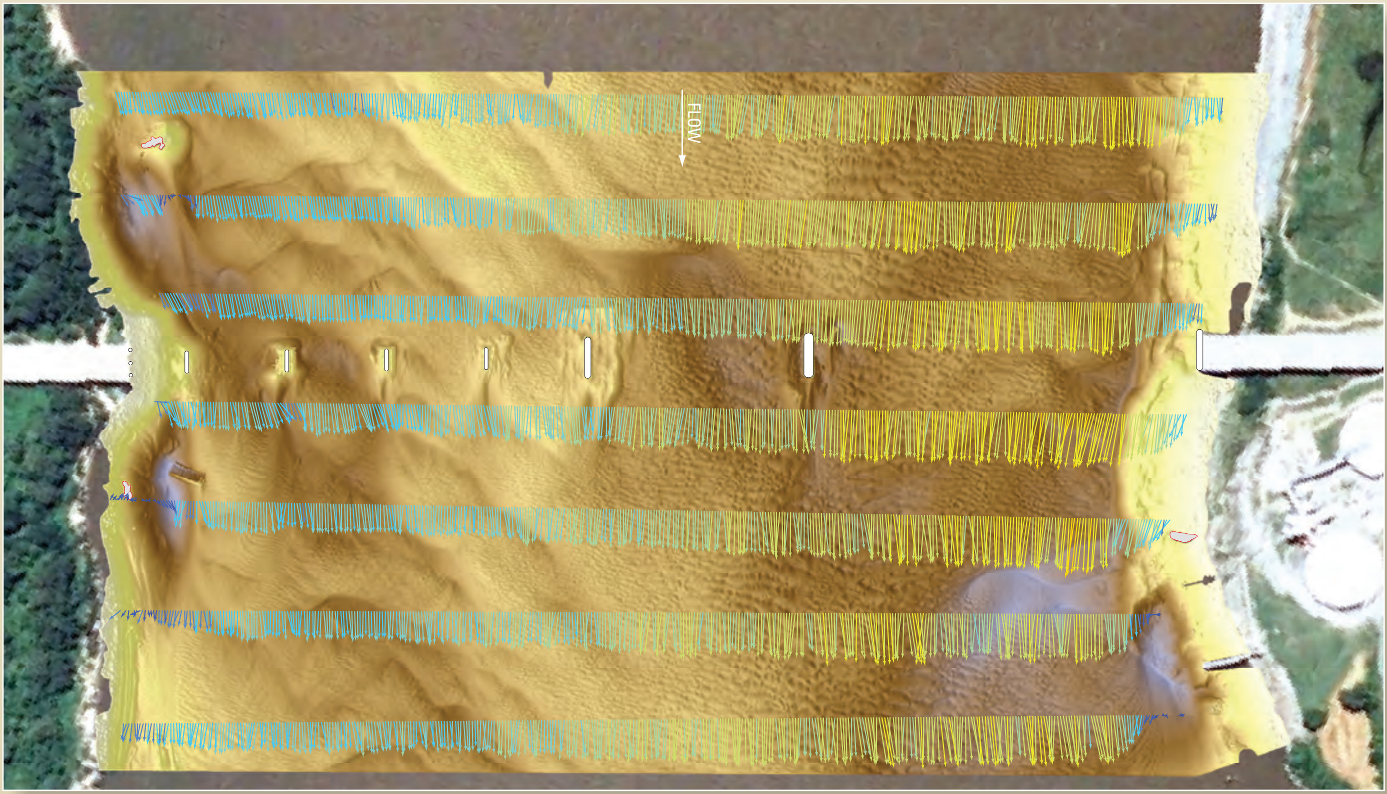
Prepared in cooperation with the Missouri Department of Transportation

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri and Mississippi Rivers on the Periphery of Missouri, June 2014



Scientific Investigations Report 2015–5048

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

Front cover. Bathymetry and vertically averaged velocities of the Mississippi River channel in the vicinity of structure A1700 on Interstate 155 near Caruthersville, Missouri, on June 11, 2014.

Back cover. Top: Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (southeast) side and *B*, right (northwest) side of main channel pier 20 of structure A1700 on Interstate 155 over the Mississippi River near Caruthersville, Missouri. Bottom: The U.S. Geological Survey boat returning from the bathymetric and velocimetric survey at structure A1700 on Interstate 155 over the Mississippi River near Caruthersville, Missouri, on June 11, 2014.

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By Richard J. Huizinga

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

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U.S. Geological Survey, Reston, Virginia: 2015

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	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.

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)
GIS	geographic information system
GNSS	Global Navigation Satellite System
IMU	inertial motion unit
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
NAVD 88	North American Vertical Datum of 1988
NMEA	National Marine Electronics Association
POS MV	Position Orientation Solution for Marine Vessels (the navigation system)
RM	river mile
RTK	real-time kinematic (a type of differential correction for navigation with GNSS)
SBET	standard best estimate of travel (a post-processed navigation solution)
TIN	triangulated irregular network
TNDOT	Tennessee Department of Transportation
TPU	total propagated uncertainty
USGS	U.S. Geological Survey
VMT	Velocity Mapping Toolbox (Parsons and others, 2013)
VRS	virtual real-time station network (a cellular network maintained by MoDOT that provides differential corrections for navigation with GNSS)
VTG	velocity track made good, and shorthand for the $GPVTG standard output format for GNSS data defined by the National Marine Electronics Association (NMEA)-0183 standard that includes information on the GNSS receiver heading and ground speed (National Marine Electronics Association, 2002).

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri and Mississippi Rivers on the Periphery of Missouri, June 2014

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, in the vicinity of 8 bridges at 7 highway crossings of the Missouri and Mississippi Rivers on the periphery of Missouri from June 3 to 11, 2014. A multibeam echosounder mapping system was used to obtain channel-bed elevations for river reaches ranging from 1,525 to 1,640 feet longitudinally, and extending laterally across the active channel from bank to bank during low- to moderate-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-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 in very shallow water (less than about 6 feet). Scour holes were observed at most piers for which bathymetry could be obtained, except at piers on channel banks, on exposed bedrock outcrops, or surrounded by riprap. Scour holes observed at the surveyed bridges were examined with respect to depth and shape, and the effects of riprap blankets or other rock near the piers. The presence of riprap blankets, depth of fluvial material on top of a riprap blanket, and alignment to flow had a substantial effect on the size of the scour hole observed for a given pier. Piers that were surrounded by riprap blankets had scour holes that were substantially smaller (to non-existent) compared to piers at which no rock or riprap was present. Although exposure of parts of foundational support elements was observed at several piers, at most sites the exposure likely can be considered minimal compared to the overall substructure that remains buried in channel-bed material; however, there were several notable exceptions where the bed material thickness between the bottom of the scour hole and bedrock was less than 6 feet. Such substantial exposure of usually buried substructural elements may warrant special observation in future flood events, even when designed to be exposed.

Previous bathymetric surveys had been done at both of the sites on the Missouri River and one of the sites on the Mississippi River examined in this study. Comparisons between bathymetric surfaces from the previous surveys during the 2011 flood and those of this study generally indicate that there was an increase in the elevation of the channel bed at these sites that likely was caused by a substantial decrease in discharge and water-surface elevation compared to the 2011 surveys. However, the scour holes observed at these sites were either the same size or larger in 2014 compared to the 2011 surveys, indicating that the flow condition is not the sole variable in the determination of the size of scour holes, and that local velocity and depth also are critical variables, as indicated by predictive pier scour equations.

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 from 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, 2014b; 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 in 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 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 Rivers between Kansas City and St. Louis, Mo., were assessed as part of more routine, non-flood surveys at bridge sites in and into Missouri (Huizinga, 2014b). This study encompasses the more routine surveys at the highway bridges across the Missouri and Mississippi Rivers on the periphery of Missouri (fig. 1) that entails 8 bridges at 7 crossings (shaded rows in tables 1 and 2).

Purpose and Scope

The purpose of this report is to document the results of bathymetric and velocimetric surveys of the Missouri and Mississippi River channels in the vicinity of 8 highway bridges at 7 crossings on the periphery of Missouri using a MBMS and an acoustic Doppler current profiler (ADCP; tables 1 and 2). 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-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 two Missouri River sites (Huizinga, 2012) also are provided, as are details of and comparison to two previous surveys (on December 10, 2008, and May 5, 2011) at structure A1700 on Interstate 155 near Caruthersville, Mo. (site 38, fig. 1; Richard J. Huizinga, U.S. Geological Survey, unpub. data, 2015).

Description of Study Area

The generalized study area for this report covers approximately 90 miles (mi) of the lower Missouri River in the northwestern part of Missouri upstream from Kansas City, Mo., and approximately 300 mi of the upper Mississippi River (upstream from the confluence with the Ohio River) and 115 mi of the lower Mississippi River (downstream from the confluence with the Ohio River) along the eastern border of Missouri, excluding St. Louis, Mo. (fig. 1). On the Missouri River, the highway crossings at Brownville, Nebraska, and St. Joseph, Mo., were examined as part of this study (fig. 1, table 1). On the Mississippi River, the highway crossings at Hannibal, Mo.; Louisiana, Mo.; Chester, Ill.; Cape Girardeau, Mo.; and near Caruthersville, Mo., were examined (fig.1, table 2). On the Missouri River, the site numbering sequence used in Huizinga (2012) will be used in this report for consistency and comparability. On the Mississippi River, site numbers are based on sequencing of the bridges maintained by MoDOT alone, inclusive of those in the greater St. Louis area.

Description of Flow Conditions

The Missouri River was transitioning from low- to moderate-flow conditions when the sites were surveyed on June 3 and 4, 2014 (fig. 2*A*). Except for the two sites upstream from St. Louis, Mo., the Mississippi River was on a slow and steady rise to moderate-flow conditions when those sites were surveyed (fig. 2*B*).

The upstream-most site on the Missouri River, structure L0098 on U.S. Highway 136 at Brownville, Neb. (site 1, fig. 1), was surveyed first on June 3 during low-flow conditions. The discharge on the Missouri River was approximately 39,800 cubic feet per second (ft^3/s), as measured at the site (table 3), slightly less than the discharge of 40,100 ft^3/s obtained from the rating curve for the USGS streamflow-gaging station (hereinafter referred to as "streamgage") on the Missouri River upstream from the study area at Nebraska City, Neb. (station 06807000; U.S. Geological Survey, 2014; fig. 1). This discharge has a daily exceedance of about 37 percent (U.S. Geological Survey, 2003), and is substantially less than the 50-percent annual exceedance probability (2-year recurrence interval) flood discharges of 88,000 ft^3/s at Nebraska City (table F-49 in U.S. Army Corps of Engineers, 2004a).

The river was rising at the time of the survey at structure A3664 on U.S. Highway 36 at St. Joseph, Mo. (site 2; figs. 1, 2*A*), and preliminary data from the streamgage upstream from the study area at Nebraska City, Neb. (fig. 1), indicated the flood pulse had peaked there on June 4 (see initial pseudo-peak in data for station 06807000 at Nebraska City, Neb., at the timing of the survey at site 2; fig. 2*A*). The discharge on

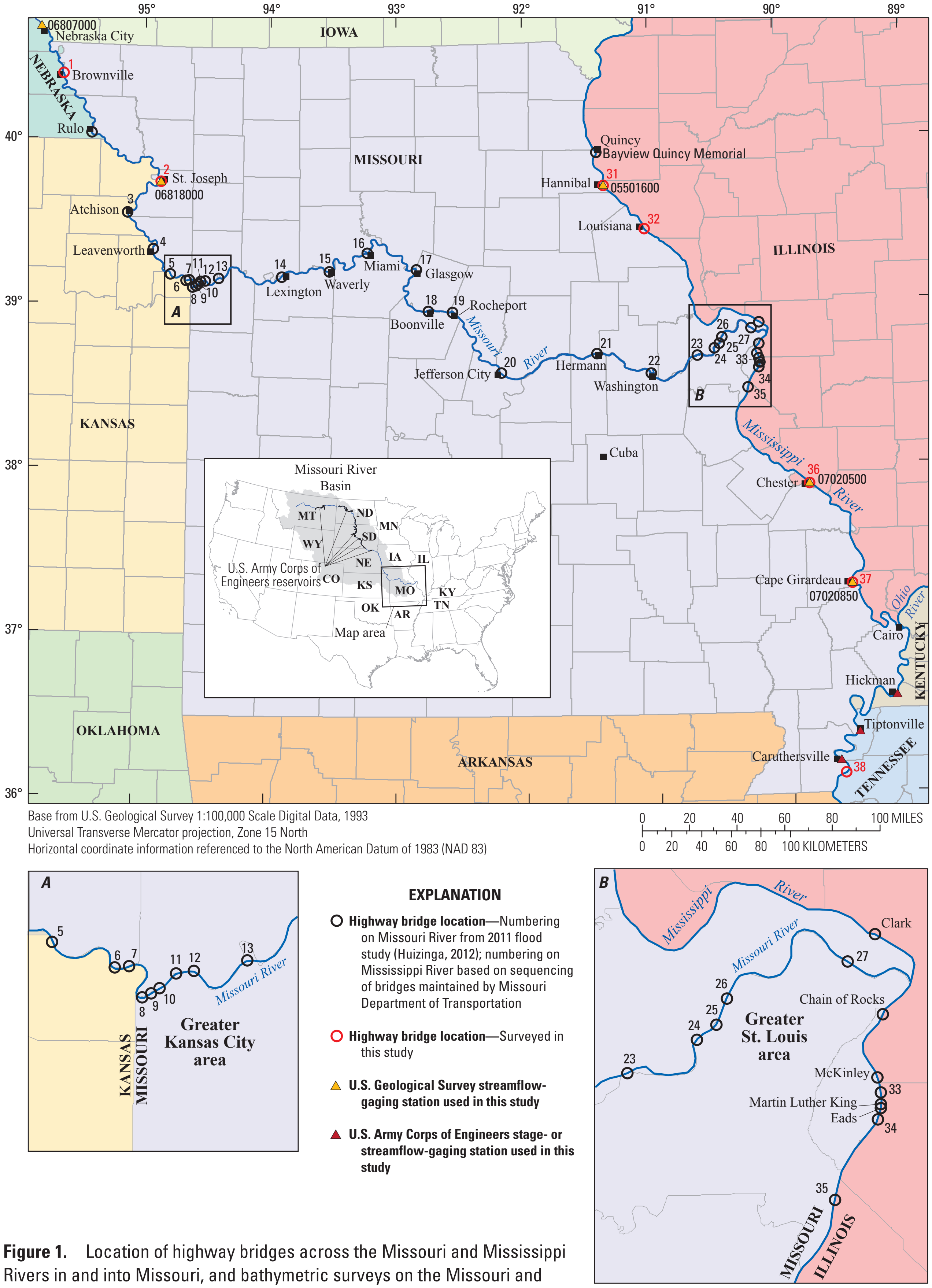


Figure 1. Location of highway bridges across the Missouri and Mississippi Rivers in and into Missouri, and bathymetric surveys on the Missouri and Mississippi River channels from June 2 to 11, 2014.

Table 1. Highway bridges crossing the Missouri River, in and into Missouri, in downstream order.

[MoDOT, Missouri Department of Transportation; US, U.S. highway; --, not known/applicable; NDOR, Nebraska Department of Roads; W, westbound; E, eastbound; KDOT, Kansas Department of Transportation; MO, Missouri State highway; K, Kansas State highway; IS, Interstate highway; S, southbound; N, northbound; shaded rows are those bridges surveyed for this study]

Site number (fig. 1)	Primary agency	Structure number	Local name	County	Route	River mile[a]	Surveyed as part of this study	Remarks	Figures
Upstream from Kansas City									
1	MoDOT	L0098	Brownville	Atchison, Mo.	US 136	535.3	Yes	--	1, 6, 7, 8, 9, 35, 1–1
--	NDOR	--	Rulo	Richardson, Nebr.	US 159	498.1	No	--	1
2	MoDOT	A3664 W	St. Joseph	Buchanan, Mo.	US 36 W	447.9	Yes	Dual bridge crossing	1, 10, 11, 12, 13, 35, 1–2
		A3664 E	St. Joseph	Doniphan, Kans.	US 36 E		Yes	Dual bridge crossing	1, 10, 11, 12, 13, 35, 1–2
3	KDOT	59-3-16.38 (013)	Atchison	Atchison, Kans.	US 59	422.5	No	--	1
4	KDOT	92-52-18.48 (026)	Leavenworth	Leavenworth, Kans.	MO 92/K 92	397.5	No	--	1
Greater Kansas City area									
5	KDOT	435-105-11.97 (235)	Parkville	Platte, Mo.	IS 435 S	383.4	No	Dual bridge crossing with 435-105-11.98 (240)	1
		435-105-11.98 (240)	Parkville	Wyandotte, Kans.	IS 435 N		No	Dual bridge crossing with 435-105-11.97 (235)	1
6	MoDOT	A1800	Riverside	Platte, Mo.	IS 635	374.1	No	--	1
7	MoDOT	K0456	Fairfax	Platte, Mo.	US 69 S	372.6	No	Dual bridge crossing with A0450	1
		A0450	Platte Purchase	Wyandotte, Kans.	US 69 N		No	Dual bridge crossing with K0456	1
8	MoDOT	A4649	Broadway Avenue	Clay, Mo.	US 169	366.2	No	--	1
9	MoDOT	A4060	Heart of America	Clay, Mo.	MO 9	365.5	No	--	1
10	MoDOT	A7650	Christopher Bond	Clay, Mo.	IS 29	364.7	No	--	1
11	MoDOT	A5817	Chouteau	Clay, Mo.	MO 269	362.3	No	--	1
12	MoDOT	A0767	Randolph	Clay, Mo.	IS 435	360.3	No	--	1
13	MoDOT	A4757	Courtney	Jackson, Mo.	MO 291 S	352.7	No	Dual bridge crossing with L0568	1
		L0568	Courtney	Jackson, Mo.	MO 291 N		No	Dual bridge crossing with A4757	1
Between Kansas City and St. Louis									
14	MoDOT	A5664	Lexington	Ray, Mo.	MO 13	314.9	No	--	1
15	MoDOT	A5910	Waverly	Lafayette, Mo.	US 24	293.2	No	--	1
16	MoDOT	K0999	Miami	Carroll, Mo.	MO 41	262.6	No	--	1
17	MoDOT	G0069	Glasgow	Saline, Mo.	MO 240	226.3	No	--	1
18	MoDOT	A4574	Boonville	Cooper, Mo.	US 40	196.6	No	--	1
19	MoDOT	L0962	Rocheport	Boone, Mo.	IS 70	185.1	No	--	1

Table 1. Highway bridges crossing the Missouri River, in and into Missouri, in downstream order.—Continued

[MoDOT, Missouri Department of Transportation; US, U.S. highway; --, not known/applicable; NDOR, Nebraska Department of Roads; W, westbound; E, eastbound; KDOT, Kansas Department of Transportation; MO, Missouri State highway; K, Kansas State highway; IS, Interstate highway; S, southbound; N, northbound; shaded rows are those bridges surveyed for this study]

Site number (fig. 1)	Primary agency	Structure number	Local name	County	Route	River mile[a]	Surveyed as part of this study	Remarks	Figures
				Between Kansas City and St. Louis—Continued					
20	MoDOT	L0550	Jefferson City	Callaway, Mo.	US 54 W	143.9	No	Dual bridge crossing with A4497	1
		A4497	Jefferson City	Cole, Mo.	US 54 E		No	Dual bridge crossing with L0550	1
21	MoDOT	A6288	Hermann	Montgomery, Mo.	MO 19	97.9	No	--	1
22	MoDOT	K0969	Washington	Franklin, Mo.	MO 47	67.6	No	--	1
				Greater St. Louis area					
23	MoDOT	A4017	Daniel Boone	St. Charles, Mo.	IS 64 E	43.9	No	Dual bridge crossing with J1000	1
		J1000	Daniel Boone	St. Louis, Mo.	IS 64 W		No	Dual bridge crossing with A4017	1
24	MoDOT	A5585 E	Page Avenue	St. Charles, Mo.	MO 364 E	32.7	No	Dual bridge crossing	1
		A5585 W	Page Avenue	St. Louis, Mo.	MO 364 W		No	Dual bridge crossing	1
25	MoDOT	A3292	Blanchette	St. Charles, Mo.	IS 70 E	29.6	No	Dual bridge crossing with L0561	1
		L0561	Blanchette	St. Louis, Mo.	IS 70 W		No	Dual bridge crossing with A3292	1
26	MoDOT	A4557 E	Discovery	St. Charles, Mo.	MO 370 E	27.0	No	Dual bridge crossing	1
		A4557 W	Discovery	St. Louis, Mo.	MO 370 W		No	Dual bridge crossing	1
27	MoDOT	A3047	Lewis & Clark	St. Charles, Mo.	US 67	8.1	No	--	1

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

Table 2. Highway bridges crossing the Mississippi River into Missouri, in downstream order.

[--, not known/applicable; IDOT, Illinois Department of Transportation; US, U.S. highway; W, westbound; E, eastbound; MoDOT, Missouri Department of Transportation; IS, Interstate highway; S, southbound; N, northbound; MO, Missouri State highway; blue shaded rows are those bridges surveyed for this study]

Site number (fig. 1)	Primary agency	Structure number	Local name	County	Route	River mile[a]	Surveyed as part of this study	Remarks	Figures
				Upstream from St. Louis					
--	IDOT	--	Bayview	Adams, Ill.	US 24 W	327.1	No	--	1
--	IDOT	--	Quincy Memorial	Marion, Mo.	US 24 E	327.0	No	--	1
31	MoDOT	A5054	Hannibal	Marion, Mo.	IS 72	309.5	Yes	--	1, 14, 15, 16, 35, 1–3, 1–4
32	MoDOT	K0932	Champ Clark	Pike, Mo.	US 54	283.2	Yes	--	1, 17, 18, 19, 35, 1–5, 1–6
				Greater St. Louis area					
--	IDOT	A4278	Clark	St. Charles, Mo.	US 67	202.6	No	--	1
--	IDOT	--	Chain of Rocks	Madison, Ill.	IS 270	190.8	No	--	1
--	IDOT	--	McKinley	St. Louis City, Mo.	--	182.6	No	--	1
33	MoDOT	A6500	Stan Musial Veterans Memorial	St. Louis City, Mo.	IS 70	181.2	No	--	1
--	IDOT	--	Martin Luther King	St. Louis City, Mo.	--	180.2	No	--	1
--	St. Louis	--	Eads	St. Louis City, Mo.	--	180.0	No	--	1
34	MoDOT	A1500	Poplar Street	St. Louis City, Mo.	IS 55	179.2	No	--	1
35	MoDOT	A4936	Jefferson Barracks	St. Louis, Mo.	IS 255 S	168.8	No	Dual bridge crossing with A1850	1
		A1850	Jefferson Barracks		IS 255 N		No	Dual bridge crossing with A4936	1
				Downstream from St. Louis					
36	MoDOT	L0135	Chester	Perry, Ill.	MO 51	109.9	Yes	--	1, 20, 21, 22, 36, 1–7
37	MoDOT	A5076	Bill Emerson Memorial	Cape Girardeau, Mo.	MO 34	51.5	Yes	--	1, 23, 24, 25, 36, 1–8
--	IDOT	--	Cairo I-57	Alexander, Ill.	IS 57	7.5	No	--	1
--	IDOT	--	Cairo Mississippi	Alexander, Ill.	US 60	1.4	No	--	1
38	MoDOT	A1700	Caruthersville	Pemiscot, Mo.	IS 155	838.9	Yes	--	1, 26, 27, 28, 29, 30, 31, 32, 33, 34, 36, 1–9, 1–10

[a]Except for site 38, river mile is measured upstream on the Upper Mississippi River, which starts at the confluence with the Ohio River at Cairo, Ill. (fig. 1), at river mile 953 of the Lower Mississippi River. For site 38, river mile is measured on the Lower Mississippi River, which is the distance upstream from the mouth of the Mississippi River at the Gulf of Mexico.

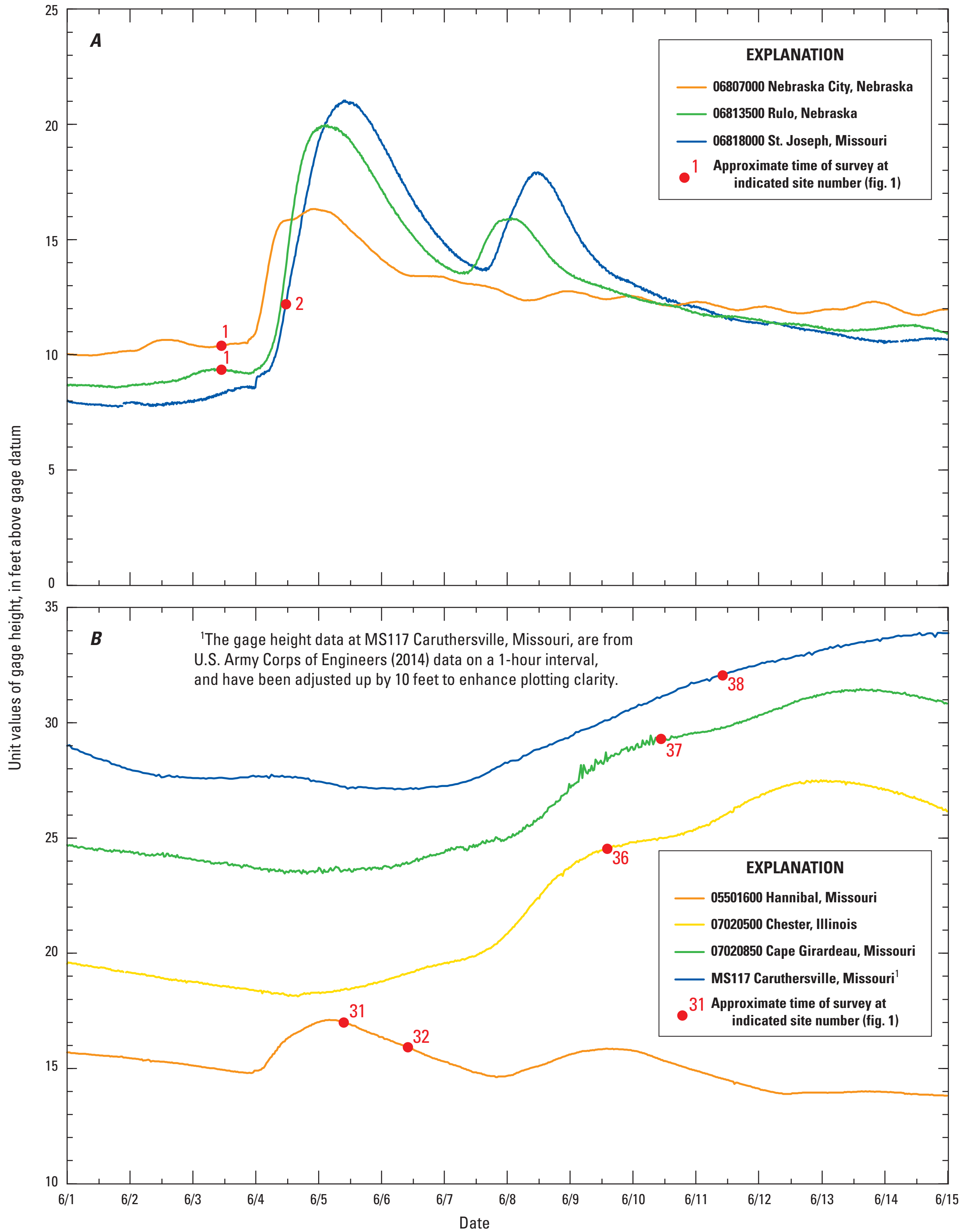


Figure 2. Unit values of gage height at selected streamflow-gaging stations in the study area on *A*, the Missouri River upstream from Kansas City, Missouri, at a 15-minute interval; and *B*, the Mississippi River along the eastern border of Missouri at a 30-minute or 1-hour interval, from June 1 to 14, 2014 (U.S Geological Survey, 2014; U.S. Army Corps of Engineers, 2014).

Table 3. Bridge and survey information, and selected channel-bed elevations from surveys on the Missouri and Mississippi Rivers on the periphery of Missouri, June 3–11, 2014.

[MoDOT, Missouri Department of Transportation; ADCP, acoustic Doppler current profiler; ft3/s, cubic feet per second; ft, feet; US, U.S. highway; E, eastbound; W, westbound; IS, Interstate 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] (ft³/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: 5th percentile (ft)	Approximate elevation of the indicated percentile of the bathymetric data: 95th percentile (ft)	Approximate minimum channel elevation[c] (ft)
1	L0098	06/03/14	US 136	535.3	39,800	884.4	868.6	864.1	877.0	844
2	A3664 E & W	06/04/14	US 36	447.9	[d]49,600	799.8	778.9	773.9	788.2	757
31	A5054	06/05/14	IS 72	309.5	198,000	464.6	437.8	427.0	448.9	418
32	K0932	06/06/14	US 54	283.2	194,000	451.2	420.0	407.1	438.6	391
36	L0135	06/09/14	MO 51	109.9	363,000	363.9	329.4	316.5	346.3	308
37	A5076	06/10/14	MO 34	51.5	377,000	331.7	293.0	278.6	316.3	272
38	A1700	06/11/14	IS 155	838.9	629,000	251.8	203.8	189.1	225.8	176

[a] The average discharge obtained while making the various velocity transects. The reported value is an average of the discharges computed using bottom-track and Global Navigation Satellite System (GNSS) velocity track made good (VTG) 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.

[d] This site had a large area of estimated flow on the right side of the channel due to floating debris that skewed the discharge results lower than the rated discharge at the streamgage at St. Joseph (station 06818000) of 66,100 ft3/s immediately upstream from the survey area. The rated discharge was used for all analyses at this site.

the Missouri River at St. Joseph was measured as approximately 49,600 ft³/s (site 2, table 3), which is substantially different than the gaged discharge of 66,100 ft³/s obtained from the rating curve for the streamgage at St. Joseph (station 06818000; U.S. Geological Survey, 2014; fig. 1; footnote "d" in table 3), likely because a substantial area of flow on the right side of the channel had to be estimated due to floating debris during the measurement, resulting in a poor measurement rating. The gaged discharge was used as the "true" discharge at this site for this study. The gaged discharge has a daily exceedance of approximately 14 percent (U.S. Geological Survey, 2003), but is substantially less than the 2-percent annual exceedance probability (2-year recurrence interval) flood discharges of 109,000 ft³/s at St. Joseph (plate E–20 in U.S. Army Corps of Engineers, 2004b). These low-flow conditions at the Missouri River sites provide a relatively extreme difference from the previous survey at each site during the 2011 Missouri River flood (Huizinga, 2012).

Structures A5054 on Interstate 72 at Hannibal, Mo., and K0932 on State Highway 24 at Louisiana, Mo., (sites 31 and 32, fig. 1), were surveyed on June 5 and 6, respectively, on the receding limb of a minor rise in the hydrograph observed at the streamgage at Hannibal, Mo. (station 05501600; fig. 1). Discharge on the Mississippi River was approximately 198,000 ft³/s as measured during the survey at structure A5054 at Hannibal, Mo., and 194,000 ft³/s as measured during the survey at K0932 at Louisiana, Mo. (table 3), both of which are slightly less than the 50-percent annual exceedance probability (2-year recurrence interval) flood discharge of 209,000 ft³/s at Hannibal (Table C-M-2 in U.S. Army Corps of Engineers, 2004c) and 210,000 ft³/s at Louisiana (Table D-28 in U.S. Army Corps of Engineers, 2004d), respectively.

Similarly, structure L0135 on State Highway 51 at Chester, Illinois (site 36, fig. 1), was surveyed on June 9, and discharge on the Mississippi River was approximately 367,000 ft³/s as obtained from the rating curve for the streamgage at Chester, Ill. (station 07020500; U.S. Geological Survey, 2014; fig. 1), and approximately 363,000 ft³/s as measured during the survey (table 3). This discharge range has a daily exceedance of between 13 and 14 percent (U.S. Geological Survey, 2003), and is slightly less than the 50-percent annual exceedance probability (2-year recurrence interval) flood discharge of 480,000 ft³/s at Chester (Table D-28 in U.S. Army Corps of Engineers, 2004d). Structure A5076 on State Highway 34 at Cape Girardeau, Mo. (site 37, fig. 1), was surveyed on June 10, and discharge on the Mississippi River was approximately 377,000 ft³/s as measured during the survey (table 3), which also is less than the 50-percent annual exceedance probability (2-year recurrence interval) flood discharge of 483,000 ft³/s at Cape Girardeau (station 07020850; Table D-28 in U.S. Army Corps of Engineers, 2004d). Although daily flow statistics and exceedance probability data are not readily available for structure A1700 on Interstate 155 near Caruthersville, Mo. (site 38, fig. 1), it is assumed that the measured discharge of 629,000 ft^3/s will follow the same trend as at upstream stations and be near or slightly less than the 50-percent annual exceedance probability at Caruthersville.

Flow conditions at or less than the 50-percent annual exceedance probability (2-year recurrence interval) flood is in the low- to moderate-flow regime. However, the site at St. Joseph, Mo., and all the sites downstream from St. Louis, Mo., were surveyed on the rising limb of the hydrograph, which generally is viewed as the initiation of live-bed scour as velocities and depths increase with time until the peak discharge (Richardson and Davis, 2001). Huizinga (2014b) noted substantial pier scour begins soon after the onset of hydrograph rise in an analysis of real-time scour monitor data at Jefferson City, Mo., although the scour often does not reach maximum depth until the peak discharge is reached or sometime later (see fig. 35 in Huizinga, 2014b). 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 remains useful for determining scour in a variety of flow conditions, particularly when combined with or compared to a scour scenario captured at high-flow conditions.

Description of Equipment

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, 2014a, 2014b; 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), a navigation and motion-sensing system, and a data-collection and data-processing computer. The MBES that was used for the 2014 surveys is the Teledyne RESON SeaBat® 7125-SV2 (fig. 3), operated at a frequency of 400 kilohertz (kHz). The SeaBat® 7125-SV2 is an updated version of the SeaBat® 7125 used in the earliest previous studies (Huizinga, 2010, 2011; Huizinga and others, 2010) with similar features and functions, but having a more streamlined transducer head, and stiffer, more compact head tilt bracket (fig. 3). The original SeaBat® 7125 system had been used in the 2008 and 2011 surveys at structure A1700 on Interstate 155 near Caruthersville, Mo. (site 38, fig. 1; Richard J. Huizinga, U.S. Geological Survey, unpub. data, 2015). The navigation and motion-sensing system that was used in all of the surveys is the Applanix Position Orientation Solution for Marine Vessels (POS MV™) WaveMaster system (hereinafter referred to as "the POS"). The navigation system locates the MBES in three-dimensional space, and the motion-sensing system measures the heave, pitch, roll, and

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

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 (VRS) network (established and maintained by MoDOT, available through registration at http://gpsweb.modot.mo.gov/) was used to provide the real-time kinematic (RTK) differential corrections to the POS for the navigation and tide solution during the 2014 surveys. For the 2008 and 2011 surveys at structure A1700 on Interstate 155 near Caruthersville, Mo. (Richard J. Huizinga, U.S. Geological Survey, unpub. data, 2015), a Global Navigation Satellite System (GNSS) base station was set up near the bridge similar to previous studies (Huizinga, 2010, 2011; Huizinga and others, 2010).

The bridge structure blocked a part of or the whole signal from the GNSS constellation of satellites when the survey vessel was near or under a bridge. The blocked signal resulted in a GNSS outage that had the potential to degrade the positional accuracy of the vessel until such time as an RTK-fixed navigation solution was re-acquired; however, as in nearly all the previous studies of bathymetry at bridge sites in Missouri (Huizinga, 2010, 2011, 2012, 2013, 2014b), the navigation information from the 2014 surveys was post-processed using the POS-Pac™ Mobile Mapping Suite (MMS™) software (Applanix Corporation, 2009), which provided tools to identify and compensate for sensor and environmental errors, and computed an optimally blended navigation solution from the GNSS and inertial motion unit (IMU) raw data. The blended navigation solution (called a "standard best estimate of travel" or "SBET" file), generated by post-processing the navigation data, was applied to the whole survey at a given bridge to minimize the effects of the GNSS outages while surveying under the bridges. An SBET file was not available for the 2008 and 2011 surveys at structure A1700 on Interstate 155 near Caruthersville, Mo. (Richard J. Huizinga, U.S. Geological Survey, unpub. data, 2015).

The data from the MBES, and navigation and motion-sensing components, were processed and integrated into a cohesive dataset for cleanup and visualization. A computer onboard the survey boat ran the HYPACK®/HYSWEEP® data acquisition software (HYPACK, Inc., 2011) 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-foot[a] (ft) data resolution. These comma-delimited data were compiled into a geographic information system (GIS) 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 for all of the surveys (except the 2008 and 2011 surveys at structure A1700 on Interstate 255 near Caruthersville, Mo.) similar to previous studies by Huizinga and others (2010), and refined in later studies by Huizinga (2012, 2013, 2014b). 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 assure the collection of quality data were the same as those used in previous studies using the MBES (Huizinga, 2010, 2011, 2012, 2013, 2014b; Huizinga and others, 2010), and the reader is referred to those reports for the details of the methods used. 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 several of the previous studies on the Missouri River (Huizinga, 2010, 2012). The surveyed areas ranged from 1,525 to 1,640 ft long in the direction of flow, positioned so that the surveyed highway bridges were approximately one-third to one-half of the total length from the upstream boundary. For the sites on the Missouri River, the surveyed areas used approximately 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. To minimize data acquisition times in the shallows, data gaps were left between the swaths. The presence of debris rafts made surveying difficult in some areas. Areas near the bridge piers

[a]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. A distance of 1.64 feet corresponds to 0.5 meter.

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 completion of 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 boat velocity was determined using the velocity track made good (VTG) National Marine Electronics Association (NMEA)-0183 sentence (National Marine Electronics Association, 2002) from the 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).

When collecting the velocity data, the bottom-track reference method for determining boat speed was anticipated to be unusable because of moving channel-bed material, and the VTG reference method was used instead. Upon later examination, however, a latency issue was observed in the GNSS data received during the measurements. The latency was determined to be between 8 and 9 seconds, and varied from one transect to the next for all of the velocity transects for all of the sites examined in this study. To remove the effects of this latency, one of the developers of VMT wrote two custom subroutines to determine the latency and correct for it (P. Ryan Jackson, U.S. Geological Survey, written commun., 2015; appendix 1).

Discharge for a site was computed as the average of the discharges for each of the 14 velocity transects (2 transects per section line). Data computed using the bottom track as a reference was not useable because of a moving channel bed, which causes the measured velocities (and subsequent discharges) to be biased low (Mueller and others, 2013). However, data computed using the VTG velocity data likely also were biased because of inaccurate position and speed of the boat during the measurement induced by the GNSS latency issue discussed above. It is presumed that the discharge measurements would be biased high, because the channel would seem narrower and the beginning edge velocity would seem higher than they actually are. Therefore, the final discharge reported for each site is the average of the bottom-track discharge (biased low) and the VTG discharge (presumed biased high). The largest difference between the bottom-track and VTG discharges was computed at the Chester, Ill., site (station 07020500; fig. 1), and was approximately 5.8 percent of the reported value of 363,000 ft^3/s; however, the reported value is only 1.1 percent lower than the rated discharge of 367,000 ft^3/s at the Chester streamgage.

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, with the exception of 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 POS, 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.

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, 2004e), 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., 2011). On May 29, 2014, a reference surface was created for a part of Indian Lake near Cuba, Mo. (fig. 1), and check lines were run across the reference surface. Included with the measurement was a sound velocity cast to document and quantify any stratification in the water column near the reference surface. The results of this beam angle check (table 4) were within the recommended performance standards used by the U.S. Army Corps of Engineers for hydrographic surveys for a majority of the angles (U.S. Army Corps of Engineers, 2004e), essentially permitting the use of the full sonar swath.

Ideally, the average depth of the reference surface used in the beam angle check would be greater than or equal to the depth in the area being surveyed. Unfortunately, the depth of the Mississippi River at the sites not previously surveyed generally was impossible to estimate before the 2014 surveys because of the dynamic nature of the channel bed and flow conditions. The average depth of the reference surface (about 30 ft) was approximately equal to or greater than the average depth observed in the 2014 surveys on the Missouri River and on the Mississippi River upstream from St. Louis

Table 4. Results of a beam angle check from two check lines over a reference surface at Indian Lake near Cuba, Missouri, on May 29, 2014.

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

Beam angle limit (degrees)	Maximum outlier (feet)	Mean difference (feet)	Standard deviation (feet)	95-percent confidence (feet)
20	0.62	0.00	0.13	0.26
25	0.62	-0.03	0.10	0.23
30	0.75	-0.03	0.10	0.20
35	0.72	-0.03	0.10	0.20
40	0.92	-0.03	0.10	0.20
45	1.51	-0.03	0.10	0.20
50	0.66	-0.03	0.10	0.20
55	1.25	0.00	0.10	0.20
60	1.21	0.03	0.10	0.20
65	0.85	0.07	0.13	0.26
70	0.79	0.10	0.16	0.30
Performance standards[a]				
	1.00	<0.20	--	<0.50
	Majority met[b]	Met	--	Met

[a]Performance standard check values are from U.S. Army Corps of Engineers (2004e), table 3–1.

[b]Beam angle check was performance in an area with a substantial amount of minor variations that had an effect on the accuracy of the reference surface.

(15.8–31.2 ft for sites 1, 2, 31, and 32; the average depth is the difference between the average water surface elevation and average channel bed elevation in table 3), but was less than the average depth observed in the 2014 surveys on the Mississippi River downstream from St. Louis (34.5–48.0 ft for sites 36–38; the average depth is the difference between the average water surface elevation and average channel bed elevation in table 3). 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.

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 POS and real-world coordinates. The patch tests are used to determine timing offsets caused by latency between the MBES and the POS, 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). The offsets determined in the patch test are applied when processing the data collected during a given survey.

Patch tests were completed twice for the 2014 surveys (table 5): once before the surveys at Indian Lake near Cuba, Mo. (fig. 1), and again several days after multiple strikes of floating debris while surveying at structure A3664 on U.S. Highway 36 at St. Joseph, Mo. (site 2; fig. 1), on June 4, 2014. The second patch test was not completed until surveying at structure A5076 on State Highway 34 at Cape Girardeau, Mo. (site 37; fig. 1), on June 10 (table 5), but nothing had struck the MBES in the intervening days.

For this study, there was no measured timing offset (table 5; $\Delta t=0$, 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, 2014a, 2014b; Huizinga and others, 2010).

The measured angular offset for roll with the transducer head untilted (a head tilt of “none” in table 5) changed from -3.05 degrees to -3.45 degrees between the first and second patch tests (table 5), whereas the measured angular offset for yaw changed from 0.45 degrees to -0.85 degrees between the first and second patch tests (table 5). The changes in these offsets likely are the result of striking several large pieces of floating debris that caused the mount to bend during the survey at structure A3664 on U.S. Highway 36 at St. Joseph, Mo. The measured angular offset for pitch was not affected, remaining constant at -1.50 degrees for both patch tests (table 5). Unexpectedly, the offset values for roll and pitch with the transducer head tilted 30 degrees to port and 30 degrees to starboard were the same for both the first and second patch tests, and only the offset value for yaw was different (table 5). 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. The measured angular offsets for roll, pitch, and yaw for the 2008 and 2011 surveys at structure A1700 on Interstate 255 near Caruthersville, Mo., were consistent with results for the boat and equipment at the times of those surveys (Richard J. Huizinga, U.S. Geological Survey, unpub. data, 2015).

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 of automatic filters and manual editing. The offsets from the first patch test were applied to data collected before the largest debris strike at structure A3664 on U.S. Highway 36 at St. Joseph, Mo, and the offsets from the second patch test were applied to all data collected after the debris strike. The bathymetric data were then projected to a three-dimensional grid at a resolution of 1.64 ft, and used to generate a gridded raster surface of the channel bed in the vicinity of each bridge (hereinafter referred to as a “bathymetric surface”) using ArcGIS.

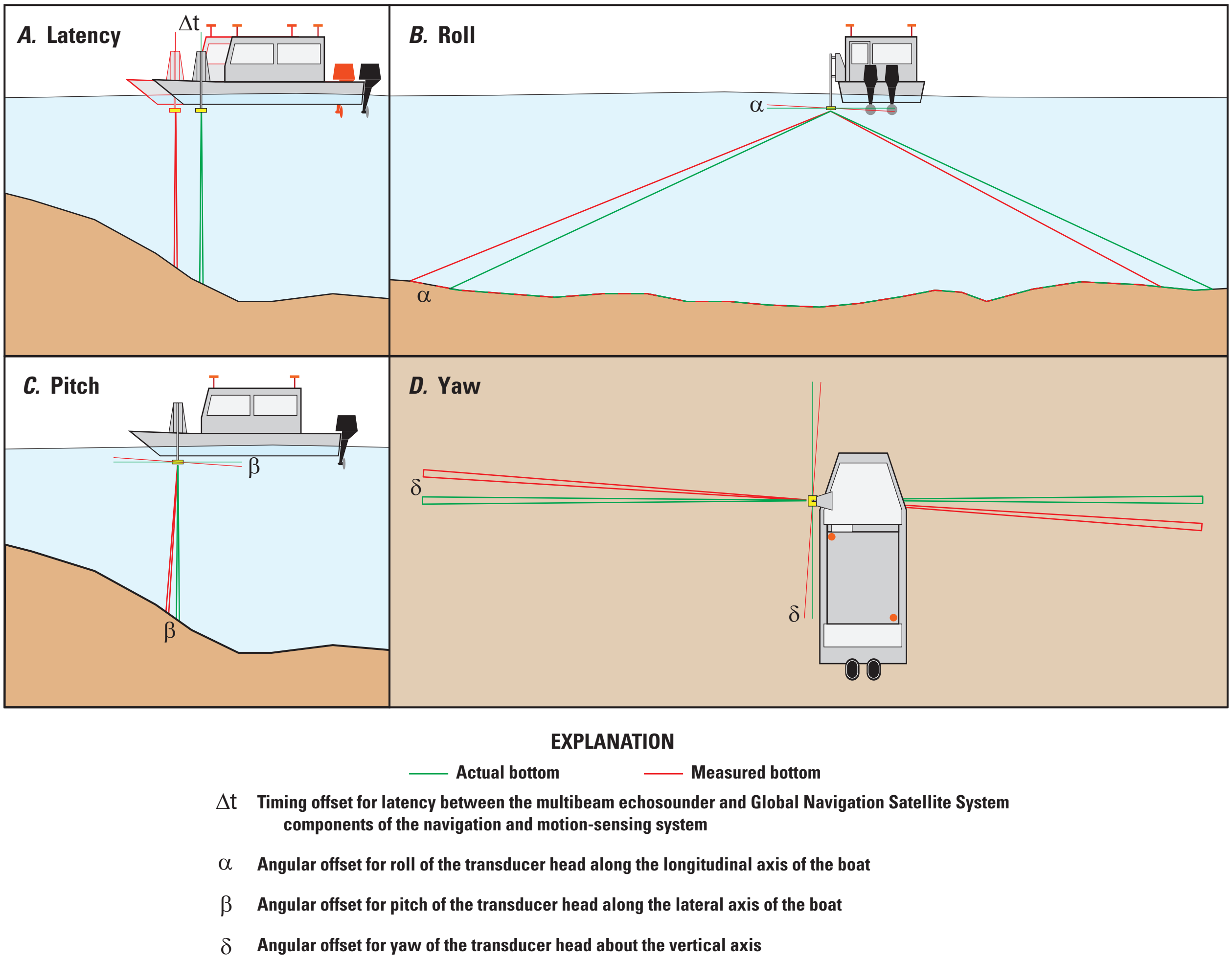


Figure 4. Generalized effects of *A,* timing offset for latency; and angular offsets for *B,* roll; *C,* pitch; and *D,* yaw on data from a multibeam echosounder.

Table 5. Patch test results from surveying on the Missouri and Mississippi Rivers on the periphery of Missouri.

[sec, seconds; deg, degrees; stbd, starboard; unshaded rows are for no tilt on the sonar head, light brown is tilted 30 degrees to starboard, and light blue is tilted 30 degrees to port]

Date of test	Timing offset (sec)	Angular offset for roll (deg)	Angular offset for pitch (deg)	Angular offset for yaw (deg)	Head tilt	Location
05/29/14	0	-3.05	-1.50	0.45	none	Indian Lake near Cuba, Missouri
05/29/14	0	-33.45	-1.50	0.45	30 deg stbd	Indian Lake near Cuba, Missouri
05/29/14	0	26.85	-1.50	0.45	30 deg port	Indian Lake near Cuba, Missouri
06/10/14	0	-3.45	-1.50	-0.85	none	Mississippi River at Cape Girardeau, Missouri
06/10/14	0	-33.45	-1.50	-0.85	30 deg stbd	Mississippi River at Cape Girardeau, Missouri
06/10/14	0	26.85	-1.50	-0.85	30 deg port	Mississippi River at Cape Girardeau, Missouri

Uncertainty Estimation

Similar to the previous studies of bathymetry in Missouri (Huizinga, 2010, 2011, 2012, 2013, 2014a, 2014b), uncertainty in the surveys was estimated by computing the total propagated uncertainty (TPU) for the bathymetric surface of each survey area, using the Combined Uncertainty Bathymetric Estimator (CUBE) method (Calder and Mayer, 2003), as implemented in the HYPACK®/HYSWEEP® software (HYPACK, Inc., 2011). 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 6, 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 A5076 on State Highway 34 at Cape Girardeau, Mo.

The largest TPU in this group of surveys was about 11.38 ft (table 6); however, as noted in previous studies, TPU values of this magnitude typically occurred near high-relief features, such as the front or side of a pier footing (fig. 5). Most of the TPU values (more than 88 percent) were less than 1.00 ft (table 6). Larger TPU values occur near moderate-relief features (banks, spur dikes, rock riprap and outcrops, and scour holes near piers; fig. 5). Occasionally, these larger TPU values also occurred in the outermost beam parts 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 occur between survey passes (fig. 5). Over one-half (59.6 percent or more) of the channel bed at the sites had TPU values of 0.50 ft or less (table 6). 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 A5076 on State Highway 34 at Cape Girardeau, Mo., had the highest mean and median values of TPU, as well as generally the lowest percentage of bathymetry points that were less than the various TPU value cutoffs (table 6). There were no substantial impediments to flow or surveying at this site and the survey was obtained with relatively smooth longitudinal swathes (fig. 5), and that was the case at nearly all of the sites surveyed in this study. The magnitude and distribution of TPU values observed at this site are representative of those observed at all of the other surveyed sites.

Table 6. Total propagated uncertainty results for bathymetric data at a 1.64-foot grid spacing from surveys on the Missouri and Mississippi Rivers on the periphery of Missouri, June 3–11, 2014.

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

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
1	L0098	11.06	0.51	0.39	0.45	98.5	90.9	64.5	25.8
2	A3664 W	6.56	0.50	0.39	0.36	99.3	92.2	64.1	21.8
31	A5054	10.66	0.43	0.33	0.40	99.0	93.6	73.0	36.3
32	K0932	10.30	0.39	0.30	0.34	99.4	95.7	77.2	37.2
36	L0135	11.25	0.40	0.33	0.32	99.5	95.4	75.9	34.0
37	A5076	11.38	0.54	0.43	0.44	98.7	88.2	59.6	25.3
38	A1700	11.06	0.47	0.36	0.41	99.0	92.9	69.2	26.1

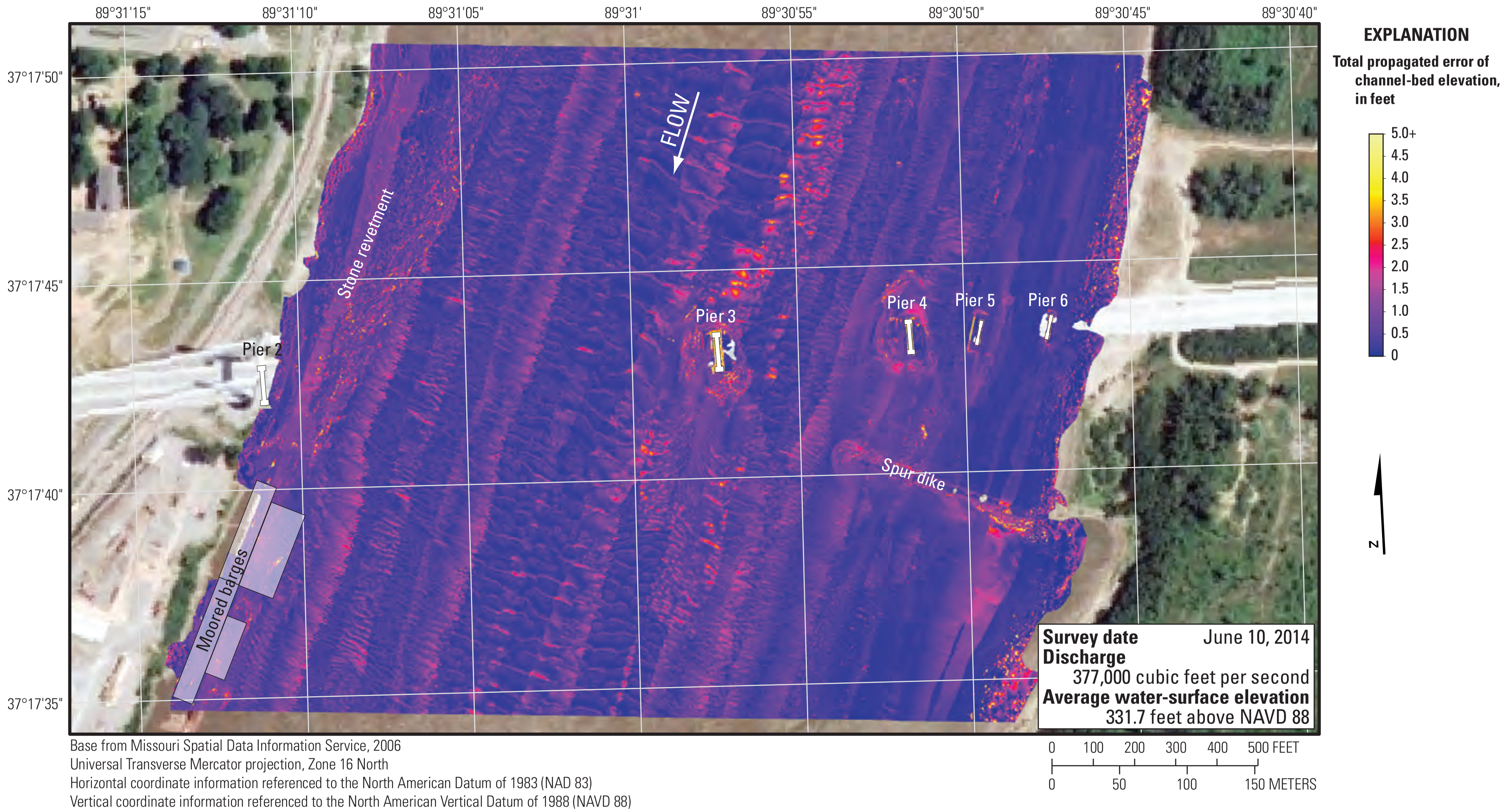


Figure 5. Total propagated uncertainty of bathymetric data from the Mississippi River channel in the vicinity of structure A5076 on State Highway 34 at Cape Girardeau, Missouri.

Results of Bathymetric and Velocimetric Surveys

The site-specific results for each bridge are discussed in the following sections grouped by river, 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 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 had occurred at both of the bridge sites on the Missouri River during the 2011 flood (Huizinga, 2012), and the site on the Mississippi River near Caruthersville was the subject of two previous bathymetric surveys (on December 10, 2008, and on May 5, 2011, during the 2011 flood; Richard J. Huizinga, U.S. Geological Survey, unpub. data, 2015). Furthermore, several of the sites on both rivers 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 area common to both surveys is included for each site with multiple surveys, and data from any previous survey is included in the cross-section plot for that bridge. 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.

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 non-uniform 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 shown for each section are an average of two velocity transects, spatially averaged to the section line using algorithms in VMT (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 the appendix figures 2–1 to 2–10.

Sites on the Missouri River

There are five unique highway crossings of the Missouri River upstream from Kansas City to the Missouri–Iowa state line (table 1; fig. 1). Two of the crossings are maintained by MoDOT, and were surveyed as part of this study.

Structure L0098 on U.S. Highway 136 at Brownville, Nebraska

Structure L0098 (site 1) on U.S. Highway 136 crosses the Missouri River at river mile (RM) 535.3 at Brownville, Nebraska, in the northwestern corner of Missouri (fig. 1). The site was surveyed on June 3, 2014, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 884.4 ft (table 3). Discharge on the Missouri River was about 39,800 ft^3/s during the survey (table 3).

The survey area was about 1,640 ft long and about 740 ft wide, extending across the active channel from bank to bank (fig. 6). The upstream end of the survey area was about 740 ft upstream from the centerline of structure L0098. The channel-bed elevations ranged from about 864 to 877 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data), except near pier 3 and on the downstream sides of the various spur dikes on the left (east) bank (table 3). The overall minimum channel-bed elevation of 844 ft was in a hole downstream from the upstream spur dike. The channel bed was covered with medium and small dunes and ripples. A rock outcrop was present on the right (west) bank upstream from the bridge, and stone revetment was present on the right bank downstream from the bridge (fig. 6).

In the vicinity of main channel pier 3, a local scour hole had a minimum channel-bed elevation of approximately 849.0 ft (table 7), about 19 ft below the average channel bed immediately upstream from the pier (fig. 6). Information from bridge plans (Missouri Department of Transportation, written commun., 2002) indicates that pier 3 is founded on sheet piling caissons on bedrock, with about 34 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of the pier (fig. 7; table 7). The unique configuration of the sheet pile caissons and ice breaker of the pier are clearly seen in the shaded TIN images for main channel pier 3 (fig. 1–1). The surveyed bed along the cross section generally was about 2 to 5 ft higher than the previous multibeam survey in 2011, except near the banks, making it more similar to the ground line from the Level II bridge scour assessment in 2002 (Huizinga and Rydlund, 2004; fig. 7). Furthermore, the channel bed from the most recent multibeam survey was more similar to the approximate ground line from bridge plans when the bridge was built in 1938 than the previous multibeam survey, except near the main channel pier.

The difference between the bathymetric surfaces from the surveys on June 3, 2014, and July 13, 2011 (fig. 8), indicates deposition of as much as 10 ft has occurred throughout most of the channel, but small areas of scour exist near the tips and downstream from the spur dikes on the left (east) side of the channel. The mean difference between the July 2011 and June 2014 bathymetric surfaces (3.93 ft; table 8) indicates moderate deposition overall, as evident in the difference map. There was as much as 20 ft of deposition on the left bank downstream from the spur dikes, and as much as 15 ft of scour near the tips of the spur dikes. About 5 ft of deposition was observed on the stone revetment on the right bank (fig. 8). The deposition likely is the result of the substantially lower flow conditions during the 2014 survey compared to the 2011 survey (table 8).

The vertically averaged velocity vectors indicated mostly uniform flow at between 4 and 6 feet per second (ft/s) in the main channel, except near the spur dikes (fig. 9). The wake vortices downstream from main channel pier 3 were not pronounced, and seemed to be no greater than the general non-uniformity of flow observed in the channel.

Structure L0098 on U.S. Highway 136 at Brownville, Nebraska.

Figure 6. Bathymetric survey of the Missouri River channel in the vicinity of structure L0098 on U.S. Highway 136 at Brownville, Nebraska.

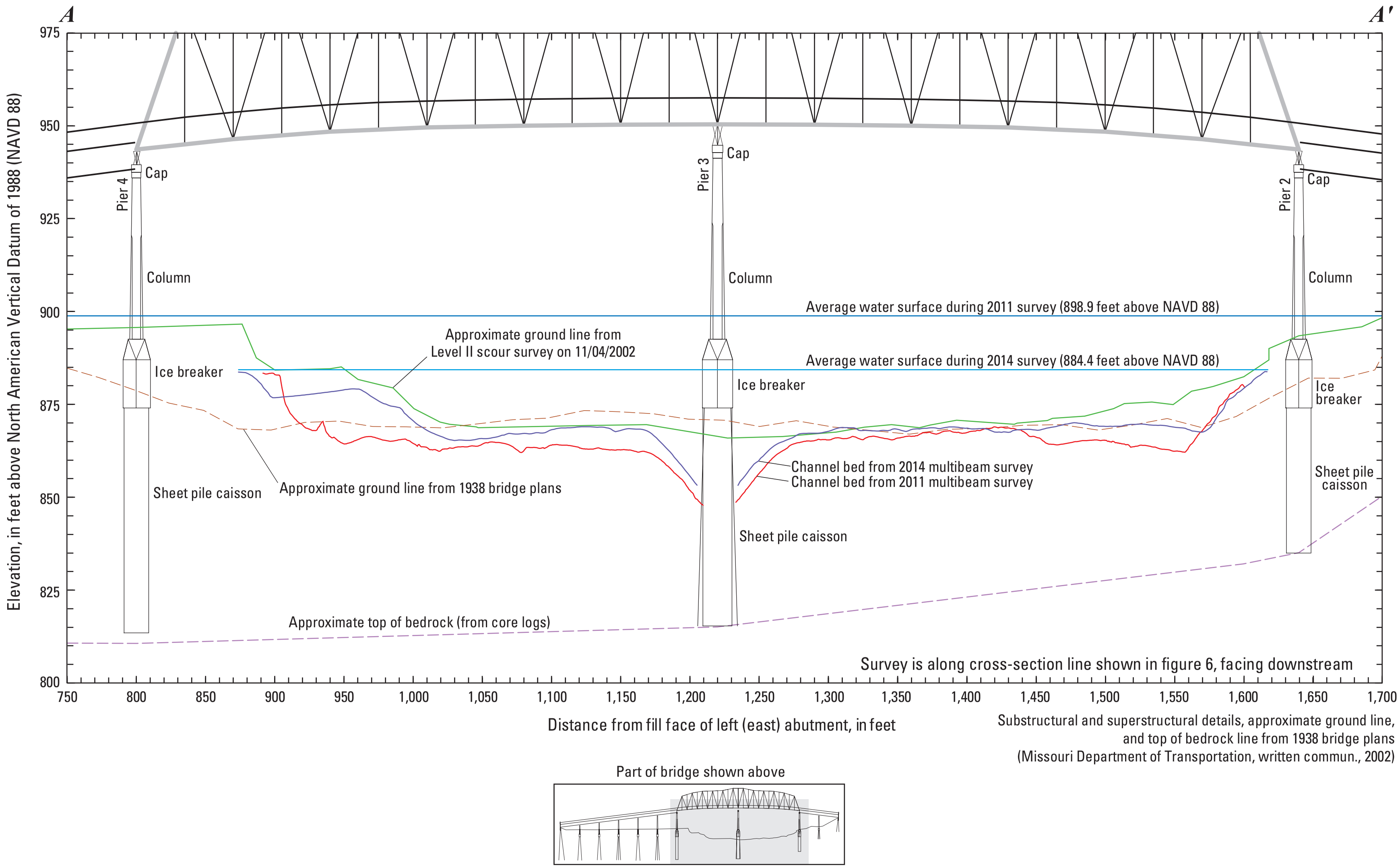


Figure 7. Key features, substructural and superstructural details, and surveyed channel bed of structure L0098 on U.S. Highway 136 over the Missouri River at Brownville, Nebraska.

Table 7. Results near piers from surveys on the Missouri and Mississippi Rivers on the periphery of Missouri, June 3–11, 2014.

[MoDOT, Missouri Department of Transportation; ft, feet; --, 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)						
1	L0098	3	Caisson	21	0	--	849	849	815	34	19	1.75
2	A3664 E & W	10	Drilled shaft	30	25	758.00	763	763	745	18	19	1.77
		9	Drilled shaft	24	25	774.00	([b])	([b])	745	([b])	([b])	([b])
		8	Pile cap	19.5	1	789.00	([b])	([b])	745	([b])	([b])	([b])
31	A5054	11	Pile cap	36	0	419.00	440	442	351	89	8	1.58
		10	Pile cap	36	0	421.00	436	[c]442	357	79	[c]11	[c]1.77
		9	Pile cap	35	0	411.00	433	[c]435	380	53	[c]8	[c]2.22
		8	Drilled shaft	36	15	405.00	418	418	394	24	19	1.80
		7	Drilled shaft	36	15	402.00	422	427	395	27	12	1.94
		6	Drilled shaft	35	15	401.00	422	424	395	27	11	2.04
		5	Drilled shaft	35	28	436.00	[d]452	[d]452	435	17	[d]0	([d])
32	K0932	5	Pile cap	16	0	414.80	426	426	371	55	6	([b])
		4	Caisson	16	1.5	--	401	401	393	8	19	1.71
		3	Caisson	18	1.5	--	410	[c]411	401	9	[c]6	[c]3.45
		2	Caisson	18	1.5	--	412	[c]416	408	4	[c]2	([c])
		1	Footing	17	1.5	--	[d]430	[d]430	430	0	[d]0	([d])
36	L0135	13	Footing	15	1	--	[d]351	[d]351	345	6	[d]0	([d])
		12	Footing	16	3	--	[d]320	[d]320	317	2	[d]0	([d])
		11	Caisson	24	1	--	308	308	266	42	16	1.85
		10	Caisson	16	2	--	330	330	245	85	6	2.70
37	A5076	7	Drilled shaft	32	19	301.00	([b])	([b])	243	([b])	([b])	([b])
		6	Drilled shaft	32	20	292.00	311	311	245	66	6	1.84
		5	Drilled shaft	32	22	285.00	297	297	245	52	3	2.16
		4	Caisson	60	1	--	275	[c]283	244	32	[c]25	[c]1.92
		3	Caisson	67	1	--	272	[c]287	250	22	[c]27	[c]1.96
		2	Footing	60	1	--	[d]323	[d]324	290	33	d0	([d])

Table 7. Results near piers from surveys on the Missouri and Mississippi Rivers on the periphery of Missouri, June 3–11, 2014.—Continued

[MoDOT, Missouri Department of Transportation; ft, feet; --, 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)						
38	A1700	21	Caisson	39	0	[e]158.52	225	225	--	--	[d]0	([d])
		20	Caisson	66	0	[e]119.20	188	191	--	--	[c]10	[c]1.71
		19	Caisson	29	0	[e]139.35	207	[c]207	--	--	[c]0	([c])
		18	Pile cap	50.8	0	188.00	210	[c]210	--	--	[c]0	([c])
		17	Pile cap	39.7	0	196.50	202	202	--	--	7	2.13
		16	Pile cap	42	0	196.50	192	200	--	--	[d]0	([d])
		15	Pile cap	39.7	0	196.92	[d]221	[d]221	--	--	[d]0	([d])
		14	Pile cap	18	0	240.00	[d]448	[d]457	--	--	[d]0	([d])

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

[b] Unable to obtain data because of substantial floating debris, or pier was in very shallow water or blocked by accumulated debris.

[c] Pier appears to be partially or totally surrounded with a riprap blanket.

[d] Scour hole at this pier is substantially affected by stone revetment or bedrock.

[e] Elevation of bottom of caisson is shown because it is not founded on bedrock.

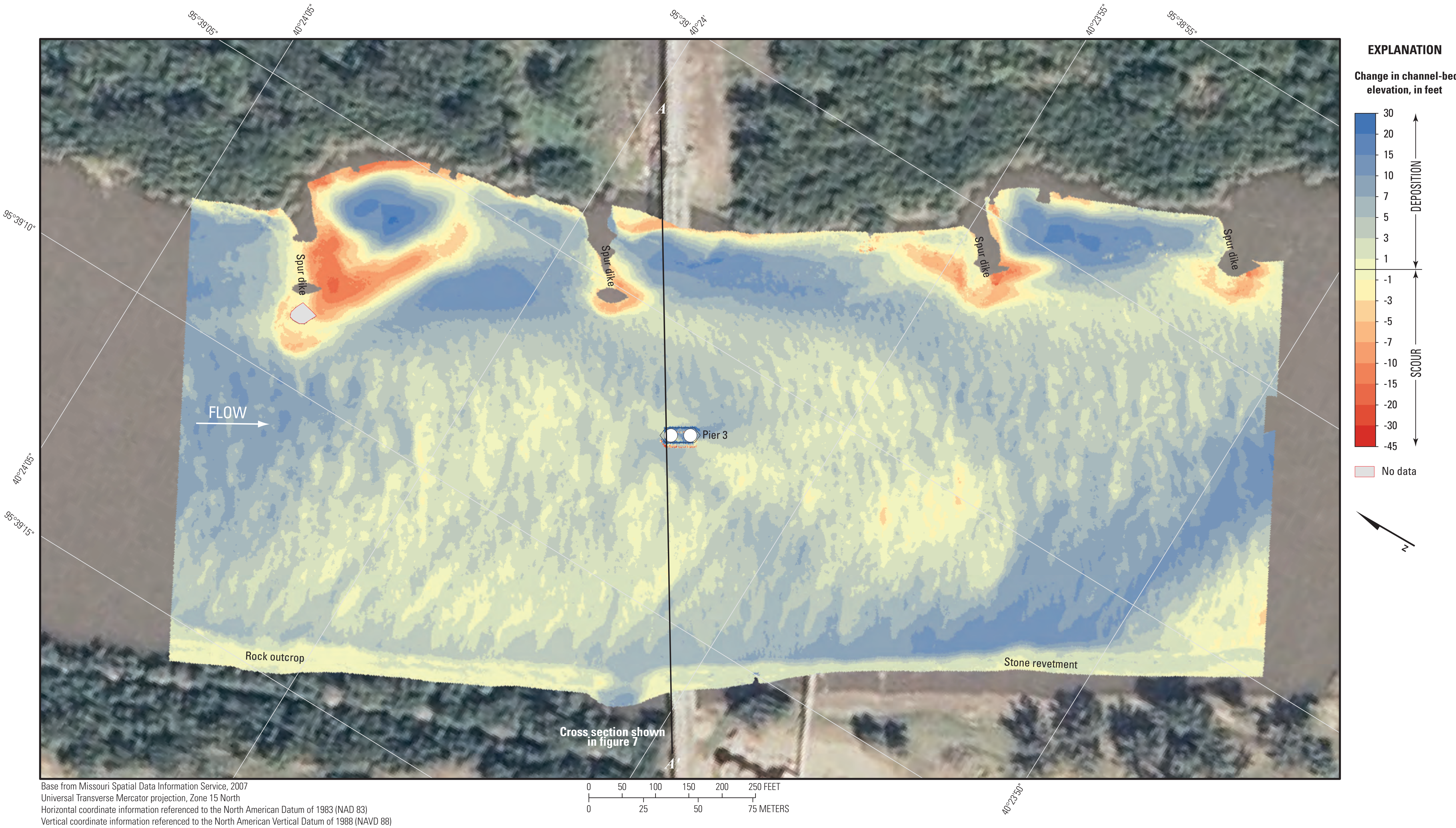


Figure 8. Difference between bathymetric surfaces created from surveys of the Missouri River channel in the vicinity of structure L0098 on U.S. Highway 136 at Brownville, Nebraska, on June 3, 2014, and July 13, 2011.

Table 8. Summary information and bathymetric surface difference statistics from surveys on the Missouri and Mississippi Rivers on the periphery of Missouri, June 3–11, 2014, and previous surveys.

[MoDOT, Missouri Department of Transportation; ft^3/s, cubic feet per second; ft^2, square feet; ft, feet; all elevations are in feet above the North American Vertical Datum of 1988]

Site number (fig. 1)	MoDOT structure number	Previous survey					Difference between 2014 survey and previous survey			Statistics of differences between 2014 and previous survey surfaces				Maximum difference near upstream pier face(s)[b c] (ft)
		Source of data	Date	Discharge (ft^3/s)	Surveyed area ($x10^6$ ft^2)	Average water-surface elevation (ft)	Discharge (ft^3/s)	Surveyed area ($x10^6$ ft^2)	Average water-surface elevation (ft)	Minimum[a b] (ft)	Maximum[a b] (ft)	Mean[b] (ft)	Standard deviation (ft)	
1	L0098	Huizinga (2012)	07/13/11	225,000	1.16	898.9	-185,200	0.032	-14.5	-29.0	34.9	3.93	3.73	5.9
2	A3664 E & W	Huizinga (2012)	07/14/11	218,000	1.44	817.2	[d]-151,900	-0.395	-17.4	-24.1	20.0	-2.04	4.76	-16.4
38	A1700	unpublished data	12/10/08	[e]156,000	3.57	228.4	473,000	0.859	23.4	-31.2	56.6	-0.52	6.85	-3.5
			5/5/2011	[f]2,040,000	4.29	277.4	-1,411,000	0.135	-25.6	-55.0	60.9	9.05	12.80	-5.5

[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 7.

[d] The difference in discharge was computed using the discharge at the St. Joseph streamgage of 66,100 ft3/s (table 3, footnote “d”).

[e] The discharge for this survey was taken from the U.S. Army Corps of Engineers streamgage upstream at Hickman, Kentucky (fig. 1), on 12/09/2008 (Jeanne C. Burns, U.S. Army Corps of Engineers, written commun., 2014). The previous day’s value was used to account for time of travel from Hickman to Caruthersville.

[f] The discharge for this survey was from a discharge measurement at the stage-gaging station upstream at Tiptonville, Tennessee (fig. 1), on 05/05/2011 (Koenig and Holmes, 2013).

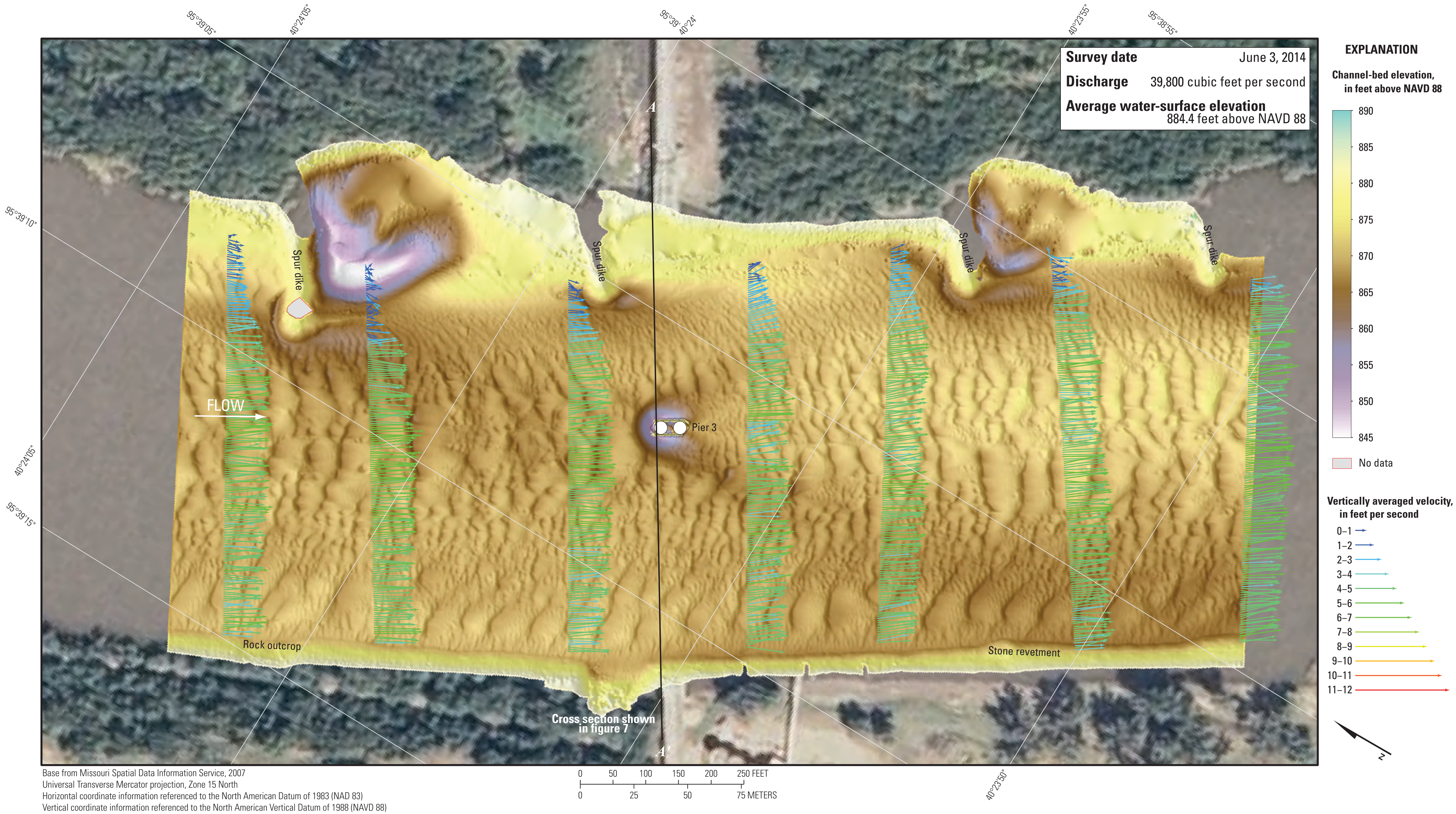


Figure 9. Bathymetry and vertically averaged velocities of the Missouri River channel in the vicinity of structure L0098 on U.S. Highway 136 at Brownville, Nebraska.

Dual Bridge Structure A3664 on U.S. Highway 36 at St. Joseph, Missouri

Structure A3664 (site 2) consists of twin bridges on U.S. Highway 36 crossing the Missouri River at RM 447.9 at St. Joseph, Mo., on the western side of Missouri north of Kansas City (fig. 1). The site was surveyed on June 4, 2014, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 799.8 ft (table 3). There was a substantial amount of floating debris during the survey date at this site, because the Missouri River was beginning to flood (fig. 2*A*). The discharge as determined by the ADCP measurements indicated 49,600 ft^3/s (table 3), but a substantial part of the right side of the channel could not be surveyed for bathymetry or velocity data due to floating debris. Flow on the Missouri River was about 66,100 ft^3/s during the survey, according to the streamgage at St. Joseph, Missouri (station 06818000; table 3, footnote "d"), and this value was used as the discharge during the survey. A dredge barge was moored near the downstream end of the reach, and mooring lines prevented survey data from being collected near it.

The survey area was about 1,640 ft long and about 655 ft wide, extending most of the way across the active channel from the left bank to an area of heavy floating debris (fig. 10). The upstream end of the survey area was about 655 ft upstream from the centerline of structure A3664. The channel-bed elevations ranged from about 774 to 788 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data), except on the downstream side of the upstream spur dikes on the right (west) bank (table 3). The overall minimum channel-bed elevation of 757 ft was in a hole downstream from the upstream spur dike on the right (west) bank near pier 10. The channel bed was covered with small dunes and ripples. Stone revetment was present on the left (east) bank throughout the reach (fig. 10).

In the vicinity of main channel pier 10, a local scour hole had a minimum channel-bed elevation of approximately 763 ft (table 7), about 19 ft below the average channel bed immediately upstream from the pier (fig. 10). The large local scour hole downstream from the upstream spur dike extended toward pier 10. Information from bridge plans (Missouri Department of Transportation, written commun., 2011) indicates that pier 10 is founded on shafts drilled into bedrock, with about 18 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of pier 10 (fig. 11; table 7).

The surveyed bed along the cross section generally was about 5 to 10 ft lower than the previous multibeam survey in 2011 for the part of the channel that was surveyed, and near pier 10 it was 20 ft lower (fig. 11). For most of the channel cross section shown in figure 11, the surveyed bed was approximately 20 to 25 ft lower than the original ground line from bridge plans at construction (1974).

The difference between the bathymetric surfaces from the surveys on June 4, 2014, and July 14, 2011 (fig. 12), indicates deposition of as much as 15 ft has occurred throughout most of the upstream part of the channel, with scour of as much as 10 ft throughout the downstream part of the channel. The mean difference between the July 2011 and June 2014 bathymetric surfaces (-2.04 ft, table 8) indicates moderate scour overall, as evident in the majority of the difference map. There was over 20 ft of scour near the tip and downstream from the spur dikes. Small areas of deposition were observed on the stone revetment on the left bank (fig. 12).

The moderate scour observed at this site may be the result of the survey on the rising limb of a local peak in 2014 (fig. 2) being compared to a survey on the receding limb the 2011 flood (see fig. 2 in Huizinga, 2012) that may have allowed a sort of stasis to develop at the site in the 2011 survey. However, although the negative mean difference indicates overall net scour between the compared bathymetric surfaces, the survey for this site covered substantially less area in 2014 than the survey in 2011 (more than 27 percent less, computed as the difference between the 2014 survey area and previous surveyed area divided by the previous surveyed area in table 8), and the surveyed area was along the thalweg and away from the spur dikes on the right bank (fig. 10), downstream from which deposition has been observed in other surveys during low to moderate-flow conditions (see figs. 29 and 40 in Huizinga, 2014b). It is likely that the area not surveyed in 2014 would have experienced deposition because it is on the inside of a bend in the river, and is implied by the deposition observed along the left edge of the 2014 survey area (fig. 12). The statistics of the differences between the bathymetric surfaces for this site may have been skewed by not including this area of potential deposition.

The vertically averaged velocity vectors indicated mostly uniform flow at between 6 and 8 ft/s in the main channel for the part of the channel for which velocity data were collected (fig. 13), with a few localized areas of higher velocity downstream from the tip of the upstream spur dike and near pier 10. However, moderate shear and wake vortices were observed throughout the channel reach, and particularly near the left bank, as indicated by the variable velocities and non-uniform orientation of the velocity vectors (fig. 13).

Dual Bridge Structure A3664 on U.S. Highway 36 at St. Joseph, Missouri.

Figure 10. Bathymetric survey of the Missouri River channel in the vicinity of dual bridge structure A3664 on U.S. Highway 36 at St. Joseph, Missouri.

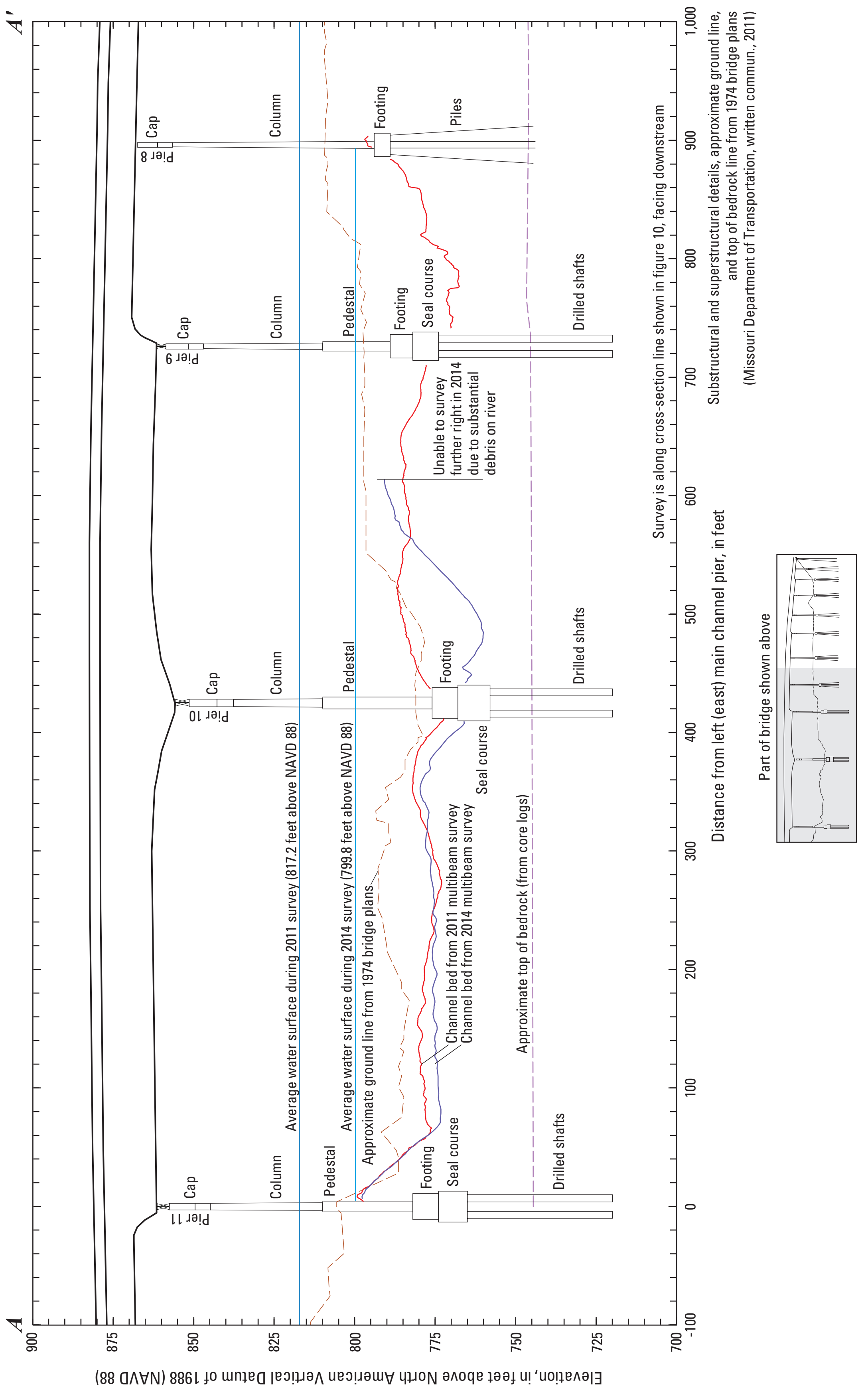


Figure 11. Key features, substructural and superstructural details, and surveyed channel bed of dual bridge structure A3664 on U.S. Highway 36 over the Missouri River at St. Joseph, Missouri

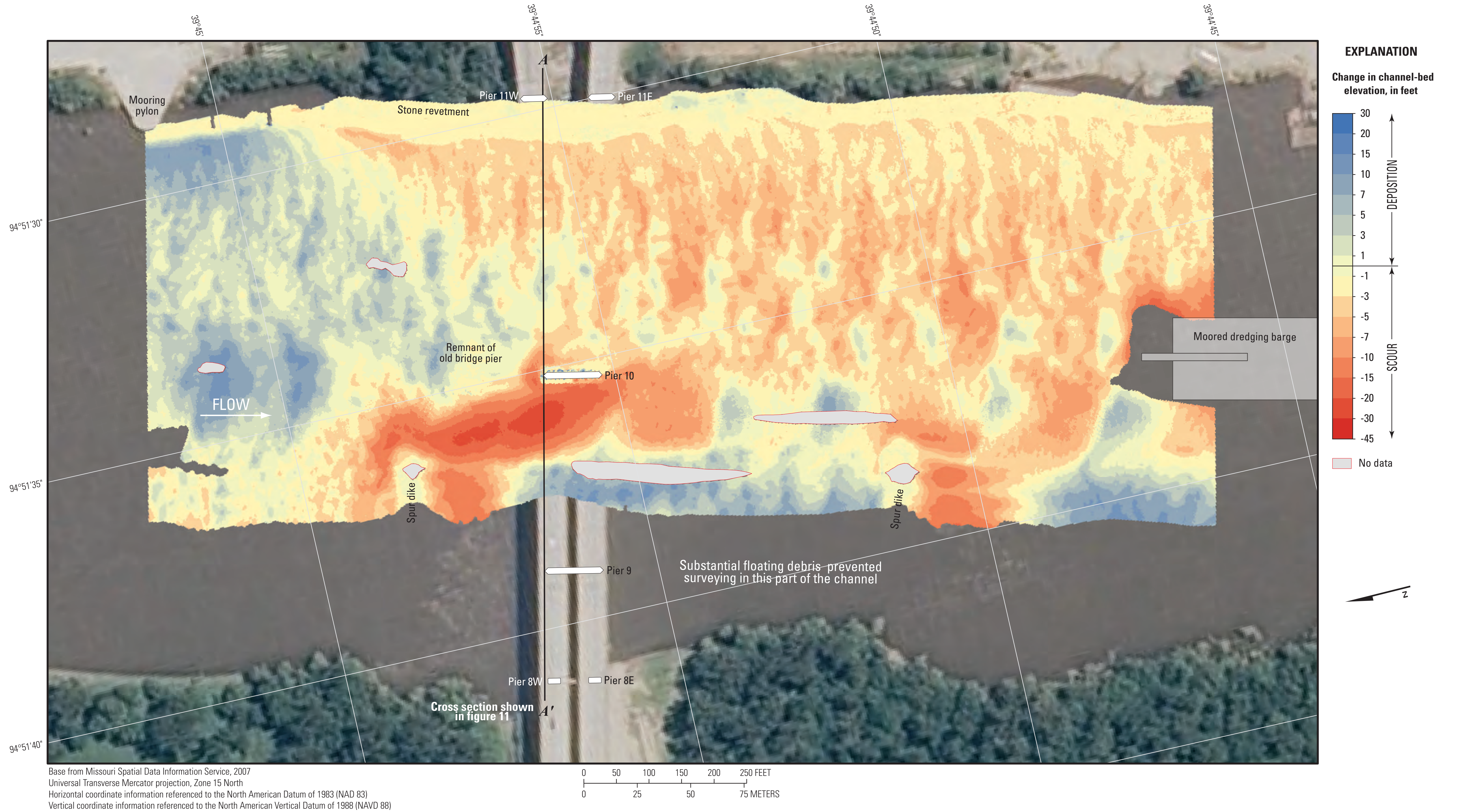


Figure 12. Difference between bathymetric surfaces created from surveys of the Missouri River channel in the vicinity of dual bridge structure A3664 on U.S. Highway 36 at St. Joseph, Missouri, on June 4, 2014, and July 14, 2011.

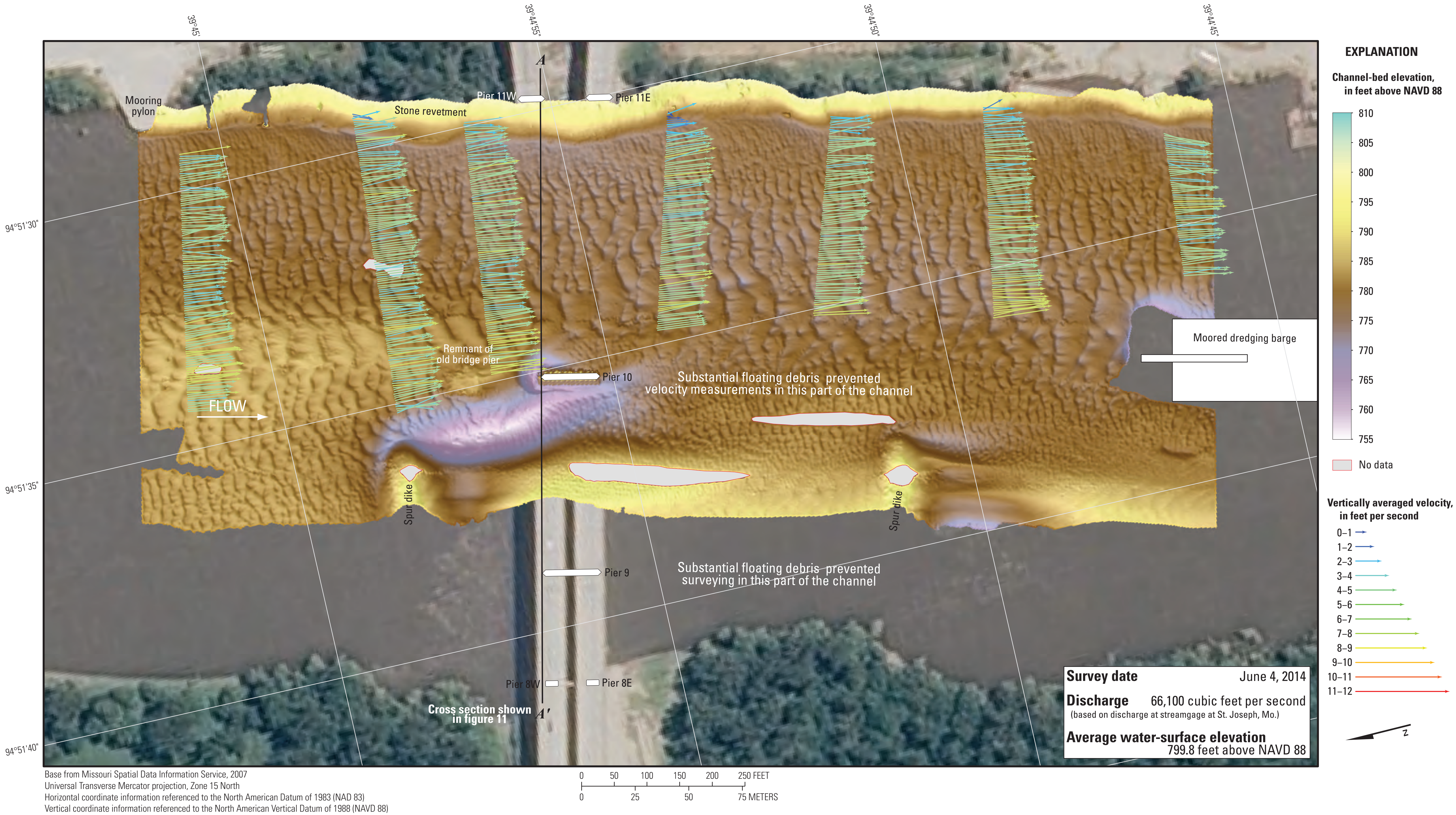


Figure 13. Bathymetry and vertically averaged velocities of the Missouri River channel in the vicinity of dual bridge structure A3664 on U.S. Highway 36 at St. Joseph, Missouri.

Sites on the Mississippi River

There are four unique highway crossings of the Mississippi River upstream from St. Louis, and five unique highway crossings of the Mississippi River downstream from St. Louis (table 2; fig. 1). Five of the Mississippi River crossings are maintained by MoDOT, and were surveyed as part of this study.

Structure A5054 on Interstate 72 at Hannibal, Missouri

Structure A5054 (site 31) on Interstate 72 crosses the Mississippi River at RM 309.5 at Hannibal, Mo., north of St. Louis, Mo., and south of Quincy, Ill. (fig. 1; table 2). The site was surveyed on June 5, 2014, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 464.6 ft (table 3). Discharge on the Mississippi River was about 198,000 ft^3/s during the survey (table 3).

The survey area was about 1,640 ft long and about 1,870 ft wide, extending across the active channel from the left (northeast) bank to the right (southwest) bank (fig. 14). The upstream end of the survey area was about 700 ft upstream from the centerline of structure A5054, and piers 5 through 11 were in the water; however, pier 5 was in shallow water on the right bank. The channel-bed elevations ranged from about 427 to 449 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data), except in the vicinity of pier 6 through 8 and the thalweg of the channel in the upstream part of the reach (table 3). The left side of the channel between the left bank and the channel thalweg was filled with small and medium dune features, and small dunes and ripples were present in the thalweg. A spur dike on the downstream left side was barely visible above the average bed in the vicinity. The right bank seems to consist of smooth rock or hardpan clay throughout the reach, with no discernable dune features (fig. 14).

The minor scour hole in the vicinity of pier 11 was difficult to discern from nearby dunes and ripples, and there was no discernable hole near pier 5 on the right bank (fig. 14). Alternatively, piers 6 through 8 had well-defined, asymmetric scour holes indicative of being skewed to approach flow. Pier 8 seems to have part of the footing exposed in the bathymetric map (figs. 14, 1–4*A*, 1–4*B*), and piers 9 and 10 seem to be surrounded by partial riprap blankets or piles of rock (figs. 14, 1–3*D*, 1–3*E*, and 1–3*F*). Information from bridge plans (Missouri Department of Transportation, written commun., 2014) indicates that piers 5 through 8 are founded on shafts drilled 15 to 30 ft into bedrock, having about 17 to 24 ft of bed material between the channel bottom and bedrock (fig. 15; table 7). Piers 9 through 11 are founded on steel H-piles driven to refusal on bedrock, having 53 ft of bed material between the channel bottom and bedrock at pier 9, 79 ft of bed material at pier 10, and 89 ft of bed material at pier 11 (fig. 15; table 7). The surveyed bed was 5 to 15 ft lower along the upstream bridge face than the original ground line from 1996 bridge plans. The cross section along the upstream bridge face indicates partial footing exposure at piers 5 through 10 (fig. 15), although it is not evident on the map (fig. 14), and not readily apparent in the shaded TIN images (figs. 1–3, 1–4), except at pier 8. However, the top of the footing is evident at pier 7 in the shaded TIN images (figs. 1–4*C*, 1–4*D*), and the footing of piers 9 and 6 may also be evident in the shaded TIN images, but seem partly obscured by a submerged log at both piers (figs. 1–3*E*, 1–3*F*, 1–4*E*, 1–4*F*).

The vertically averaged velocity vectors indicate mostly uniform flow throughout most of the channel, ranging from about 4 to 8 ft/s (fig. 16). Areas of non-uniform flow caused by the skewed orientation of the piers is evident the in the velocity sections downstream from the bridge, as well as near the spur dike on the right bank downstream from the bridge. Similar areas of non-uniform flow are apparent in the upstream sections as well, caused by a railroad bridge located about 1,130 ft upstream from the surveyed reach (fig. 16).

Structure A5054 on Interstate 72 at Hannibal, Missouri.

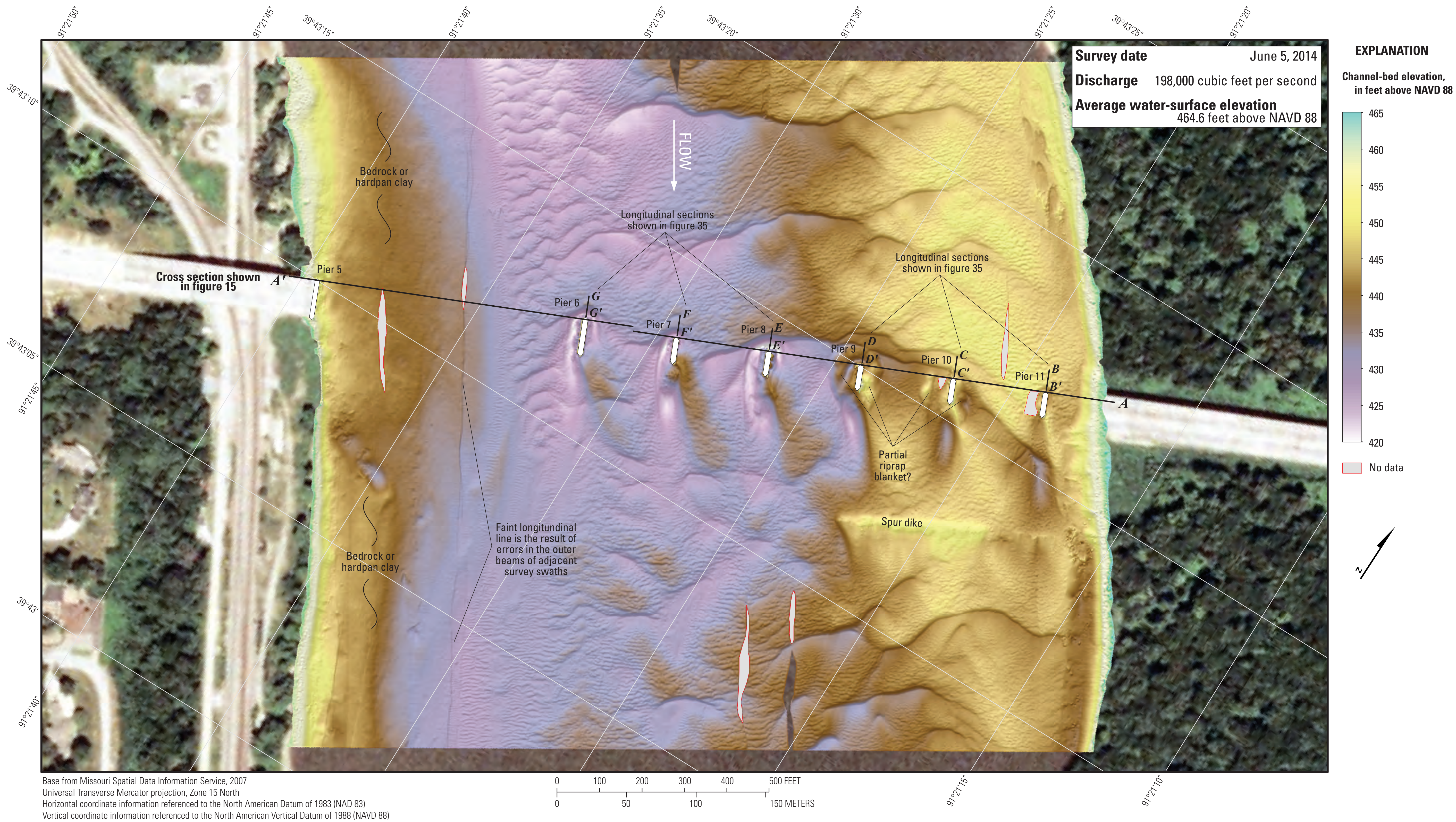


Figure 14. Bathymetric survey of the Mississippi River channel in the vicinity of structure A5054 on Interstate 72 at Hannibal, Missouri.

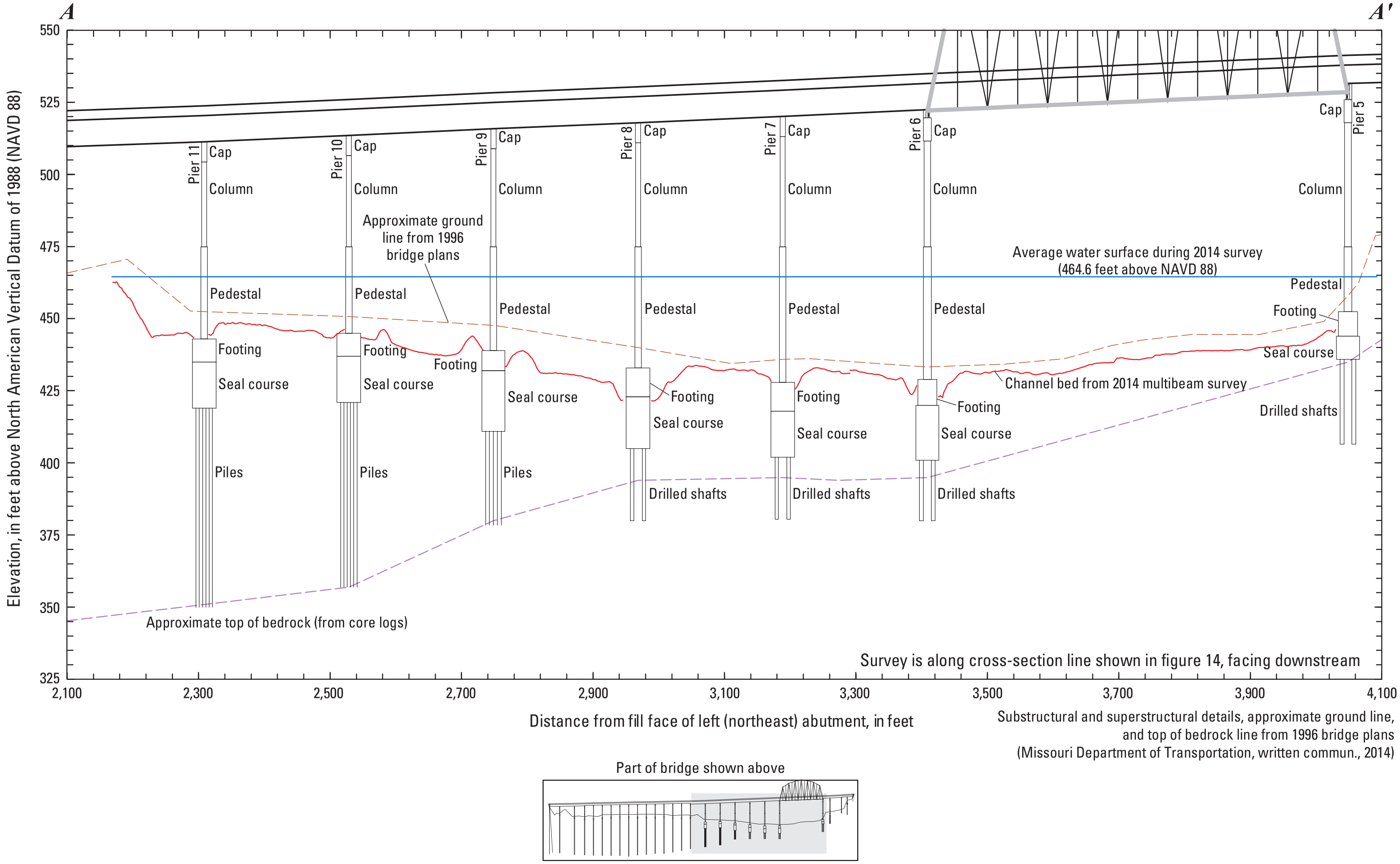


Figure 15. Key features, substructural and superstructural details, and surveyed channel bed of structure A5054 on Interstate 72 at Hannibal, Missouri.

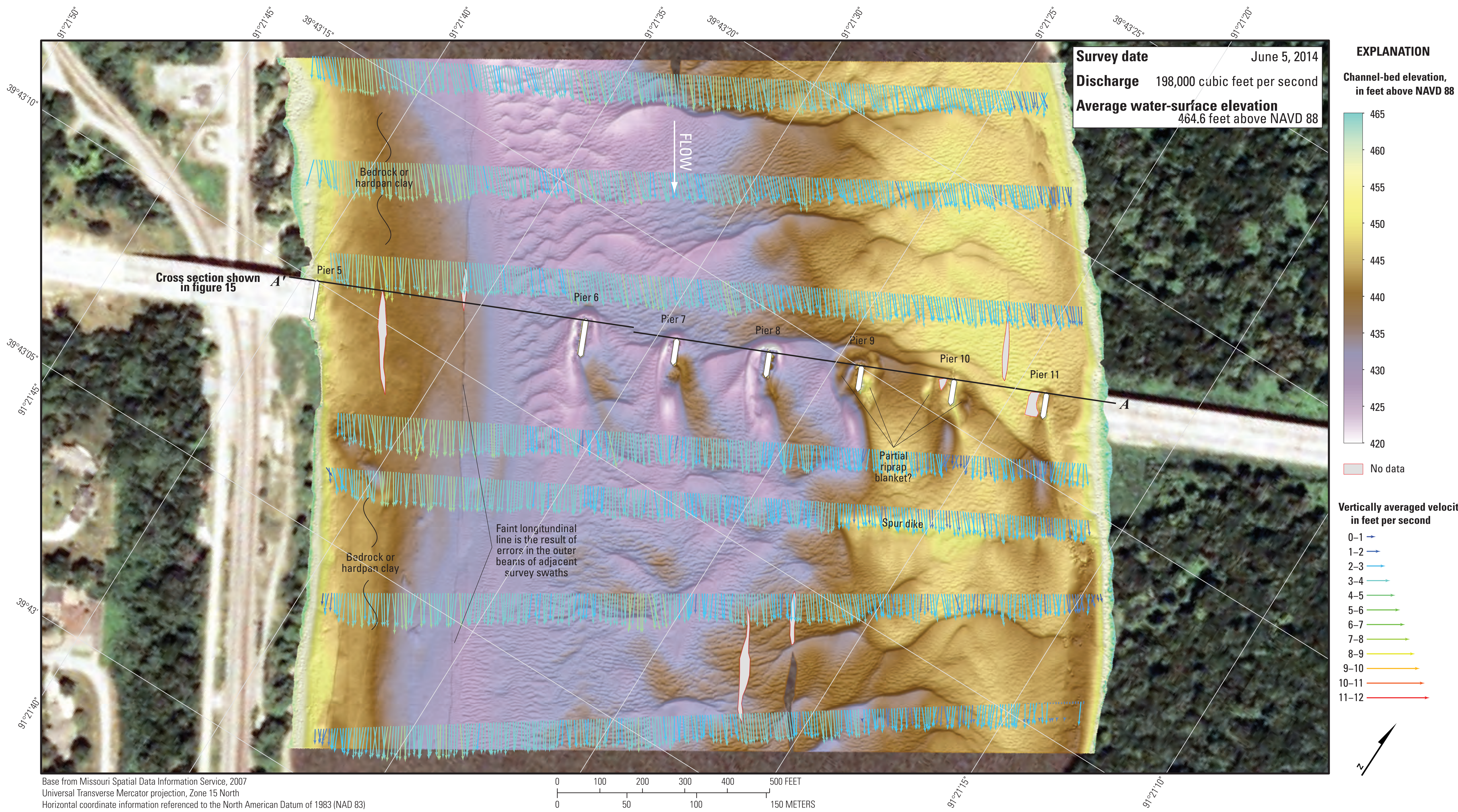


Figure 16. Bathymetry and vertically averaged velocities of the Mississippi River channel in the vicinity of structure A5054 on Interstate 72 at Hannibal, Missouri.

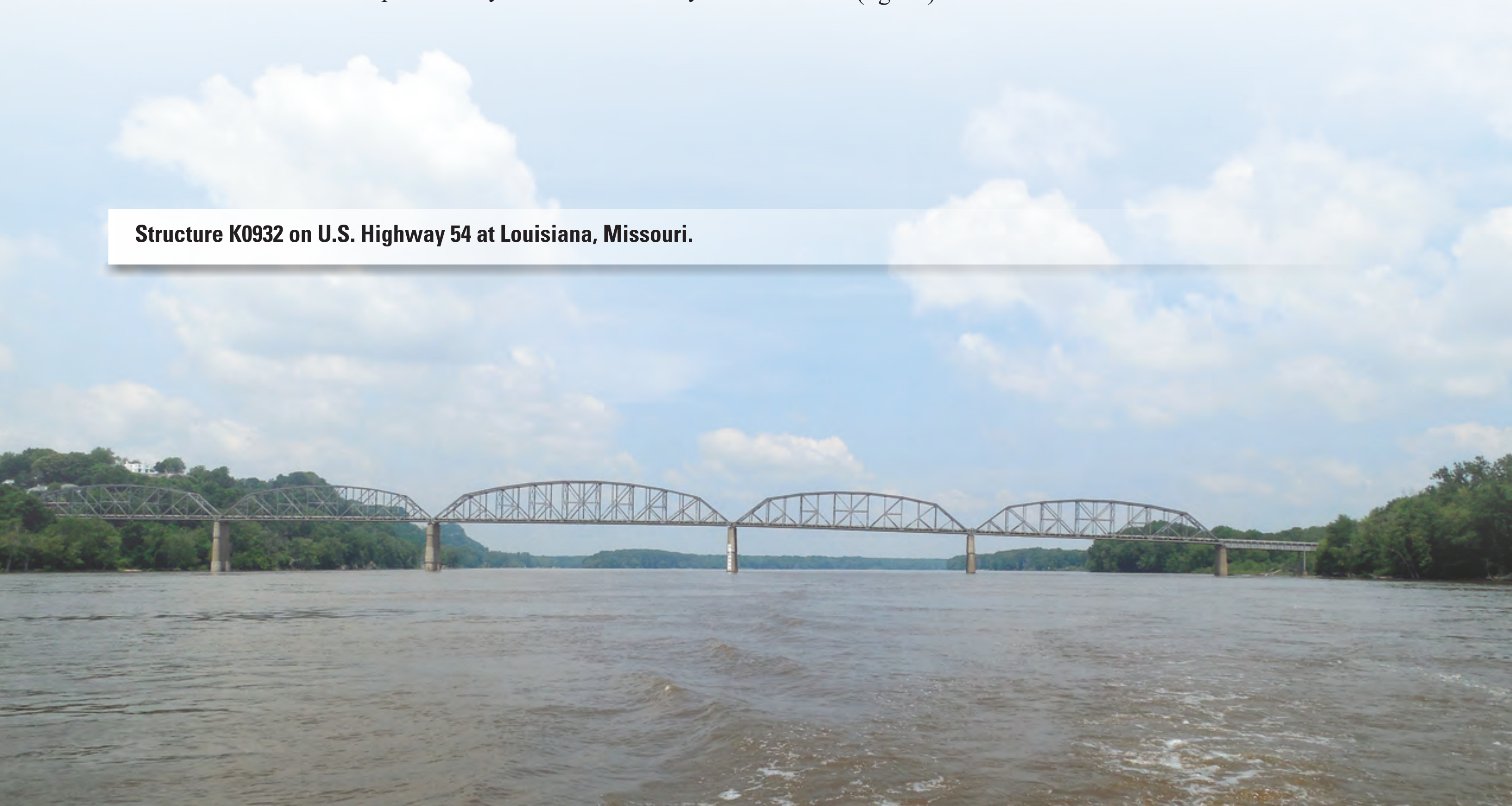
Structure K0932 on U.S. Highway 54 at Louisiana, Missouri

Structure K0932 (site 32) on U.S. Highway 54 crosses the Mississippi River at RM 283.2 at Louisiana, Mo., between Hannibal and St. Louis, Mo. (fig. 1; table 2). The site was surveyed on June 6, 2014, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 451.2 ft (table 3). Discharge on the Mississippi River was about 194,000 ft^3/s during the survey (table 3).

The survey area was about 1,640 ft long and ranged from about 1,670 ft wide at the upstream end to about 1,450 ft wide at the downstream end, extending across the active channel from the left (northeast) bank to the right (southwest) bank (fig. 17). The upstream end of the survey area was about 700 ft upstream from the centerline of structure K0932, and piers 1 through 5 were in the water; however, pier 5 was immediately upstream from a large spur dike near the left bank. The channel-bed elevations ranged from about 407 to 439 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data), except in the vicinity of pier 4 and downstream from the spur dike on the left bank immediately downstream from the bridge (table 3). The channel was filled with small and medium dune features, and small dunes and ripples were present near the left bank upstream from the bridge. The right bank seems to consist of smooth rock or hardpan clay throughout the reach, with partial dune features (fig. 17).

Piers 2 and 3 did not have a discernable scour hole, and were surrounded by riprap blankets (figs. 17, 1–5*D*, 1–5*E*, 1–6*A*, 1–6*B*) installed in the early 1990’s (Dale Henderson, Missouri Department of Transportation, written comm., 2015). A moderate scour hole near pier 4 likely was exacerbated by flow diverted by the nearby spur dike (fig. 17). Information from bridge plans (Missouri Department of Transportation, written commun., 2014) indicates that piers 2 through 4 are caissons founded on bedrock, having between 4 and 9 ft of bed material between the bottom of the scour hole (or minimum channel-bed elevation near the pier) and bedrock (fig. 18; table 7). Pier 1 is a footing founded on the exposed bedrock on the right bank (figs. 17, 18; table 7), and pier 5 is founded on steel H-piles driven to refusal on bedrock, having about 55 ft of bed material between the bottom of the scour hole and bedrock (fig. 18, table 7). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (American Association of State Highway Transportation Officials, 2012; Brown and others, 2010), but full exposure of usually buried substructural elements warrants special consideration and observation, even when designed to be exposed. The surveyed bed generally was lower than the original ground line from 1926 bridge plans, and is similar to the ground line from the Level II bridge scour assessment in 2002 (Huizinga and Rydlund, 2004; fig. 18), particularly on the right side of the channel; however, the ground line from the Level II bridge scour assessment was along the downstream side of the bridge and may have incorporated part of the downstream spur dike (fig. 17).

The vertically averaged velocity vectors indicate mostly uniform but variable flow throughout most of the channel, with velocities ranging from about 3 to 8 ft/s for most of the channel (fig. 19). Substantial non-uniform flow indicated by flow deflection and reversal was observed downstream from the spur dike on the left bank, along the banks, and downstream from piers 2 and 3 despite the piers being well-aligned with flow (fig. 19).



Structure K0932 on U.S. Highway 54 at Louisiana, Missouri.

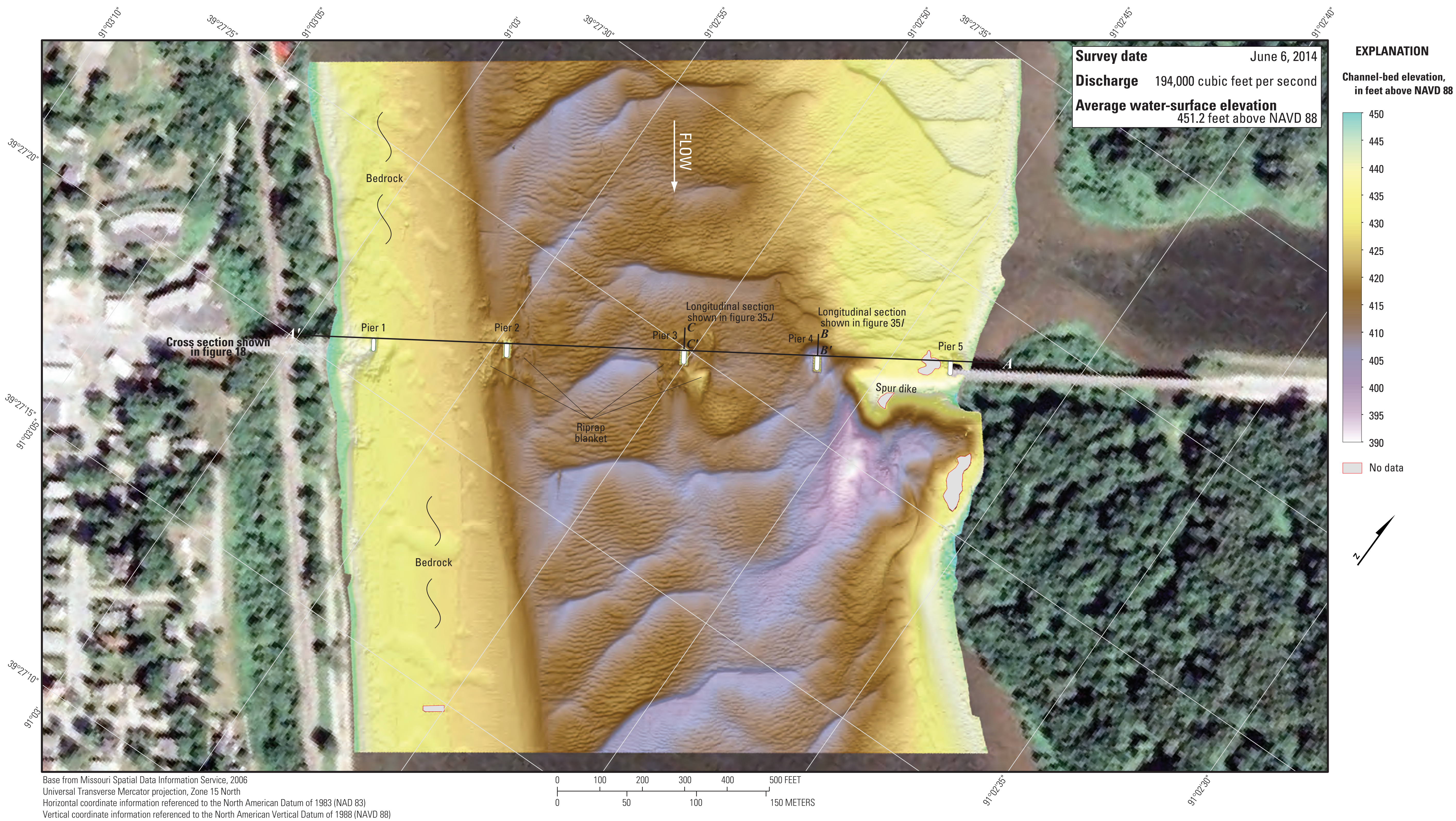


Figure 17. Bathymetric survey of the Mississippi River channel in the vicinity of structure K0932 on U.S. Highway 54 at Louisiana, Missouri.

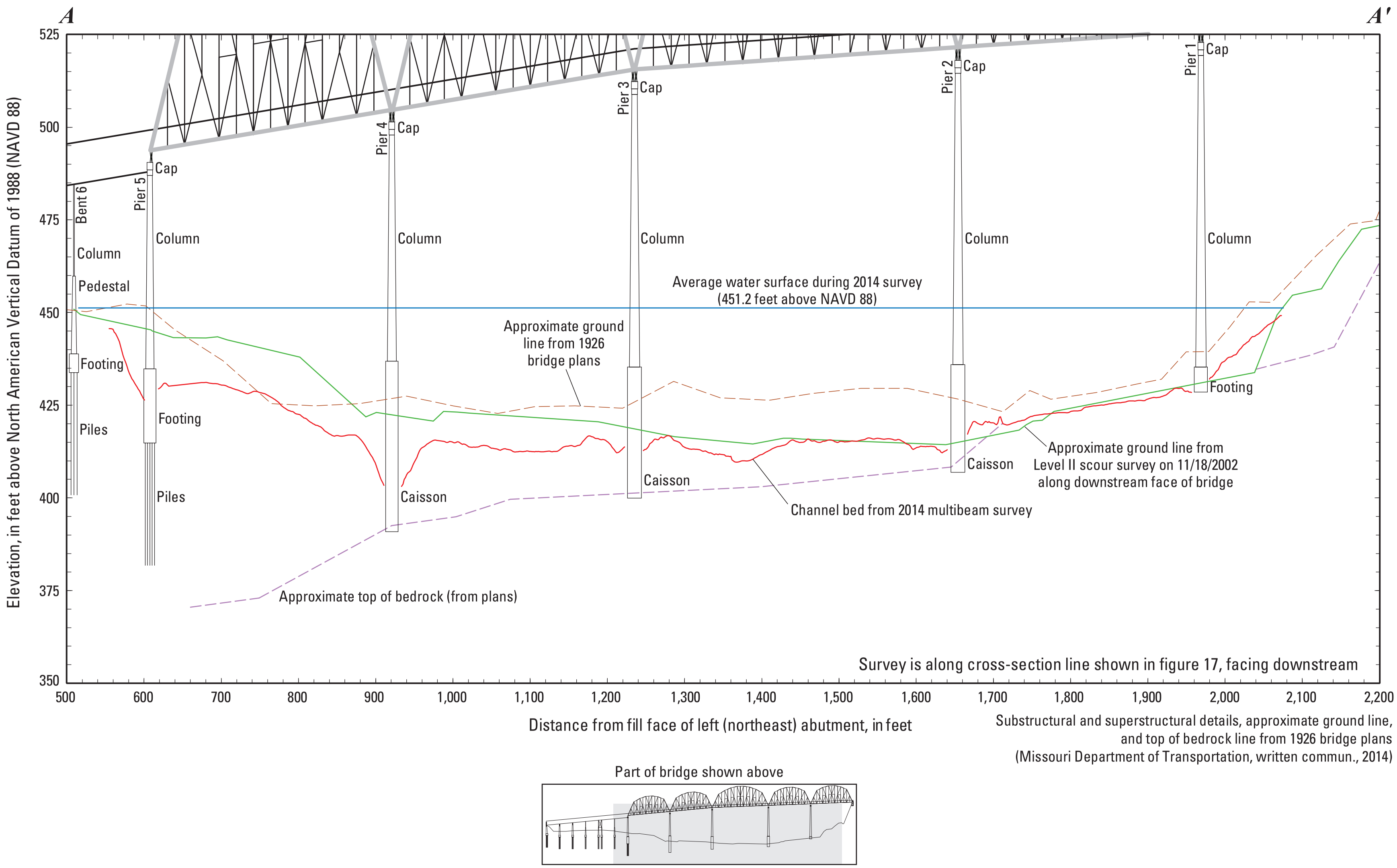


Figure 18. Key features, substructural and superstructural details, and surveyed channel bed of structure K0932 on U.S. Highway 54 at Louisiana, Missouri.

Figure 19. Bathymetry and vertically averaged velocities of the Mississippi River channel in the vicinity of structure K0932 on U.S. Highway 54 at Louisiana, Missouri.

Structure L0135 on State Highway 51 at Chester, Illinois

Structure L0135 (site 36) on State Highway 51 crosses the Mississippi River at RM 109.9 at Chester, Ill., southeast of and downstream from St. Louis, Mo. (fig. 1; table 2). The site was surveyed on June 9, 2014, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 363.9 ft (table 3). Discharge on the Mississippi River was about 363,000 ft^3/s during the survey (table 3).

The survey area was about 1,640 ft long and about 1,840 ft wide, extending across the active channel from the left (northeast) bank to the right (southwest) bank in the main channel (fig. 20). The upstream end of the survey area was about 655 ft upstream from the centerline of structure L0135, and piers 10 through 13 were in the water; however, pier 13 was in shallow water on the left bank. The channel-bed elevations ranged from about 316 to 346 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data), except near pier 11 and in the thalweg along the left side of the channel (table 3). A series of medium to large dunes were present in the thalweg, with numerous medium and small dunes and ripples present throughout the rest of the channel. A bedrock outcrop was present on the left (northeast) bank, and stone revetment was present on the right bank (fig. 20).

In the vicinity of pier 11 (fig. 20), a substantial scour hole had a minimum channel-bed elevation of about 308 ft (table 7), which is about 16 ft below the average channel elevation upstream from the pier (fig. 21). Information from bridge plans (Missouri Department of Transportation, written commun., 2000) indicates that pier 11 is founded on a caisson on bedrock, having about 42 ft of bed material between the bottom of the scour hole and bedrock (fig. 21; table 7). In the vicinity of pier 10 (fig. 20), a moderate scour hole had a minimum channel-bed elevation of about 330 ft (table 7), which is about 6 ft below the average channel elevation upstream from the pier (fig. 21). Pier 10 also is founded on a caisson on bedrock, having about 85 ft of bed material between the bottom of the scour hole and bedrock (fig. 21; table 7). Piers 12 and 13 are founded on footings on the exposed bedrock on the right bank, with no apparent scour hole near either (figs. 20, 21; table 7). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (American Association of State Highway Transportation Officials, 2012; Brown and others, 2010), but full exposure of usually buried substructural elements warrants special consideration and observation, even when designed to be exposed. The surveyed bed generally was lower than the original ground line from 1940 bridge plans between piers 9 and 10 and between piers 11 and 13, and higher than the original ground line between piers 10 and 11 (fig. 21). The surveyed bed was approximately the same as the bed from the Level II scour survey in 2000 (Huizinga and Rydlund, 2004), except on the left bank (fig. 21); however, the ground line from the Level II bridge scour assessment was along the downstream side of the bridge and may have incorporated part of the downstream spur dike (fig. 20).

The vertically averaged velocity vectors indicate mostly uniform flow in the thalweg, with areas of shear along the right side of the channel (fig. 22). Velocities ranged from about 7 to 9 ft/s for most of the channel, with locally lower velocities and flow reversal along the banks and downstream from pier 10. Furthermore, flow approached pier 10 from the left, causing an asymmetric scour hole that is longer and slightly deeper on the left side (fig. 20). The other piers were mostly aligned with flow, causing minimal flow disturbance downstream (fig. 22).

Structure L0135 on State Highway 51 at Chester, Illinois.

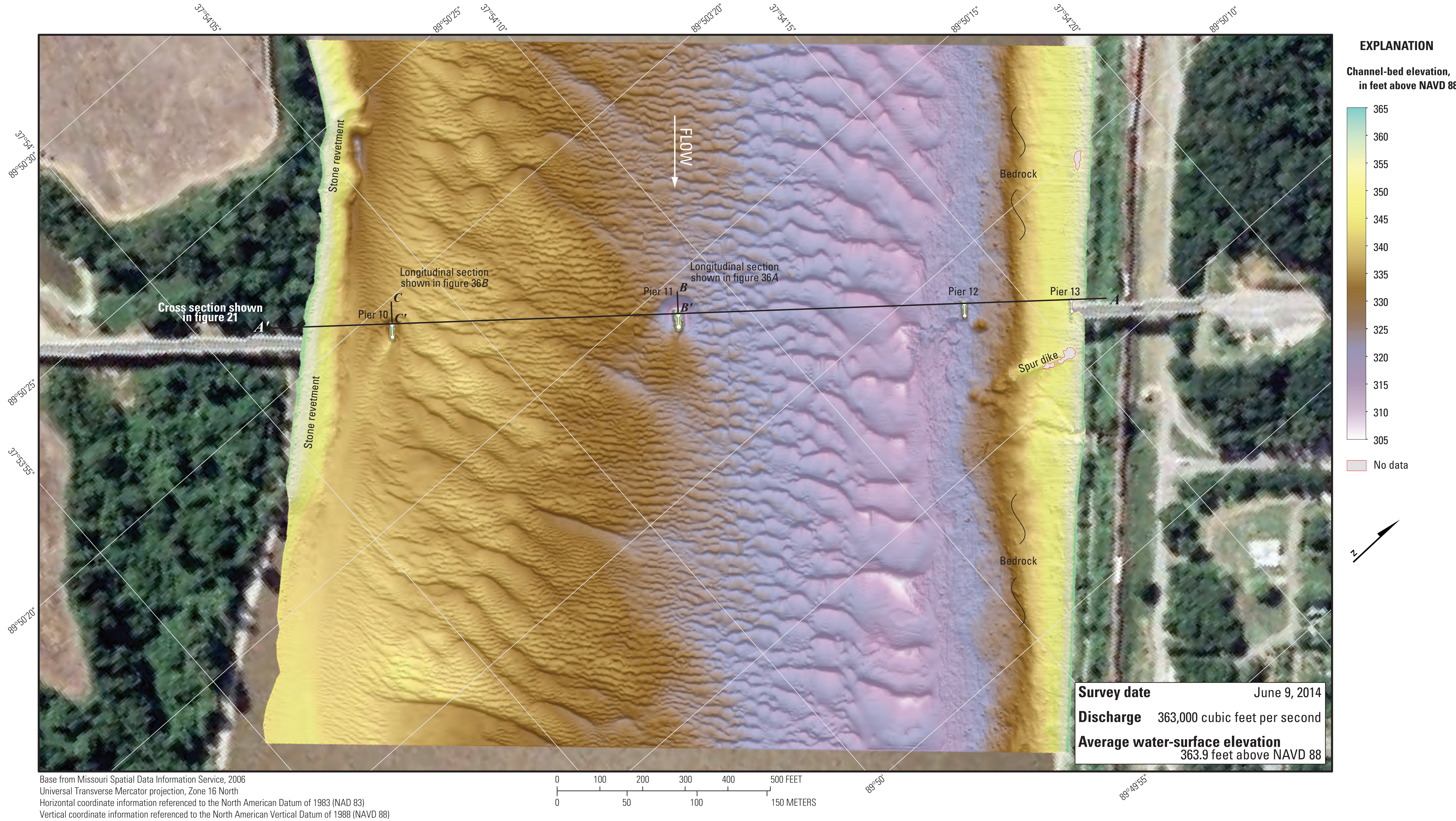


Figure 20. Bathymetric survey of the Mississippi River channel in the vicinity of structure L0135 on State Highway 51 at Chester, Illinois.

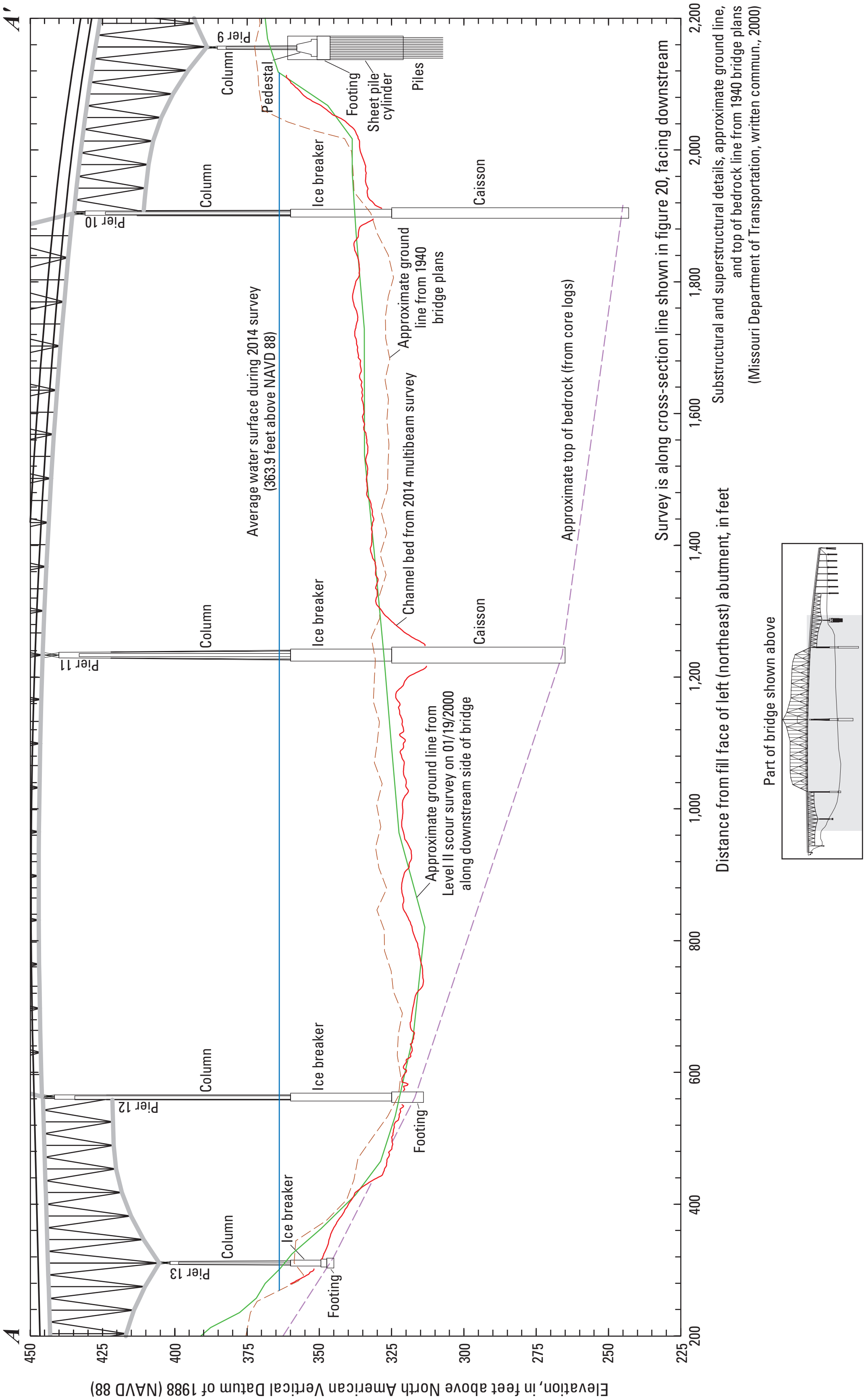


Figure 21. Key features, substructural and superstructural details, and surveyed channel bed of structure L0135 on State Highway 51 over the Mississippi River at Chester, Illinois.

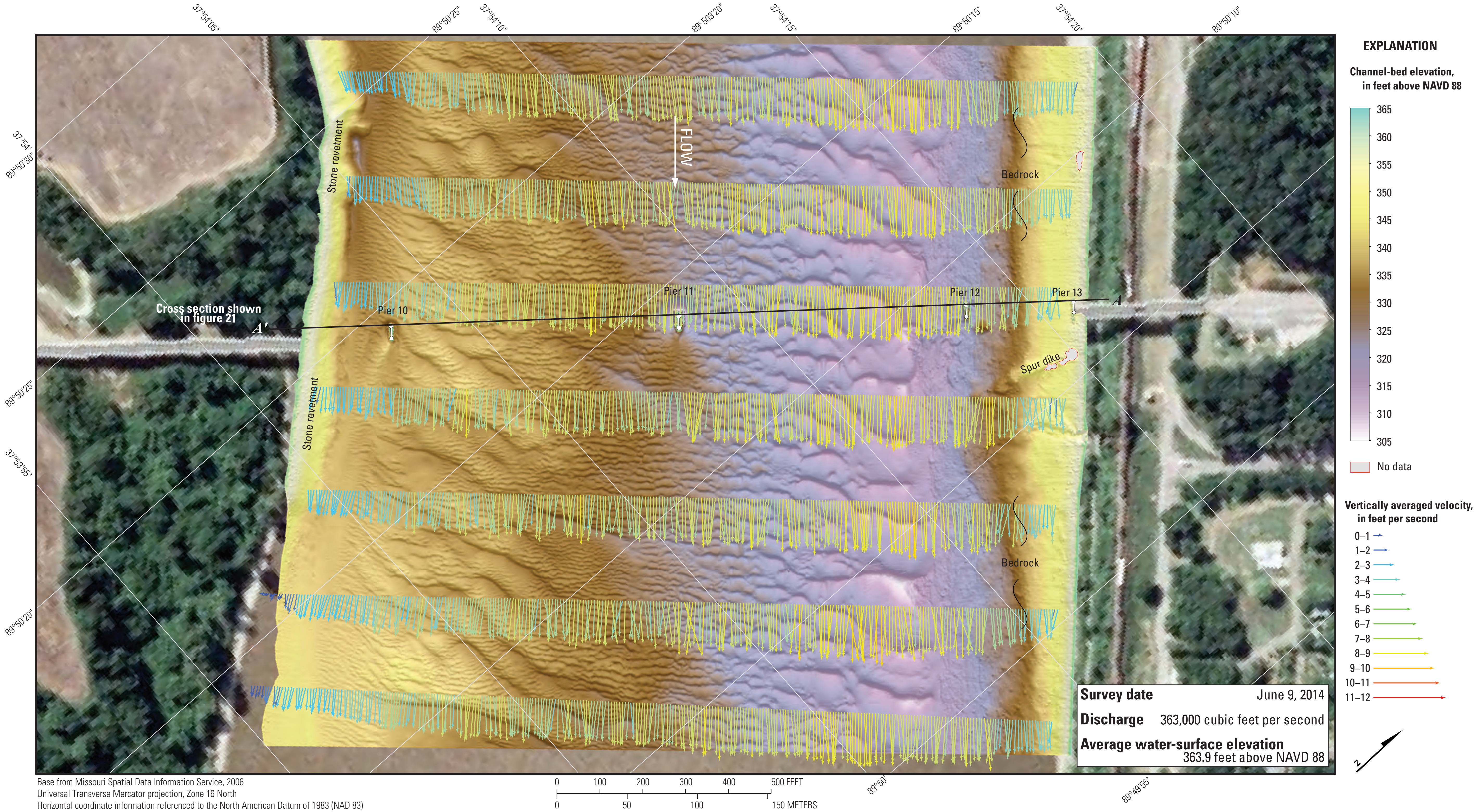


Figure 22. Bathymetry and vertically averaged velocities of the Mississippi River channel in the vicinity of structure L0135 on State Highway 51 at Chester, Illinois.

Structure A5076 on State Highway 34 at Cape Girardeau, Missouri

Structure A5076 (site 37) on State Highway 34 crosses the Mississippi River at RM 51.5 at Cape Girardeau, Mo., southeast of and downstream from Chester, Ill., and St. Louis, Mo. (fig. 1; table 2). The site was surveyed on June 10, 2014, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 331.7 ft (table 3). Discharge on the Mississippi River was about 377,000 ft^3/s during the survey (table 3).

The survey area was about 1,640 ft long and about 1,970 ft wide (perpendicular to flow), extending across the active channel from the left (east) bank to the right (west) bank in the main channel (fig. 23). The upstream end of the survey area was about 730 ft upstream from the centerline of structure A5076 at pier 3, and piers 2 through 7 were in the water; however, piers 2 and 7 were in very shallow water on the right and left banks, respectively. The channel-bed elevations ranged from about 279 to 316 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data), except in the well-defined channel thalweg along the right bank, and downstream from piers 3 and 4 (table 3). Numerous small to medium dunes and ripples were present throughout the channel. The area on the left bank upstream from the bridge was approximately 15 to 20 ft shallower than on the right side of the channel (fig. 23).

Piers 3 and 4 seemed to be partially surrounded by piles of riprap or rock (figs. 23, 1–8*E* through 1–8*H*), with additional scour downstream from the piers reaching a minimum elevation of 272 ft near pier 3 and 275 near pier 4 (fig. 23; table 7). Poorly defined, minor scour holes were observed near piers 5 and 6 (figs. 23, 1–8*A* through 1–8*D*), having a minimum channel-bed elevation of about 297 ft at pier 5 and 311 ft at pier 6 (table 7). The minimum channel-bed elevation near pier 5 is about 12 ft above the elevation of the bottom of the pier seal course of 285.00 ft, and the minimum channel-bed elevation near pier 6 is about 19 ft above the elevation of the bottom of the pier seal course of 292.00 ft (fig. 24; table 7). Information from bridge plans (Missouri Department of Transportation, written commun., 2014) indicates that piers 3 and 4 are founded on caissons on bedrock, having about 22 ft of bed material between the bottom of the scour hole and bedrock at pier 3, and 32 ft of material at pier 4. Piers 5 through 7 are founded on shafts drilled as much as 22 ft into bedrock, having about 52 ft of bed material between the bottom of the scour hole and bedrock at pier 5, and about 66 ft of material at pier 6 (fig. 24; table 7). The surveyed bed generally was similar to the original ground line in 1996 from bridge plans, except near pier 4 (fig. 24).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the thalweg of the channel along the right bank, ranging from about 5 to 9 ft/s with minor variations in velocity across the sections (fig. 25). Moderate non-uniform flow was observed along the left side of the channel, particularly downstream from the spur dike on the left bank. Piers 3 and 4 were skewed to approach flow, causing substantial wake vortices with flow reversal and well-defined deposition ridges downstream (figs. 23, 25).

Structure A5076 on State Highway 34 at Cape Girardeau, Missouri.

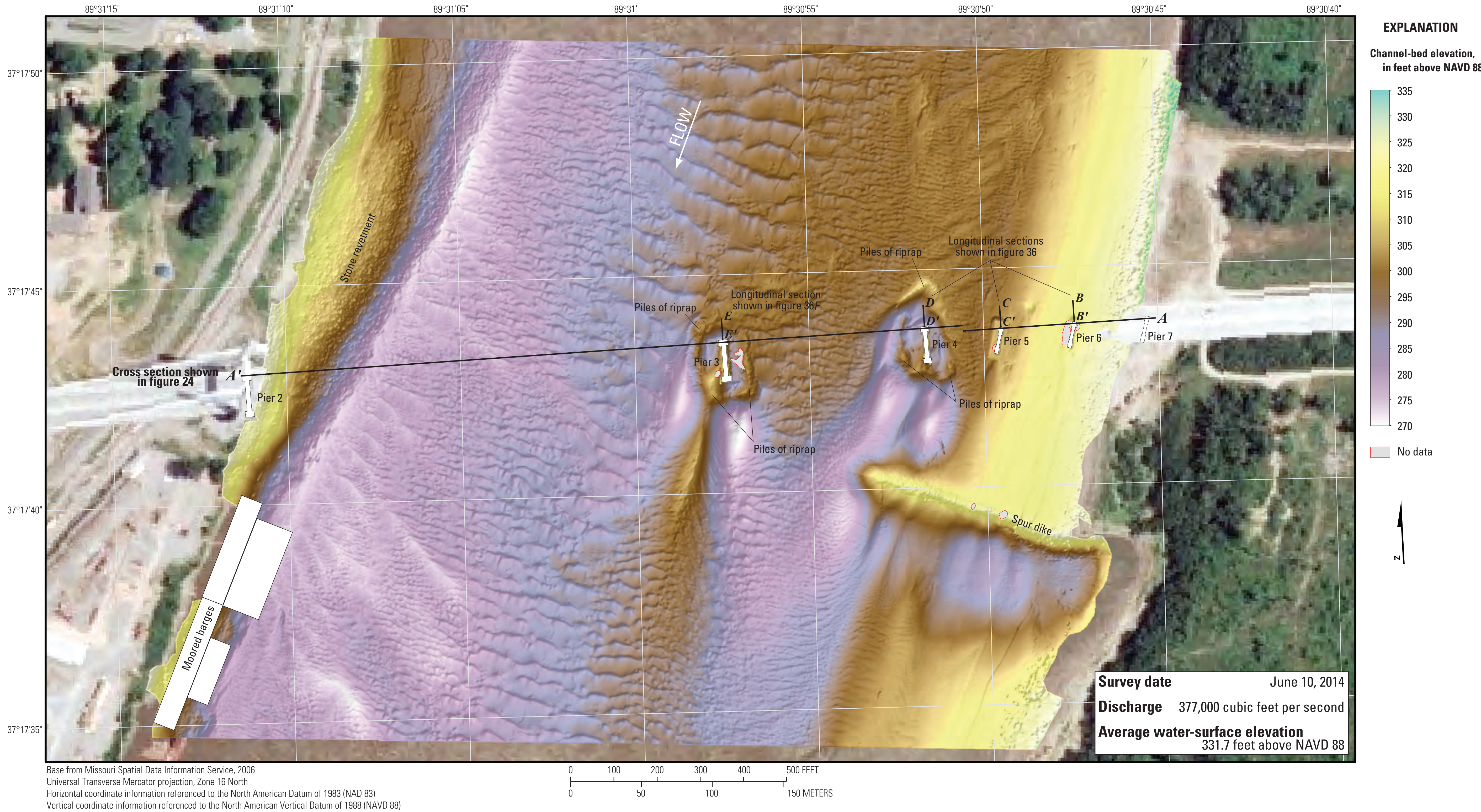


Figure 23. Bathymetric survey of the Mississippi River channel in the vicinity of structure A5076 on State Highway 34 at Cape Girardeau, Missouri.

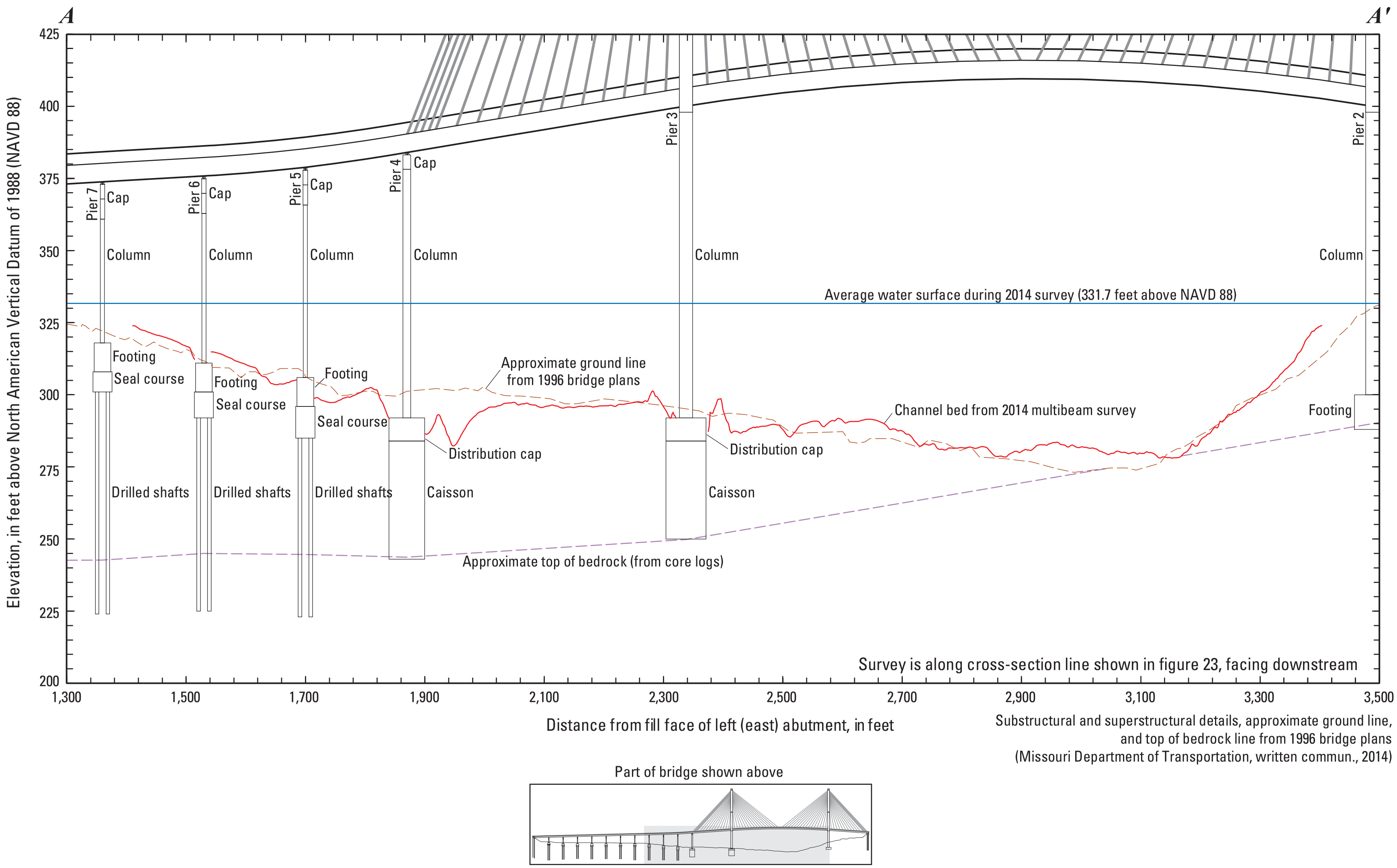


Figure 24. Key features, substructural and superstructural details, and surveyed channel bed of structure A5076 on State Highway 34 over the Mississippi River at Cape Girardeau, Missouri.

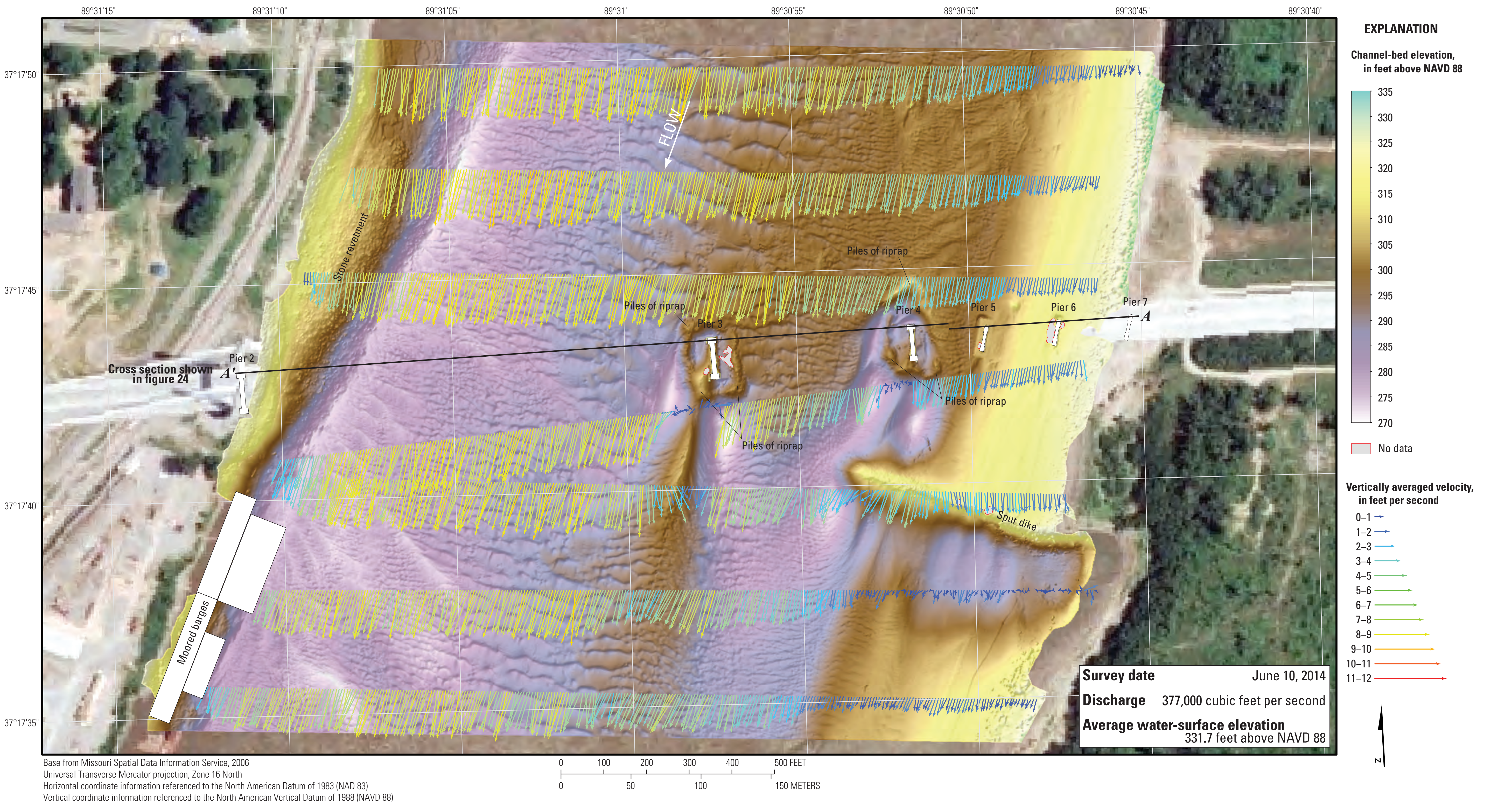


Figure 25. Bathymetry and vertically averaged velocities of the Mississippi River channel in the vicinity of structure A5076 on State Highway 34 at Cape Girardeau, Missouri.

Structure A1700 on Interstate 155 near Caruthersville, Missouri

Structure A1700 (site 38) on Interstate 155 crosses the Mississippi River at RM 838.9 (of the lower Mississippi River) near Caruthersville, Mo., in the southeastern corner of Missouri. (fig. 1; table 2). The site was surveyed on June 11, 2014, for the current (2014) study (hereinafter referred to as “the 2014 survey”), and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 251.8 ft (table 3). Discharge on the Mississippi River was about 629,000 ft^3/s during the 2014 survey (table 3).

The 2014 survey area was about 1,640 ft long and about 2,710 ft extending across the active channel from the left (southeast) bank to the right (northwest) bank in the main channel (fig. 26). The upstream end of the 2014 survey area was about 675 ft upstream from the centerline of structure A1700, and bent 14 and piers 15 through 21 were in the water; however, bent 14 and pier 21 were in shallow water on the right and left banks, respectively. The channel-bed elevations ranged from about 189 to 226 ft for most of the surveyed area (5 to 95 percentile range of the bathymetric data), except in areas of local scour on the right bank near the bridge and on the left bank near the downstream end of the reach (table 3). A few medium to large dunes were observed in the channel, as well as numerous small dunes and ripples throughout the channel (fig. 26).

In the vicinity of pier 20, a small to moderate scour hole had a minimum channel-bed elevation of about 188 ft (table 7), which is about 10 ft below the average channel elevation upstream from the pier (fig. 26; table 7). In the vicinity of pier 17, a small scour hole had a minimum channel-bed elevation of about 202 ft (table 7), which is about 7 ft below the average channel elevation upstream from the pier (fig. 26; table 7). Although a discernable scour hole was not observed near pier 16 (fig. 26), the minimum channel-bed elevation near that pier was 192 ft, which is about 4.5 ft below the bottom of the seal course elevation for that pier (fig. 27; table 7).

Information from bridge plans (Missouri Department of Transportation, written commun., 2007) indicates that bent 14 and piers 15 to 18 are founded on piles, and piers 19 to 21 are founded on caissons, all with an unknown depth to bedrock (fig. 27; table 7); however, piers 18, 19, and 20 each are surrounded by a riprap blanket that seems to mitigate scour to some extent (fig. 27). These riprap blankets were installed at the time of bridge construction in 1973 (Missouri Department of Transportation, written commun., 2007), and were observed during the 2014 survey (figs. 1–9*B* through 1–9*G*). Piers 15 and 21 were embedded in the stone revetment along the banks (figs. 26, 1–9*A*, 1–10*E*, 1–10*F*), and pier 16 seems to be surrounded by several almost random piles of riprap which may help mitigate scour (figs. 26, 1–10*C*, 1–10*D*).

This site has been the subject of several multibeam surveys that provide bathymetry at a variety of flow conditions for comparison. The earliest survey was a proof-of-concept survey on December 10, 2008 (hereinafter referred to as “the 2008 survey”), in cooperation with the Tennessee Department of Transportation (TNDOT). The average water-surface elevation of the river in the survey area for the 2008 survey, determined by the RTK GNSS tide solution, was 228.4 ft (table 8). Discharge on the Mississippi River was about 156,000 ft^3/s during the 2008 survey, as determined at the U.S. Army Corps of Engineers streamgage upstream at Hickmann, Ky., for December 9, 2008, to allow for time of travel to Caruthersville (Jeanne C. Burns, U.S. Army Corps of Engineers, written commun., 2014; fig. 1; table 8).

The 2008 survey area was about 1,525 ft long and about 2,380 ft wide, extending across most of the active channel from the left (southeast) bank to the base of the right (northwest) bank in the main channel (fig. 28). The upstream end of the 2008 survey area was about 690 ft upstream from the centerline of structure A1700, and piers 15 through 20 were in the water; however, pier 15 was in shallow water on the right bank, and not surveyed. A few medium to large dunes with few ripples were observed in the right side of the channel, and numerous small dunes and ripples were observed in the left side of the channel (fig. 28).

Structure A1700 on Interstate 155 near Caruthersville, Missouri.

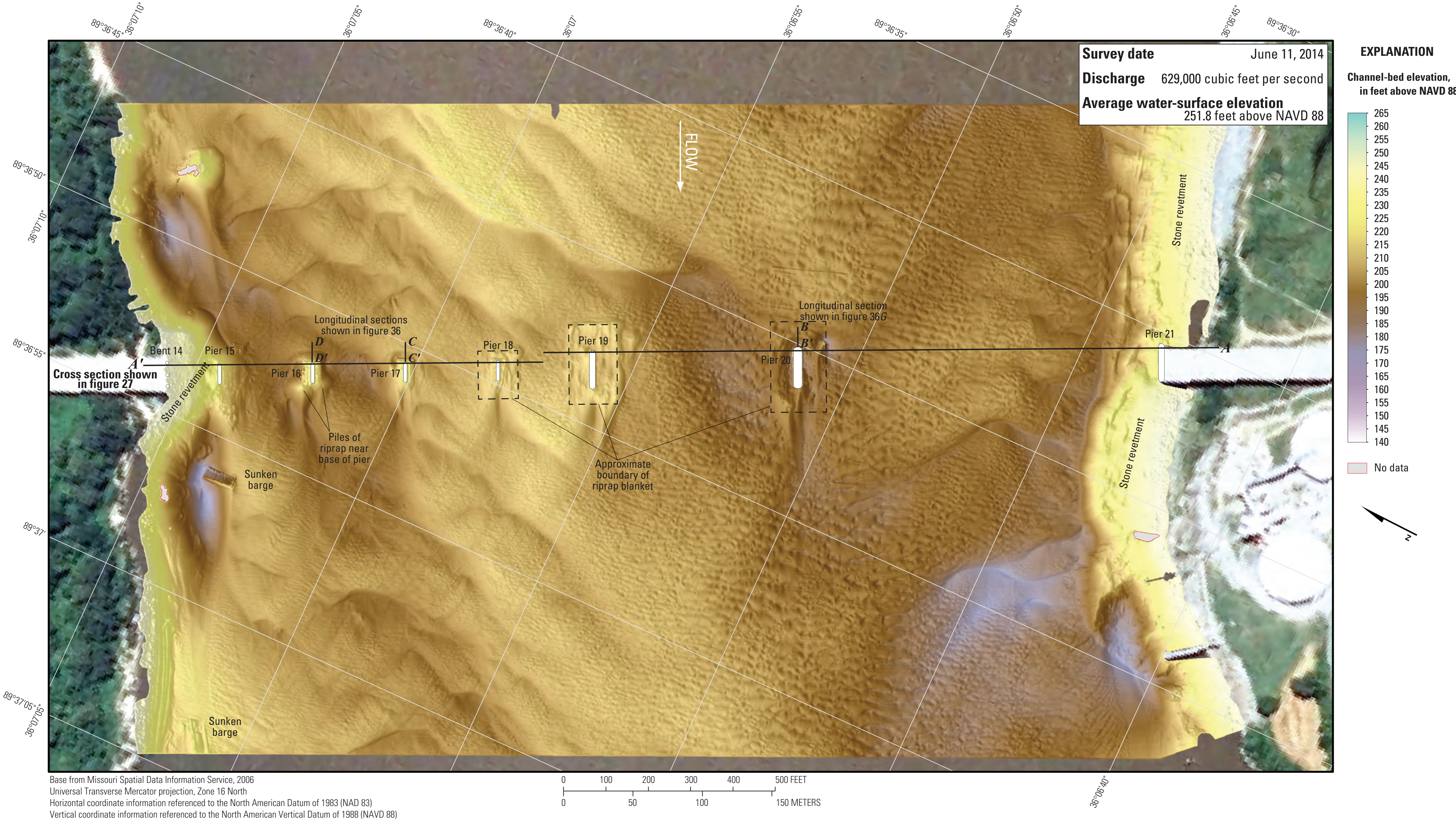


Figure 26. Bathymetric survey of the Mississippi River channel in the vicinity of structure A1700 on Interstate 155 near Caruthersville, Missouri, on June 11, 2014.

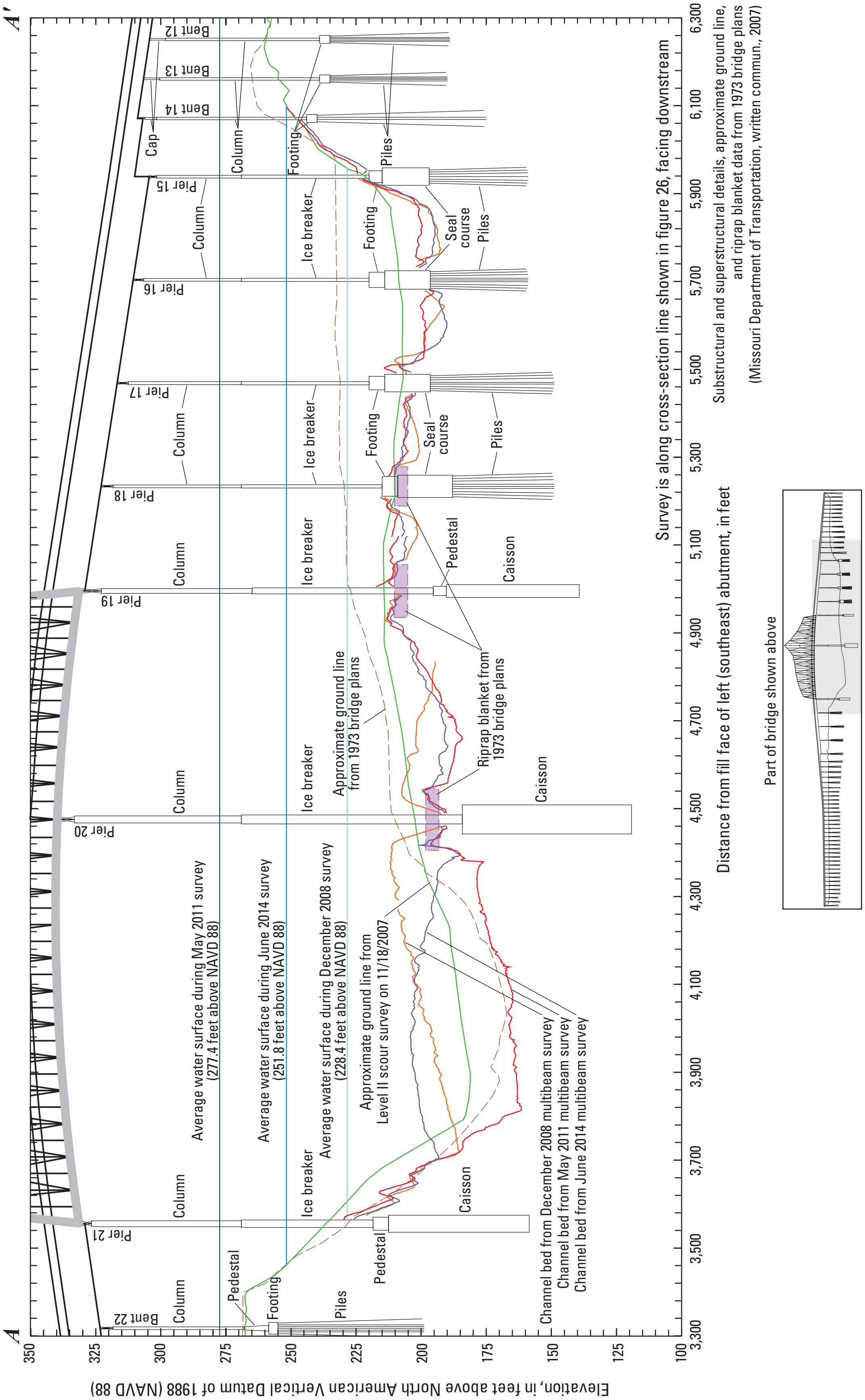


Figure 27. Key features, substructural and superstructural details, and surveyed channel bed of structure A1700 on Interstate 155 near Caruthersville, Missouri.

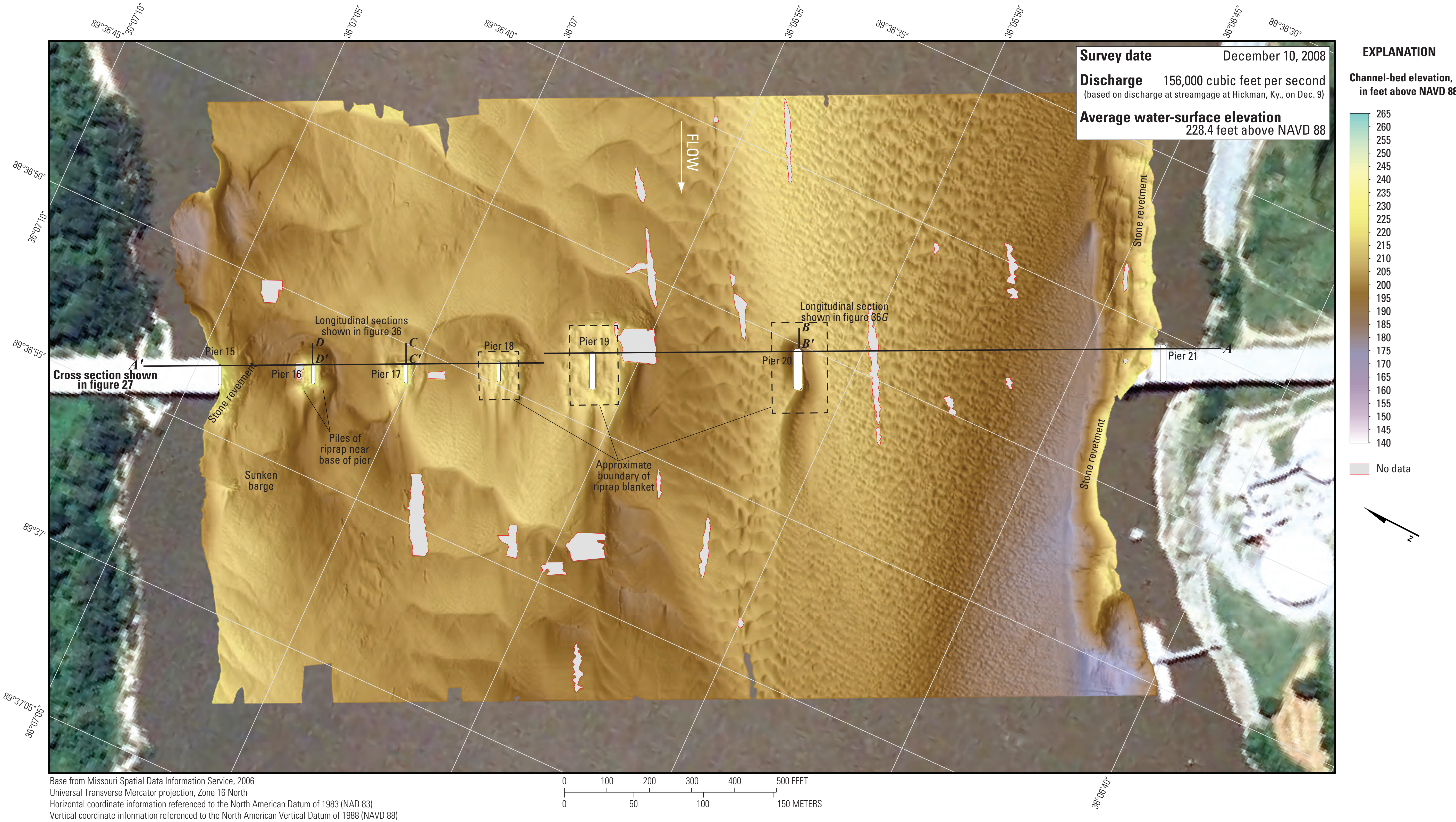


Figure 28. Bathymetric survey of the Mississippi River channel in the vicinity of structure A1700 on Interstate 155 near Caruthersville, Missouri, on December 10, 2008.

During the 2008 survey, a moderate to substantial scour hole observed near pier 20 (fig. 28) had a minimum channel-bed elevation of about 191 ft, about 20 ft below the average channel elevation upstream from the pier (fig. 28). The scour hole is asymmetric, which implies the pier is skewed to approach flow, likely the result of a substantial bend in the river upstream from the survey area and the bulge in the left bank downstream from the bridge (fig. 28). Similar to the 2014 survey, a discernable scour hole was not observed near pier 16 (fig. 28), the piles of riprap were observed, and the minimum channel-bed elevation near that pier was 192 ft, which is about 4.5 ft below the bottom of the seal course elevation for that pier (fig. 27; table 7). As in the 2014 survey, the riprap blankets around piers 18 and 19 were observed during the 2008 survey (fig. 28); the blanket around pier 20 was not observed, but apparently was covered in 15 to 20 feet of fluvial material deposited on top of the riprap blanket (fig. 27).

An emergency survey of the site occurred during flooding on May 5, 2011 (hereinafter referred to as "the 2011 survey") at the request of MoDOT and TNDOT. Structure A1700 is the only bridge crossing the Mississippi River between Cairo, Ill., and Memphis, Tenn., and it was highly desirable that the bridge remain open to traffic, provided it was safe to do so given the record flood conditions on the Mississippi River at the time. The average water-surface elevation of the river in the survey area for the 2011 survey, determined by the RTK GNSS tide solution, was 277.4 ft (table 8). Discharge on the Mississippi River was about 2,040,000 ft^3/s during the 2011 survey, determined from a special discharge measurement at the stage-gaging station upstream at Tiptonville, Tenn. (Koenig and Holmes, 2013; fig. 1; table 8).

The 2011 survey area was about 1,640 ft long and about 2,625 ft wide, extending across the active channel from the left (southeast) bank to the right (northwest) bank in the main channel (fig. 29). The upstream end of the 2011 survey area was about 790 ft upstream from the centerline of structure A1700 (fig. 29). Because of the flood conditions on the Mississippi River, all the piers and bents of the bridge were in the water; however, the condition of the channel bed near bent 14 and piers 15 through 21 were of principal concern. Bent 14 and pier 21 were in shallow water on the right and left banks, respectively (fig. 29). A substantial, deep thalweg was present throughout the reach along the left bank, with several very large dunes (17 to 20 ft), and numerous other large, medium, and small dunes and ripples were observed throughout the channel (fig. 29).

In the 2011 survey, the riprap blanket around pier 20 was evident (figs. 29, 30), and the scour hole from the 2008 survey was obliterated by the removal of a substantial depth of bed material (figs. 27, 29). Similar to the 2008 and 2014 surveys, a discernable scour hole was not observed near pier 16 (fig. 29), the piles of riprap were observed, and the minimum channel-bed elevation near that pier was 195 ft, which is about 1.5 ft below the bottom of the seal course elevation for that pier (fig. 27; table 7). As in the 2008 and 2014 surveys, the riprap blankets around piers 18 and 19 were observed during the 2011 survey (fig. 29). The lower elevations of the thalweg caused several sunken barges to appear that were buried in sediment in the other surveys (fig. 29). The extent of the riprap blanket around pier 20 is clearly seen in the shaded TIN images for pier 20, as is more of the sunken object near the pier (fig. 30).

The surveyed bed generally varied substantially between surveys on the left side of the channel (from the left bank to pier 19), and varied minimally on the right side (from pier 19 to the right bank; fig. 27). The 2008 survey was during relatively low flow conditions on the Mississippi River, and the cross-section along the upstream side of the bridge generally was the highest of all the surveys in the left side of the channel; however, on the right side of the channel, the 2008 surveyed bed generally was the lowest (fig. 27). Conversely, the 2011 survey was during extreme flood conditions, and the cross-section was the lowest in the left side of the channel, and the highest in the right side (fig. 27). At the deepest point, the 2011 surveyed bed was 161 ft, which is 24 ft below the lowest elevation of the cross sections from both the 2008 survey and 2014 survey of 185 ft. The riprap blanket around pier 20 is not apparent in the 2008 survey (fig. 28), and the scour hole observed during the 2008 survey seems to penetrate the riprap blanket around that pier (fig. 27). The riprap blanket is much more evident in the subsequent 2011 and 2014 surveys (figs. 26, 29), and the cross sections from those subsequent surveys confirm that the riprap blanket has seemed to slump around the nose of the pier (fig. 27). Whether this slumped blanket is the result of how the riprap was dumped around the pier, or the result of armoring of subsequent scour activity is unknown.

The difference between the surveys on June 11, 2014, and the flooding of May 5, 2011 (fig. 31), indicates substantial deposition of as much as 30 ft has occurred throughout the left side of the channel. On the right side of the channel, scour of as much as 20 ft along with deposition of as much as 10 ft has occurred (fig. 31). The mean difference between the May 2011 and June 2014 bathymetric surfaces (9.05 ft, table 8) indicates substantial deposition overall, as evident in the difference map, and consistent with the much lower flow rate of the 2014 survey compared to the 2011 survey (table 8); however, the maximum difference observed near the upstream pier faces was -5.5 ft (table 8). The stone revetment on the left bank seems to have areas of scour and deposition indicative of sediment deposit and removal of slumping of the revetment (fig. 31). No scour or deposition was observed on the stone revetment on the right bank near bent 14 and pier 15. There was scour and deposition of up to 5 ft within the boundaries of the riprap blankets around piers 18, 19, and 20. The appearance of substantial deposition or scour near the piers results from changes near vertical surfaces from minor horizontal positional variances (of about 3 feet) between the surveys (fig. 31).

The difference between the surveys on June 11, 2014, and December 10, 2008 (fig. 32), indicates an apparent balance between areas of moderate scour and moderate deposition of up to 15 ft each; however, the 2011 flood event obviously

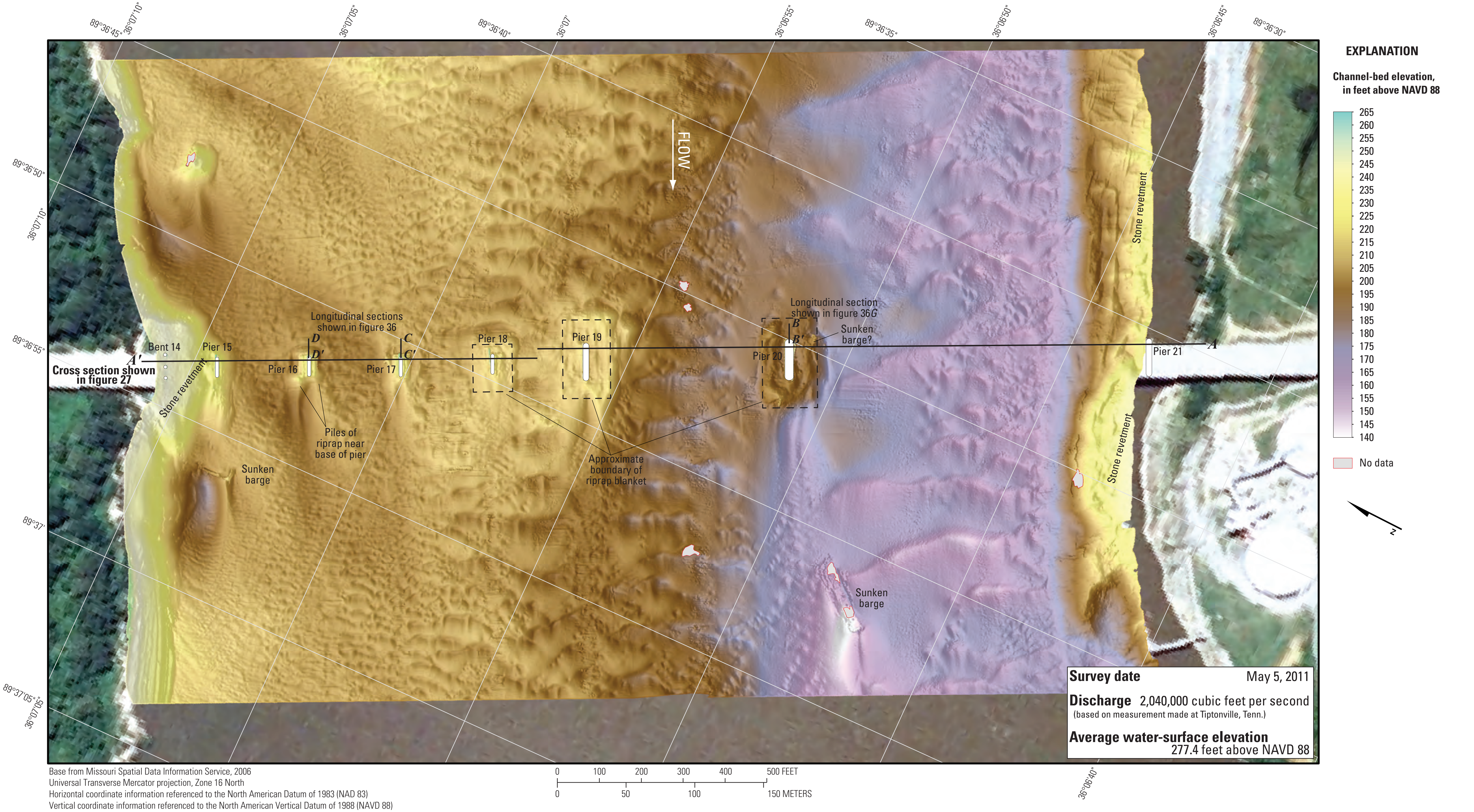


Figure 29. Bathymetric survey of the Mississippi River channel in the vicinity of structure A1700 on Interstate 155 near Caruthersville, Missouri, during flooding on May 5, 2011.

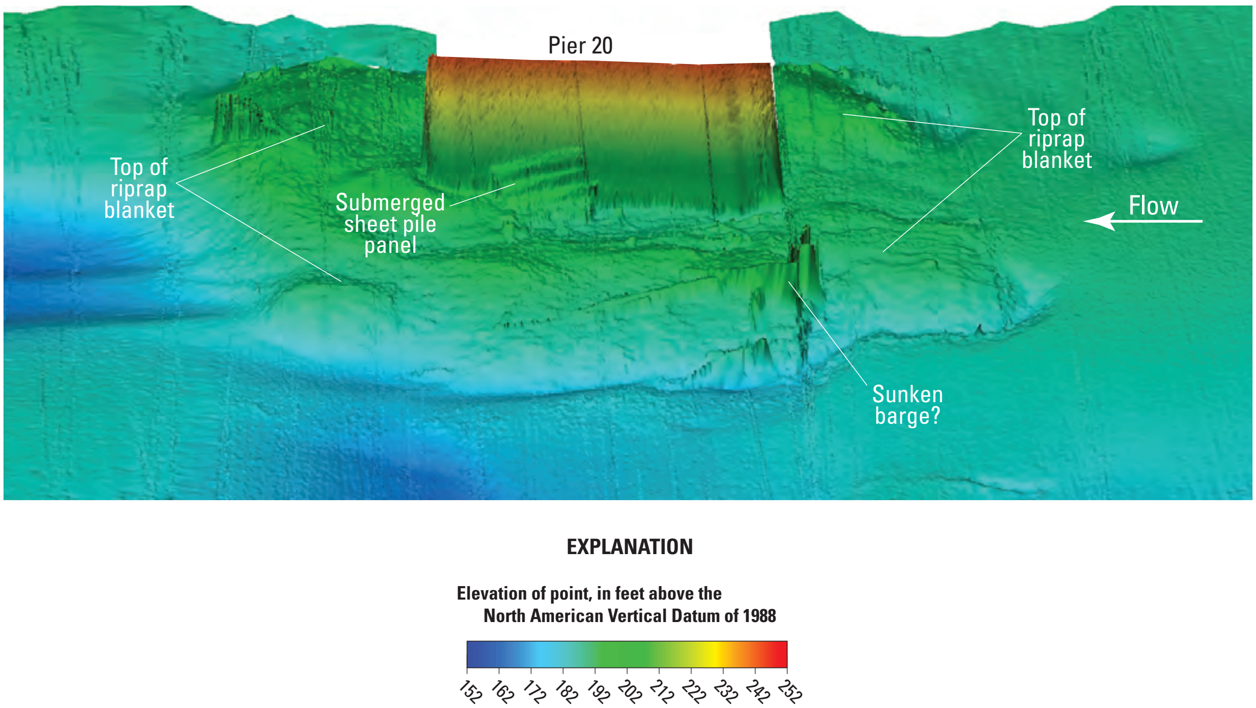


Figure 30. Shaded triangulated irregular network (TIN) visualization of the channel bed and left (southeast) side of main channel pier 20 of structure A1700 on Interstate 155 over the Mississippi River near Caruthersville, Missouri, during flooding on May 5, 2011.

had a substantial impact on the bathymetry between these two surveys. The mean difference between the December 2008 and June 2014 bathymetric surfaces (-0.52 ft, table 8) indicates only minor apparent scour overall, despite the substantially different flow rates (473,000 ft^3/s difference, table 8). The maximum difference observed near the upstream pier faces was -3.5 ft (table 8). The stone revetment on the left bank seems to have only small areas of scour and deposition indicative of sediment deposit and removal, whereas scour of as much as 5 ft has occurred at the stone revetment on the right bank near bent 14 and pier 15 (fig. 32). Only minor deposition was observed within the boundaries of the riprap blankets around piers 18 and 19, whereas the bed material near pier 20 experienced moderate to substantial scour, likely down to the riprap blanket as indicated by the area of no change near the pier. The appearance of substantial deposition or scour near the piers results from changes near vertical surfaces from minor horizontal positional variances (of about 3 feet) between the surveys (fig. 32).

The difference between the surveys during flooding on May 5, 2011, and December 10, 2008 (fig. 33), indicates substantial scour of as much as 75 ft has occurred throughout the left side of the channel. On the right side of the channel, scour of as much as 20 ft is balanced by deposition of as much as 20 ft. The mean difference (-10.8 ft) indicates substantial scour overall, as evident in the difference map, and consistent with the much higher flow rate of the 2011 survey compared to the 2008 survey (table 8). The stone revetment on the left bank seems to have areas of scour and deposition indicative of sediment deposit and removal or of slumping of the revetment, as does the stone revetment near pier 15 (fig. 33). There was deposition of up to 3 ft within the boundaries of the riprap blankets around piers 18 and 19, whereas the bed material near pier 20 experienced substantial scour, likely down to the riprap blanket as indicated by the area of no change near the pier. The appearance of substantial deposition or scour near the piers (particularly piers 16 and 17) results from changes near vertical surfaces from minor horizontal positional variances (of about 3 feet) between the surveys (fig. 33).

The vertically averaged velocity vectors for the 2014 survey indicate mostly uniform flow throughout a majority of the reach, with small areas of flow disturbance and shear flow, particularly along the banks near the constrictions at the bridge and downstream (fig. 34). Velocities ranged from about 6 to 10 ft/s for the left side of the channel, and from 2 to 6 ft/s for the right side of the channel, and low velocities and flow reversals were observed downstream from the bank constrictions at the bridge and the pile near the upstream end of the reach. The piers generally were aligned with flow, with minimal wake vortices observed downstream (fig. 34). Velocity data were not collected in the 2008 or 2011 surveys.

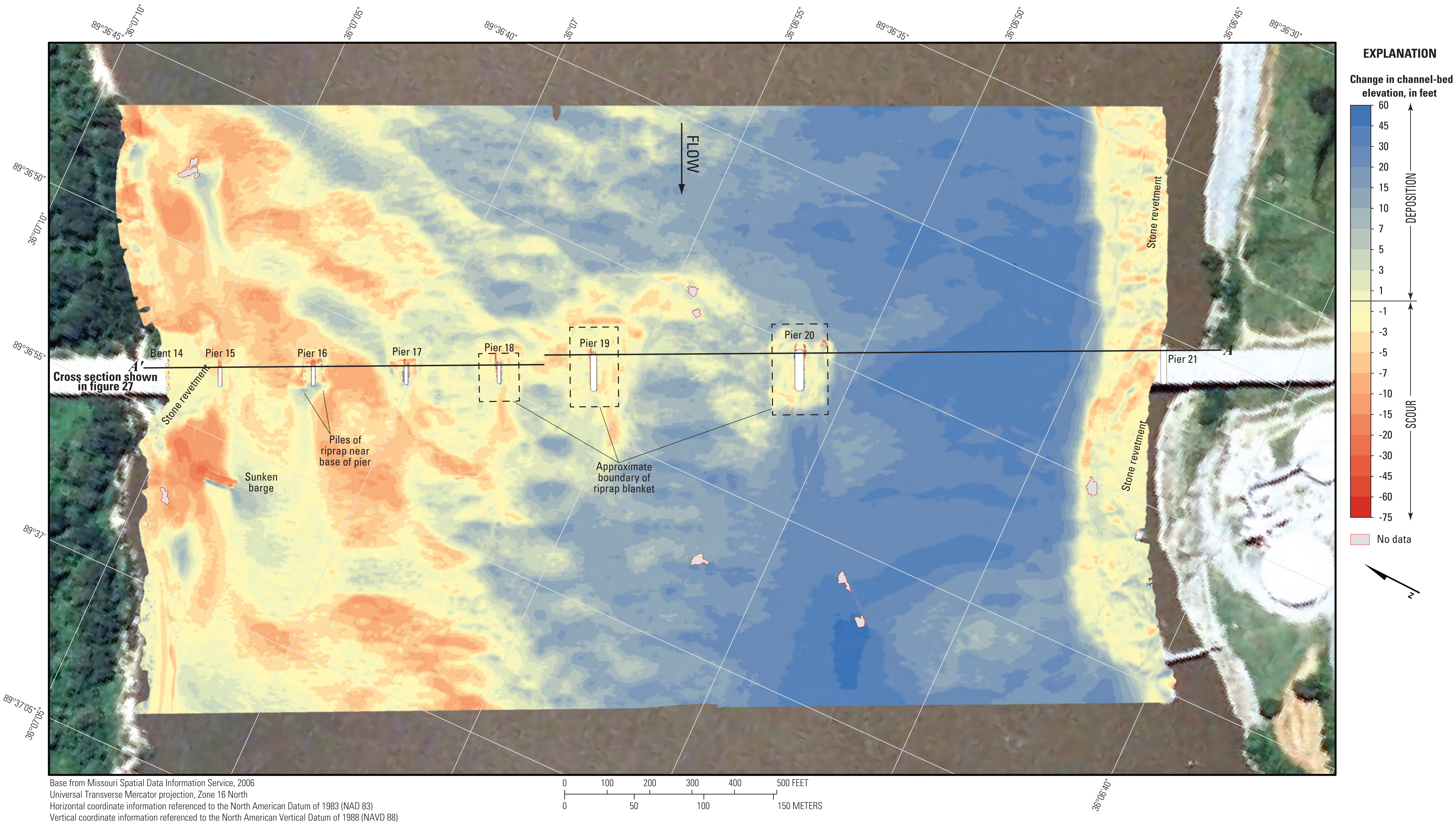


Figure 31. Difference between bathymetric surfaces created from surveys of the Mississippi River channel in the vicinity of structure A1700 on Interstate 155 near Caruthersville, Missouri, on June 11, 2014, and May 5, 2011.

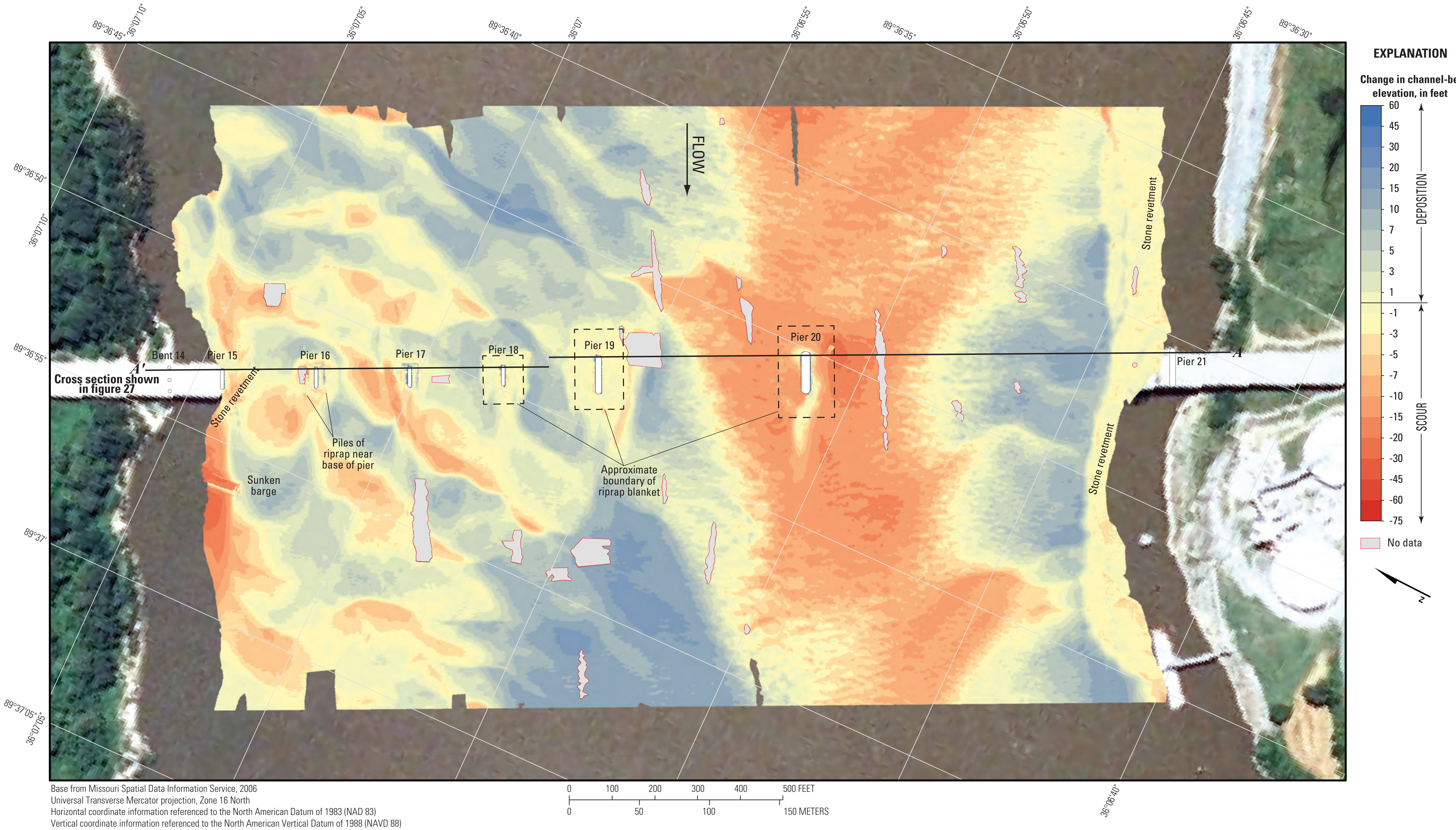


Figure 32. Difference between bathymetric surfaces created from surveys of the Mississippi River channel in the vicinity of structure A1700 on Interstate 155 near Caruthersville, Missouri, on June 11, 2014, and December 10, 2008.

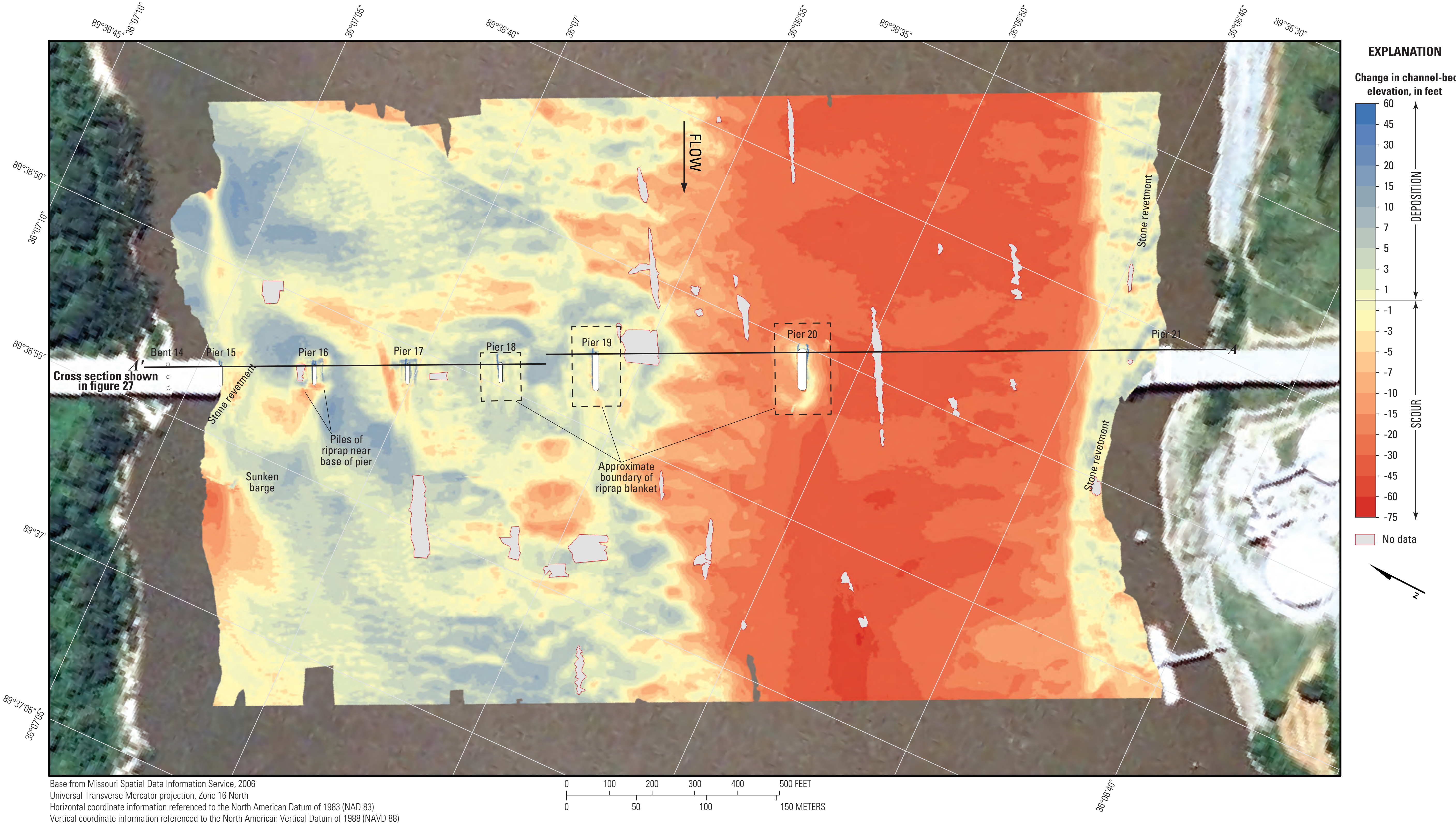


Figure 33. Difference between bathymetric surfaces created from surveys of the Mississippi River channel in the vicinity of structure A1700 on Interstate 155 near Caruthersville, Missouri, on May 5, 2011, and December 10, 2008.

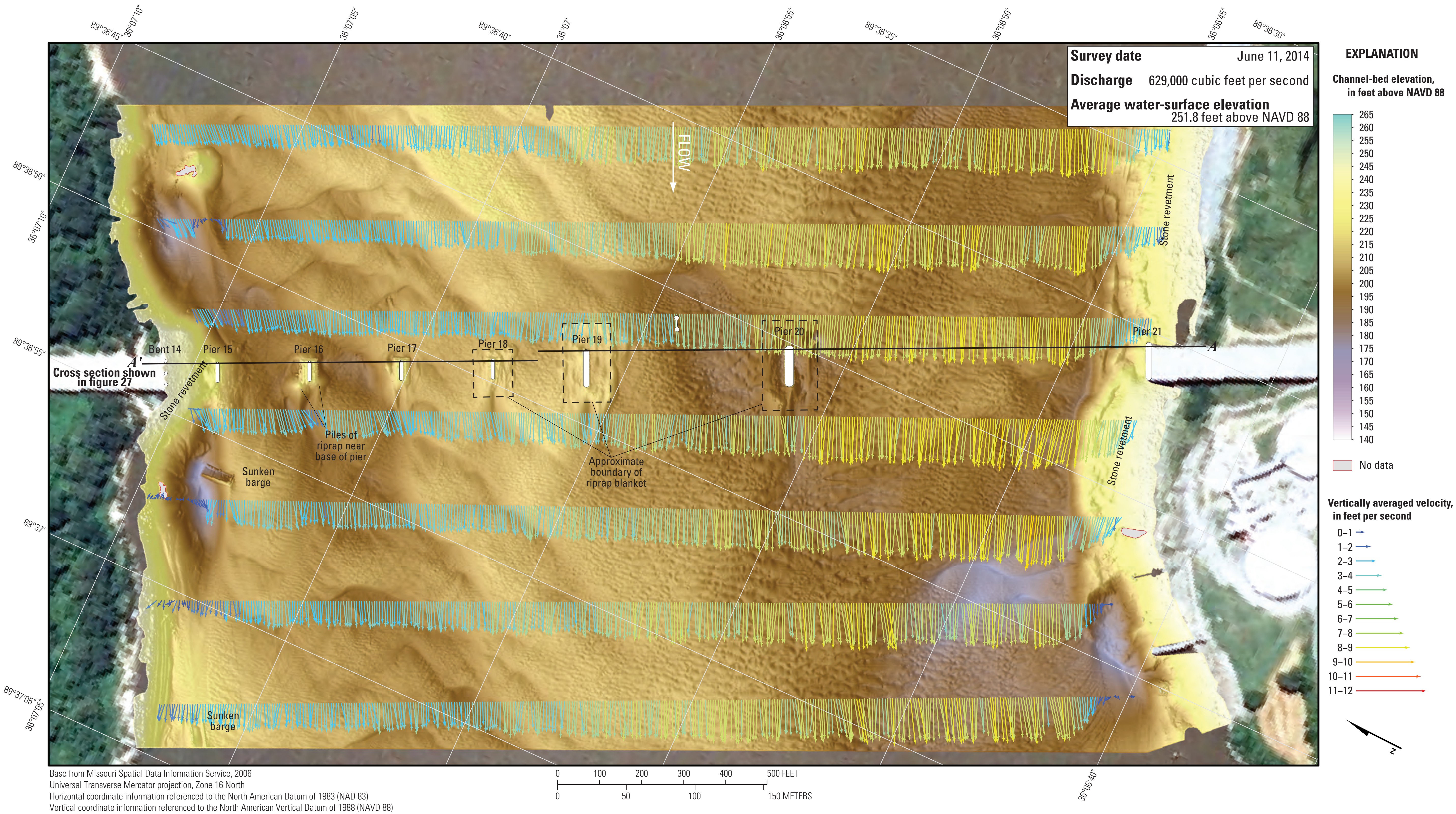


Figure 34. Bathymetry and vertically averaged velocities of the Mississippi River channel in the vicinity of structure A1700 on Interstate 155 near Caruthersville, Missouri, on June 11, 2014.

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 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 occurs 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, and result in a decrease and subsequent increase of the channel-bed elevation during the passage of a flood.

Dynamics of flooding can be slightly different between the Missouri and Mississippi Rivers. Most large flood durations on both rivers can be measured in weeks and months because of the large upstream contributing drainage area; however, the presence of locks and dams on the Mississippi River upstream from St. Louis can lessen the magnitude and lengthen the duration of a given flood wave, particularly upstream from St. Louis. Downstream from St. Louis, the increase in drainage area from the Missouri River can increase the magnitude and lengthen the duration of a given flood wave if flood conditions on the Missouri River combine with flood conditions on the Mississippi, or a flood wave on one river may be entirely mitigated if the other river is not in flood. A similar phenomenon exists on the Mississippi River downstream from Cairo, Ill., based on the flow conditions on the Ohio River. As described in the "Description of Flow Conditions" section earlier in this report, the two surveys on the Missouri River (sites 1 and 2) were before or on the rising limb of a short-duration flood pulse (fig. 2*A*), the surveys at Hannibal and Louisiana on the Mississippi River upstream from St. Louis (sites 31 and 32) were near the peak or on the receding limb of a very short-duration flood pulse (fig. 2*B*), and the three surveys on the Mississippi River downstream from St. Louis (sites 36–38) were on the rising limb of a longer-duration flood pulse (fig. 2*B*). Huizinga (2014b) noted the fixed scour monitors on structures L0550 and A4997 at Jefferson City, Mo., indicated that many of the scour holes observed at the upstream nose of the piers does not fill in rapidly after the recession of a flood (see fig. 35 in Huizinga, 2014b); nevertheless, deposition does occur in the scour holes upon flood recession. At the sites for which previous bathymetry data exist and a change from flood conditions is available (sites 1, 2, and 38), 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 a lesser magnitude than the scour observed during a previous survey during flood conditions. Generally, this assumption proved to be true, particularly with respect to the depth of observed scour near the piers when compared to results from the 2011 flood.

For the two sites on the Missouri River (structure L0098 at Brownville, Neb., and dual bridge structure A3664 at St. Joseph, Mo. [sites 1 and 2]), flows were about 18 and 30 percent of the 2011 flow rate during the 2014 surveys, and water-surface elevations were about 14 and 17 ft lower in 2014 than in 2011 for site 1 and 2, respectively (table 8). At structure A1700 near Caruthersville, Mo. (site 38), the flow was 31 percent of the 2011 flow rate, and the 2014 water-surface elevation was about 26 ft lower than in 2011 (table 8). As expected, the bathymetric surfaces from the 2014 surveys were higher than the 2011 surveys for structures L0098 at Brownville, Neb., and A1700 near Caruthersville, Mo., with a mean difference between the bathymetric surfaces of 3.93 ft and 9.05 ft (higher) for L0098 and A1700, respectively (table 8; figs. 8, 31), likely the result of less material in transport through the bridge opening. However, the bathymetric surface from the 2014 survey was lower than the 2011 survey for structure A3664 at St. Joseph, Mo., with a mean difference between the bathymetric surfaces of -2.04 ft in 2014 than 2011 (table 8; fig. 12). Although this negative mean difference indicates overall net scour between the compared bathymetric surfaces, the survey at this site covered substantially less area in 2014 than the survey in 2011 (more than 27 percent less; table 8), and the area surveyed was along the thalweg and away from the spur dikes on the right bank (fig. 10), downstream from which deposition has been observed in other surveys during low to moderate-flow conditions (see figs. 29 and 40 in Huizinga, 2014b). It is likely that the area not surveyed in 2014 would have experienced deposition because it is on the inside of a bend in the river, and is implied by the deposition observed along the left edge of the 2014 survey area. The statistics of the differences between the bathymetric surfaces for this site may have been skewed by not including this area of potential deposition.

Despite the general deposition observed in 2014 compared to 2011, the depth of the scour hole from the upstream channel bed near the piers was greater in 2014 than in 2011 for the bridges on the Missouri River, which seems inconsistent with the lower flow conditions. At pier 3 of structure L0098 at Brownville, Neb. (site 1, fig. 1), the depth of the scour hole from the upstream channel was 19 ft in 2014 (table 7) compared to 17 ft in 2011 (table 6 in Huizinga [2012]). The relative similarity of the scour hole depths likely is a result of the similarity of the velocities in 2014 and 2011, which both were about 6 to 8 ft/s near pier 3 (fig. 9; see fig. 10 in Huizinga [2012]). At pier 10 of dual bridge structure A3664 at St. Joseph, Mo. (site 2, fig. 1), the depth of the scour hole was substantially greater at 19 ft in 2014 (table 7) compared to 10 ft in 2011 (table 6 from Huizinga [2012]). The velocities in the immediate vicinity of pier 10 were somewhat less in 2014 (about 8 ft/s, fig. 13) compared to 2011 (about 10 ft/s; see fig. 13 in Huizinga [2012]); however, the channel bed elevation was substantially lower near the end and downstream from the spur dike near pier 10 in 2014 compared to 2011 (figs. 11, 12), possibly because of wake vortices and shear flow from the end of the spur dike, all of which (depth, wake vortices, and shear) may have contributed to the difference in scour hole depth at the pier. Velocity differences and non-uniform flow were noted by Huizinga (2014b) to contribute to the relative size of scour holes in different events, which is consistent with the pier scour predictive equations in Richardson and Davis (2001). On the Mississippi River, at structure A1700 near Caruthersville, Mo. (site 38, fig. 1), the depth of the scour hole from the upstream channel bed near pier 20 was greatest during the lowest flow conditions in 2008 (fig. 28); however, scour at pier 20 was mitigated in 2011 and 2014 by the presence of a riprap blanket (figs. 29, 26), and the scour hole observed in 2008 was in bed sediment previously deposited above the riprap blanket (fig. 27).

A comparison of the dune sizes at the various sites also is indicative of the different flow regimes between 2011 and 2014. At structures L0098 at Brownville, Neb. (site 1, fig. 1), and A3664 at St. Joseph, Mo. (site 2, fig. 1), the dunes were smaller in magnitude, sometimes substantially, in 2014 (figs. 6, 10) than in 2011 (figs. 8, 12). Similarly, at structure A1700 near Caruthersville, Mo. (site 38, fig. 1), the dunes were substantially smaller in magnitude in the channel thalweg on the left side in 2014 than in 2011, whereas the dunes are smaller in 2011 than 2014 for the right side of the channel (figs. 26, 29). The dune sizes were similar on the right side of the channel in both the 2008 and 2014 surveys (figs. 26, 28). The small dunes and ripples superimposed on the larger dunes in the left side of the channel in 2014 were of a similar size to the small dunes and ripples throughout the left side of the channel in 2008 (figs. 26, 28).

Effects of Riprap Blankets near Piers

Several of the piers at the Mississippi River bridges had riprap blankets or piles of rock surrounding them (see figs. 14, 17, 23, 26). It is unknown whether all these features were specifically designed to resist scour, or if they simply were construction detritus or an ad-hoc placement of riprap to mitigate observed exposure of a particular substructural bridge element. Nevertheless, the presence of such a feature had a substantial effect on the observed scour at a given pier, particularly when compared to other piers at the same site without such a feature.

Piers 2 and 3 of structure K0932 at Louisiana, Mo. (site 32, fig. 1), were surrounded by riprap blankets, whereas pier 4 was not (fig. 17). The width and depth of the scour hole at pier 4 was substantially different from those at piers 2 and 3 (table 7; figs. 17, 18). Although the scour hole at pier 4 may have been exacerbated by the pier's proximity to the spur dike on the left bank immediately downstream from the bridge, the presence of a riprap blanket near piers 2 and 3 seemed to substantially limit the scour at those piers.

Piers 18 through 20 of structure A1700 near Caruthersville, Mo. (site 38, fig. 1), also were surrounded by riprap blankets (fig. 27) that were a minimum of 5 ft thick per the 1973 bridge plans (Missouri Department of Transportation, written commun., 2007). The blankets limited pier scour near piers 18 and 19 in all of the surveys, and prevented additional scour near pier 20 during the two later surveys at the site (figs. 26, 28, and 29); although scour was observed near pier 20 during the 2008 survey, the hole was in material deposited on top of the blanket (fig. 27). The top surface of the blanket around pier 20 is very irregular (figs. 26, 28, 29), and seemed to have a depression adjacent to the pier that seems to penetrate the top of the blanket (fig. 27), which may have been the result of back-filling an existing scour hole or other low spot when the blanket was installed, per 1973 bridge plans (Missouri Department of Transportation, written commun., 2007). The random piles of riprap around the base of pier 16 (figs. 26, 28, 29) may help mitigate scour near that pier.

Several other piers seemed partially surrounded by random piles of riprap or rock, which may or may not help mitigate scour near those piers. Piers 9 and 10 of structure A5054 at Hannibal, Mo. (site 31, fig. 1), have hummocks on either side that may be partial riprap blankets (fig. 14), and piers 3 and 4 of structure A5076 at Cape Girardeau, Mo. (site 37, fig. 1), seemed to be partially surrounded with piles of coarse material (fig. 23). However, the effectiveness of the scour mitigation is uncertain, because the placement seems random and non-uniform. Scour immediately downstream from piers 3 and 4 of structure A5076 at Cape Girardeau, Mo., was substantial (fig. 23).

Size and Shape of Scour Holes

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

For the various bridges in this study, flow velocities generally were greater in the deeper parts of the channel (the thalweg) and lower in the shallow parts of the channel. Of course, there were local exceptions, such as downstream from a spur dike where a local deep area may have had a low velocity (for example, figs. 9, 19, 25). Exceptions notwithstanding, the size of the scour holes at sites having more than one pier in the water was related to the depth and velocity of flow upstream from the pier in question, and consistent with the local pier scour equation in Richardson and Davis (2001); deeper flow or higher velocity generally resulted in larger, deeper scour holes than shallow flow or lower velocities (figs. 16, 22, 25) in the absence of a rock outcrop or riprap blanket that might limit local scour (piers 1–3 in fig. 19, piers 12–13 in fig. 22, and piers 18–20 in figs. 26, 28, 29). Similar findings have been observed during the various previous studies using the MBMS in Missouri (Huizinga, 2010, 2011, 2012, 2014b).

A longitudinal profile was drawn upstream from the nose of each pier with a well-defined scour hole (figs. 35, 36), and the approximate frontal slope (computed as horizontal distance over vertical distance, or run over rise) was determined for each hole (table 7). The frontal slope was not determined for piers with poorly defined scour holes or those on bedrock; however, the frontal slope was determined for scour holes at several piers surrounded by riprap blankets because they often were sufficiently well-defined to be observed and profiled (fig. 36).

The approximate frontal slope (defined herein as run over rise for relatability to highway embankment slopes) of the well-defined scour holes ranged from 1.58 to 3.45 (figs. 35, 36; table 7); however, the hole with the largest slope value—or the shallowest frontal slope—(3.45 at structure K0932 pier 3 [figs. 17, 35*J*; table 7]) is at a pier surrounded by a riprap blanket and likely is not indicative of scour in a purely fluvial material. Similarly, the third largest slope value (2.22 at structure A5054 pier 9 [figs. 14, 35*E*; table 7]) is at a pier that also seems surrounded by riprap or rock. The second largest slope value (2.70 at structure L0135 pier 10 [figs. 20, 36*B*; table 7]) is at a pier in a lower velocity area of the channel. If the three largest slope values are not included, the frontal slopes ranged from 1.58 to 2.16, with a mean value of 1.86. 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 (2014) study generally are similar to the values noted in Richardson and Davis (2001), and to values determined for scour holes in the Kansas City and St. Louis, Mo., areas (Huizinga, 2010, 2011).

As discussed in the section titled "Structure A1700 on Interstate 155 near Caruthersville, Missouri," the presence of a riprap blanket near pier 20 had a substantial effect on the size and depth of the scour hole observed at that pier in the three different surveys. The frontal slopes of the scour holes observed in the 2008 and 2014 surveys are very similar, whereas there is no discernable hole in the 2011 survey (fig. 36*G*). The bottom of the scour hole seemed to have coincident elevations in the 2008 and 2011 surveys, whereas the bottom of the scour hole is about 1 ft lower in the 2014 survey (fig. 36*G*). It is unknown if this difference is a function of minor horizontal or vertical position differences between the surveys, or an actual change in the elevation of the top of the riprap blanket near the front of the pier. The pile of riprap in front of pier 16 indicates a similar minor change between the three surveys (fig. 36*I*).

Several of the surveyed bridges had piers that were skewed to approach flow, resulting in asymmetric scour holes at those bridges: pier 10 of structure A3664 on U.S. Highway 36 at St. Joseph, Mo. (fig. 10); piers 6 through 8 of structure A5054 on Interstate 72 at Hannibal, Mo. (fig. 14); pier 10 of structure L0135 on State Highway 51 at Chester, Ill. (fig. 20); piers 3 and 4 of structure A5076 on State Highway 34 at Cape Girardeau, Mo. (fig. 23); and pier 20 of structure A1700 on Interstate 155 near Caruthersville, Mo., during the 2008 survey (fig. 28). The scour hole typically was deeper and longer on the side of the pier with impinging flow, with some amount of deposition on the leeward side. At all of the structures except A1700, the skew to approach flow is apparent in the velocity vectors (figs. 13, 16, 22, 25). At structure A3664, the skew seems to be partly caused by shear flow from the spur dike upstream from the pier (fig. 13). Velocity data were not collected during the 2008 survey at structure A1700, so no specific conclusions can be drawn beyond those based on observations during the survey.

Occasionally, in the previous bathymetric survey studies on the Missouri River and particularly in the Kansas City area (Huizinga, 2010, 2012) and at Jefferson City, Mo. (Huizinga, 2012), 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 during a new flood event occurring 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 of the bridges that resulted in substantial and dynamic movement of bed material, yet "steps" and waves were observed at only a few bridges. No such "steps" or waves were observed in the most-recent previous study on the Missouri River between Kansas City and St. Louis (Huizinga, 2014b), presumably because of the low to moderate-flow conditions. However, no such "steps" or waves were observed in the present (2014) study, perhaps because of the timing of the surveys on the rising limb of the hydrograph at most of the sites or because the observed scour holes were the result of a local temporal maximal flow.

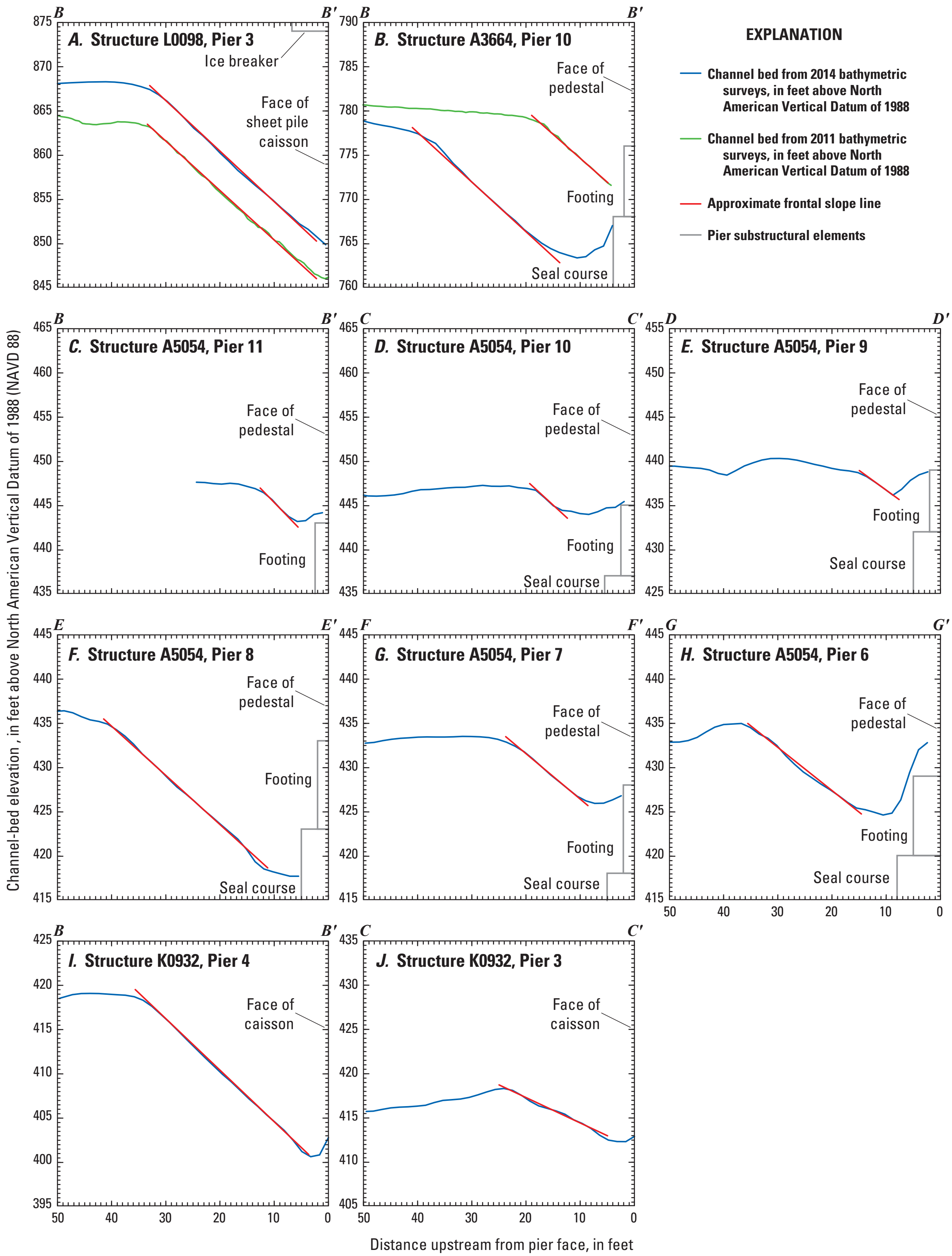


Figure 35. Longitudinal profiles upstream from selected piers at structures L0098 and A3664 over the Missouri River upstream from Kansas City, Missouri, and structures A5054 and K0932 over the Mississippi River upstream from St. Louis, Missouri.

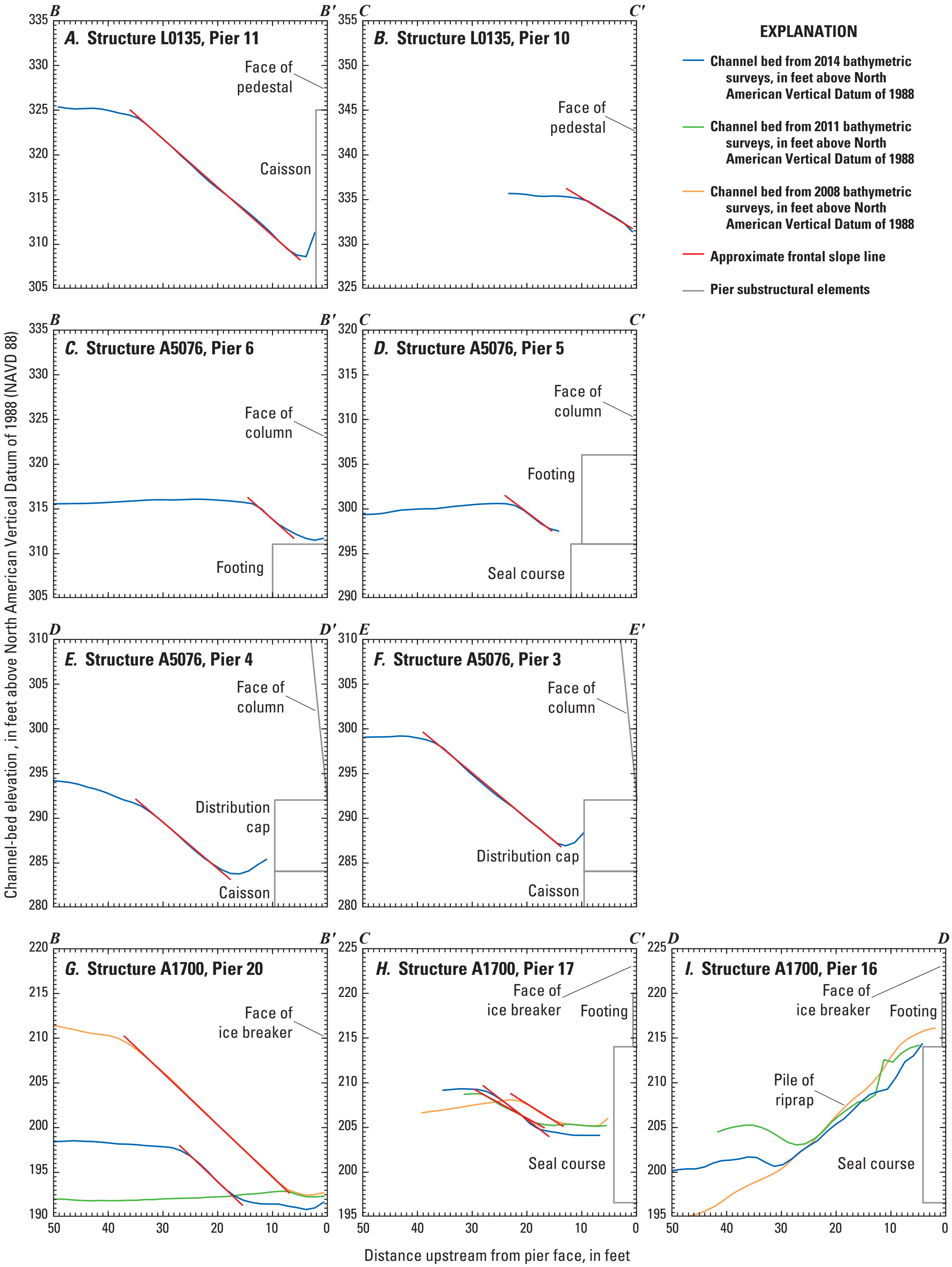


Figure 36. Longitudinal profiles upstream from selected piers at structures L0135, A5076, and A1700 over the Mississippi River downstream from St. Louis, Missouri.

Summary and Conclusions

Bathymetric and velocimetric data were collected on the Missouri and Mississippi Rivers in the vicinity of 8 highway bridges at 7 crossings on the periphery of 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 1,525 to 1,640 feet longitudinally, and generally extending across the active channel from bank to bank in the Missouri and Mississippi Rivers during low- to moderate-flow conditions. These bathymetric surveys provide a "snapshot" of 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 used by the Missouri Department of Transportation as a low- to 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 over 88 percent of the bathymetric data at all the sites have a total propagated uncertainty of less than 1.00 feet, and more than one-half (59.6 percent or more) of the channel bed at the sites have a total propagated uncertainty of 0.50 feet or less.

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

Bathymetric data were collected around every pier that was in water, except those at the edge of water or in very shallow water (less than 6 feet of depth). Scour holes were observed at most piers in the main channel area, except those on banks, on bedrock, or surrounded by riprap. The observed scour holes at the surveyed bridges were examined with respect to shape and depth, and the effects of riprap blankets or other rock near the piers.

Although exposure of parts of substructural support elements was observed at several piers, at most sites the exposure likely can be considered minimal compared to the overall substructure that remains buried in bed material at these piers. The notable exceptions are piers 1 and 2 at structure K0932 on U.S. Highway 54 at Louisiana, Missouri, and piers 12 and 13 at structure L0135 on State Highway 34 at Chester, Ill.; at these piers, the bed material thickness between the minimum channel-bed elevation near the pier and bedrock was 6 feet or less. In modern construction, bridge substructural elements usually are pinned or socketed to bedrock, but full exposure of usually buried substructural elements warrants special consideration and observation, even when designed to be exposed.

Previous bathymetric surveys had been done at both of the sites on the Missouri River in this study, and at structure A1700 over the Mississippi River near Caruthersville, Mo. Comparisons between bathymetric surfaces from the previous surveys during the 2011 flood and those of this study generally indicate that there was an increase in the elevation of the channel bed at these sites that likely was caused by a substantial decrease in discharge and water-surface elevation compared to the 2011 surveys, resulting in less material in transport through the bridge opening. However, the scour holes observed at these sites were either the same size or larger in 2014 compared to the 2011 surveys, indicating that the overall flow condition is not the sole variable in the determination of the size of scour holes, and that local velocity and depth also are critical, as indicated by predictive pier scour equations.

The presence of riprap blankets, depth of fluvial material on top of a riprap blanket, and alignment to flow had a substantial effect on the size of the scour hole observed for a given pier. Piers that were surrounded by riprap blankets had scour holes that were substantially smaller (to non-existent) compared to piers at which no rock or riprap was present. The notable exception was at pier 20 of structure A1700 near Caruthersville, Mo., during a survey in December 2008, wherein a substantial scour hole was observed in the 15 to 20 feet of fluvial material on top of the riprap blanket near that pier. The frontal slope values determined for scour holes observed in the current (2014) study generally are similar to recommended values in the literature and to values determined for scour holes in the Kansas City and St. Louis, Mo., areas in previous bathymetric surveys. Several of the structures had piers that were skewed to primary approach flow, and scour holes near these piers generally displayed deposition on the leeward side of the pier and greater depth on the side of the pier with impinging flow.

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Appendixes 1–2

Appendix 1. Correction of Latency Issue Observed in Global Navigation Satellite System Reference Timing in Velocity Transects

As explained in the "Surveying Methods" section of the main text, a latency issue was observed in the Global Navigation Satellite System (GNSS) data received during velocity measurements with the acoustic Doppler current profiler (ADCP). This appendix provides some background on the ADCP velocity reference methods, as well as the subroutines used to adjust for the observed latency.

Measurement of water velocity with an ADCP from a moving boat will yield the velocity of the water relative to the boat (Mueller and others, 2013). Therefore, to determine the velocity of the water relative to the earth, the velocity of the boat must be determined by bottom tracking or through the use of a GNSS. Bottom tracking determines the velocity of the boat by measuring the Doppler shift of acoustic signals reflected from the channel bottom, but is susceptible to error caused by a moving bed, often present in large, sand-bed rivers (Mueller and others, 2013). Therefore, using a GNSS to measure the boat velocity is the preferred method of data collection when moving-bed conditions are present (Mueller and others, 2013). There are two options for determining boat velocity from a GNSS: differentiated position using the GNSS fix data (GGA) National Marine Electronics Association (NMEA)-0183 output sentence or the velocity reported in the velocity track made good (VTG) NMEA-0183 output sentence (National Marine Electronics Association, 2002) from the GNSS receiver (Mueller and others, 2013).

As mentioned in the "Surveying Methods" section of the main text, the bottom-track reference method for determining boat speed was anticipated to be unusable because of moving channel-bed material, and the VTG reference method was used instead (Mueller and others, 2013). On review of the velocity data, however, a latency issue was observed between the timestamps of the ADCP and GNSS data received during the measurements. Two custom Matlab® subroutines were written to determine the amount of latency and to correct for it. In the first subroutine (fig. 1–1), the amount of the latency is determined by minimizing the difference between the boat speed as determined by the two GNSS methods and the bottom-track reference method. Although the bottom-track boat velocity likely was biased by moving-bed conditions, the pattern of the time series of boat speed as the boat traverses the channel is very similar in all of the reference methods, and the time series patterns can be matched by a time shift (analogous to a phase shift to match a sine and cosine wave). The GNSS data are iteratively adjusted from -20 to 0 seconds in 0.05 second increments, and the difference in the GGA and VTG velocities from the bottom-track reference at each time step are computed. The time step with the minimum difference between the GNSS and bottom-track references was taken to be the latency amount for that transect. The second subroutine (fig. 1–2) allows the user to adjust the GNSS data by the determined latency amount and create a corrected file that can be used in the Velocity Mapping Toolbox (VMT; Parsons and others, 2013).

```
function lat_sec = ADCP_EstimateLatency(ADCP);

% This function estimates the latency of a GPS signal by comparing the bottom-track boat speed
% timeseries to that from the GGA and VTG strings.

% P.R. Jackson, USGS, 2-17-15

%% Determine the latency

tshifts = -20:0.05:0;  %Range of time shifts from -20 sec to 0 seconds
n = length(tshifts);

figure(2); clf
para1 = ADCP.Vb.bt;
para2 = ADCP.Vb.vtg;
tvarpara = nan.*ones(1,n);
sdpara = nan.*ones(1,n);
for i = 1:n
    ShiftedTime_T = ADCP.dtnum -(tshifts(i)/86400);
    newpara2 = interp1(ADCP.dtnum,para2,ShiftedTime_T);
    sdpara(i) = nansum(abs(newpara2-para1));
    if 0 %k == 4
        figure(3); clf;
        plot(ADCP.ens,newpara2,'r.'); hold on
        plot(ADCP.ens,para1,'k.'); hold on
        ylabel('Boat Speed')
        xlabel('Ensemble number')
        tshifts(i)
        pause
    end
end
figure(2);
semilogy(tshifts,sdpara,'k.-')
xlabel('Time Shift, in seconds')
ylabel('SV')

optindx = find(sdpara == min(sdpara));
lat_sec = tshifts(optindx) ;

ShiftedTime_T = ADCP.dtnum -(lat_sec/86400);
newpara2 = interp1(ADCP.dtnum,para2,ShiftedTime_T);
figure(3); clf
plot(ADCP.ens,para1,'k-'); hold on
plot(ADCP.ens,newpara2,'r-'); hold on
ylabel('Boat Speed')
xlabel('Ensemble number')
```

Figure 1–1. Subroutine used to determine the amount of latency observed between the Global Navigation Satellite System and acoustic Doppler current profiler timestamps.

```
function A = Huizinga_CustomAscii(A,fileName);

%Correct latency issue for Huizinga data

%P.R. Jackson, USGS, 2-6-15

%% Select the file to load

% defaultpath = 'C:\';
% datpath = [];
% if exist('ASC\ASC_LastDir.mat') == 2
%     load('ASC\ASC_LastDir.mat');
%     if exist(datpath) == 7
%         [file,datpath] = uigetfile({'*.dat;*.txt'},'Select ASCII Data File',datpath);
%     else
%         [file,datpath] = uigetfile({'*.dat;*.txt'},'Select ASCII Data File',defaultpath);
%     end
% else
%     [file,datpath] = uigetfile({'*.dat;*.txt'},'Select ASCII Data File',defaultpath);
% end
% infile = [datpath file];

[file_path,file_name,extension] = fileparts(fileName);
tsct = file_name(end-15:end-13);  %transect number

infile = [file_path '\boatvelts_ascii_template_' tsct '_ASC.txt'];

disp('Processing ASCII File...' );
disp(infile);

%% Load the custom ascii data
data = dlmread(infile);

%% Parse the data

ens = data(:,1);
yr  = data(:,2);
mo  = data(:,3);
day = data(:,4);
hr  = data(:,5);
min = data(:,6);
sec = data(:,7) + data(:,8)/100;
lat = data(:,9);
lon = data(:,10);
VggaE = data(:,11);
VggaN = data(:,12);
VvtgE = data(:,13);
VvtgN = data(:,14);
VbtE  = data(:,15);
VbtN  = data(:,16);
Vb_bt  = data(:,17);
Vb_gga = data(:,18);
Vb_vtg = data(:,19);
dtnum = datenum([yr mo day hr min sec]);

%clear data
```

Figure 1–2. Subroutine used to adjust the Global Navigation Satellite System data by the determined latency and create a corrected file for use in the Velocity Mapping Toolbox (Parsons and others, 2013).

```
% Remove bad values
VggaE(VggaE==-32768) = nan;
VggaN(VggaN==-32768) = nan;
VvtgE(VvtgE==-32768) = nan;
VvtgN(VvtgN==-32768) = nan;
VbtE(VbtE==-32768) = nan;
VbtN(VbtN==-32768) = nan;
Vb_bt(Vb_bt==-32768) = nan;
Vb_gga(Vb_gga==-32768) = nan;
Vb_vtg(Vb_vtg==-32768) = nan;

% Make a data structure to pass to the latency script
ADCP.Vb.bt = Vb_bt;
ADCP.Vb.gga = Vb_gga;
ADCP.Vb.vtg = Vb_vtg;
ADCP.ens = ens;
ADCP.dtnum = dtnum;

%% Plot the boat speed timeseries
figure(1); clf;
subplot(2,1,1)
plot(ens,Vb_bt,'y-'); hold on
plot(ens,Vb_gga,'m-'); hold on
plot(ens,Vb_vtg,'k-'); hold on
xlabel('Ensemble')
ylabel('Boat Speed, in m/s')
title('Uncorrected')
legend('BT','GGA','VTG')

%% Estimate latency
lat_sec = ADCP_EstimateLatency(ADCP)

%% Correct the data in the A structure
if 1
    ShiftedTime = dtnum -(lat_sec/86400);
    lat_s = interp1(dtnum,lat,ShiftedTime);
    lon_s = interp1(dtnum,lon,ShiftedTime);
    VggaE_s = interp1(dtnum,VggaE,ShiftedTime);
    VggaN_s = interp1(dtnum,VggaN,ShiftedTime);
    VvtgE_s = interp1(dtnum,VvtgE,ShiftedTime);
    VvtgN_s = interp1(dtnum,VvtgN,ShiftedTime);
    Vb_gga_s = interp1(dtnum,Vb_gga,ShiftedTime);
    Vb_vtg_s = interp1(dtnum,Vb_vtg,ShiftedTime);
end
%% Plot the corrected boat speed timeseries
figure(1);
subplot(2,1,2)
plot(ens,Vb_bt,'y-'); hold on
plot(ens,Vb_gga_s,'m-'); hold on
plot(ens,Vb_vtg_s,'k-'); hold on
xlabel('Ensemble')
ylabel('Boat Speed, in m/s')
title('Corrected')
legend('BT','GGA','VTG')
%pause
```

Figure 1–2. Subroutine used to adjust the Global Navigation Satellite System data by the determined latency and create a corrected file for use in the Velocity Mapping Toolbox (Parsons and others, 2013).—Continued

```
%% Correct the A data structure
% Unapply boat velocity (sets reference back to none)
for i = 1:A.Sup.nBins
    A.Wat.vEast(i,:) = A.Wat.vEast(i,:) + A.Nav.bvEast';
    A.Wat.vNorth(i,:) = A.Wat.vNorth(i,:) + A.Nav.bvNorth';
    A.Wat.vVert(i,:) = A.Wat.vVert(i,:) + A.Nav.bvVert';
end
% Compute the ensemble time vector (datenum)
ensdtnum = datenum([(A.Sup.year + 2000) A.Sup.month  A.Sup.day  A.Sup.hour  A.Sup.minute
(A.Sup.second + A.Sup.sec100/100)]);
% Compute the shifted time
ensdtnum_shifted = ensdtnum -(lat_sec/86400);
% Compute the corrected GPS data at the shifted time
A.Nav.lat_deg = interp1(ensdtnum,A.Nav.lat_deg,ensdtnum_shifted);
A.Nav.long_deg = interp1(ensdtnum,A.Nav.long_deg,ensdtnum_shifted);
A.Nav.bvEast  = interp1(ensdtnum,A.Nav.bvEast,ensdtnum_shifted);
A.Nav.bvNorth = interp1(ensdtnum,A.Nav.bvNorth,ensdtnum_shifted);
A.Nav.bvVert  = interp1(ensdtnum,A.Nav.bvVert,ensdtnum_shifted);
%figure(1); subplot(2,1,2); hold on; plot(A.Sup.ensNo,sqrt(A.Nav.bvEast.^2 +
   A.Nav.bvNorth.^2)/100,'b-');
% Reapply boat velocity (sets reference back to gps)
for i = 1:A.Sup.nBins
    A.Wat.vEast(i,:) = A.Wat.vEast(i,:) - A.Nav.bvEast';
    A.Wat.vNorth(i,:) = A.Wat.vNorth(i,:) - A.Nav.bvNorth';
    A.Wat.vVert(i,:) = A.Wat.vVert(i,:) - A.Nav.bvVert';
end
% Recompute the velocity magnitude and direction
A.Wat.vMag = sqrt(A.Wat.vEast.^2 + A.Wat.vNorth.^2);
A.Wat.vDir = ari2geodeg((atan2(A.Wat.vNorth, A.Wat.vEast))*180/pi);
```

Figure 1–2. Subroutine used to adjust the Global Navigation Satellite System data by the determined latency and create a corrected file for use in the Velocity Mapping Toolbox (Parsons and others, 2013).—Continued

References Cited

Mueller, D.S., Wagner, C.R., Rehmel, M.S., Oberg, K.A., and Rainville, Francois, 2013, Measuring discharge with acoustic Doppler current profilers from a moving boat (ver. 2.0, December 2013): U.S. Geological Survey Techniques and Methods, book 3, chap. A22, 95 p. [Also available at http://dx.doi.org/10.3133/tm3A22.]

National Marine Electronics Association, 2002, NMEA 0183 Standard for interfacing marine electronic devices, version 3.01: National Marine Electronics Association, 88 p.

Parsons, D.R., Jackson, P.R., Czuba, J.A., Engel, F.L., Rhoads, B.L., Oberg, K.A., Best, J.L., Mueller, D.S., Johnson, K.K., and Riley, J.D., 2013, Velocity Mapping Toolbox (VMT)—A processing and visualization suite for moving-vessel ADCP measurements: Earth Surface Processes and Landforms, v. 38, p. 1244–1260. [Also available at http://dx.doi.org/10.1002/esp.3367.]

Appendix 2. Shaded Triangulated Irregular Network (TIN) Images of Channel and Side of Pier for Each Surveyed Pier

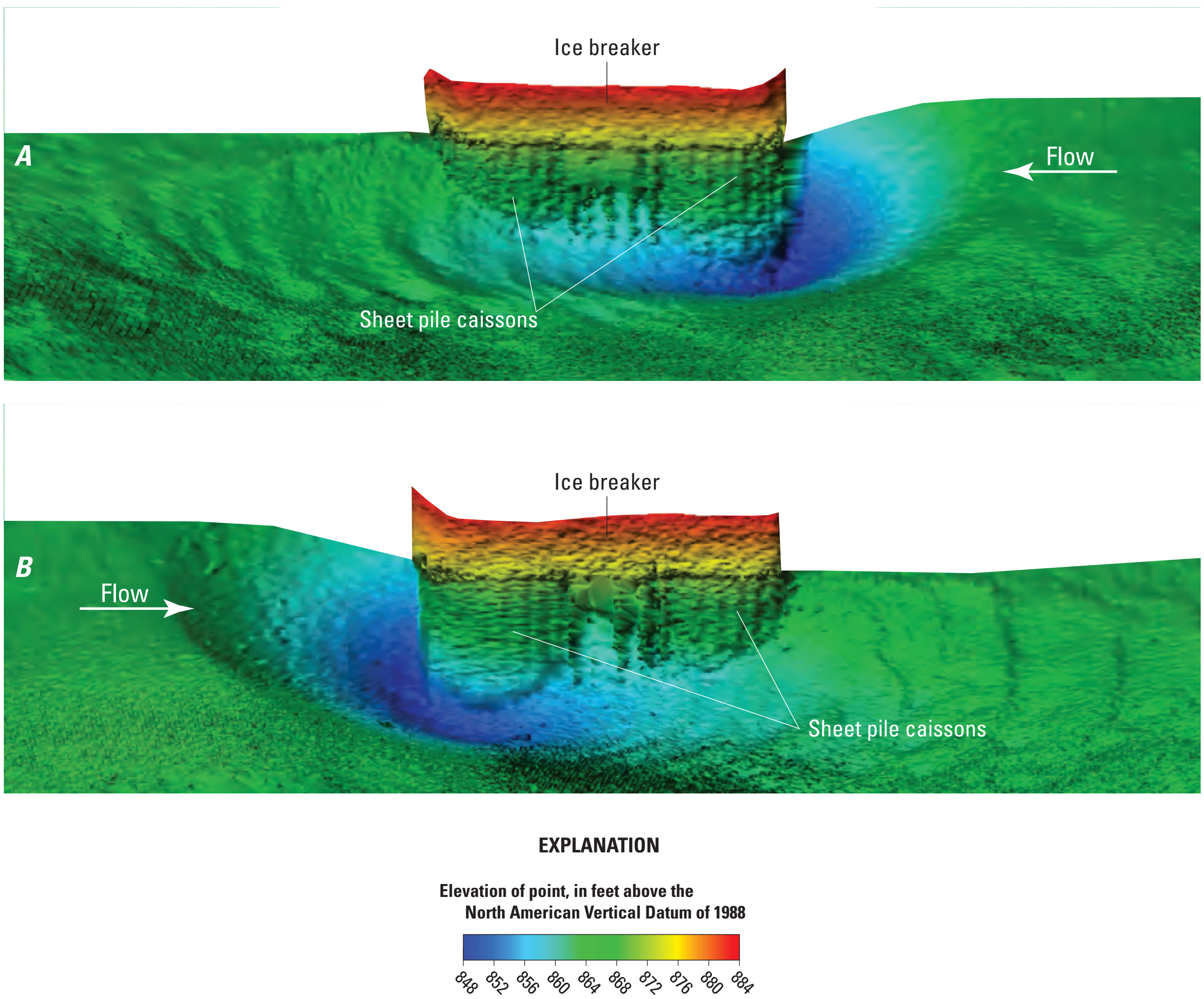


Figure 2–1. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (northeast) side and *B*, right (southwest) side of main channel pier 3 of structure L0098 on U.S. Highway 136 over the Missouri River at Brownville, Nebraska.

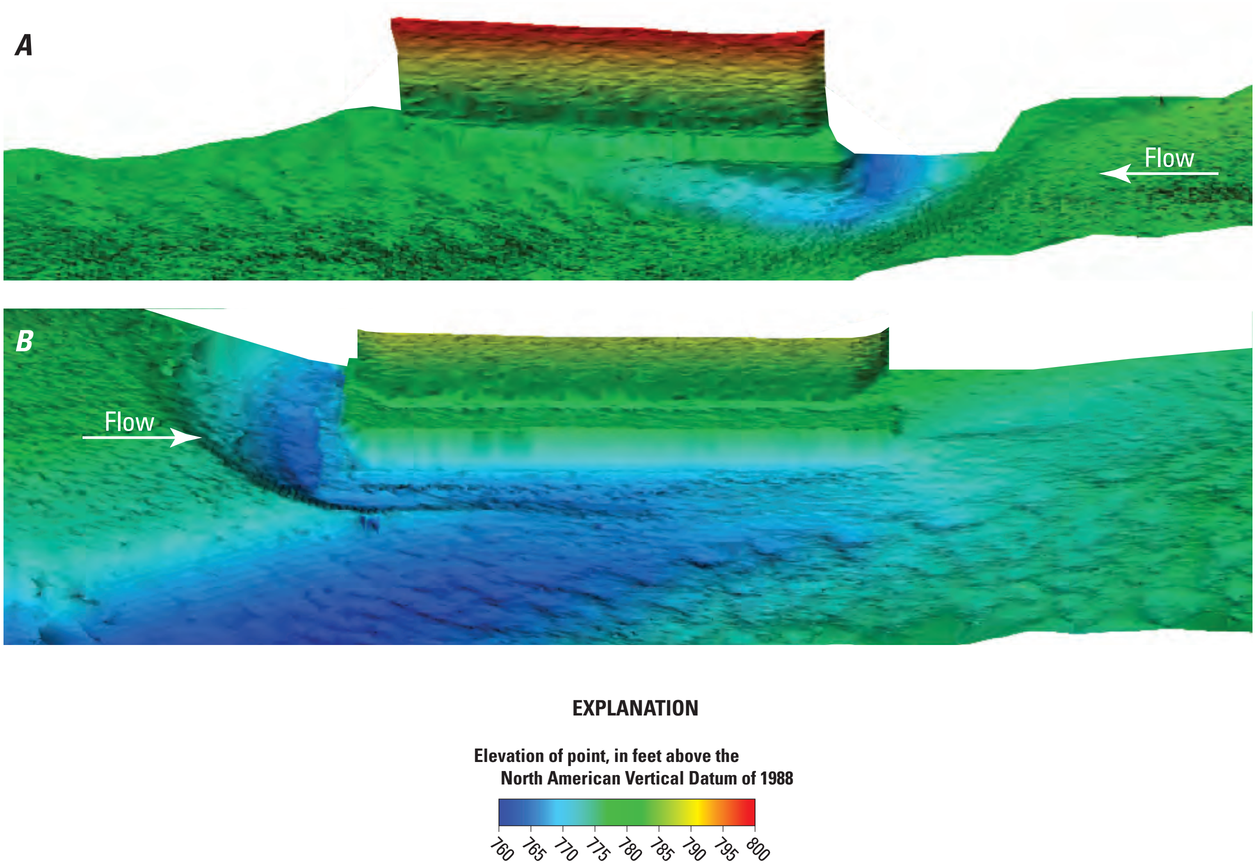


Figure 2–2. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (east) side and *B*, right (west) side of main channel pier 10 of dual bridge structure A3664 on U.S. Highway 36 over the Missouri River at St. Joseph, Missouri.

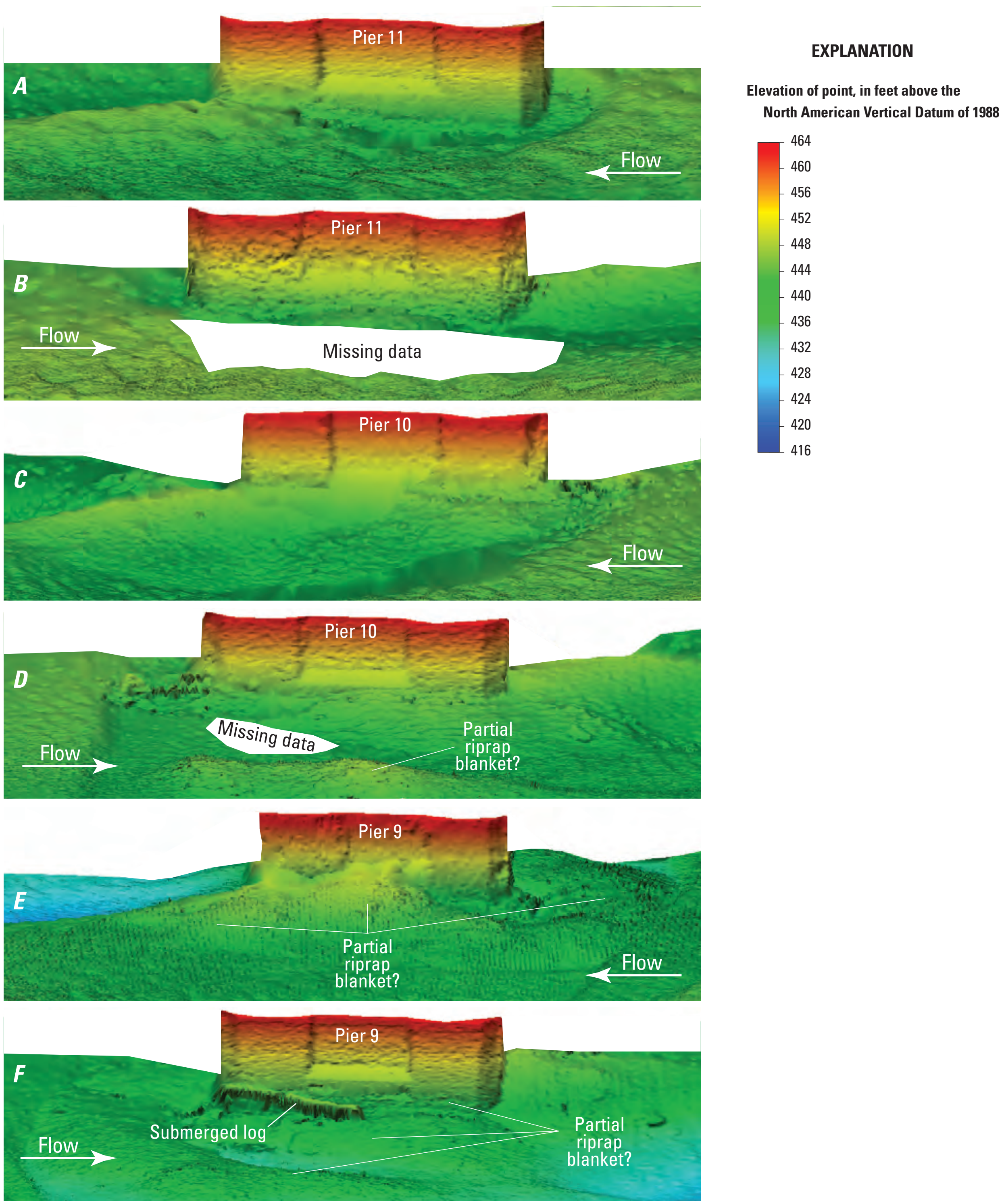


Figure 2–3. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (northeast) side and *B*, right (southwest) side of main channel pier 11; *C*, left (northeast) side and *D*, right (southwest) side of main channel pier 10; and *E*, left (northeast) side and *F*, right (southwest) side of main channel pier 9 of structure A5054 on Interstate 72 over the Mississippi River at Hannibal, Missouri.

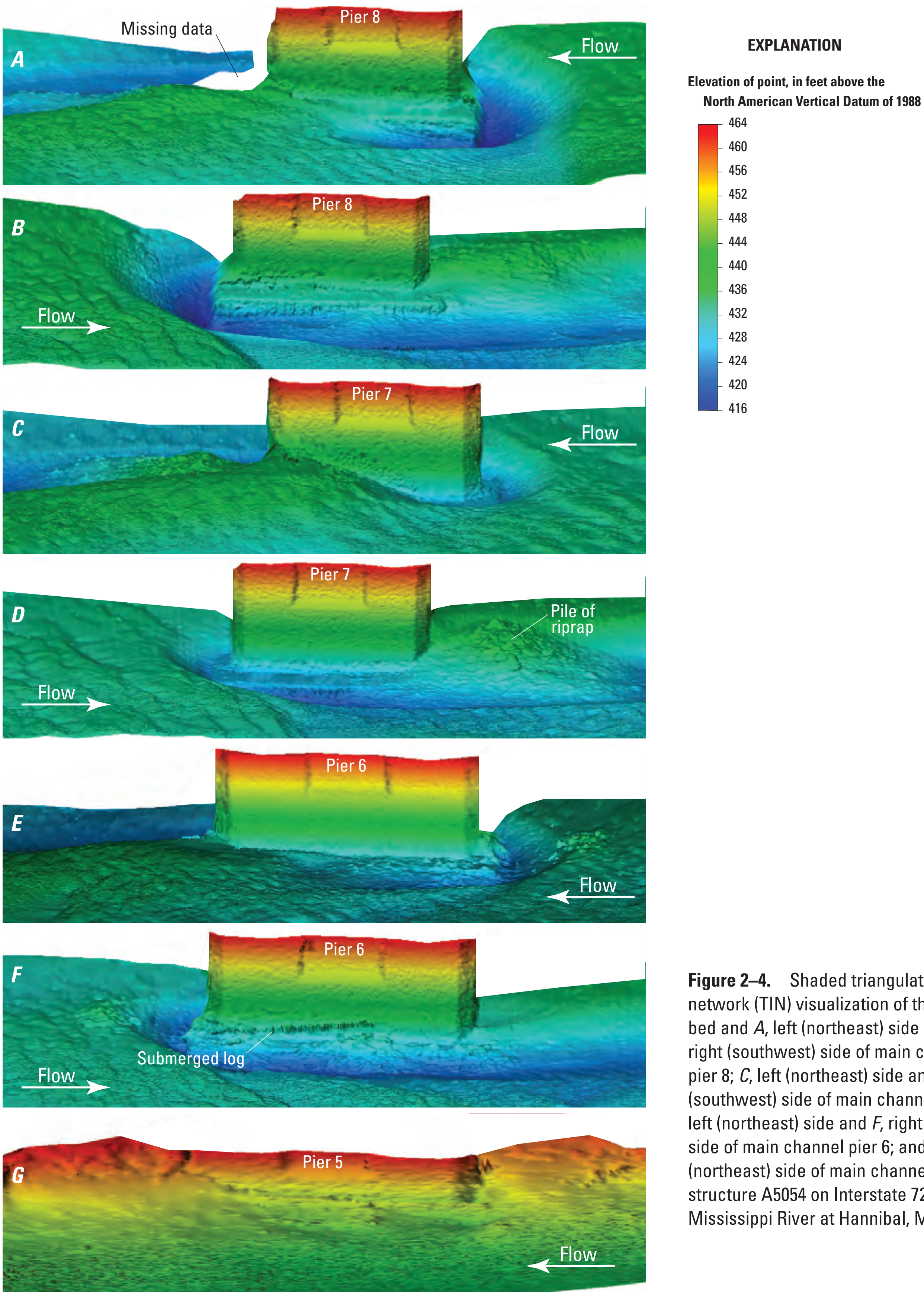


Figure 2–4. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (northeast) side and *B*, right (southwest) side of main channel pier 8; *C*, left (northeast) side and *D*, right (southwest) side of main channel pier 7; *E*, left (northeast) side and *F*, right (southwest) side of main channel pier 6; and *G*, left (northeast) side of main channel pier 5 of structure A5054 on Interstate 72 over the Mississippi River at Hannibal, Missouri.

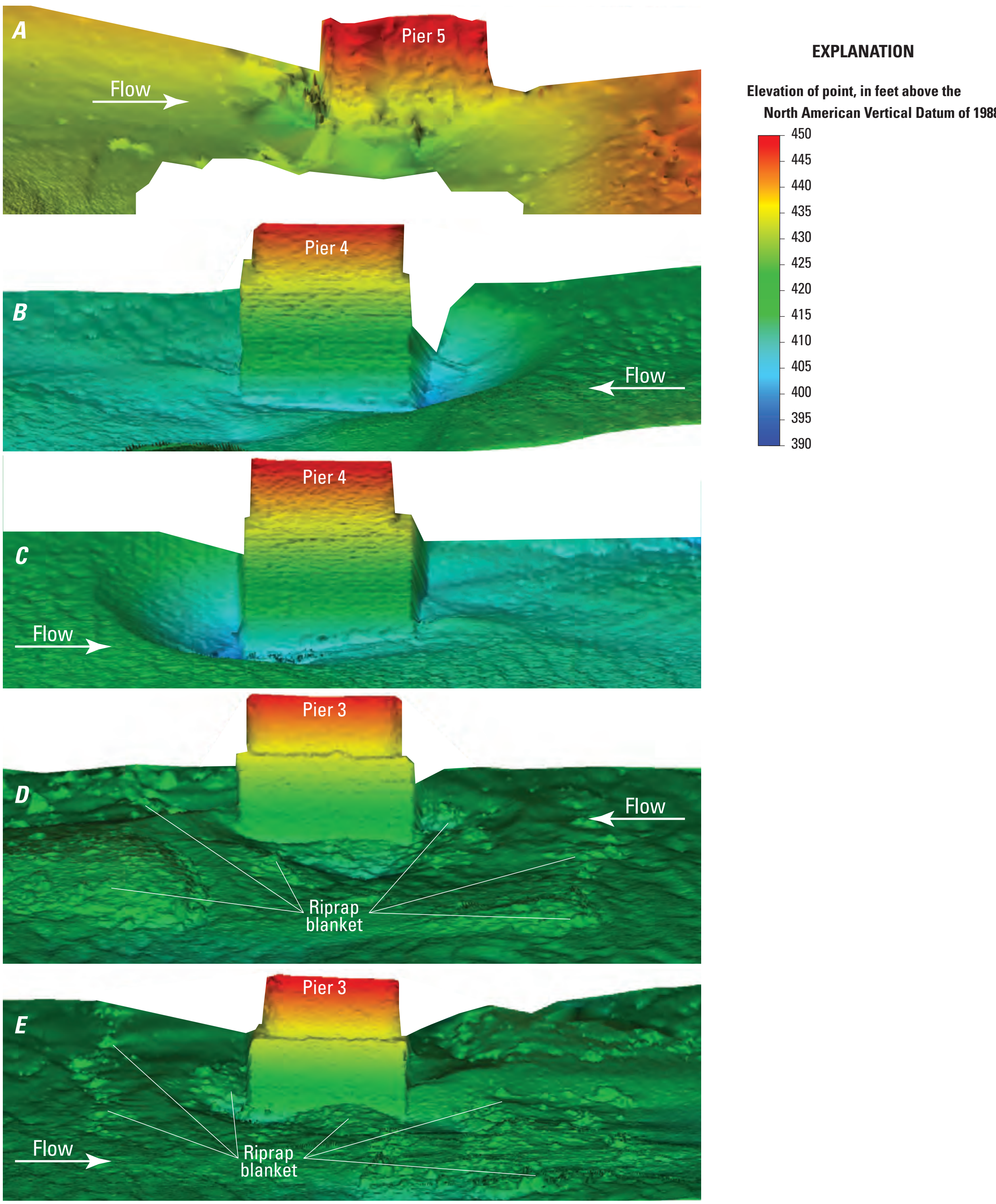


Figure 2–5. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, right (southwest) side of main channel pier 5; *B*, left (northeast) side and *C*, right (southwest) side of main channel pier 4; and *D*, left (northeast) side and *E*, right (southwest) side of main channel pier 3 of structure K0932 on U.S. Highway 54 over the Mississippi River at Louisiana, Missouri.

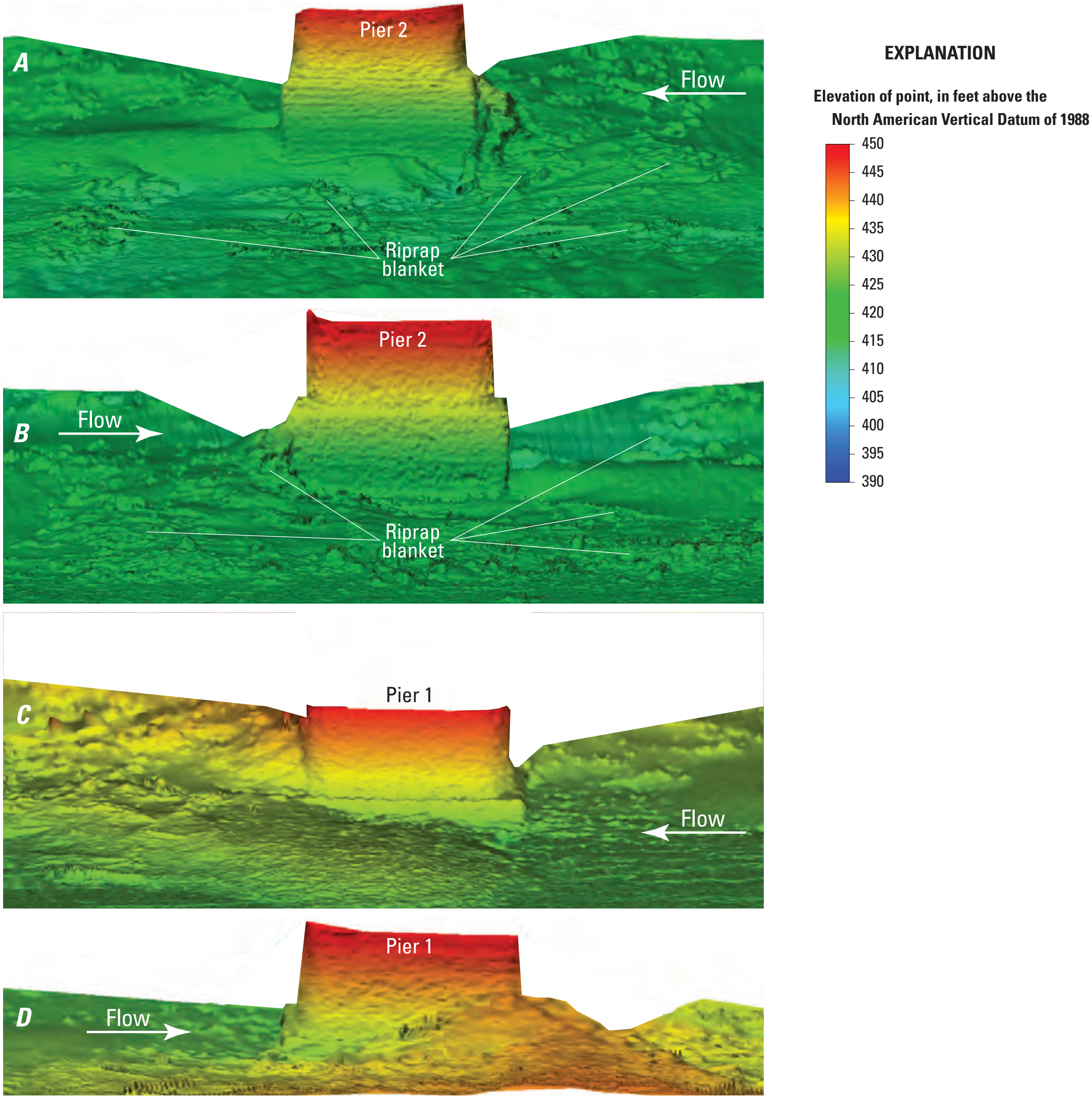


Figure 2–6. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (northeast) side and *B*, right (southwest) side of main channel pier 2; and *C*, left (northeast) side and *D*, right (southwest) side of main channel pier 1 of structure K0932 on U.S. Highway 54 over the Mississippi River at Louisiana, Missouri.

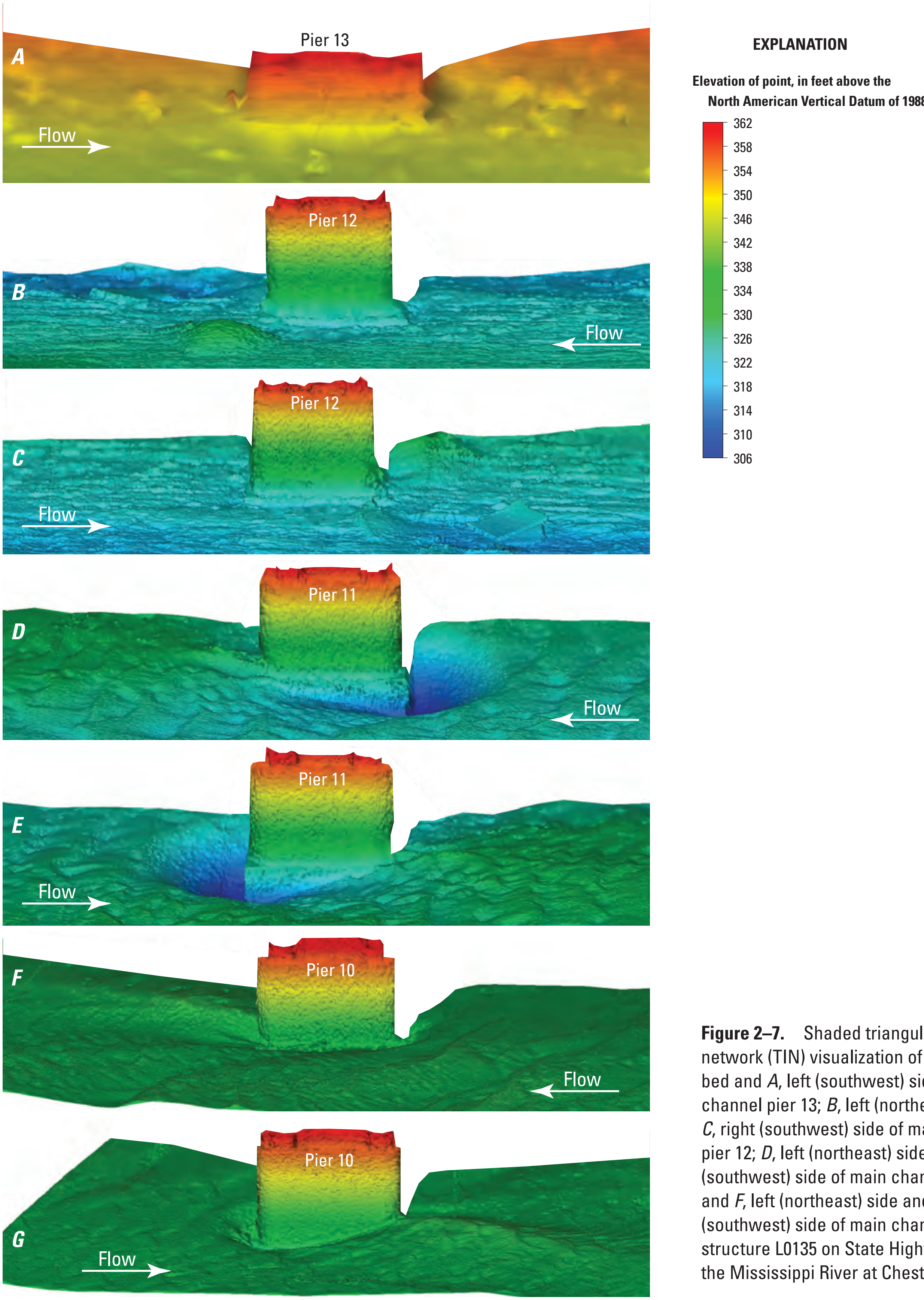
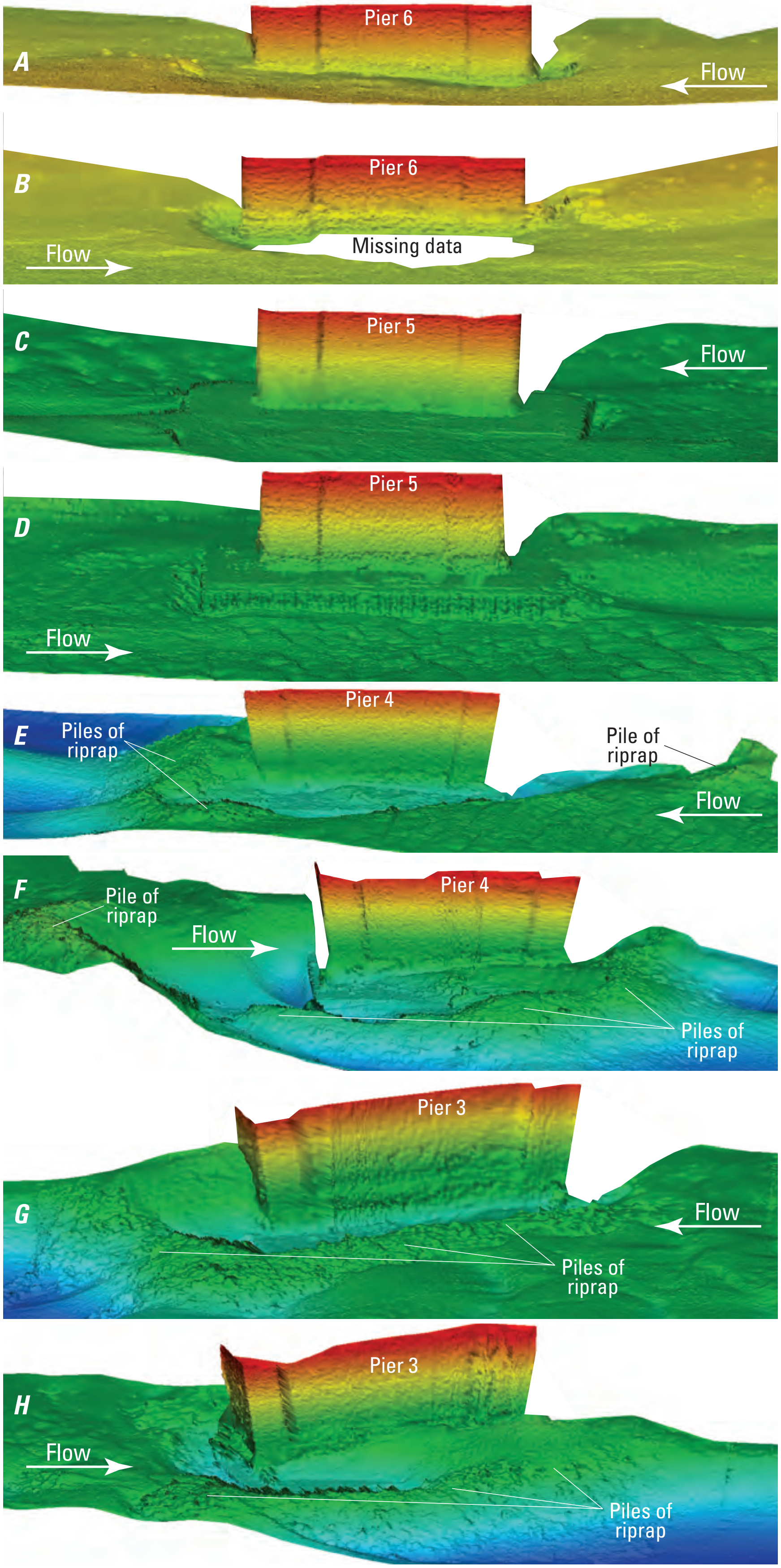


Figure 2–7. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (southwest) side of main channel pier 13; *B*, left (northeast) side and *C*, right (southwest) side of main channel pier 12; *D*, left (northeast) side and *E*, right (southwest) side of main channel pier 11; and *F*, left (northeast) side and *G*, right (southwest) side of main channel pier 10 of structure L0135 on State Highway 51 over the Mississippi River at Chester, Illinois.



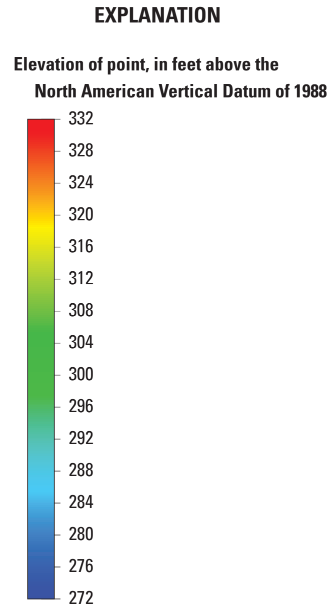


Figure 2–8. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (east) side and *B*, right (west) side of main channel pier 6; *C*, left (east) side and *D*, right (west) side of main channel pier 5; *E*, left (east) side and *F*, right (west) side of main channel pier 4; and *G*, left (east) side and *H*, right (west) side of main channel pier 3 of structure A5076 on State Highway 34 over the Mississippi River at Cape Girardeau, Missouri.

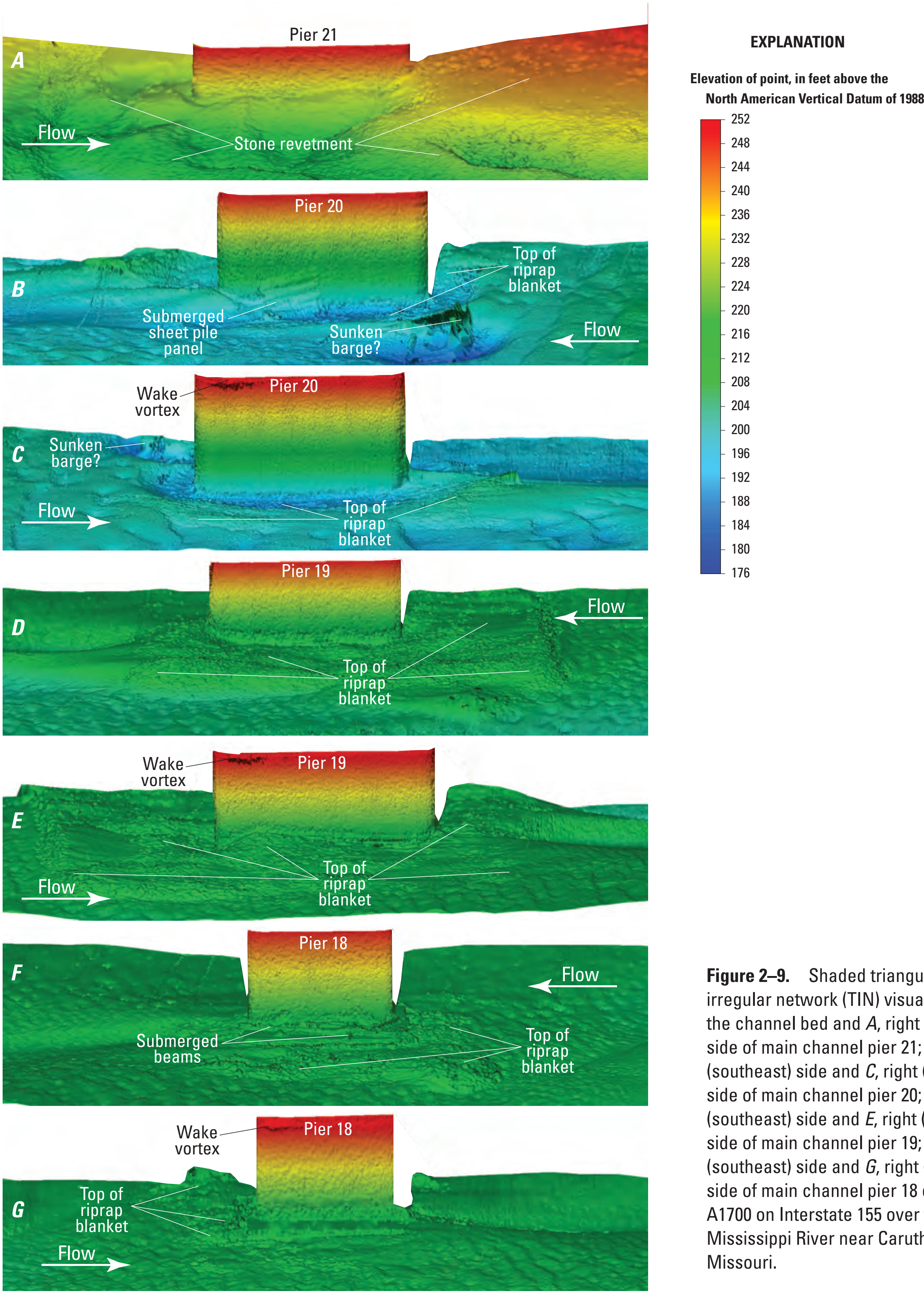


Figure 2–9. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, right (northwest) side of main channel pier 21; *B*, left (southeast) side and *C*, right (northwest) side of main channel pier 20; *D*, left (southeast) side and *E*, right (northwest) side of main channel pier 19; and *F*, left (southeast) side and *G*, right (northwest) side of main channel pier 18 of structure A1700 on Interstate 155 over the Mississippi River near Caruthersville, Missouri.

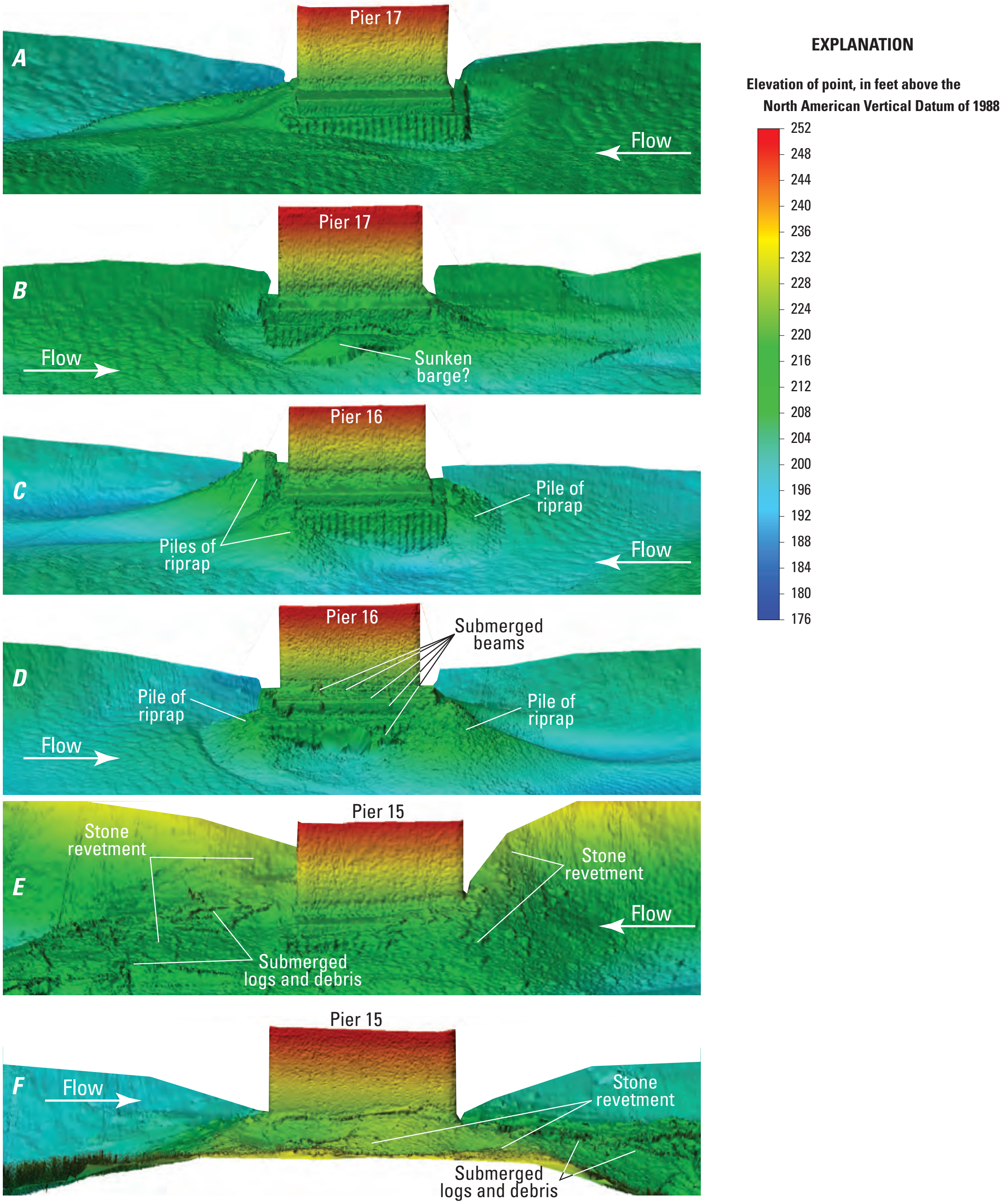


Figure 2–10. Shaded triangulated irregular network (TIN) visualization of the channel bed and *A*, left (southeast) side and *B*, right (northwest) side of main channel pier 17; *C*, left (southeast) side and *D*, right (northwest) side of main channel pier 16; and *E*, left (southeast) side and *F*, right (northwest) side of main channel pier 15 of structure A1700 on Interstate 155 over the Mississippi River near Caruthersville, Missouri.

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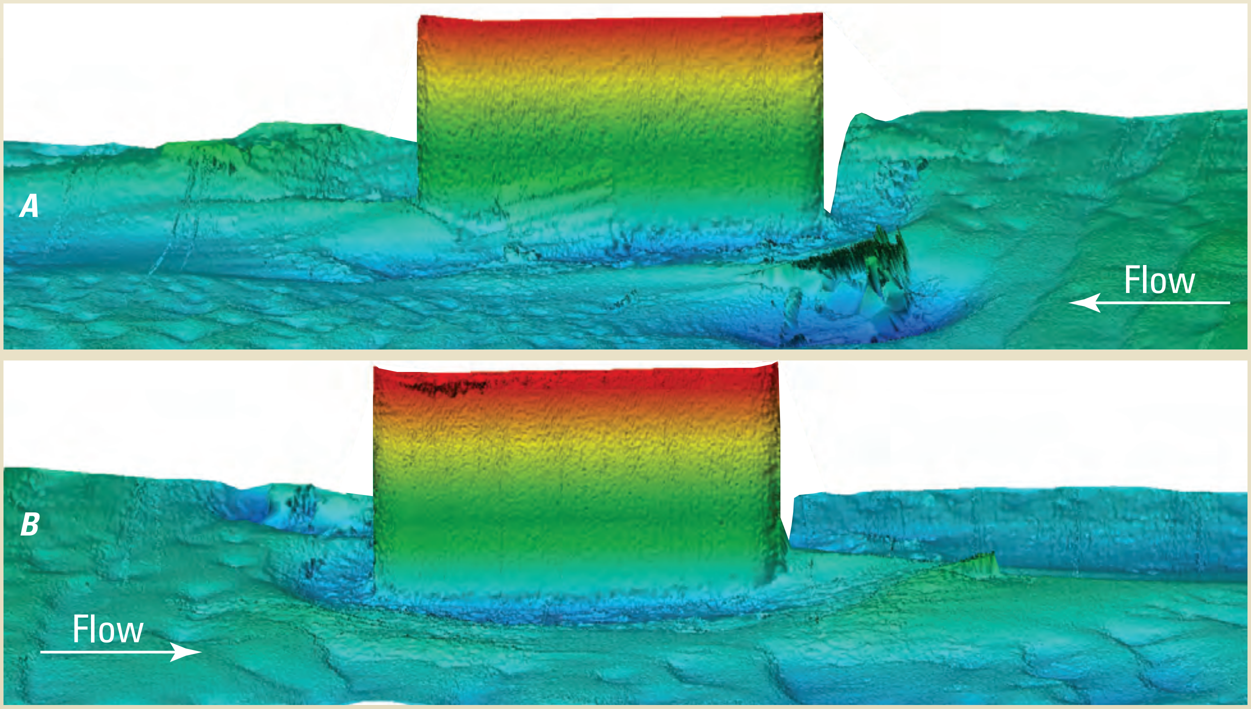

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