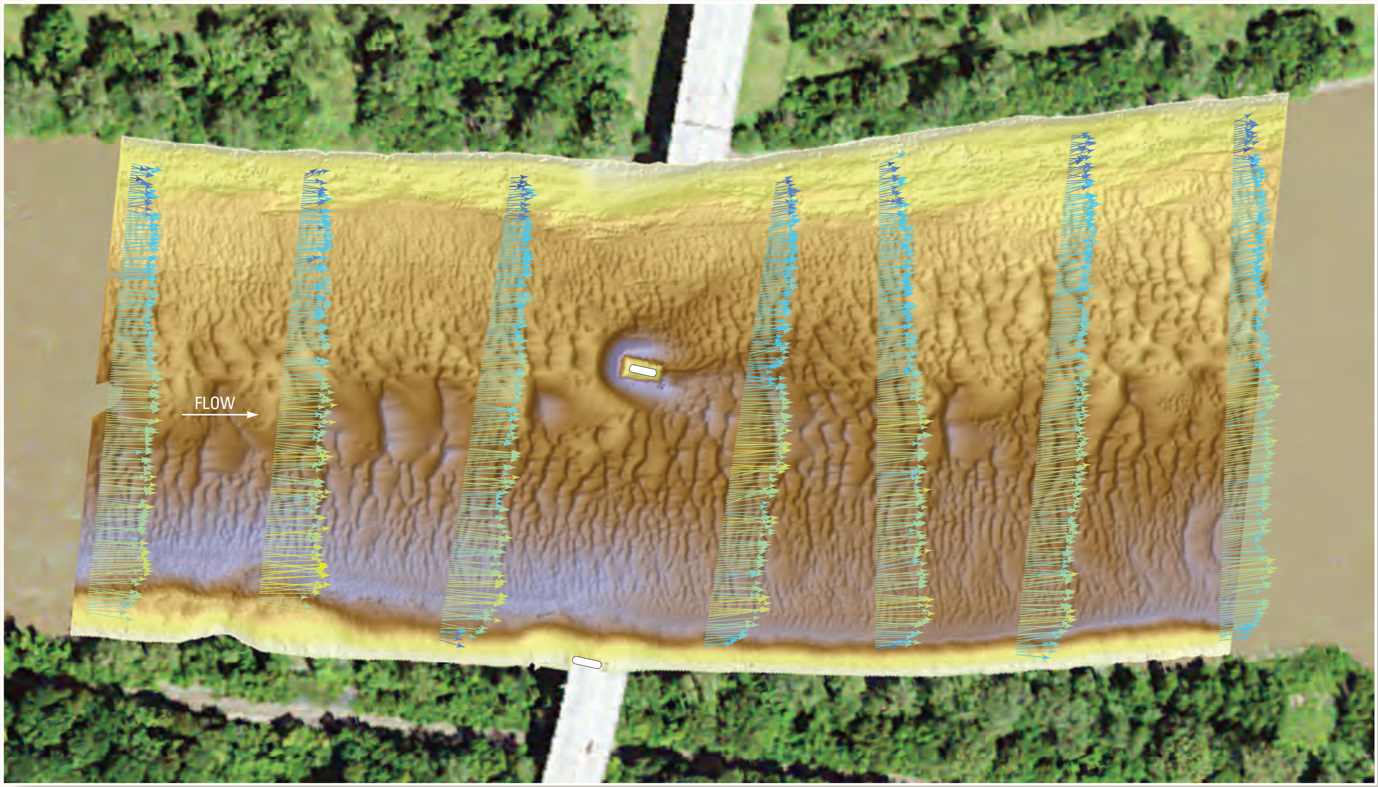
Prepared in cooperation with the Missouri Department of Transportation

# Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri River near Kansas City, Missouri, June 2–4, 2015




Scientific Investigations Report 2016–5061

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

**Front cover:** Bathymetry and vertically averaged velocities of the Missouri River channel near structure A1800 on Interstate 635 near Kansas City, Missouri, on June 2, 2015.

**Back cover:** Top: Shaded triangulated irregular network (TIN) visualization of the channel bed and A, left (northeast) side and B, right (southwest) side of main channel pier 3 of structure A1800 on Interstate 635 crossing the Missouri River near Kansas City, Missouri, on June 2, 2015. Bottom: The U.S. Geological Survey boat preparing for the bathymetric and velocimetric surveys at bridges near Kansas City, Missouri, on June 4, 2015.

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By Richard J. Huizinga

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

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

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

U.S. Geological Survey, Reston, Virginia: 2016

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## Conversion Factors

U.S. customary units to International System of Units

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Volume | |
| cubic yard ($yd^3$) | 0.7646 | cubic meter ($m^3$) |
| | Flow rate | |
| foot per second (ft/s) | 0.3048 | meter per second (m/s) |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second ($m^3/s$) |

## Datum

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

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

## Supplemental Information

In this report, the words “left” and “right” generally refer to directions that would be reported by an observer facing downstream.

Distance on the Missouri River is given in river miles (RM) upstream from the confluence with the Mississippi River.

Frequency is given in kilohertz (kHz).

Data were collected, processed, and output in the International System of Units, and converted to inch/pound units for presentation in the report at the request and for the convenience of the cooperator.

## Abbreviations

| | |
|---|---|
| ADCP | acoustic Doppler current profiler |
| CUBE | Combined Uncertainty Bathymetric Estimator |
| GGA | shorthand for the $GPGGA standard output format for Global Navigation Satellite System (GNSS) essential fix data defined by the National Marine Electronics Association (NMEA)-0183 standard that includes information on the three-dimensional location and accuracy of the GNSS receiver (National Marine Electronics Association, 2002) |
| GNSS | Global Navigation Satellite System |
| IMU | inertial motion unit |
| INS | inertial navigation system |
| MBES | multibeam echosounder (the sonar system) |
| MBMS | multibeam echosounder mapping system (the sonar, navigation, and data acquisition system) |
| MMS™ | POS-Pac™ Mobile Mapping Suite (the navigation solution post-processing software) |
| MoDOT | Missouri Department of Transportation |
| NMEA | National Marine Electronics Association |
| POS MV™ | Position Orientation Solution for Marine Vessels (the inertial navigation system) |
| RTK | real-time kinematic (a type of differential correction for navigation with GNSS) |
| SBET | standard best estimate of travel (a postprocessed navigation solution) |
| TIN | triangulated irregular network |
| TPU | total propagated uncertainty |
| USGS | U.S. Geological Survey |
| VMT | Velocity Mapping Toolbox (Parsons and others, 2013) |

# Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri River near Kansas City, Missouri, June 2–4, 2015

By Richard J. Huizinga


## Abstract

Bathymetric and velocimetric data were collected by the U.S. Geological Survey, in cooperation with the Missouri Department of Transportation, near 8 bridges at 7 highway crossings of the Missouri River in Kansas City, Missouri, from June 2 to 4, 2015. A multibeam echosounder mapping system was used to obtain channel-bed elevations for river reaches ranging from 1,640 to 1,660 feet longitudinally and extending laterally across the active channel from bank to bank during low to moderate flood flow conditions. These bathymetric surveys indicate the channel conditions at the time of the surveys and provide characteristics of scour holes that may be useful in the development of predictive guidelines or equations for scour holes. These data also may be useful to the Missouri Department of Transportation as a low to moderate flood flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour during floods.

Bathymetric data were collected around every pier that was in water, except those at the edge of water or surrounded by a debris raft, and scour holes were observed at most surveyed piers. The observed scour holes at the surveyed bridges were examined with respect to shape and depth. Although exposure of parts of substructural support elements was observed at several piers, the exposure likely can be considered minimal compared to the overall substructure that remains buried in bed material at these piers.

The frontal slope values determined for scour holes observed in the current (2015) study generally are similar to recommended values in the literature and values determined for scour holes in previous bathymetric surveys. Several of the structures had piers that were skewed to primary approach flow, and generally the scour hole was deeper and longer on the side of the pier with impinging flow, with some amount of deposition on the leeward side, typical of conditions observed at piers skewed to approach flow; however, at structure A7650 (site 10), the scour hole was deeper and longer on the leeward side of the pier, possibly because of a deflection and contraction of flow caused by a protrusion of the corresponding bank at the bridge.

Previous bathymetric surveys exist for all the sites examined in this study. Comparisons between bathymetric surfaces from the previous surveys (in March 2010 and during the 2011 flood) and those of this study do not indicate any consistent correlation in channel-bed elevations with flow conditions. A simplified assumption of equal to lesser magnitude scour for the lower discharge in the 2015 surveys did not consistently prove to be true, particularly in respect to the depth of observed scour near the piers when compared to results collected during the 2011 flood.

A local spatial minimum average channel-bed elevation at structure A7650 (site 10) compared to adjacent sites may indicate this site is at or near a local feature that controls sediment deposition and scour. The average channel-bed elevation values and the distribution of channel-bed elevations imply that sediment unable to deposit near structure A7650 is flushed downstream and deposits at the next downstream site, structure A5817 (site 11).


## Introduction

Scour in alluvial channels is the removal of channel bed and bank material by flowing water and is the leading cause of bridge failures in the United States (Richardson and Davis, 2001). Scour at a bridge site is the result of short- and long-term geomorphic processes and the local effects caused by elements of the structure in or adjacent to the waterway (Richardson and Davis, 2001; Huizinga and Rydlund, 2004). Because the effects of scour can be severe and dangerous, bridges and other structures over waterways are routinely assessed and inspected. Scour processes can be exacerbated during high-flow conditions because velocity and depth typically increase during high-flow conditions.

The Missouri Department of Transportation (MoDOT) is responsible for most of the transportation infrastructure in the State. A part of this responsibility is fulfilled through periodic inspections of highway structures, including bridges that span waterways. At most of these structures, all or most of the structure can be fully inspected from land or personnel lift trucks deployed from the roadway of the structure; however, for structures over primary waterways, such as the Missouri River, inspection of the part of the bridge that is underwater requires a different approach.

The U.S. Geological Survey (USGS), in cooperation with MoDOT, began assessing scour at waterway crossings throughout the State in 1991 (Huizinga and Rydlund, 2004). In 2007, the USGS, in cooperation with MoDOT, began determining channel bathymetry and monitoring bridges for scour using single-beam echosounders and a multibeam echosounder mapping system (MBMS; Rydlund, 2009; Huizinga, 2010, 2011, 2013, 2014, 2015; Huizinga and others, 2010). In particular, the MBMS has proven to be a useful tool not only in determining channel bathymetry but also in providing a medium- to high-resolution representation of bridge structural elements below the water line. In 2010, the USGS, in cooperation with MoDOT, began collecting bathymetric data at various highway bridges across primary waterways in Missouri. In March 2010, 9 highway bridges at 7 crossings over the Missouri River near Kansas City, Missouri, were assessed using the MBMS (Huizinga, 2010); and in October 2010, 12 highway bridges at 7 crossings over the Missouri and Mississippi Rivers near St. Louis, Mo., were assessed (Huizinga, 2011). During high-flow conditions in June–August 2011, many of the highway bridges and several of the railroad bridges along the entirety of the Missouri River downstream from Montana were assessed (Densmore and others, 2013; Dietsch and others, 2014), including the 37 highway bridges (at 28 crossings) that span the Missouri River in and into Missouri (Huizinga, 2012). In April and May 2013, 10 highway bridges at 9 crossings over the Missouri River between Kansas City and St. Louis, Mo., were assessed as part of more routine, nonflood surveys at bridge sites in and into Missouri (Huizinga, 2014). In June 2014, 8 highway bridges at 7 crossings over the Missouri and Mississippi Rivers on the periphery of Missouri also were assessed as part of the routine, nonflood surveys at bridge sites (Huizinga, 2015).

The current (2015) study is the second round of routine, nonflood surveys at the highway bridges across the Missouri River in Kansas City, Mo. (fig. 1), and entails 8 bridges at 7 crossings (table 1). Two bridges at one crossing that were part of the previous surveys in Kansas City (structures K0456 and A0450 on U.S. Highway 69; Huizinga, 2010, 2012) currently (2015) are being replaced and were not surveyed as part

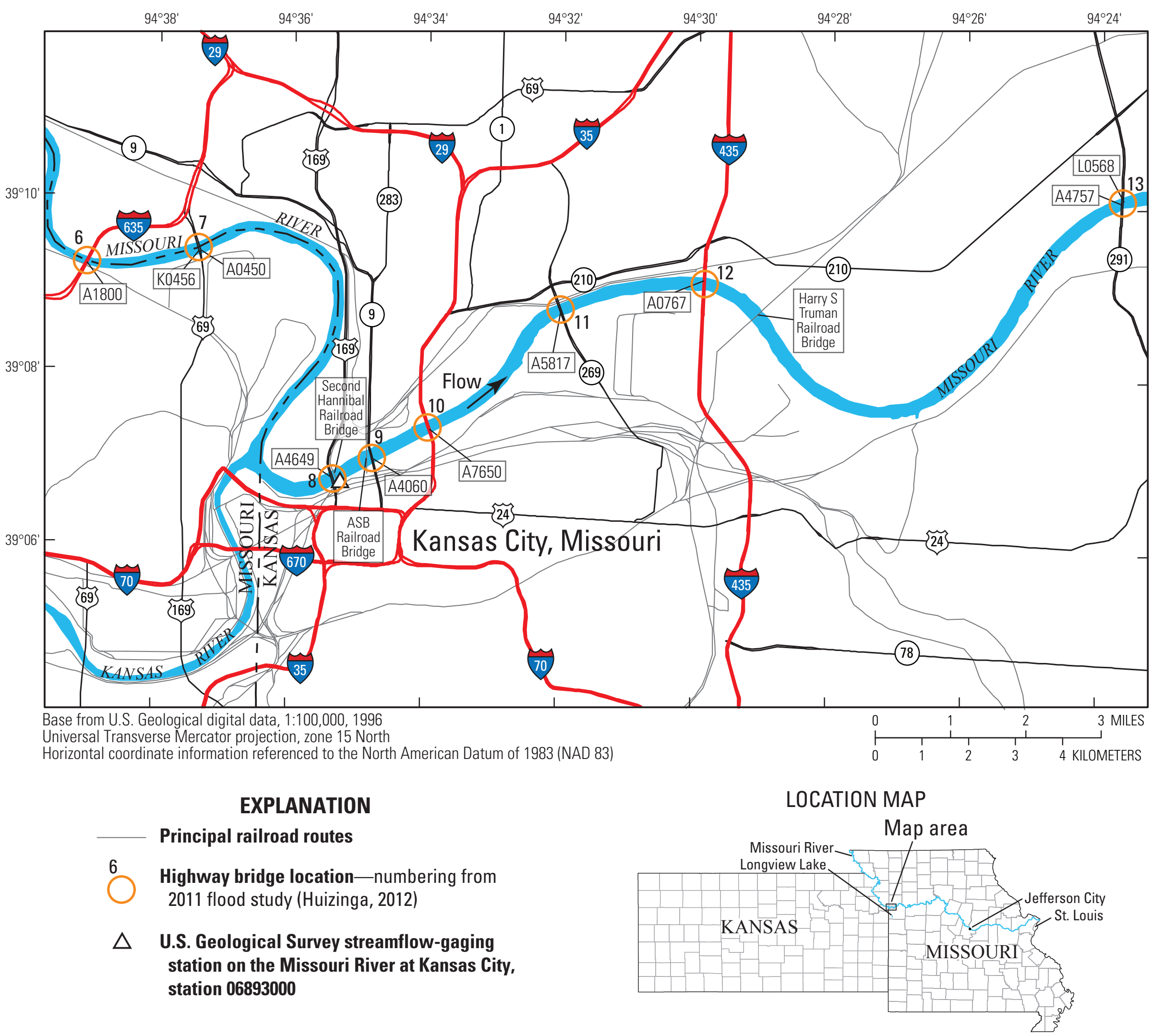



**Figure 1.** Location of bridges across the Missouri River in the Kansas City, Missouri, area.

**Table 1.** Highway bridges crossing the Missouri River in and into Missouri in the Kansas City area, in downstream order.

[KDOT, Kansas Department of Transportation; IS, Interstate highway; S, southbound; N, northbound; MoDOT, Missouri Department of Transportation; --, not known/applicable; US, U.S. highway; MO, Missouri State highway]

| Site number[1] (fig. 1) | Primary agency | Structure number | Local name | County | Route | River mile[2] | Surveyed as part of this study | Remarks | Figure(s) |
|---|---|---|---|---|---|---|---|---|---|
| 5 | KDOT | 435-105-11.97 (235) | Parkville | Platte, Missouri | IS 435 S | 383.4 | No | Dual bridge crossing with 435-105-11.98 (240) | Not shown. |
| | | 435-105-11.98 (240) | Parkville | Wyandotte, Kansas | IS 435 N | | No | Dual bridge crossing with 435-105-11.97 (235) | Not shown. |
| 6 | MoDOT | A1800 | Riverside | Platte, Missouri | IS 635 | 374.1 | Yes | -- | 1, 6–11, 49–51, 2–1 |
| 7 | MoDOT | K0456 | Fairfax | Platte, Missouri | US 69 S | 372.6 | No | Dual bridge crossing with A0450, being replaced | 1 |
| | | A0450 | Platte Purchase | Wyandotte, Kansas | US 69 N | | No | Dual bridge crossing with K0456, being replaced | 1 |
| 8 | MoDOT | A4649 | Broadway Avenue | Clay, Missouri | US 169 | 366.2 | Yes | -- | 1, 12–17, 49–51, 2–2 |
| 9 | MoDOT | A4060 | Heart of America | Clay, Missouri | MO 9 | 365.5 | Yes | -- | 1, 18–3, 49–51, 2–3 |
| 10 | MoDOT | A7650 | Christopher Bond | Clay, Missouri | IS 35 | 364.7 | Yes | -- | 1, 24–28, 49–51, 2–4 |
| 11 | MoDOT | A5817 | Chouteau | Clay, Missouri | MO 269 | 362.3 | Yes | -- | 1, 29–34, 49–51, 2–5 |
| 12 | MoDOT | A0767 | Randolph | Clay, Missouri | IS 435 | 360.3 | Yes | -- | 1, 35–41, 49–51, 2–6 |
| 13 | MoDOT | A4757 | Courtney | Jackson, Missouri | MO 291 S | 352.7 | Yes | Dual bridge crossing with L0568 | 1, 42–44, 46–51, 2–7 |
| | | L0568 | Courtney | Jackson, Missouri | MO 291 N | | Yes | Dual bridge crossing with A4757 | 1, 42, 43, 45–51, 2–7 |

[1]Site number of bridges in "Greater Kansas City area" from Huizinga (2012).

[2]River mile is the distance upstream from the confluence of the Missouri River with the Mississippi River at St. Louis, Mo. (fig. 1).

of this study (table 1); however, one bridge that was surveyed as part of the series during the 2011 flood study (structure A7650 on Interstate 29; Huizinga, 2012) is included in the current study.

## Purpose and Scope

The purpose of this report is to document the results of 2015 bathymetric and velocimetric surveys of the Missouri River channel near 8 highway bridges at 7 crossings in the greater Kansas City, Mo. (fig. 1), area using a MBMS and an acoustic Doppler current profiler (ADCP; table 1). Equipment and methods used and results obtained are described. The results obtained from the bathymetric and velocimetric surveys of the channel document the channel-bed conditions and velocity distribution at the time of the surveys and provide characteristics of scour holes that may be useful in developing predictive guidelines or equations for scour holes. These data also may be used by MoDOT as a low to moderate flood flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour. Comparison of results to previous surveys at the sites (Huizinga, 2010, 2012) also are provided.

## Description of Study Area

The study area for this report is the Missouri River in Kansas City, Mo. (fig. 1). The Missouri River flows through the Kansas City area from west to east, meandering across the flood plain. The river is highly channelized in the Kansas City area, with rock revetment and spur dikes along the banks to maintain the channel alignment, and levees and floodwalls on the upper banks to limit flooding in the industrial, commercial, and agricultural areas on the flood plains. The site numbering sequence used in Huizinga (2012) is used in this report for consistency and comparability.

## Description of Flow Conditions

Data from the streamflow-gaging station (hereinafter referred to as "streamgage") on the Missouri River at Kansas City, Mo. (station 06893000; U.S. Geological Survey, 2015; fig. 1), indicates the Missouri River was between flood rises when the sites were surveyed June 2–4, 2015 (fig. 2*A*); however, the trough happened during generally higher summer flows (fig. 2*B*), during low to moderate flood flow conditions of nearly 100,000 cubic feet per second ($ft^3/s$), compared to 45,000–50,000 $ft^3/s$ observed during troughs in early May and late August.

The discharge on the Missouri River as measured at the Kansas City streamgage ranged from about 92,900 to 116,000 $ft^3/s$ during the surveys. This discharge range has a daily exceedance range of about 6 to 11 percent (U.S. Geological Survey, 2003) and is less than the 50-percent annual exceedance probability (2-year recurrence interval) flood discharge of 142,000 $ft^3/s$ (U.S. Army Corps of Engineers, 2004, plate E–20).

Flow conditions at or less than the 50-percent annual exceedance probability (2-year recurrence interval) flood is in the low to moderate flood flow regime. In an analysis of real-time scour monitor data at Jefferson City, Mo., Huizinga (2014) noted that substantial pier scour begins soon after the onset of hydrograph rise (substantial rise of 8 feet [ft] or more), although the scour often does not reach maximum depth until the peak stage is reached or sometime thereafter (see fig. 35, Huizinga [2014]). Although the peak discharge for the summer happened shortly after the surveys, several moderate peaks had been observed at the Kansas City streamgage, and flow was substantially higher than base flow based on the daily exceedance values during the surveys (fig. 2*B*). Although the scour scenario captured at the sites in this study may not represent the maximum scour potential at the sites, the cumulative information gathered at each site during the course of the three surveys in 2010, 2011, and 2015 remains useful for determining scour for a variety of flow conditions, particularly when combined with, or compared to, a scour scenario captured at high flood flow conditions.

## Description of Equipment and Basic Processing

The bathymetry of the Missouri River at each of the bridges was determined using a high-resolution MBMS. The various components of the MBMS used for this study are described in reports about studies on the Missouri and Mississippi Rivers in Missouri (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015; Huizinga and others, 2010) and on the Missouri and Yellowstone Rivers in North Dakota (Densmore and others, 2013). The survey methods used to obtain the data were similar to these previous studies, as were the measures used to ensure data quality. A brief description of the equipment follows; a complete description of the various system components and methods used in this study is available in the previous reports by Huizinga (2010), Huizinga and others (2010), and Densmore and others (2013).

An MBMS is an integration of several individual components: the multibeam echosounder (MBES), an inertial navigation system (INS), and a data-collection and data-processing computer. The MBES that was used for the 2015 surveys is the Teledyne RESON SeaBat® 7125-SV2 (fig. 3), operated at a frequency of 400 kilohertz (kHz). The INS that was used is the Applanix Position Orientation Solution for Marine Vessels (POS MV™) WaveMaster system. The INS provides position in three-dimensional space and measures the heave, pitch, roll, and heading of the vessel (and, thereby, the MBES) to accurately position the data received by the MBES. A cellular network link to the virtual real-time station network (established and maintained by MoDOT, available through registration at http://gpsweb3.modot.mo.gov/) was used to provide the real-time kinematic (RTK) differential corrections to the INS for the navigation and tide solution during the 2015 surveys.

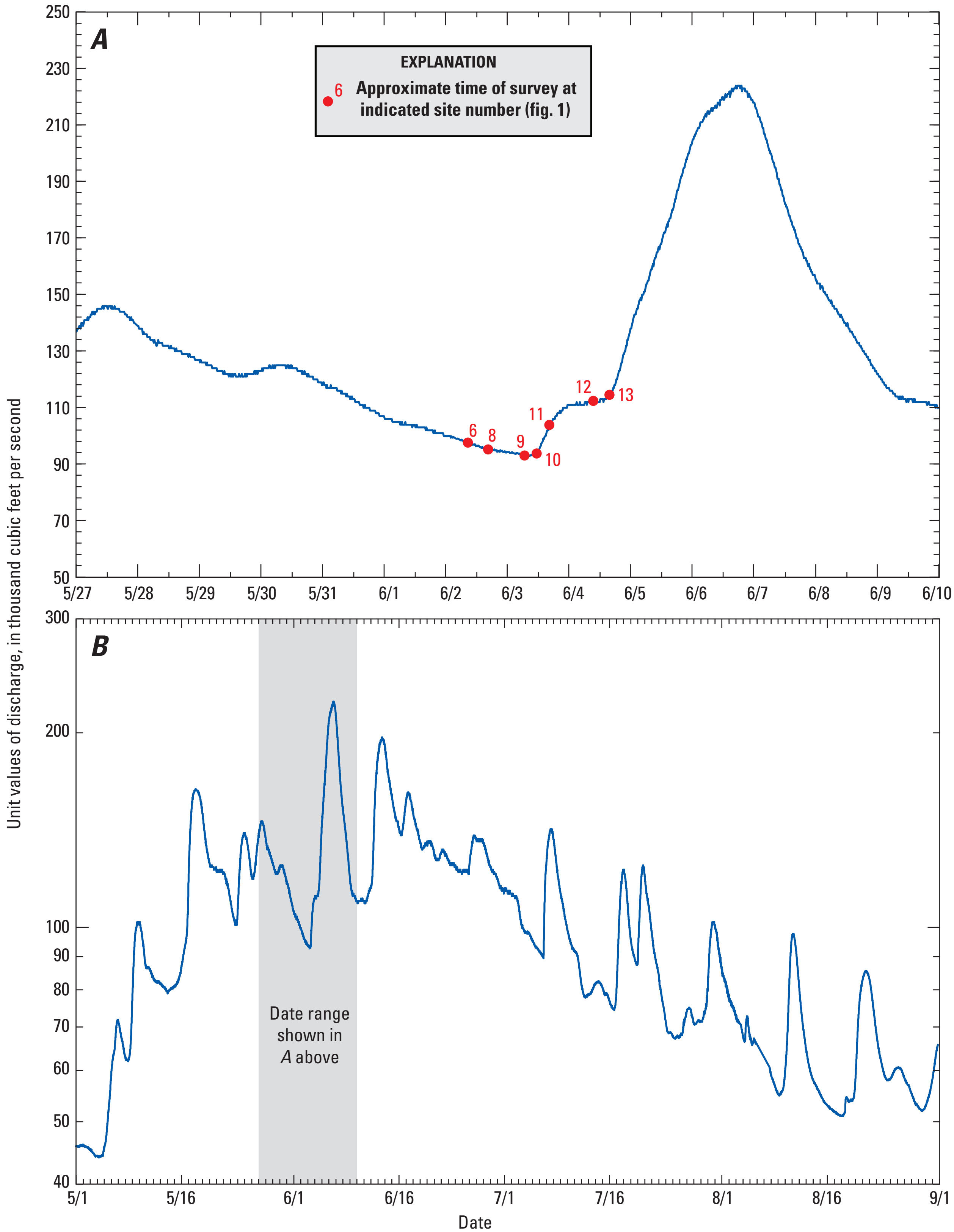



**Figure 2.** Unit values of discharge (15-minute interval) from the streamflow-gaging station on the Missouri River at Kansas City, Missouri (station 06893000; U.S Geological Survey, 2015). *A*, May 27 through June 10, 2015. *B*, May 1 through August 31, 2015.


**Figure 3.** The Teledyne RESON SeaBat® 7125-SV2 multibeam echosounder. *A*, viewed from the bottom. *B*, mounted on the port side of the U.S. Geological Survey boat.

As in previous surveys (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015), the navigation information from the 2015 surveys was postprocessed using the POS-Pac™ Mobile Mapping Suite (MMS™) software (Applanix Corporation, 2009) to mitigate the effects of degraded positional accuracy of the vessel while near or under a bridge. POS-Pac™ MMS™ provides tools to identify and compensate for sensor and environmental errors and computes an optimally blended navigation solution from the Global Navigation Satellite System (GNSS) and inertial motion unit (IMU) raw data. The blended navigation solution (called a "standard best estimate of travel" or "SBET" file) generated by postprocessing the navigation data was applied to the survey at a given bridge to minimize the effects of the GNSS outages while surveying under the bridges.

The data from the MBES and INS components were processed and integrated into a cohesive dataset for cleanup and visualization. A computer onboard the survey vessel ran the HYPACK®/HYSWEEP® data acquisition software (HYPACK, Inc., 2015) that was used to prepare for the bathymetric surveys and collect the survey data. After completing the surveys, the acquired depth data were further processed to remove data spikes and other spurious points in the multibeam swath trace, georeferenced using the navigation and position solution data from the SBET file from POS-Pac™ MMS™, and visualized in HYPACK®/HYSWEEP® as a triangulated irregular network (TIN) surface or a point cloud. The georeferenced data were output to a comma-delimited file, either having no data reduction or filtered and reduced to a 1.64-ft data resolution. These comma-delimited data were compiled into a geographic information system database for each site using the ArcGIS package (Environmental Systems Research Institute, 2013).

Information about the velocity of the river at various points throughout each study reach were collected by means of an ADCP, similar to recent previous studies by Huizinga (2012, 2013, 2014, 2015). A Teledyne RD Instruments Rio Grande ADCP operating at 600 kHz was used to obtain velocities at 1.64-ft increments, or "bins," throughout the water column. The Rio Grande 600 kHz ADCP operates in depths from 2.3 to 230 ft and determines the velocity of the water by measuring the Doppler shift of an acoustic signal reflected from various particles suspended in the water (Mueller and others, 2013). By measuring the Doppler shift in four different beam directions, the velocity of the water in each bin can be determined in three dimensions.

## Basic Description of Methods

The methods used to acquire and ensure the collection of quality data were the same as those used in previous studies using the MBES (methods are detailed in Huizinga, 2010, 2012; Huizinga and others, 2010). A brief summary of—and differences from—these methods are highlighted below.

### Surveying Methods

Generally, the surveyed area extended across the active channel from bank to bank, as had been done in the previous studies on the Missouri River near Kansas City (Huizinga, 2010, 2012). The surveyed reaches ranged from 1,640 to 1,660 ft long in the direction of flow, positioned so that the surveyed highway bridges were about one-third to one-half of the total length from the upstream boundary, using about the same upstream and downstream boundaries as were used in the 2011 flood study (Huizinga, 2012). The upstream and downstream boundaries of the surveyed areas were assumed to be beyond the substantial hydraulic effects (wake vortices and shear flow) in the immediate vicinity of the bridge structures.

As in previous studies, bathymetric data were obtained along longitudinal transect lines, and each survey was designed so that there was overlap of the survey swaths to attempt to ensure complete coverage of the channel bed and minimize sonic “shadows.” Substantial overlap was achieved for many of the surveyed swaths, except in shallow areas near the channel banks or spur dikes and near debris rafts. The presence of debris rafts made surveying difficult in some areas. Areas near the bridge piers and along the banks also were surveyed in an upstream direction with the MBES head tilted at either 30 degrees to port or starboard to increase the acquisition of bathymetric data in the shallow areas, and higher on the banks and the sides of the piers. To limit damage to the MBES head, most of the very shallow areas (less than about 6 ft of water depth) were not surveyed.

After completing the bathymetric survey with the MBMS at a given site, the velocity data were obtained with the ADCP on seven lateral sections across the channel within the study area. The position and speed of the boat was determined using a differential GNSS receiver mounted on a pole directly above the ADCP. The bottom-track reference method for determining boat speed was anticipated to be unusable because of moving channel-bed material, so the boat velocity was determined using the GNSS essential fix (GGA) National Marine Electronics Association (NMEA)–0183 sentence (National Marine Electronics Association, 2002) from the differential GNSS receiver. The distance between the velocity section lines generally was about 260 ft. Three sections were upstream and four sections were downstream from the bridge in question. Each section line was traversed in each direction across the river. The reported velocity values are the average from the two traverses of a given section line, using averaging algorithms from the Velocity Mapping Toolbox (VMT; Parsons and others, 2013). Discharge for a site was computed as the average of the discharges for each of the 14 velocity transects (2 transects per section line).

## Survey Quality-Assurance/Quality-Control Measures

A quality-assurance plan has been established for discharge measurements using ADCPs that includes several instrument diagnostic checks and calibrations. These standard operating procedures were followed when acquiring the velocity profile data for these surveys, including a moving-bed test. For a detailed discussion of these procedures, see Mueller and others (2013).

For the MBMS, the principal quality-assurance measures were assessed in real time during the survey. The MBMS operator continuously assessed the quality of the collected data during the survey by making visual observations of across-track swaths (such as convex, concave, or skewed bed returns in flat, smooth bottoms), noting data quality flags and alarms from the MBES and the INS, and noting comparisons between adjacent overlapping swaths. In addition to the real-time quality-assurance assessments during the survey, beam angle checks and a suite of patch tests were executed to ensure quality data were acquired from the MBMS. Additional testing and comparison of data using different surveying patterns and collected on different days was completed at Longview Lake in Kansas City (fig. 1) as an additional quality-assurance measure and is included in this report as appendix 1.

### Beam Angle Check

A beam angle check is used to determine the accuracy of the depth readings obtained by the outer beams (greater than 25 degrees from nadir [vertical]) of the MBES (U.S. Army Corps of Engineers, 2013), which may change with time as a result of inaccurate sound velocities, physical configuration changes, and overall depth being surveyed. The HYPACK®/HYSWEEP® software has a utility that develops a statistical assessment of the quality of the outer beams compared to a reference surface (HYPACK, Inc., 2015). On June 1, 2015, a reference surface was created for a part of Longview Lake in Kansas City (fig. 1), and check lines were run across the reference surface. Included with the measurement was a sound-velocity profile cast to document and quantify any stratification in the water column near the reference surface. The results of this beam angle check (table 2) were within the recommended performance standards used by the U.S. Army Corps of Engineers for hydrographic surveys for all the representative angles (U.S. Army Corps of Engineers, 2013), permitting the use of the full sonar swath.

Ideally, the average depth of the reference surface used in the beam angle check would be equal to or greater than the depth in the area being surveyed. The depth of the Missouri River in each study reach generally was impossible to estimate before each survey because of the dynamic nature of the channel bed and flow conditions; however, the average depth of the reference surface (about 72 ft) was expected to be substantially greater than the average depth observed in the 2015 surveys, because the average depths observed during the 2011 flood surveys in the Kansas City area were less than 40 ft (the average depth is the difference between the average water surface elevation and average channel bed elevation in table 5, Huizinga [2012]). As described in the “Surveying Methods” section earlier in this report, areas with depths greater than the average depths generally had substantial overlap of the surveyed swath with adjacent swaths. Data from the outer beams in these areas were able to be either verified or removed to mitigate any detrimental effects caused by beam angle inaccuracies.

**Table 2.** Results of a beam angle check from two check lines over a reference surface at Longview Lake near Kansas City, Missouri, on June 1, 2015.

[<, less than; --, no data]

| Beam angle limit (degrees) | Maximum outlier (foot) | Mean difference (foot) | Standard deviation (foot) | 95-percent confidence (foot) |
|---|---|---|---|---|
| 0 | 0.56 | -0.13 | 0.13 | 0.26 |
| 5 | 0.59 | -0.13 | 0.13 | 0.26 |
| 10 | 0.59 | -0.07 | 0.13 | 0.23 |
| 15 | 0.56 | -0.03 | 0.13 | 0.26 |
| 20 | 0.62 | 0.03 | 0.13 | 0.26 |
| 25 | 0.69 | 0.03 | 0.13 | 0.23 |
| 30 | 0.82 | 0.07 | 0.13 | 0.23 |
| 35 | 0.59 | 0.03 | 0.10 | 0.23 |
| 40 | 0.82 | 0.03 | 0.13 | 0.23 |
| 45 | 0.72 | 0.00 | 0.10 | 0.23 |
| 50 | 0.85 | 0.00 | 0.10 | 0.20 |
| 55 | 0.39 | 0.03 | 0.10 | 0.20 |
| 60 | 0.59 | 0.07 | 0.07 | 0.16 |
| Performance standards[a] | | | | |
| -- | 1.00 | <0.20 | -- | <0.80 |
| -- | Met | Met | -- | Met |

[a]Performance standard check values are from U.S. Army Corps of Engineers (2013), table 3–1.

## Patch Tests

Patch tests are a series of dynamic calibration tests that are used to check for subtle variations in the orientation and timing of the MBES with respect to the INS and real-world coordinates. The patch tests are used to determine timing offsets caused by latency between the MBES and the INS, and angular offsets to roll, pitch, and yaw caused by the alignment of the transducer head (fig. 4). These offsets have been observed to be essentially constant for a given survey, barring an event that causes the mount to change such as striking a floating or submerged object (Huizinga, 2010, 2011, 2012, 2014, 2015). The offsets determined in the patch test are applied when processing the data collected during a given survey.

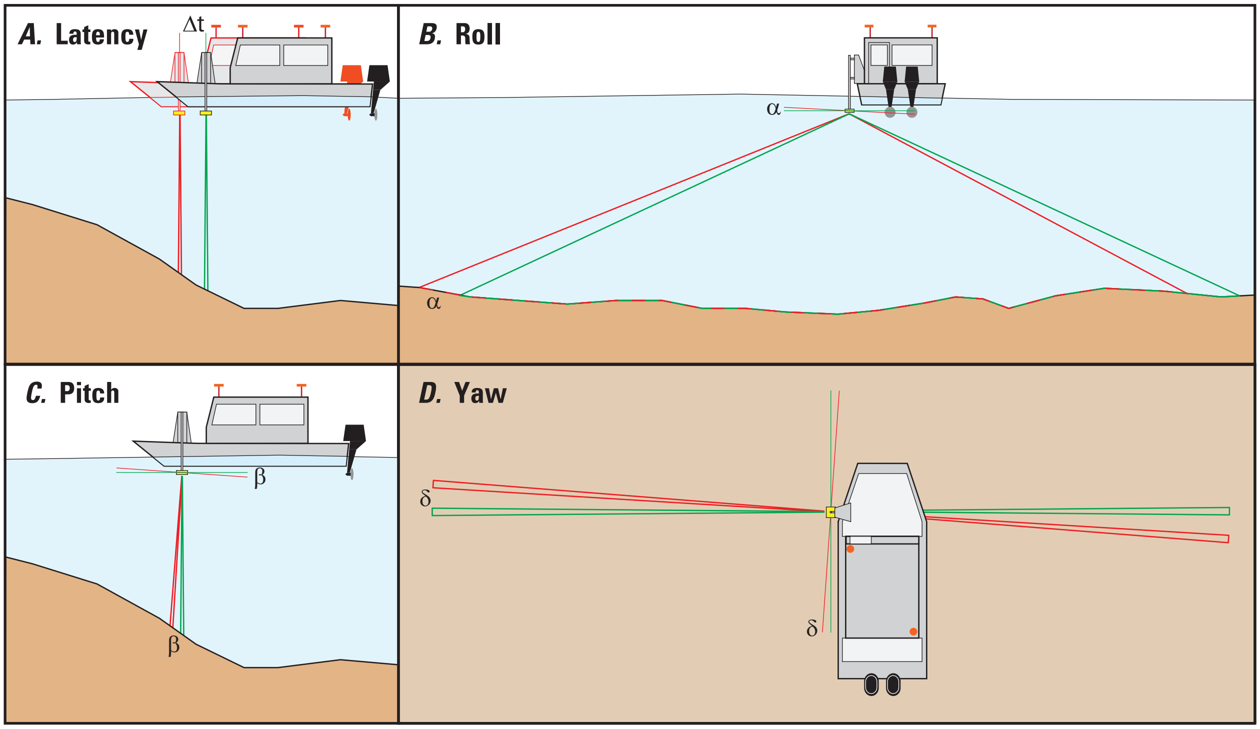
Patch tests were completed before and after the 2015 surveys (table 3) at Longview Lake in Kansas City (fig. 1). On the last day of surveying, the MBES was temporarily snagged in a sand bar downstream from pier 8 at structure A0767 on Interstate 435, with a resultant change of the pitch angle and a slight change (0.1 degrees) in the tilted roll angles from the beginning to the end of the surveys (table 3). There were no other strikes of floating debris or submerged objects during the surveys.

For this study, there was no measured timing offset (table 3; Δt=0, fig. 4), which is consistent with latency test results for this boat and similar equipment configuration used in other surveys (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015; Huizinga and others, 2010). The measured angular offset for pitch changed from -0.30 degrees to -0.70 degrees between the first and second patch tests (table 3). The measured angular offset for roll with the transducer head untilted (a head tilt of “none” in table 3) and the yaw for all head-tilt configurations remained constant at -2.45 degrees and 2.25 degrees, respectively, for both patch tests (table 3). Unexpectedly, the offset values for roll with the transducer head tilted 30 degrees to port and starboard were slightly different between the first and second patch tests, changing by -0.10 degrees for the starboard tilt and +0.10 degrees for the port tilt settings (table 3). All changes in the offsets likely are the result of snagging the MBES in the sandbar at structure A0767 on Interstate 435. It was noted in Huizinga (2010) that a sensitivity analysis of the four offsets implied that the ultimate position of surveyed points in three-dimensional space was least sensitive to the angular offset for yaw, whereas it was most sensitive to the angular offset for roll. It is presumed that the observed changes in roll for the two head-tilt configurations are a secondary effect of the change in pitch between the patch tests.

The bathymetric data were processed to apply the offsets determined from the patch tests, and to remove data spikes and other spurious points in the multibeam swaths through the use

**Table 3.** Patch test results at Longview Lake from surveying on the Missouri River near Kansas City, Missouri.

| Date of test | Timing offset (second) | Angular offset for roll (degree) | Angular offset for pitch (degree) | Angular offset for yaw (degree) | Head tilt |
|---|---|---|---|---|---|
| 06/01/15 | 0 | -2.45 | -0.30 | 2.25 | none. |
| 06/05/15 | 0 | -2.45 | -0.70 | 2.25 | none. |
| 06/01/15 | 0 | -32.35 | -0.30 | 2.25 | 30 degrees starboard. |
| 06/05/15 | 0 | -32.45 | -0.70 | 2.25 | 30 degrees starboard. |
| 06/01/15 | 0 | 27.65 | -0.30 | 2.25 | 30 degrees port. |
| 06/05/15 | 0 | 27.75 | -0.70 | 2.25 | 30 degrees port. |




**EXPLANATION**

**Actual bottom** — **Measured bottom**

Δt **Timing offset for latency between the multibeam echosounder and Global Navigation Satellite System components of the navigation and motion-sensing system**

α **Angular offset for roll of the transducer head along the longitudinal axis of the boat**

β **Angular offset for pitch of the transducer head along the lateral axis of the boat**

δ **Angular offset for yaw of the transducer head about the vertical axis**

**Figure 4.** Generalized effects on data from a multibeam echosounder. *A*, timing offset for latency. *B*, angular offset for roll. *C*, angular offset for pitch. *D*, angular offset for yaw.

of automatic filters and manual editing. The offsets from the first patch test were applied to data collected before the sand bar strike at structure A0767 on Interstate 435, and the offsets from the second patch test were applied to all data collected after the sand bar strike. The bathymetric data were then projected to a three-dimensional grid at a resolution of 1.64 ft using the Combined Uncertainty Bathymetric Estimator (CUBE) method (Calder and Mayer, 2003), as implemented in the HYPACK®/HYSWEEP® software (HYPACK, Inc., 2015) and used to generate a gridded raster surface of the channel bed near each bridge (hereinafter referred to as a "bathymetric surface") using ArcGIS. The bathymetric surface for each site from the 2015 survey was compared to similar bathymetric surfaces created from previous surveys at a bridge by taking the difference between the 2015 raster surface and the previous survey raster surface. Statistics of the elevations for each bathymetric surface were determined, as were statistics of the differences between the surfaces. Sediment volumes for cut (scour) and fill (deposition) between the 2015 survey and previous surveys in 2010 and 2011also were determined from differences in the raster surfaces using ArcGIS.

## Uncertainty Estimation

Similar to the previous studies of bathymetry in Missouri (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015), uncertainty in the surveys was estimated by computing the total propagated uncertainty (TPU) for each survey-grid cell in the bathymetric surface of each survey area, using the CUBE method (Calder and Mayer, 2003). The CUBE method allows all random system component uncertainties and resolution effects to be combined and propagated through the data processing steps, which provides a robust estimate of the spatial distribution of possible uncertainty within the survey area (Czuba and others, 2011); thus, the TPU of a point is a measure of the accuracy to be expected for such a point when all relevant error sources are taken into account (Czuba and others, 2011). Statistics of TPU for each of the survey areas are shown in table 4, and an example of the spatial distribution of TPU typically observed in the survey data is shown in figure 5 for the bathymetric data at structure A0767 on Interstate 435.

The largest TPU in this group of surveys was about 11.97 ft (table 4); however, as noted in previous studies, TPU values of this magnitude typically happened near high-relief

**Table 4.** Total propagated uncertainty results for bathymetric data at a 1.64-foot grid spacing from surveys on the Missouri River near Kansas City, Missouri, June 2–4, 2015.

[MoDOT, Missouri Department of Transportation; ft, foot]

| Site number (fig. 1) | MoDOT structure number | Maximum value of uncertainty (ft) | Mean value of uncertainty (ft) | Median value of uncertainty (ft) | Standard deviation of uncertainty (ft) | Percent of bathymetry points with uncertainty value less than | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 2.00 ft | 1.00 ft | 0.50 ft | 0.25 ft |
| 6 | A1800 | 9.25 | 0.47 | 0.36 | 0.36 | 99.2 | 93.4 | 68.6 | 26.5 |
| 8 | A4649 | 10.99 | 0.47 | 0.36 | 0.37 | 99.1 | 93.5 | 68.4 | 24.8 |
| 9 | A4060 | 11.97 | 0.46 | 0.36 | 0.38 | 99.0 | 93.7 | 69.1 | 27.2 |
| 10 | A7650 | 9.97 | 0.43 | 0.36 | 0.34 | 99.3 | 94.9 | 71.8 | 30.1 |
| 11 | A5817 | 6.59 | 0.36 | 0.30 | 0.29 | 99.7 | 96.6 | 80.7 | 41.4 |
| 12 | A0767 | 9.65 | 0.50 | 0.36 | 0.43 | 98.3 | 91.4 | 66.0 | 25.9 |
| 13 | A4757/ L0568 | 10.17 | 0.45 | 0.33 | 0.39 | 99.2 | 91.3 | 71.2 | 34.7 |

features, such as the front or side of a pier footing (fig. 5). Most of the TPU values (more than 91 percent) were less than 1.00 ft (table 4). The TPU values were larger near moderate-relief features (banks, spur dikes, rock riprap and outcrops, and scour holes near piers; fig. 5). Occasionally, the TPU values also were larger (greater than 1.00 ft) in the outermost beam extents of the multibeam swath in the overlap with an adjacent swath, particularly when the MBES head was tilted for the survey lines along the banks or near the piers (fig. 5). Overlapping adjacent swaths in the channel thalweg (the line of maximum depth in the channel) also can display larger TPU values because substantial bed movement can happen between survey passes (fig. 5). Nearly two-thirds (66 percent or more) of the channel bed at the sites had TPU values of 0.50 ft or less (table 4). The tops of bridge substructural elements (pier footings and seal courses) typically had TPU values of 0.50 ft or less.

The survey at structure A0767 on Interstate 435 had the highest mean value of TPU, as well as generally the lowest percentage of bathymetry points that were less than the various TPU value cutoffs (table 4). There were no substantial impediments to flow or surveying at this site other than a debris raft at pier 8 with a sand bar downstream, and the survey was obtained with relatively smooth longitudinal swathes (fig. 5), which was the case at nearly all the sites surveyed in this study. The primary anomaly at this site was along the upstream left bank, where an apparent error in the position data between adjacent swaths caused a bulge in the bank with substantial TPU values (fig. 5). Generally, the magnitude and distribution of TPU values observed at this site are representative of those observed at all of the other surveyed sites.

# Results of Bathymetric and Velocimetric Surveys

The site-specific results for each bridge are discussed in the following sections, starting with the upstream-most bridge site and progressing downstream. The site-specific results are followed by a discussion of general findings that are not specific to a particular site. The range of bed elevations described as "the channel-bed elevations" for each survey was based on statistical analysis of the gridded raster surface of the bathymetry data at each site, and covers the percentile range from 5 to 95 percent of the data. Because the surveys generally were limited to the active channel from bank to bank excluding overbank areas, this percentile range generally covered the channel bed but excluded the banks and localized high or low spots, such as spur dikes or scour holes near piers. All elevation data were referenced to the North American Vertical Datum of 1988 (NAVD 88).

For consistency with earlier studies, dune sizes are described in general terms for each of the bridge sites using the categories set by Huizinga (2012) for the discussion of bathymetry during the 2011 flood. In this report, small dunes and ripples are those that are less than 5 ft high from crest to trough, medium dunes are those that are 5 to 10 ft high, large dunes are those that are 10 to 15 ft high, and very large dunes are those that are 15 ft or more in height.

Previous bathymetric surveys have happened at all of the bridge sites in this study (Huizinga, 2010, 2012); furthermore, most of the sites had a Level II bridge scour assessment (Lagasse and others, 1991; Huizinga and Rydlund, 2004). A map showing the difference in channel-bed elevation for the

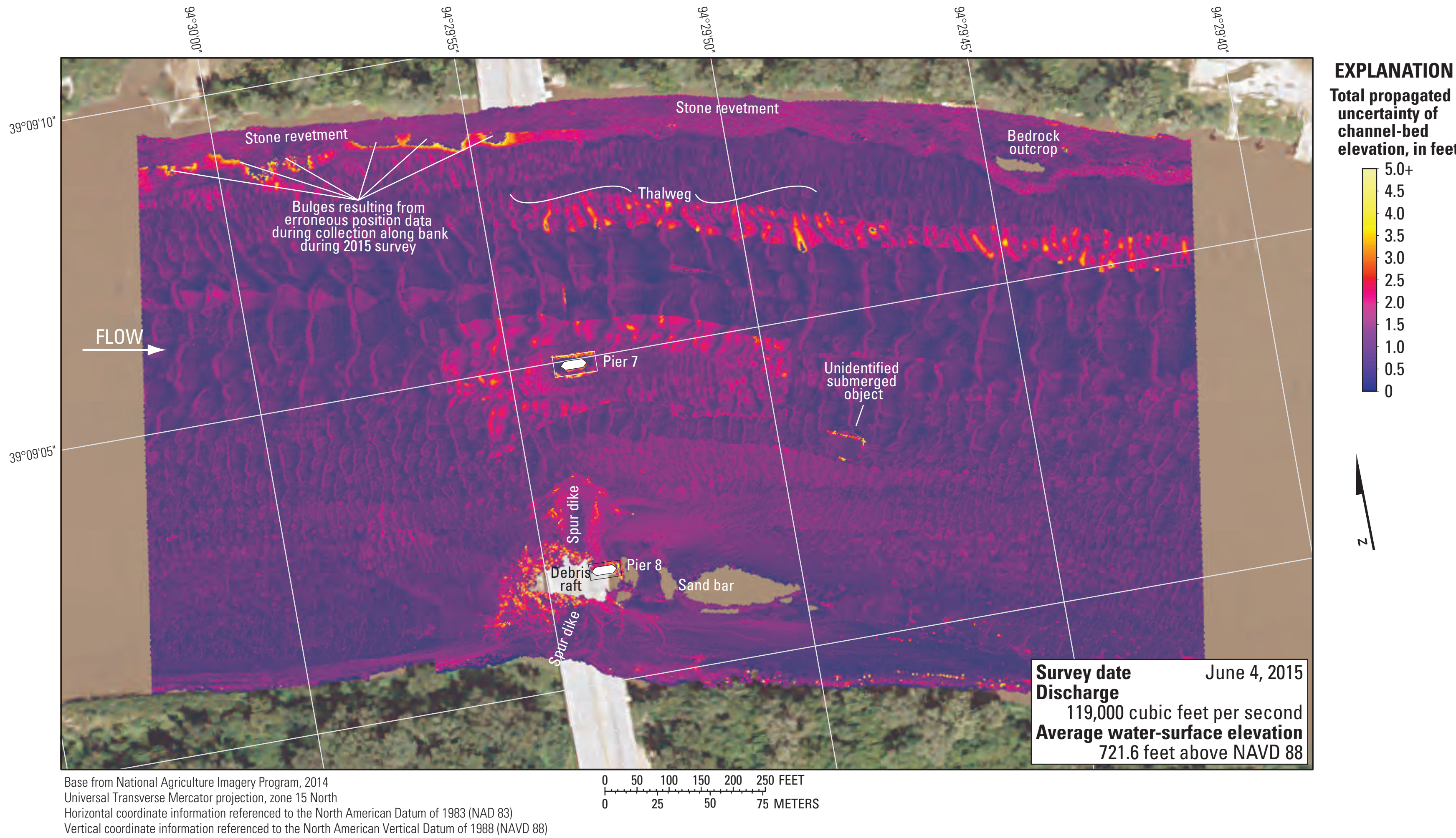


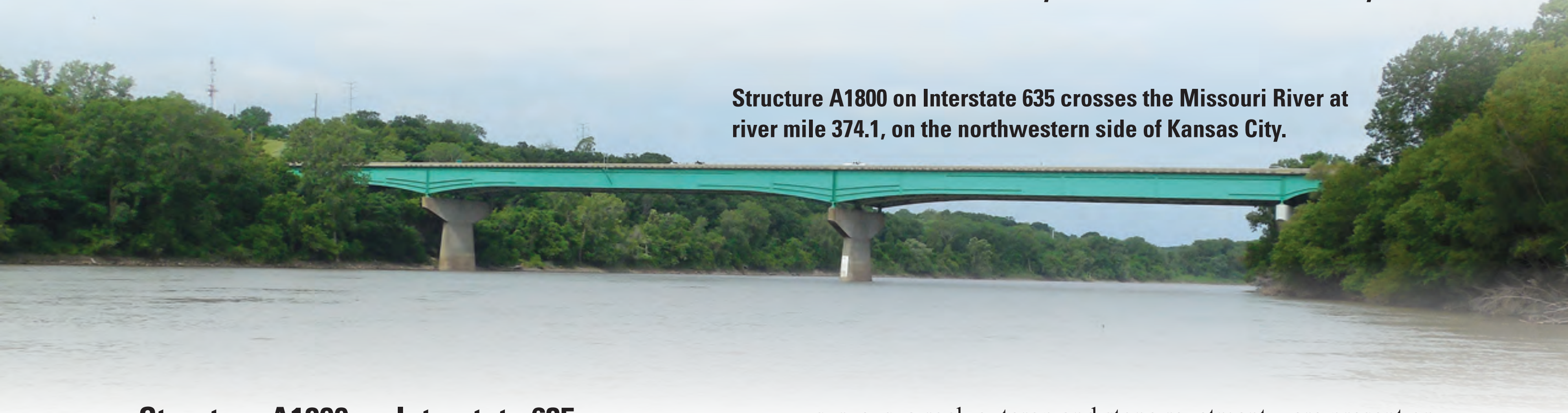

**Figure 5.** Total propagated uncertainty of bathymetric data from the Missouri River channel near structure A0767 on Interstate 435 in Kansas City, Missouri.

area common to each surveys is included for each site, and data from previous surveys are included in the cross-section plot for that bridge. The difference maps were created by taking the difference between the 2015 raster surface and a previous survey raster surface at a given bridge, and summary statistics (maximum, minimum, mean) of the difference rasters were determined. The surveys are broadly compared based on their timing and the discharge at the time of the survey. If a site was subject to a Level II assessment, the cross section of the channel on the downstream side of the bridge obtained during the Level II assessment is included on the cross-section plot for that bridge.

While the configuration of the channel bed and the underlying sediment transport conditions at a given site are associated with an instantaneous discharge in the discussions that follow, a given bathymetric surface actually is a reflection of more than those instantaneous transport conditions. A wide variety of factors influence the channel-bed configuration of a reach for a given discharge (Gilbert, 1914), including flow velocities and velocity distribution, the size and timing of previous flood rises, whether or not the stage currently is rising or falling, and other local hydraulic conditions; furthermore, the channel-bed configuration at a site is affected by upstream and local sediment conditions and contributions, as well as water temperature and other seasonal variations. Because of the myriad number and interactions of factors affecting sediment transport conditions and the resultant bed configuration, it would be simplistic to assume that the configuration and size of bed forms observed during the current (2015) surveys near Kansas City are dependent only upon the instantaneous discharge at a given site. Although it is beyond the scope of the current (2015) study to examine all of the antecedent conditions that created the observed channel-bed configuration, the comparisons with previous surveys under different flow conditions nevertheless contribute to understanding the many complexities of sediment transport.

As in recent previous studies (Huizinga, 2012, 2013, 2014, 2015), when discussing the vertically averaged velocity values obtained during the surveys in the sections that follow, neighboring vectors having random variations in direction and magnitude were taken as an indication of nonuniform flow in the section resulting from shear and wake vortices. Conversely, neighboring vectors having gradual and systematic variations were taken as an indication of uniform flow in the section. The velocity data for each section are an average of two velocity transects, spatially averaged to the section line using algorithms in Velocity Mapping Toolbox (Parsons and others, 2013).

Shaded TIN images of the channel and side of pier were prepared for each surveyed pier. These visualizations are shown in appendix figures 2–1 to 2–7.



Structure A1800 on Interstate 635 crosses the Missouri River at river mile 374.1, on the northwestern side of Kansas City.

## Structure A1800 on Interstate 635

Structure A1800 (site 6) on Interstate 635 crosses the Missouri River at river mile (RM) 374.1, on the northwestern side of Kansas City (fig. 1). The site was surveyed on June 2, 2015, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 730.4 ft (table 5). Discharge on the Missouri River was about 73,000 ft$^3$/s during the survey (table 5).

The survey area was about 1,640 ft long and about 755 ft wide, extending across the active channel from bank to bank (fig. 6). The upstream end of the survey area was about 770 ft upstream from the centerline of structure A1800 (fig. 6). The channel-bed elevations ranged from about 701 to 722 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data; table 5; fig. 7). A thalweg along the outside of the channel bend on the right (south) bank was about 15 ft deeper than the channel bed on the inside of the bend on the left (north) bank (fig. 6). Several medium to large dune features were detected in the middle of the channel, and the left (north) side and thalweg on the right (south) side were covered with numerous small dunes and ripples (fig. 6). As in previous surveys, a rock outcrop and stone revetment were present on the right (south) bank throughout the reach (fig. 6).

The scour hole near main channel pier 3 had a minimum channel-bed elevation of about 695 ft (table 6), about 15 ft below the average channel bed immediately upstream from the pier (fig. 6), and about 7 ft below the elevation of the bottom of the pier seal course of 702.28 ft (fig. 8; table 6). Information from bridge plans indicates that pier 3 is founded on shafts drilled 20 ft into bedrock, with about 43 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of pier 3 (fig. 8; table 6).

The difference between the survey on June 2, 2015, and the previous flood survey on July 16, 2011 (fig. 9), indicates substantial bed variation from 2011 to 2015, particularly near the thalweg where large dune features were present in the 2011 survey (Huizinga, 2012). There seemed to be an area of net scour on the left (north) side in the downstream reach in 2015, with a corresponding area of substantial deposition on the right side in the troughs of the dunes detected in the 2011 survey (fig. 9). The average difference between the bathymetric surfaces (the statistical mean value of the gridded raster surface [fig. 9] created from the difference between the 2015 and

**Table 5.** Bridge and survey information, and selected channel-bed elevations from surveys on the Missouri River near Kansas City, Missouri, June 2–4, 2015.

[MoDOT, Missouri Department of Transportation; ADCP, acoustic Doppler current profiler; ft$^3$/s, cubic foot per second; ft, foot; IS, Interstate highway; US, U.S. highway; MO, State highway; all elevations are in feet above the North American Vertical Datum of 1988]

| Site number (fig. 1) | MoDOT structure number | Survey date | Route | River mile | Discharge from ADCP measurements[a] (ft$^3$/s) | Average water-surface elevation in vicinity of bridge (ft) | Average channel bed elevation[b] (ft) | Approximate elevation of the indicated percentile of the bathymetric data | | Approximate minimum channel elevation[c] (ft) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 5th percentile (ft) | 95th percentile (ft) | |
| 6 | A1800 | 06/02/15 | IS 635 | 374.1 | 73,000 | 730.4 | 709.3 | 700.6 | 722.3 | 695 |
| 8 | A4649 | 06/02/15 | US 169 | 366.2 | 94,500 | 724.6 | 703.5 | 692.0 | 715.2 | 679 |
| 9 | A4060 | 06/03/15 | MO 9 | 365.5 | 93,900 | 723.7 | 700.9 | 695.7 | 710.2 | 679 |
| 10 | A7650 | 06/03/15 | IS 35 | 364.7 | 97,100 | 723.1 | 699.1 | 691.8 | 708.9 | 676 |
| 11 | A5817 | 06/03/15 | MO 269 | 362.3 | 103,000 | 721.9 | 701.5 | 689.8 | 709.7 | 679 |
| 12 | A0767 | 06/04/15 | IS 435 | 360.3 | 119,000 | 721.6 | 696.5 | 686.9 | 709.6 | 675 |
| 13 | A4757/ L0568 | 06/04/15 | MO 291 | 352.7 | 112,000 | 715.9 | 690.0 | 681.1 | 705.7 | 668 |

[a]The average discharge obtained while making the various velocity transects. The reported value is the discharges computed using Global Navigation Satellite System (GNSS) essential fix GGA data string as the reference, as described in the "Surveying Methods" section of the text.

[b]The statistical average of the surveyed channel-bed elevations.

[c]The minimum channel-bed elevation, not necessarily in any scour holes near the bridge.


**Figure 6.** Bathymetric survey of the Missouri River channel near structure A1800 on Interstate 635 near Kansas City, Missouri.

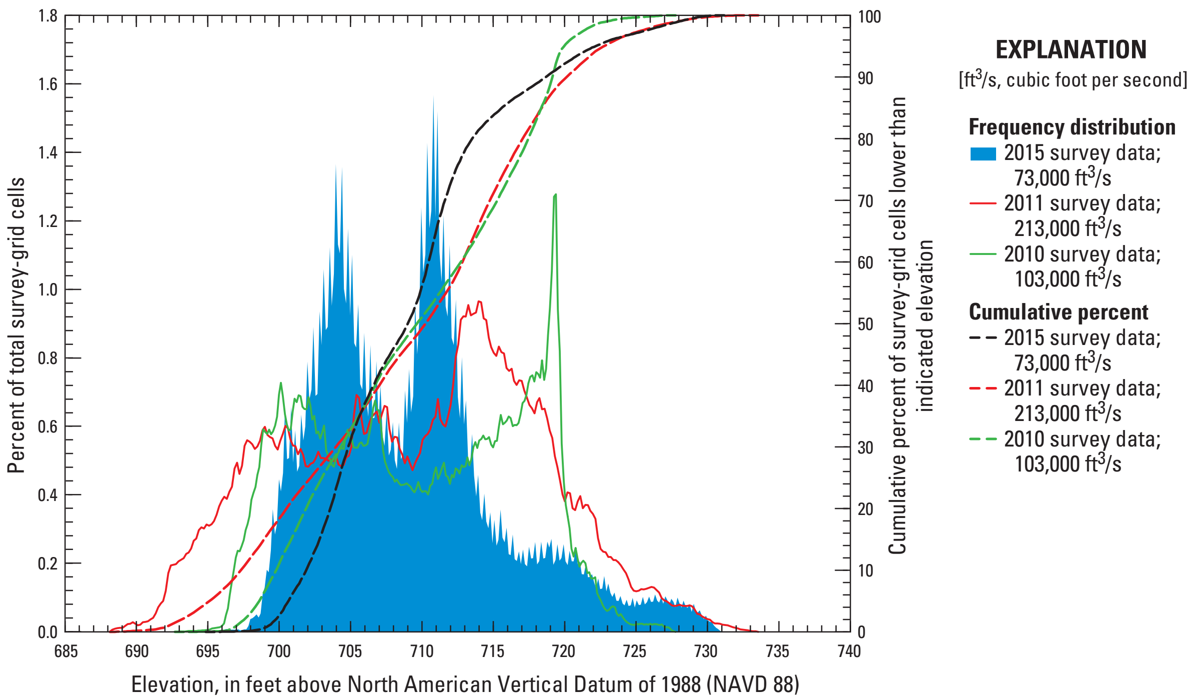



**Figure 7.** Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A1800 on Interstate 635 near Kansas City, Missouri, on June 2, 2015, compared to previous surveys.

2011 gridded raster bathymetric surfaces) was -0.35 ft (table 7), indicating overall minor channel degradation between the 2011 and 2015 surveys. The net volume of cut in the reach from 2011 to 2015 was about 82,100 cubic yards (yd$^3$), and the net volume of fill was about 66,600 yd$^3$, resulting in a net loss of about 15,500 yd$^3$ of sediment between 2011 and 2015. The cross sections from the two surveys along the upstream face of the bridge are not substantially different from one another (fig. 8); however, the frequency distribution of bed elevations was substantially narrower in 2015 than in 2011, with a higher minimum channel-bed elevation (fig. 7). The scour hole near pier 3 was slightly narrower in 2015 than in 2011 (fig. 8), as evidenced by the overall pattern of deposition in a horseshoe shape around the upstream face of the pier (fig. 9). The rock outcrop on the upstream right (south) bank showed no signs of substantial change except for a small area of deposition immediately upstream from the bridge (fig. 9). Although rock ultimately is an erodible material, its rate of erosion is substantially slower than that of sand and silt (Richardson and Davis, 2001). The stone revetment on the downstream right (south) bank also showed no signs of substantial change (fig. 9). Substantial deposition or scour apparent at the faces of the pier results from minor horizontal positional variances between the surveys (see “Uncertainty Estimation” section).

The difference between the survey on June 2, 2015, and the previous nonflood survey on March 15, 2010 (fig. 10), indicates moderate bed variation from 2010 to 2015. There seems to be an area of net scour on the left (north) side of the channel throughout the reach in 2015, with a corresponding area of net deposition in the thalweg on the right (south) side, in a horseshoe shape around the pier and in the troughs of the dunes detected in the 2010 survey (fig. 10). The average difference between the bathymetric surfaces was -1.53 ft (table 7), indicating moderate channel degradation between the 2010 and 2015 surveys. The net volume of cut in the reach from 2010 to 2015 was about 71,200 yd$^3$, and the net volume of fill was about 29,900 yd$^3$, resulting in a net loss of about 41,300 yd$^3$ of sediment between 2010 and 2015. The cross sections from the 2010 and 2015 surveys are not substantially different from one another (fig. 8); however, the frequency distribution of bed elevations was substantially narrower in 2015 than in 2010, with a higher minimum channel-bed elevation and a greater percentage of survey-grid cells at a lower elevation than 2010 (fig. 7). The scour hole near pier 3 was substantially narrower in 2015 than in 2010 (fig. 8), as evidenced by the overall pattern of deposition in a horseshoe shape around the pier (fig. 10). The rock outcrop on the upstream right (south) bank showed no signs of change, as would be expected (fig. 10). Areas of localized scour that were apparent in the 2011 survey on the stone revetment of the downstream right (south) bank and theorized as likely being from localized slumping (Huizinga, 2012) were confirmed in the 2015 survey (fig. 10). As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the pier results from minor horizontal positional variances between the surveys (see “Uncertainty Estimation” section).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, with a maximum velocity of 8 feet per second (ft/s) in the channel thalweg and a minimum of 2 ft/s along the inside of the bend on the left (north) bank (fig. 11). A minor decrease in velocity was observed near pier 3, likely exacerbated by the pier being skewed to flow (fig. 11). Minor turbulence was present in all of the sections (fig. 11).

**Table 6.** Results near piers from surveys on the Missouri River near Kansas City, Missouri, June 2–4, 2015.

[MoDOT, Missouri Department of Transportation; ft, foot; --, not known/applicable; all elevations are in feet above the North American Vertical Datum of 1988]

| Site number (fig. 1) | MoDOT structure number | MoDOT pier number | Foundation information | | | | Approximate minimum elevation in scour hole near pier[a] (ft) | Approximate elevation of scour hole at upstream pier face (ft) | Approximate elevation of bedrock near pier (ft) | Approximate distance between bottom of scour hole and bedrock (ft) | Depth of scour hole from upstream channel bed (ft) | Approximate frontal slope of scour hole (ft/ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Type | Width (ft) | Penetration into bedrock (ft) | Seal course or pile cap bottom elevation (ft) | | | | | | |
| 6 | A1800 | 3 | Drilled shaft | 28 | 20 | 702.28 | 694.7 | 695 | 652 | 43 | 15 | 1.94 |
| 8 | A4649 | 2 | Caisson | 24 | 1 | -- | 680.1 | 681 | 670 | 10 | 23 | 1.71 |
| 9 | A4060 | 5 | Drilled shaft | 28 | 20 | 696.26 | 693.2 | 693 | 667 | 26 | 9 | 2.07 |
| | | 6 | Drilled shaft | 34 | 20 | 696.26 | 688.4 | [b]688 | 670 | 18 | [b]9 | 2.26 |
| 10 | A7650 | Pylon | Drilled shaft | 46 | 32 | 699.50 | 680.9 | 686 | 647 | 34 | 13 | 1.69 |
| 11 | A5817 | 2 | Drilled shaft | 24 | 20 | 687.26 | 693.2 | 693 | 677 | 16 | 9 | 1.82 |
| | | 3 | Drilled shaft | 24 | 20 | 689.26 | 701.4 | 701 | 657 | 44 | 3 | -- |
| 12 | A0767 | 7 | Drilled shaft | 32 | 20 | 689.26 | 678.6 | 679 | 660 | 19 | 15 | 1.79 |
| | | 8 | Drilled shaft | 28 | 20 | 689.26 | 694.0 | (c) | 648 | 46 | (c) | (c) |
| 13 | A4757 | 2C | Drilled shaft | 35 | 20 | 666.26 | 667.8 | 668 | 619 | 49 | 20 | 1.96 |
| | L0568 | 5 | Caisson | 20 | 2 | -- | 673.9 | [b]674 | 618 | 56 | [b]14 | 1.97 |

[a]The point of lowest elevation in the scour hole near the bridge pier, not necessarily at the upstream pier face.

[b]Scour hole at this pier is substantially affected by upstream pier.

[c]Unable to obtain data because of accumulated debris.

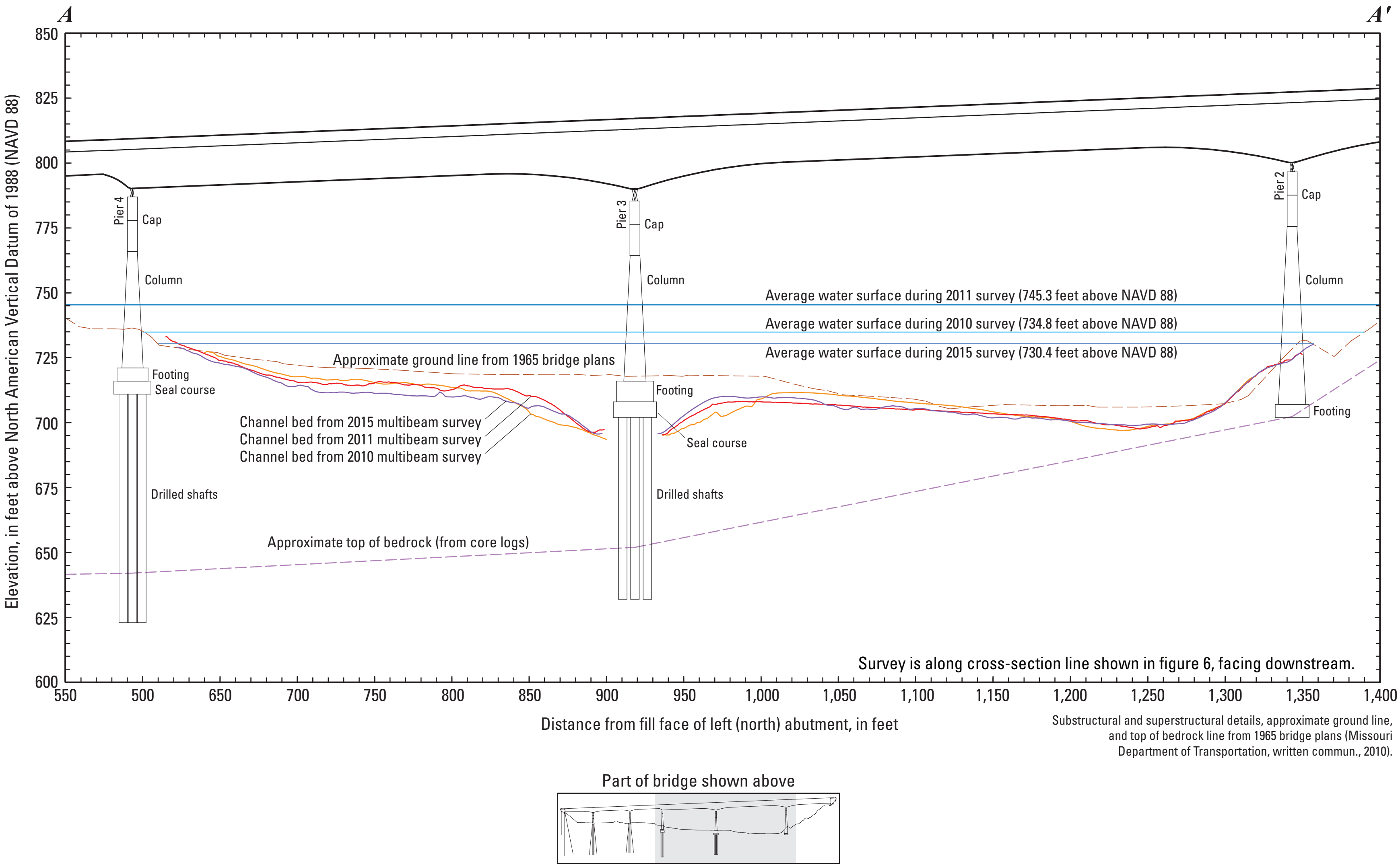



**Figure 8.** Key features, substructural and superstructural details, and surveyed channel bed of structure A1800 on Interstate 635 crossing the Missouri River near Kansas City, Missouri.

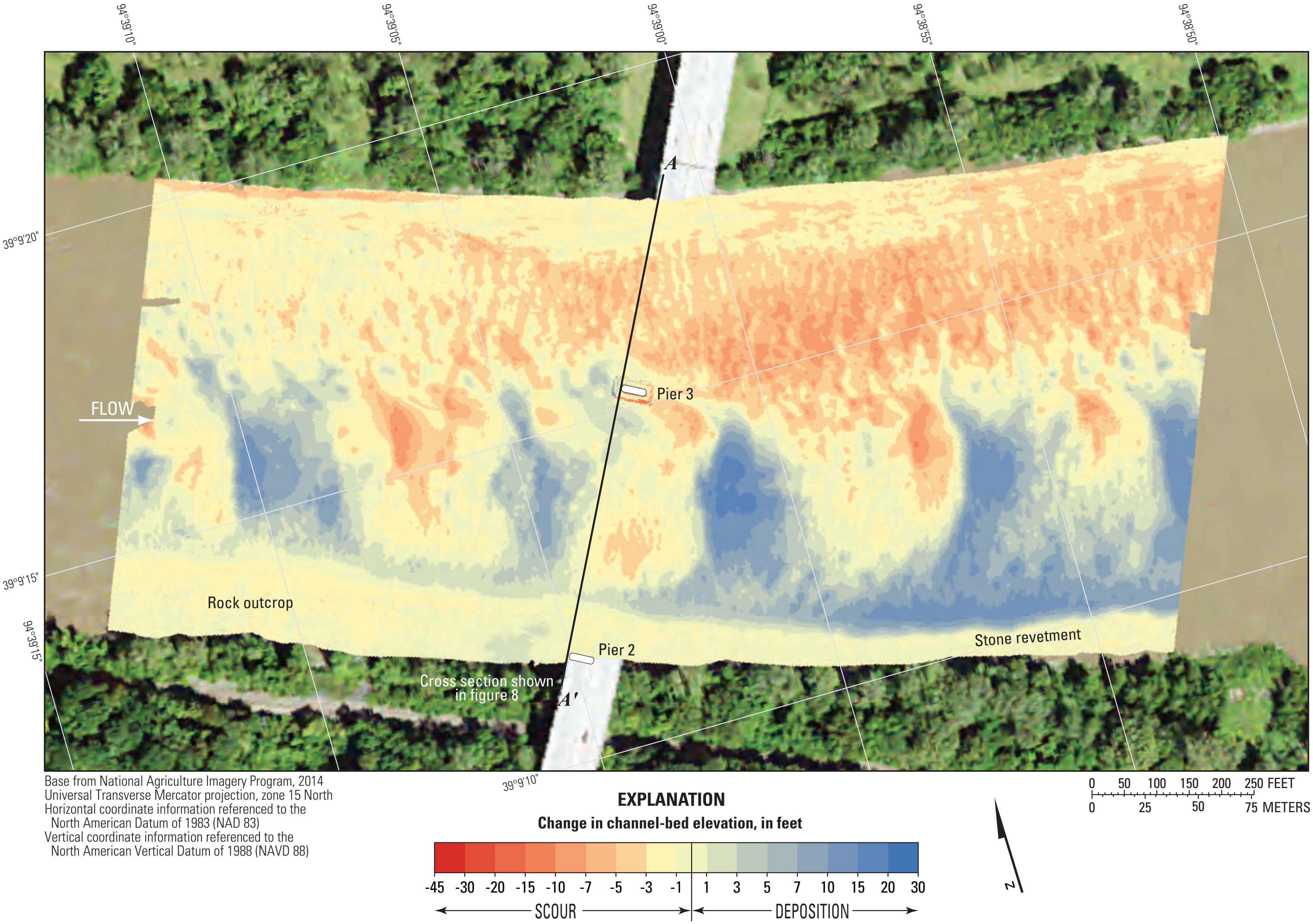



**Figure 9.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A1800 on Interstate 635 near Kansas City, Missouri, on June 2, 2015, and July 16, 2011.

**Table 7.** Summary information and bathymetric surface difference statistics from surveys on the Missouri River near Kansas City, Missouri, from June 2–4, 2015, and previous surveys.

[MoDOT, Missouri Department of Transportation; ft$^3$/s, cubic foot per second; ft$^2$, square foot; ft; A, Huizinga (2010); B, Huizinga (2012); foot; all elevations are in feet above the North American Vertical Datum of 1988]

| Site number (fig. 1) | MoDOT structure number | Previous survey | | | | | Difference between 2015 survey and previous survey | | | Statistics of differences between 2015 and previous survey surfaces | | | | Maximum difference near up-stream pier face(s)[b,c] (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Source of data | Date | Discharge (ft$^3$/s) | Surveyed area (x$10^6$ ft$^2$) | Average water-surface elevation (ft) | Discharge (ft$^3$/s) | Surveyed area (x$10^6$ ft$^2$) | Average water-surface elevation (ft) | Minimum[a,b] (ft) | Maximum[a,b] (ft) | Mean[b] (ft) | Standard deviation (ft) | |
| 6 | A1800 | A | 03/15/10 | [d]103,000 | 1.134 | 734.8 | -30,000 | 0.093 | -4.4 | -19.3 | 12.7 | -1.53 | 3.31 | -3.5 |
| | | B | 07/16/11 | 213,000 | 1.209 | 745.3 | -140,000 | 0.019 | -15.0 | -19.4 | 19.2 | -0.35 | 4.32 | 3.3 |
| 8 | A4649 | A | 03/16/10 | 127,000 | 1.485 | 727.9 | -32,500 | 0.039 | -3.3 | -20.8 | 41.2 | 1.11 | 3.95 | 5.9 |
| | | B | 07/17/11 | 217,000 | 1.471 | 737.6 | -122,500 | 0.053 | -13.1 | -34.3 | 31.9 | -3.82 | 4.68 | -10.8 |
| 9 | A4060 | A | 03/16/10 | 126,000 | 1.492 | 727.1 | -32,100 | -0.103 | -3.4 | -32.9 | 31.9 | 0.75 | 3.74 | 12.5 |
| | | B | 07/17/11 | 217,000 | 1.434 | 737.1 | -123,100 | -0.045 | -13.4 | -32.7 | 40.2 | -1.25 | 4.21 | 7.7 |
| 10 | A7650 | B | 07/17/11 | 217,000 | 1.372 | 736.4 | -119,900 | -0.054 | -13.3 | -35.3 | 25.8 | 1.84 | 4.63 | -3.2 |
| 11 | A5817 | A | 03/17/10 | 124,000 | 1.666 | 724.1 | -21,000 | -0.093 | -2.2 | -15.1 | 17.3 | 0.28 | 2.92 | 10.0 |
| | | B | 07/18/11 | 212,000 | 1.609 | 733.7 | -109,000 | -0.037 | -11.8 | -18.6 | 13.5 | -2.99 | 2.81 | -13.1 |
| 12 | A0767 | A | 03/17/10 | 123,000 | 1.540 | 722.5 | -4,000 | -0.076 | -0.9 | -25.1 | 36.2 | -0.13 | 3.05 | 4.0 |
| | | B | 07/18/11 | 212,000 | 1.540 | 732.3 | -93,000 | -0.076 | -10.7 | -24.3 | 40.4 | 1.59 | 4.04 | 8.2 |
| 13 | A4757/ L0568 | A | 03/18/10 | 120,000 | 1.455 | 717.2 | -8,000 | -0.054 | -1.3 | -24.0 | 23.4 | -0.92 | 3.96 | 8.8 |
| | | B | 07/19/11 | 212,000 | 1.359 | 726.7 | -100,000 | 0.042 | -10.9 | -21.6 | 24.5 | 1.33 | 4.58 | 9.6 |

[a]The maximum or minimum value of change likely is near a vertical pier face and affected by minor position variances.

[b]A positive value represents deposition, a negative value represents scour.

[c]The maximum difference near the upstream pier face was taken near the location of the "approximate elevation of scour hole at upstream pier face" in table 6.

[d]This discharge is the value reported for the streamgage at St. Joseph, Missouri, for March 14, 2010, and does not match the value reported in Huizinga (2010). The value reported in Huizinga (2010) for March 15, 2010, is for the streamgage at Kansas City, and includes inflow from the Kansas River and therefore would be higher than the discharge measured at this site upstream from the confluence. TThe value for the previous day at the St. Joseph streamgage was used to account for travel time between St. Joseph and Kansas City.

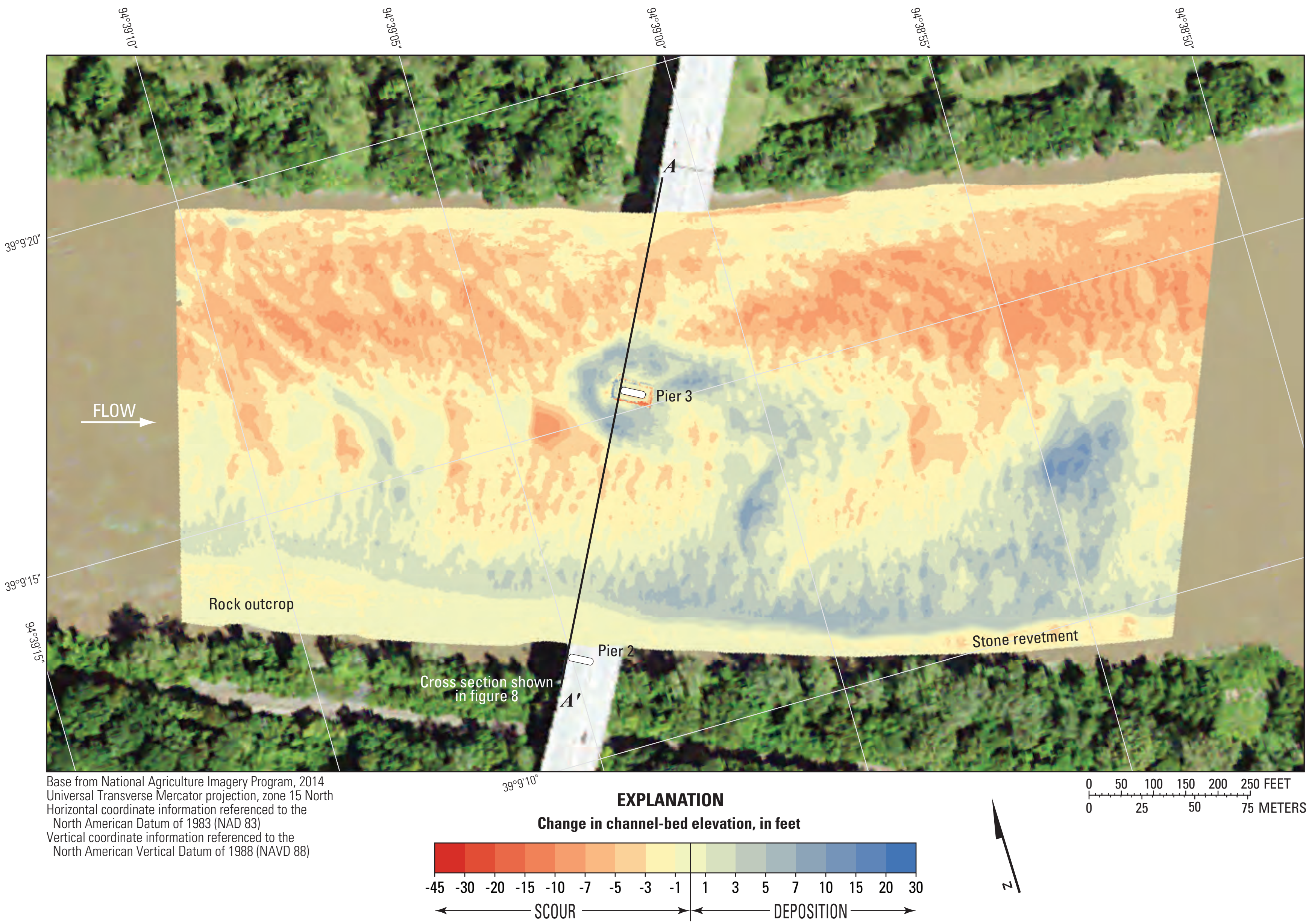



**Figure 10.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A1800 on Interstate 635 near Kansas City, Missouri, on June 2, 2015, and March 15, 2010.

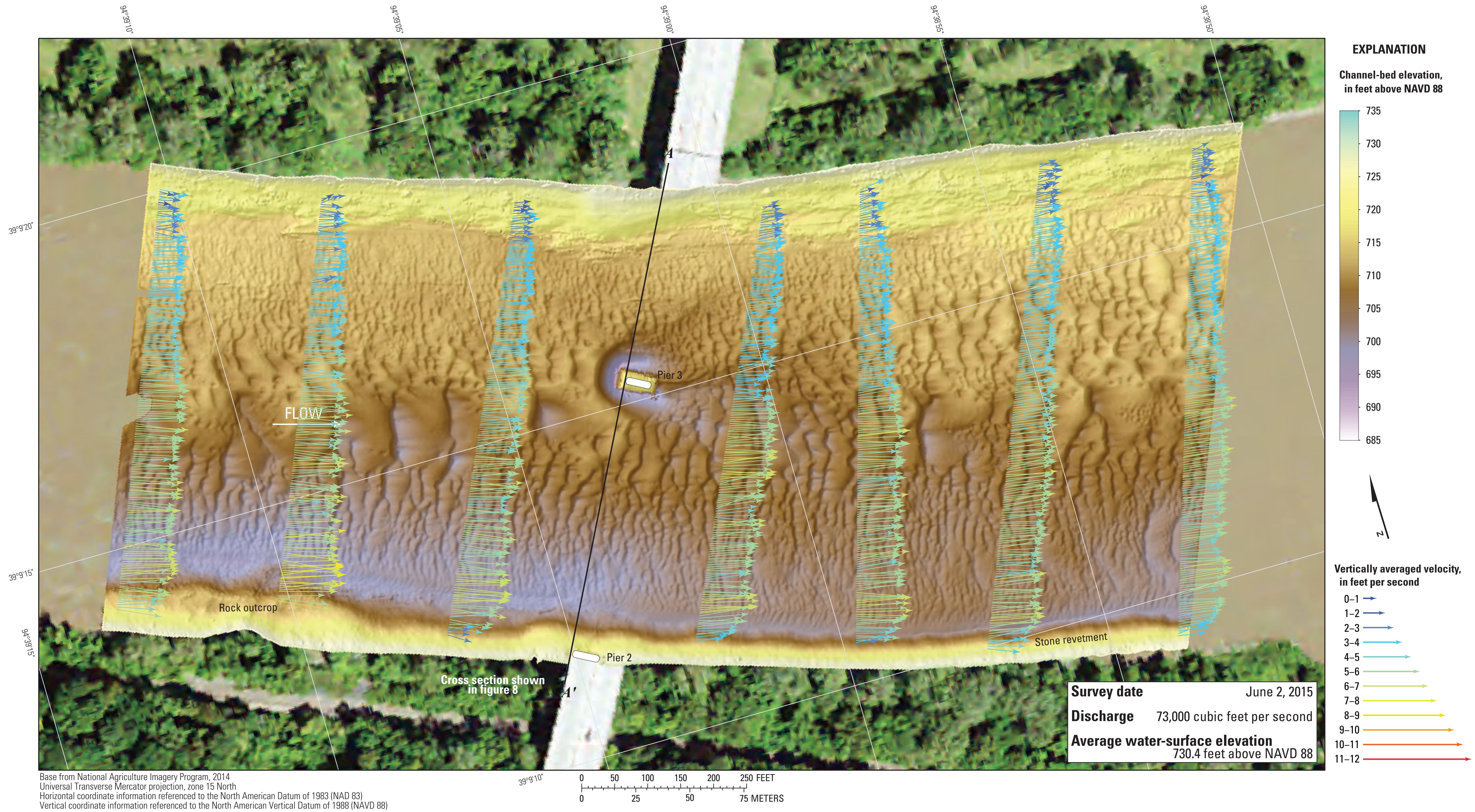



**Figure 11.** Bathymetry and vertically averaged velocities of the Missouri River channel near structure A1800 on Interstate 635 near Kansas City, Missouri.

## Structure A4649 on U.S. Highway 169

Structure A4649 (site 8) on U.S. Highway 169 crosses the Missouri River at RM 366.2, immediately north of downtown Kansas City, Mo. (fig. 1). The site was surveyed on June 2, 2015, and the average water-surface elevation of the river in the survey area, determined by the RTK GPS tide solution, was 724.6 ft (table 5). Flow on the Missouri River was about 94,500 $ft^3$/s during the survey (table 5).

The survey area was about 1,660 ft long and about 905 ft wide, extending from bank to bank in the main channel (fig. 12). The upstream end of the survey area was about 720 ft upstream from the centerline of structure A4649 at pier 2 (fig. 12). The channel-bed elevations ranged from about 692 to 715 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data; table 5; fig. 13), except near pier 2 of structure A4649, the various railroad bridge piers, and the concrete nose upstream from the railroad bridge turntable pier (fig. 12). A deep thalweg on the right (south) bank on the upstream end of the surveyed area was about 20 ft deeper than the channel bed in the middle of the channel (fig. 12). The thalweg became shallower and shifted to the left at the bridges and downstream (fig. 12). Remnants of piers from an old bridge were evident downstream from the existing railroad bridge (fig. 12). Numerous medium and small dunes and ripples were detected throughout the channel, with slightly larger features in the channel thalweg upstream from structure A4649 and on the left side of the channel downstream from the railroad bridge (fig. 12). As in previous surveys, stone revetment was present on the right (south) bank throughout the reach (fig. 12).

A scour hole near main channel pier 2 (fig. 12) had a minimum channel-bed elevation of about 680 ft (table 6), about 23 ft below the average channel bed immediately upstream from the pier (table 6). As in previous surveys at this site (Huizinga, 2010, 2012), the scour hole extended farther around the right side of the pier, with a submerged remnant of a structure near the left downstream side of the pier (figs. 12 and 2–2), presumably a nose for the railroad bridge downstream similar to the concrete nose upstream from the railroad bridge turntable pier. Also, as in the previous surveys at this site, the remnants of the old railroad bridge piers were clearly defined, as were the piles of particulate rock debris around them. The remnant downstream from the existing railroad bridge turntable pier had a maximum elevation of about 710 ft, which is about 13 ft above the channel bed immediately upstream from it and only about 15 ft below the water surface at the time of the 2015 survey. Avoidance of this pier remnant might be difficult in flow conditions lower than those on the day of the survey. The overall minimum channel-bed elevation was 679 ft (table 5), and was observed upstream from the left railroad bridge pier. Information from bridge plans indicate that main channel pier 2 of structure A4649 is a caisson on bedrock, with about 10 ft of bed material between the bottom of the scour hole and the bottom of the caissons (fig. 14; table 6).

The difference between the survey on June 2, 2015, and the previous survey on July 17, 2011 (fig. 15), indicates substantial degradation throughout the reach from the 2011 to 2015 surveys, with an average difference of -3.82 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2015 was about 219,400 $yd^3$, and the net volume of fill was about 19,200 $yd^3$, resulting in a net loss of about 200,200 $yd^3$ of sediment between 2011 and 2015. The shallow area observed in the upstream left part of the channel in the 2011 survey was not observed in the 2015 survey, and there were areas in the middle of the upstream channel and the downstream left where degradation of 10 to 15 ft was observed (fig. 15). Small areas of deposition were observed around the piers and in the trough of the very large dune observed in the upstream channel of the 2011 survey (fig. 15). Minimal scour or deposition was observed along the downstream right bank (fig. 15), indicating this may be a scour resistant area of rock; a similar lack of change had been observed between 2010 and 2011 in the previous study at this site (Huizinga, 2012). The cross sections from the two surveys also were substantially different from one another (fig. 14), with the 2015 section 10 to 15 ft lower than in 2011. The frequency distribution of bed elevations was narrower in 2015 than in 2011, with a greater percentage of survey-grid cells at a lower elevation than 2011 (fig. 13). The scour hole near main channel pier 2 in 2015 was narrower and deeper than in 2011 (fig. 14), as evidenced by the small area of deposition upstream from the pier, and the overall indication

**Structure A4649 on U.S. Highway 169 crosses the Missouri River at river mile 366.2, immediately north of downtown Kansas City, Missouri.**

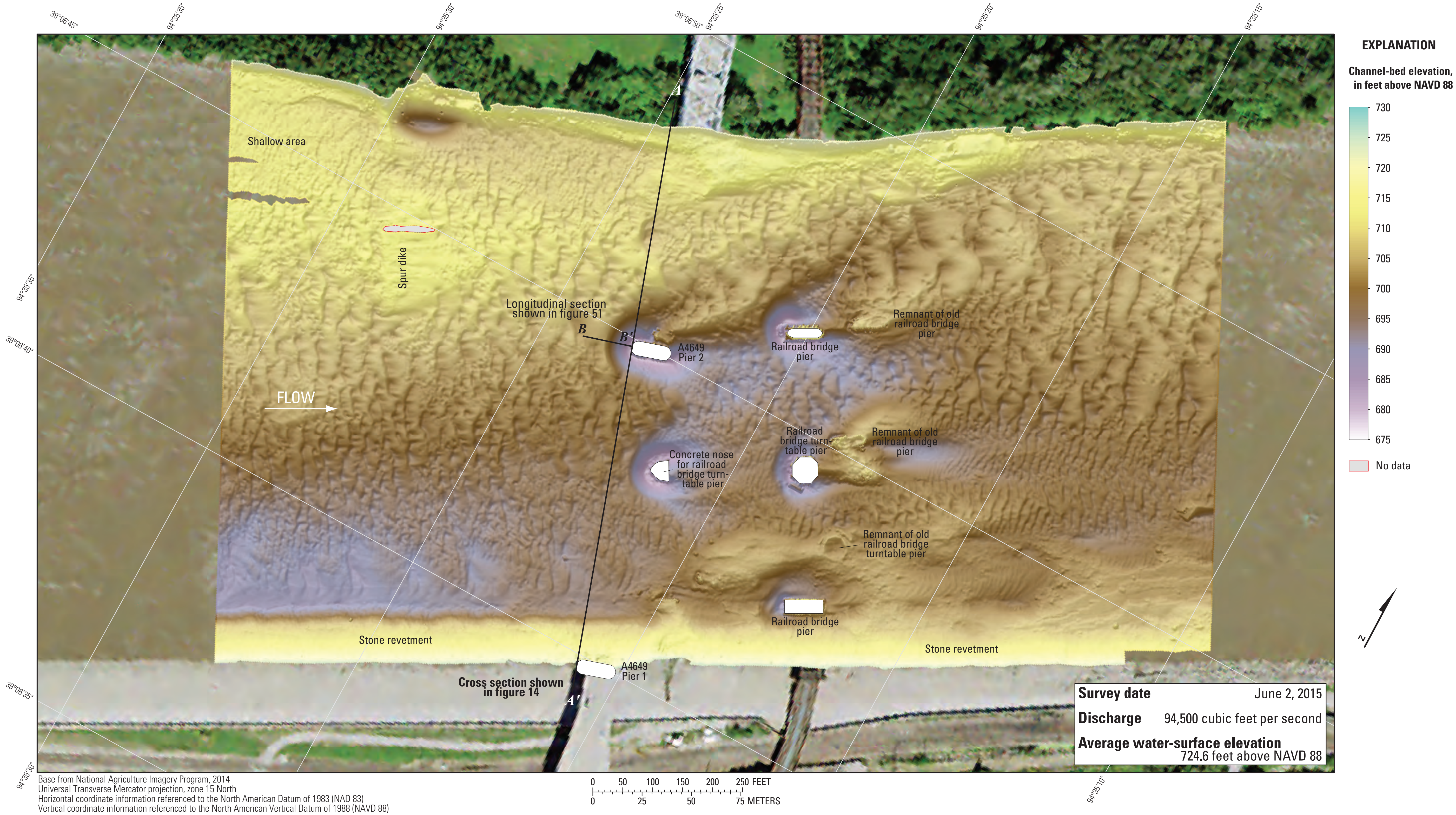



**Figure 12.** Bathymetric survey of the Missouri River channel near structure A4649 on U.S. Highway 169 in Kansas City, Missouri.

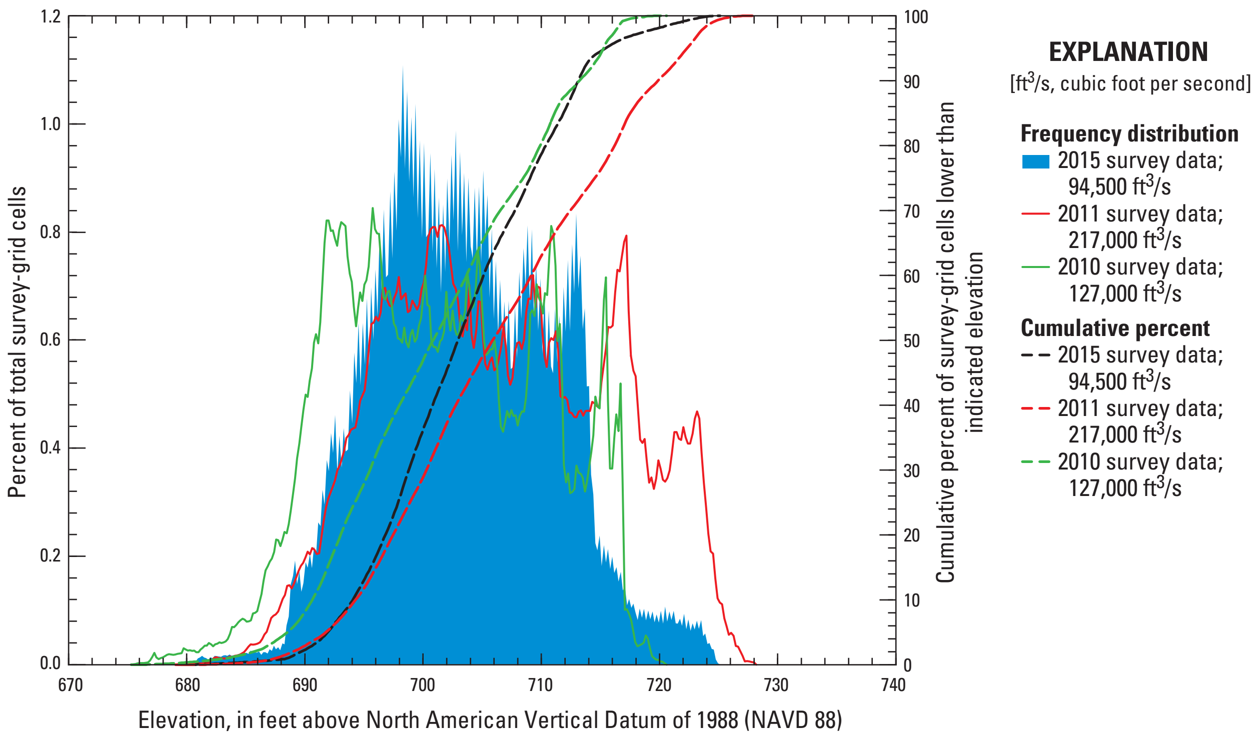



**Figure 13.** Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A4649 on U.S. Highway 169 in Kansas City, Missouri, on June 2, 2015, compared to previous surveys.

of scour in a horseshoe shape around the pier (fig. 15); however, near the railroad bridge piers and concrete nose, the scour holes are about the same between the two surveys (fig. 15). Substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see "Uncertainty Estimation" section).

The difference between the survey on June 2, 2015, and the previous nonflood survey on March 16, 2010 (fig. 16) indicates moderate deposition throughout the reach from the 2010 to 2015 surveys, with an average difference of +1.11 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2010 to 2015 was about 47,000 $yd^3$, and the net volume of fill was about 103,100 $yd^3$, resulting in a net gain of about 56,100 $yd^3$ of sediment between 2010 and 2015. Substantial deposition had been observed between the 2010 and 2011 surveys (Huizinga, 2012), but ongoing sediment transport processes at this site have removed much of the sediment deposits as indicated by the substantial scour observed between 2011 and 2015 (fig. 15). Some of the deposition remained or returned after the 2011 survey, with small areas of scour along the left bank upstream and downstream from the bridge (fig. 16). An area of as much as 5 ft of scour was observed along the toe of the upstream right bank (fig. 16) and may represent an area of slumped revetment. Smaller areas of scour are apparent in the same area in the difference between the 2011 and 2015 surveys (fig. 15). The cross sections from the 2010 and 2015 surveys were similar to one another for most of the right side of the channel and part of the left (fig. 14); however, the frequency distribution of bed elevations was narrower in 2015 than in 2010, with a higher minimum channel-bed elevation and a greater percentage of survey-grid cells at a higher elevation than 2010 (fig. 13). The scour hole near main channel pier 2 was substantially narrower and somewhat shallower in 2015 than in 2010 (fig. 14); however, near the railroad bridge turntable pier and the concrete nose, the scour holes are about the same between the two surveys (fig. 16). As in the previous difference maps (fig. 15), minimal scour or deposition was observed along the downstream right bank (fig. 16), confirming this may be a scour resistant area of rock. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see "Uncertainty Estimation" section).

The vertically averaged velocity vectors indicate mostly uniform flow upstream from the structure A4649 ranging from a minimum of 2 ft/s along the inside of the bend on the upstream left (north) bank to a maximum velocity of about 9 ft/s in the channel thalweg along the outside of the bend on the right (south) bank (fig. 17). Exceptions to uniform conditions include diagonal flows across the channel in the immediately vicinity of structure A4649 (fig. 17), which may help explain the shift in the channel thalweg towards the left (north) bank. Substantial turbulence also was observed between structure A4649 and the railroad bridge and downstream from the railroad bridge piers (fig. 17).

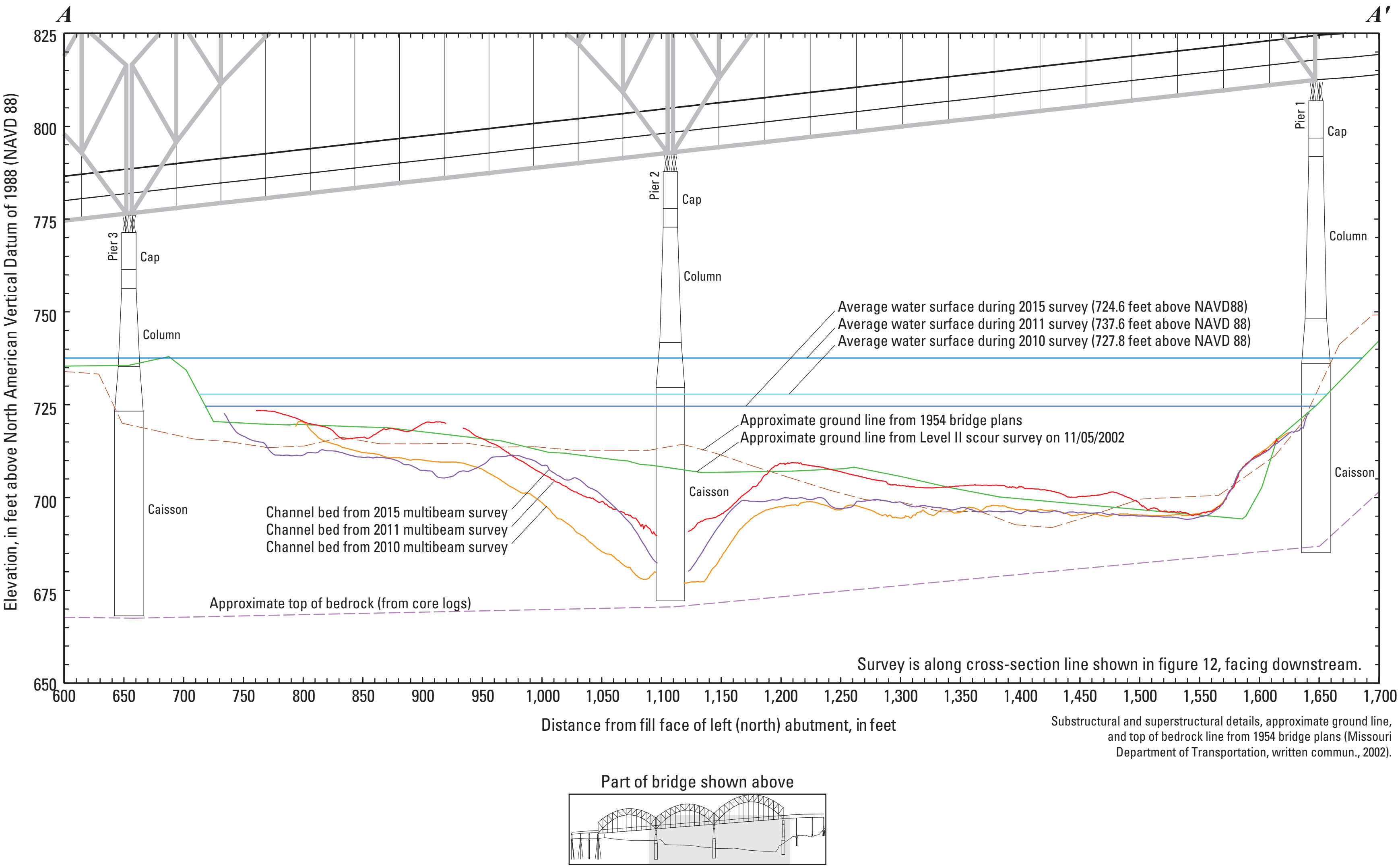



**Figure 14.** Key features, substructural and superstructural details, and surveyed channel bed of structure A4649 on U.S. Highway 169 crossing the Missouri River in Kansas City, Missouri.

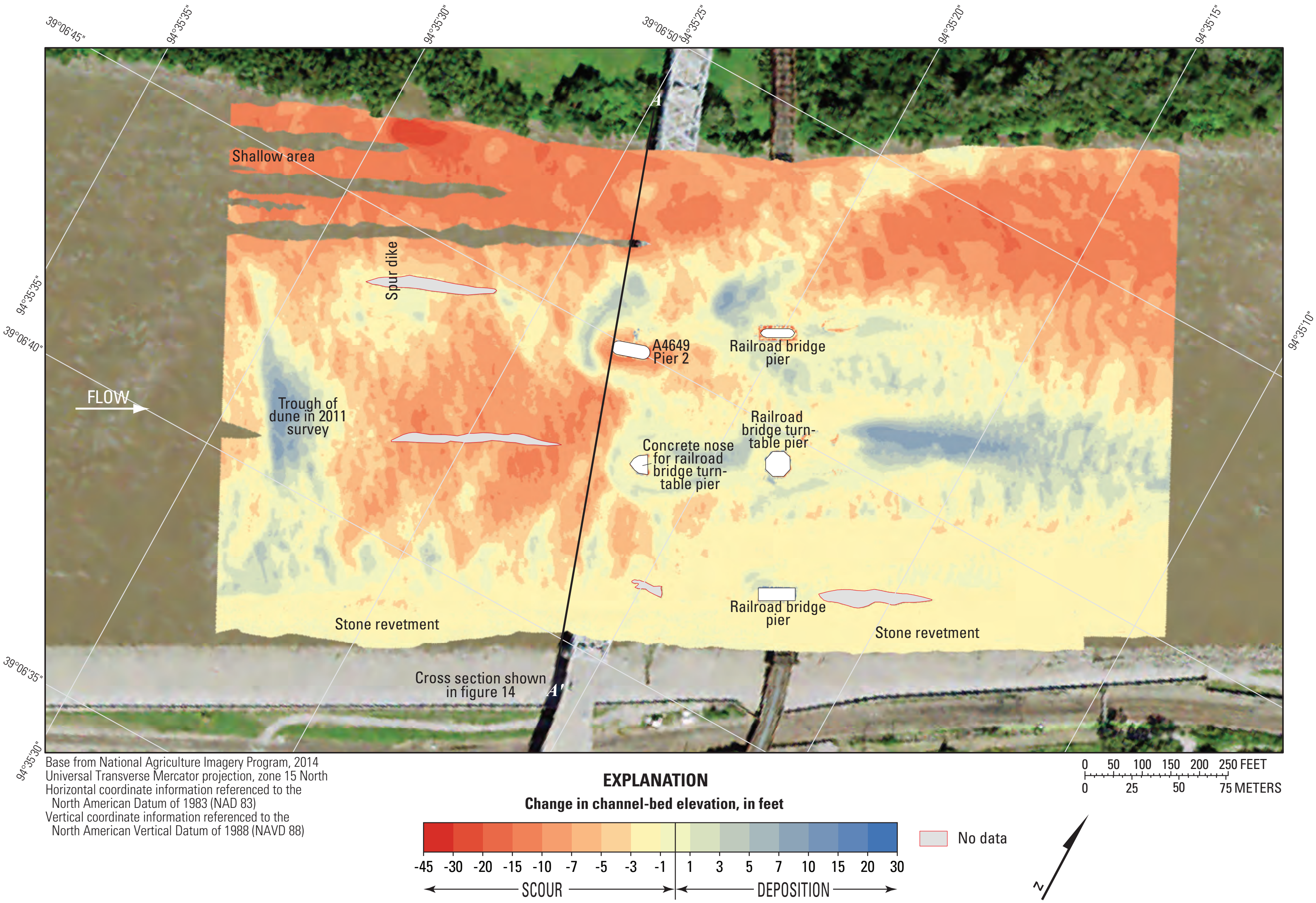



**Figure 15.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4649 on U.S. Highway 169 in Kansas City, Missouri, on June 2, 2015, and July 17, 2011.

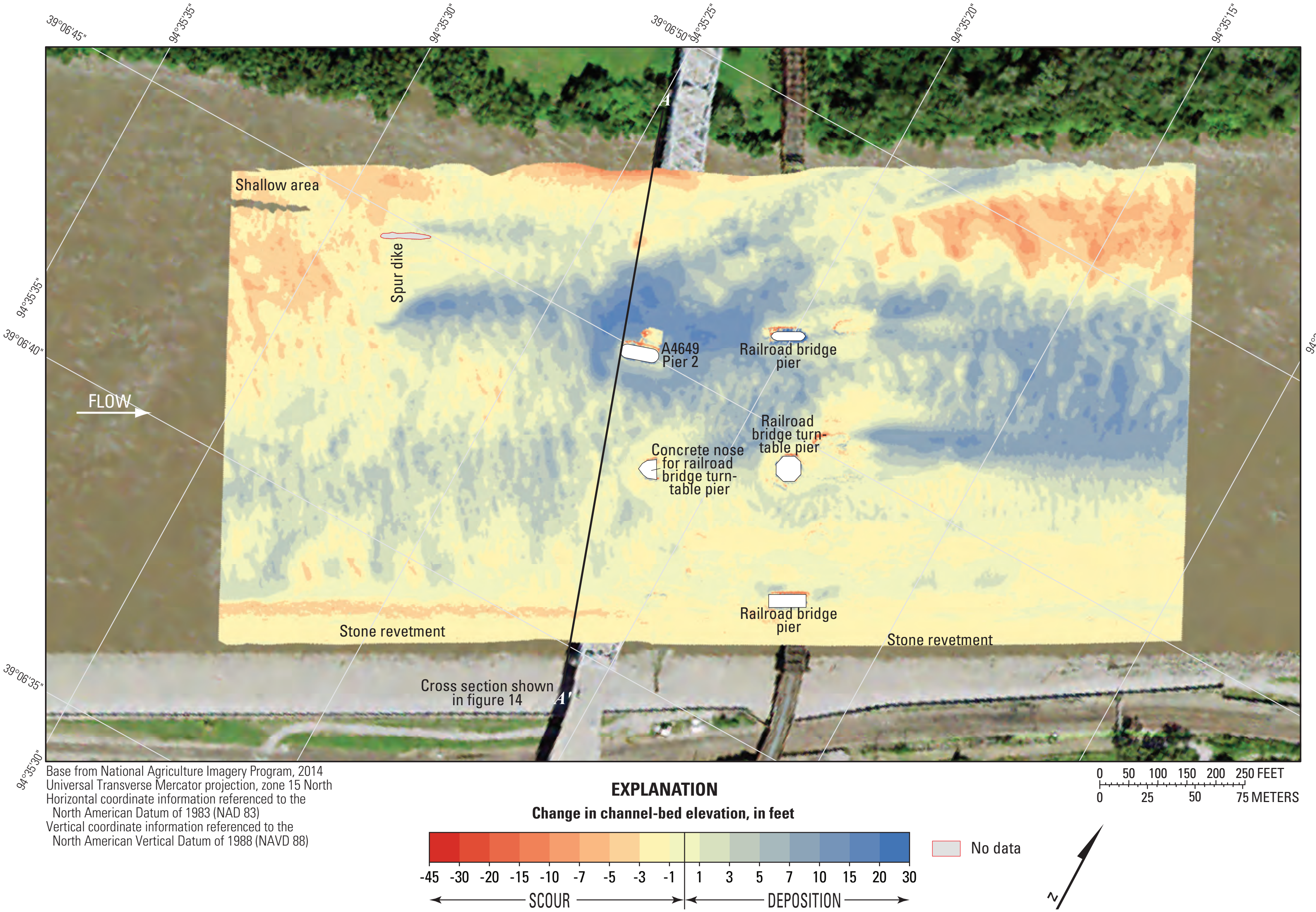



**Figure 16.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4649 on U.S. Highway 169 in Kansas City, Missouri, on June 2, 2015, and March 16, 2010.

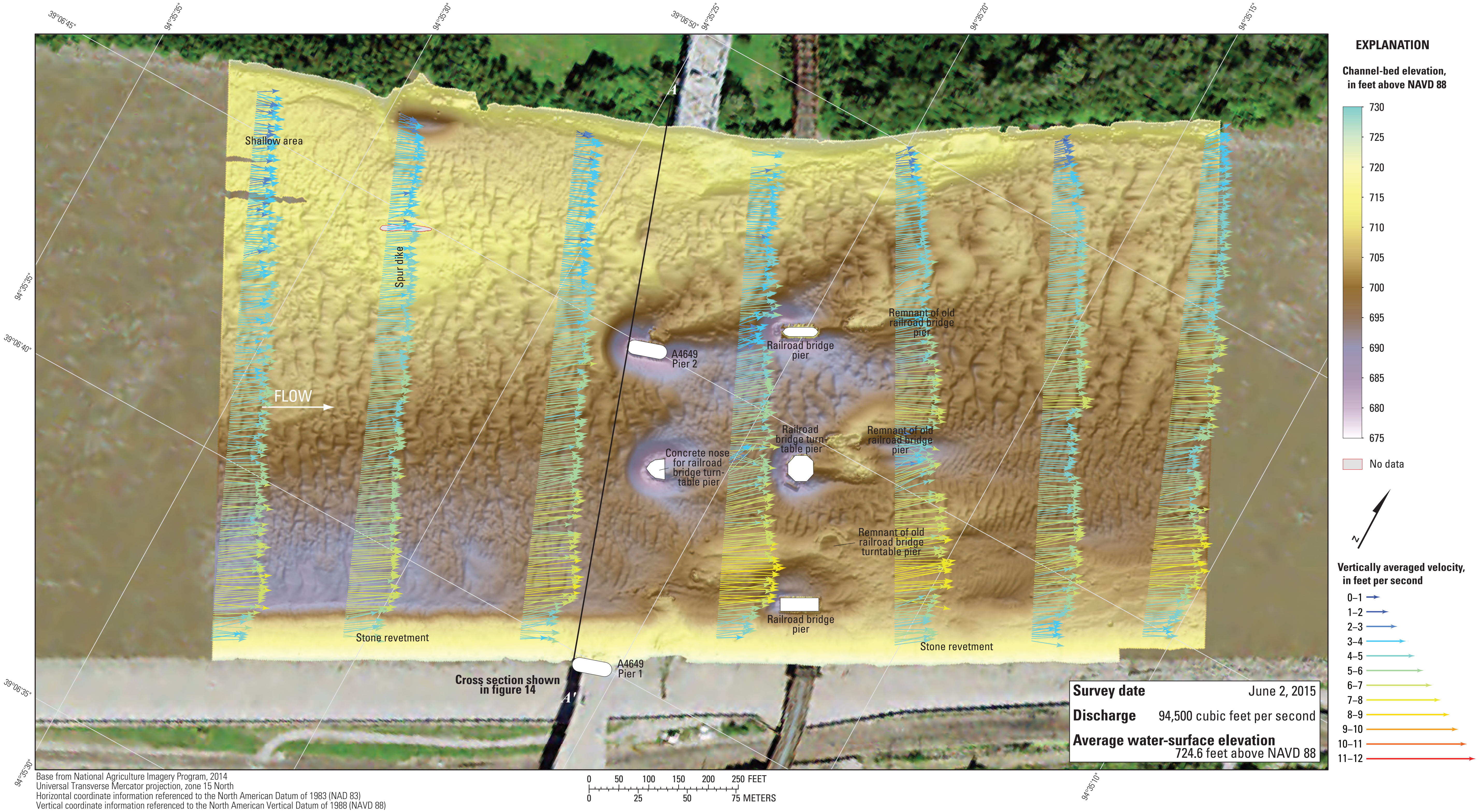



**Figure 17.** Bathymetry and vertically averaged velocities of the Missouri River channel near structure A4649 on U.S. Highway 169 in Kansas City, Missouri.

## Structure A4060 on State Highway 9

Structure A4060 (site 9) on State Highway 9 crosses the Missouri River at RM 365.5, immediately north of downtown Kansas City, Mo. (fig. 1), and is about 3,400 ft downstream from structure A4649 on U.S. Highway 169. The site was surveyed on June 3, 2015, and the average water-surface elevation of the river in the survey area, determined by the RTK GPS tide solution, was 723.7 ft (table 5). Flow on the Missouri River was about 93,900 $ft^3/s$ during the survey (table 5).

The survey area was about 1,640 ft long and about 840 ft wide, extending from bank to bank in the main channel (fig. 18). Piers 5 and 6 were in the water and away from the banks, and the upstream end of the survey area was about 665 ft upstream from the centerline of structure A4060 at pier 6 (fig. 18). The channel-bed elevations ranged from about 696 to 710 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data; table 5; fig. 19), except near the railroad bridge pier upstream from pier 6 of structure A4060 (fig. 18). The channel did not have a noticeable thalweg, although the channel was slightly deeper along the right (south) side throughout the surveyed area (fig. 18). A few medium dune features were detected in the middle of the channel upstream from the bridges, and numerous smaller dunes and ripples were present throughout the channel reach (fig. 18). As in previous surveys, stone revetment was present on the right (south) bank throughout the reach (fig. 18).

A scour hole near main channel pier 5 (fig. 18) had a minimum channel-bed elevation of about 693 ft (table 6), about 3 ft below the elevation of the bottom of the pier seal course of 696.26 ft (fig. 20; table 6). Submerged debris with several beams or trees were protruding from the channel bed immediately upstream from pier 5 (figs. 18 and 2–3). Near the right (south) main channel pier 6 (fig. 18), a scour hole had a minimum channel-bed elevation of about 688 ft (table 6), about 8 ft below the elevation of the bottom of the pier seal course of 696.26 ft (fig. 20; table 6). A substantially deeper scour hole was observed near the upstream railroad bridge pier (fig. 18), with a minimum elevation of about 679 ft, which is the overall minimum channel-bed elevation observed in this reach (table 5). This deeper hole likely was the result of flow over large sheet piling panels that were lying on the channel bottom on the right (south) side of the upstream railroad bridge pier first observed in the 2010 survey (Huizinga, 2010). Information from bridge plans indicates that piers 5 and 6 are founded on shafts drilled 20 ft into bedrock, with about 26 ft of bed material between the bottom of the scour hole and bedrock at pier 5 and 18 ft of material at pier 6 (fig. 20; table 6).

The difference between the survey on June 3, 2015, and the previous survey on July 17, 2011 (fig. 21), indicates moderate degradation throughout the reach from 2011 to 2015, with an average difference of -1.25 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2015 was about 118,500 $yd^3$, and the net volume of fill was about 55,100 $yd^3$, resulting in a net loss of about 63,400 $yd^3$ of sediment between 2011 and 2015. Substantial deposition had been observed between the 2010 and 2011 surveys (Huizinga, 2012), but ongoing sediment transport processes at this site seem to have removed some of the sediment deposits. There was an area of substantial scour in the upstream channel, and moderate scour along the left (north) side of the downstream channel (fig. 21). The thalweg observed along the right (south) bank in 2011 experienced deposition, and the substantial scour hole downstream from the right railroad bridge pier also had 7 to 10 ft of deposition (fig. 21). The cross sections from the two surveys were similar to one another to the left of pier 6, whereas to the right of pier 6, the 2015 survey is 5 to 10 ft higher (fig. 20); however, the frequency distribution of bed elevations was substantially narrower in 2015 than in 2011, with a higher minimum channel-bed elevation and a much greater percentage of survey-grid cells at a lower elevation than 2011 (fig. 19). The scour hole near main channel pier 5 in 2015 was of a similar shape to that in 2011, albeit substantially shallower on the right side (figs. 20 and 21). The localized scour observed on the stone revetment on the right (south) bank in 2011 (Huizinga, 2012) seemed to have stabilized between 2011 and 2015 (fig. 21). As with all difference maps in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see "Uncertainty Estimation" section).

**Structure A4060 on State Highway 9 crosses the Missouri River at river mile 365.5, immediately north of downtown Kansas City, Missouri.**

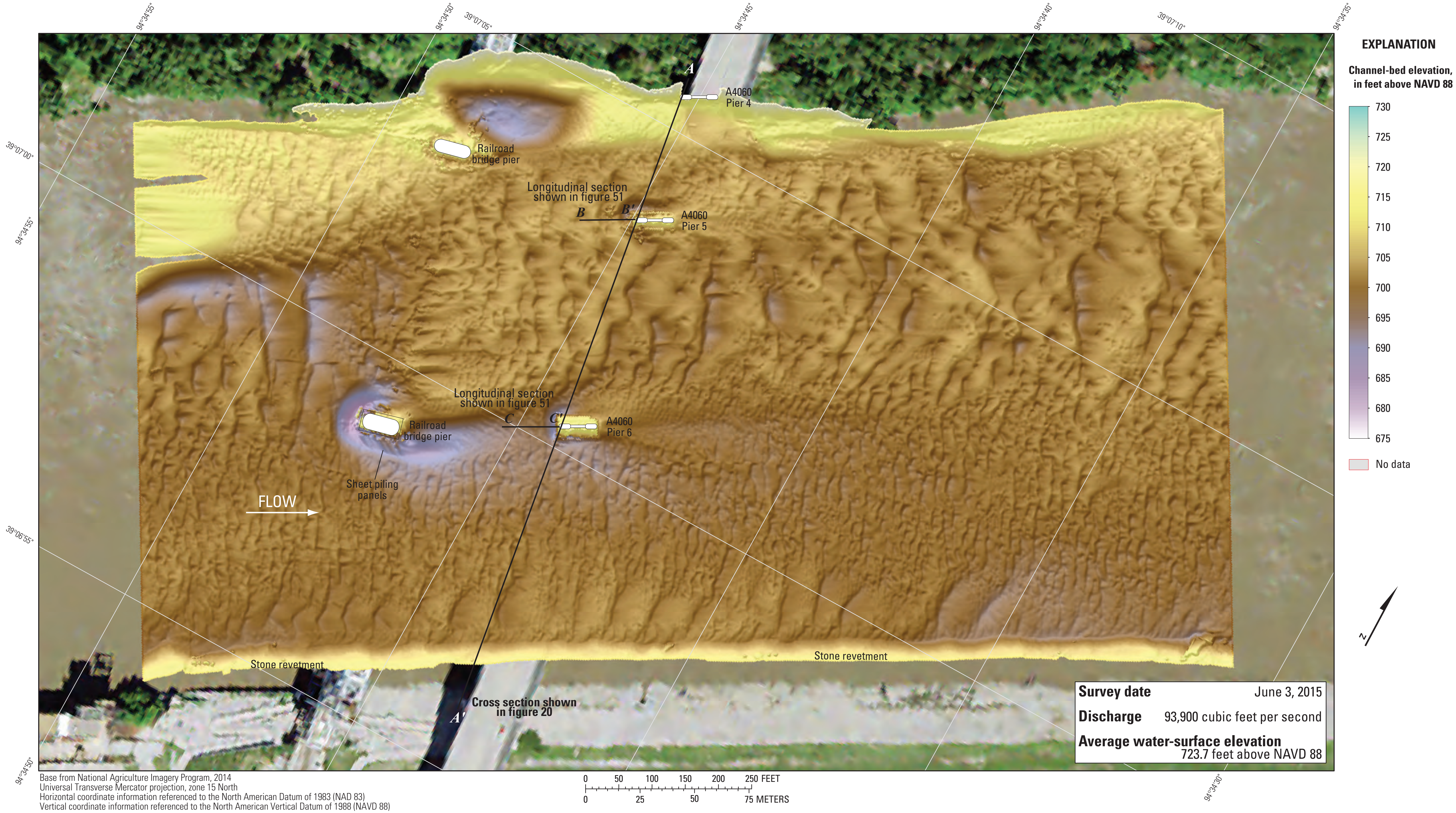



**Figure 18.** Bathymetric survey of the Missouri River channel near structure A4060 on State Highway 9 in Kansas City, Missouri.

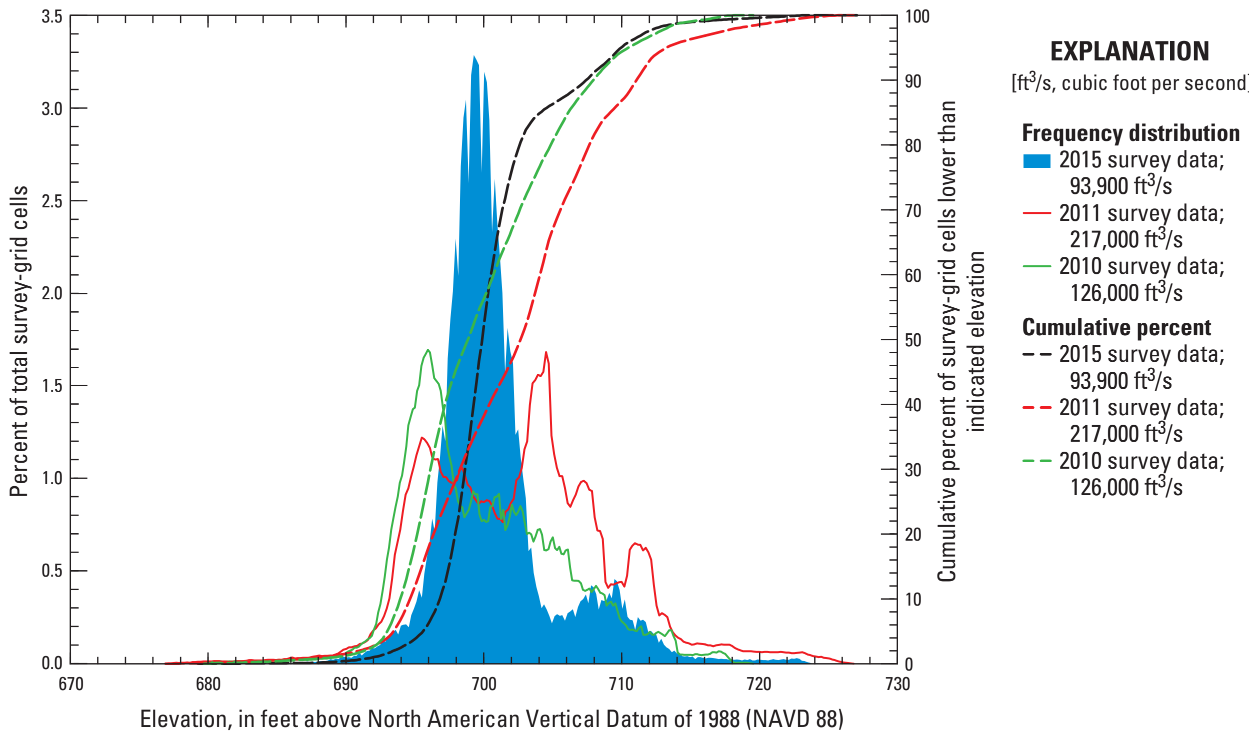



**Figure 19.** Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A4060 on State Highway 9 in Kansas City, Missouri, on June 3, 2015, compared to previous surveys.

The difference between the survey on June 3, 2015, and the previous nonflood survey on March 16, 2010 (fig. 22), indicates minor deposition throughout the reach from 2010 to 2015, with an average difference of +0.75 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2010 to 2015 was about 57,500 $yd^3$, and the net volume of fill was about 93,700 $yd^3$, resulting in a net gain of about 36,200 $yd^3$ of sediment between 2010 and 2015. Substantial scour was observed in the middle of the upstream channel in 2015, and minor to moderate scour was observed along the left (north) bank; however, deposition was observed throughout most of the reach (fig. 22). The cross sections from the two surveys further indicate the deposition except to the left of pier 5 (fig. 20). The frequency distribution of bed elevations was substantially narrower in 2015 than in 2010, with a greater percentage of survey-grid cells at a higher elevation than 2010 (fig. 19). The localized scour observed on the stone revetment on the right (south) bank in 2011 (Huizinga, 2012) is present in the difference between the 2015 and 2010 surveys (fig. 22). As with all difference maps in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see "Uncertainty Estimation" section).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the channel, ranging from about 3 to 8 ft/s (fig. 23). Exceptions to uniform conditions include flow reversal observed in the area downstream from the left (north) railroad bridge pier (fig. 23). Substantial turbulence also was observed downstream from the right (south) piers of the railroad bridge and structure A4060 (fig. 23).

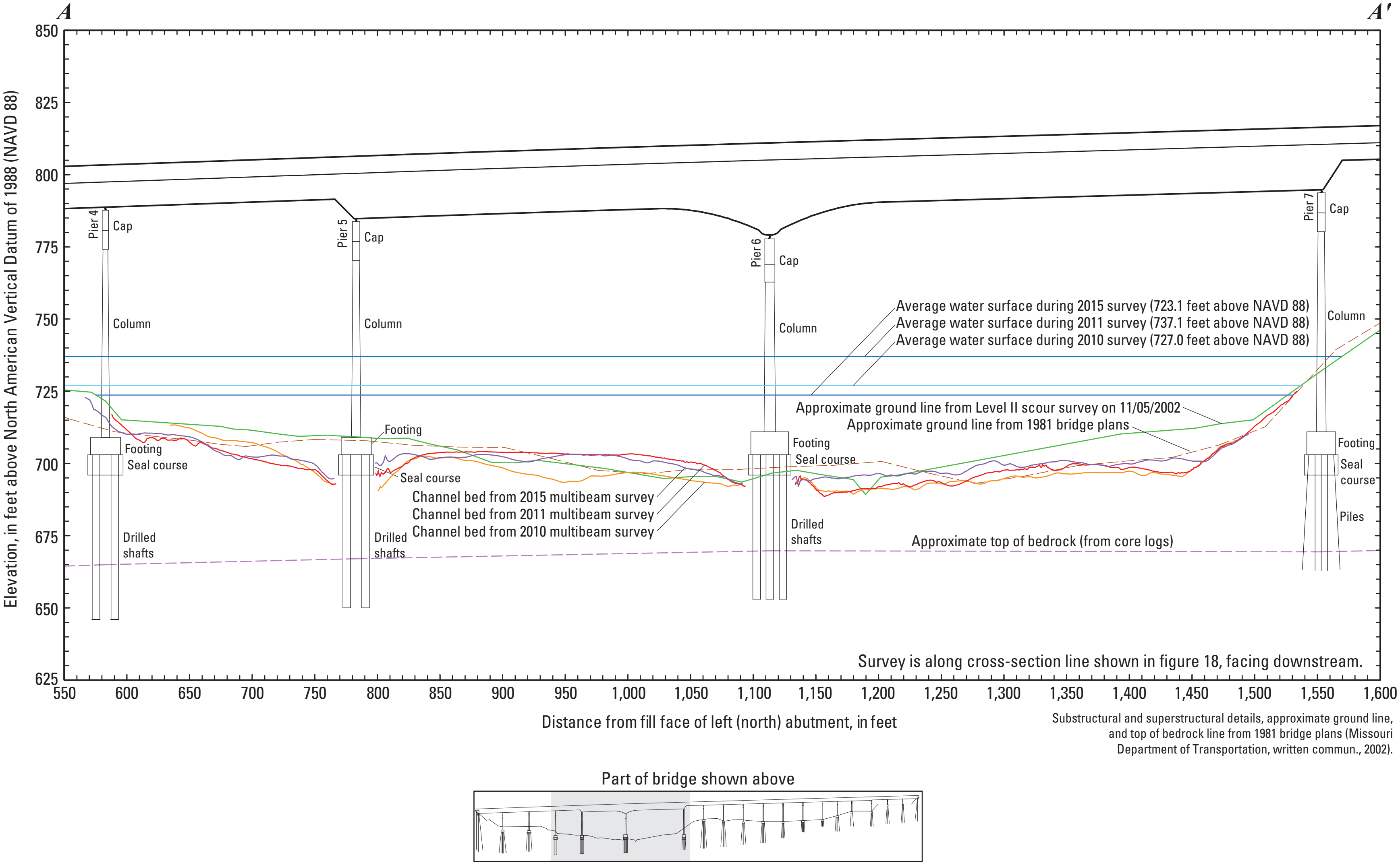



**Figure 20.** Key features, substructural and superstructural details, and surveyed channel bed of structure A4060 on State Highway 9 crossing the Missouri River in Kansas City, Missouri.

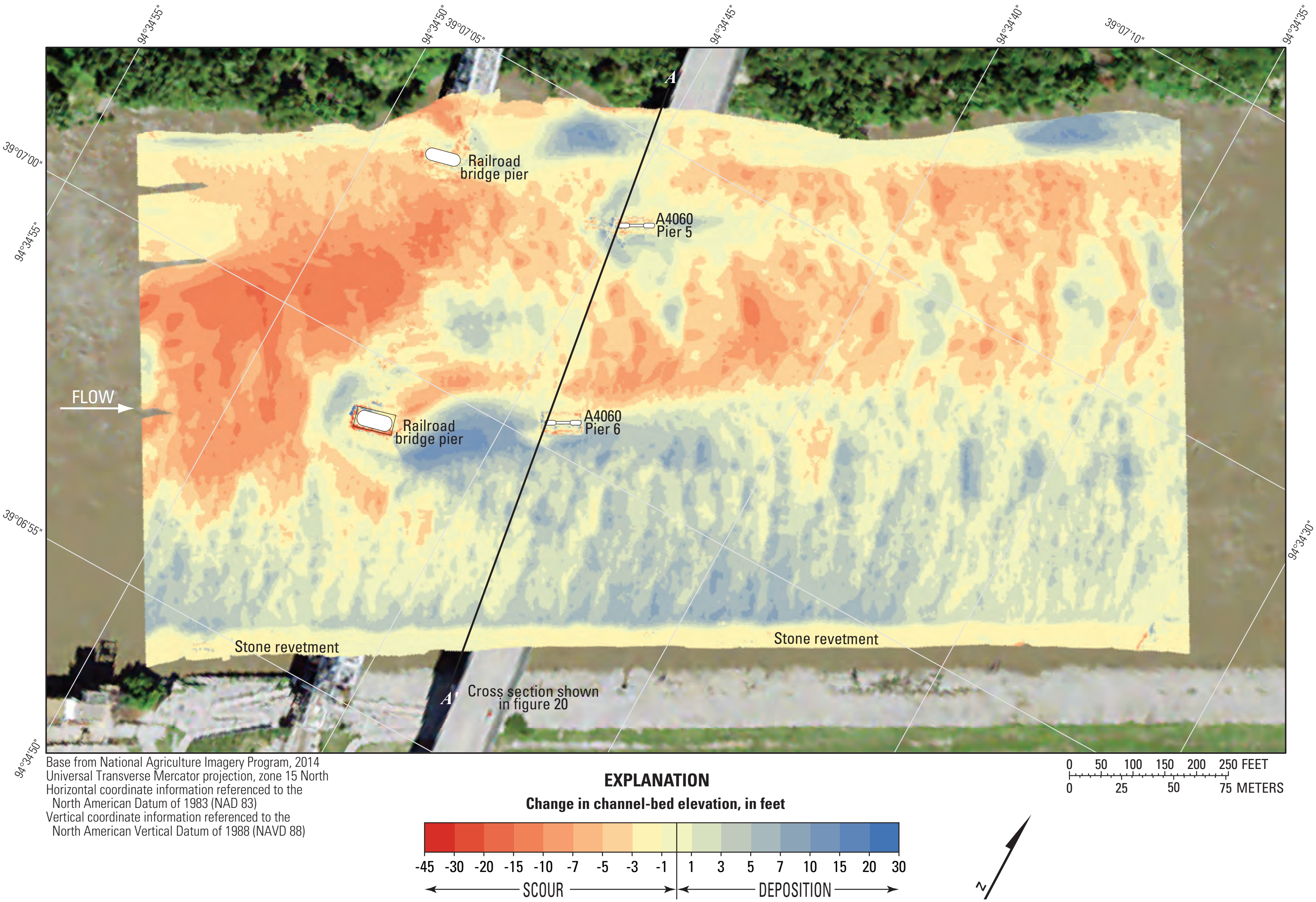



**Figure 21.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4060 on State Highway 9 in Kansas City, Missouri, on June 3, 2015, and July 17, 2011.

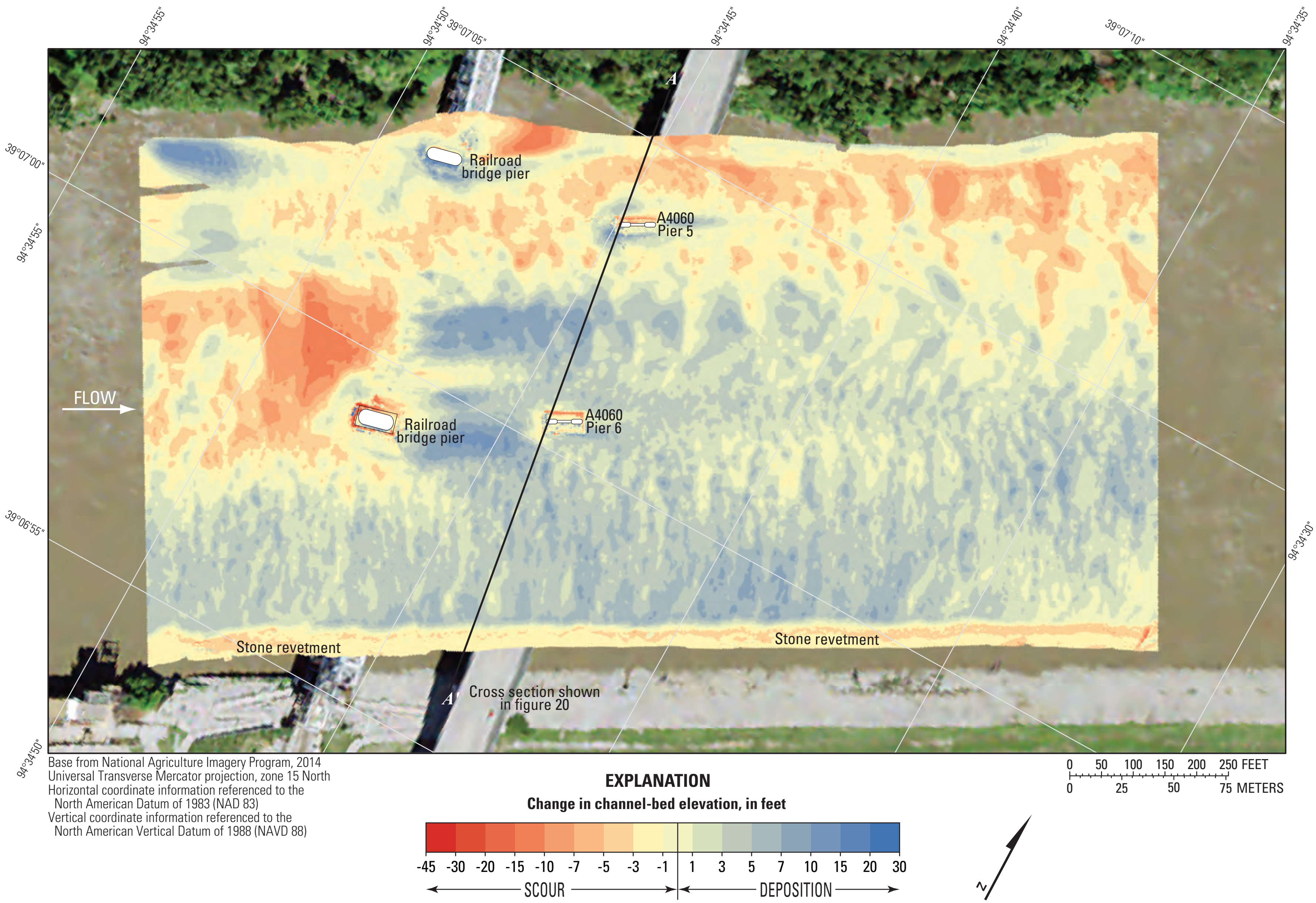



**Figure 22.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4060 on State Highway 9 in Kansas City, Missouri, on June 3, 2015, and March 16, 2010.

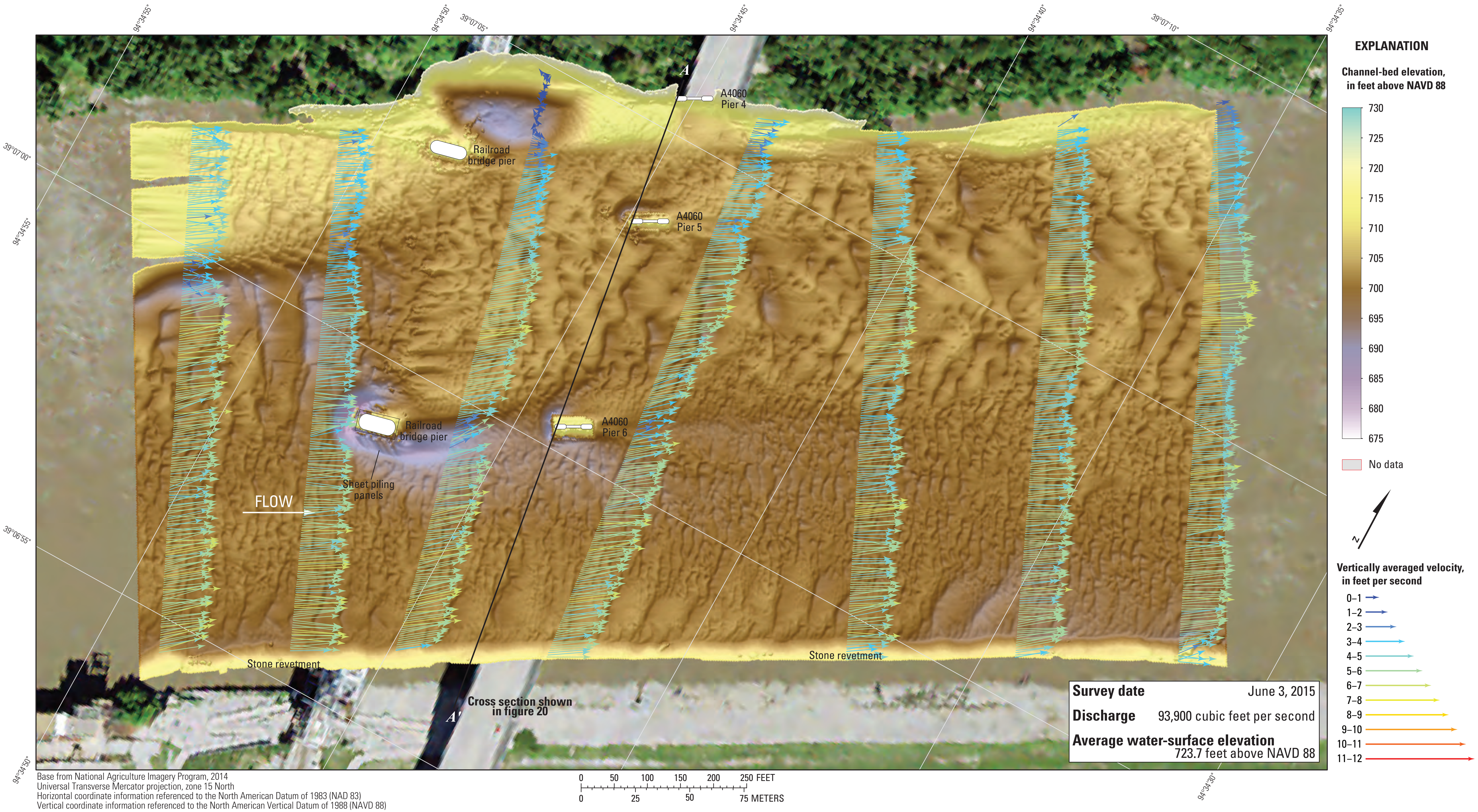



**Figure 23.** Bathymetry and vertically averaged velocities of the Missouri River channel near structure A4060 on State Highway 9 in Kansas City, Missouri.

## Structure A7650 on Interstate 35

Structure A7650 (site 10) on Interstate 35 crosses the Missouri River at RM 364.7, immediately north of downtown Kansas City, Mo. (fig. 1), and is about 4,300 ft downstream from structure A4060 on State Highway 9. The site was surveyed on June 3, 2015, and the average water-surface elevation of the river in the survey area, determined by the RTK GPS tide solution, was 723.1 ft (table 5). Flow on the Missouri River was about 97,100 $ft^3/s$ during the survey (table 5).

The survey area was about 1,640 ft long and about 805 ft wide, extending from bank to bank in the main channel (fig. 24). The upstream end of the survey area was about 700 ft upstream from the centerline of structure A7650 at the main channel pylon (fig. 24). The channel-bed elevations ranged from about 692 to 709 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data; table 5; fig. 25), except near the pylon and downstream from the spur dike on the downstream left (north) bank (fig. 24). Similar to upstream structure A4060, there was no definitive thalweg along either side of the channel (fig. 24). Numerous medium and small dunes and ripples were present throughout the channel (fig. 24). Downstream from the spur dike on the left (north) side of the downstream reach, the minimum channel-bed elevations of 676 ft was observed (fig. 24; table 5). Stone revetment was present on the right (south) bank throughout the reach (fig. 24) and seemed to have an area where it had slumped near the downstream end of the reach.

The main channel pylon seemed to be surrounded by a mound of rock riprap, with a local minimum channel-bed elevation of about 681 ft near the downstream left (north) corner (fig. 24; table 6). The top of the riprap around the upstream face of the pylon was at an elevation of about 697 ft, which is slightly below the elevation of the bottom of the pylon seal course of 699.50 ft (table 6); the top of the riprap along the sides of the pylon is lower than at the upstream face (figs. 24 and 26). The minimum channel-bed elevation near the pylon was about 19 ft below the elevation of the bottom of the pylon seal course (fig. 24; table 6). Information from bridge plans indicates that the pylon is founded on shafts drilled 32 ft into bedrock, with about 34 ft of bed material between the bottom of the scour hole and bedrock (fig. 26; table 6).

The difference between the survey on June 3, 2015, and the previous survey on July 17, 2011 (fig. 27), indicates moderate deposition throughout the reach from 2011 to 2015, with an average difference of +1.84 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2015 was about 37,100 $yd^3$, and the net volume of fill was about 124,600 $yd^3$, resulting in a net gain of about 87,500 $yd^3$ of sediment between 2011 and 2015. There were areas of substantial deposition in 2015, particularly downstream from the main channel pylon and in the area of a scour hole present in the 2011 survey near the old pier of structure L0734 (fig. 27); however, there also was an area of substantial scour (of nearly 35 ft) downstream from the spur dike on the downstream left (north) bank, and smaller areas of moderate scour scattered throughout the reach (fig. 27). The cross sections from the two surveys were similar to one another except in the area downstream from the old pier of structure L0734 about 1,250 ft from the fill face of the left (north) abutment (fig. 26). The frequency distribution of bed elevations was of a similar shape but narrower in 2015 than in 2011, with a greater percentage of survey-grid cells at a higher elevation than 2011 (fig. 25). The scour hole near the main channel pylon in 2015 was of a similar size and shape to that in 2015, albeit shallower on the outer side edges (figs. 26 and 27). The stone revetment on the right (south) bank seemed to have several areas of localized deposition and scour (fig. 27).

**Structure A7650 on Interstate 35 crosses the Missouri River at river mile 364.7, immediately north of downtown Kansas City, Missouri.**

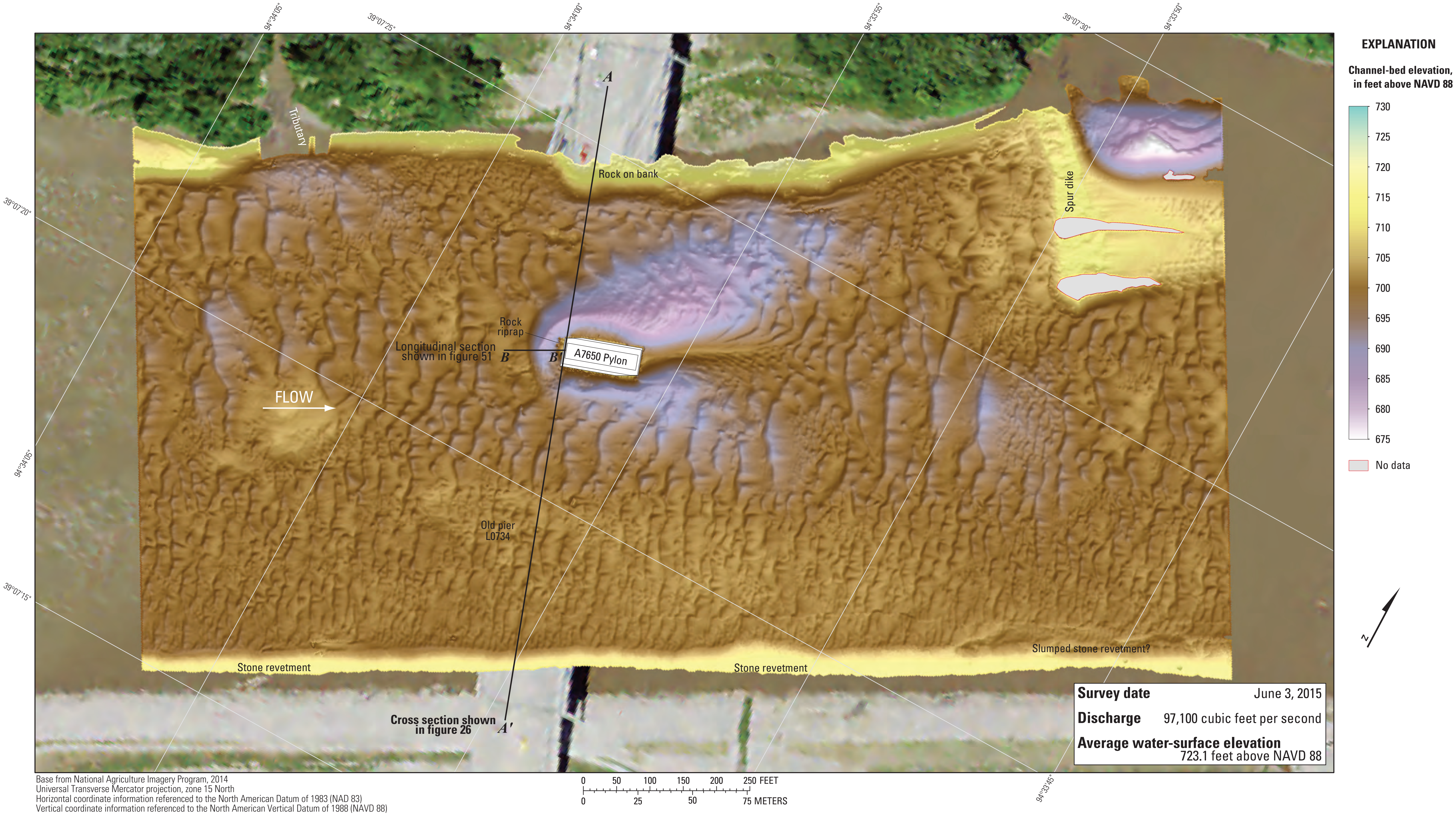



**Figure 24.** Bathymetric survey of the Missouri River channel near structure A7650 on Interstate 35 in Kansas City, Missouri.

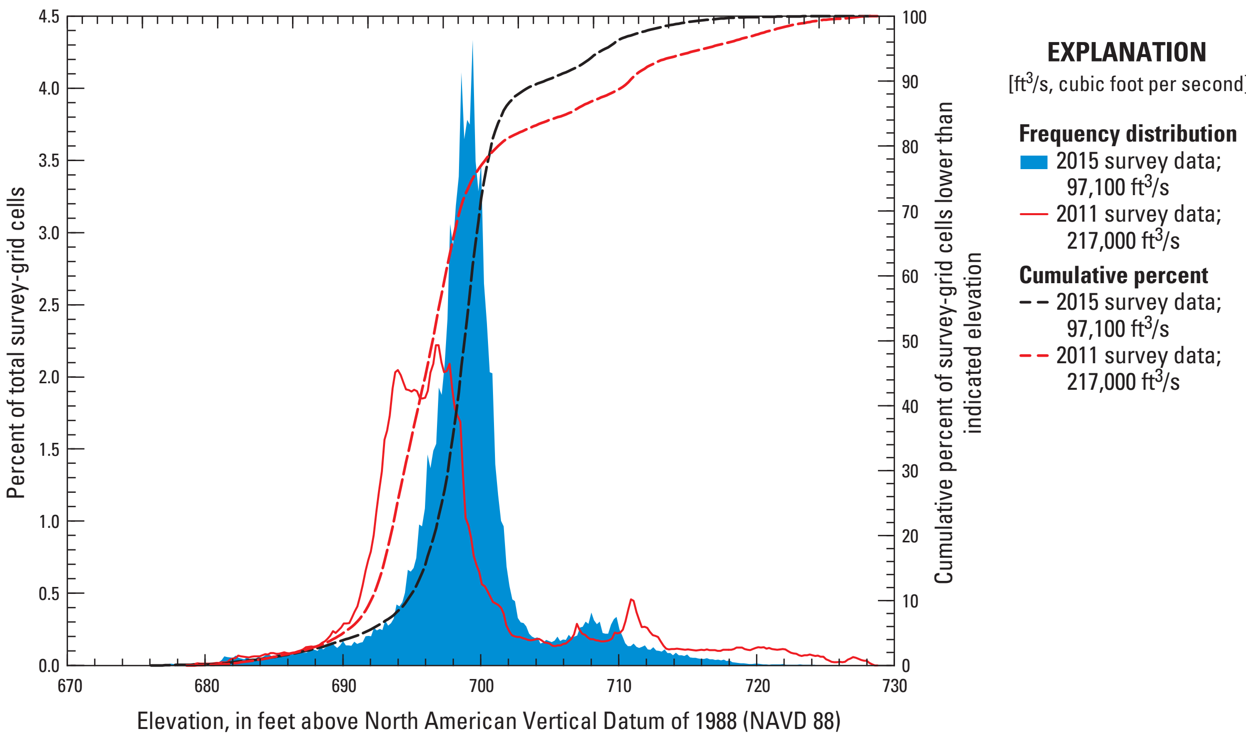
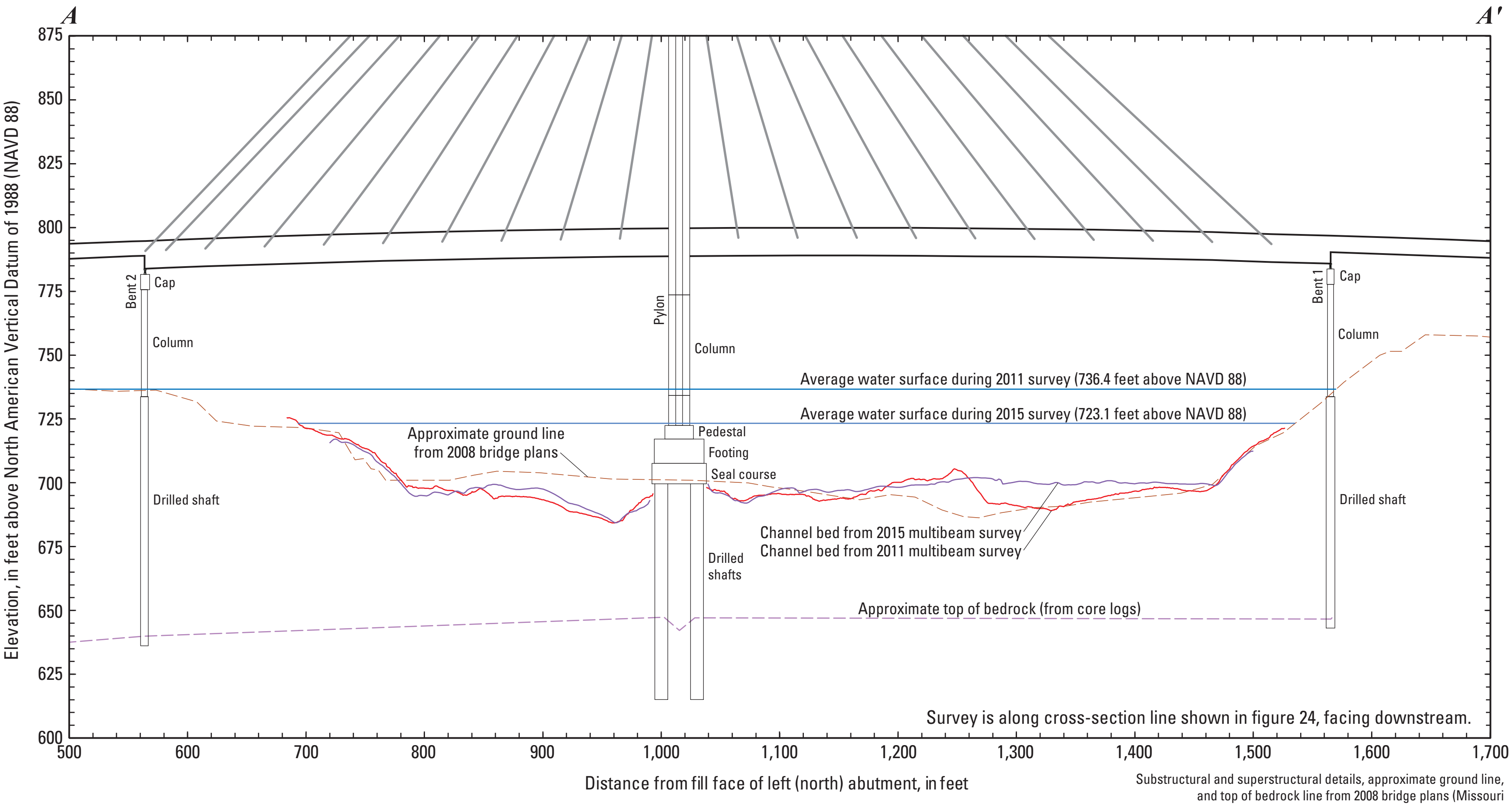



**Figure 25.** Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A7650 on Interstate 35 in Kansas City, Missouri, on June 3, 2015, compared to previous surveys.

The vertically averaged velocity vectors indicate mostly uniform flow throughout most of the reach, with velocities ranging from about 3 to 8 ft/s (fig. 28). Exceptions to uniform conditions include flow reversal on the left (north) bank near the upstream tributary and in the pool downstream from the spur dike (fig. 28). Substantial turbulence also was observed downstream from the main channel pylon (fig. 28), likely as a result of the pylon being skewed to flow. The velocities do not seem to be higher near the bulge in the left bank at the bridge, but a velocity cross section was not taken in the constriction.




Substructural and superstructural details, approximate ground line, and top of bedrock line from 2008 bridge plans (Missouri Department of Transportation, written commun., 2011).

Part of bridge shown above

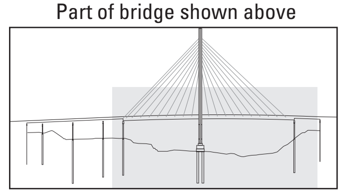


**Figure 26.** Key features, substructural and superstructural details, and surveyed channel bed of structure A7650 on Interstate 35 crossing the Missouri River in Kansas City, Missouri.

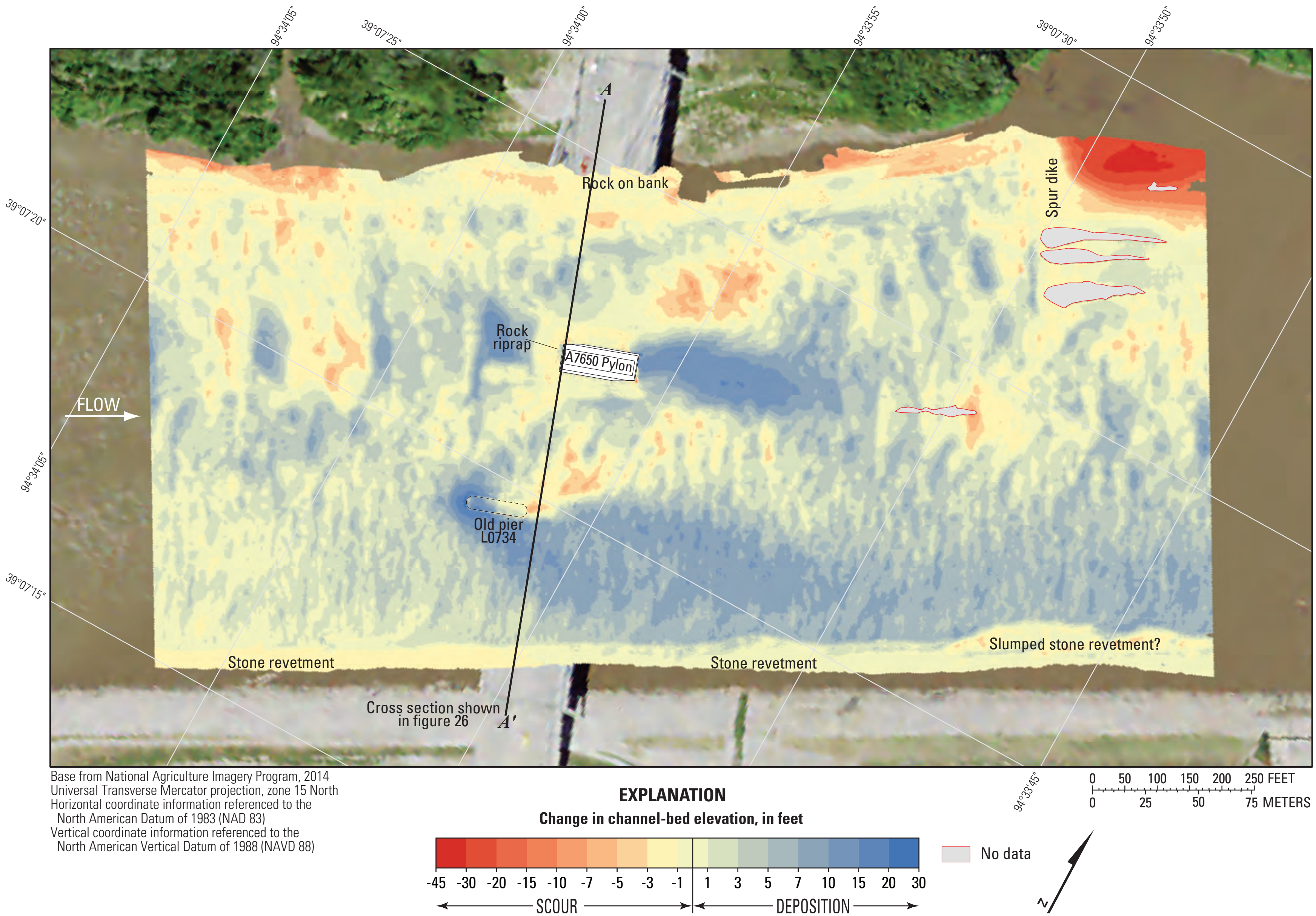



**Figure 27.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A7650 on Interstate 35 in Kansas City, Missouri, on June 3, 2015, and July 17, 2011.

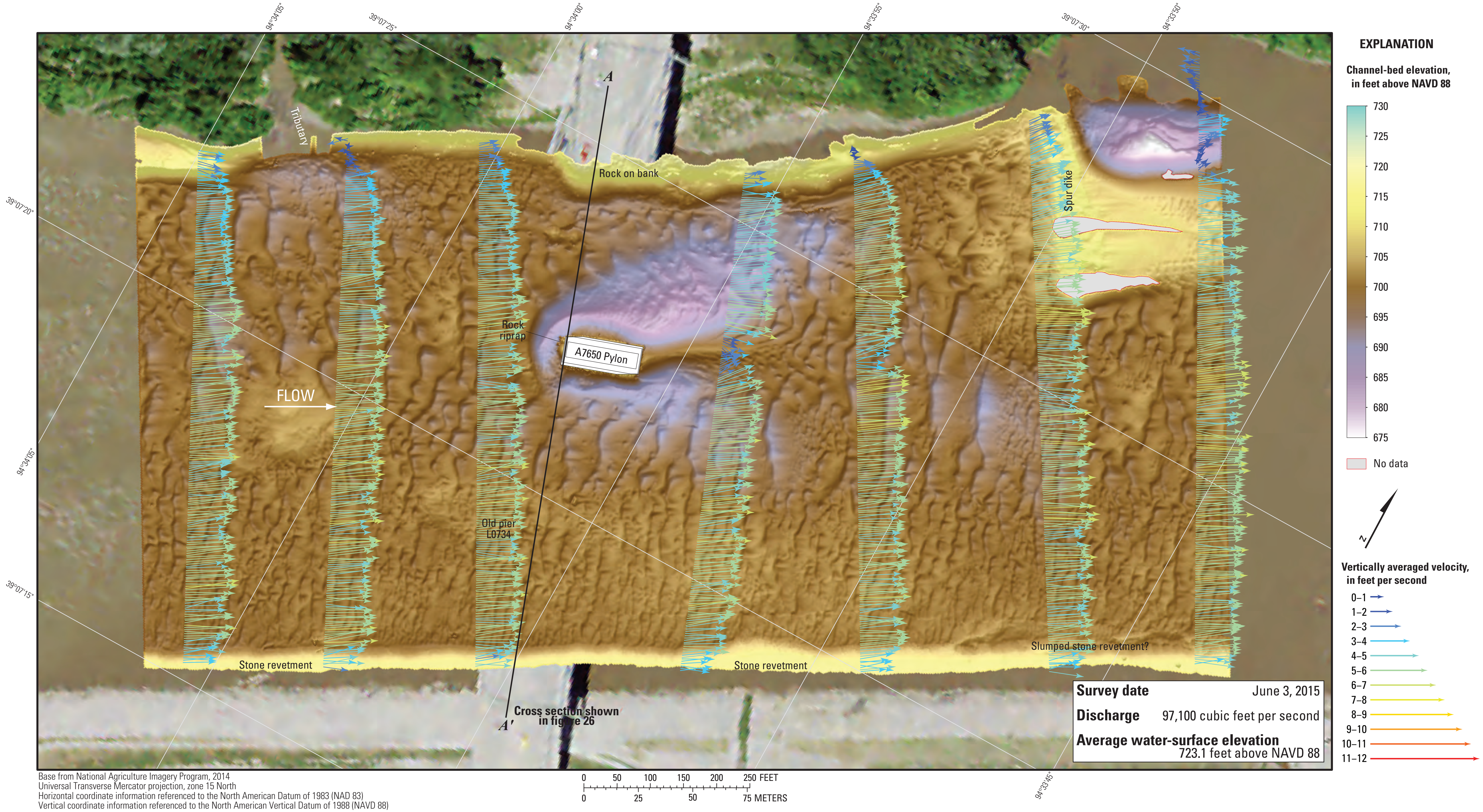



**Figure 28.** Bathymetric survey of the Missouri River channel near structure A7650 on Interstate 35 in Kansas City, Missouri.

## Structure A5817 on State Highway 269

Structure A5817 (site 11) on State Highway 269 crosses the Missouri River at RM 362.3, northeast of downtown Kansas City, Mo. (fig. 1). The site was surveyed on June 3, 2015, and the average water-surface elevation of the river in the survey area, determined by the RTK GPS tide solution, was 721.9 ft (table 5). Flow on the Missouri River was about 103,000 $ft^3/s$ during the survey (table 5).

The survey area was about 1,640 ft long and about 970 ft wide, extending from bank to bank in the main channel (fig. 29). Piers 2 and 3 were in the water and away from the banks, and the upstream end of the survey area was about 670 ft upstream from the centerline of structure A5817 at pier 2 (fig. 29). The channel-bed elevations ranged from about 690 to 710 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data; table 5; fig. 30). A deep thalweg along the left (north) bank throughout the surveyed area contained evidence of bedrock exposure and was about 15 to 20 ft deeper than the channel bed in the middle of the channel (fig. 29). Numerous medium dune features were observed in the channel thalweg, and numerous medium to small dunes and ripples were present throughout the rest of the channel, decreasing in size towards the right (south) bank (fig. 29). In addition to the rock outcrops on the left (north) bank, stone revetment also was present on the left bank throughout the reach (fig. 29).

A minor scour hole near main channel pier 2 (fig. 29) had a minimum channel-bed elevation of about 693 ft (table 6), about 6 ft above the elevation of the bottom of the pier seal course of 687.26 ft (fig. 31; table 6). The top of the pier footing was evident along the length of the pier during the survey (fig. 29). The minor scour hole near pier 3 was difficult to discern from nearby small dunes and ripples (fig. 29). Information from bridge plans indicates that piers 2 and 3 of structure A5817 are founded on shafts drilled 20 ft into bedrock, with about 16 ft of bed material between the bottom of the scour hole and bedrock at pier 2 and about 44 ft of material at pier 3 (fig. 31; table 6).

The difference between the survey on June 3, 2015, and the previous survey on July 18, 2011 (fig. 32), indicates substantial degradation throughout the reach from 2011 to 2015, with an average difference of -2.99 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2015 was about 184,000 $yd^3$, and the net volume of fill was about 11,500 $yd^3$, resulting in a net loss of about 172,500 $yd^3$ of sediment between 2011 and 2015. Substantial deposition had been observed between the 2010 and 2011 surveys (Huizinga, 2012), but ongoing sediment transport processes at this site have removed much of the sediment deposits as indicated by the substantial scour observed between 2011 and 2015 (fig. 32). There were a few areas of moderate deposition from 2011 to 2015, predominantly in the upstream reach and in the downstream thalweg (fig. 32). The cross sections from the two surveys also indicated substantial degradation throughout (fig. 31). The frequency distribution of bed elevations was of a similar shape but narrower in 2015 than in 2011, with a greater percentage of survey-grid cells at a lower elevation than 2011 (fig. 30). Whereas the bottom of the scour hole near main channel pier 2 was below the seal course in 2010 and at the top of the footing in 2011, in 2015 it was near the interface between the pier footing and seal course (fig. 31). The stone revetment on the left (north) bank showed no signs of substantial change (fig. 32).

The difference between the survey on June 3, 2015, and the previous nonflood survey on March 17, 2010 (fig. 33), indicates minor deposition throughout the reach from 2010 to 2015, with an average difference +0.28 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2010 to 2015 was about 54,000 $yd^3$, and the net volume of fill was about 69,500 $yd^3$, resulting in a net gain of about 15,500 $yd^3$ of sediment between 2010 and 2015. Primarily deposition was observed in the channel thalweg along the left (north) bank in 2015, whereas primarily scour was observed along the inside of the channel bend along the right (south) bank (fig. 33). The cross sections from the two surveys indicate the balance of deposition and scour from left to right across the channel (fig. 31). The frequency distribution

**Structure A5817 on State Highway 269 crosses the Missouri River at river mile 362.3, northeast of downtown Kansas City, Missouri.**

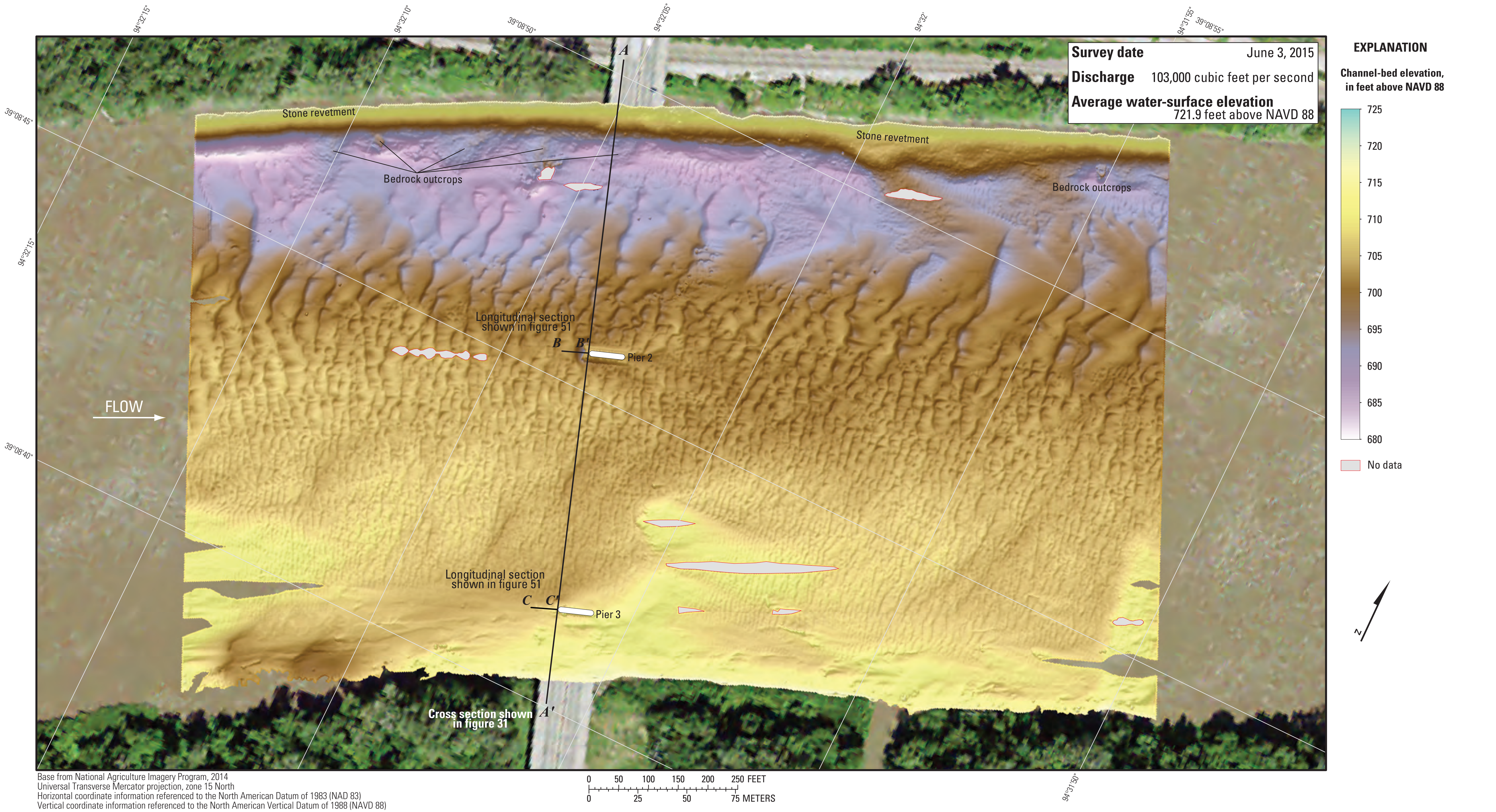



**Figure 29.** Bathymetric survey of the Missouri River channel near structure A5817 on State Highway 269 in Kansas City, Missouri.

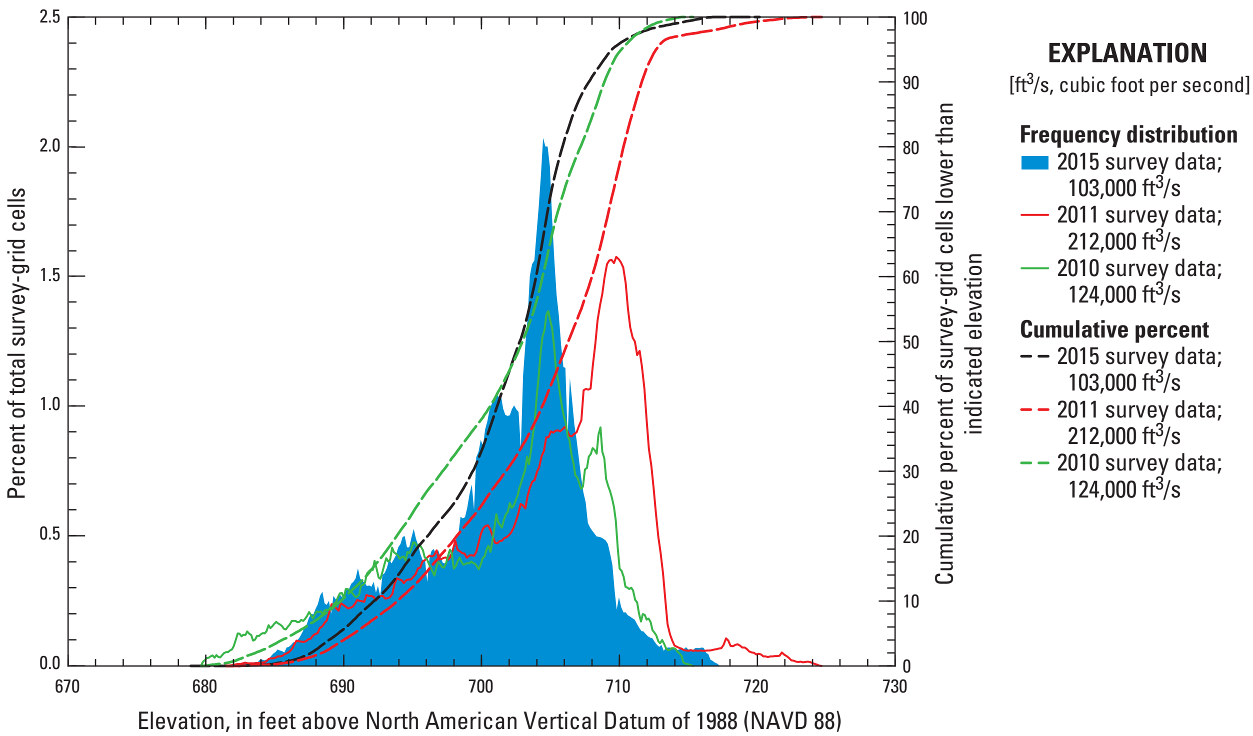



**Figure 30.** Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A5817 on State Highway 269 in Kansas City, Missouri, on June 3, 2015, compared to previous surveys.

of bed elevations was of a similar shape in 2015 compared to 2010 but with a higher minimum channel-bed elevation and a greater percentage of survey-grid cells at a given elevation than in 2010 (fig. 30). The localized scour observed at the stone revetment on the left (north) bank observed between 2010 and 2011 (Huizinga, 2012) also was evident (fig. 33).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 3 ft/s along the inside of the bend on the right (south) bank to 9 ft/s in the downstream thalweg (fig. 34). Exceptions to uniform flow include flows angled to the left (north) in the upstream part of the reach because of the bend in the channel (fig. 34). Moderate turbulence also was observed along the thalweg near the bedrock outcrops and along the inside of the bend along the right (south) bank (fig. 34).

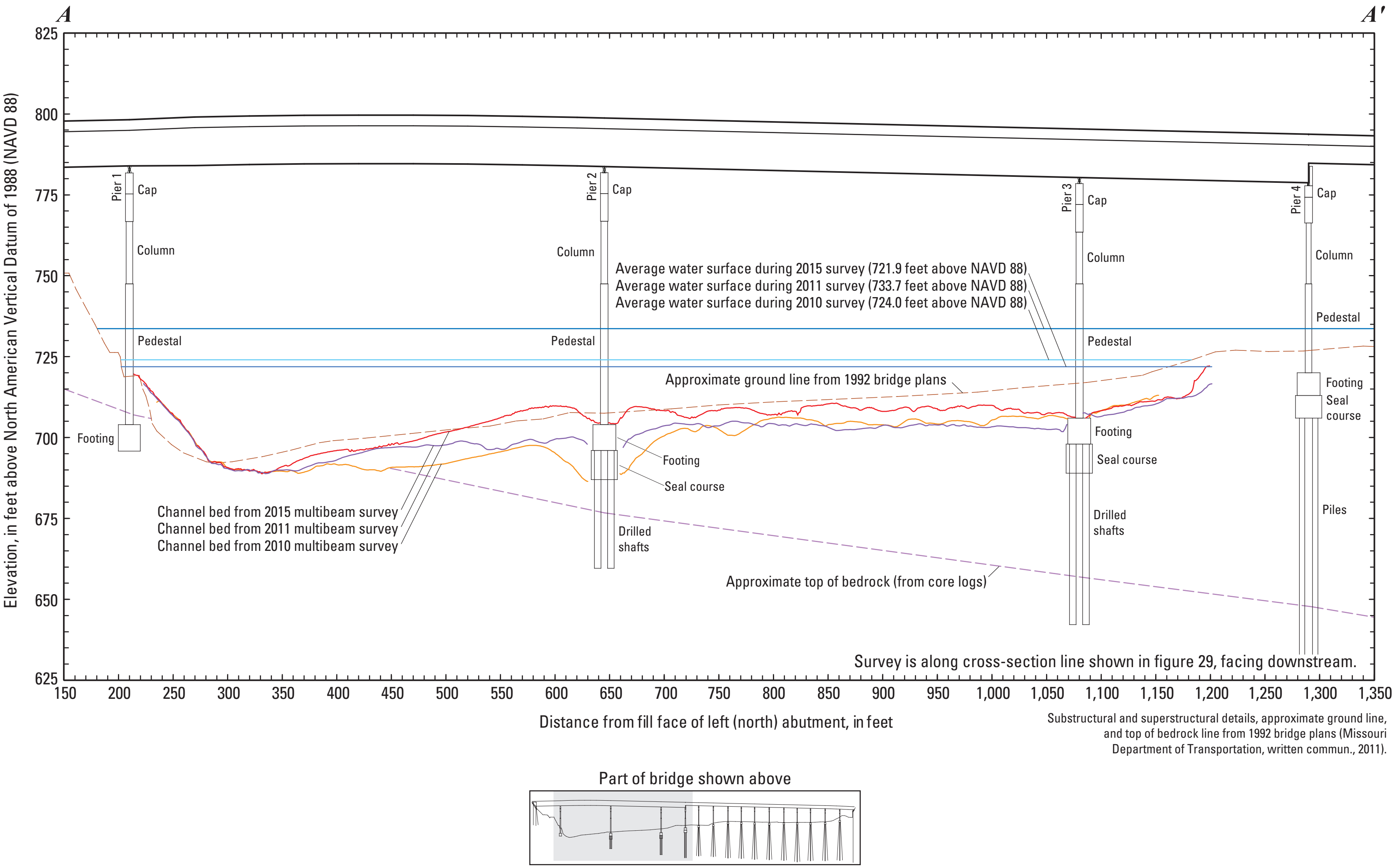



**Figure 31.** Key features, substructural and superstructural details, and surveyed channel bed of structure A5817 on State Highway 269 crossing the Missouri River in Kansas City, Missouri.

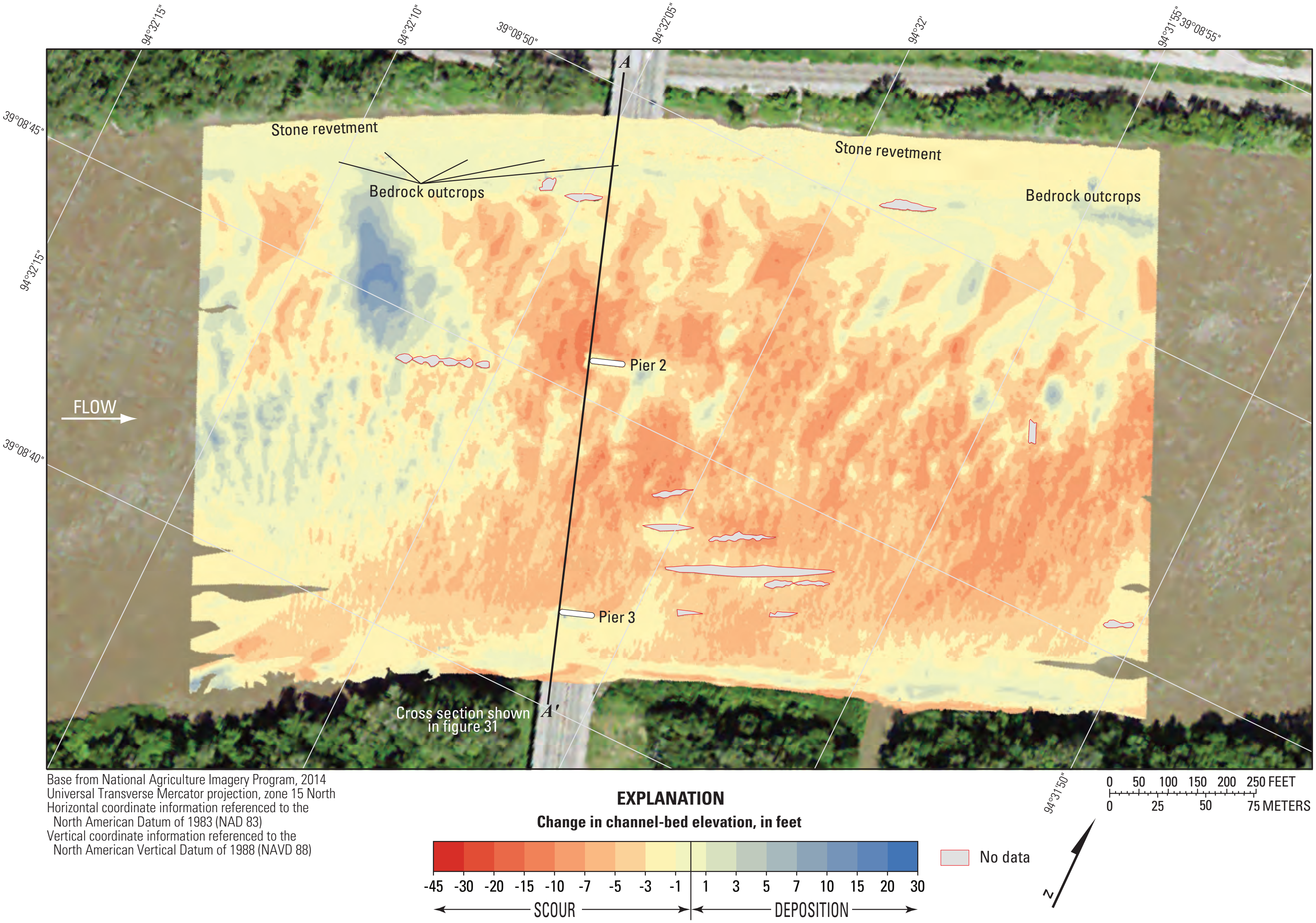



**Figure 32.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5817 on State Highway 269 in Kansas City, Missouri, on June 3, 2015, and July 18, 2011.

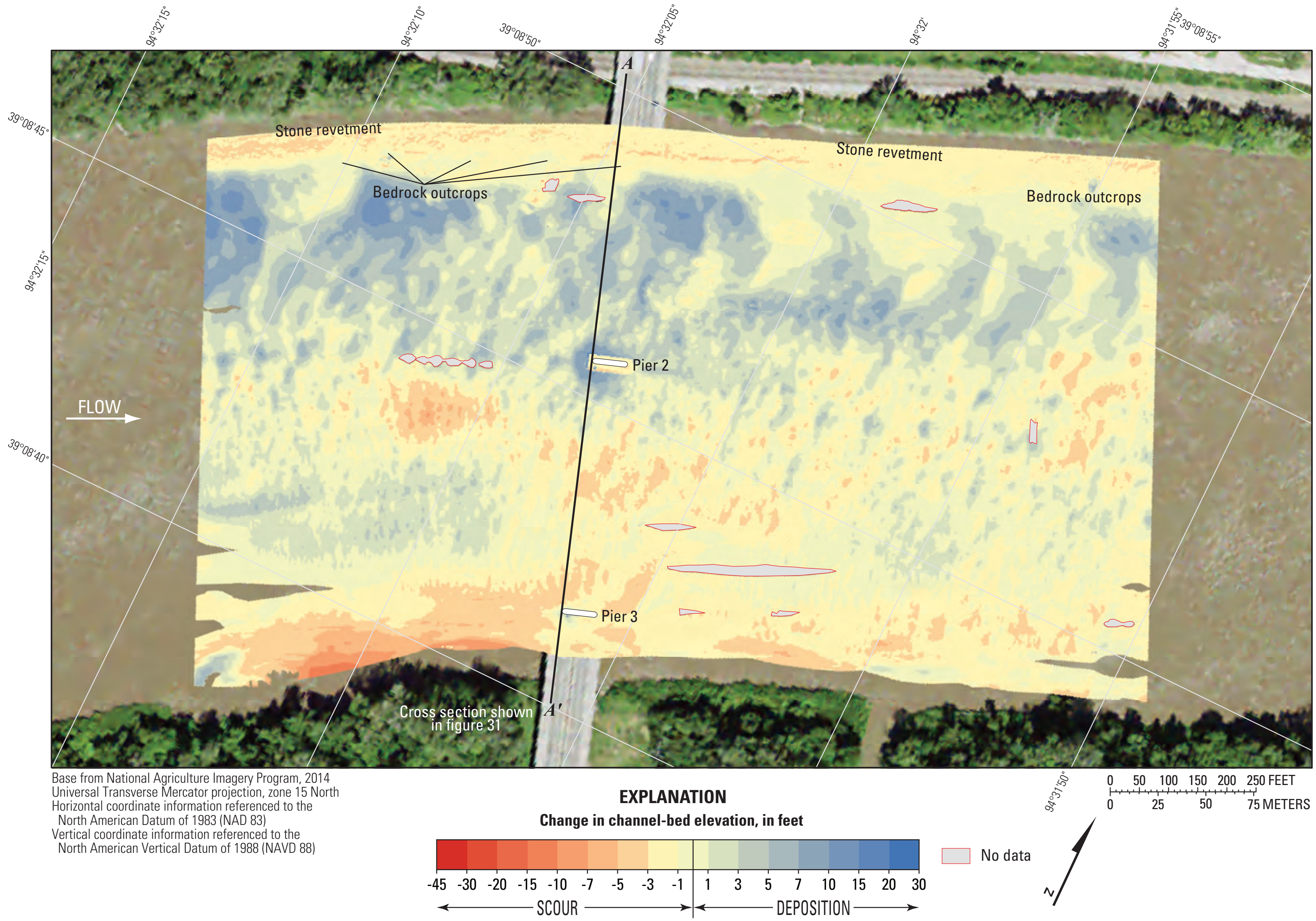



**Figure 33.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5817 on State Highway 269 in Kansas City, Missouri, on June 3, 2015, and March 17, 2010.

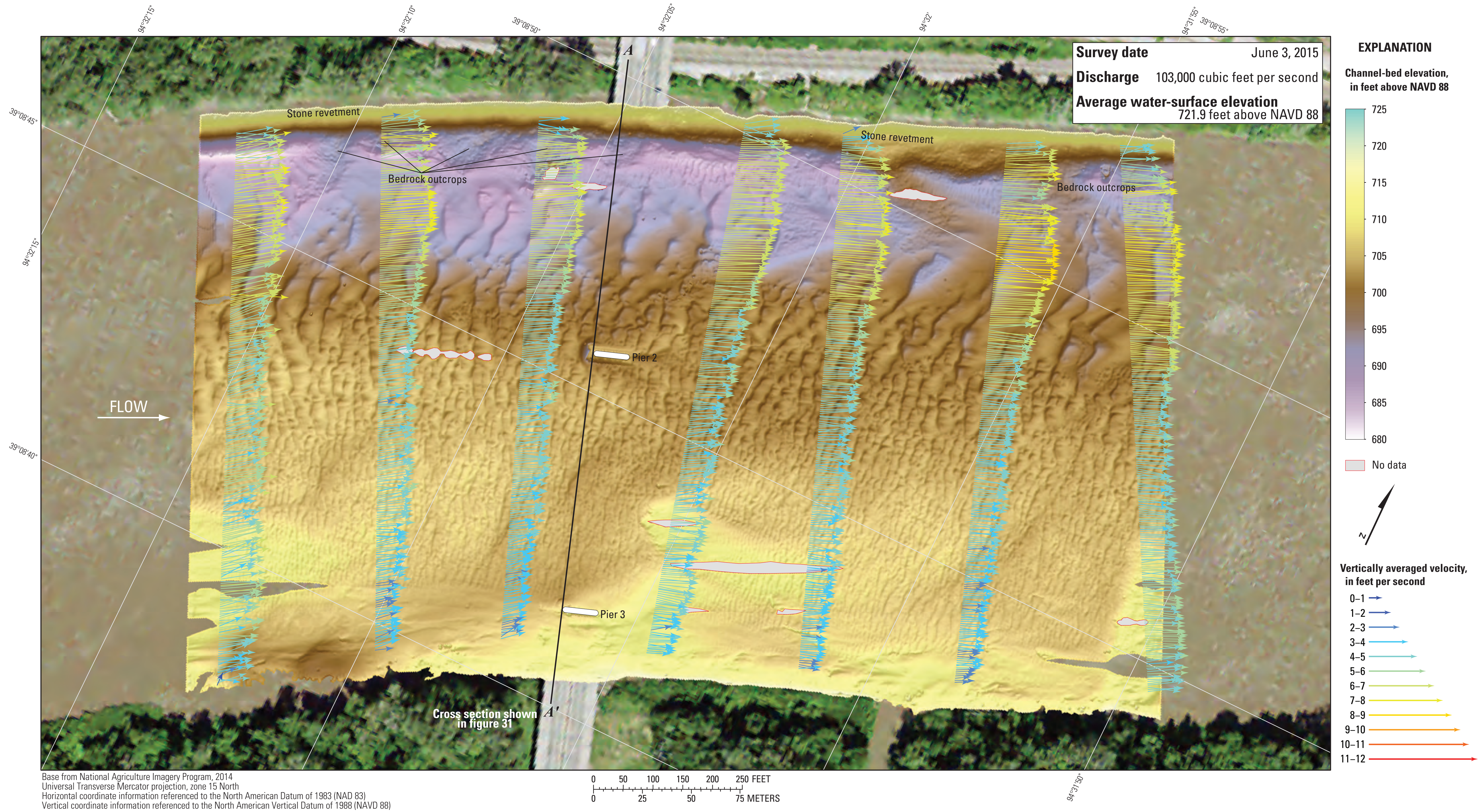



**Figure 34.** Bathymetry and vertically averaged velocities of the Missouri River channel near structure A5817 on State Highway 269 in Kansas City, Missouri.

## Structure A0767 on Interstate 435

Structure A0767 (site 12) on Interstate 435 crosses the Missouri River at RM 360.3, on the northeastern side Kansas City, Mo. (fig. 1). The site was surveyed on June 4, 2015, and the average water-surface elevation of the river in the survey area, determined by the RTK GPS tide solution, was 721.6 ft (table 5). Flow on the Missouri River was about 119,000 ft$^3$/s during the survey (table 5).

The survey area was about 1,640 ft long and about 890 ft wide, extending from bank to bank in the main channel (fig. 35). Piers 7 and 8 were in the water and away from the banks at structure A0767; however, as in previous surveys (Huizinga, 2010, 2012), pier 8 was immediately downstream from a spur dike and surrounded by a persistent substantial debris raft, and only limited bathymetric data could be obtained near it (fig. 35). A substantial and persistent sand bar also was present downstream from pier 8, as in previous surveys. The upstream end of the survey area was about 660 ft upstream from the centerline of structure A0767 at pier 7 (fig. 35). The channel-bed elevations ranged from about 687 to 710 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data; table 5; fig. 36), except downstream from the tip of the spur dike and in the downstream reach near the rock outcrop on the left (north) bank (fig. 35). The channel thalweg was along the left (north) bank throughout the surveyed area, and became deeper in the downstream direction. The channel was filled with numerous medium dune features in the middle of the channel and numerous small dunes and ripples throughout the rest of the channel, decreasing in size towards the banks (fig. 35). Bedrock outcrops and stone revetment were present on the left (north) bank throughout the reach (fig. 35). Erroneous positioning during data collection created an offset of the data along the upstream left (north) bank between survey passes resulting in the appearance of bulges and data shifts in that area (figs. 5 and 35).

The scour hole near main channel pier 7 (fig. 35) had a minimum channel-bed elevation of about 679 ft (table 6), about 10 ft below the elevation of the bottom of the pier seal course of 689.26 ft (fig. 37; table 6). The upstream end of pier 8 was embedded in the rock spur dike and could not be surveyed because of the persistent substantial debris raft (fig. 35). The top of the footing on the downstream end of the pier was visible (fig. 35), but the minimum channel elevation was 694 ft, about 5 ft higher than the bottom of the seal course elevation of 689.26 ft (fig. 35; table 6). Information from bridge plans indicates that piers 7 and 8 are founded on shafts drilled 20 ft into bedrock, with about 19 ft of bed material between the bottom of the scour hole and bedrock at pier 7 and about 46 ft of material at pier 8 (fig. 37; table 6). The undermined seal course and upstream-most drilled shaft are evident in a shaded TIN image of the right (south) side of pier 7 (fig. 38).

The difference between the survey on June 4, 2015, and the previous survey on July 18, 2011 (fig. 39), indicates moderate deposition throughout the reach from 2011 to 2015, with an average difference of +1.59 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2015 was about 40,000 yd$^3$, and the net volume of fill was about 123,900 yd$^3$, resulting in a net gain of about 83,900 yd$^3$ of sediment between 2011 and 2015. There were a few areas of substantial deposition of more than 20 ft downstream from pier 7 and the spur dike near pier 8 in 2015, and in the troughs of large and very large dunes detected in the 2011 survey on the left (north) side of the channel (fig. 39). The cross sections from the two surveys were similar to each other, with the 2015 survey alternating being above and below the 2011 survey section (fig. 37). The frequency distribution of bed elevations was of a similar shape but narrower in 2015

**Structure A0767 on Interstate 435 crosses the Missouri River at river mile 360.3, on the northeastern side Kansas City, Missouri.**

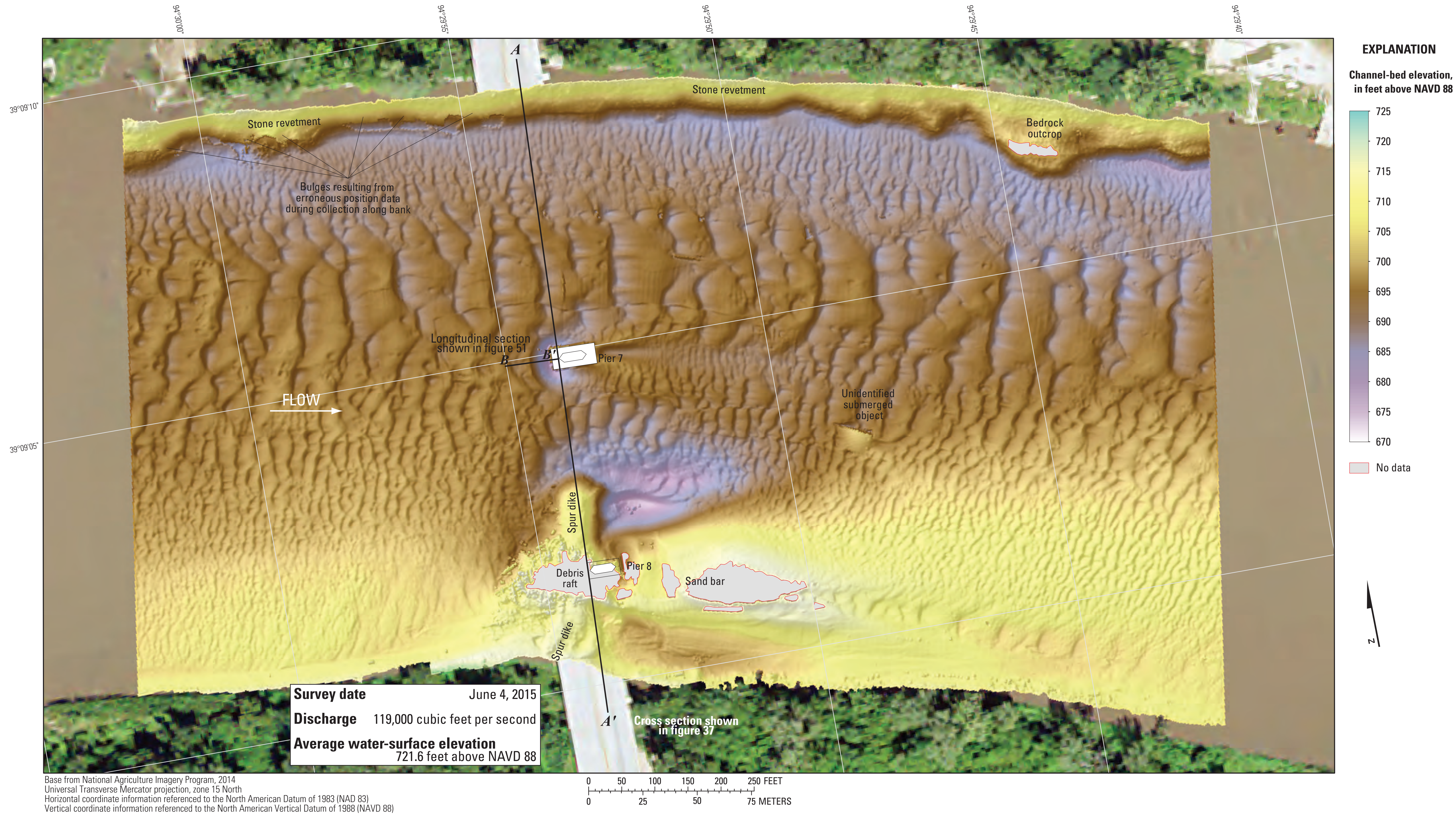



**Figure 35.** Bathymetric survey of the Missouri River channel near structure A0767 on Interstate 435 in Kansas City, Missouri.

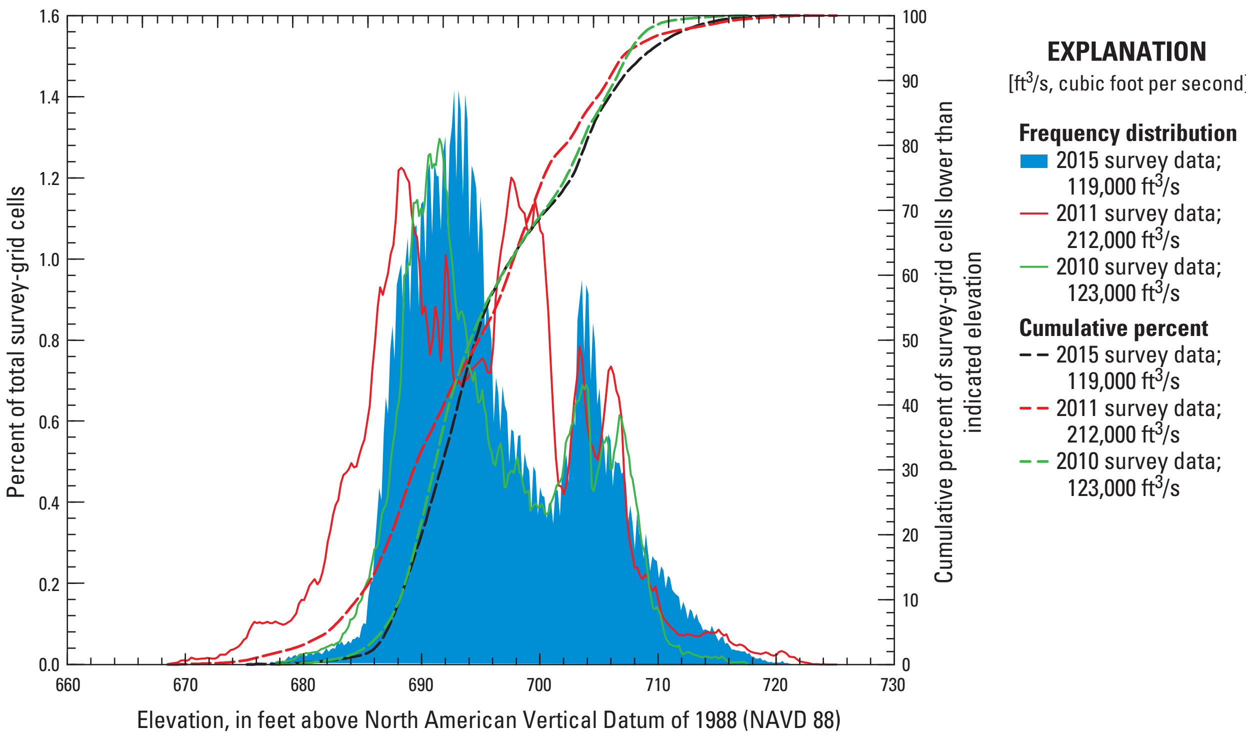



**Figure 36.** Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A0767 on Interstate 435 in Kansas City, Missouri, on June 4, 2015, compared to previous surveys.

compared to 2011 and had a higher minimum channel-bed elevation and slightly different distribution of survey-grid cells at a given elevation than in 2011 (fig. 36). The scour hole near pier 7 was shallower and smaller in 2015 than in 2011, as evidenced by the horseshoe-shaped area of deposition around it (figs. 37 and 39). The positional offset of data along the upstream stone revetment on the left (north) bank creates the appearance of substantial deposition in 2015; additional areas of localized shifting evidenced by areas of deposition and scour along the downstream left bank may also be the result of erroneous position data between the 2011 and 2015 surveys (fig. 39).

The difference between the survey on June 4, 2015, and the previous nonflood survey on March 17, 2010 (fig. 40), indicates minor degradation throughout the reach from 2010 to 2015, with an average difference of -0.13 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2010 to 2015 was about 61,700 yd$^3$, and the net volume of fill was about 55,000 yd$^3$, resulting in a net loss of about 6,700 yd$^3$ of sediment between 2010 and 2015. There were a few areas of moderate to substantial deposition downstream from pier 7 and the spur dike near pier 8 in 2015 (fig. 40). The cross sections from the two surveys were similar to each other, with the 2015 survey alternating being above and below the 2011 survey section (fig. 37). The frequency distribution of bed elevations was similar in shape in 2015 compared to 2010 (fig. 36). The scour hole near pier 7 was slightly shallower and smaller in 2015 than in 2010, as evidenced by the moderate deposition along the sides and downstream (figs. 37 and 40). The positional offset of data along the upstream stone revetment on the left (north) bank again creates the appearance of substantial deposition in 2015; additional areas of localized shifting evidenced by areas of deposition and scour along the downstream left bank may also be the result of erroneous position data between the 2010 and 2015 surveys (fig. 39). Apparently, something near the left bank adversely affects the INS at this site.

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 2 ft/s along the inside of the bend on the right (south) bank to 8 ft/s in the thalweg (fig. 41); however, turbulence and velocity reduction were observed downstream from the spur dike, debris raft, and pier 8, and moderate turbulence was observed in several transects (fig. 41).

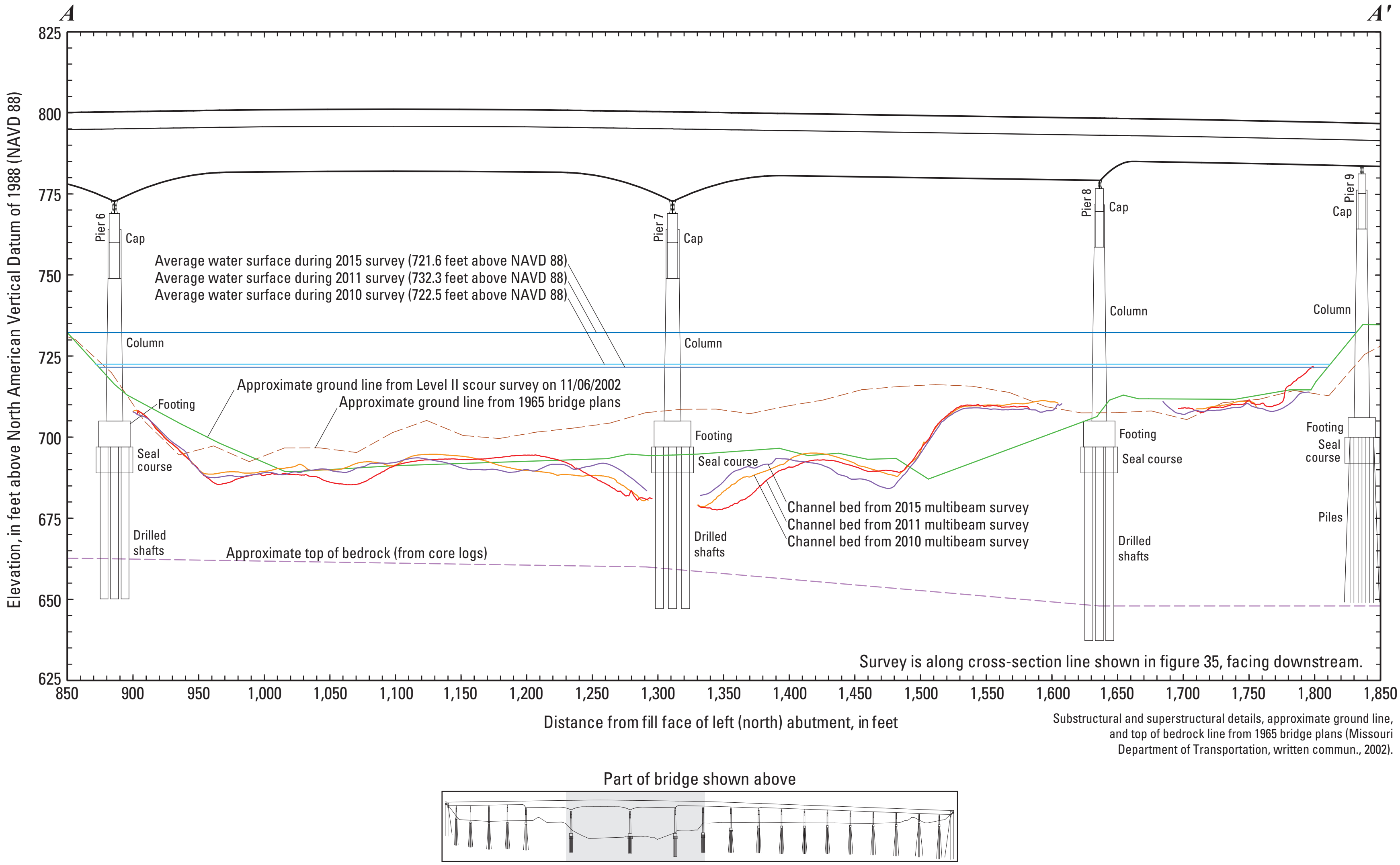



**Figure 37.** Key features, substructural and superstructural details, and surveyed channel bed of structure A0767 on Interstate 435 crossing the Missouri River in Kansas City, Missouri.

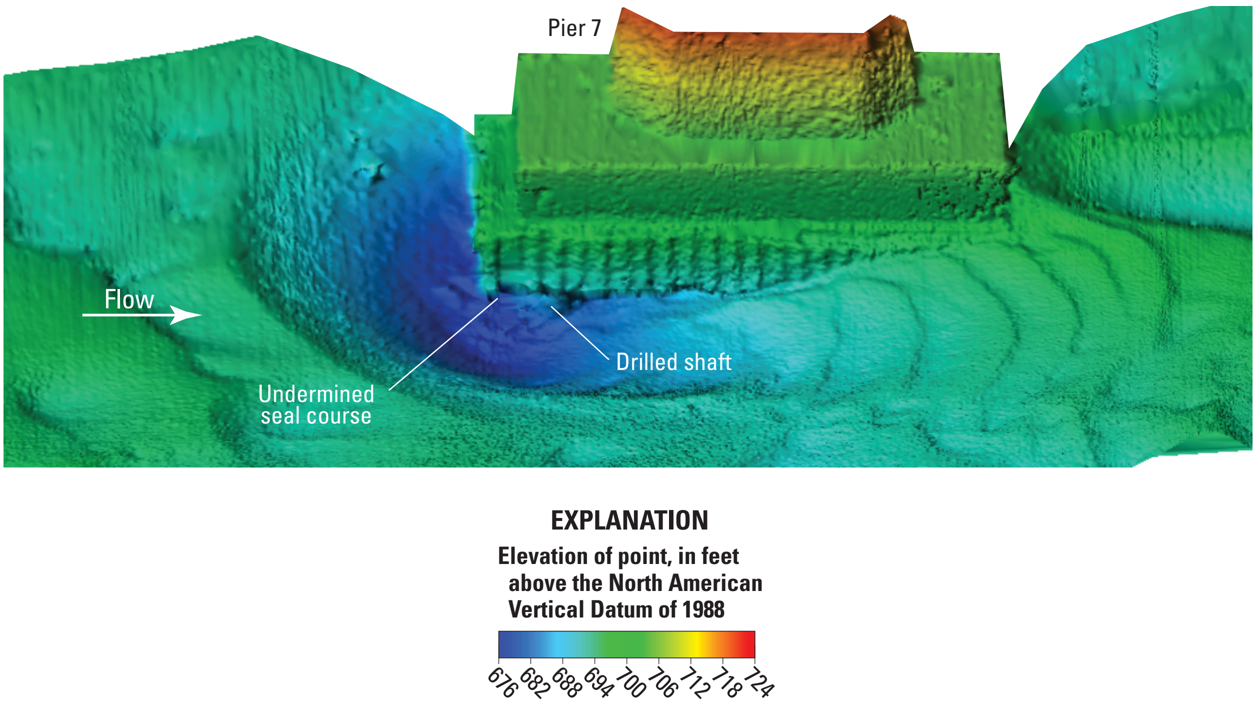



**Figure 38.** Shaded triangulated irregular network visualization of the channel bed and right (south) side of main channel pier 7 of structure A0767 on Interstate 435 crossing the Missouri River in Kansas City, Missouri.

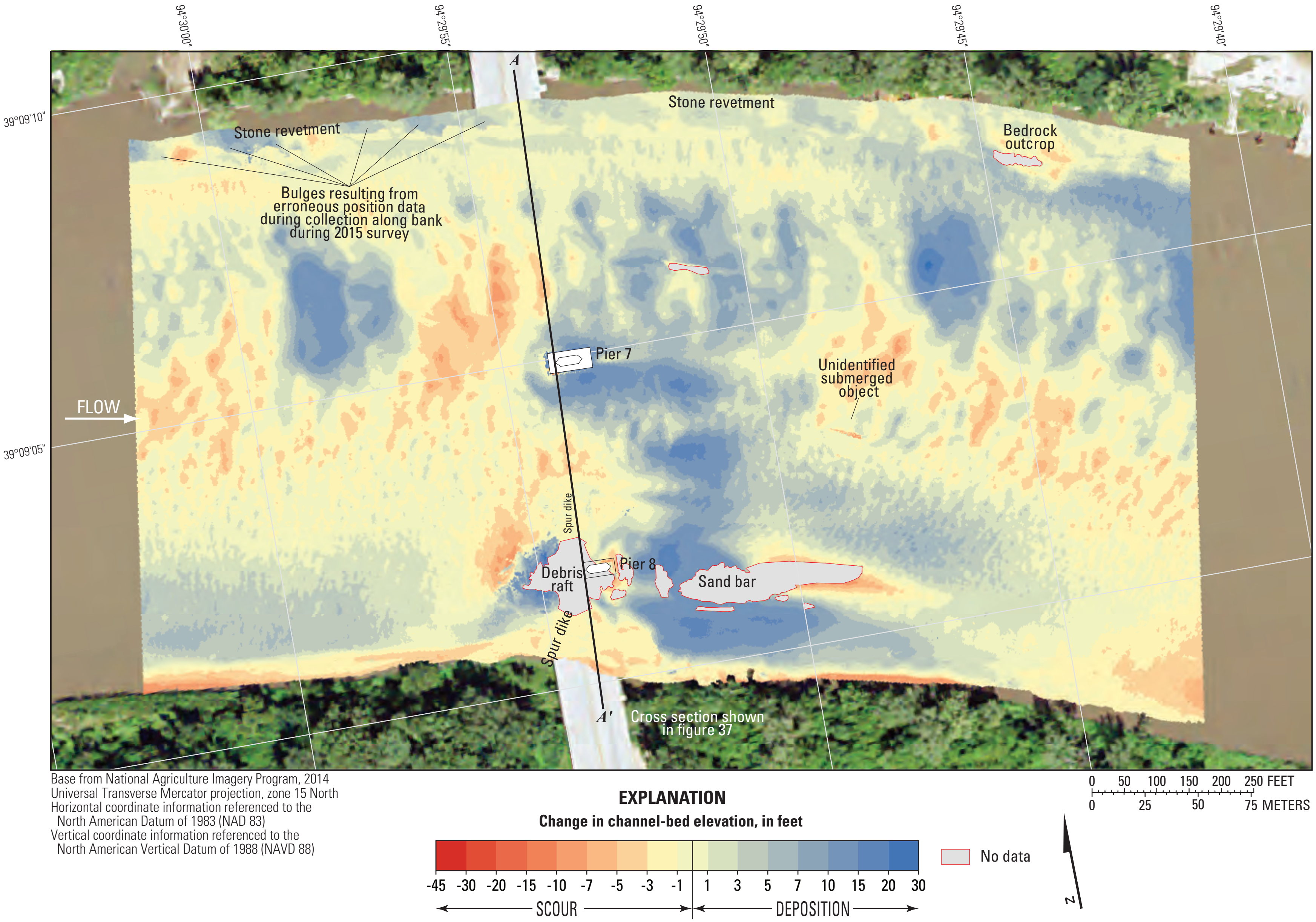



**Figure 39.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A0767 on Interstate 435 in Kansas City, Missouri, on June 4, 2015, and July 18, 2011.

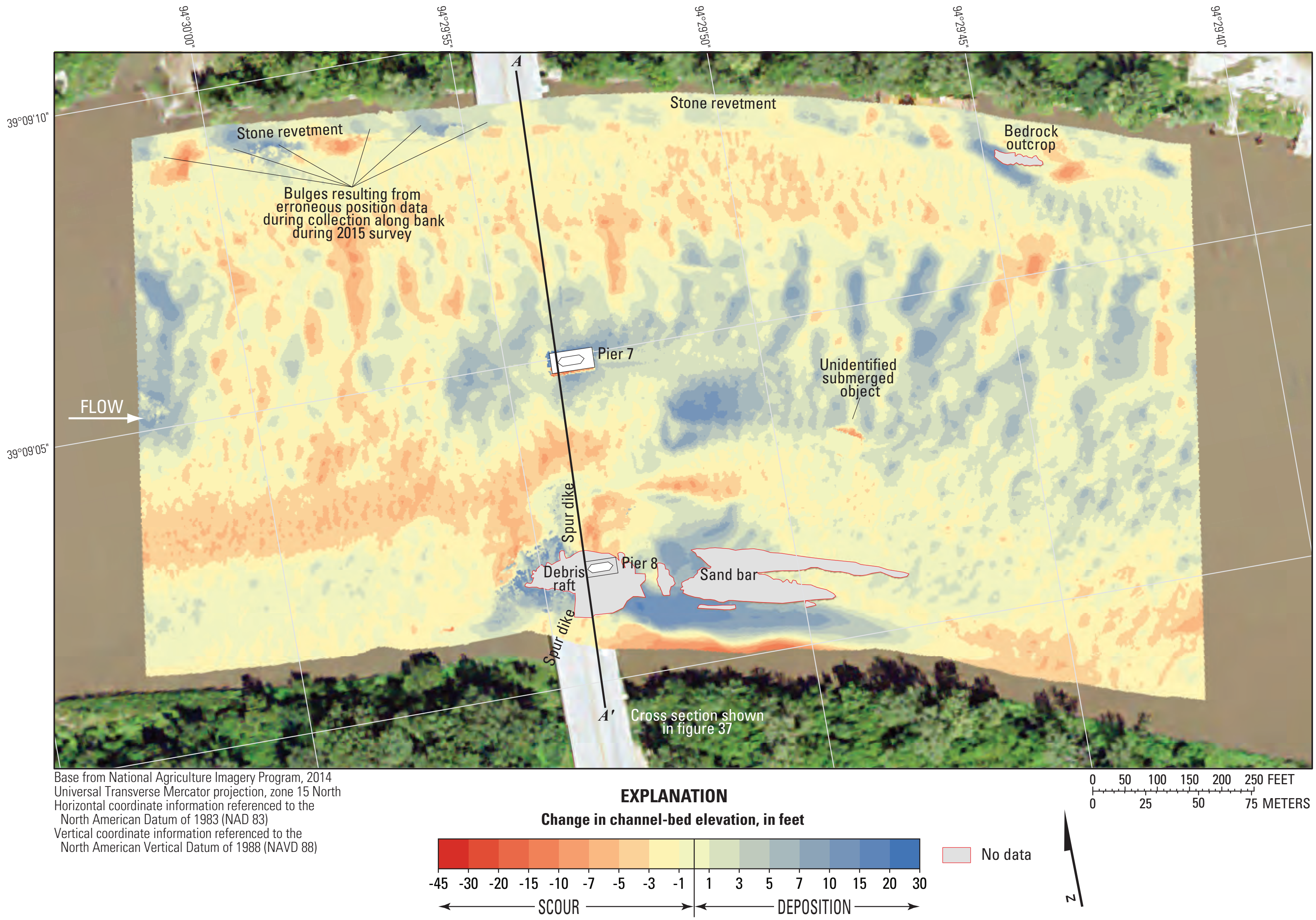



**Figure 40.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A0767 on Interstate 435 in Kansas City, Missouri, on June 4, 2015, and March 17, 2010.

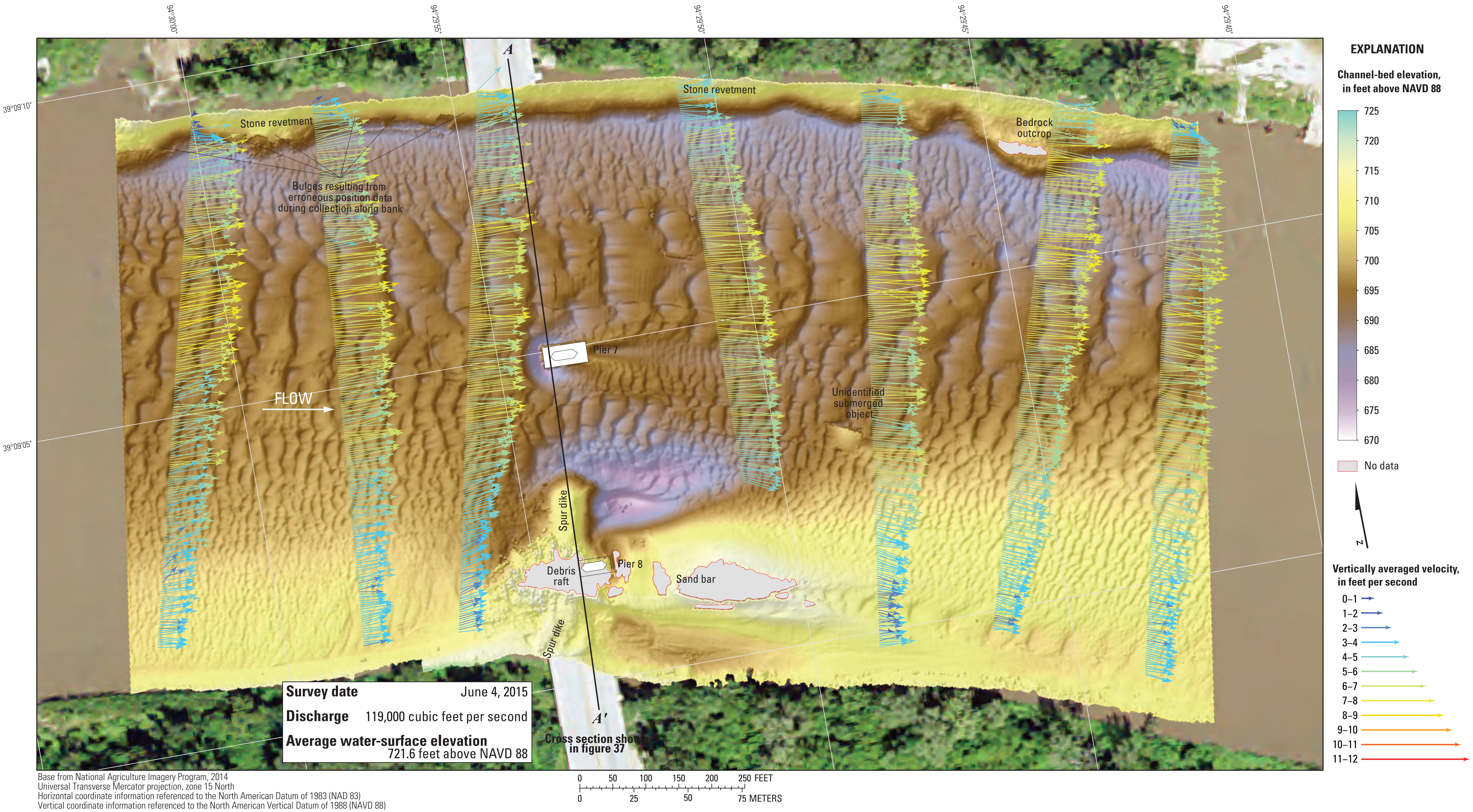



**Figure 41.** Bathymetry and vertically averaged velocities of the Missouri River channel near structure A0767 on Interstate 435 in Kansas City, Missouri.

## Structures A4757 and L0568 on State Highway 291

Structures A4757 and L0568 (site 13) are dual bridges on State Highway 291, crossing the Missouri River at RM 352.7 on the northeastern side of the Kansas City, Mo., metropolitan area (fig. 1). The site was surveyed on June 4, 2015, and the average water-surface elevation of the river in the survey area, determined by the RTK GPS tide solution, was 715.9 ft (table 5). Flow on the Missouri River was about 112,000 $ft^3/s$ during the survey (table 5).

The survey area was about 1,640 ft long and about 850 ft wide, extending from bank to bank in the main channel (fig. 42). The upstream end of the survey area was about 720 ft upstream from the centerline between structures A4757 and L0568 (fig. 42). The channel-bed elevations ranged from about 681 to 706 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data; table 5; fig. 43), except near the main channel piers of structures A4757 and L0568 (fig. 42). A narrow channel thalweg was along the left (north) bank throughout the channel and was about 10 ft deeper than the middle of the channel (fig. 42). A row of medium dune features were observed in the left side of the channel, along with numerous small dunes and ripples throughout the rest of the channel (fig. 42). As in previous surveys, a noticeable channel constriction was at and immediately downstream from the bridges, and the left (north) bank seemed to be covered with stone revetment (fig. 42).

A large scour hole near the main channel piers (fig. 42) that essentially encompasses both piers had a minimum channel-bed elevation of about 668 ft (table 6), which also was the minimum channel-bed elevation for the entire reach (table 5). The main channel piers were skewed to the approaching flow, which caused a wide scour hole with somewhat unique characteristics as compared to scour holes at the other surveyed bridges. Pier 5 of structure L0568 was in the wake of pier 2C of structure A4757 and, therefore, had a poorly defined scour hole near it (fig. 42). At the upstream end of pier 2C of structure A4757, the minimum channel-bed elevation was about 668 ft, and at the upstream end of pier 5 of structure L0568, the minimum channel-bed elevation was about 674 ft (fig. 42; table 6). Information from bridge plans indicates that the main channel pier of structure A4757 is founded on shafts drilled 20 ft into bedrock (fig. 44), with about 49 ft of bed material between the bottom of the scour hole and bedrock at the point of minimum elevation of the scour hole near the upstream pier face (fig. 44; table 6). At the point of minimum elevation, the surveyed channel bed was about 2 ft above the bottom of the seal course elevation of 666.26 ft (table 6). Information from bridge plans indicate that the main channel pier of structure L0568 is a caisson on bedrock (fig. 45), with about 56 ft of bed material between the bottom of the scour hole and bedrock at the point of minimum elevation of the scour hole near the upstream pier face (fig. 45; table 6).

The difference between the survey on June 4, 2015, and the previous survey on July 19, 2011 (fig. 46), indicates moderate deposition throughout the reach from 2011 to 2015, with an average difference of +1.33 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2015 was about 59,400 $yd^3$, and the net volume of fill was about 126,200 $yd^3$, resulting in a net gain of about 66,800 $yd^3$ of sediment between 2011 and 2015. There was moderate deposition of over 10 ft on the right (south) side of the main channel piers and throughout most of the (north) side of the channel in 2015 (fig. 46); however, substantial scour of more than 15 ft had was observed in the upstream channel, and minor scour was observed along the right (south) side of the channel (fig. 46). The cross section from the 2015 survey compared to the 2011 survey also shows deposition throughout most of the left side of the channel and on the right side of the main channel piers, with minor scour on the right side (figs. 44 and 45). The frequency distribution of bed elevations was substantially narrower in 2015 than in 2011, with a higher minimum channel-bed elevation than in 2011 (fig. 43). The scour hole near pier 2C of structure A4757 was substantially

**Structure A4757 and L0568 are dual bridges on State Highway 291, crossing the Missouri River at river mile 352.7 on the northeastern side of the Kansas City, Missouri metropolitan area.**

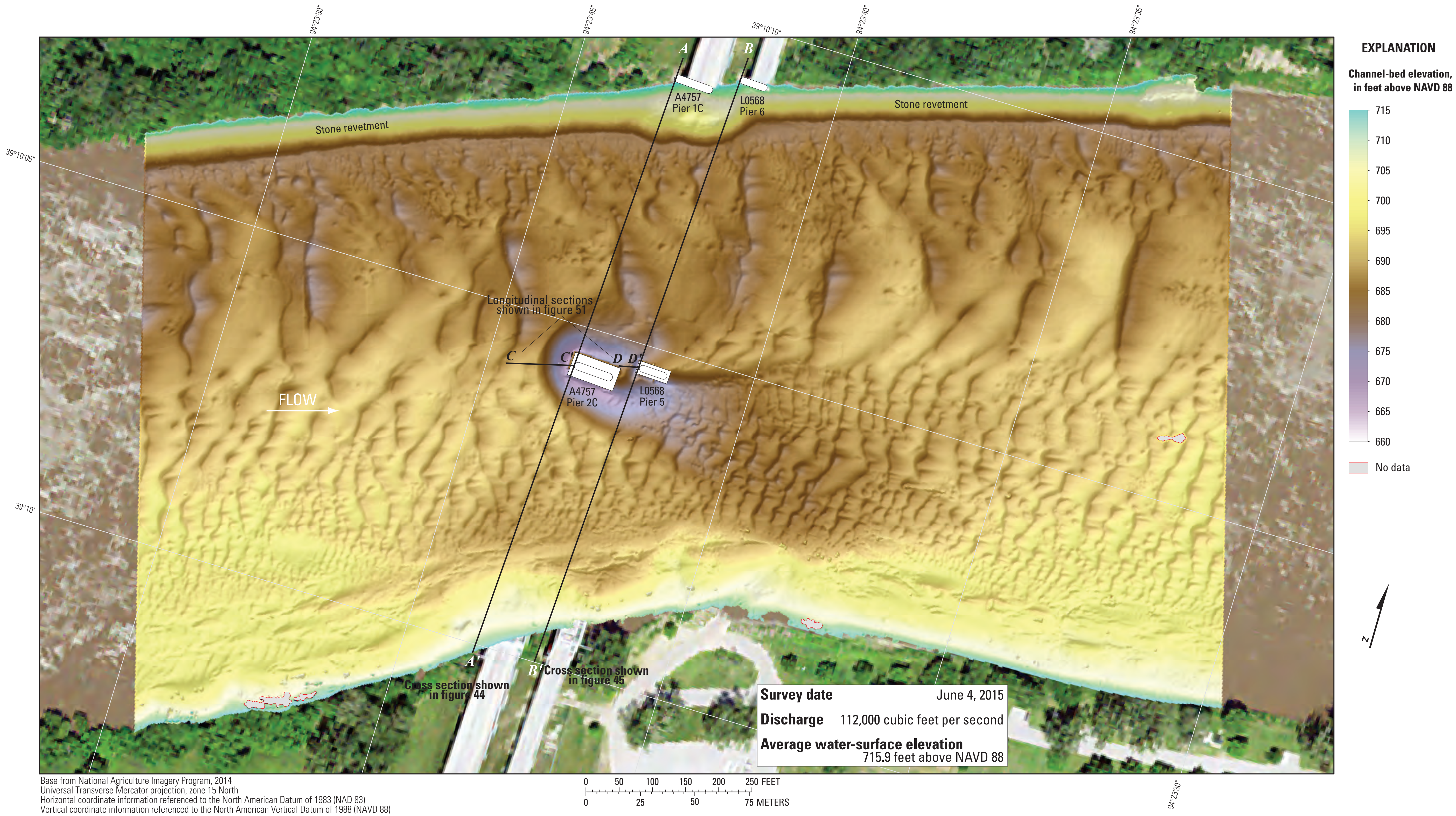



**Figure 42.** Bathymetric survey of the Missouri River channel near structures A4757 and L0568 on State Highway 291 near Kansas City, Missouri.

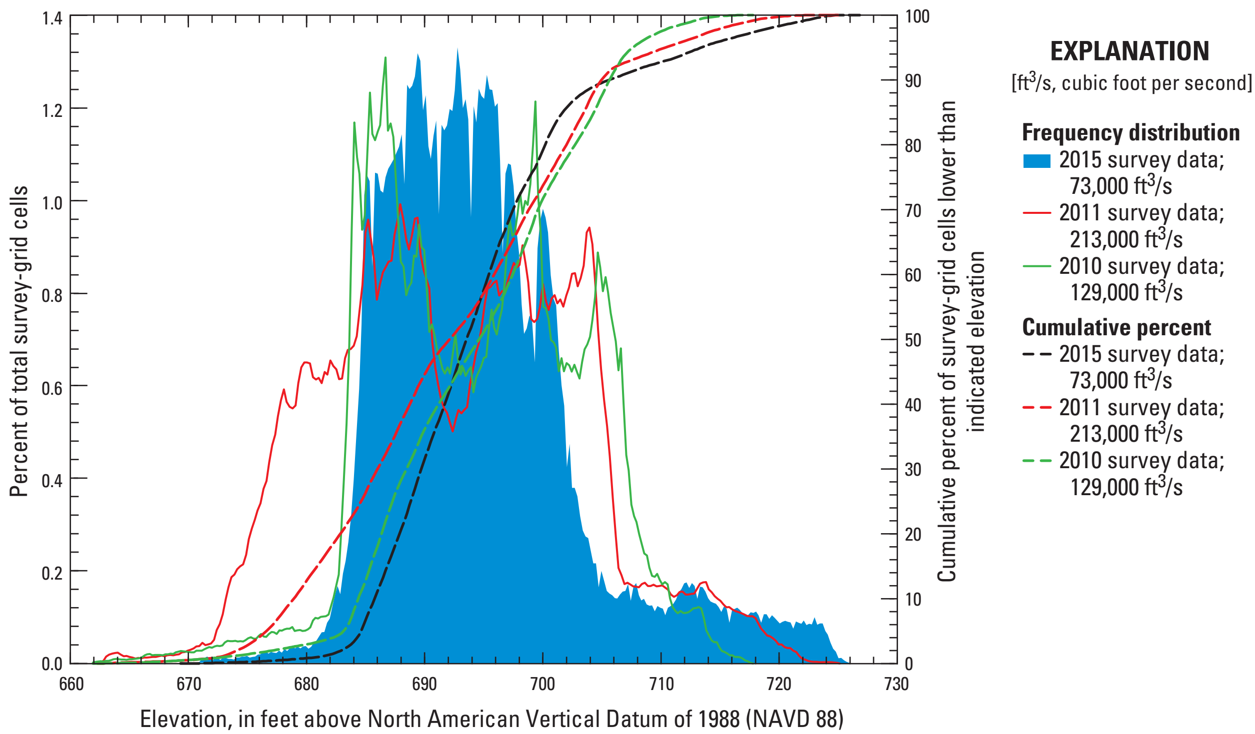



**Figure 43.** Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structures A4757 and L0568 on State Highway 291 near Kansas City, Missouri, on June 4, 2015, compared to previous surveys.

narrower and shallower in 2015 than in 2011 (figs. 44 and 46), whereas the scour hole near pier 5 of structure L0568 was of a similar shape but substantially shallower in 2015 than in 2011 (figs. 45 and 46). The stone revetment on the left (north) bank showed no signs of substantial change, whereas the right (south) bank near the bridges and downstream showed signs of localized deposition and scour (fig. 46). As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see “Uncertainty Estimation” section).

The difference between the survey on June 4, 2015, and the previous nonflood survey on March 18, 2010 (fig. 47), indicates moderate scour throughout the reach from 2010 to 2015, with an average difference of -0.92 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2010 to 2015 was about 103,300 yd$^3$, and the net volume of fill was about 58,200 yd$^3$, resulting in a net loss of about 45,100 yd$^3$ of sediment between 2010 and 2015. There were a few areas of deposition, predominantly along the left (north) side of the downstream reach and in the scour hole around main channel piers 2C and 5 between 2010 and 2015 (fig. 47); however, there was widespread scour throughout the upstream channel and along the right (south) side of the downstream reach. The cross sections from the 2015 survey generally were more similar to the 2010 survey than the 2011 survey at both bridges (figs. 44 and 45). The frequency distribution of bed elevations was slightly narrower in 2015 than in 2010, with a higher minimum channel-bed elevation and a greater percentage of survey-grid cells at a lower elevation than 2010 (fig. 43). The scour hole near main channel piers 2C and 5 was substantially shallower and slightly narrower at the top in 2015 than in 2010 (figs. 44, 45, and 47). The localized scour observed at the stone revetment on the left (north) bank observed between 2010 and 2011 (Huizinga, 2012) also is evident (fig. 47). As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see “Uncertainty Estimation” section).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 2 ft/s along the inside of the bend on the right (south) bank to about 9 ft/s in the thalweg (fig. 48). Exceptions to uniform flow include flows angled to the left (north) near the upstream and downstream faces of the bridges (fig. 48). Moderate turbulence also was observed in several transects, particularly near the bank protrusions near the bridges and downstream from the main channel piers (fig. 48). Velocities were slightly lower downstream from the bridges, likely caused by the flow expansion downstream from the constriction at the bridges (fig. 48).

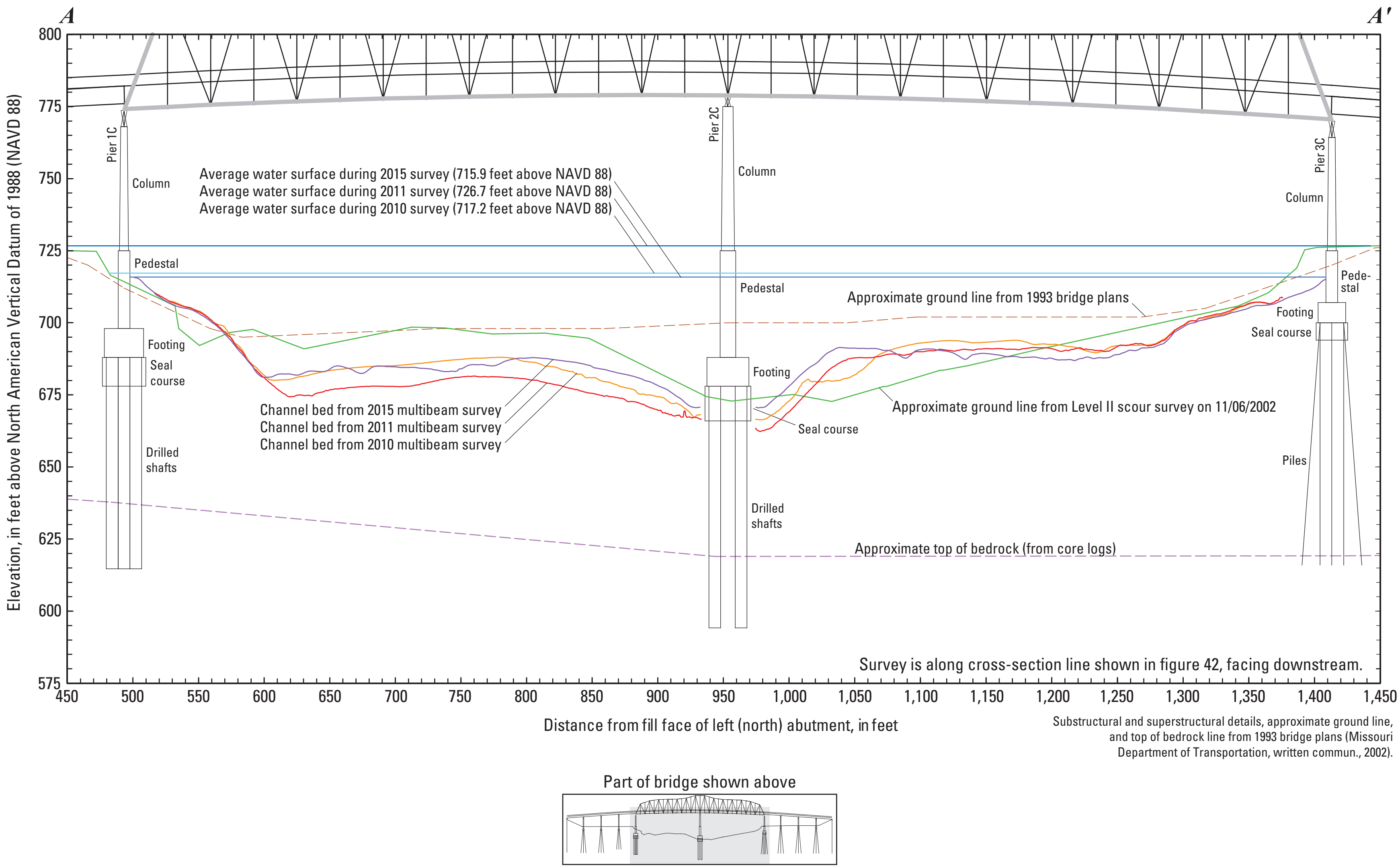



**Figure 44.** Key features, substructural and superstructural details, and surveyed channel bed of structure A4757 on State Highway 291 crossing the Missouri River near Kansas City, Missouri.

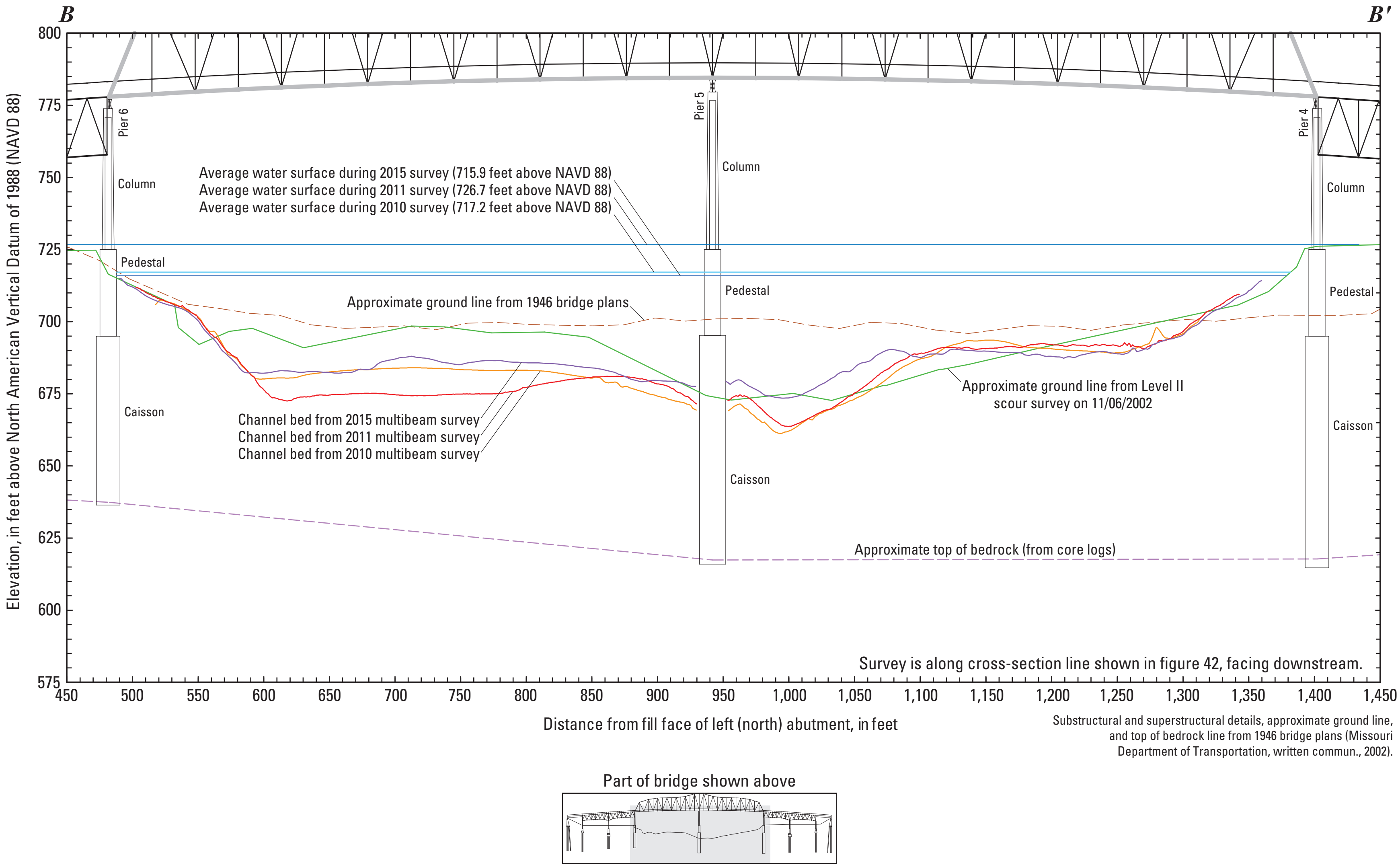



**Figure 45.** Key features, substructural and superstructural details, and surveyed channel bed of structure L0568 on State Highway 291 crossing the Missouri River near Kansas City, Missouri.

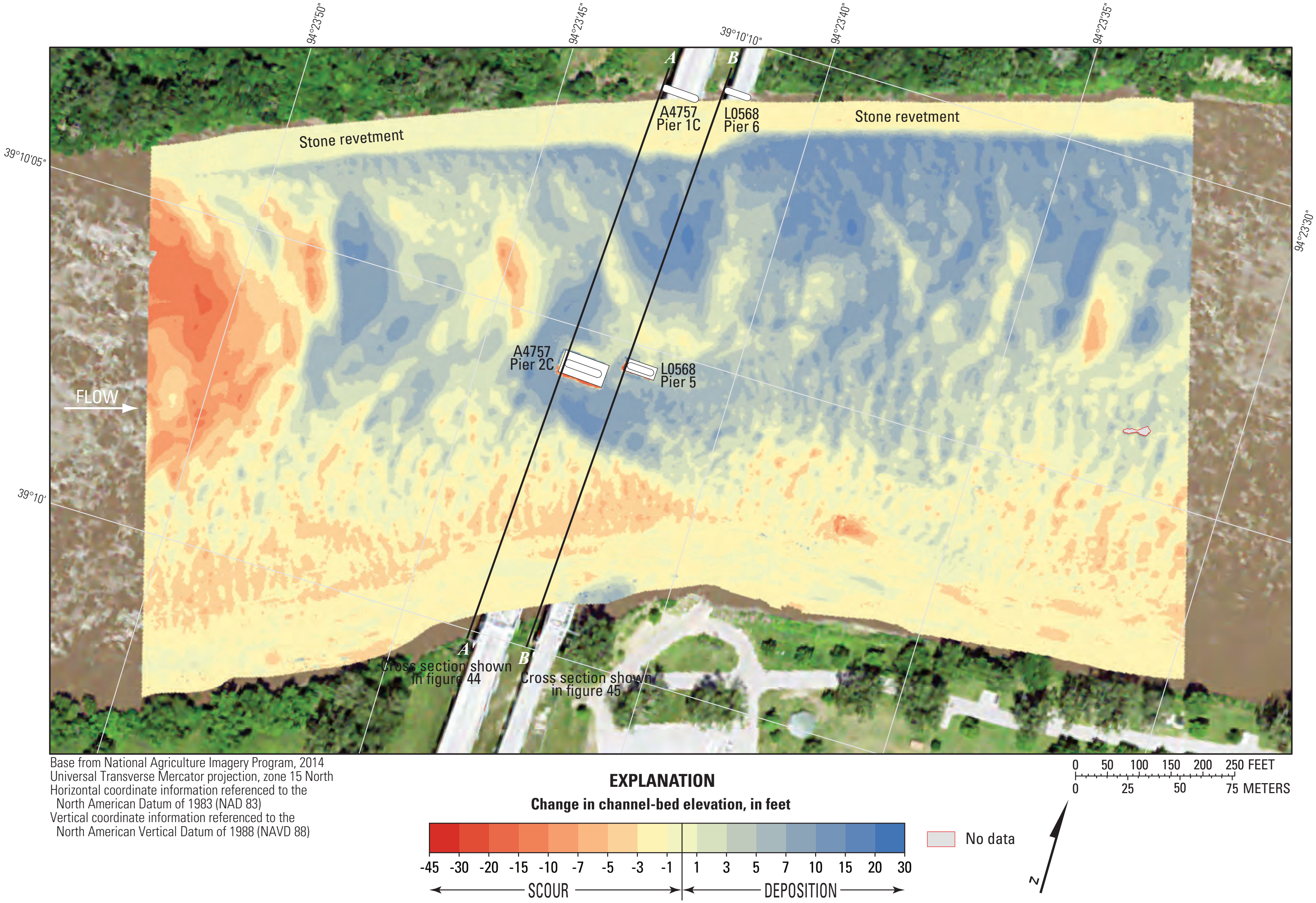
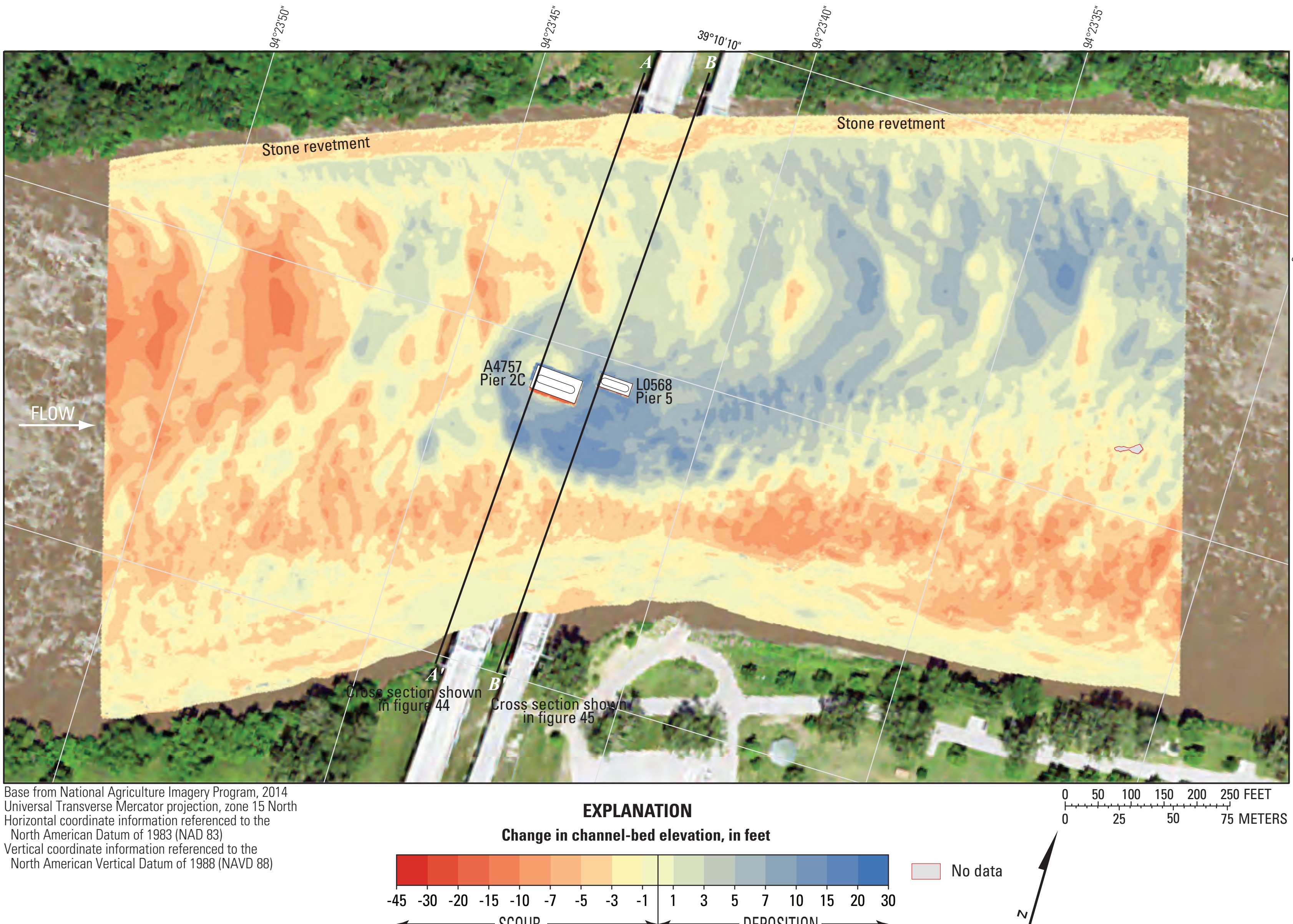
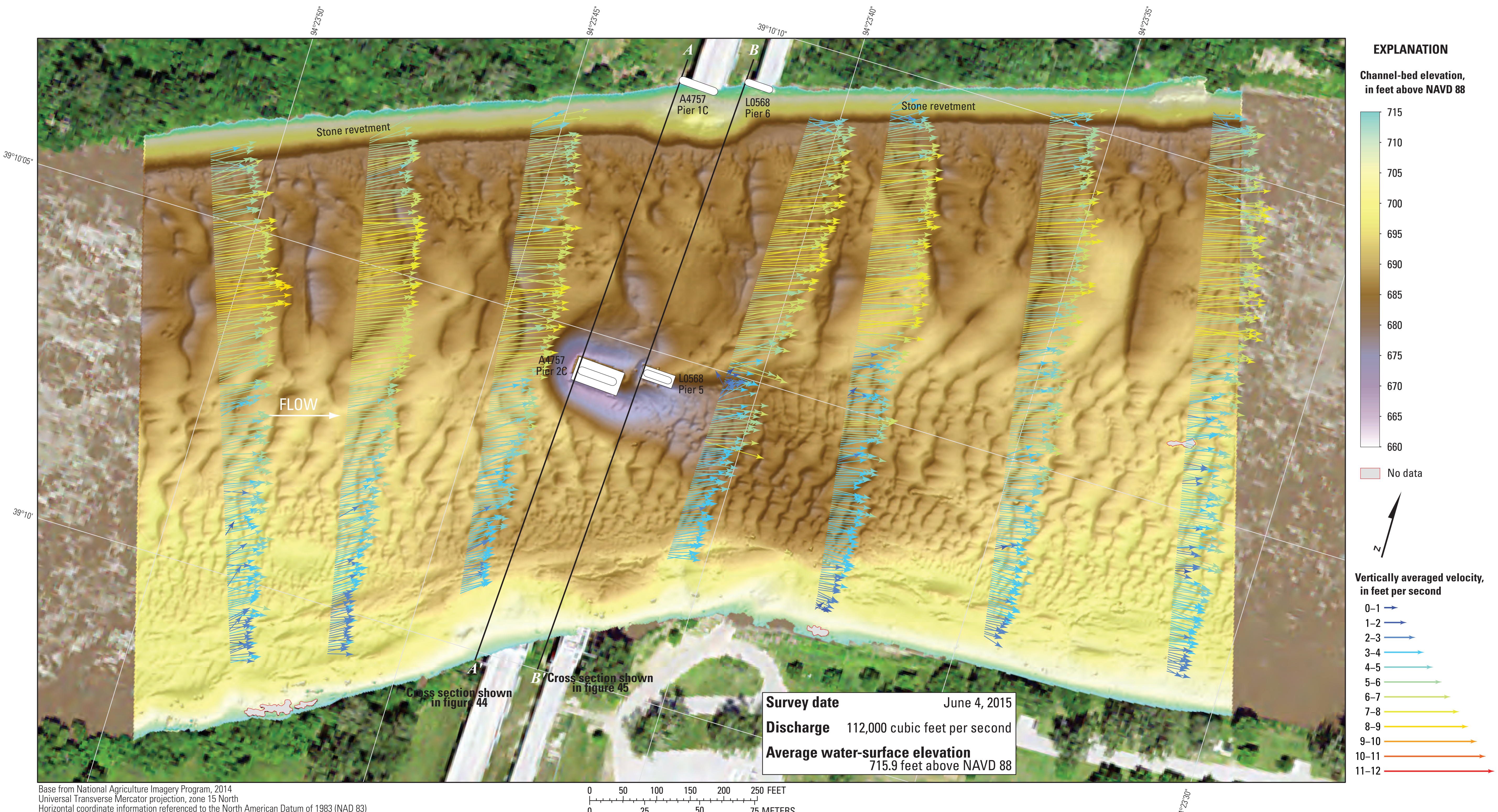



**Figure 46.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures A4757 and L0568 on State Highway 291 near Kansas City, Missouri, on June 4, 2015, and July 19, 2011.




Base from National Agriculture Imagery Program, 2014
Universal Transverse Mercator projection, zone 15 North
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)
Vertical coordinate information referenced to the North American Vertical Datum of 1988 (NAVD 88)

**Figure 47.** Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures A4757 and L0568 on State Highway 291 near Kansas City, Missouri, on June 4, 2015, and March 18, 2010.




Base from National Agriculture Imagery Program, 2014
Universal Transverse Mercator projection, zone 15 North
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)
Vertical coordinate information referenced to the North American Vertical Datum of 1988 (NAVD 88)

**Figure 48.** Bathymetry and vertically averaged velocities of the Missouri River channel near structures A4757 and L0568 on State Highway 291 near Kansas City, Missouri.

## General Findings and Implications

Several of the findings at each surveyed bridge were common to all of the bridges, and some findings were evident only when results of the surveys were examined as a set. These general findings are of benefit in the assessment of scour at the surveyed bridges, as well as other bridges in the vicinity or in similar settings.

### Effects of Low to Moderate Flooding Compared to Previous Surveys

Richardson and Davis (2001) separate long-term aggradation and degradation of a channel from the contraction and local scour that happens at a bridge site during floods. Contraction scour is the general change in the channel-bed elevation across a bridge opening resulting from the passage of a flood through a constriction, where more material is in suspension and transport. Local scour is the localized erosion of material caused by flow vortex action that forms near bridge piers and abutments. Although all of the scour processes (long term, contraction, and local scour) continually are at work, contraction and local scour generally are cyclic for the live-bed scour typically observed in alluvial channels and generally result in a decrease and subsequent increase of the channel-bed elevation during the passage of a flood.

As stated in the introductory comments of the “Results of Bathymetric and Velocimetric Surveys” section above, a wide variety of factors influence the channel-bed configuration of a reach for a given discharge (Gilbert, 1914). Because of the myriad number and interactions of factors affecting sediment transport conditions and the resultant bed configuration, it is recognized as simplistic to assume that the configuration and size of bed forms observed during the current (2015) surveys near Kansas City (fig. 1) are dependent only upon the instantaneous discharge at a given site. While it is beyond the scope of the current (2015) study to examine all of the antecedent conditions that created the observed channel-bed configuration, the following discussion attempts to draw conclusions based on the conditions observed at each site during the current (2015) and previous surveys.

A comparison of the dune sizes at the various sites is indicative of the different flow regimes between 2011 and 2015. Whereas many of the surveys in the 2011 had a planar bed area and large to very large dune features, the 2015 surveys were filled throughout with mostly medium to small dune features and ripples (figs. 6, 12, 18, 24, 29, 35, and 42). The largest dune features in the 2015 surveys were observed at structures A0767 (site 12, fig. 35), and A4757/L0568 (site 13, fig. 42), which were surveyed on the rising limb of a substantial flood (fig. 2). The smaller size and amplitude of the dune features compared to 2011 indicates less bed-material and bedload transport because of the lower flow values (Simons and others, 1965).

Many flood durations on the Missouri River near Kansas City can be measured in days to weeks because of the large upstream contributing drainage area; however, as described in the “Description of Flow Conditions” section earlier in this report, most of the surveys in this study happened during a trough between flood rises during generally higher summer flows (fig. 2), and the measured discharge at these sites was the lowest compared to previous surveys. The fixed scour monitors on structures L0550 and A4497 at Jefferson City, Mo., located about 200 river miles downstream from the Kansas City metropolitan area, discussed in Huizinga (2014) indicate that many of the local scour holes observed at the upstream nose of the piers at that site did not fill in rapidly after the recession of a flood (see fig. 35, Huizinga [2014]); nevertheless, flood recession generally leads to deposition and not additional scour. Examining results based purely on instantaneous discharge and ignoring effects from antecedent flow conditions, it might be reasonable to assume that the scour holes near the piers and the general scour observed under the bridge crossings might be of an equal to lesser magnitude than that observed during the previous surveys during the July 2011 flood and during moderate flooding in 2010; however, this assumption did not consistently prove to be true, particularly with respect to the depth of observed scour near the piers when compared to results from the 2011 flood.

Flow rate during the 2015 surveys ranged from about 43 to 56 percent of the 2011 flow rate, and water-surface elevations were about 10 to 15 ft lower in 2015 than in 2011 (table 7). Flow rate during the 2015 surveys ranged from about 71 to 93 percent of the 2010 flow rate, and water-surface elevations were about 1 to 4 ft lower in 2015 than in 2010 (table 7); however, the average difference (statistical mean) between the bathymetric surfaces varied from 3.8 ft lower to 1.8 ft higher in 2015 than 2011, and varied from 1.5 ft lower to 1.1 ft higher in 2015 than 2010 (table 7). At structures K0456/A0450 (site 7; table 1), A4649 (site 8), A4060 (site 9), and A5817 (site 11), the channel bed was at a temporal minimum in 2010 and a temporal maximum in 2011 when the average channel-bed elevation is examined with time (fig. 49); the 2015 average channel-bed elevation fell between the two previous surveys. These sites all had a negative average difference between the bathymetric surfaces from 2015 to 2011, and a positive average difference between 2015 and 2010 (table 7). In contrast, at structures A7650 (site 10), A0767 (site 12), and A4757/L0568 (site 13), the channel bed was at a temporal minimum in 2011 and a temporal maximum in 2015; these sites all had a positive average difference between the bathymetric surfaces from 2015 to 2011 and a negative average difference between 2015 and 2010 (table 7). This configuration of average channel-bed elevations and average differences shows that greater discharge alone does not necessarily result in more scour at a site (as would be evidenced by lower average channel-bed elevations with increased discharge). It was hypothesized in the 2011 flood study at Kansas City (Huizinga, 2012) that perhaps a plug of sediment was traveling through the upstream part of the Kansas City area during course of the 2011 surveys; the results of the current (2015) surveys may imply this plug of sediment had been eroded away between 2011 and 2015.

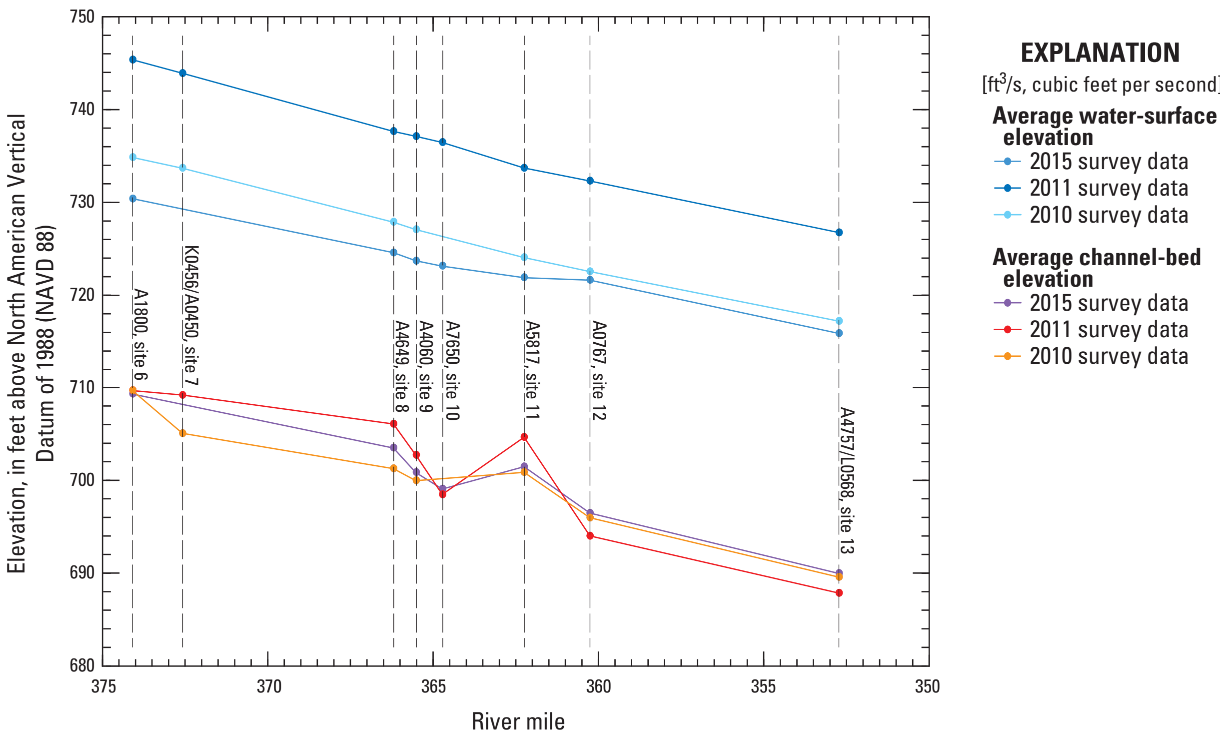



**Figure 49.** Average channel-bed and water-surface elevations near bridges on the Missouri River near Kansas City, Missouri, from surveys in 2010, 2011, and 2015.

Of particular interest is the local spatial minimum observed for the average channel-bed elevations near structure A7650 (site 10) irrespective of time (fig. 49). Whereas the sites immediately upstream and downstream from structures A4060 (site 9) and A7650 (site 10) display evidence of the hypothetical “plug” of sediment in the Kansas City area during the 2011 flood, it is less apparent at structure A4060 and not apparent at structure A7650 (fig. 49); furthermore, although the average channel-bed elevation in 2015 is similar to 2011 at structure A7650, the average difference between the bathymetric surfaces from 2015 to 2011 is positive (figs. 25 and 27), indicating moderate deposition throughout that bridge reach from 2011 to 2015. The average difference between the bathymetric surfaces at structure A4060 from 2015 to 2011 is negative (figs. 19 and 21), indicating moderate degradation throughout that bridge reach from 2011 to 2015.

The local spatial minimum at structure A7650 (site 10) may indicate this site is at or near a local feature that controls sediment deposition and scour. The feature may be a combination of the minor constriction at this site (fig. 24) and being near the downstream end of the relatively straight reach of river between structures A4649 and A7650 (fig 1); furthermore, perhaps the sediment unable to deposit near structure A7650 is flushed downstream and deposits at the next downstream site, structure A5817 (site 11), as indicated by the average channel bed curve (fig. 49).

An examination of the frequency distributions of the 2015 surveys compared to the previous surveys reveals additional differences that may be the result of flow conditions during the 2015 surveys (fig. 50). The frequency distributions generally were narrower in the 2015 survey than in either the 2010 or 2011 survey at each site, with a higher percentage of survey-grid cells in a particular elevation range (fig. 50*A*). The narrower distribution curves result in generally steeper accumulation curves in 2015 than in 2010 or 2011 (fig. 50*B*). Accumulation curves that are steep indicate a channel bed with a narrower range of elevations (more level throughout the reach), whereas those that are less steep indicate a wider variation of elevations. Accumulation curves with “steps” indicate a channel with distinct groups of elevations, such as thalweg on one side and a shallow area on the opposite side of the channel (such as structure A1800, figs. 6 and 7).

The frequency distributions seem to confirm the hypothetical scenario of a sediment control feature near structure A7650 postulated in the average channel-bed elevation curve discussion above. The frequency distribution curves for structures A4060 and A7650 have local maxima with a higher percentage of survey-grid cells than other sites (fig. 50*A*), and the accumulation curves for these two sites are steeper than the other surveys in the area (fig. 50*B*), which indicates a more level bed with less variation in elevation at these sites. As would be expected, these maxima are at a lower elevation than sites upstream from them and generally at a higher elevation than most of sites downstream; however, the distribution curve for downstream structure A5817 consistently has a local maximum that is at a higher elevation than the two upstream

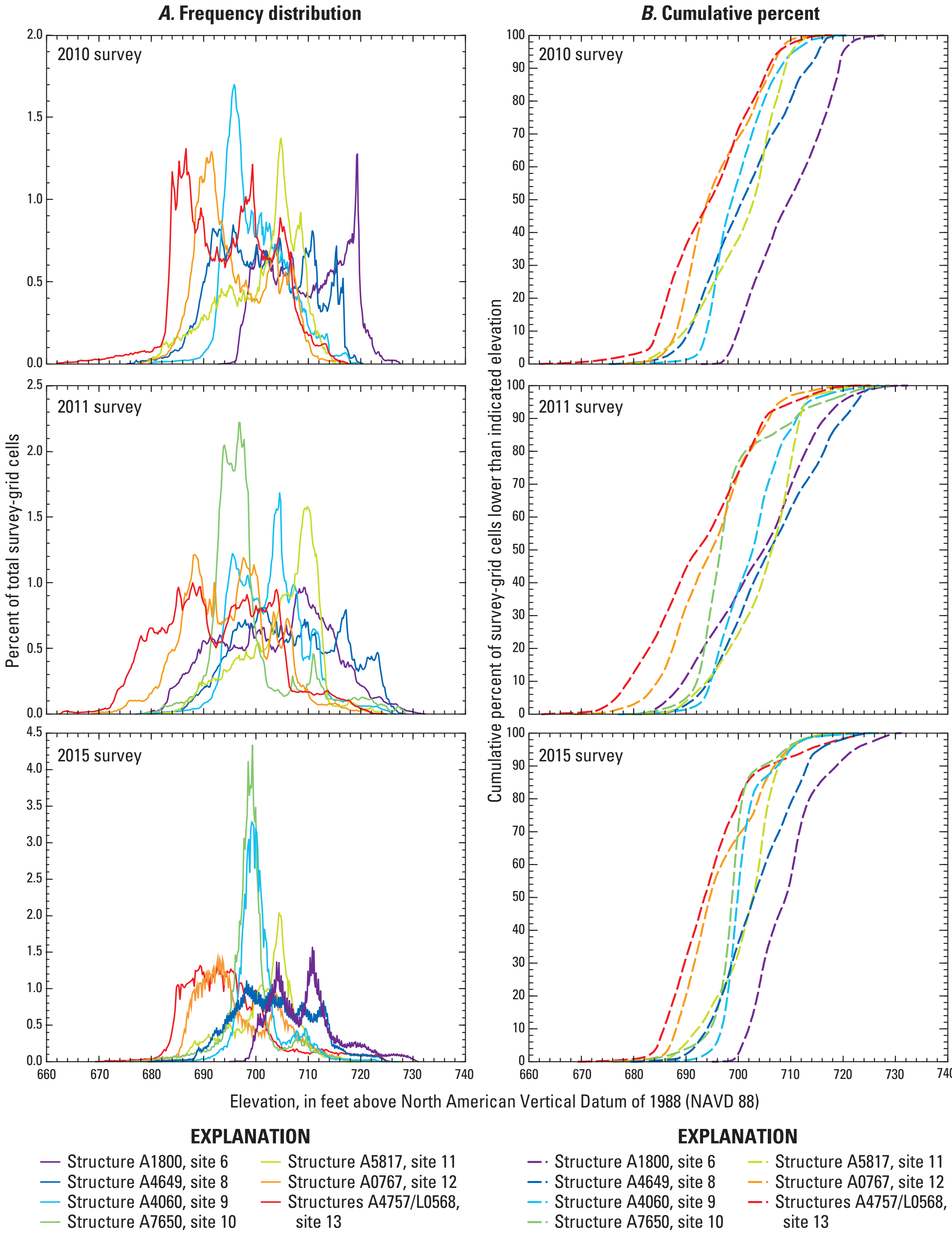



**Figure 50.** Comparison of frequency distribution and cumulative percent of bed elevations for bathymetric survey-grid cells from various surveys on the Missouri River near Kansas City, Missouri. *A*, frequency distribution. *B*, cumulative percent.

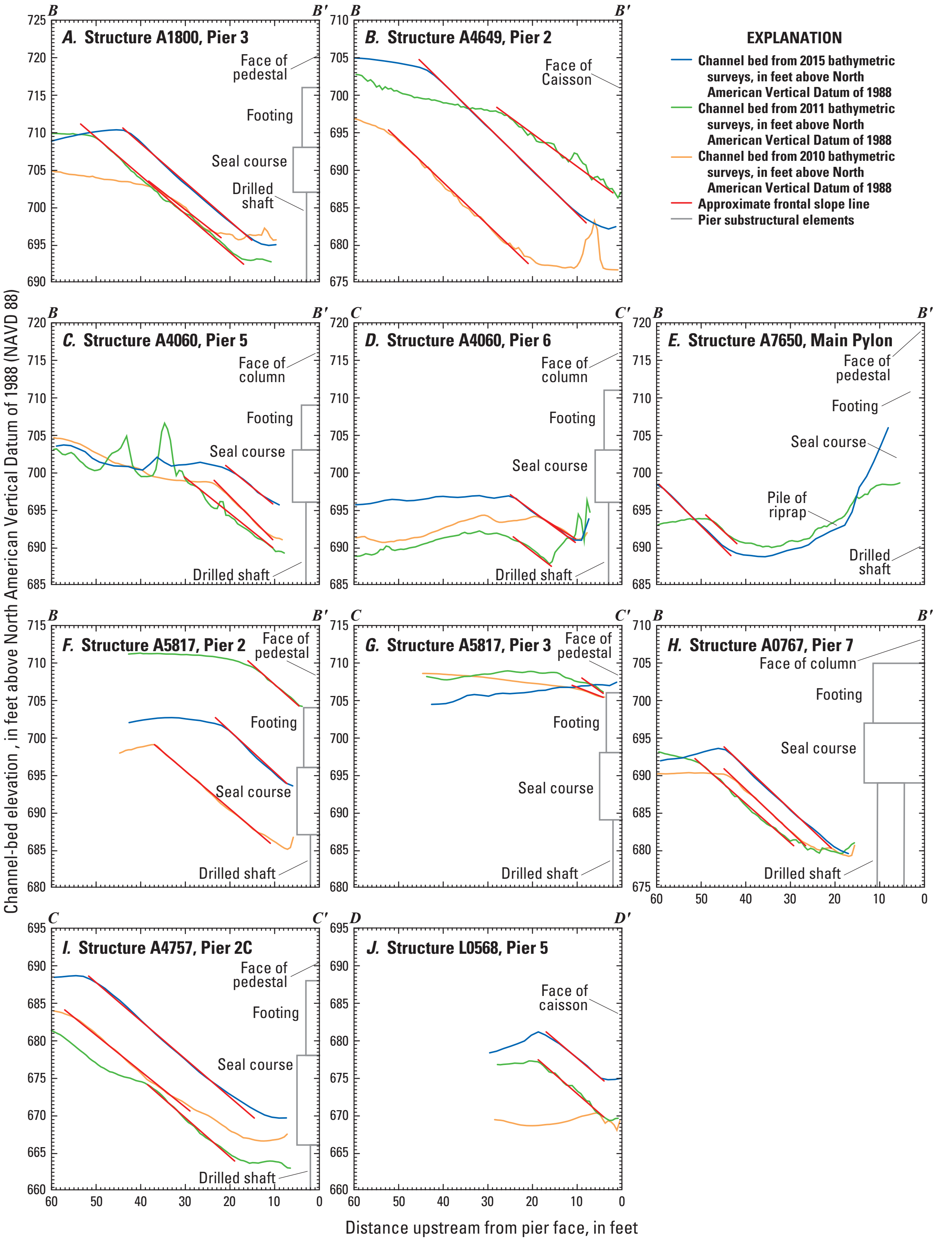



**Figure 51.** Longitudinal profiles upstream from selected piers at bridges crossing the Missouri River near Kansas City, Missouri. *A*, structure A1800, pier 3. *B*, structure A4649, pier 2. *C*, structure A4060, pier 5. *D*, structure A4060, pier 6. *E*, structure A7650, main pylon. *F*, structure A5817, pier 2. *G*, structure A5817, pier 3. *H*, structure A0767, pier 7. *I*, structure A4757, pier 2C. *J*, structure L0568, pier 5.

sites, and the accumulation curve is to the right of (implying a higher elevation than) several of the upstream sites in the surveys (fig. 50*B*).

### Size and Shape of Scour Holes

Scour holes were observed at most piers in the main channel area, except those on banks or surrounded by riprap or debris rafts. As discussed in summaries of previous bathymetric surveys in Missouri (Huizinga, 2010, 2011, 2012, 2014, 2015), the size and shape of these holes often was different from pier to pier because pier scour is a function of several factors, including the depth and velocity of approach flow, the width and nose shape of the pier, and the angle of approach flow (Richardson and Davis, 2001). Several of these factors are discussed below.

A longitudinal profile was drawn upstream from the nose of each pier with a well-defined scour hole (fig. 51), and the approximate frontal slope (computed as horizontal distance over vertical distance, or run over rise, for relatability to highway embankment slopes) was determined for each hole (table 6). The frontal slope was not determined for piers with poorly defined scour holes.

The approximate frontal slope of the well-defined scour holes ranged from 1.69 to 2.26 (fig. 51; table 6); however, the hole with the largest slope value—or the shallowest frontal slope—(2.26 at structure A4060 pier 6; figs. 18 and 51*D*; table 6]) was observed at a pier that in earlier surveys seemed to be surrounded by riprap or rock and may not be indicative of scour of purely fluvial material; furthermore, the scour hole at this pier likely is affected by flow around the upstream railroad bridge pier (fig. 18). The mean value of the frontal slopes is 1.91. Richardson and Davis (2001) noted that the side slope of a scour hole in cohesionless sand in air could range from 1.0 to 1.8 depending on the composition of the bed material and its dry angle of repose, and suggest using a value of 2.0 for design purposes to account for the wet angle of repose. The slope values determined in the current (2015) study generally are similar to the values noted in Richardson and Davis (2001) and to values determined for scour holes in similar studies (Huizinga, 2010, 2011, 2015), and are similar to previous surveys at these sites (fig. 51).

Several of the surveyed bridges had piers that were skewed to approach flow, resulting in asymmetric scour holes at those bridges: pier 3 of structure A1800 on Interstate 635 (fig. 6); pier 2 of structure A4649 on U.S. Highway 169 (fig. 12); the railroad bridge pier upstream from pier 6 of structure A4060 on State Route 9 (fig. 18); the main channel pylon of structure A7650 on Interstate 35 (fig. 24); and pier 2C of structure A4757 and pier 5 of structure L0568 on State Highway 291 (fig. 42). At all of the structures except A7650, the scour hole was deeper and longer on the side of the pier with impinging flow, with some amount of deposition on the leeward side, as typically has been observed at piers skewed to approach flow; however, at structure A7650, the scour hole was deeper and longer on the leeward side of the pier, possibly because of a deflection and contraction of flow caused by the protruding left bank at the bridge (fig. 24). Although the velocities were not substantially affected by the constriction (fig. 28), there may be enough turbulence created by the pylon and constriction to pull sediment into suspension. At all of the structures, the skew to approach flow is apparent in the velocity vectors (figs. 11, 17, 23, 28, and 48). At structures A4757/L0568, the skew seems to be partly caused by shear flow from the contraction of the right bank at the bridge (fig. 48).

In the previous bathymetric survey studies on the Missouri River in the Kansas City area (Huizinga, 2010, 2012), occasionally it was observed that the movement of bed material affected the shape of the scour holes at some of the bridges such that several of the scour holes displayed subtle "steps" and waves in the front of or along the sides of the holes. These "steps" are presumed to be caused by lateral or longitudinal sand input into a larger scour hole remnant (Huizinga, 2010, 2012), perhaps during the receding limb of the hydrograph or a new flood event happening a short time after a more substantial flood event (a local temporal maxima). During the 2011 flood study (Huizinga, 2012), the Missouri River was in moderate- to high-flow conditions at all the bridges that resulted in substantial and dynamic movement of bed material, yet "steps" and waves were observed at only a few bridges; however, no such "steps" or waves were observed in the present (2015) study, perhaps because of the timing of the surveys in the trough between higher flow conditions (fig. 2) with little infilling during the receding limb of the hydrograph from the previous higher flow.

## Summary and Conclusions

Bathymetric and velocimetric data were collected on the Missouri River near 8 highway bridges at 7 crossings in Kansas City, Missouri, by the U.S. Geological Survey in cooperation with the Missouri Department of Transportation. A multibeam echosounder mapping system was used to obtain channel-bed elevations for areas ranging from 1,640 to 1,660 feet longitudinally and generally extending across the active channel from bank to bank in the Missouri River during low to moderate flood flow conditions. These surveys document the channel-bed conditions and velocity distribution at the time of the surveys and provide characteristics of scour holes that may be useful in the development of predictive guidelines or equations for scour holes. These data also may be used by the Missouri Department of Transportation as a moderate-flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour during floods.

The estimated total propagated uncertainty for the bathymetric surface of each survey area was computed as an estimate of the accuracy to be expected for each point with all relevant error sources taken into account. An analysis of the surveys indicated that more than 91 percent of the bathymetric data at all the sites have a total propagated uncertainty of less than 1.00 feet, and nearly two-thirds (66 percent or more) of the channel bed elevations at the sites have a total propagated uncertainty of 0.50 feet or less.

At all the surveyed bridges, a variety of fluvial features were detected in the channel ranging from small ripples to large dunes that indicate moderate transport of bedload. Rock outcrops also were detected along one bank at several sites where the alluvial material of the channel bed had been washed away.

Bathymetric data were collected around every pier that was in water, except those at the edge of water or surrounded by a debris raft, and scour holes were observed at most surveyed piers. The observed scour holes at the surveyed bridges were examined with respect to shape and depth. Although exposure of parts of substructural support elements was observed at several piers, the exposure likely can be considered minimal compared to the overall substructure that remains buried in bed material at these piers.

Previous bathymetric surveys had been done at all the sites in this study. Comparisons between bathymetric surfaces from the previous surveys (in March 2010 and during the 2011 flood) and those of this study do not indicate any consistent correlation in channel-bed elevations with flow conditions. Most of the surveys in the current (2015) study happened during a trough between flood rises during generally higher summer flows, and the measured discharge was the lowest compared to previous surveys; however, a simplified assumption of equal to lesser magnitude scour with lower discharge did not consistently prove to be true, particularly with respect to the depth of observed scour near the piers when compared to results from the 2011 flood. Flow rate during the 2015 surveys ranged from about 43 to 56 percent of the 2011 flow rate, and water-surface elevations were about 10 to 15 ft lower in 2015 than in 2011. Flow rate during the 2015 surveys ranged from about 71 to 93 percent of the 2010 flow rate, and water-surface elevations were about 1 to 4 ft lower in 2015 than in 2010; however, the average difference between the bathymetric surfaces varied from 3.8 ft lower to 1.8 ft higher in 2015 than 2011, and varied from 1.5 ft lower to 1.1 ft higher in 2015 than 2010.

A local spatial minimum average channel-bed elevation at structure A7650 (site 10) compared to adjacent sites may indicate this site is at or near a local feature that controls sediment deposition and scour. The feature may be a combination of the minor constriction at the site and being near the downstream end of the relatively straight reach of river; furthermore, the average channel-bed elevation values and the distribution of channel-bed elevations imply the sediment unable to deposit near structure A7650 is flushed downstream and deposits at the next downstream site, structure A5817 (site 11).

The frontal slope values determined for scour holes observed in the current (2015) study generally are similar to recommended values in the literature and to values determined for scour holes in previous bathymetric surveys. Several of the structures had piers that were skewed to primary approach flow, and at most of the structures, the scour hole was deeper and longer on the side of the pier with impinging flow, with some amount of deposition on the leeward side, as typically has been observed at piers skewed to approach flow; however, at structure A7650 (site 10), the scour hole was deeper and longer on the leeward side of the pier, possibly because of a deflection and contraction of flow caused by a protrusion of the corresponding bank at the bridge.

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# Appendixes 1 and 2

# Appendix 1—Bathymetric Data Reproducibility Test Results

As explained in the “Survey Quality-Assurance/Quality Control Measures” section of the main text, a series of surveys (hereinafter referred to as the “test surveys”) were completed over an area near the dam at Longview Lake near Kansas City, Missouri (fig. 1–1), as an additional quality-assurance measure. These surveys were completed using different surveying patterns and on different days to provide a set of bathymetric results that could be compared for reproducibility of bathymetric data collected with the multibeam mapping system (MBMS) used in this study. Upon further examination during processing, these surveys also provided an important test of the angular offset for roll of the transducer head of the multibeam echosounder (MBES). The results of these tests are useful for determining the reproducibility of surveys completed on lakes or rivers.

The area was surveyed twice on each of two test days, June 1 and June 5, 2015, using techniques detailed in the main text. The test surveys were completed on a lake because it was assumed the bed elevations would not substantively change between the various tests, thereby providing quantitative results of reproducibility. The reproducibility of bathymetric data is essentially impossible to quantify in the dynamic alluvial setting of a river because the elevation of a given location varies rapidly as the bedforms change in the flowing water. Because the test surveys were completed on a lake, a sound-velocity profile cast was made at the beginning of each survey day to account for variations in the sound-velocity profile with depth. The results of each day’s cast were used in the processing of the data for that day. As in surveys on the river, bathymetric data were obtained along transect lines. For the test surveys, the spacing between the lines was set to the anticipated mean depth to ensure nearly 100 percent overlap of the adjacent survey swaths to ensure complete coverage of the channel bed and minimize sonic “shadows.” A set of seven survey lines were oriented in a southwest to northeast direction, and another set of seven lines were oriented at 90 degrees to the first set (fig. 1–2). The bathymetric surface created by each set of seven survey lines was considered a separate surface, resulting in two different surfaces each test day for comparison purposes. Because of abrupt changes of elevation along the perimeter of the survey area, small portions of each bathymetric surface were missed during different aspects of the surveys, so the final data were cropped to a roughly square area for which data were present in each bathymetric surface for all of the surveys (fig. 1–2).

As in the surveys at bridges discussed in the main text, the navigation information from the test surveys was postprocessed using the POS-Pac™ Mobile Mapping Suite (MMS™) software (Applanix Corporation, 2009) to mitigate the effects of degraded positional accuracy of the vessel during the survey. The blended navigation solution (the “standard best estimate of travel” or “SBET” file) generated by postprocessing the navigation data was applied to the test surveys. The bathymetric data were further processed to apply the offsets determined from the patch tests and remove data spikes and other spurious points in the multibeam swaths through the use of automatic filters and manual editing. The georeferenced data were filtered and reduced to a 1.64-foot (ft) data resolution and output to comma-delimited files, one for each survey on each test date. These comma-delimited data were compiled into a geographic information system (GIS) database for comparison using the ArcGIS package (Environmental Systems Research Institute, 2013).

## Angular Offset for Roll Tests

During initial processing, an angular offset for roll (hereinafter referred to as “roll angle”) of 2.45 degrees was used based on the results of the patch tests completed immediately before the test surveys; however, when examining the bathymetric data for one of the surfaces in profile as part of the normal processing routine, “tails” were evident on the ends of the lines in the profile view (fig. 1–3*A*), which is indicative of a roll angle error. Based on this apparent roll angle issue, the test survey data were reprocessed to attempt to determine the optimum roll angle that removed these tails. The optimum roll angle was -2.55 degrees for the June 1 data, and -2.50 degrees for the June 5 data, and these adjustments effectively removed the tails in the profile view (fig. 1–3*B*); therefore, these optimized roll angles were used to process the data from both test surveys on both test dates (this is hereinafter referred to as the “optimized roll angle data”).

When the bathymetric surfaces from the optimized roll angle data were compared for reproducibility, anomalies in the difference maps seemed to be related to the orientation of the survey line groups being compared (fig. 1–4). If the second survey surface perfectly reproduced the first survey surface in the comparison, there would be a zero difference value for all the compared cells in the difference maps. A comparison of the first survey line group on the two test days (same direction, different days; fig. 1–4*A*) resulted in a difference map that seems to have a slight tilt as indicated by the positive differences on the northwest side of the survey area and the negative differences on the southeast side; however, a comparison of the second survey line group on the two test days (opposite direction, different days; fig. 1–4*B*) exhibited a strong alternating pattern between the survey lines, which is indicative of an incorrect roll angle. The largest differences between the surfaces happens at the midpoint between the survey lines, which implies that the outermost beams of one line swath were well aligned with the nadir beam of the adjacent swath (thus the lack of “tails” when looking at the surface in profile in fig. 1–3*B*), but any artifact introduced by using the optimized roll angle would be exacerbated between the survey lines. Comparison of the orthogonal survey line groups (figs. 1–4*C*, 1–4*D*, 1–4*E*, and 1–4*F*) displayed a strong checkerboard pattern with the maximum difference being at the midpoint

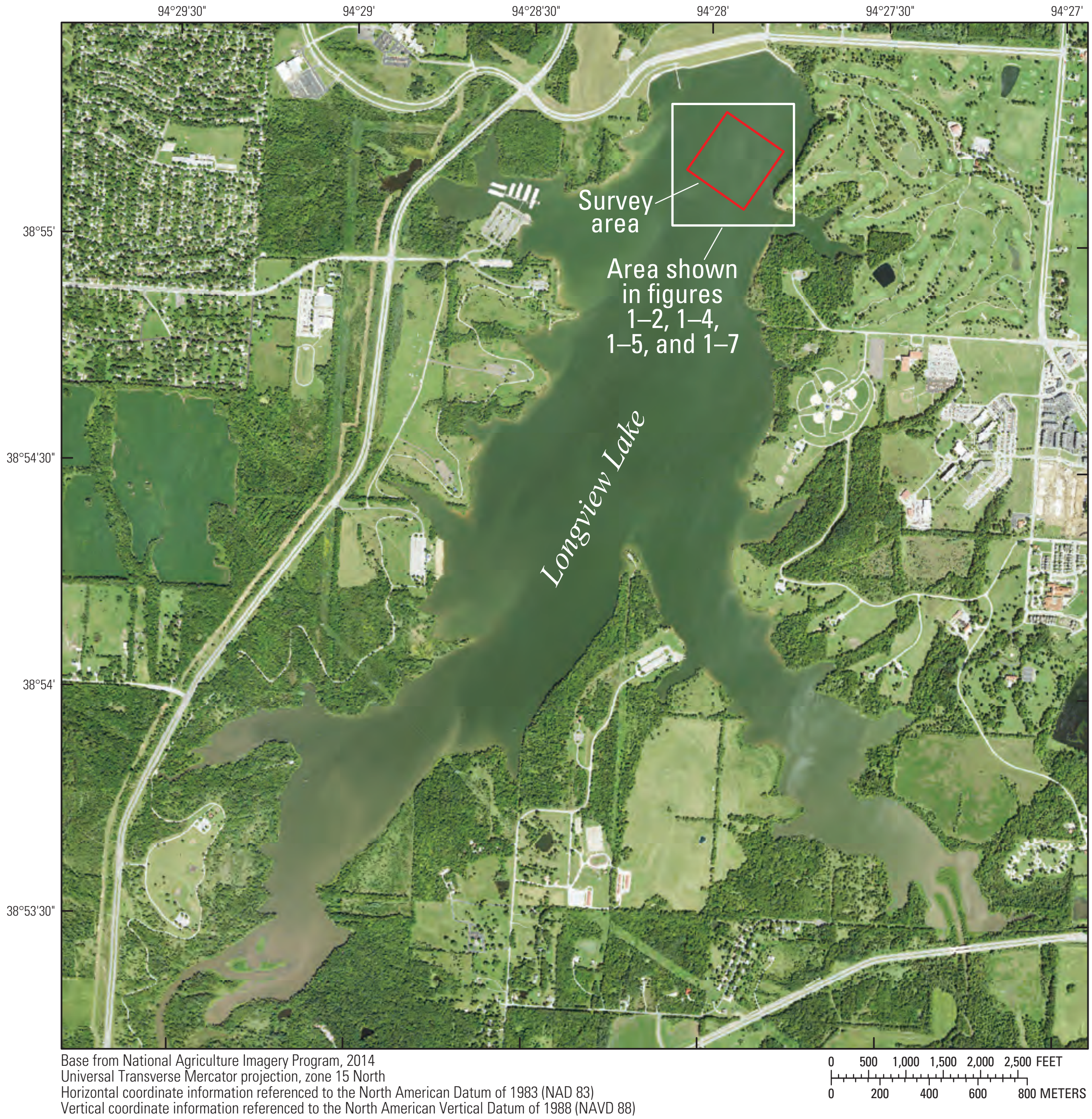



**Figure 1–1.** Location of test survey area on Longview Lake near Kansas City, Missouri, on June 1 and June 5, 2015.

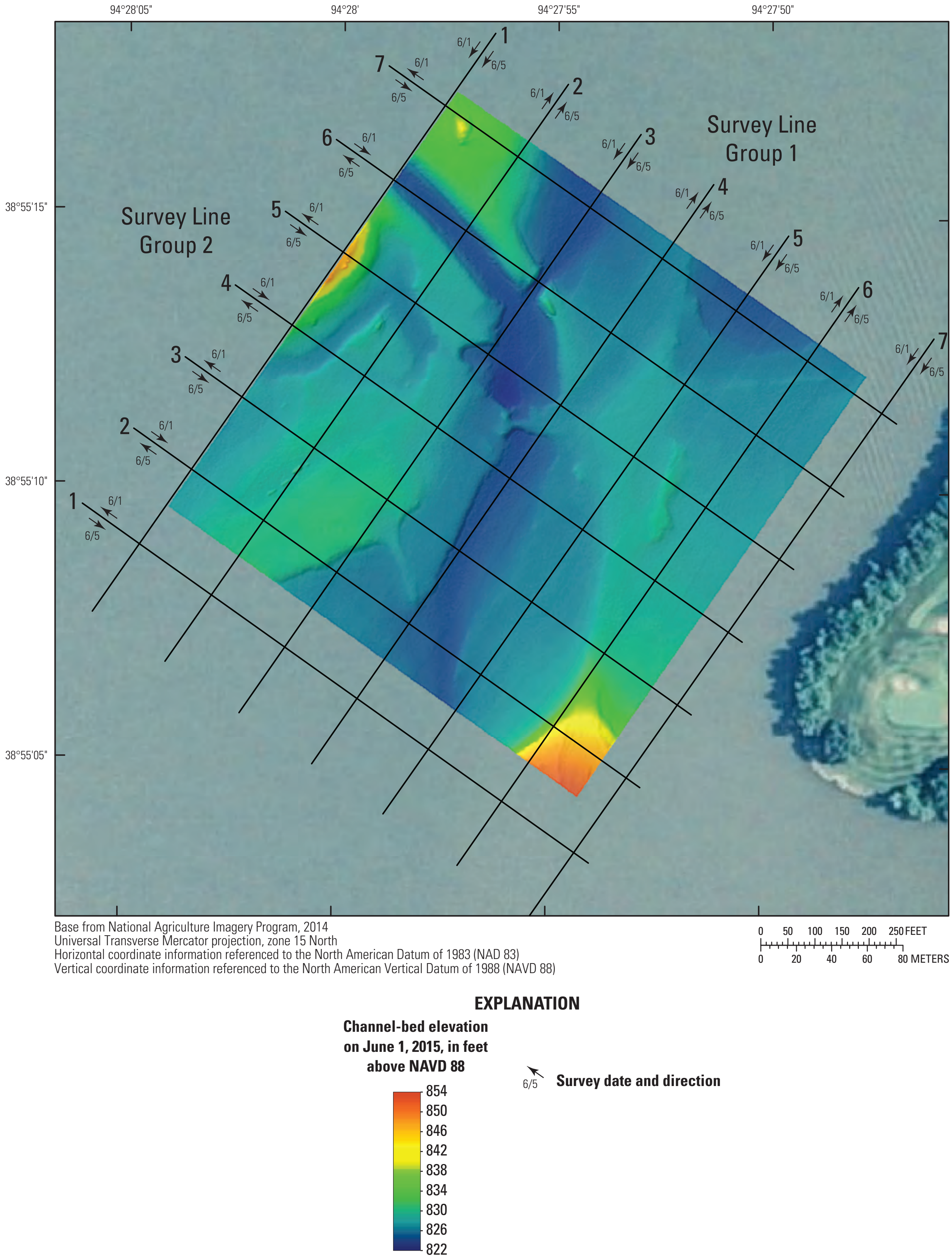


**Figure 1–2.** Configuration of test survey area on Longview Lake near Kansas City, Missouri.

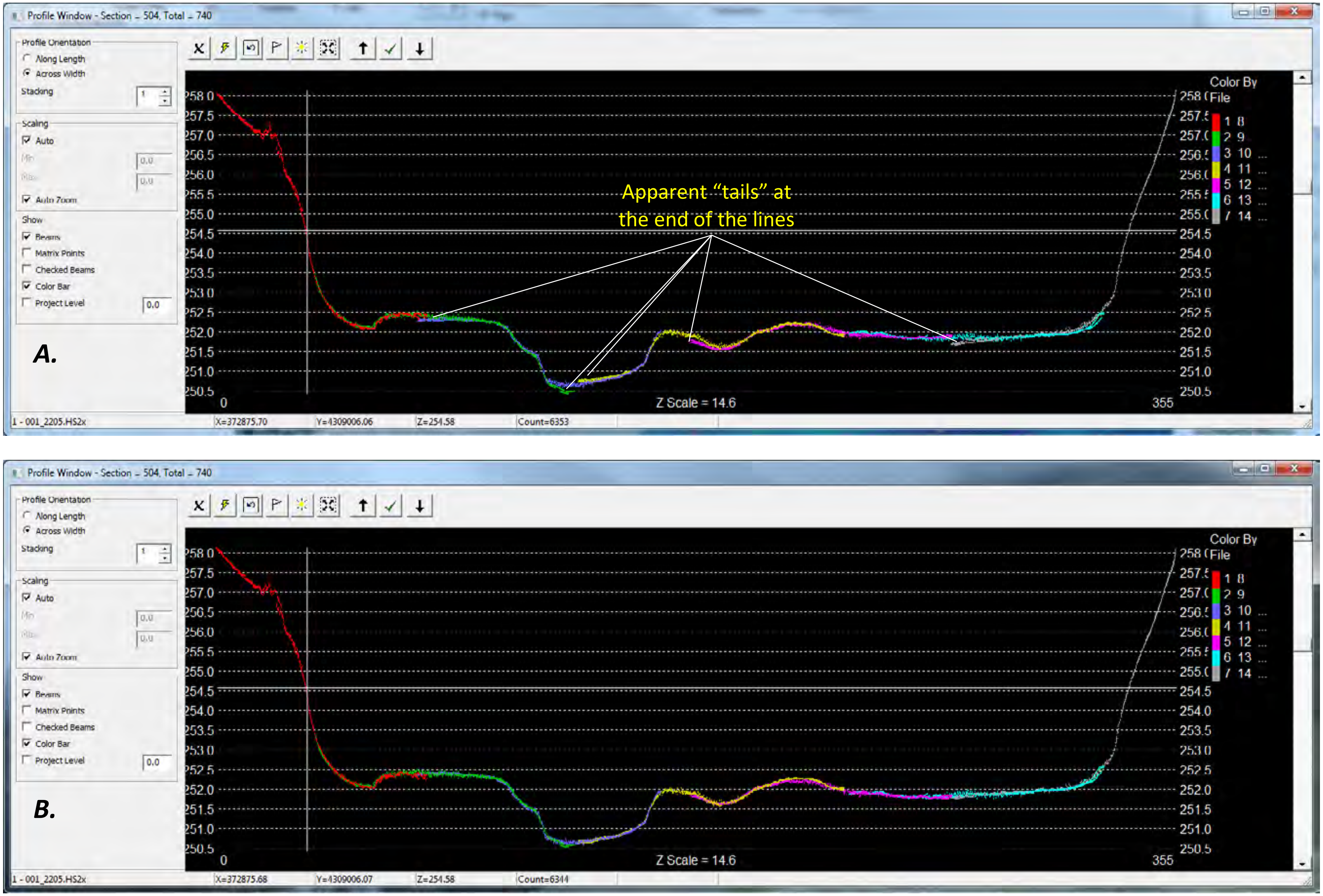


**Figure 1–3.** Screen-capture images of a profile through a bathymetric surface processed with an angular offset for roll. *A*, -2.45 degrees as determined by the patch test. *B*, optimized to minimize “tails.”

between survey lines, which further confirms the roll angle issue. Summary statistics for the six sets of difference data for the optimized roll angle data are in table 1–1.

The anomalous results in the optimized data prompted a reevaluation of the roll angle used to process the test surveys. An additional set of data was created using the roll angle of -2.45 degrees determined from the patch tests for the two surveys on the test dates (hereinafter referred to as the "corrected roll angle data"). This was the roll angle used when processing the river surveys (see table 3 in the main text). The comparison of the first survey line group on the two test days (same direction, different days; fig. 1–5*A*) once again resulted in a difference map that seems to have a slight tilt, as indicated by the positive differences on the northwest side of the survey area and the negative differences on the southeast side. A comparison of the second survey line group on the two test days (opposite direction, different days; fig. 1–5*B*) continued to exhibit a partial alternating pattern between the survey lines, but the largest differences between the surfaces happens immediately adjacent to the survey lines. The change in location of the largest difference implies the outermost beams of one line swath are more poorly-aligned with the nadir beam of the adjacent swath (creating the "tails" when looking at the surface in profile in fig. 1–3*A*), but alignment issues primarily seem to be limited to the outer beams. Comparison of the orthogonal survey line groups (figs. 1–5*C*, 1–5*D*, 1–5*E*, and 1–5*F*) displayed a checkerboard pattern similar to the optimized roll angle data, but the location of the largest differences are once again adjacent to the survey lines, which implies the alignment issues seem to be limited to the outer beams. Summary statistics for the six sets of difference data for the corrected roll angle data are in table 1–1.

A final set of data for each of the two surveys on the test dates was created using the corrected roll angle of -2.45 degrees, but with data for outer beams (greater than 60 degrees from nadir) cropped out (hereinafter referred to as the "cropped roll angle data"). Cropping the outer beam data limits potential errors caused by lack of alignment of the outer beams, and a profile view of the data reveal there were no tails on the individual survey lines (fig. 1–6). The comparison of the first survey line group on the two test days (same direction, different days; fig. 1–7*A*) once again resulted in a difference map that seems to have a slight tilt, as indicated by the positive differences on the northwest side of the survey area and the negative differences on the southeast side; however, the differences are smaller than with either the optimized roll angle data (fig. 1–4) or the corrected roll angle data (fig. 1–5), and the largest differences become more apparent on the slope near the southern tip of the survey area (figs.1–2 and 1–7*A*). The alternating pattern is substantially reduced from the comparison of the second survey line group on the two test days (opposite direction, different days; fig. 1–7*B*), as is the checkerboard pattern in the comparisons of the orthogonal survey line groups (figs. 1–7*C*, 1–7*D*, 1–7*E*, and 1–7*F*). Distinct lines along which the difference abruptly changes from positive to negative are present between several of the survey lines in most of the difference maps that compare to the second survey on June 1 (figs. 1–7*B*, 1–7C, and 1–7*F*). Summary statistics for the six sets of difference data for the cropped roll angle data are shown in table 1–1.

Each change in the configuration of the roll angle and cropping has an effect on the resultant bathymetric surface used in the comparisons; for example, removing the outer beams beyond 60 degrees from nadir in the cropped roll angle data (fig. 1–7) did not simply remove the pronounced differences observed in the corrected roll angle data (fig. 1–5), but rather altered the overall surfaces such that some areas that had a small negative difference in the corrected roll angle dataset (fig. 1–5) may exhibit a small positive difference in the cropped roll angle dataset (fig. 1–7).

Ultimately, examination of the summary statistics alone for the various roll angle configurations is not sufficient to determine the "best" roll configuration (table 1–1). If the statistics alone were used, the optimized roll angle data configuration has the overall smallest mean values in all the tests. The standard deviations for the optimized roll angle data, however, tend to be the largest; furthermore, the visual examination of the comparison tests discussed above indicates the optimized roll angle data has the most anomalous data.

It is hypothesized that the issue observed with the roll angle and resultant anomalies was caused by spatial variation in sound velocity with depth because the outer beams are particularly affected by subtle changes in the speed of sound with depth. A sound-velocity profile cast was completed immediately before the patch tests each survey date, in the deepest part of the lake just northeast of the test survey area; however, it has been observed in other lake surveys (Richard Huizinga, U.S. Geological Survey, unpub. data, 2016) that the sound-velocity profile can vary spatially during the summer, as the sun warms the surface of the lake particularly in shallow areas. The survey area was not very different from the area where the profile cast was taken, but perhaps a cooler pocket of water in the deepest area of the lake near the cast affected the lower part of the sound-velocity profile in a way that did not accurately represent the test survey area. The effect of the theorized different sound-velocity profile manifested as a roll error at the depths of the test survey area. Although the variation of speed of sound with depth can be a problem in still-water situations, such as on a lake because of the stratification of water temperature with depth, it is essentially nonexistent on rivers where natural and man-made features in the flow promote mixing, resulting in a more homogeneous temperature gradient throughout the water column with depth. The outer beams typically are observed to be unaffected in river surveys (they are observed to have reasonable good alignment of adjacent swaths) because of the more homogeneous temperatures, and typically have not been and were not cropped in the river surveys completed to date (2015).

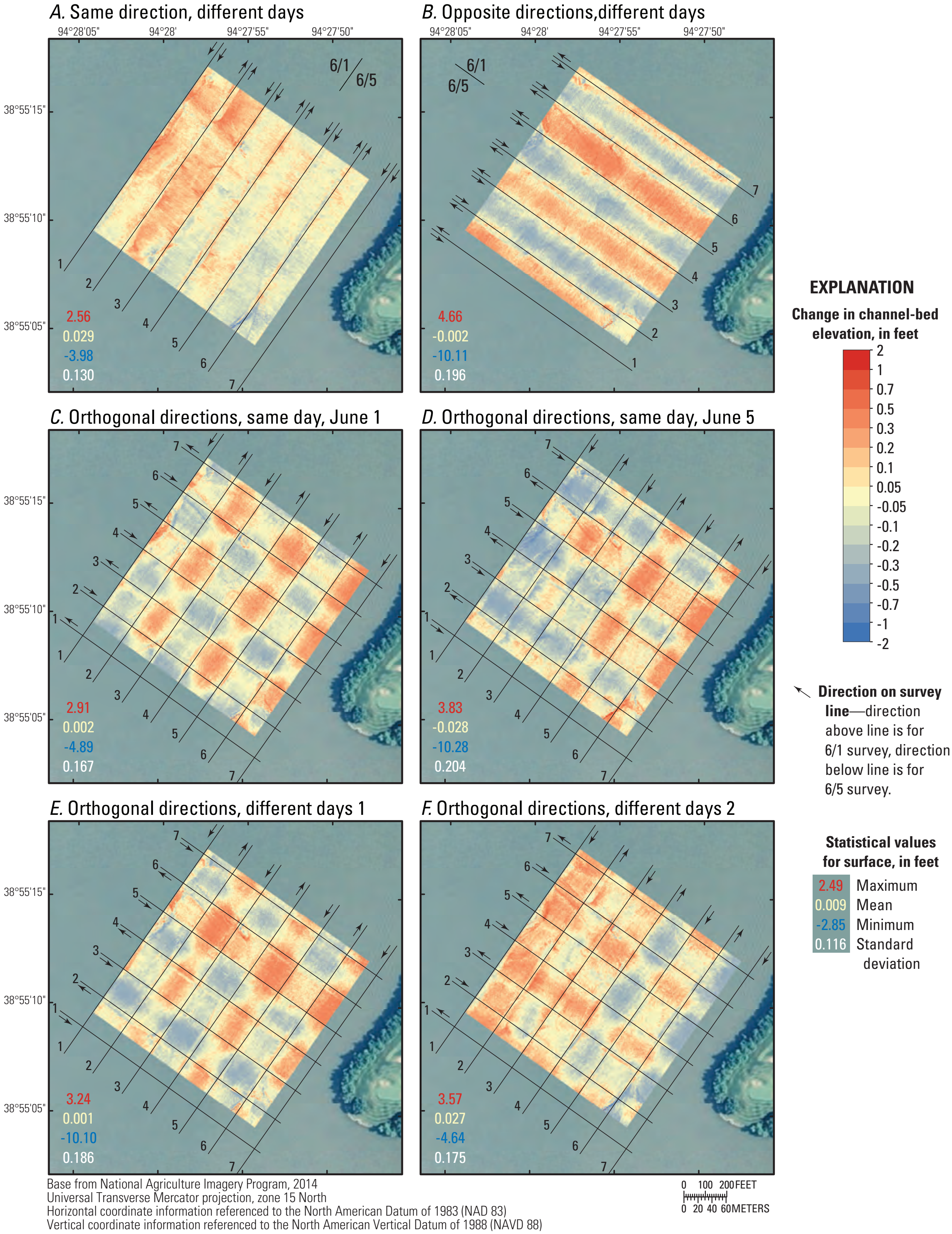


**Figure 1–4.** Difference maps for six comparison tests of bathymetric surfaces created using an optimized roll angle. *A*, same direction, different days. *B*, opposite directions, different days. *C*, orthogonal directions, same day, June 1. *D*, orthogonal directions, same day, June 5. *E*, orthogonal directions, different days 1. *F*, orthogonal directions, different days 2.

**Table 1–1.** Summary of difference results for bathymetric data at a 1.64-foot grid spacing from test surveys on Longview Lake near Kansas City, Missouri, on June 1 and June 5, 2015.

| Test | Comparison type | First date survey number | Second date survey number | Maximum value of difference (foot) | Mean value of difference (foot) | Minimum value of difference (foot) | Standard deviation of difference (foot) |
|---|---|---|---|---|---|---|---|
| "Optimized" roll angle | | | | | | | |
| 1 | Same direction, different days | 6/1 - 1 | 6/5 - 1 | 2.56 | 0.029 | -3.98 | 0.130 |
| 2 | Opposite direction, different days | 6/1 - 2 | 6/5 - 2 | 4.66 | -0.002 | -10.11 | 0.196 |
| 3 | Orthogonal directions, same day 1 | 6/1 - 1 | 6/1 - 2 | 2.91 | 0.002 | -4.89 | 0.167 |
| 4 | Orthogonal directions, same day 2 | 6/5 - 1 | 6/5 - 2 | 3.83 | -0.028 | -10.28 | 0.204 |
| 5 | Orthogonal directions, different days 1 | 6/1 - 1 | 6/5 - 2 | 3.24 | 0.001 | -10.10 | 0.186 |
| 6 | Orthogonal directions, different days 2 | 6/1 - 2 | 6/5 - 1 | 3.57 | 0.027 | -4.64 | 0.175 |
| Corrected roll angle, -2.45 degrees, with no outer beam cropping | | | | | | | |
| 1 | Same direction, different days | 6/1 - 1 | 6/5 - 1 | 2.18 | 0.022 | -2.87 | 0.147 |
| 2 | Opposite direction, different days | 6/1 - 2 | 6/5 - 2 | 4.38 | 0.005 | -9.92 | 0.157 |
| 3 | Orthogonal directions, same day 1 | 6/1 - 1 | 6/1 - 2 | 2.97 | -0.004 | -4.69 | 0.160 |
| 4 | Orthogonal directions, same day 2 | 6/5 - 1 | 6/5 - 2 | 3.51 | -0.020 | -10.18 | 0.174 |
| 5 | Orthogonal directions, different days 1 | 6/1 - 1 | 6/5 - 2 | 3.40 | 0.002 | -9.88 | 0.154 |
| 6 | Orthogonal directions, different days 2 | 6/1 - 2 | 6/5 - 1 | 3.32 | 0.025 | -4.69 | 0.183 |
| Cropped roll angle, -2.45 degrees, with 60 degrees outer beam cropping | | | | | | | |
| 1 | Same direction, different days | 6/1 - 1 | 6/5 - 1 | 2.49 | 0.009 | -2.85 | 0.116 |
| 2 | Opposite direction, different days | 6/1 - 2 | 6/5 - 2 | 2.96 | -0.035 | -14.07 | 0.133 |
| 3 | Orthogonal directions, same day 1 | 6/1 - 1 | 6/1 - 2 | 4.44 | 0.016 | -4.71 | 0.118 |
| 4 | Orthogonal directions, same day 2 | 6/5 - 1 | 6/5 - 2 | 3.05 | -0.028 | -14.19 | 0.152 |
| 5 | Orthogonal directions, different days 1 | 6/1 - 1 | 6/5 - 2 | 2.25 | -0.019 | -14.11 | 0.135 |
| 6 | Orthogonal directions, different days 2 | 6/1 - 2 | 6/5 - 1 | 2.79 | -0.007 | -4.32 | 0.140 |

## Reproducibility of Data

As stated in the Introduction to this appendix, the reproducibility of bathymetric data is essentially impossible to quantify in the dynamic alluvial setting of a river because the elevation of a given location varies rapidly as the bedforms change in the flowing water; therefore, the test surveys were completed on a lake because it was assumed the bed elevations would not substantively change between the various tests, thereby providing quantitative results of reproducibility.

As stated in previous section, if the second survey surface perfectly reproduced the first survey surface in the comparisons, there would be a zero difference value for all the compared cells in the difference maps; however, there are a multitude of factors that affect the final bathymetric surface created from a survey, and minor differences will result in differences between surveys of the same area. These factors include, but are not limited to, the following: the configuration of the inertial navigation system and the accuracy of the position and orientation solution; the configuration and accuracy of the MBES; and the configuration and accuracy of the measured offsets and lever arms of each component of the MBMS with relation to each other, and the ability to measure changes in this configuration. The accuracy of the position and orientation solution is affected by GNSS outages, satellite configuration during the survey, and abruptness of vessel maneuvers during the survey, among other things. Because the MBES measures time of travel rather than distance, the accuracy of the MBES is affected by changes to the speed of sound in water, whether spatially or with depth, or both. As discussed in the previous section, the outer beams are the most affected by variations in the speed of sound with depth. The effects are somewhat mitigated by measuring the speed of sound at the MBES transducer head, but the variations with depth need to be determined in still-water applications. All these variables and more can have an effect on the ultimate accuracy and reproducibility of bathymetric data obtained with a MBMS.

As mentioned in the main text, uncertainty in surveys can be estimated by computing the total propagated uncertainty (TPU) for each survey-grid cell in the bathymetric surface of each survey area, using the CUBE method (Calder and Mayer, 2003). The CUBE method allows all random system component uncertainties and resolution effects to be combined and propagated through the data processing steps, which provides

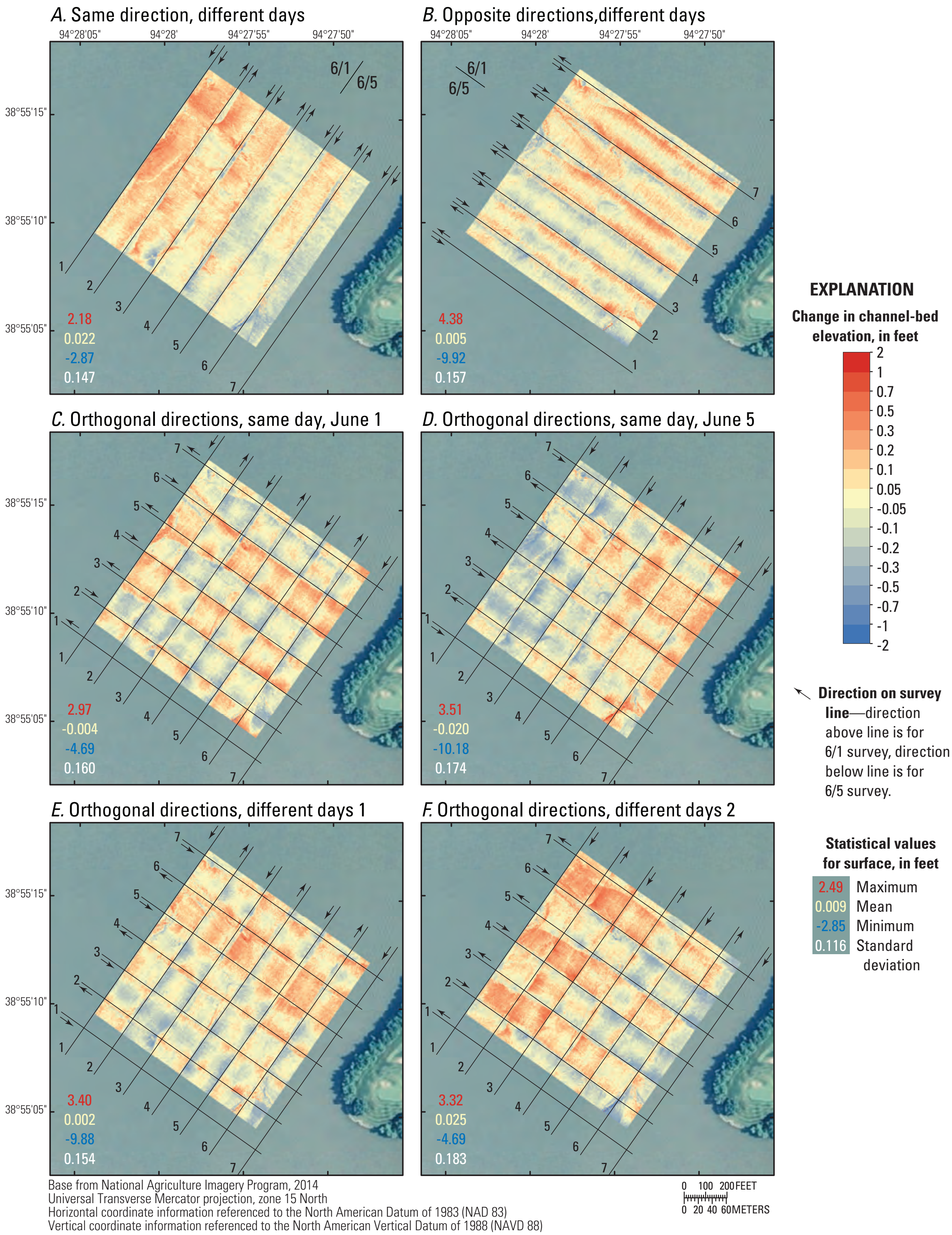


**Figure 1–5.** Difference maps for six comparison tests of bathymetric surfaces created using the corrected roll angle. *A*, same direction, different days. *B*, opposite directions, different days. *C*, orthogonal directions, same day, June 1. *D*, orthogonal directions, same day, June 5. *E*, orthogonal directions, different days 1. *F*, orthogonal directions, different days 2.

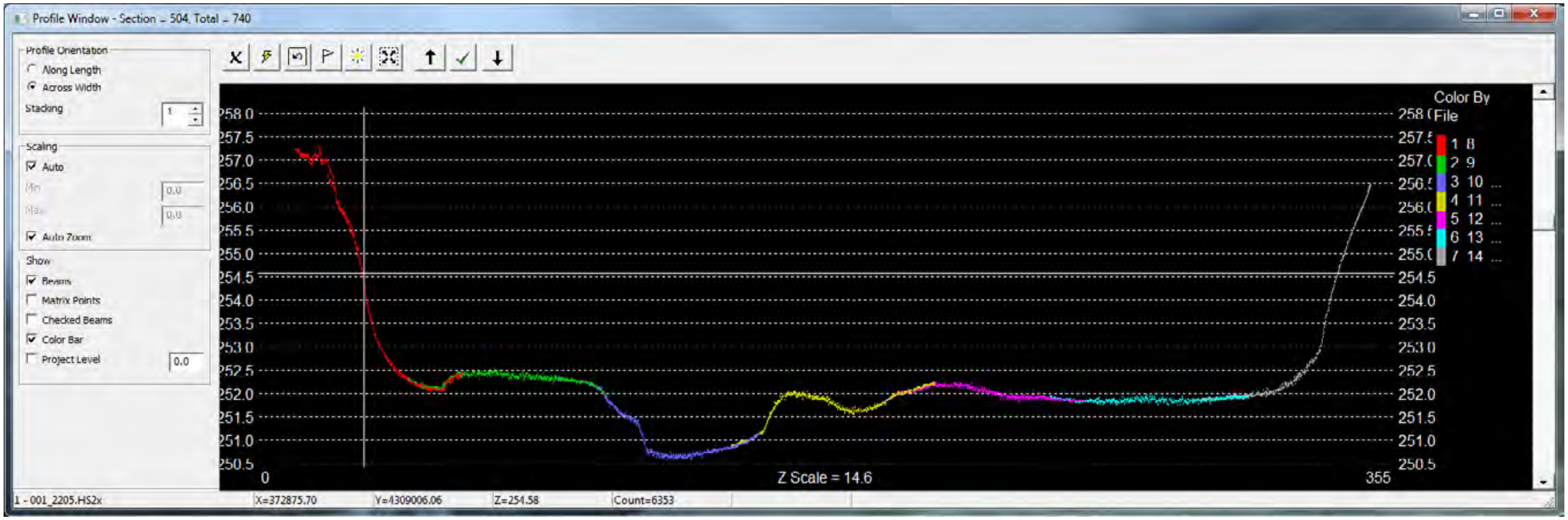


**Figure 1–6.** Screen-capture image of a profile through a bathymetric surface processed with the corrected roll angle and cropped to remove beams beyond 60 degrees from nadir.

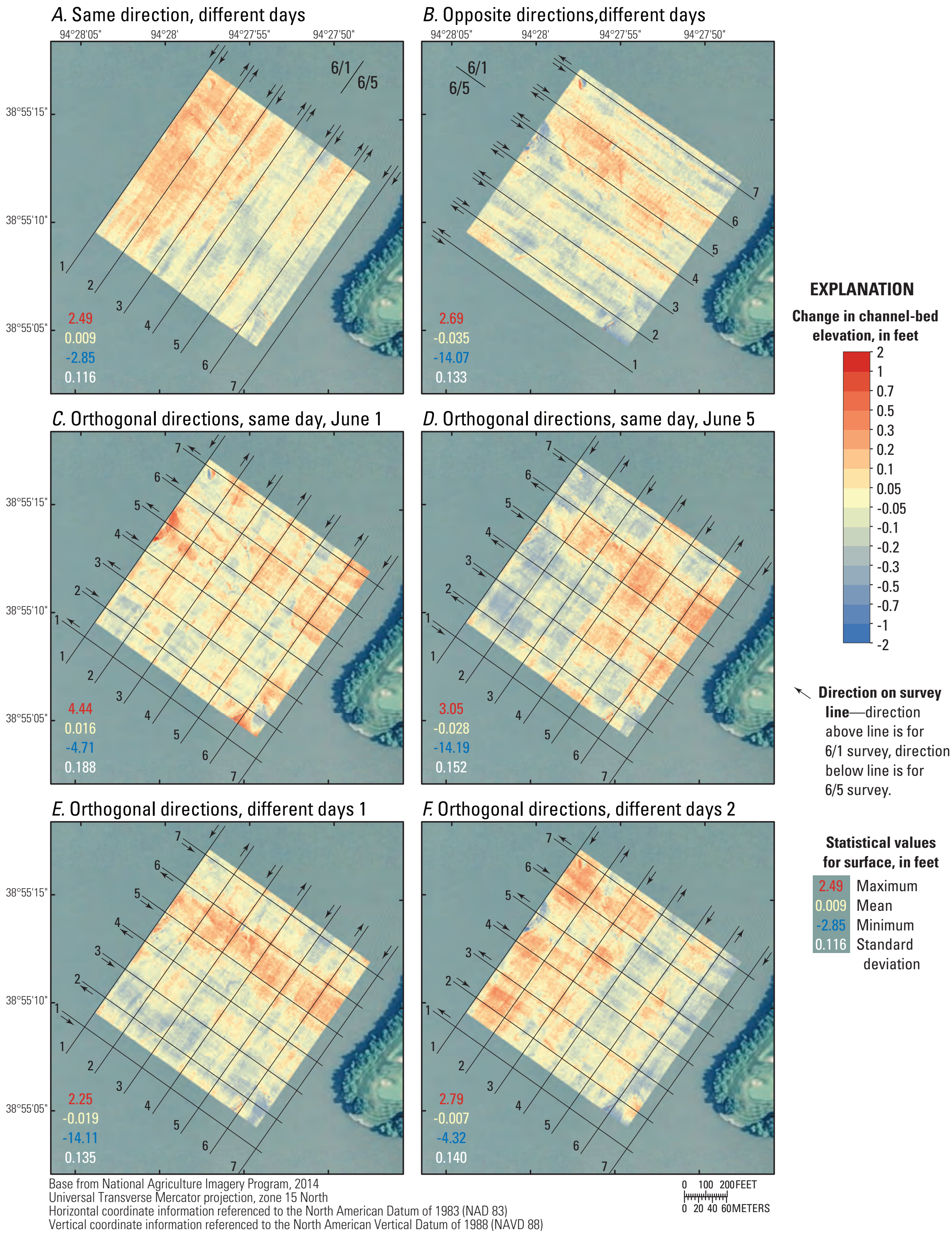


**Figure 1–7.** Difference maps for six comparison tests of bathymetric surfaces created using the cropped roll angle (corrected roll angle and cropped to remove beams beyond 60 degrees from nadir). *A*, same direction, different days. *B*, opposite directions, different days. *C*, orthogonal directions, same day, June 1. *D*, orthogonal directions, same day, June 5. *E*, orthogonal directions, different days 1. *F*, orthogonal directions, different days 2.

**Table 1–2.** Total propagated uncertainty results for bathymetric data at a 1.64-foot grid spacing from test surveys on Longview Lake near Kansas City, Missouri, on June 1 and June 5, 2015.

[ft, foot]

| Date | Survey number | Maximum value of uncertainty (ft) | Mean value of uncertainty (ft) | Median value of uncertainty (ft) | Standard deviation of uncertainty (ft) | Percent of bathymetry points with uncertainty value less than | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 2.00 ft | 1.00 ft | 0.50 ft | 0.25 ft |
| "Optimized" Roll Angle | | | | | | | | | |
| 6/1 | 1 | 6.66 | 0.23 | 0.20 | 0.17 | 99.9 | 99.3 | 95.1 | 70.9 |
| 6/1 | 2 | 10.86 | 0.25 | 0.20 | 0.19 | 99.9 | 99.1 | 93.9 | 64.4 |
| 6/5 | 1 | 8.37 | 0.28 | 0.23 | 0.19 | 99.9 | 99.1 | 92.3 | 51.1 |
| 6/5 | 2 | 7.22 | 0.28 | 0.26 | 0.19 | 99.9 | 99.1 | 93.1 | 49.3 |
| Corrected roll angle, -2.45 degrees, with no outer beam cropping | | | | | | | | | |
| 6/1 | 1 | 7.32 | 0.27 | 0.23 | 0.19 | 99.9 | 99.2 | 91.0 | 59.4 |
| 6/1 | 2 | 8.86 | 0.29 | 0.23 | 0.22 | 99.9 | 99.0 | 87.4 | 52.6 |
| 6/5 | 1 | 8.23 | 0.30 | 0.26 | 0.19 | 99.9 | 99.1 | 90.2 | 48.6 |
| 6/5 | 2 | 7.22 | 0.30 | 0.26 | 0.20 | 99.9 | 99.1 | 90.1 | 47.4 |
| Cropped roll angle, -2.45 degrees, with 60 degrees outer beam cropping | | | | | | | | | |
| 6/1 | 1 | 7.74 | 0.22 | 0.20 | 0.16 | 100.0 | 99.4 | 95.9 | 73.6 |
| 6/1 | 2 | 8.86 | 0.23 | 0.20 | 0.17 | 99.9 | 99.3 | 95.7 | 70.3 |
| 6/5 | 1 | 9.71 | 0.25 | 0.23 | 0.16 | 100.0 | 99.3 | 95.3 | 61.1 |
| 6/5 | 2 | 11.58 | 0.27 | 0.23 | 0.17 | 99.9 | 99.3 | 95.3 | 52.8 |

a robust estimate of the spatial distribution of possible uncertainty within the survey area (Czuba and others, 2011); thus, the TPU of a point is a measure of the accuracy to be expected for such a point when all relevant error sources are taken into account (Czuba and others, 2011). While not a measure of reproducibility per se, TPU is a measure of accuracy and a useful indication of the quality of the bathymetric surface. Statistics of TPU for each of the test survey areas are shown in table 1–2. The TPU values are good for all three roll angle configurations, as generally more than 90 percent of the points had a TPU of 0.50 ft or less; however, obvious improvement was gained using the corrected roll angle and cropping the data to remove beams beyond 60 degrees from nadir (the cropped roll angle data), such that over 95 percent of the points had a TPU of 0.50 ft or less (table 1–2).

Having addressed the roll angle issue in the previous section, further analysis of the cropped roll angle data was used to determine the reproducibility of bathymetric data collected with the MBMS in this setting. Examining the data collected orthogonally on the same day (figs. 1–7*C* and 1–7*D*), the difference between the survey surfaces are relatively uniformly distributed across the test survey area, with the differences being somewhat larger for the June 5 surveys than the June 1 surveys. Examining data collected in the same direction on different days indicates the June 1 data were higher than the June 5 data on the northwest side, and generally lower than the June 5 data on the southeast with a local variation along line 6 (fig. 1–7*A*). Data collected in opposite directions on different days indicates the June 1 data are generally higher than the June 5 data along the northeast side, and generally lower than the June 5 data on the southwest side (fig. 1–7*B*). The orthogonal lines collected on different days (figs. 1–7*E* and 1–7*F*) imply similar trends to the surveys in same and opposing directions on different day (figs. 1–7*A* and 1–7*B*).

The vast majority of the differences are less than ±0.4 ft for all of the comparisons of the cropped roll angle data, when one examines the frequency distribution of the differences (fig. 1–8*A*). The mean value of the frequency distributions tends to be negative, as indicated in the summary statistics (table 1–1), forcing the cumulative percent to be above 50 percent when crossing the zero abscissa (fig. 1–8*B*); nevertheless, the slope of the cumulative percent curves are similar for all the comparisons of the cropped roll angle data, particularly when compared to the optimized roll angle data (fig. 1–8*D*). The frequency distributions for the optimized data are substantially wider than for the cropped data. The slope of the cumulative percent curves also is similar for the corrected roll angle data comparisons (fig. 1–8*F*), and the mean is less negative for those comparisons (fig. 1–8*E*; table 1–1). Ultimately, the differences between the various test survey surfaces all fall within the TPU of a majority of the points (table 1–2). Given the number of factors that affect the accuracy of bathymetric data collected with the MBMS combined with the added complication of the theorized sound-velocity profile variations in this lake setting, the fact that the differences between the various surfaces falls within the TPU of the data implies that the reproducibility of the data is good.

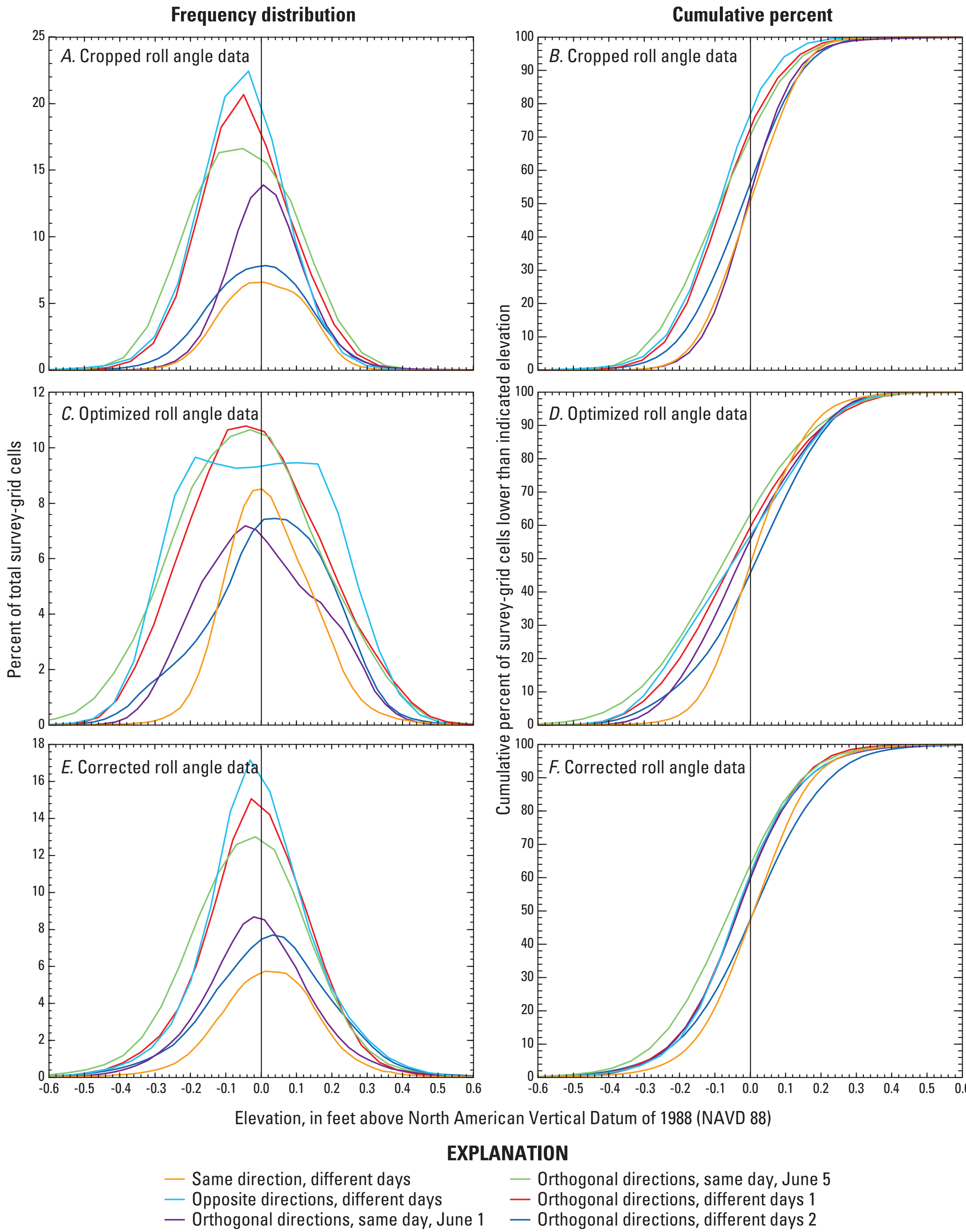


**Figure 1–8.** Comparison of frequency distribution and cumulative percent of differences in bed elevation for bathymetric survey-grid cells from various test surveys on Longview Lake near Kansas City, Missouri. *A*, cropped roll angle data frequency distribution. *B*, cropped roll angle data cumulative percent. *C*, optimized roll angle data frequency distribution. *D*, optimized roll angle data cumulative percent. *E*, corrected roll angle data frequency distribution. *F*, corrected roll angle data cumulative percent.

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# Appendix 2—Shaded Triangulated Irregular Network Images of Channel and Side of Pier for Each Surveyed Pier

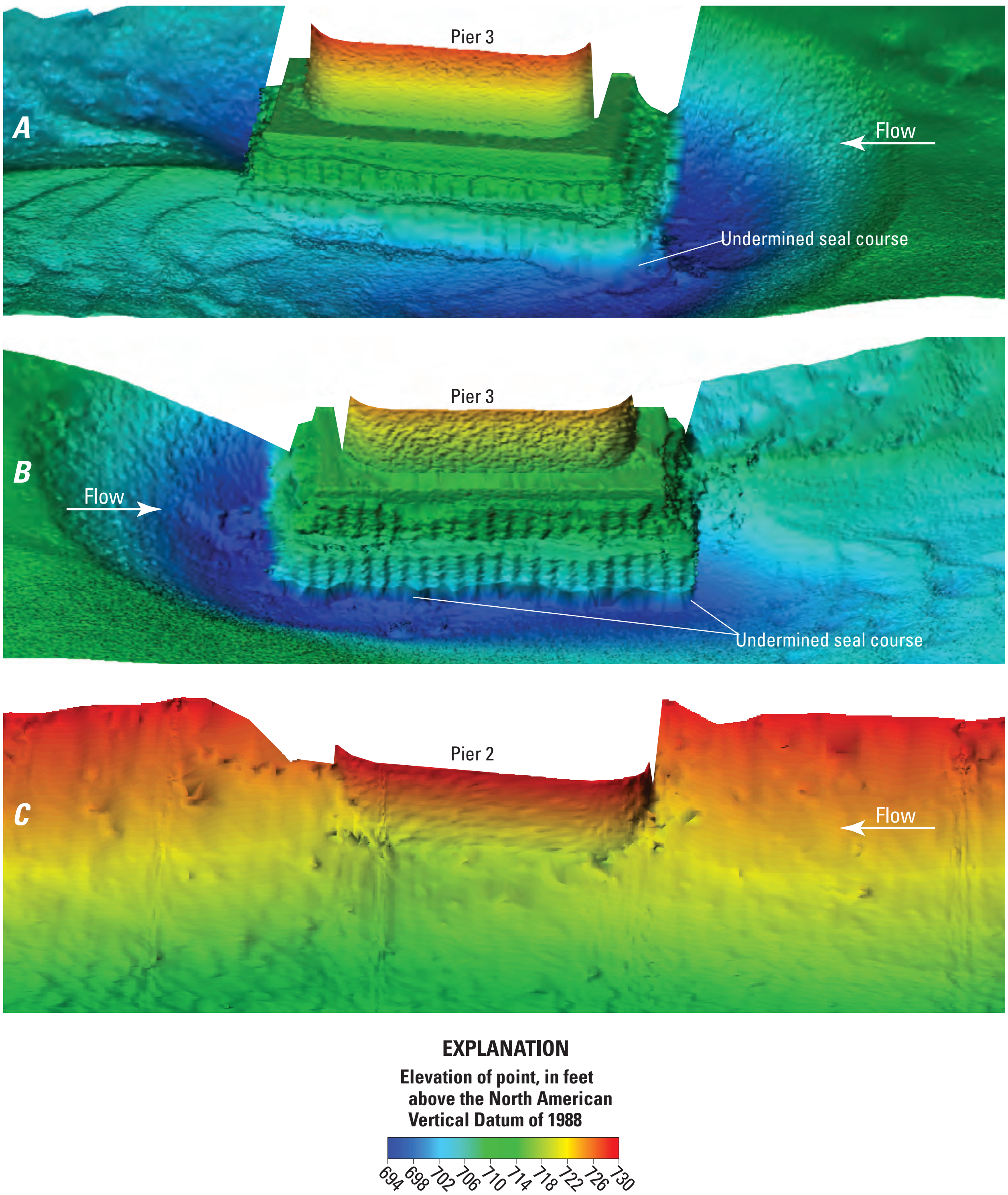


**Figure 2–1.** Shaded triangulated irregular network visualization of the channel bed of structure A1800 on Interstate 635 crossing the Missouri River near Kansas City, Missouri. *A*, left (northeast) side of main channel pier 3. *B*, right (southwest) side of main channel pier 3. *C*, left (northeast) side of main channel pier 2.

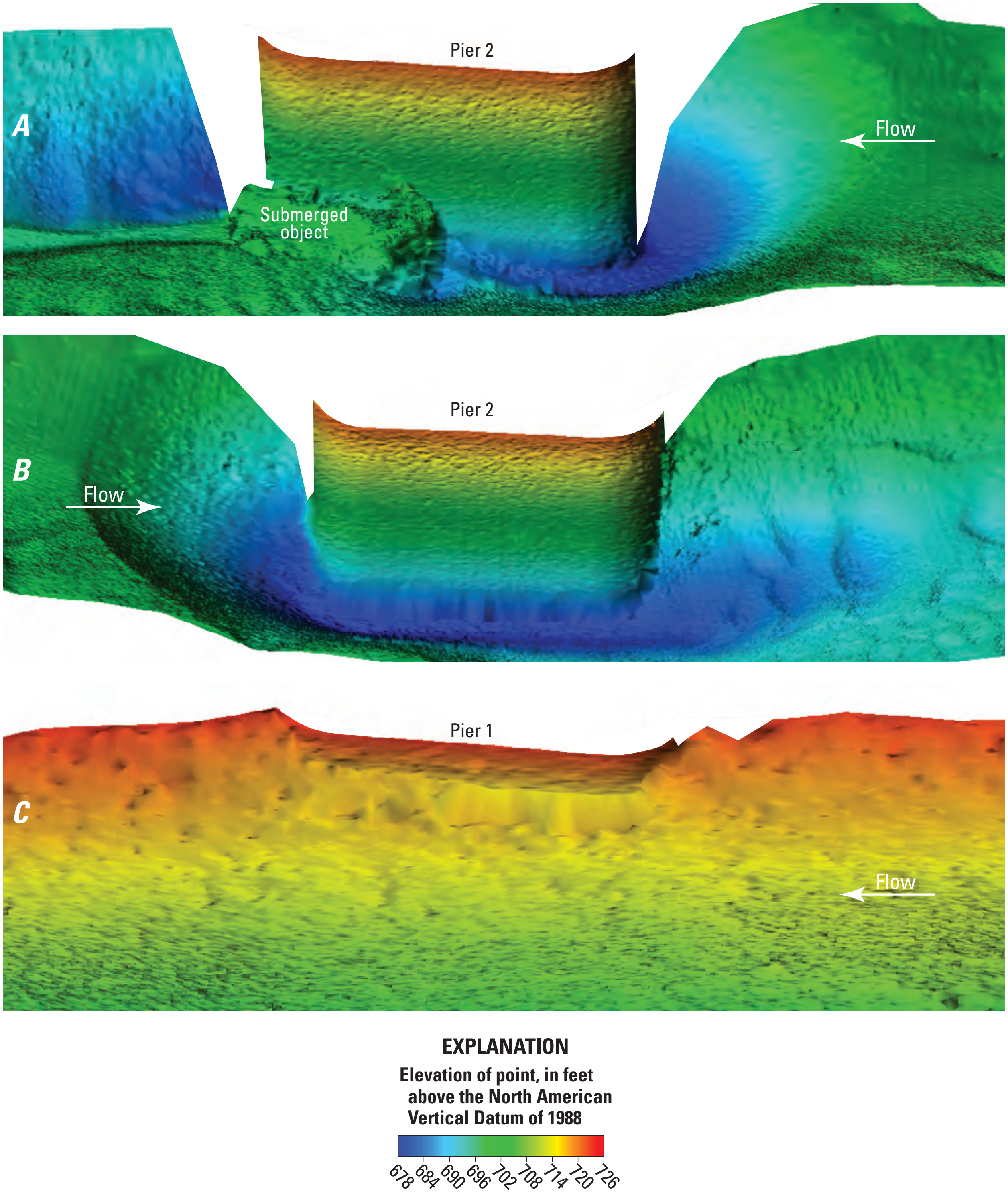


**Figure 2–2.** Shaded triangulated irregular network visualization of the channel bed of structure A4649 on U.S. Highway 169 crossing the Missouri River in Kansas City, Missouri. *A*, left (northwest) side of main channel pier 2. *B*, right (southeast) side of main channel pier 2. *C*, left (northwest) side of main channel pier 1.

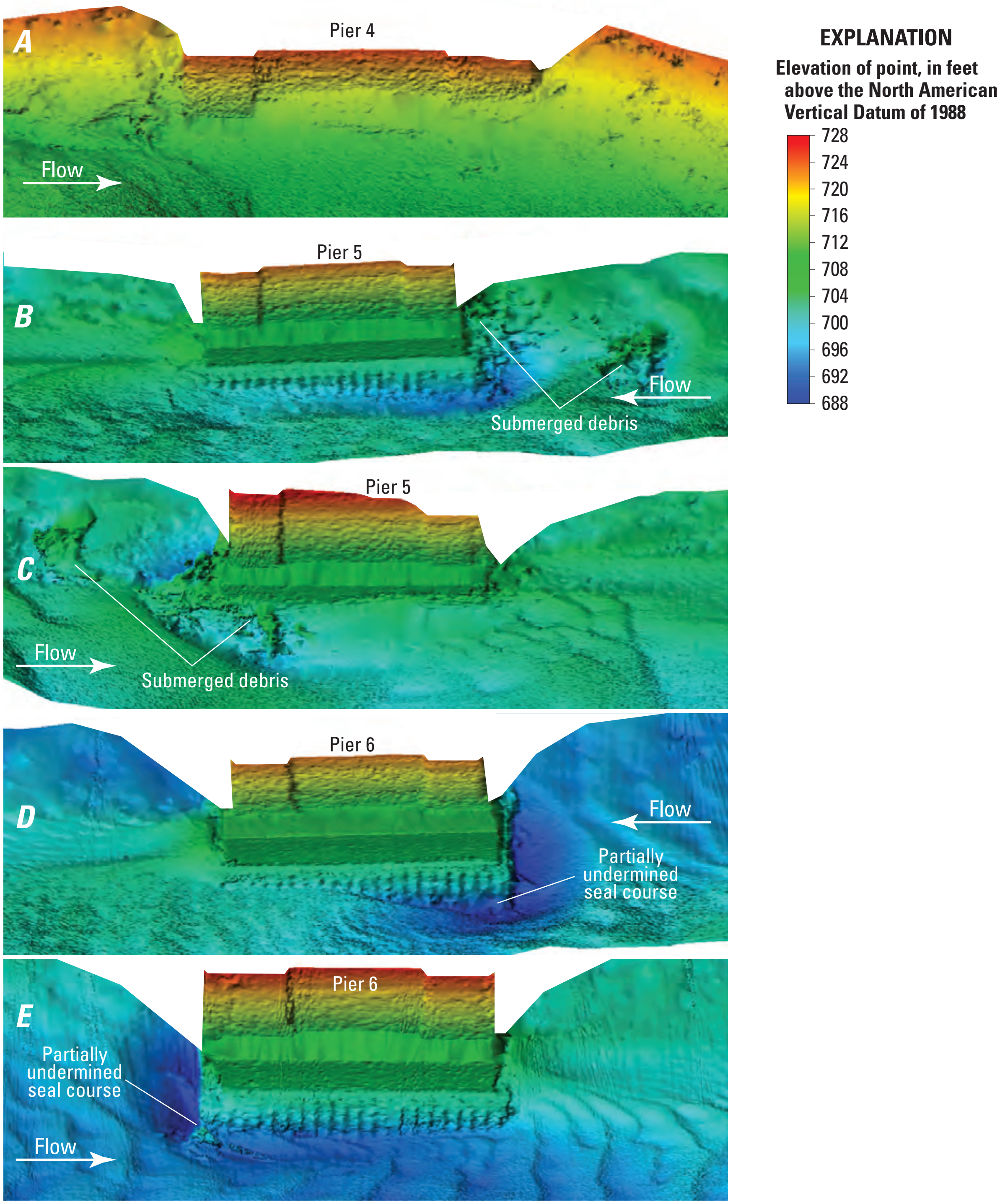


**Figure 2–3.** Shaded triangulated irregular network visualization of the channel bed of structure A4060 on State Highway 9 crossing the Missouri River in Kansas City, Missouri. *A*, right (southeast) side of main channel pier 4. B, left (northwest) side of main channel pier 5. *C*, right (southeast) side of main channel pier 5. *D*, left (northwest) side of main channel pier 6. *E*, right (southeast) side of main channel pier 6.

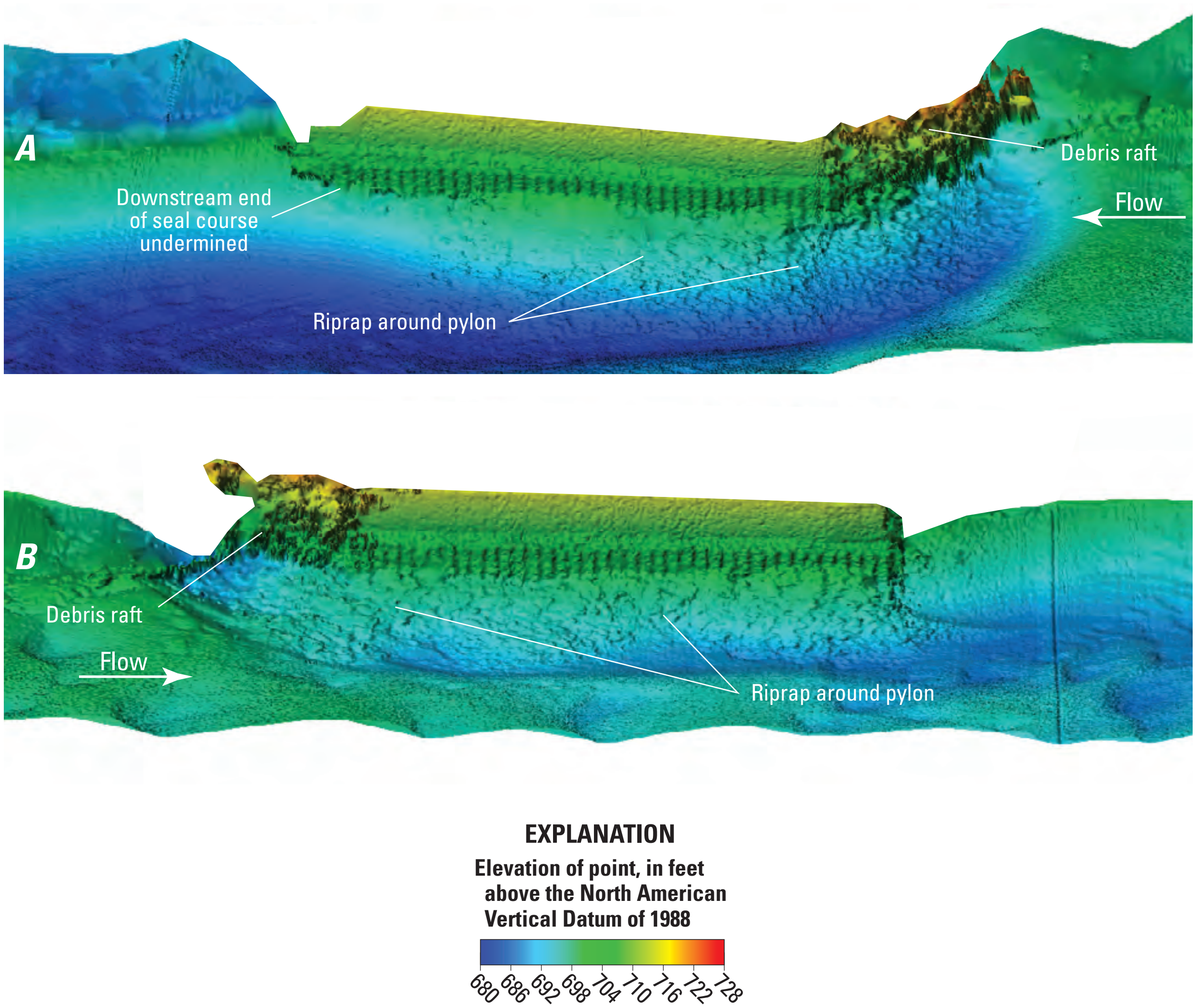


**Figure 2–4.** Shaded triangulated irregular network visualization of the channel bed of main channel pylon of structure A7650 on Interstate 35 crossing the Missouri River in Kansas City, Missouri. *A*, left (northwest) side. *B*, right (southeast) side.

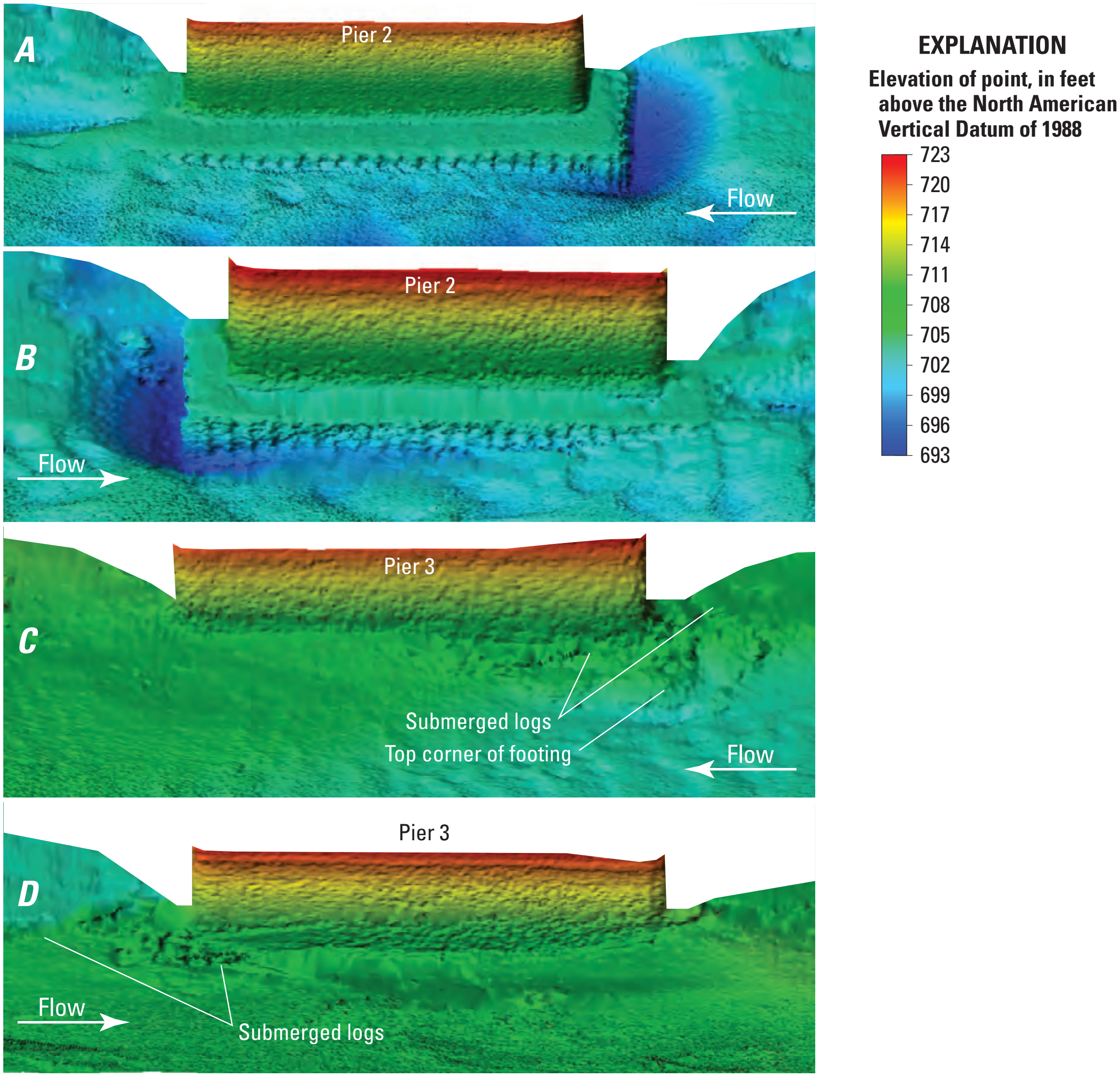


**Figure 2–5.** Shaded triangulated irregular network visualization of the channel bed of structure A5817 on State Highway 269 crossing the Missouri River in Kansas City, Missouri. *A*, left (northwest) side of main channel pier 2. *B*, right (southeast) side of main channel pier 2. *C*, left (northwest) side of main channel pier 3. *D*, right (southeast) side of main channel pier 3.

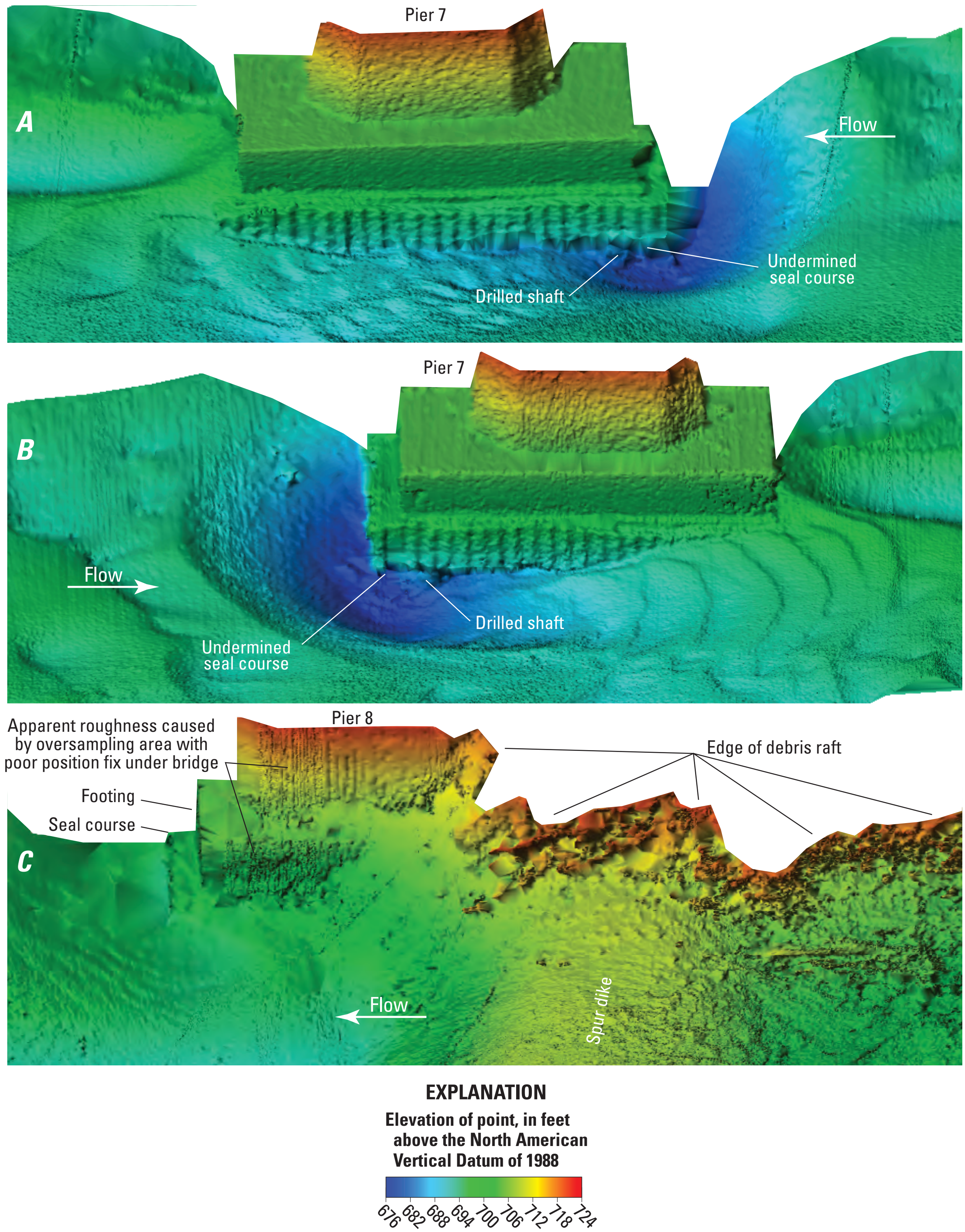


**Figure 2–6.** Shaded triangulated irregular network visualization of the channel bed of structure A0767 on Interstate 435 crossing the Missouri River in Kansas City, Missouri. *A*, left (north) side of main channel pier 7. *B*, right (south) side of main channel pier 7. *C*, left (north) side of main channel pier 8.

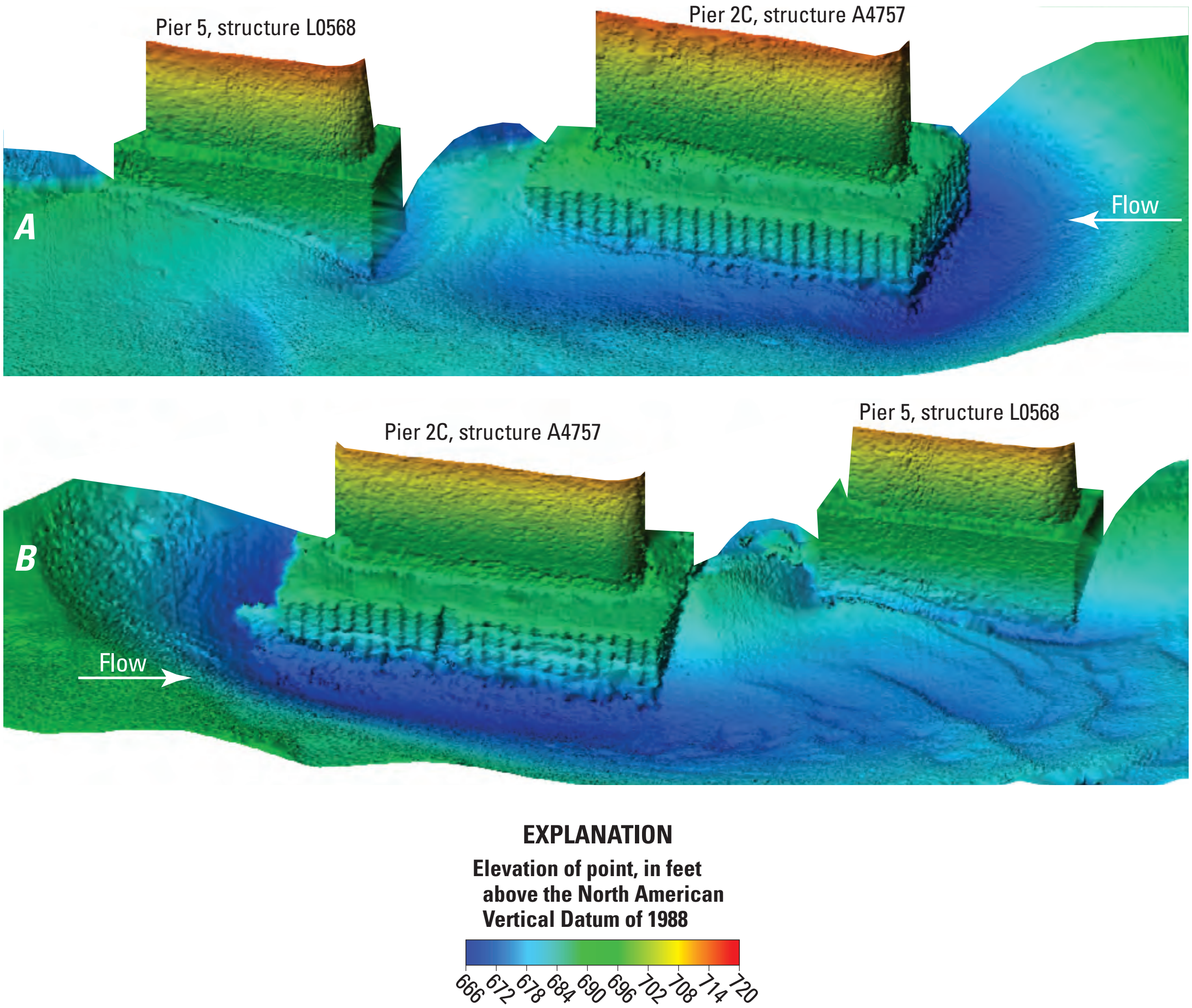


**Figure 2–7.** Shaded triangulated irregular network visualization of the channel bed of main channel pier 2C of structure A4757 and pier 5 of structure L0568 on State Highway 291 crossing the Missouri River near Kansas City, Missouri. *A*, left (north) side. *B*, right (south) side.

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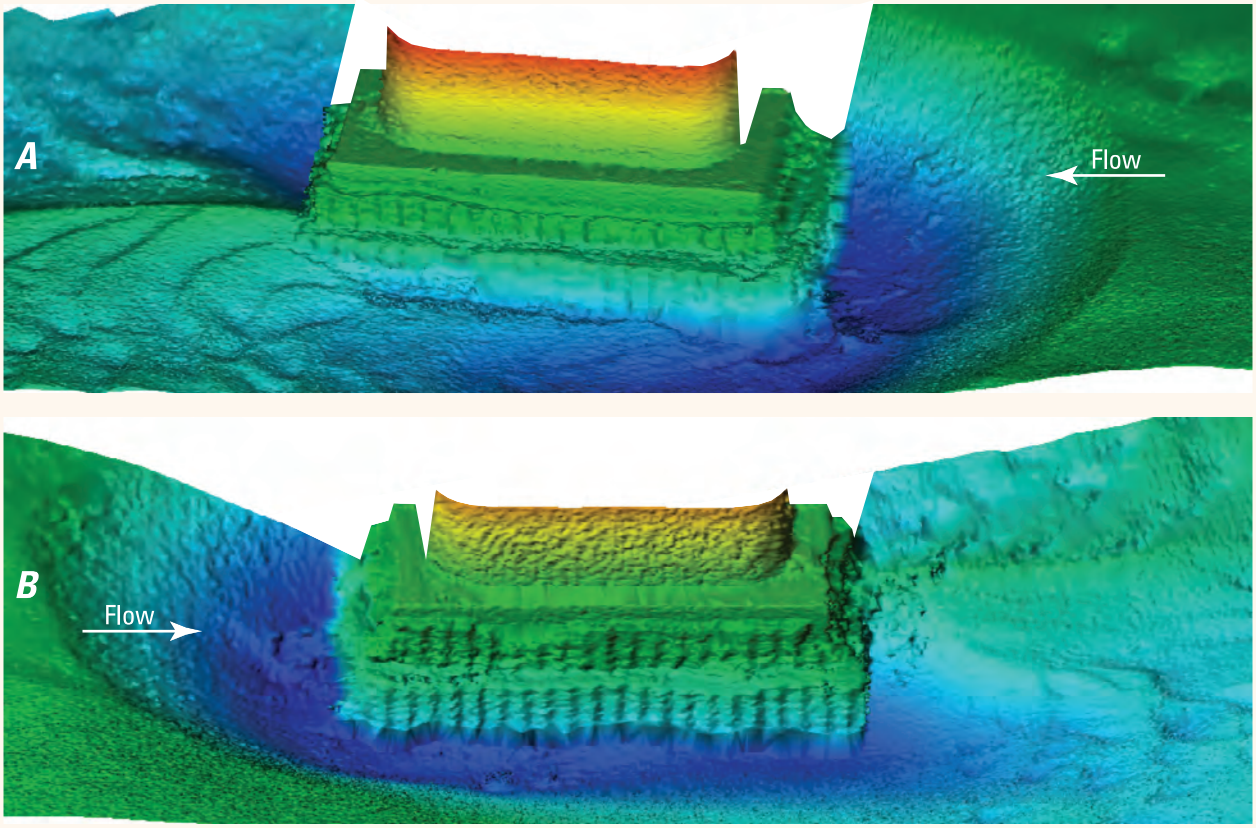



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