= 24.647
Observations	= 21

ANOVA

	Degrees of freedom (df)	Sum of squares (SS)	Mean squared error (MS)	Overall F test for the null hydpothesis (F)	Significance F (Significance of the associated P-value)
Regression	1	8,966.953	8,966.953	14.762	0.001
Residual	19	11,541.618	607.454		
Total	20	20,508.571			

	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	10.894	12.241	0.89	0.385	-14.727	36.515
Turbidity	4.193	1.091	3.842	0.001	1.909	6.477

RESIDUAL OUTPUT

Waypoint	Predicted bacteria	Residual
1	52	-36
6	35	5
7	34	36
8	39	27
9	78	32
10	50	16
11	49	-9
12	61	13
13	86	-58
14	41	-25
15	52	-26
16	103	17
17	91	29
18	53	-5
19	70	-20
20	41	-3
21	48	12
22	37	-9
23	42	13
24	31	-3
25	23	-5

Table 2-2. Statistics for regression between suspended sediment less than 0.125 millimeter and *Escherichia coli* bacteria, excluding waypoints 1, 2, 13, and 18, for figure 24.

[<, less than; %, percent; SSC, suspended sedument concentration]

Regression statistics as output from EXCEL

Multiple R	= 0.708
R Square	= 0.502
Adjusted R Square	= 0.475
Standard error	= 31.315
Observations	= 21

ANOVA

	Degrees of freedom (df)	Sum of squares (SS)	Mean squared error (MS)	Overall F test for the null hydpothesis (F)	Significance F (Significance of the associated P-value)
Regression	1	18,747.959	18,747.959	19.118	0.000
Residual	19	18,631.850	980.624		
Total	20	37,379.810			

	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	5.513	15.998	0.345	0.734	-27.972	38.997
SSC < 0.125	6.885	1.575	4.372	0	3.589	10.181

RESIDUAL OUTPUT

Observation	Predicted bacteria	Residual
3	40	70
4	118	42
5	109	42
6	31	9
7	63	7
8	33	33
9	97	13
10	80	-14
11	71	-31
12	87	-13
14	40	-24
15	68	-42
16	116	4
17	93	27
19	105	-55
20	46	-8
21	60	0
22	47	-19
23	87	-33
24	33	-5
25	21	-3

Table 2-3. Statistics for regression between turbidity and suspended sediment, excluding waypoint 18, for figure 25.

[%, percent; SSC, suspended sediment concentration]

Regression statistics as output from EXCEL

Multiple R	= 0.741
R Square	= 0.549
Adjusted R square	= 0.529
Standard error	= 6.866
Observations	= 24

ANOVA

	Degrees of freedom (df)	Sum of squares (SS)	Mean squared error (MS)	Overall F test for the null hydpothesis (F)	Significance F (Significance of the associated P-value)
Regression	1	1,262.700	1,262.700	26.782	3.45E-5
Residual	22	1,037.259	47.148		
Total	23	2,299.958			

	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-2.006	3.257	-0.616	0.544	-8.761	4.748
Turbidity	1.548	0.299	5.175	0	0.928	2.168

RESIDUAL OUTPUT

Waypoint	Predicted SSC	Residual
1	13	13
2	14	-4
3	7	-2
4	13	5
5	11	11
6	7	-3
7	7	3
8	8	-4
9	23	-8
10	12	-1
11	12	-2
12	17	-5
13	26	1
14	9	-4
15	13	-4
16	32	7
17	27	-14
19	20	16
20	9	-3
21	12	-3
22	8	-1
23	9	3
24	6	-2
25	3	1

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