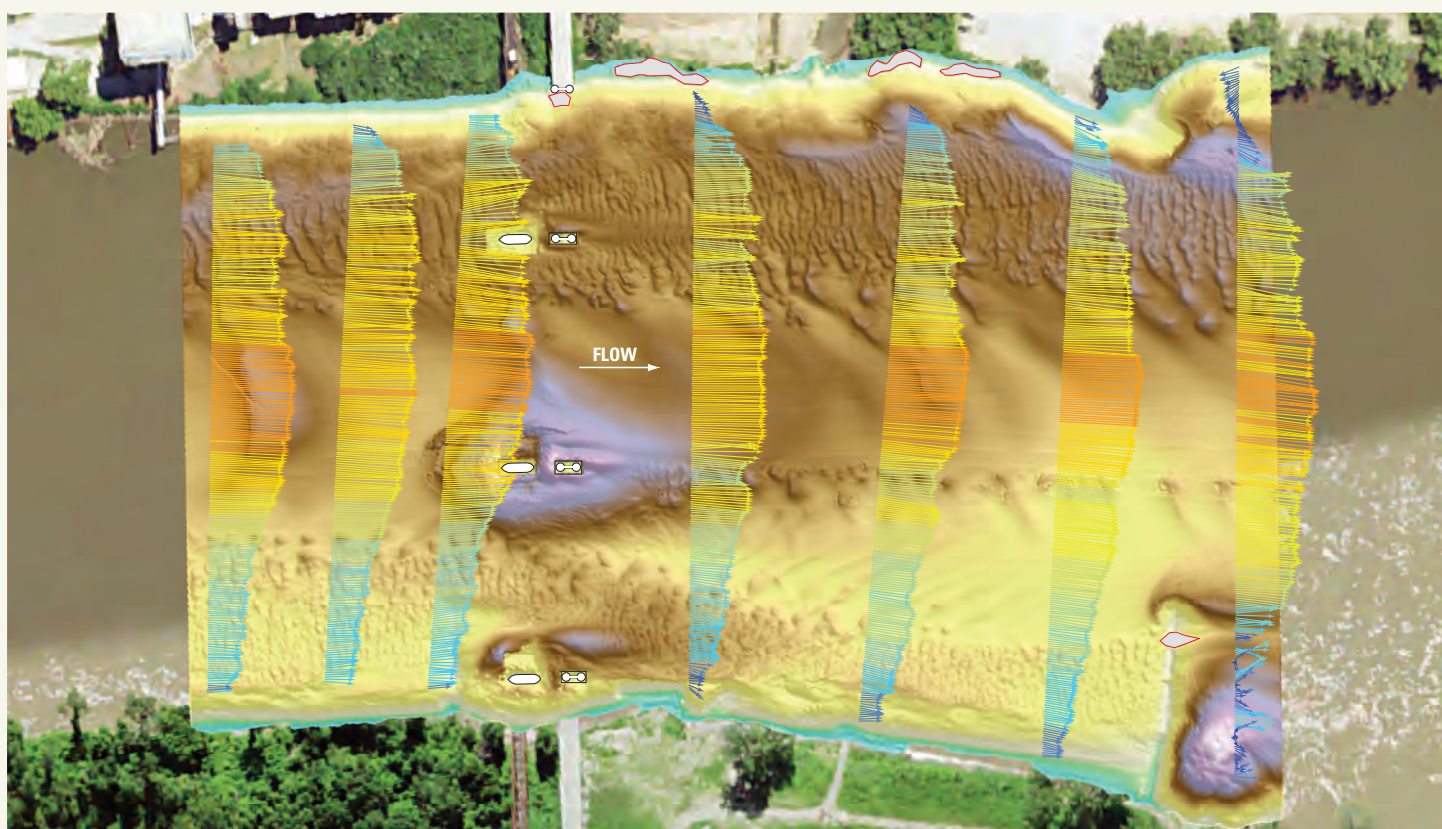


Prepared in cooperation with the Missouri Department of Transportation

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri River between Kansas City and St. Louis, Missouri, May 22–31, 2017



Scientific Investigations Report 2020–5018

Covers. Bathymetry and vertically averaged velocities of the Missouri River channel near structure G0069 on State Highway 240 at Glasgow, Missouri (front). Photograph showing the U.S. Geological Survey boat preparing for the bathymetric and velocimetric survey at structure A5910 on U.S. Highway 24 over the Missouri River at Waverly, Missouri, on May 23, 2017 (back).

All photographs by Richard Huizinga, U.S. Geological Survey.

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By Richard J. Huizinga

Prepared in cooperation with the Missouri Department of Transportation

Scientific Investigations Report 2020–5018

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

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2020

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Conversion Factors

U.S. customary units to International System of Units

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

Datum

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

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

Supplemental Information

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

Distance on the Missouri River is given in river miles (RM) upstream from the confluence with the Mississippi River at St. Louis, Missouri, at river mile 195.2 of the Upper Mississippi River.

Frequency is given in kilohertz (kHz).

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

Abbreviations

ADCP	acoustic Doppler current profiler
CUBE	Combined Uncertainty and Bathymetry Estimator
GNSS	Global Navigation Satellite System
IHO	International Hydrographic Organization
IMU	inertial measurement unit
INS	inertial navigation system
MBES	multibeam echosounder (the sonar system)
MBMS	multibeam echosounder mapping system (the sonar, navigation, and data acquisition system)
MMS	POSPac Mobile Mapping Suite (the navigation solution postprocessing software)
MoDOT	Missouri Department of Transportation
POS MV	Position Orientation Solution for Marine Vessels (the inertial navigation system)
RTK	real-time kinematic (a type of differential correction for navigation with GNSS)
SBET	smoothed best estimate of trajectory (a postprocessed navigation solution)
sonar	sound navigation and ranging
TPU	total propagated uncertainty
USGS	U.S. Geological Survey

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri River between Kansas City and St. Louis, Missouri, May 22–31, 2017

By Richard J. Huizinga

Abstract

Bathymetric and velocimetric data were collected by the U.S. Geological Survey, in cooperation with the Missouri Department of Transportation, near 10 bridges at 9 highway crossings of the Missouri River between Kansas City and St. Louis, Missouri, from May 22 to 31, 2017. A multibeam echosounder mapping system was used to obtain channel-bed elevations for river reaches ranging from 1,550 to 1,840 feet longitudinally and generally extending laterally across the active channel from bank to bank during moderate flood flow conditions. These surveys indicate the channel conditions at the time of the surveys and provide characteristics of scour holes that may be useful in the development of predictive guidelines or equations for scour holes. These data also may be useful to the Missouri Department of Transportation as a low to moderate flood flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour during floods.

Bathymetric data were collected around every pier that was in water, except those at the edge of water, and scour holes were observed at most surveyed piers. Occasionally, the scour hole near a pier was difficult to discern from nearby bed features. The observed scour holes at the surveyed bridges were generally examined with respect to shape and depth.

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 4 and 5 at structure K0999 on Missouri State Highway 41 at Miami, Mo.; piers 2 and 3 at structure G0069 on Missouri State Highway 240 at Glasgow, Mo.; and pier 5 at structure A4574 on Missouri State Highway 5 at Boonville, Mo. At these structures, the bed-material thickness between the bottom of the scour hole and bedrock was less than 6 feet.

Pier size, nose shape, and alignment to flow had a profound effect on the size of the scour hole observed for a given pier. Narrow piers having round or sharp noses that were aligned with flow often had scour holes that were difficult to

discern from nearby bed features, whereas piers having wide or blunt noses resulted in larger, deeper scour holes. Several structures had piers that were skewed to primary approach flow, and scour holes near these piers generally indicated deposition on the leeward side of the pier and greater depth on the side of the pier with impinging flow. A riprap blanket constructed in 2015 around pier 4 of structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Mo., effectively mitigates the scour observed near those piers in previous surveys.

Previous bathymetric surveys exist for all the sites examined in this study. Bathymetric surfaces from a nonflood survey in 2013 and a flood survey in July 2011 at most of the sites are compared to the 2017 survey surfaces. The average channel-bed elevation at structure A4574 was remarkably similar in all three surveys and higher than what might be implied by a trendline along the reach between Kansas City and St. Louis, which may indicate this site is at or near a local feature that controls sediment deposition and scour.

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.

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 and Mississippi Rivers, 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 and others, 2010; Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017a, b). The MBMS has proven to be a useful tool not only in determining channel bathymetry but also in providing a medium- to high-resolution representation of bridge structural elements below the water line. In 2010, the USGS, in cooperation with MoDOT, began collecting bathymetric data at various highway bridges across primary waterways in Missouri. In March 2010, 9 highway bridges at 7 crossings over the Missouri River near Kansas City, Missouri, were assessed using the MBMS (Huizinga, 2010); and in October 2010, 12 highway bridges at 7 crossings over the Missouri and Mississippi Rivers near St. Louis, Mo., were assessed (Huizinga, 2011). During high-flow conditions in June–August 2011, many of the highway bridges and several of the railroad bridges along the entirety of the Missouri River downstream from Montana were assessed (Densmore and others, 2013; Dietsch and others, 2014), including the 37 highway bridges (at 28 crossings) that span the Missouri River in and into Missouri (Huizinga, 2012). In April and May 2013, 10 highway bridges at 9 crossings over the Missouri River between Kansas City and St. Louis, Mo., were assessed as part of more routine nonflood surveys at bridge sites in and into Missouri (Huizinga, 2014). In June 2014, 8 highway bridges at 7 crossings over the Missouri and Mississippi Rivers on the periphery of Missouri also were assessed as part of the routine nonflood surveys at bridge sites (Huizinga, 2015).

Starting in 2015, a second round of routine nonflood surveys at the highway bridges across the Missouri and Mississippi Rivers throughout Missouri commenced, beginning with the Kansas City area bridges in June 2015 (Huizinga, 2016) and continuing with St. Louis in May 2016 (Huizinga, 2017a, b). The study detailed in this report is the continuation of this second round of routine nonflood surveys at the highway bridges across the Missouri River between Kansas City and St. Louis, Mo. (fig. 1); however, this study also includes a survey at structure A8340 on U.S. Highway 69 in Kansas City, which was being replaced during the Kansas City area surveys in 2015 (Huizinga, 2016). Therefore, the study detailed in this report includes 10 bridges at 9 crossings (site numbers 7 and 14–21, table 1).

Purpose and Scope

The purpose of this report is to document the results of bathymetric and velocimetric surveys completed in May

22–31, 2017, of the Missouri River channel near 10 highway bridges at 9 crossings between Kansas City and St. Louis, Mo. (fig. 1; table 1), using an MBMS and an acoustic Doppler current profiler (ADCP). Equipment and methods used and results obtained are described. The results obtained from the bathymetric and velocimetric surveys of the channel document the channel-bed conditions and velocity distribution at the time of the surveys and provide characteristics of scour holes that may be useful in developing predictive guidelines or equations for scour holes. These data also may be used by MoDOT as a low to moderate flood flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour. A comparison of results to previous surveys at the sites (Huizinga and others, 2010; Huizinga, 2010, 2012, 2014) also is provided.

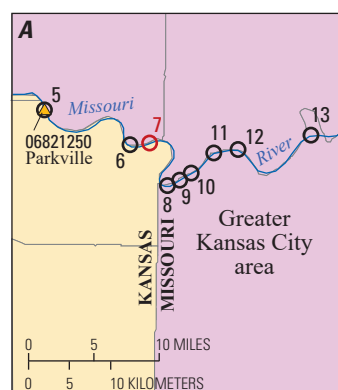
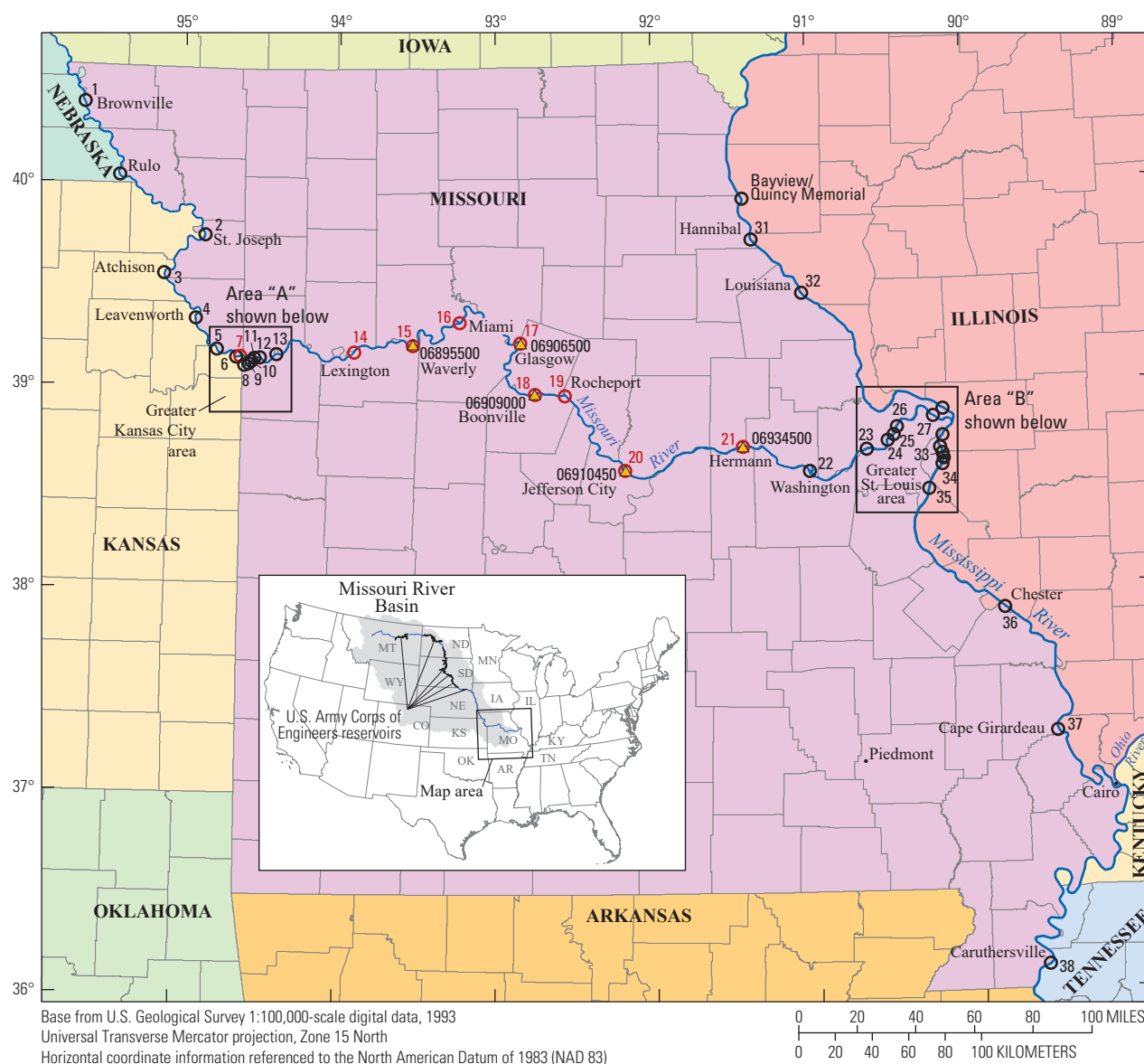
Description of Study Area

The study area for this report is 275 miles (mi) of the Missouri River between Kansas City and St. Louis, Mo., and includes a site in Kansas City (fig. 1A). From Kansas City, the Missouri River flows generally eastward to the greater St. Louis area, joining the Mississippi River north of downtown St. Louis, Mo. (fig. 1). All the highway crossings on the Missouri River between Lexington and Hermann, Mo. (sites 14 through 21), and the new bridge at the U.S. Highway 69 crossing in Kansas City (site 7), were examined as part of this study. The site numbering sequence used in previous studies on the Missouri and Mississippi Rivers (Huizinga, 2012, 2015) is used in this report for consistency and comparability.

Description of Flow Conditions

Data from the selected streamflow-gaging stations (hereinafter referred to as “streamgages”) on the Missouri River above Parkville (station 06821250), at Waverly (station 06895500), at Glasgow (station 06906500), at Boonville (station 06909000), at Jefferson City (station 06910450), and at Hermann, Mo. (station 06934500; U.S. Geological Survey, 2019; fig. 1), indicate the Missouri River was on a minor flood rise when the sites on the Missouri River were surveyed on May 22–31, 2017 (fig. 2A); furthermore, this rise happened during generally higher late-spring flows (fig. 2B). The rise was the highest during March 1 through September 1, 2017, for the streamgage above Parkville (station 06821250) and is among the highest for the other stations as well (fig. 2B).

The measured streamflow on the Missouri River at the U.S. Highway 69 crossing in Kansas City (site 7) was 140,000 cubic feet per second (ft³/s) during the survey. This streamflow has a daily exceedance probability of about 4.9 percent (based on flow duration analysis; U.S. Geological Survey, 2003) at the streamgage on Interstate 435 upstream from Parkville and is between the 20-percent and 50-percent annual exceedance probability (5-year and 2-year recurrence interval) flood flows of 162,000 and 120,000 ft³/s,



EXPLANATION

1○ Highway bridge location—Numbering on Missouri River from 2011 flood study (Huizinga, 2012); numbering on Mississippi River based on sequencing of bridges maintained by Missouri Department of Transportation

7○ Highway bridge location—Surveyed in this study

06895500 ▲ U.S. Geological Survey streamflow-gaging station and identifier

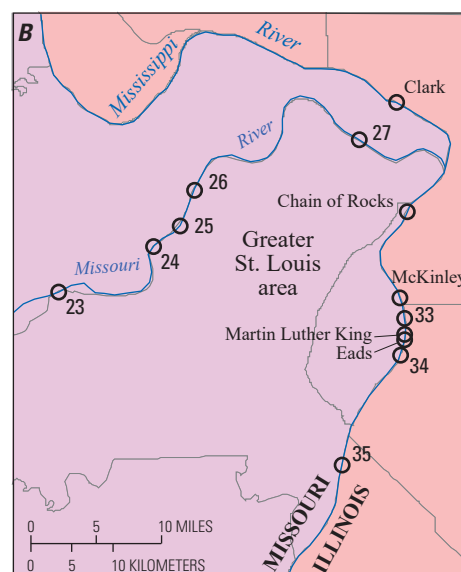


Figure 1. Location of highway bridges crossing the Missouri and Mississippi Rivers in and into Missouri, and bathymetric surveys of the Missouri River channel from May 22 to May 31, 2017.

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

[MoDOT, Missouri Department of Transportation; Mo., Missouri; US, U.S. highway; --, not known/applicable; NDOR, Nebraska Department of Roads; Nebr., Nebraska; W, westbound; E, eastbound; Kans., Kansas; KDOT, Kansas Department of Transportation; MO, Missouri State highway; K, Kansas State highway; IS, Interstate highway; S, southbound; N, northbound]

Site number (fig. 1)	Primary agency	Structure number	Local name	County	Route	River mile ^a	Surveyed as part of this study	Remark	Figures
Upstream from Kansas City									
1	MoDOT	L0098	Brownville	Atchison, Mo.	US 136	535.3	No	--	1
--	NDOR	--	Rulo	Richardson, Nebr.	US 159	498.1	No	--	1
2	MoDOT	A3664 W	St. Joseph	Buchanan, Mo.	US 36 W	447.9	No	Dual bridge crossing	1
		A3664 E	St. Joseph	Doniphan, Kans.	US 36 E		No	Dual bridge crossing	1
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	A8340	Fairfax	Platte, Mo.	US 69	372.6	Yes	Replaced K0456/A0450 in 2016	1, 6, 7, 8, 9, 10, 11, 1.1
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	kcICON	Clay, Mo.	IS 35	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	Yes	--	1, 12, 13, 14, 15, 16, 17, 1.2
15	MoDOT	A5910	Waverly	Lafayette, Mo.	US 24	293.2	Yes	--	1, 18, 19, 20, 21, 22, 23, 1.3
16	MoDOT	K0999	Miami	Carroll, Mo.	MO 41	262.6	Yes	--	1, 24, 25, 26, 27, 28, 29, 1.4

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

[MoDOT, Missouri Department of Transportation; Mo., Missouri; US, U.S. highway; --, not known/applicable; NDOR, Nebraska Department of Roads; Nebr., Nebraska; W, westbound; E, eastbound; Kans., Kansas; KDOT, Kansas Department of Transportation; MO, Missouri State highway; K, Kansas State highway; IS, Interstate highway; S, southbound; N, northbound]

Site number (fig. 1)	Primary agency	Structure number	Local name	County	Route	River mile ^a	Surveyed as part of this study	Remark	Figures
Between Kansas City and St. Louis—Continued									
17	MoDOT	G0069	Glasgow	Saline, Mo.	MO 240	226.3	Yes	--	1, 30, 31, 32, 33, 34, 35, 1.5
18	MoDOT	A4574	Boonville	Cooper, Mo.	MO 5	196.6	Yes	--	1, 36, 37, 38, 39, 40, 41, 1.6
19	MoDOT	L0962	Rocheport	Boone, Mo.	IS 70	185.1	Yes	--	1, 42, 43, 44, 45, 46, 47, 1.7
20	MoDOT	L0550	Jefferson City	Callaway, Mo.	US 54 S	143.9	Yes	Dual bridge crossing with A4497	1, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 1.8
		A4497	Jefferson City	Cole, Mo.	US 54 N		Yes	Dual bridge crossing with L0550	
21	MoDOT	A6288	Hermann	Montgomery, Mo.	MO 19	97.9	Yes	--	1, 5, 59, 60, 61, 62, 63, 64, 1.9
22	MoDOT	K0969	Washington	Franklin, Mo.	MO 47	67.6	No	Replaced in 2018	1
Greater St. Louis area									
23	MoDOT	A4017	Daniel Boone	St. Charles, Mo.	US 40 E	43.9	No	Dual bridge crossing with J1000	1
		J1000	Daniel Boone	St. Louis, Mo.	US 40 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 and Clark	St. Charles, Mo.	US 67	8.1	No	--	1

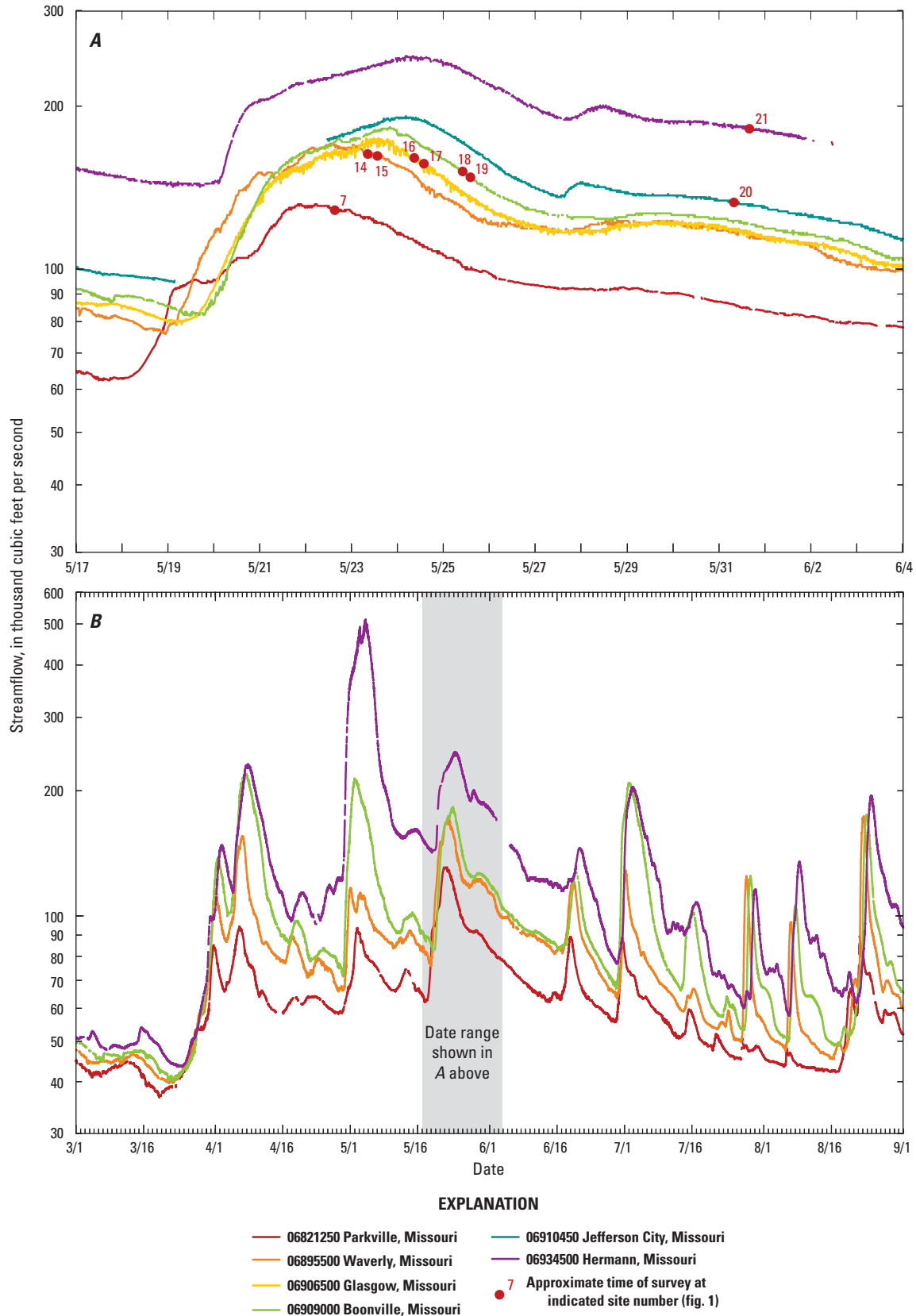


Figure 2. Unit values of streamflow (in 15-minute intervals) at selected streamflow-gaging stations in the study area on the Missouri River between Kansas City and St. Louis, Missouri. A, from May 17 through June 4, 2017; B, from March 1 through September 1, 2017 (U.S. Geological Survey, 2019).

respectively, for that reach (U.S. Army Corps of Engineers, 2003, plate E–20). Conversely, the measured streamflow at the Missouri State Highway 19 crossing at Hermann (site 21) was 192,000 ft³/s during the survey. This streamflow has a daily exceedance probability range of about 7 percent (based on flow duration analysis; U.S. Geological Survey, 2003) at the streamgage at Hermann and is slightly less than the 50-percent annual exceedance probability (2-year recurrence interval) flood flow of 248,000 ft³/s (U.S. Army Corps of Engineers, 2003, table E–20).

Streamflow conditions in this daily and annual exceedance range are in the moderate flood-flow regime. In an analysis of real-time scour monitoring data at Jefferson City, Mo., Huizinga (2014) noted that substantial pier scour begins soon after the onset of hydrograph rise (substantial rise of 8 feet [ft] or more), although the scour often does not reach maximum depth until the peak stage is reached or sometime thereafter (see fig. 35 in Huizinga, 2014). Although the flow conditions for these surveys may not have been at the peak flow for the spring, a series of moderate peaks had been observed at the streamgages on this reach, and flow was substantially higher than base flow based on the daily exceedance values during the surveys (fig. 2B). Although the scour scenario captured at the sites in this study likely does not represent the maximum scour potential, the cumulative information gathered at several sites during the course of multiple surveys in 2010, 2011, 2013, and 2017 remains useful for determining scour for a variety of flow conditions, particularly when combined with, or compared to, a scour scenario captured at high flood flow conditions such as in 2011.

Description of Equipment and Basic Processing

The bathymetry of the Missouri River at each of the bridges was determined using a high-resolution MBMS. The various components of the MBMS used for this study are as described in reports about studies on the Missouri and Mississippi Rivers in Missouri (Huizinga and others, 2010; Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017a) and on the Missouri and Yellowstone Rivers in North Dakota (Densmore and others, 2013). The survey methods used to obtain the data were similar to these previous studies, as were the measures used to ensure data quality. A brief description of the equipment follows; a complete description of the various system components and methods used in this study is available in the previous reports by Huizinga (2010), Huizinga and others (2010), and Densmore and others (2013).

An MBMS is an integration of several individual components: the multibeam echosounder (MBES), an inertial navigation system (INS), and a data-collection and data-processing computer. The MBES that was used for the 2017 surveys is the Teledyne RESON SeaBat 7125–SV2 (fig. 3), operated at a frequency of 400 kilohertz (kHz). The INS that was used is the Applanix Position Orientation Solution for Marine Vessels

(POS MV) WaveMaster system. The INS provides position in three-dimensional space and measures the heave, pitch, roll, and heading of the vessel (and, thereby, the MBES) to accurately position the data received by the MBES. Real-time kinematic (RTK) differential corrections for the INS came from cellular communication with the MoDOT Global Navigation Satellite System (GNSS) real-time network for the navigation and tide solution during the 2017 surveys.

As in previous surveys (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017a, b), the navigation information from the 2017 surveys was postprocessed using the POSpac Mobile Mapping Suite (MMS) software (Applanix Corporation, 2009) to mitigate the effects of degraded positional accuracy of the vessel while near or under a bridge. POSpac MMS provides tools to identify and compensate for sensor and environmental errors and computes an optimally blended navigation solution from the GNSS and inertial measurement unit (IMU) raw data. The blended navigation solution (called a “smoothed best estimate of trajectory” or “SBET” file) generated by postprocessing the navigation data was applied to the survey at a given bridge to minimize the effects of the GNSS outages while surveying under the bridges.

The data from the MBES and INS components were processed and integrated into a cohesive dataset for cleanup and visualization. A computer onboard the survey vessel ran the HYPACK/HYSWEEP data acquisition software (HYPACK, Inc., 2015) that was used to prepare for the bathymetric surveys and collect the survey data. After completing the surveys, the acquired depth data were further processed to remove data spikes and other spurious points in the multibeam swath trace, georeferenced using the navigation and position solution data from the SBET file from POSpac MMS, and visualized in HYPACK/HYSWEEP as a triangulated irregular network surface (also known as a “TIN” surface) or a point cloud. The georeferenced data were output to a comma-delimited file, either having no data reduction or filtered and reduced to a 1.64-ft data resolution. These comma-delimited data were compiled into a geographic information system database for each site using the ArcGIS package (Esri, 2013). Data generated during this study are available as USGS data releases (Huizinga, 2020a, b), along with legacy bathymetric data generated during previous studies at these sites.

Information about the velocity of the river at various points throughout each study reach was collected using an ADCP, similar to recent previous studies by Huizinga (2012, 2013, 2014, 2015, 2016, 2017a, b). 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 beam directions, the velocity of the water in each bin can be determined in three dimensions.

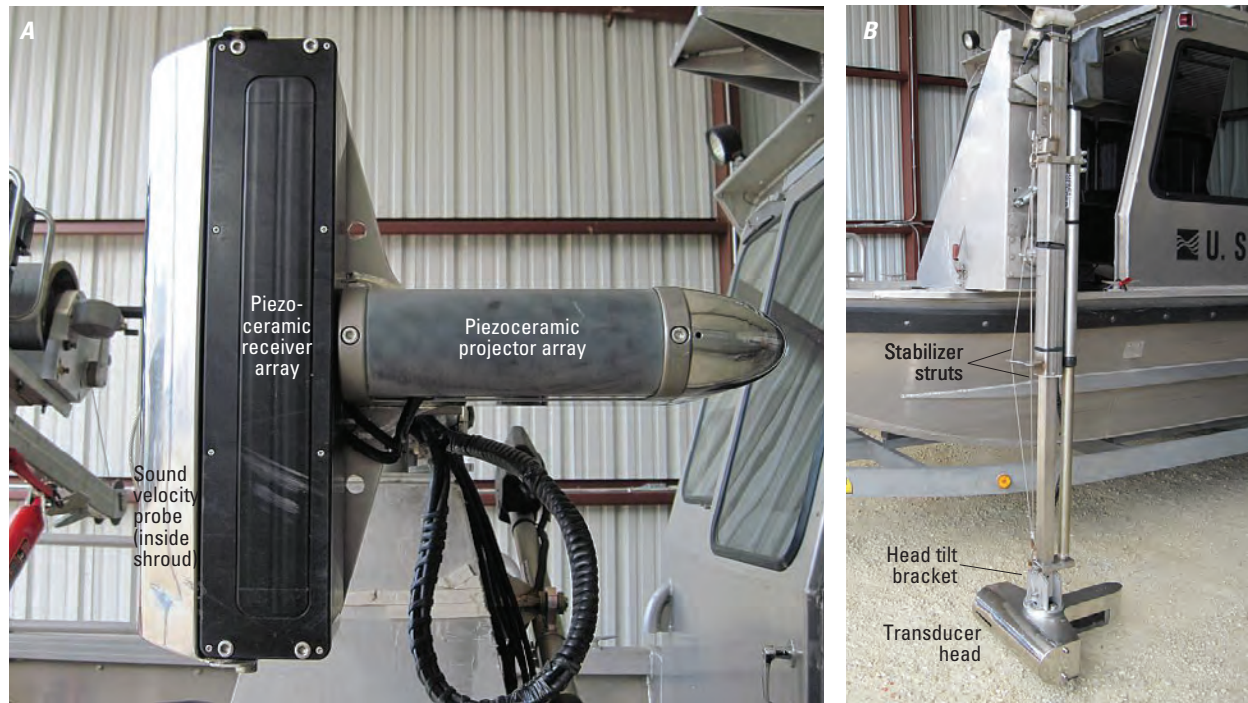


Figure 3. The Teledyne RESON SeaBat 7125-SV2 multibeam echosounder. *A*, viewed from the bottom. *B*, mounted on the port side of the U.S. Geological Survey boat.

Basic Description of Methods

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

Surveying Methods

Generally, the surveyed area extended across the active channel from bank to bank, as had been done in the previous studies on the Missouri River between Kansas City and St. Louis (Huizinga, 2010, 2012, 2014). The surveyed reaches ranged from 1,550 to 1,840 ft long in the direction of flow, positioned so that the surveyed highway bridges were about one-third to one-half of the total length from the upstream boundary, generally using about the same upstream and downstream boundaries as were used in the 2011 flood study (Huizinga, 2012). The upstream and downstream boundaries of the surveyed areas were assumed to be beyond the substantial hydraulic effects (wake vortices and shear flow) 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” (Huizinga and others, 2010). Substantial overlap was achieved for many of the surveyed

swaths, except in shallow areas near the channel banks or spur dikes and near inflow structures, debris rafts, or moored barges. The presence of debris rafts also made surveying difficult in some areas. Areas near the bridge piers and along the banks also were surveyed in an upstream direction with the MBES head tilted at either 30 degrees to port or starboard to increase the acquisition of bathymetric data in the shallow areas, and higher on the banks and the sides of the piers. To limit potential damage to the MBES head, most of the shallow areas (less than about 6 ft of water depth) were not surveyed.

After completing the bathymetric survey with the MBMS at a given site, the velocity data were obtained with the ADCP on seven lateral sections across the channel within the study area. The position and speed of the boat were determined using a differential GNSS receiver mounted on a pole directly above the ADCP. The bottom-track reference method for determining boat speed was anticipated to be unusable because of moving channel-bed material, so the boat velocity was determined using the GNSS essential fix data (the NMEA-0183 GGA string [shorthand for the \$GPGGA standard output format for GNSS essential fix data defined by the National Marine Electronics Association 0183 standard that includes information on the three-dimensional location and accuracy of the GNSS receiver; National Marine Electronics Association, 2002]) from the differential GNSS receiver. The distance between the velocity section lines generally was about 260 ft. Three sections were upstream and four sections were downstream from the bridge in question. Each section line was traversed in each direction across the river. The reported velocity

values are the average from the two traverses of a given section line, using averaging algorithms from the Velocity Mapping Toolbox (Parsons and others, 2013). Streamflow for a site was computed as the average of the streamflows from reciprocal pairs (two transects per section line) at the various sections in the reach. Generally, measured streamflow for an individual transect was within 5 percent of the average.

Survey Quality-Assurance/Quality-Control Measures

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

For the MBMS, the principal quality-assurance measures were assessed in real time during the survey. The MBMS operator continuously assessed the quality of the collected data during the survey by making visual observations of across-track swaths (such as convex, concave, or skewed bed returns in flat, smooth bottoms), noting data-quality flags and alarms from the MBES and the INS and noting comparisons between adjacent overlapping swaths. In addition to the real-time quality-assurance assessments during the survey, beam angle checks and a suite of patch tests were executed to ensure quality data were acquired from the MBMS before the 2017 surveys. These tests were completed at Clearwater Lake near Piedmont, Mo. (fig. 1). Additional patch tests were completed on the second day of the 2017 surveys after striking an object during the survey on the Missouri River at Waverly to document any changes to the mounting angles from the strike.

Beam Angle Check

A beam angle check is used to determine the accuracy of the depth readings obtained by the outer beams (greater than 25 degrees from nadir [vertical]) of the MBES (U.S. Army Corps of Engineers, 2013), which may change with time as a result of inaccurate sound velocities, physical configuration changes, and overall depth being surveyed. The HYPACK/HYSWEEP software has a utility that develops a statistical assessment of the quality of the outer beams compared to a reference surface (HYPACK, Inc., 2015). On May 3, 2017, a reference surface was surveyed for a part of Clearwater Lake near Piedmont (fig. 1, main map), and check lines were run across the reference surface. Included with the measurement was a sound-velocity profile cast to document and quantify any stratification in the water column near the reference surface. The results of this beam angle check (table 2) were within the recommended performance standards used by the U.S. Army Corps of Engineers for hydrographic surveys for all the representative angles below 55 degrees (U.S. Army Corps of Engineers, 2013), permitting the use of the central

110 degrees of the sound navigation and ranging (sonar) swath with confidence.

Ideally, the average depth of the reference surface used in the beam angle check would be equal to or greater than the depth in the area being surveyed. The depth of the Missouri River in each study reach generally was impossible to estimate before each survey because of the dynamic nature of the channel-bed and flow conditions. However, the average depth of the reference surface (greater than 100 ft) was expected to be greater than the average depth observed in the 2017 surveys because the average depths observed during the flood surveys in 2011 generally were less than 40 ft (the average depth is the difference between the average water-surface elevation and average channel-bed elevation in Huizinga [2012, table 5]). As described earlier in the “Surveying Methods” section 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 INS and real-world coordinates. The patch tests are used to determine timing offsets caused by latency between the MBES and the INS and angular offsets to roll, pitch, and yaw caused by the alignment of the transducer head (fig. 4). These offsets have been observed to be virtually constant for a given survey, barring an event that causes the mount to change such as striking a floating or submerged object (Huizinga, 2010, 2011, 2012, 2014, 2015, 2016, 2017a). The offsets determined in the patch test are applied when processing the data collected during a given survey.

Patch tests were completed before the 2017 surveys at Clearwater Lake near Piedmont, Mo. (fig. 1), and again on the second day of surveying, while at site 15 (structure A5910 on U.S. Highway 24; fig. 1) over the Missouri River at Waverly, after striking a substantial floating log at that site (table 3). Although the MBES had several other minor strikes of floating debris at various times during the 2017 surveys, there were no other apparent changes to the roll, pitch, or yaw angles from the beginning to the end of the surveys (table 3).

For this study, there was no measured timing offset (table 3; $\Delta t=0$, fig. 4), which is consistent with latency test results for this boat and a similar equipment configuration used in other surveys (Huizinga and others, 2010; Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017a). At the beginning of the surveys, the measured angular offset for pitch was -1.00 degree for all head-tilt configurations, which changed to -1.50 degrees after the log strike at Waverly (table 3). At the beginning of the surveys, the measured angular offset for yaw was different for each head-tilt configuration; 0.00 degree for no head tilt, 1.00 degree for 30 degrees to starboard tilt,

Table 2. Results of a beam angle check from two check lines over a reference surface at Clearwater Lake near Piedmont, Missouri, on May 3, 2017.

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

Beam angle limit (degrees)	Maximum outlier (feet)	Mean difference (feet)	Standard deviation (feet)	95-percent confidence (feet)
0	0.52	0.00	0.10	0.20
5	0.62	0.03	0.13	0.23
10	0.56	0.03	0.13	0.23
15	0.72	0.07	0.13	0.23
20	0.62	0.07	0.13	0.26
25	0.69	0.10	0.13	0.26
30	0.66	0.10	0.13	0.26
35	0.69	0.16	0.13	0.26
40	0.69	0.16	0.13	0.26
45	0.69	0.16	0.13	0.23
50	0.66	0.20	0.10	0.23
55	0.85	0.23	0.13	0.26
60	2.10	0.26	0.16	0.33
65	1.44	0.20	0.16	0.36
Performance standards ^a				
	1.00	<0.30	--	<0.80
	Met, angle <60	Met	--	Met

^aPerformance standard check values are from U.S. Army Corps of Engineers (2013, table 3–1) for soft sand/silt bottoms.

and –1.00 degree for 30 degrees to port tilt; these values changed to 1.50, 2.00, and 1.50 for the head-tilt configurations, respectively, after the log strike (table 3). The measured angular offset for roll changed from –2.40 degrees before to –2.75 degrees after the log strike for no tilt, –32.45 degrees before to –32.75 degrees after for 30 degrees to starboard tilt, and 27.95 degrees before to 27.50 degrees after for 30 degrees to port tilt. The measured offset angles for roll, pitch, and yaw from before the log strike at Waverly are similar to previous surveys with this equipment (see table 3, Huizinga, 2017a). It was noted in the earliest work with the MBMS in Missouri (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 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 bathymetric data were then projected to a three-dimensional grid at a resolution of 1.64 ft using the Combined Uncertainty and Bathymetry Estimator (CUBE) method (Calder and Mayer, 2003), as implemented in the MB-MAX processing package of the HYPACK/HYSWEEP software (HYPACK, Inc., 2015), and used to generate a gridded raster surface of the channel

bed near each bridge (hereinafter referred to as a “bathymetric surface”) using ArcGIS. The bathymetric surface for each site from the 2017 survey was compared to similar bathymetric surfaces created from previous surveys at a bridge by taking the difference between the 2017 raster surface and the previous survey raster surface. Statistics of the elevations for each bathymetric surface were determined, as were statistics of the differences between the surfaces. Sediment volumes for cut (scour) and fill (deposition) between the 2017 survey and previous surveys in 2010, 2011, and 2013 also were determined from differences in the raster surfaces using ArcGIS.

Uncertainty Estimation

Similar to the previous studies of bathymetry in Missouri (Huizinga, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017a, b), uncertainty in the surveys was estimated by computing the total propagated uncertainty (TPU) for each survey-grid cell in the bathymetric surface of each survey area, using the CUBE method (Calder and Mayer, 2003) as implemented in the MB-MAX processing package of the HYPACK/HYSWEEP software (HYPACK, Inc., 2015). 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

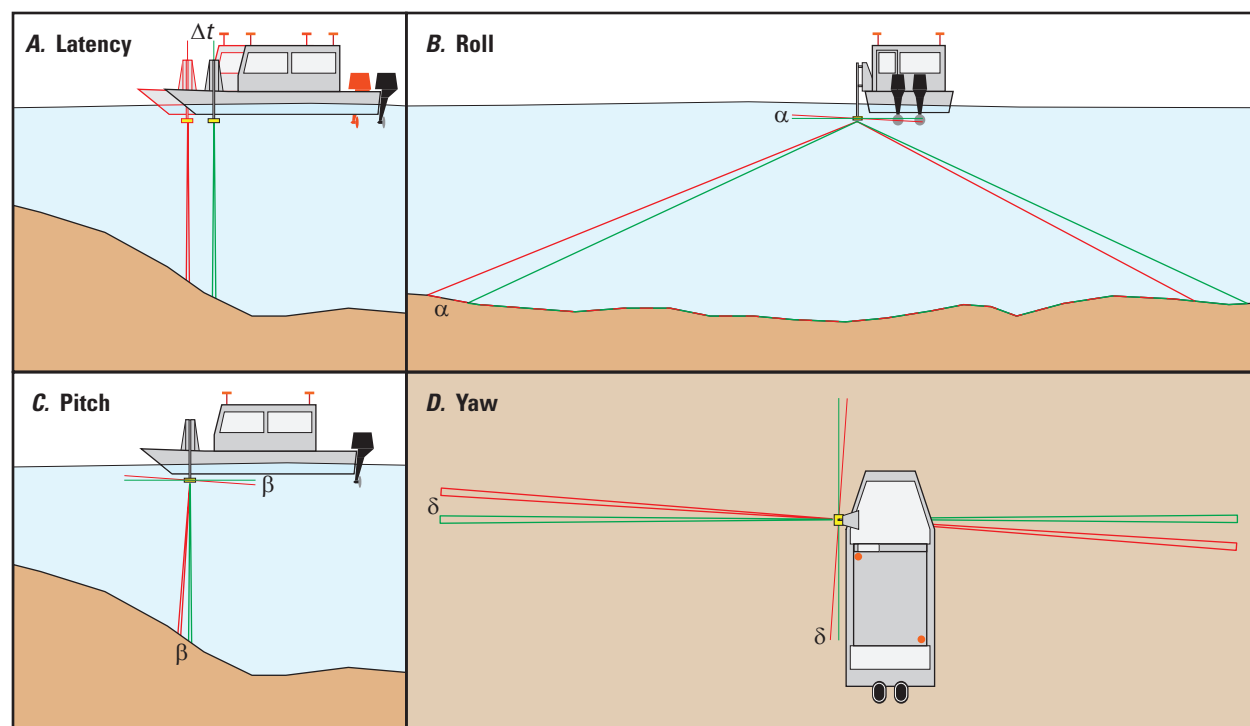


Figure 4. Generalized effects on data from a multibeam echosounder. *A*, timing offset for latency; *B*, angular offset for roll; *C*, angular offset for pitch; *D*, angular offset for yaw.

Table 3. Patch test results at Clearwater Lake near Piedmont, Missouri, on May 8, 2017, and on the Missouri River at Waverly, Missouri, on May 23, 2017.

Date of test	Timing offset (seconds)	Angular offset for roll (degrees)	Angular offset for pitch (degrees)	Angular offset for yaw (degrees)	Head tilt
05/08/17	0	-2.40	-1.00	0.00	None.
05/23/17	0	-2.75	-1.50	1.50	None.
05/08/17	0	-32.45	-1.00	1.00	30 degrees starboard.
05/23/17	0	-32.75	-1.50	2.00	30 degrees starboard.
05/08/17	0	27.95	-1.00	-1.00	30 degrees port.
05/23/17	0	27.50	-1.50	1.50	30 degrees port.

within the survey area (Czuba and others, 2011). Thus, the TPU of a point is a measure of the accuracy to be expected for such a point when all relevant error sources are taken into account (Czuba and others, 2011). Statistics of TPU for each of the survey areas are shown in table 4, and an example of the spatial distribution of TPU typically observed in the survey data is shown in figure 5 for the bathymetric data at structure A6288 on State Highway 19 over the Missouri River.

The largest TPU in this group of surveys was 1.74 ft (table 4); however, as noted in previous studies, TPU values of this magnitude typically happened near high-relief features, such as the front or side of a pier footing (fig. 5). More than 97 percent of the TPU values were less than 0.50 ft (table 4), which is within the specifications for a “Special Order” survey, the most stringent survey standard of the International Hydrographic Organization (IHO; International Hydrographic Organization, 2008). As has been noted in previous surveys with this equipment, the TPU values were larger near moderate-relief features (banks, spur dikes, rock riprap and outcrops, and scour holes near piers; fig. 5). Occasionally, the TPU values also were larger (1.00 ft or greater) in the outermost beam extents of the multibeam swath in the overlap with an adjacent swath, particularly when the MBES head was tilted for the survey lines along the banks or near the piers (fig. 5). Overlapping adjacent swaths in the channel thalweg (the line of maximum depth in the channel) also can indicate larger TPU values because substantial bed movement can happen between survey passes (fig. 5). More than 80 percent of the TPU values were 0.25 ft or less (table 4). The tops of bridge substructural elements (pier footings and seal courses) typically had TPU values of 0.25 ft or less.

The survey at structure A6288 on Missouri State Highway 19 had the highest average value of TPU, and generally the lowest percentage of bathymetry points that were less than the various TPU value cutoffs (table 4). There were a few impediments to surveying at this site in the form of lateral and longitudinal spur dikes along both banks, but otherwise, the survey was obtained with generally smooth longitudinal swathes (fig. 5), which was true at nearly all the sites surveyed in this study. The primary anomaly at this site was along the banks, where the sonar was used in a tilted head configuration to extend the potential coverage in these areas, resulting in substantial TPU values (fig. 5). Generally, the magnitude and distribution of TPU values observed at this site are representative of those observed at all the other surveyed sites.

Results of Bathymetric and Velocimetric Surveys

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

Table 4. Total propagated uncertainty results for bathymetric data at a 1.64-foot grid spacing from surveys on the Missouri River between Kansas City and St. Louis, Missouri, from May 22 to May 31, 2017.

[MoDOT, Missouri Department of Transportation]

Site number (fig. 1)	MoDOT structure number	Maximum value of uncertainty (feet)	Mean value of uncertainty (feet)	Median value of uncertainty (feet)	Standard deviation of uncertainty (feet)	Percent of bathymetry points with uncertainty value less than			
						2.00 feet	1.00 foot	0.50 foot	0.25 foot
7	A8340	1.44	0.17	0.16	0.09	100.0	99.8	99.1	93.3
14	A5664	1.48	0.14	0.13	0.08	100.0	99.8	99.3	96.9
15	A5910	1.51	0.15	0.13	0.08	100.0	99.9	99.4	94.6
16	K0999	1.51	0.15	0.13	0.10	100.0	99.8	98.5	90.8
17	G0069	1.35	0.13	0.10	0.08	100.0	99.8	99.2	96.0
18	A4574	1.57	0.16	0.13	0.10	100.0	99.9	98.2	88.9
19	L0962	1.74	0.18	0.16	0.11	100.0	99.7	98.0	87.9
20	L0550/ A4497	1.48	0.19	0.16	0.10	100.0	99.8	98.7	85.0
21	A6288	1.57	0.21	0.20	0.12	100.0	99.7	97.1	80.3

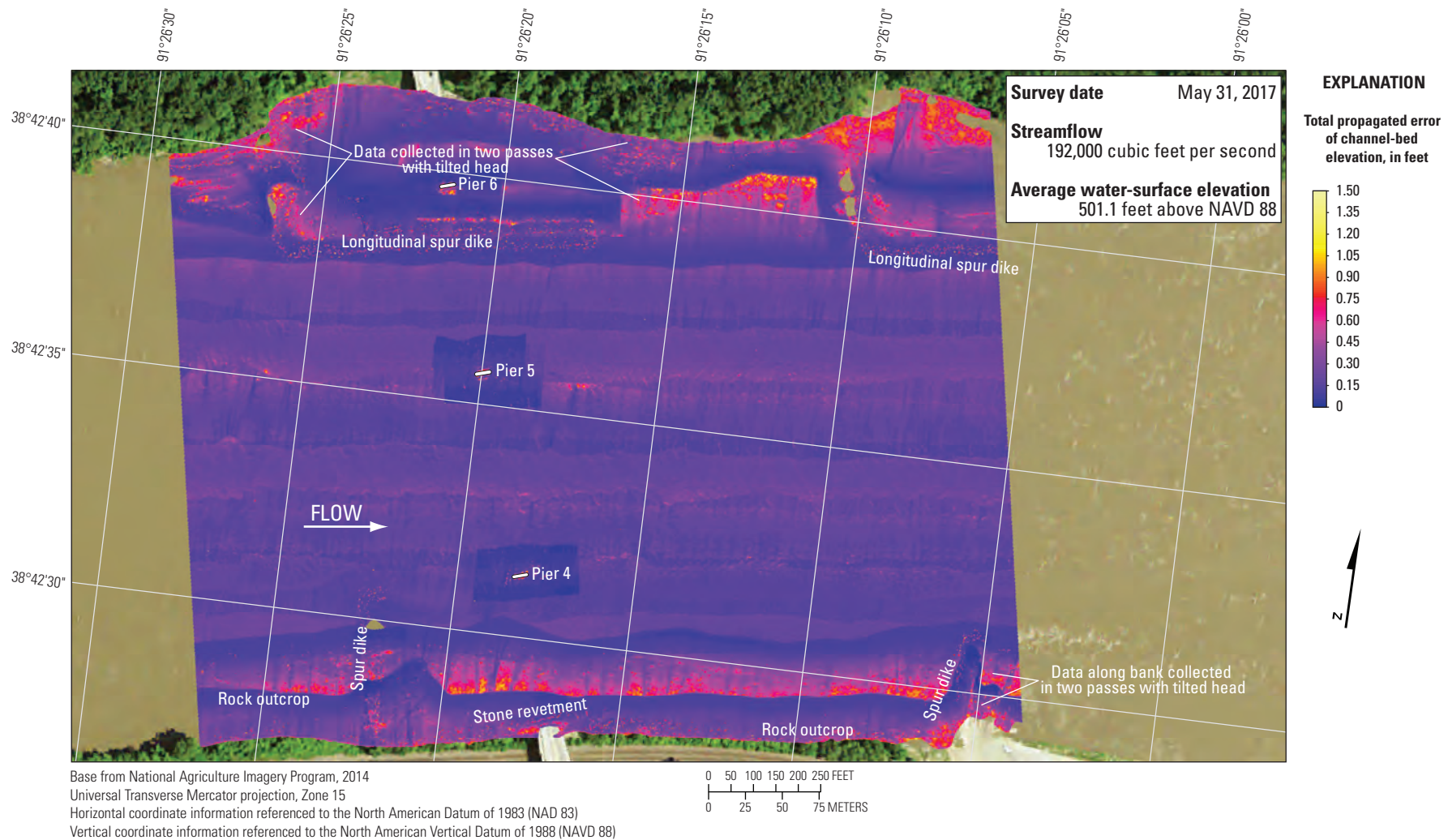


Figure 5. Total propagated uncertainty of bathymetric data from the Missouri River channel near structure A6288 on Missouri State Highway 19 at Hermann, Missouri.

scour holes near piers. All elevation data were referenced to the North American Vertical Datum of 1988 (NAVD 88).

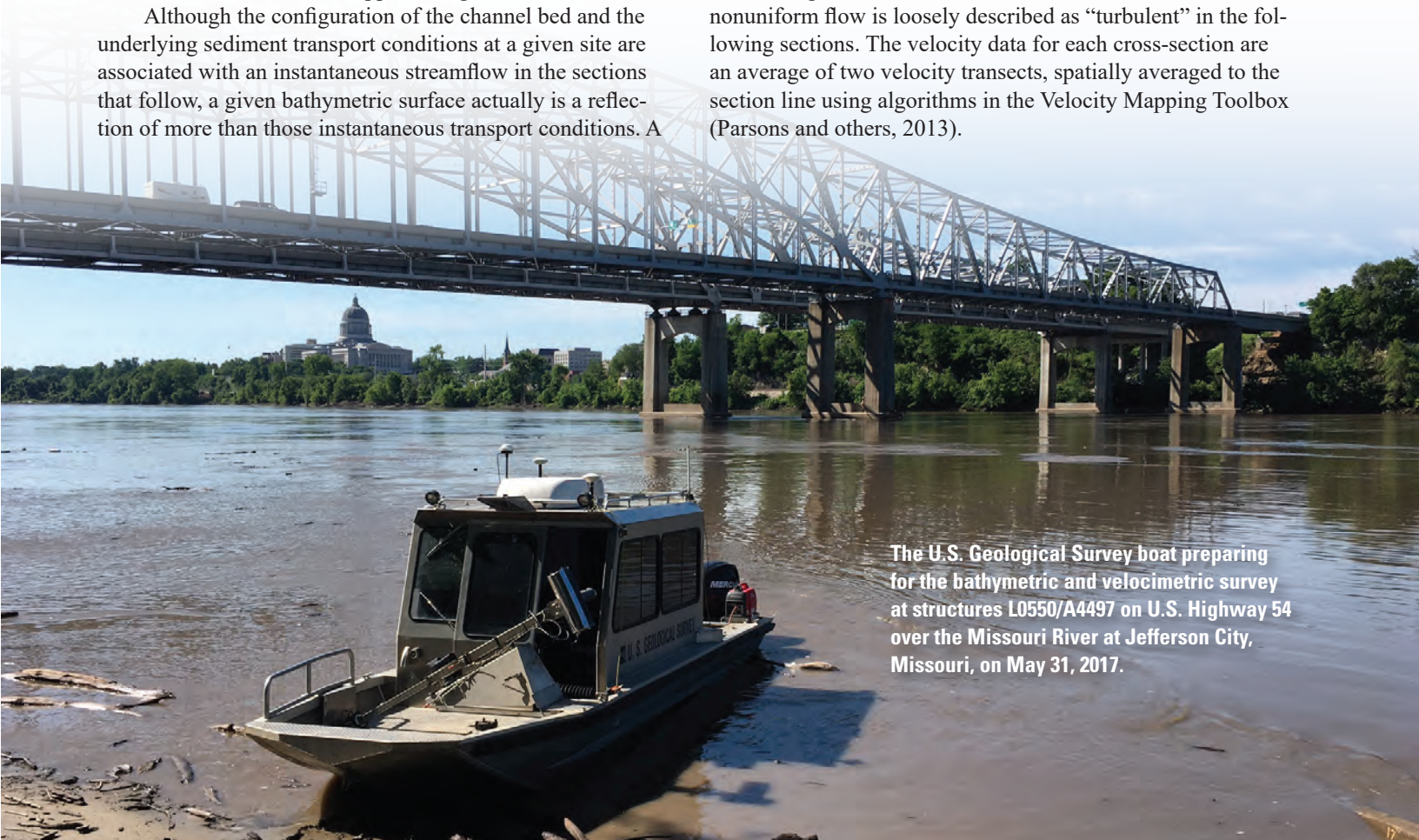
For consistency with earlier studies, dune sizes are described in general terms for each of the bridge sites using the categories set by Huizinga (2012) for the discussion of bathymetry during the 2011 flood. In this report, small dunes and ripples are those that are less than 5 ft high from crest to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

Previous bathymetric surveys have been completed at all the bridge sites in this study (Huizinga, 2010, 2012, 2014); furthermore, several of the sites had a Level 2 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 each of the surveys is included for each site, and data from previous surveys are included in the cross-section plot for that bridge. The difference maps were created by taking the difference between the 2017 raster surface and a previous survey raster surface at a given bridge, and summary statistics (maximum, minimum, and average) of the difference rasters were determined. The surveys are broadly compared based on their timing and the streamflow at the time of the survey. If a site was subject to a Level 2 assessment, the cross section of the channel at the bridge (typically on the downstream side of the bridge) obtained during the Level 2 assessment is included on the cross-section plot for that bridge. Additionally, shaded TIN images of the channel and side of pier were prepared for each surveyed pier. These visualizations are shown in appendix figures 1.1 to 1.9.

Although the configuration of the channel bed and the underlying sediment transport conditions at a given site are associated with an instantaneous streamflow in the sections that follow, a given bathymetric surface actually is a reflection of more than those instantaneous transport conditions. A

wide variety of factors affect the channel-bed configuration of a reach for a given streamflow (Gilbert and Murphy, 1914), including flow velocities and velocity distribution, the size and timing of previous flood rises, whether or not the stage currently is rising or falling, and other local hydraulic conditions. Furthermore, the channel-bed configuration at a site is affected by upstream and local sediment conditions and contributions, as well as water temperature and other seasonal variations. Because of the myriad number and interactions of factors affecting sediment transport conditions and the resultant bed configuration, it can be assumed that the configuration and size of bed forms observed during the current (2017) surveys between Kansas City and St. Louis depend on more than the instantaneous streamflow at a given site. Although it is beyond the scope of the current (2017) study to examine all the antecedent conditions that created the observed channel-bed configuration, the comparisons with previous surveys under different flow conditions nevertheless contribute to understanding the many complexities of sediment transport.

As in recent previous studies (Huizinga, 2012, 2013, 2014, 2015, 2016, 2017a), 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 assumed to be an indication of nonuniform flow in the section resulting from shear and wake vortices. Conversely, neighboring vectors having gradual and systematic variations were assumed to be an indication of uniform flow in the section. The Missouri River is highly turbulent, even in the absence of structures that generate strong shear or wakes, but in the interest of conciseness, nonuniform flow is loosely described as “turbulent” in the following sections. The velocity data for each cross-section are an average of two velocity transects, spatially averaged to the section line using algorithms in the Velocity Mapping Toolbox (Parsons and others, 2013).



The U.S. Geological Survey boat preparing for the bathymetric and velocimetric survey at structures L0550/A4497 on U.S. Highway 54 over the Missouri River at Jefferson City, Missouri, on May 31, 2017.

Structure A8340 on U.S. Highway 69

Structure A8340 (site 7) is a single bridge on U.S. Highway 69, crossing the Missouri River at river mile (RM) 372.6, on the northwestern side of the Kansas City metropolitan area (fig. 1). This site was not included in the routine surveys of the Kansas City area bridges in 2015 (Huizinga, 2016) because the former bridges on U.S. Highway 69, structures K0456 and A0450, were in the process of being replaced at that time. The site was surveyed on May 22, 2017, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 736.9 ft (table 5). Streamflow on the Missouri River was about 140,000 ft³/s during the survey (table 5).

The survey area was about 1,550 ft long and about 900 ft wide, extending across the active channel from bank to bank (fig. 6). The upstream end of the survey area was about 680 ft upstream from the centerline of structure A8340 (fig. 6). The channel-bed elevations ranged from about 701 to 721 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 7), except near the central main channel bent 4 of structure A8340 and downstream from the spur dikes on the left (north) bank (fig. 6). There was a defined thalweg along the toe of the right (south) bank, which was about 9 ft deeper than the channel bed in the middle of the channel (fig. 6). A series of medium dunes was present in the middle of the channel, and numerous other small dunes and

ripples were present throughout the rest of the channel (fig. 6). As in previous surveys (Huizinga, 2010, 2012), stone revetment was present on the right (south) bank throughout the reach, and two spur dikes were present on the left (north) bank (fig. 6). Partial remnants of piers from old structures K0456 and A0450 are evident to the right and downstream from bent 4 of structure A8340 (fig. 6).

A local scour hole near bent 4 had an approximate minimum channel-bed elevation of about 695 ft (table 6), about 10 ft above the approximate minimum channel-bed elevation of 685 ft (table 5), and about 5 ft below the average channel bed immediately upstream from the bent (the value of the “depth of scour hole from upstream channel bed” in table 6; fig. 6). A local scour hole near bent 5 had a minimum elevation of 710 ft, about 7 ft below the average channel bed immediately upstream from the pier (fig. 6; table 6). Bent 3 is surrounded by the rock revetment on the right (south) bank, but a very small depression of about 3 ft was present in the revetment near the upstream face of the upstream column (fig. 6; table 6). Information from bridge plans indicates that all the main channel bents of structure A8340 are shafts drilled 23 to 28 ft into bedrock and have about 57 ft of bed material between the bottom of the scour hole and bedrock at bent 4 (fig. 8; table 6); bent 5 and bent 3 have about 73 ft and 86 ft of bed material between the bottom of the scour hole and bedrock, respectively (fig. 8; table 6).

Structure A8340 on U.S. Highway 69



Table 5. Bridge and survey information, and selected channel-bed elevations from surveys on the Missouri River between Kansas City and St. Louis, Missouri, from May 22 to May 31, 2017.

[MoDOT, Missouri Department of Transportation; ADCP, acoustic Doppler current profiler; ft³/s, cubic foot per second; ft, foot; US, U.S. highway; MO, Missouri State highway; IS, Interstate 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 ^a	Streamflow from ADCP measurements ^b (ft ³ /s)	Average water-surface elevation near the bridge (ft)	Average channel-bed elevation ^c (ft)	Approximate elevation of the indicated percentile of the bathymetric data		Approximate minimum channel elevation ^d (ft)
								5th percentile (ft)	95th percentile (ft)	
7	A8340	05/22/17	US 69	372.6	140,000	736.9	709.6	700.9	721.4	685
14	A5664	05/23/17	MO 13	314.9	160,000	687.8	661.2	654.1	673.5	641
15	A5910	05/23/17	US 24	293.2	160,000	668.8	643.4	632.4	654.9	619
16	K0999	05/24/17	MO 41	262.6	152,000	641.9	619.5	608.2	627.7	594
17	G0069	05/24/17	MO 240	226.3	167,000	610.8	583.3	574.4	595.7	559
18	A4574	05/25/17	MO 5	196.6	153,000	584.7	561.8	554.4	569.0	547
19	L0962	05/25/17	IS 70	185.1	155,000	574.7	547.3	537.7	562.0	513
20	L0550/ A4497	05/31/17	US 54	143.9	125,000	537.0	512.0	503.9	524.8	500
21	A6288	05/31/17	MO 19	97.9	192,000	501.1	472.7	464.0	487.0	444

^aRiver mile is the distance upstream on the Lower Missouri River, starting at the confluence with the Mississippi River at St. Louis, Mo. (fig. 1), at river mile 195.2 of the Upper Mississippi River.

^bThe average streamflow obtained while making the various velocity transects. The reported value is the streamflow computed using Global Navigation Satellite System (GNSS) essential fix GGA data string as the reference, as described in the “Surveying Methods” section of the text.

^cThe statistical average of the gridded raster surface of channel-bed elevations.

^dThe minimum channel-bed elevation of the gridded raster surface, not necessarily in any scour holes near the bridge.

^eThe reported streamflow is from a routine ADCP measurement made at this site at approximately the same time as the bathymetric survey. The data for the various velocity transects collected at this site were lost. The streamflow from the rating at this site was 133,000 ft³/s.

The difference between the survey on May 22, 2017, and the previous flood survey on July 16, 2011, indicates several areas of substantial bed variation between 2011 and 2016 (fig. 9). There was an area of substantial deposition of more than 20 ft near the former location of the main channel bridge piers for structures K0456 and A0450, where a scour hole present in the 2011 survey (Huizinga, 2012) has subsequently been filled (fig. 9). Additional deposition was observed in the thalweg along the toe of the right (south) bank and in the troughs of several large dunes present in the middle of the channel in the 2011 survey (fig. 9). However, there was an area of substantial scour of more than 30 ft downstream from the spur dike on the left (north) bank upstream from the bridge (fig. 9) and an apparent widening of the channel to the north (figs. 8, 9). Minor scour indicated along the stone revetment on the right (south) bank may be the result of minor positional variations between the surveys. The average difference between the bathymetric surfaces (the statistical average value of the gridded raster surface [fig. 9] created from the difference between the 2017 and 2011 [previous] survey gridded

raster bathymetric surfaces) was −0.33 ft (table 7), indicating minor overall channel degradation between the 2011 and 2017 surveys. The net volume of cut in the reach from 2011 to 2017 was about 91,800 cubic yards (yd³), and the net volume of fill was about 76,300 yd³, resulting in a net loss of about 15,500 yd³ of sediment between 2011 and 2017.

The difference between the survey on May 22, 2017, and the previous nonflood survey on March 15, 2010, indicates more widespread deposition between 2010 and 2017, with substantial deposition of more than 20 ft again near the former location of the main channel bridge piers for structures K0456 and A0450, where a scour hole present in the 2010 survey (Huizinga, 2010) has subsequently been filled (fig. 10). Additional deposition was observed throughout the middle of the channel and downstream from the spur dike on the left (north) bank upstream from the bridge (fig. 10). However, there was an area of substantial scour of more than 30 ft downstream from the spur dike on the left (north) bank downstream from the bridge and scour generally along the left (north) side of the channel near the bridge and downstream (fig. 10). Minor scour

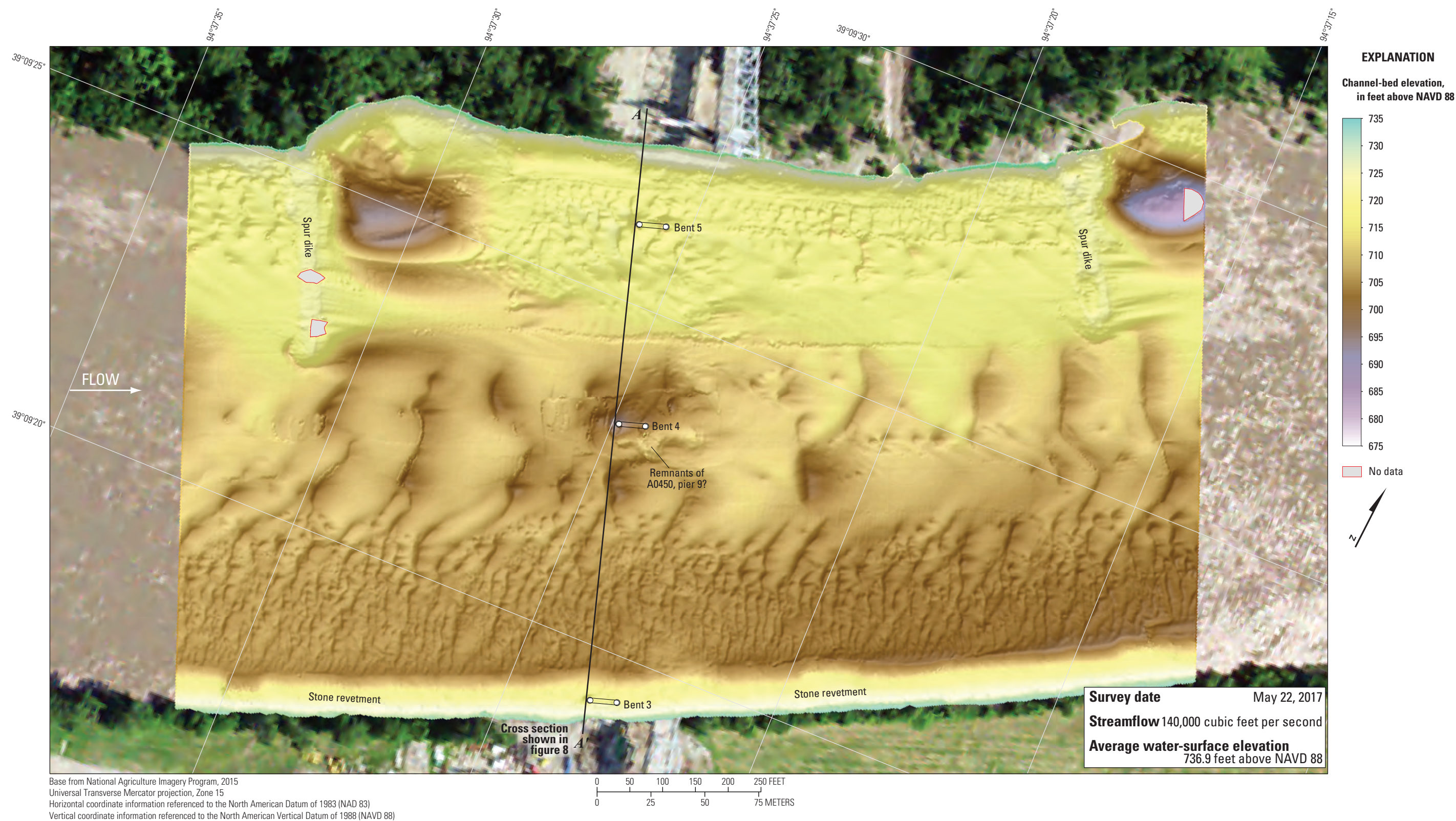


Figure 6. Bathymetric survey of the Missouri River channel near structure A8340 on U.S. Highway 69 in Kansas City, Missouri.

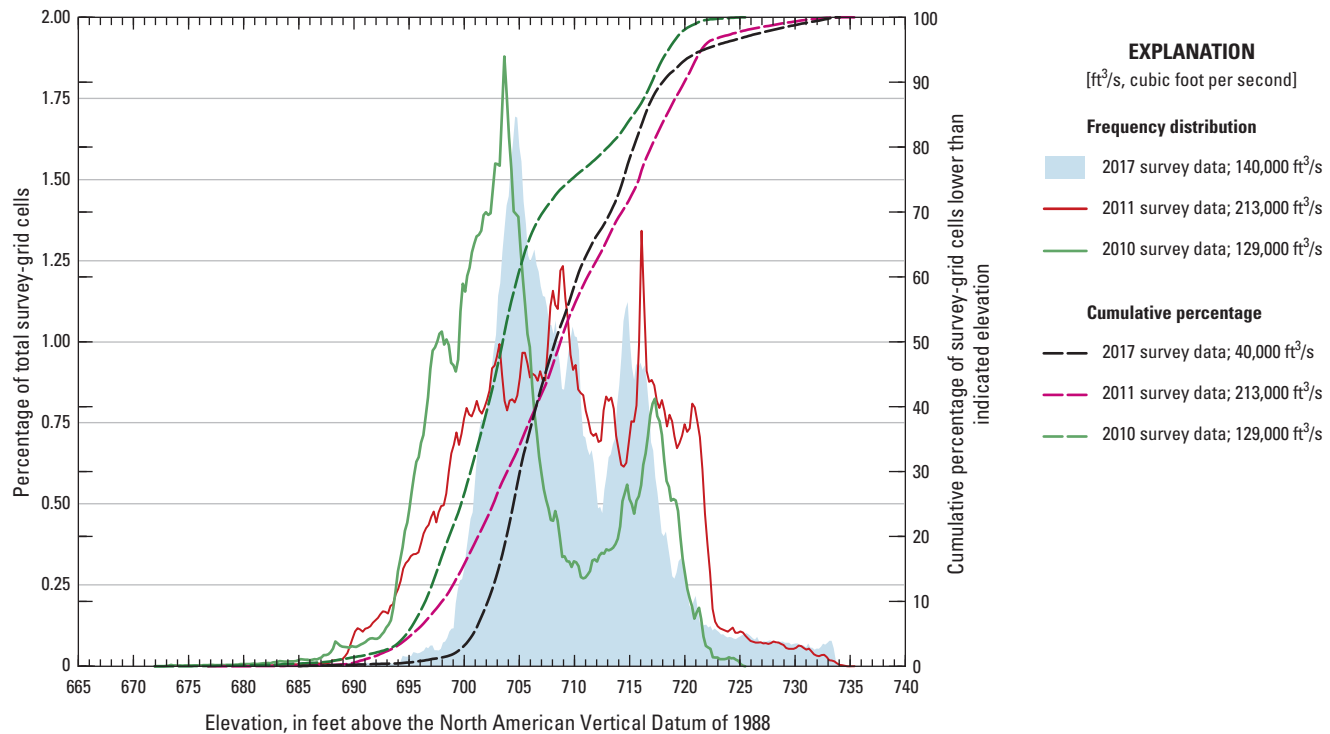


Figure 7. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A8340 on U.S. Highway 69 in Kansas City, Missouri, on May 22, 2017, compared to previous surveys.

indicated along the stone revetment on the right (south) bank, again, may be the result of minor positional variations between the surveys. The average difference between the bathymetric surfaces was 2.90 ft (table 7), indicating substantial overall channel aggradation between the 2010 and 2017 surveys for the area common to both surveys. The net volume of cut in the reach from 2010 to 2017 was about 28,700 yd³, and the net volume of fill was about 142,300 yd³, resulting in a net gain of about 113,600 yd³ of sediment.

The removal of the old bridges and change in column configuration of the new bridge resulted in a substantial change in the cross sections as well (fig. 8). The cross sections from the various surveys along the upstream face of the bridge are not substantially different from one another between bents 3 and 4, but the 2017 cross section is substantially different near the left bank, between bents 4 and 5, and near the former location of the main channel pier of structure K0456; the change of the stone revetment elevation near bent 3 also is apparent (fig. 8). Near the former upstream center of pier 7 of structure K0456, as much as 25.2 ft of deposition had occurred

by 2017 (table 7; fig. 8). The frequency distribution of bed elevations was similar in shape in 2017 when compared to 2011 and 2010, but the highest percentage of survey-grid cells occurred at a higher elevation, and in a substantially narrower range of elevations from 700 to 720 ft (fig. 7). The frequency distribution had a broader elevation range in 2011 (ranging from 693 to 722 ft), and in 2010, there was a higher percentage of survey-grid cells with elevations between 695 and 705 ft (fig. 7). The cumulative percentages further demonstrate the shift to a narrower range of generally higher channel-bed elevations in 2017 (fig. 7).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach (fig. 11). A maximum velocity of about 10 feet per second (ft/s) was present in the upstream middle of the channel, and a minimum velocity of about 1 ft/s was present with flow reversal downstream from the various spur dikes in the reach (fig. 11). Minimal effect on the velocity was observed downstream from bent 4 (fig. 11), indicating the new pier design is appropriately hydrodynamic. Minor turbulence was present in all the sections (fig. 11).

Table 6. Results near piers and bents from surveys on the Missouri River between Kansas City and St. Louis, Missouri, from May 22 to May 31, 2017.

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

Site number (fig. 1)	MoDOT structure number	MoDOT pier/bent number	Foundation information				Approximate minimum elevation in scour hole near pier/bent ^a (ft)	Approximate elevation of scour hole at upstream pier/bent face (ft)	Approximate elevation of bedrock near pier/bent (ft)	Approximate distance between bottom of scour hole and bedrock (ft)	Depth of scour hole from upstream channel bed (ft)
			Type	Width (feet)	Penetration into bedrock (ft)	Bottom of seal course elevation (ft)					
7	A8340	5	Drilled shaft	10.5	23	--	710	710	638	73	7
		4	Drilled shaft	10.5	28	--	695	695	638	57	5
		3	Drilled shaft	10.5	23	--	714	714	628	86	3
14	A5664	21	Drilled shaft	49.2	28	631.55	651	654	604	47	5
		22	Drilled shaft	31.2	50	634.83	659	659	632	28	5
15	A5910	10	Drilled shaft	32	30	628.00	646	646	605	41	4
		11	Drilled shaft	32	42	614.00	634	634	600	34	4
16	K0999	6	Caisson	16.5	0	--	609	609	574	36	11
		5	Caisson	16.5	0	--	594	594	588	6	23
		4	Footing	12	6	--	625	625	620	5	0
17	G0069	2	Footing	19.5	1	--	574	579	579	^b —5	^b 5
		3	Caisson	19.5	1	--	560	563	562	^b —2	^b 20
		4	Caisson	19.5	1	--	572	579	557	15	^b 9
18	A4574	8	Drilled shaft	32	26	527.00	547	547	506	41	^c 4
		7	Drilled shaft	32	39	533.00	553	553	513	39	8
		6	Footing	30	2	--	560	560	551	9	4
		5	Footing	29	2	--	^c 560	560	560	^c 0	0
19	L0962	16	Footing	12	2	--	(^d)	(^d)	536	(^d)	(^d)
		15	Caisson	18	3	--	^c 534	(^d)	519	^c 15	(^d)
		14	Caisson	24	1	--	522	522	498	24	23
20	L0550	4	Caisson	24	1	--	^c 508	^c 508	459	49	^c 0
	A4497	4	Drilled shaft	29.9	11	493.50	^c 509	^c 509	459	50	^c 0
21	A6288	6	Drilled shaft	32	27	442.00	465	468	401	64	3
		5	Drilled shaft	32	26	444.50	465	467	413	51	1
		4	Drilled shaft	32	25	451.50	463	463	443	20	5

^aThe point of lowest elevation in the scour hole near the bridge pier/bent, not necessarily at the upstream face.^bScour hole at this pier/bent is substantially affected by upstream pier/bent.^cScour hole is substantially affected by adjacent spur dike.^dUnable to obtain data because pier was out of water or blocked by accumulated debris.^eScour hole mitigated by riprap blanket around pier(s).

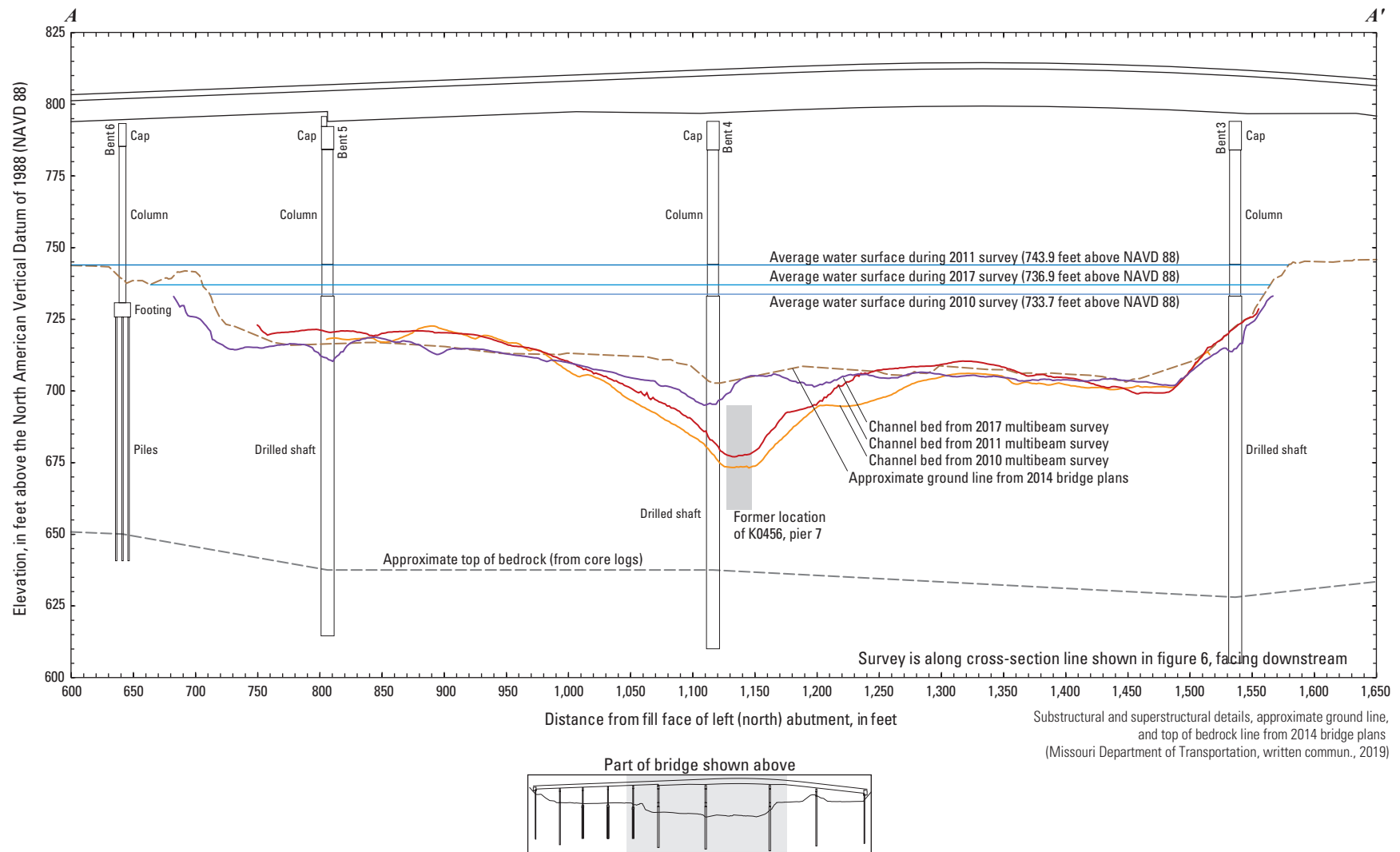


Figure 8. Key features, substructural and superstructural details, and surveyed channel bed of structure A8340 on U.S. Highway 69 crossing the Missouri River in Kansas City, Missouri.

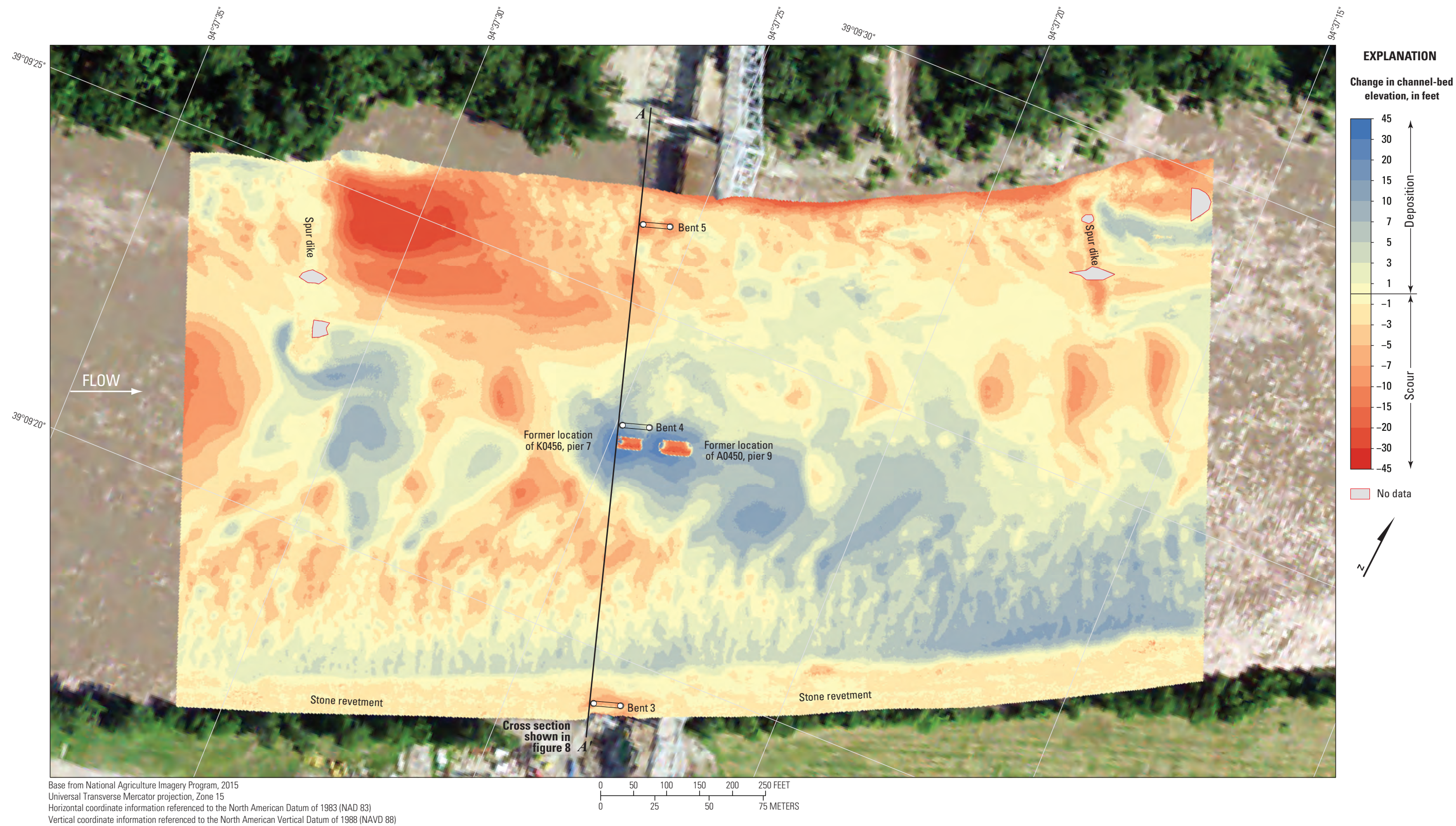


Figure 9. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A8340 on U.S. Highway 69 in Kansas City, Missouri, on May 22, 2017, and July 16, 2011.

Table 7. Summary information and bathymetric surface difference statistics from surveys on the Missouri River between Kansas City and St. Louis, Missouri, from May 22 to May 31, 2017, and previous surveys.

[MoDOT, Missouri Department of Transportation; ft³/s, cubic foot per second; ft², square foot; ft, foot; A, Huizinga (2010); B, Huizinga (2012); C, Huizinga (2014); all elevations are in feet above the North American Vertical Datum of 1988]

Site number (fig. 1)	MoDOT structure number	Previous survey					Difference between 2017 survey and previous survey			Statistics of differences between 2017 and previous survey surfaces				Maximum difference near upstream pier/bent face(s) ^{b,c}
		Source of data	Date	Streamflow (ft³/s)	Surveyed area (×10⁶ ft²)	Average water-surface elevation (ft)	Streamflow (ft³/s)	Surveyed area (×10⁶ ft²)	Average water-surface elevation (ft)	Minimum ^{a,b} (ft)	Maximum ^{a,b} (ft)	Average ^b (ft)	Standard deviation (ft)	
7	A8340	A	03/15/10	129,000	1.165	733.7	11,000	0.186	3.2	−30.5	39.7	2.90	5.19	^d 25.2
		B	07/16/11	213,000	1.326	743.9	−73,000	0.024	−7.0	−27.2	35.0	−0.33	5.12	^d 20.5
14	A5664	B	07/20/11	211,000	1.630	693.9	−51,000	0.053	−6.1	−15.7	25.3	3.33	3.58	−0.4
		C	04/24/13	41,100	1.263	675.4	118,900	0.420	12.4	−16.8	22.4	−0.89	3.50	−0.6
15	A5910	B	07/21/11	213,000	1.700	674.3	−53,000	0.054	−5.5	−29.3	25.4	0.64	4.68	−0.4
		C	04/25/13	41,100	1.185	657.0	118,900	0.569	11.7	−14.5	21.0	−0.96	4.08	−5.7
16	K0999	B	07/21/11	213,000	1.890	648.3	−61,000	0.040	−6.4	−22.8	33.6	0.68	3.45	−2.4
		C	04/25/13	44,600	1.131	630.3	107,400	0.799	11.6	−22.1	31.5	0.95	2.82	−6.8
17	G0069	B	07/22/11	214,000	1.570	615.7	−47,000	0.065	−4.9	−24.5	37.6	1.41	4.32	−7.8
		C	04/26/13	71,000	1.524	602.0	96,000	0.111	8.8	−31.2	26.5	0.43	3.60	−8.6
18	A4574	B	07/25/11	219,000	2.034	590.9	−66,000	0.054	−6.2	−17.3	23.2	−0.04	2.76	−7.6
		C	04/29/13	58,700	1.889	576.0	94,300	0.199	8.7	−15.7	25.5	−0.18	2.23	−7.7
19	L0962	B	07/26/11	219,000	1.851	580.9	−64,000	0.017	−6.2	−27.6	36.7	0.22	4.72	−4.6
		C	04/29/13	63,400	1.527	566.5	91,600	0.341	8.2	−35.4	22.5	−0.56	2.53	−10.9
20	L0550/ A4497	B	01/26/10	155,000	1.526	540.1	−30,000	0.147	−3.1	−10.9	37.3	−0.63	3.95	^e 36.9
		B	03/01/11	145,000	1.537	540.0	−20,000	0.136	−3.0	−9.9	41.9	0.76	4.05	^e 40.1
		B	07/27/11	219,000	1.651	544.7	−94,000	0.022	−7.7	−10.3	49.8	3.88	4.79	^e 49.8
		C	04/30/13	62,500	1.578	530.3	62,500	0.095	6.7	−12.4	46.3	0.47	3.30	^e 23.8
21	A6288	B	07/28/11	215,000	2.475	504.2	−23,000	0.070	−3.1	−23.2	25.7	−0.73	3.07	3.9
		C	05/02/13	108,000	2.145	494.6	84,000	0.400	6.5	−22.8	22.7	−1.95	2.56	−6.4

^aThe maximum or minimum value of change likely is near a vertical pier/bent face and affected by minor position variances.

^bA positive value represents deposition, a negative value represents scour.

^cThe maximum difference near the upstream pier/bent face was taken near the location of the “approximate elevation of scour hole at upstream pier/bent face” in table 6.

^dNear the location of a new pier/bent, compared at the location of the old pier in the previous survey.

^eScour hole in previous surveys mitigated by riprap blanket around pier(s).

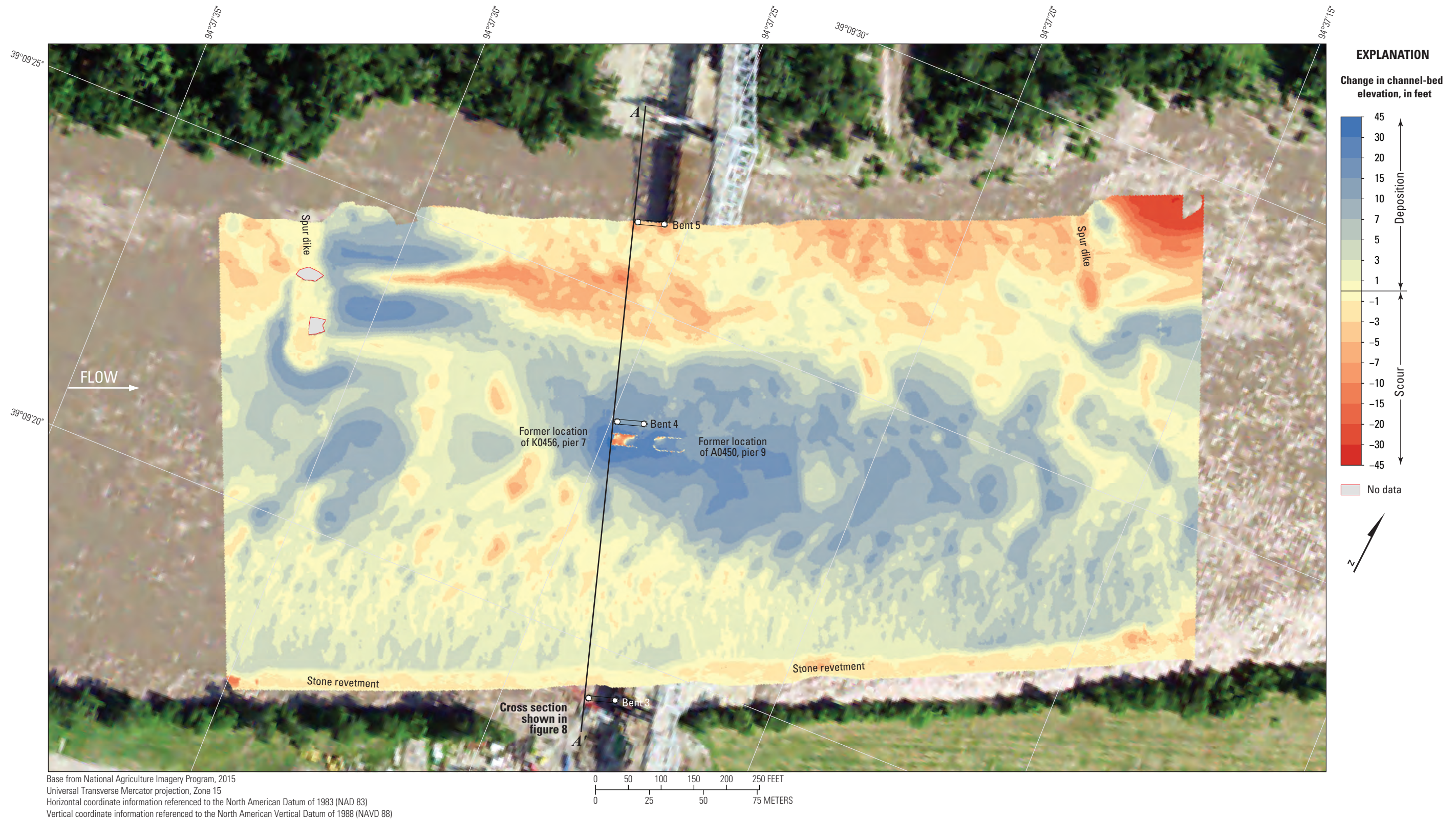


Figure 10. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A8340 on U.S. Highway 69 in Kansas City, Missouri, on May 22, 2017, and March 15, 2010.

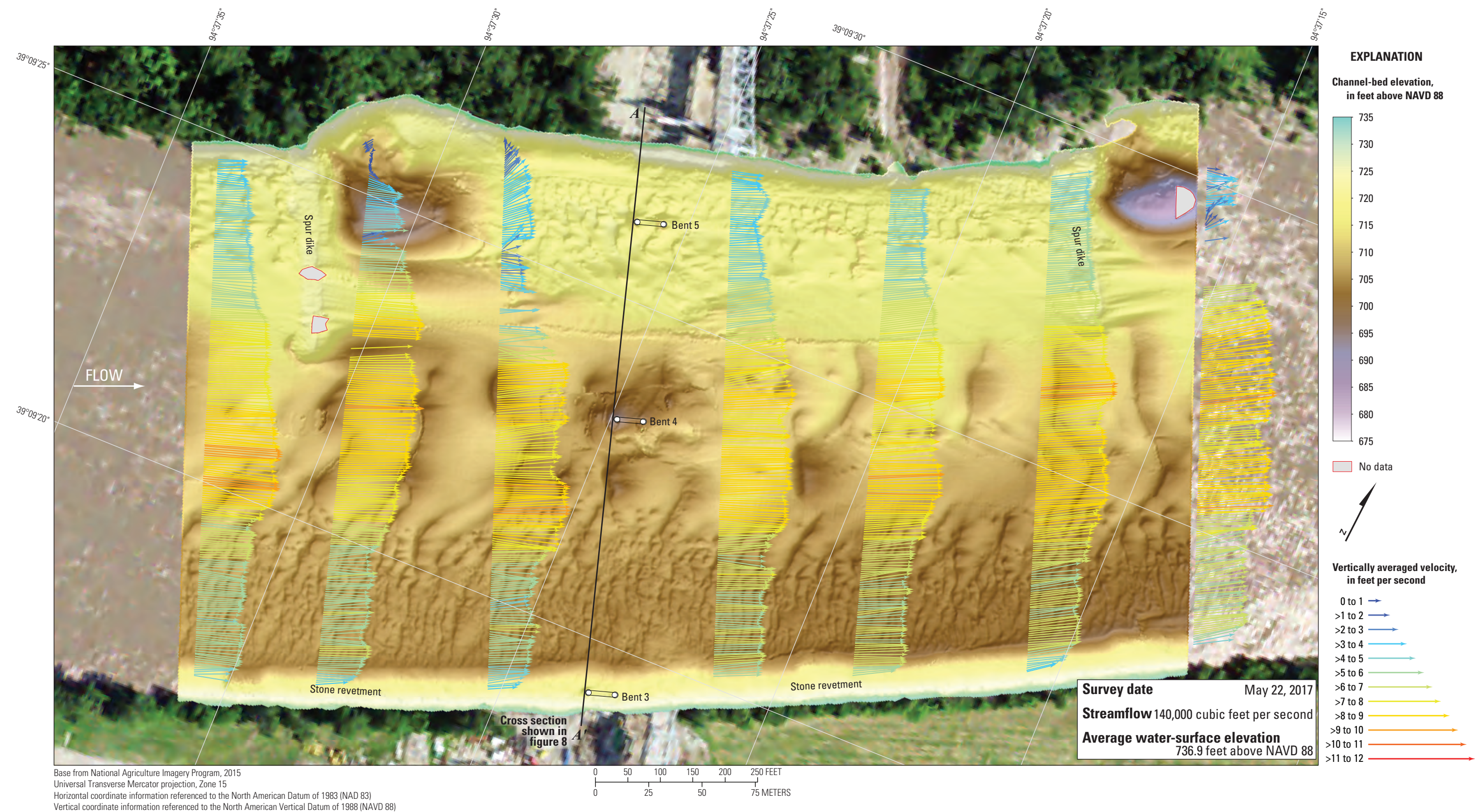


Figure 11. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A8340 on U.S. Highway 69 in Kansas City, Missouri.

Structure A5664 on Missouri State Highway 13 at Lexington, Missouri

Structure A5664 (site 14) on Missouri State Highway 13 crosses the Missouri River at RM 314.9 at Lexington, Mo., east of Kansas City, Mo. (fig. 1; table 1). The site was surveyed on May 23, 2017, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 687.8 ft (table 5). Streamflow on the Missouri River was about 160,000 ft³/s during the survey (table 5).

The survey area was about 1,640 ft long and about 1,000 ft wide, extending from bank to bank in the main channel (fig. 12). The upstream end of the survey area was about 670 ft upstream from the centerline of structure A5664, and piers 21 and 22 were in the water and away from the banks (fig. 12). The approximate channel-bed elevations ranged from about 654 to 674 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 13), except near the spur dikes on the right (south) bank (fig. 12; table 5). The channel bed between the left (north) bank and the spur dikes was filled with medium to large dune features, and small dunes and ripples were present in the area between the spur dikes on the right (south) side of the channel (fig. 12). Localized scour holes were present downstream from the spur dikes on the right (south) side (fig. 12).

The minor scour hole near main channel pier 21 was difficult to discern from nearby dunes and ripples (fig. 12); however, the top of the footing was evident on the left (north) side of the pier. Similarly, a minor scour hole was evident

near pier 22 near the right (south) bank (fig. 12). Information from bridge plans indicates that piers 21 and 22 are founded on shafts drilled 28 to 50 ft into bedrock, having about 47 ft of bed material between the channel bottom and bedrock at pier 21 and about 28 ft of material at pier 22 (fig. 14; table 6). The surveyed bed generally was similar to the previous multibeam survey on April 24, 2013, except on the left side of pier 21 (fig. 14).

The difference between the survey on May 23, 2017, and the previous nonflood survey on April 24, 2013 (fig. 15), indicates a generally uniform distribution of scour and deposition throughout the reach between 2013 and 2017, resulting in an average difference of -0.89 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2013 to 2017 was about 82,500 yd³, and the net volume of fill was about 41,200 yd³, resulting in a net loss of about 41,300 yd³ of sediment. The frequency distribution of channel-bed elevations in 2017 was similar to 2013, with a higher percentage of survey-grid cells at elevations between 658 and 668 ft compared to 2017. However, the peak of the data was lower and wider than in 2013, resulting in a slightly different cumulative percentage curve shape at higher percentages than 2013. Data also were captured higher along the banks in 2017 than in 2013, as indicated by the frequency distribution and cumulative percentage curves (fig. 13).

The difference between the survey on May 23, 2017, and the previous flood survey on July 20, 2011, indicates substantial deposition of more than 15 ft throughout most of the reach between 2011 and 2017, except downstream from the

Structure A5664 on Missouri State Highway 13



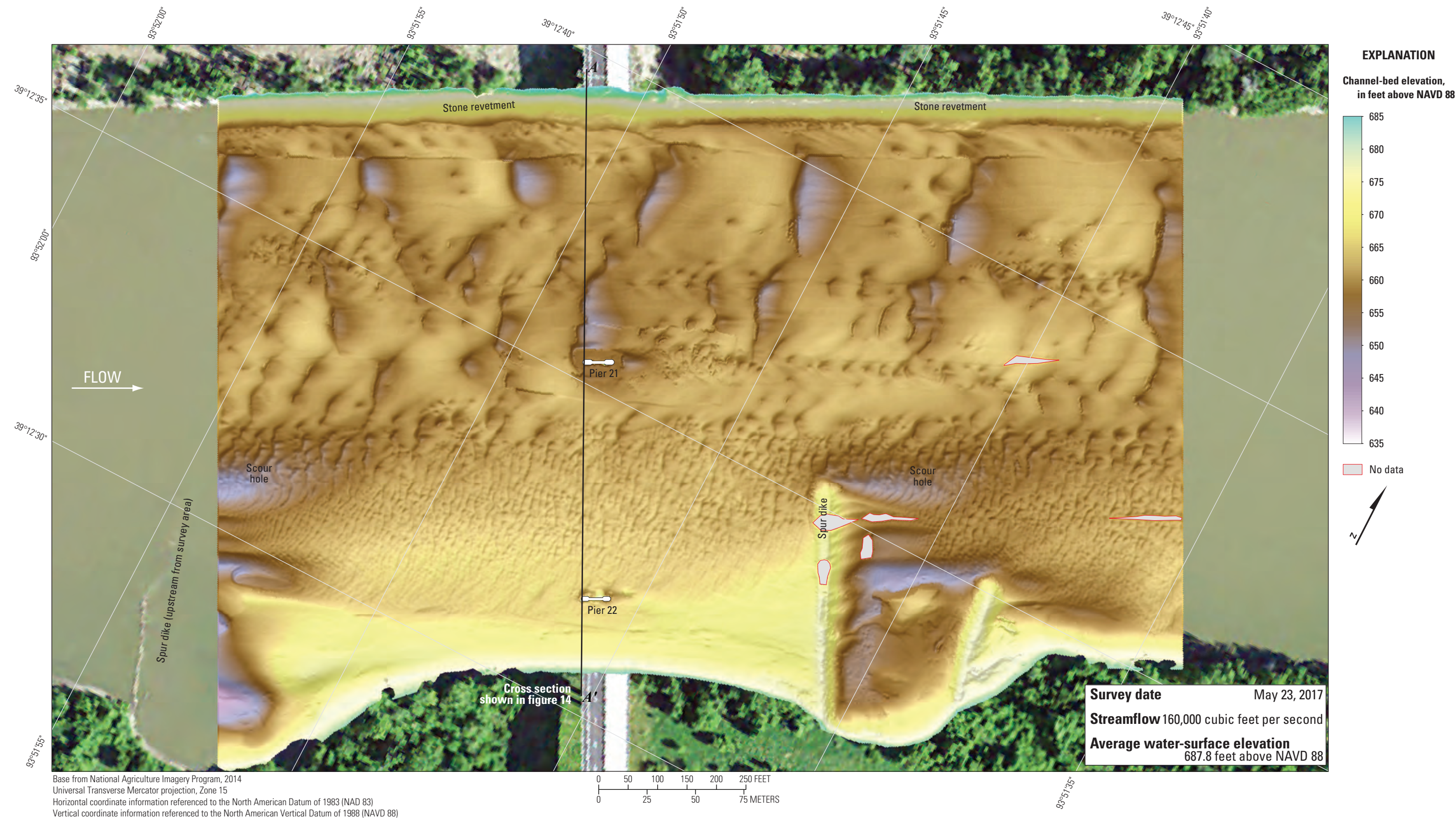


Figure 12. Bathymetric survey of the Missouri River channel near structure A5664 on Missouri State Highway 13 at Lexington, Missouri.

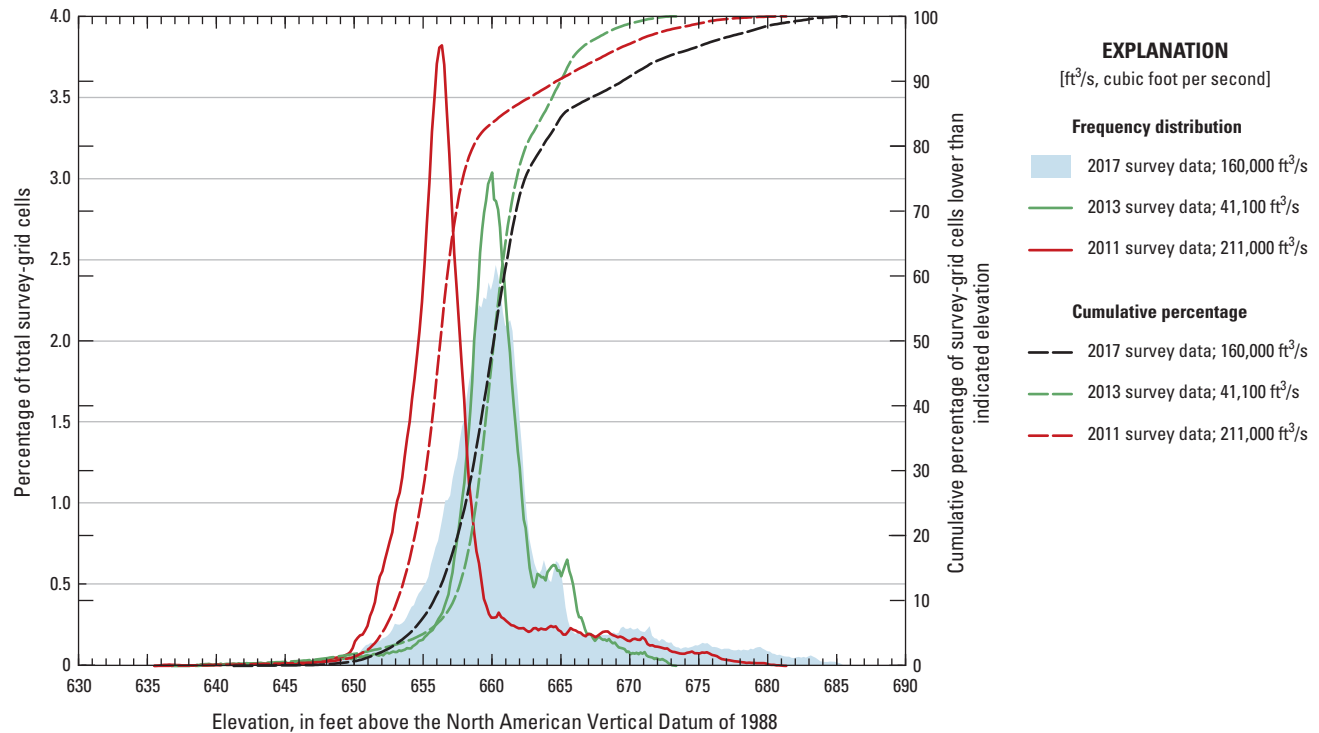


Figure 13. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A5664 on Missouri State Highway 13 at Lexington, Missouri, on May 23, 2017, compared to previous surveys.

spur dikes on the right (south) side of the channel (fig. 16). The average difference between the bathymetric surfaces was 3.33 ft (table 7), indicating substantial overall channel aggradation between the 2011 and 2017 surveys for the area common to both surveys. The net volume of cut in the reach from 2011 to 2017 was about 21,200 yd³, and the net volume of fill was about 220,300 yd³, resulting in a net gain of about 199,100 yd³ of sediment. The frequency distribution of channel-bed elevations in 2017 was similar to 2011, with a higher percentage of survey-grid cells at elevations between 658 and 668 ft. Data were captured higher along the banks in 2017 than in 2011, as indicated by the frequency distribution and cumulative percentage curves (fig. 13).

Although the stone revetment on the left (north) bank indicated no signs of substantial change between the 2013 and 2017 surveys (fig. 15), substantial deposition of as much as 10 ft was evident along the left (north) bank between 2011 and 2017 (fig. 16). The cross sections also indicate this change

(fig. 14), which may indicate material was added along this bank after the 2011 flood. This increase was noted in the previous survey at this site (Huizinga, 2014), but the lower flow conditions during the 2013 survey resulted in a more limited vertical extent of the bathymetry data and precluded inferences as to the cause of the observed change.

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach (fig. 17). A maximum velocity of about 10 ft/s was present in the downstream middle of the channel, and a minimum velocity of about 1 ft/s was present with flow reversal downstream from the various spur dikes in the reach (fig. 17). Minimal to moderate turbulence was observed at several transects (fig. 17), likely as a result of localized flow disturbances caused by the spur dikes and bedforms. The bridge piers were aligned with flow, with only moderate effects on the velocity and no evident turbulence downstream from either pier (fig. 17).

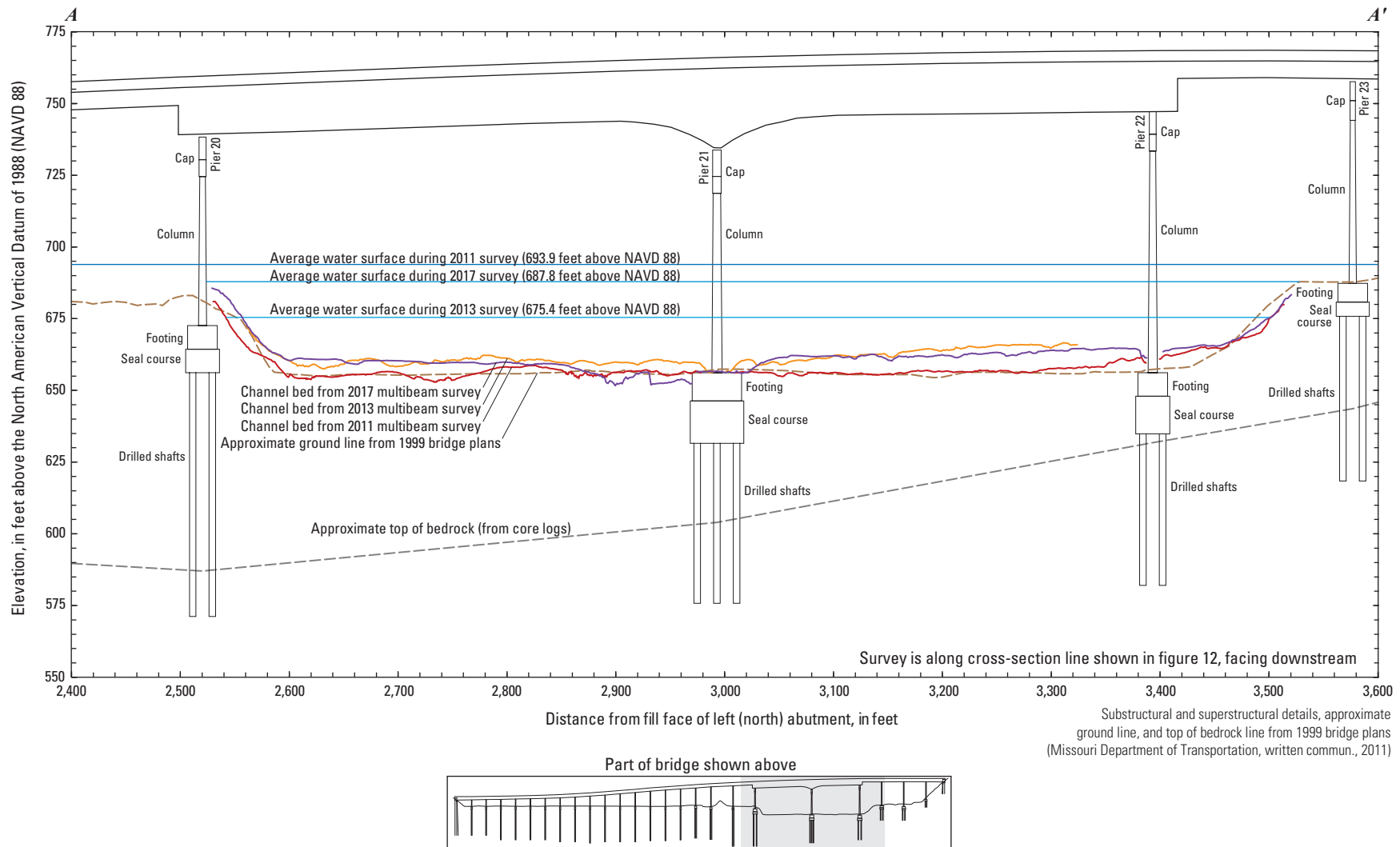


Figure 14. Key features, substructural and superstructural details, and surveyed channel bed of structure A5664 on Missouri State Highway 13 crossing the Missouri River at Lexington, Missouri.

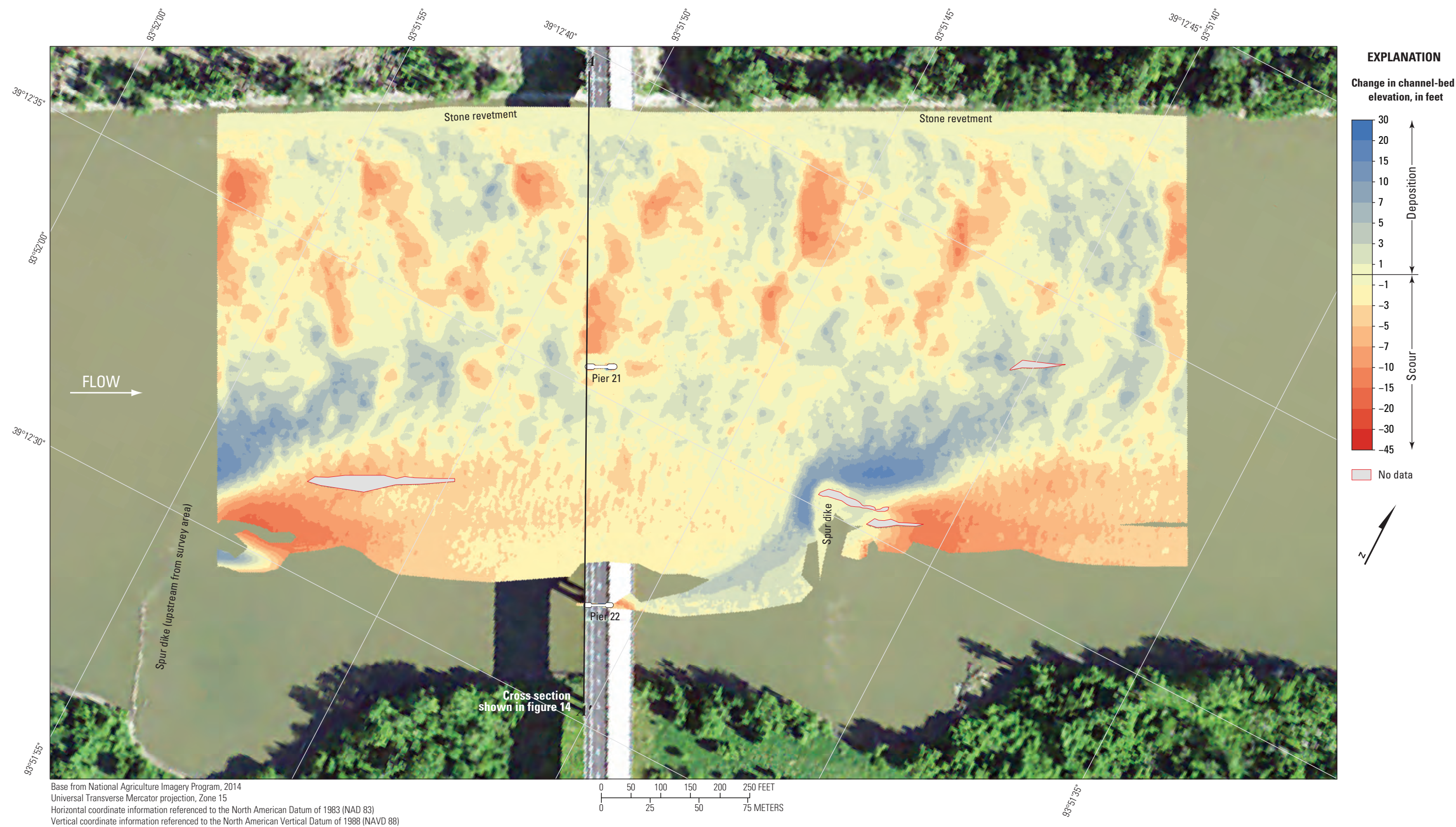


Figure 15. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5664 on Missouri State Highway 13 at Lexington, Missouri, on May 23, 2017, and April 24, 2013.

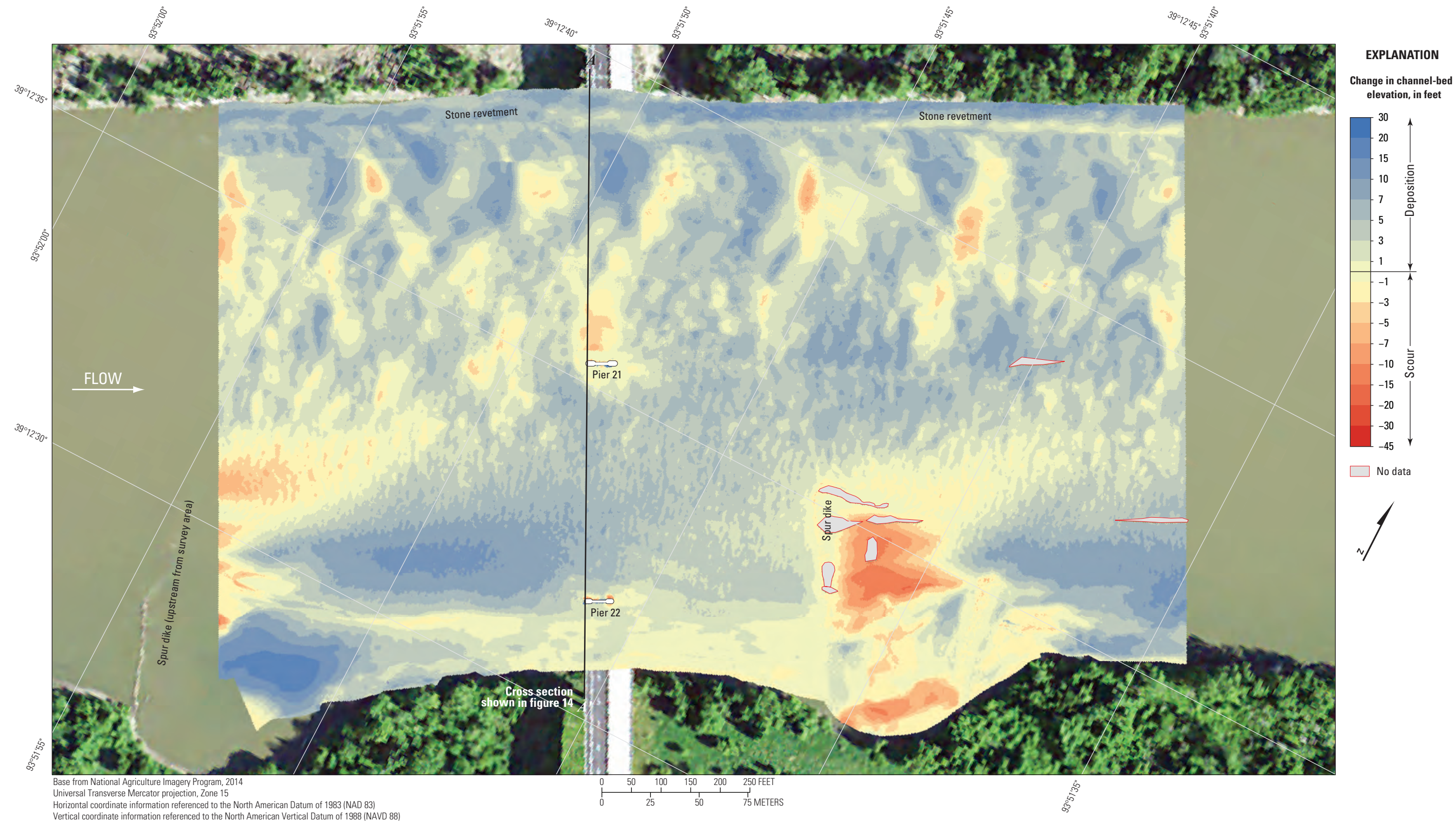


Figure 16. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5664 on Missouri State Highway 13 at Lexington, Missouri, on May 23, 2017, and July 20, 2011.

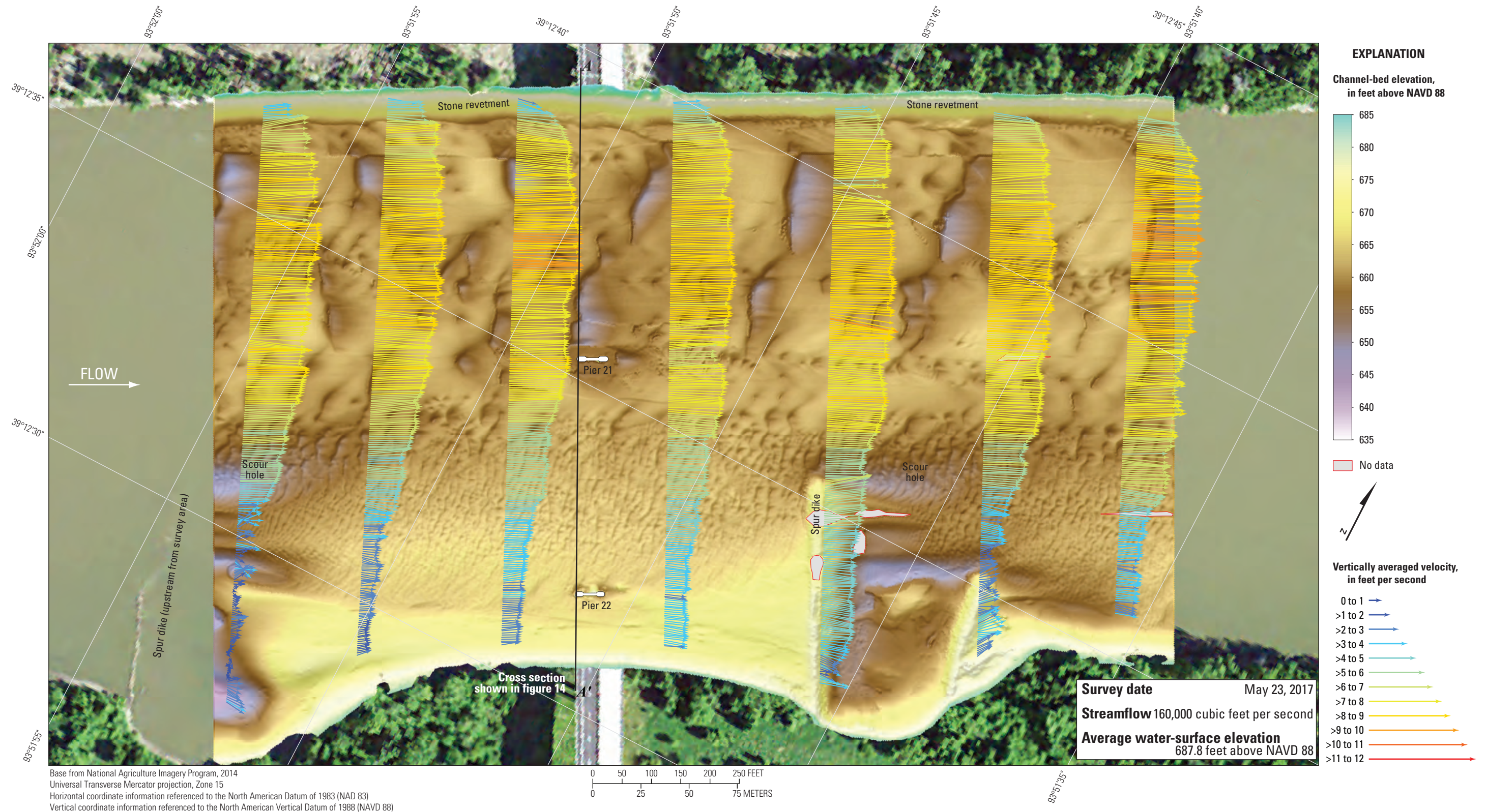


Figure 17. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A5664 on Missouri State Highway 13 at Lexington, Missouri.

Structure A5910 on U.S. Highway 24 at Waverly, Missouri

Structure A5910 (site 15) on U.S. Highway 24 crosses the Missouri River at RM 293.2 at Waverly, Mo., east of Lexington and Kansas City, Mo. (fig. 1; table 1). The site was surveyed on May 23, 2017, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 668.8 ft (table 5). Streamflow on the Missouri River was about 160,000 ft³/s during the survey (table 5).

The survey area was about 1,640 ft long and about 1,090 ft wide, extending from bank to bank in the main channel (fig. 18). The upstream end of the survey area was about 650 ft upstream from the centerline of structure A5910, and piers 10 and 11 were in the water and away from the banks (fig. 18). The approximate channel-bed elevations ranged from about 632 to 655 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 19), except downstream from the spur dikes on the left (north) bank and in the channel thalweg along the toe of the right (south) bank (fig. 18). The thalweg was about 15 to 19 ft deeper than the channel bed in the middle of the channel (fig. 18). A line of medium to large dune features was observed in the middle of the channel through the survey reach, and numerous smaller dunes and ripples were present throughout the channel reach (fig. 18). A localized deep scour hole downstream from the upstream spur dike on the left bank had a minimum channel-bed elevation of about 619 ft (fig. 18). As in previous surveys (Huizinga, 2012, 2014), a rock outcrop was evident on the right (south) bank and the upstream end of the reach, and the stone revetment and a longitudinal spur dike also were present on the right bank throughout the reach (fig. 18).

The minor scour holes near piers 10 and 11 were difficult to discern from nearby dunes and ripples (figs. 18, 20). Information from bridge plans indicates that piers 10 and 11 are founded on shafts drilled 30 to 42 ft into bedrock, having about 34 ft of bed material between the bottom of the scour hole and bedrock at pier 11 (fig. 20; table 6). The surveyed bed generally was similar to a previous multibeam survey on July 21, 2011, but with 5 to 10 ft of deposition between piers 10 and 11 (fig. 20).

The difference between the survey on May 23, 2017, and the previous nonflood survey on April 25, 2013 (fig. 21), indicates a relative balance of deposition and scour throughout the reach between 2013 and 2017, resulting in an average difference of -0.96 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2013 to 2017 was about 91,400 yd³, and the net volume of fill was about 49,400 yd³, resulting in a net loss of about 42,000 yd³ of sediment. There was substantial deposition of more than 15 ft in the scour hole downstream from the upstream spur dike in the 2013 survey (Huizinga, 2014) and moderate deposition in the middle of the channel throughout the reach (fig. 21). However, moderate localized scour was observed in the channel thalweg along the toe of the right (south) bank and along the right side of the channel throughout the reach (fig. 21). The cross sections from the two surveys indicate the changes between the surveys (figs. 20, 21). The frequency distribution of bed elevations was substantially wider in 2017 than in 2013, and more survey-grid cells were at a lower elevation in 2017 than 2013 (fig. 19). The minor localized scour observed on the stone revetment on the right (south) bank likely is a function of positional variations between the surveys.

Structure A5910 on U.S. Highway 24





Figure 18. Bathymetric survey of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri.

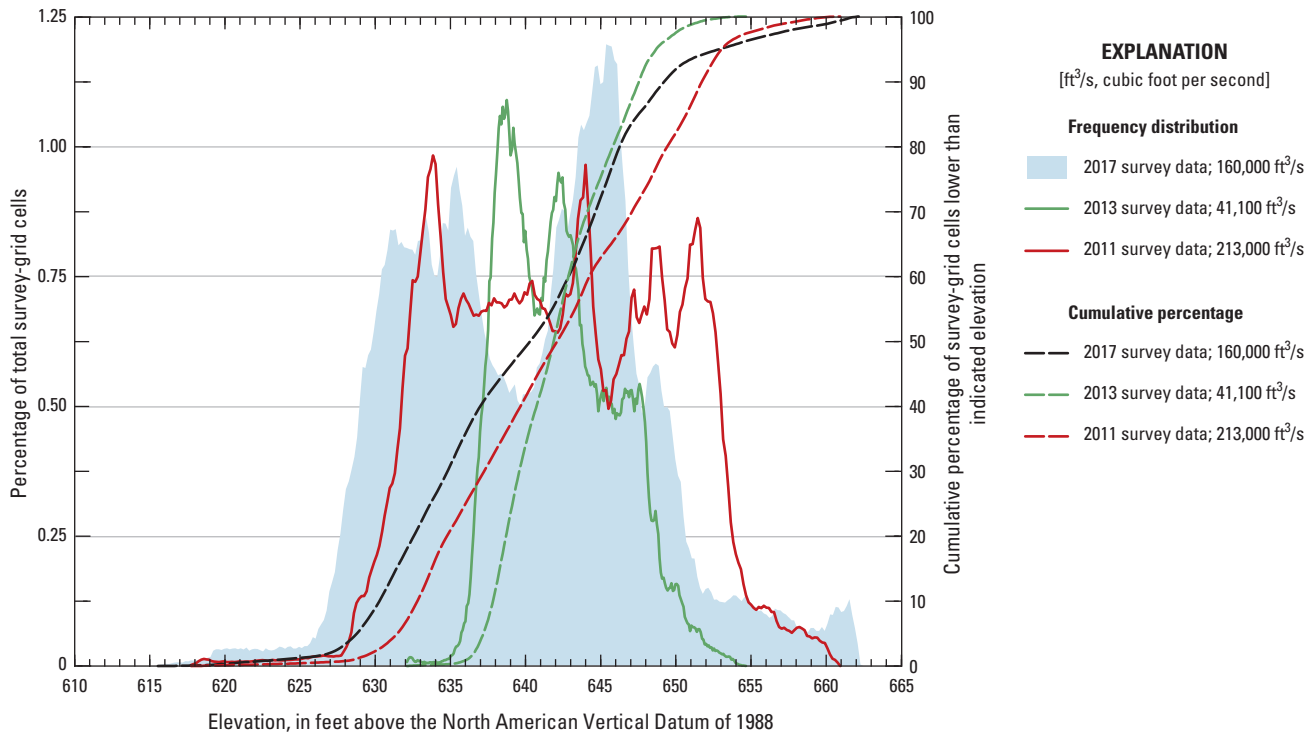


Figure 19. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A5910 on U.S. Highway 24 at Waverly, Missouri, on May 23, 2017, compared to previous surveys.

The difference between the survey on May 23, 2017, and the previous flood survey on July 21, 2011 (fig. 22), indicates a relative balance of deposition and scour throughout the reach between 2011 and 2017, resulting in an average difference of +0.64 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2017 was about 77,800 yd³, and the net volume of fill was about 118,000 yd³, resulting in a net gain of about 40,200 yd³ of sediment. There was substantial deposition of more than 15 ft in the troughs of the large dunes observed in the middle of the channel in the 2011 survey, but a substantial scour hole was present downstream from the downstream spur dike in the 2017 survey that was not present in the 2011 survey (fig. 22; Huizinga, 2012). The cross-section data from the 2017 survey demonstrate the pattern of deposition in the middle of the channel between piers 10 and 11 compared to the 2011 survey (figs. 20, 22). The frequency distribution of bed elevations was similar in 2017 and 2011; however, more survey-grid cells were present

at lower elevations than in 2011, as evident in the cumulative percentage curves (fig. 19). Minor deposition or scour of the stone revetment on the right (south) bank likely is the result of minor positional variations between the surveys (figs. 20, 22).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach (fig. 23). A maximum velocity of about 9 ft/s was present in the downstream middle of the channel, and a minimum velocity of about 1 ft/s was present with flow reversal downstream from the various spur dikes in the reach (fig. 23). Minimal to moderate turbulence was observed at several transects (fig. 23), likely as a result of localized flow disturbances caused by the spur dikes and bedforms as at other sites in this study. The bridge piers were aligned with flow, with only moderate effects on the velocity and no evident turbulence downstream from either pier (fig. 23). Data for the downstream-most velocity transect were incomplete, although there was no indication of any problems during the survey.

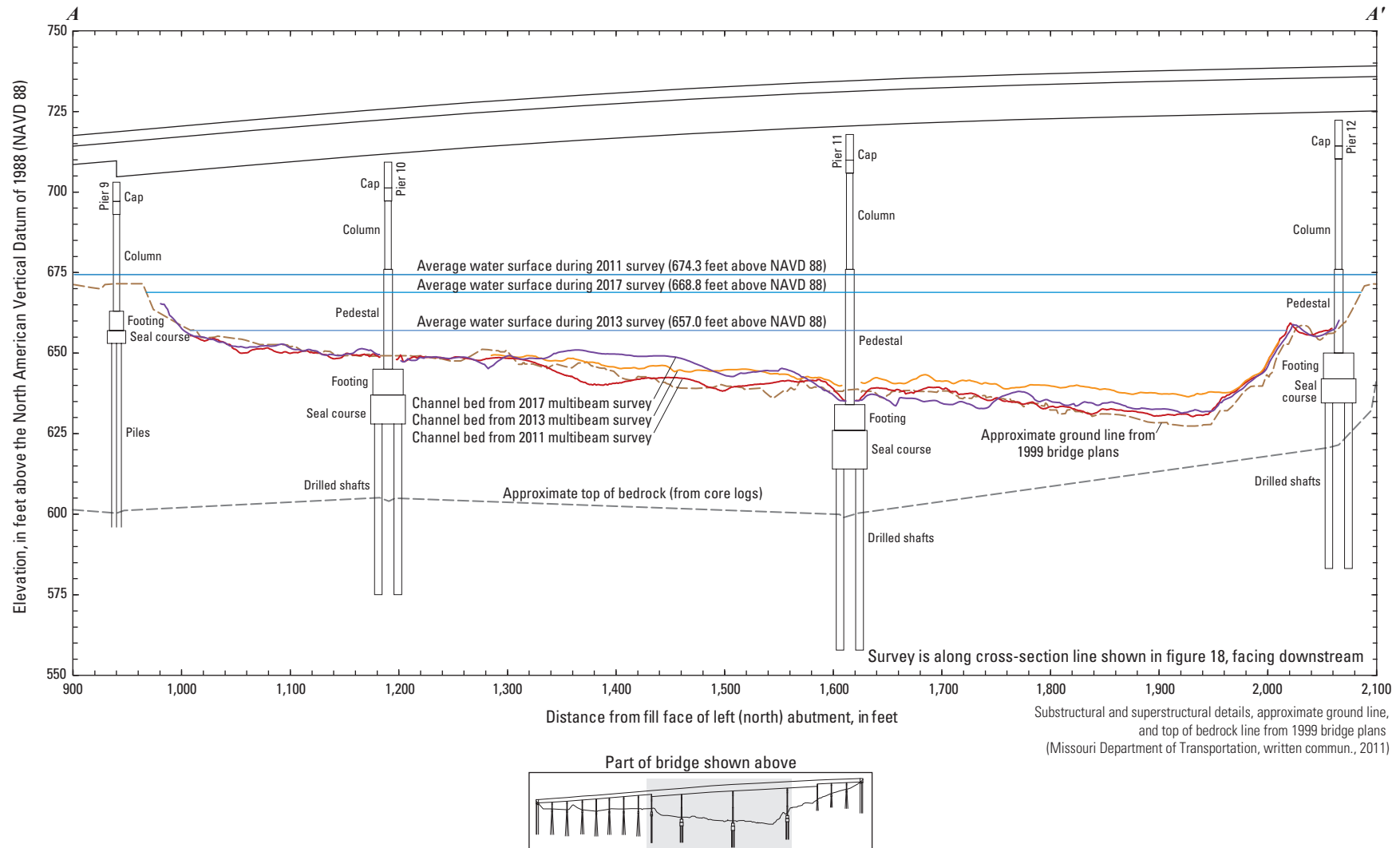


Figure 20. Key features, substructural and superstructural details, and surveyed channel bed of structure A5910 on U.S. Highway 24 crossing the Missouri River at Waverly, Missouri.

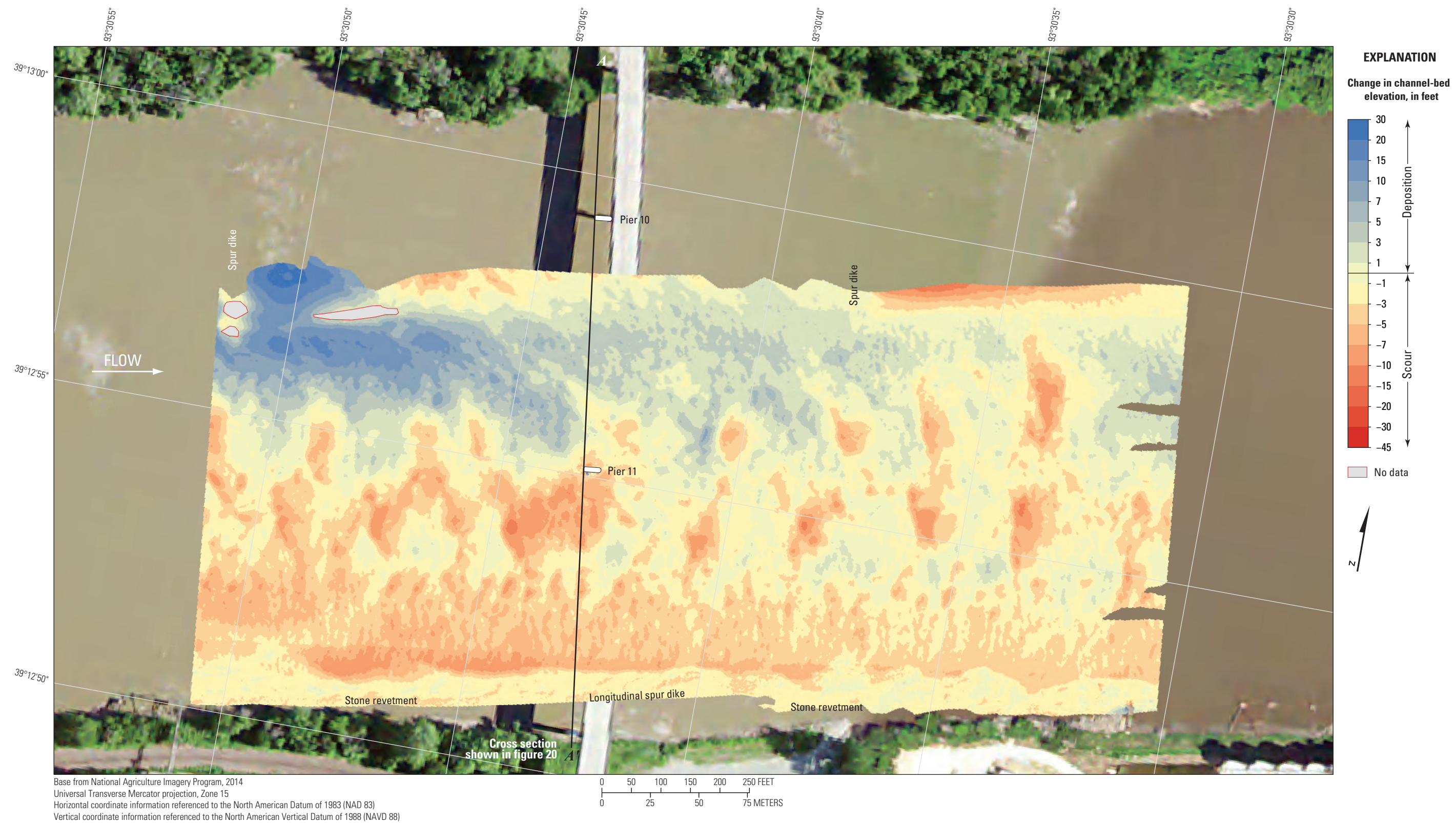


Figure 21. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri, on May 23, 2017, and April 25, 2013.

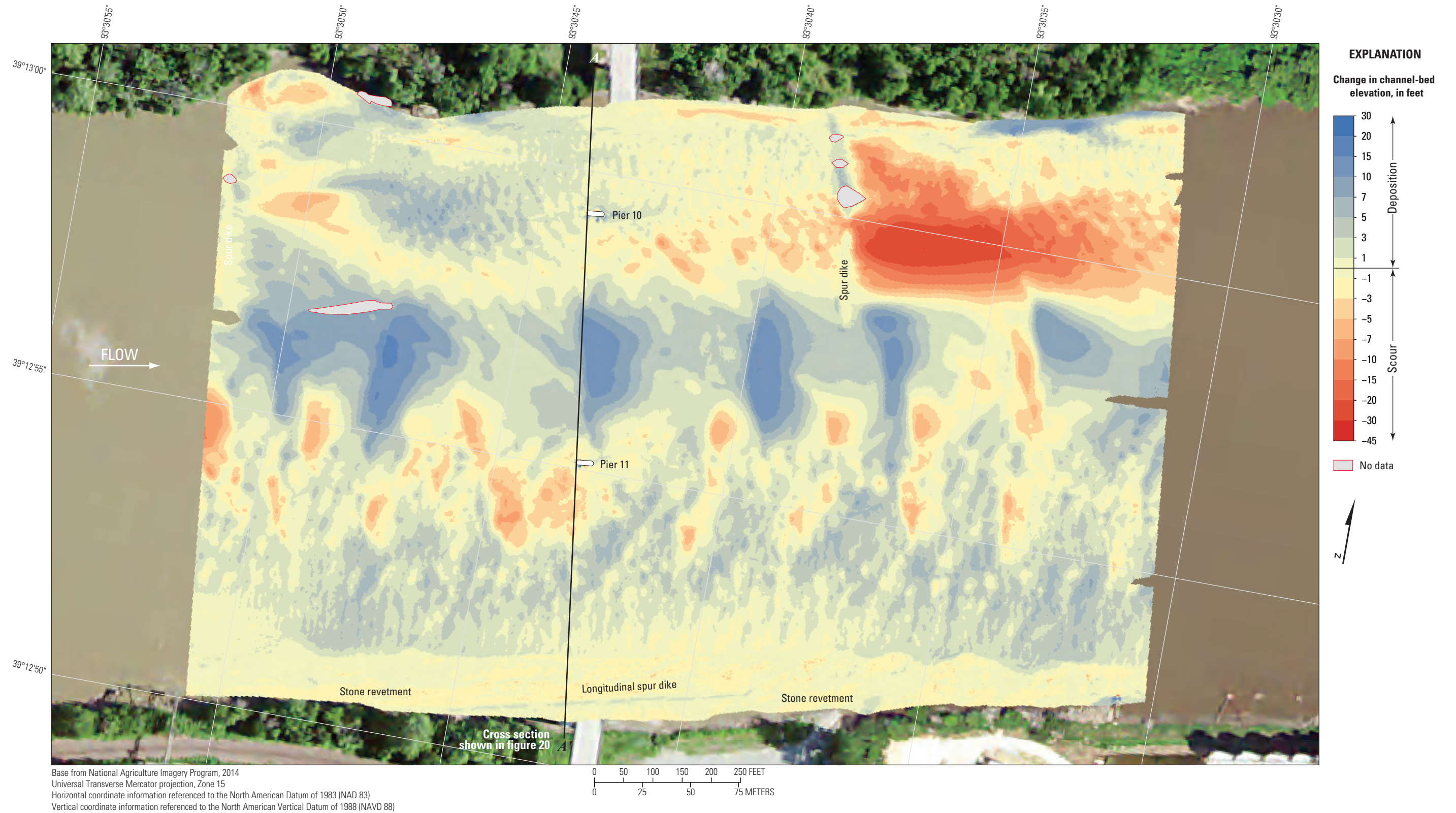


Figure 22. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri, on May 23, 2017, and July 21, 2011.

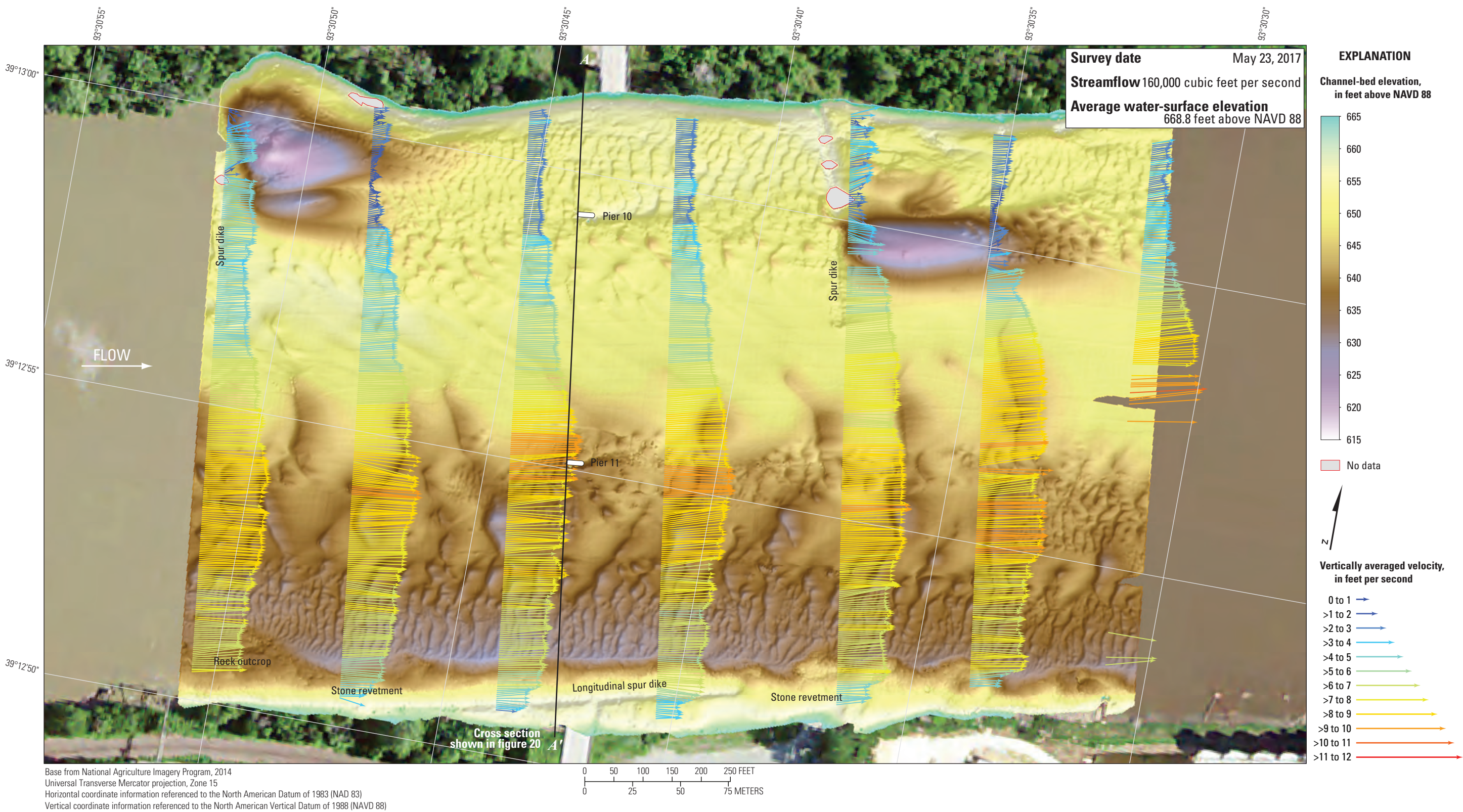


Figure 23. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri.

Structure K0999 on Missouri State Highway 41 at Miami, Missouri

Structure K0999 (site 16) on Missouri State Highway 41 crosses the Missouri River at RM 262.6 at Miami, Mo., east of Waverly and Kansas City, Mo. (fig. 1). The site was surveyed on May 24, 2017, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 641.9 ft (table 5). Streamflow on the Missouri River was about 152,000 ft³/s during the survey (table 5).

The survey area was about 1,640 ft long and varied from about 1,380 ft wide at the upstream end to about 1,050 ft wide near the downstream end, extending from bank to bank in the main channel (fig. 24). The upstream end of the survey area was about 625 ft upstream from the centerline of structure K0999; piers 5 and 6 were in the water and away from the banks, and pier 4 was surrounded by rock revetment on the right (south) bank (fig. 24). The approximate channel-bed elevations ranged from about 608 to 628 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 25), except near pier 5, in the scour hole downstream from the spur dike on the left (north) bank, and in the troughs of the large dune features in the thalweg along the toe of the rock outcrop along the right (south) side of the channel (fig. 24). The approximate minimum channel-bed elevation of 594 ft was at the bottom of the scour hole at pier 5 (fig. 24; tables 5, 6). In addition to the large dune features observed in the channel thalweg, numerous small dunes and ripples were detected throughout most of the rest of the channel (fig. 24).

As indicated above, a substantial scour hole was observed near pier 5 (figs. 24, 26; table 6). Information from bridge plans indicates that piers 5 and 6 are caissons founded on bedrock, with about 36 ft of bed material between the bottom of the scour hole and bedrock at pier 6 but only about 6 ft of bed material between the bottom of the scour hole and bedrock at pier 5 (fig. 26; table 6). Pier 4 is founded on a footing on bedrock according to bridge plans (fig. 26; table 6), and no scour hole was observed near the pier (fig. 24). The surveyed bed along the cross section generally was similar to the multibeam survey in 2011 (fig. 26). The approximate top-of-bedrock line from bridge plans confirms that the fluvial material near the right bank has washed away, exposing the bedrock along the thalweg, as in previous surveys (fig. 26). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (Brown and others, 2010; American Association of State Highway Transportation Officials, 2012), but full exposure of usually buried substructural elements warrants special consideration and observation.

The difference between the survey on May 24, 2017, and the previous nonflood survey on April 25, 2013 (fig. 27), indicates only minor deposition between 2013 and 2017, as indicated by an average difference of +0.95 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2013 to 2017 was about 26,000 yd³, and the net volume of fill was about 65,800 yd³, resulting in a net gain of about 39,800 yd³ of sediment. There was an area of scour around pier 5, and some additional scour in the middle of the channel downstream from the bridge; however, minor

Structure K0999 on Missouri State Highway 41



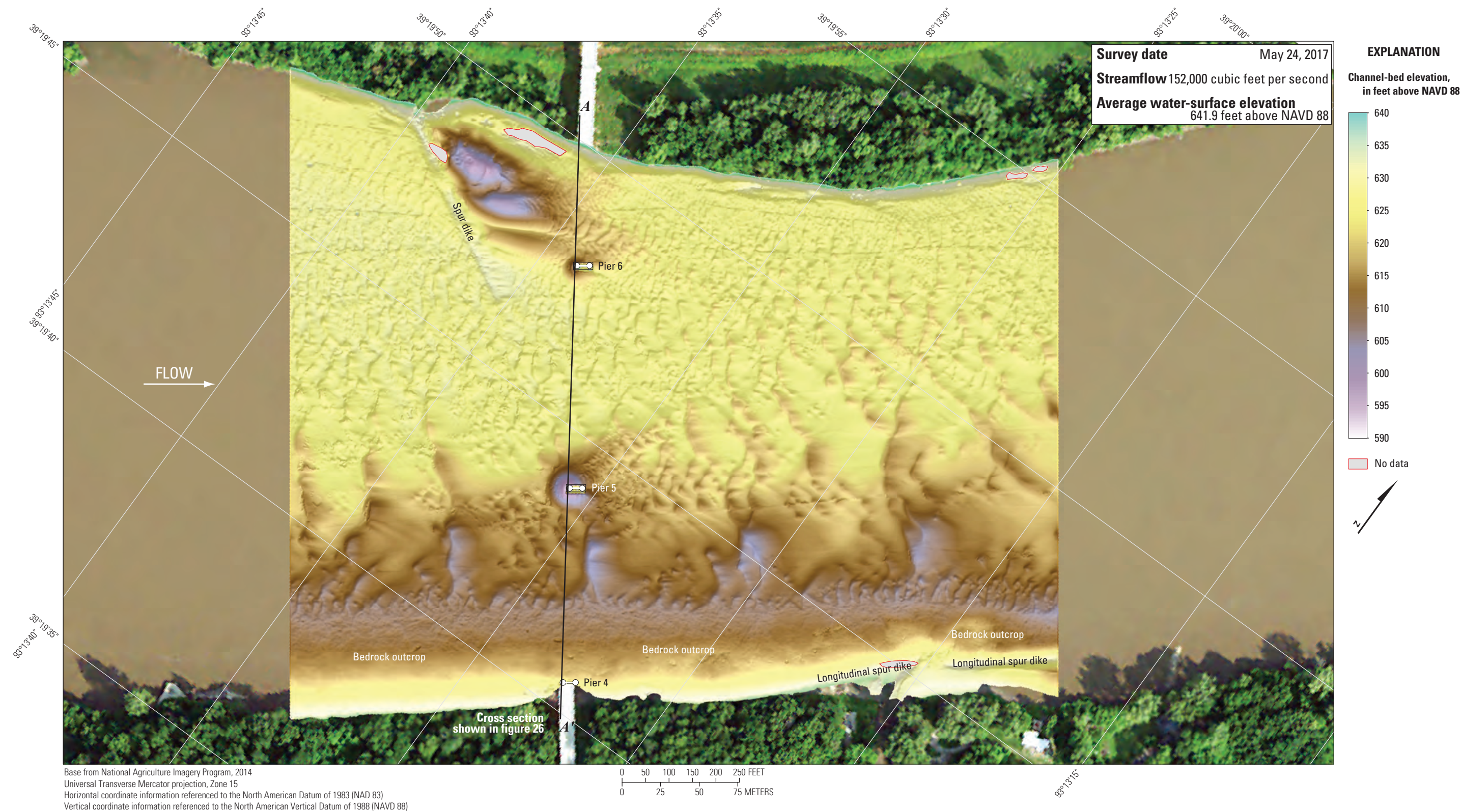


Figure 24. Bathymetric survey of the Missouri River channel near structure K0999 on Missouri State Highway 41 at Miami, Missouri.

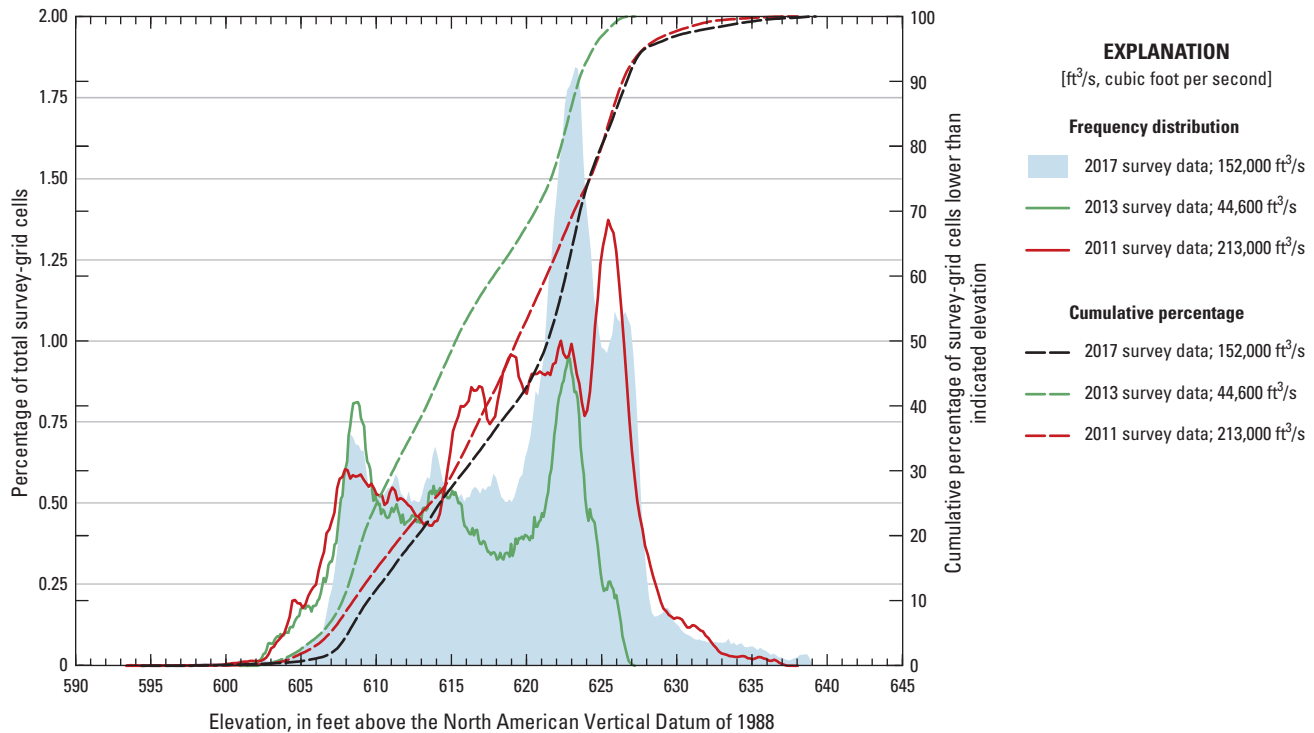


Figure 25. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure K0999 on Missouri State Highway 41 at Miami, Missouri, on May 24, 2017, compared to previous surveys.

deposition was present throughout the rest of the reach, with moderate deposition in the thalweg downstream from the bridge (fig. 27). The cross sections from these two surveys generally were similar to one another except near pier 5 (figs. 26, 27). The general shape of the frequency distribution of bed elevations was similar in all three of the surveys to date at this site (fig. 25), but the 2017 survey has a substantially higher percentage of survey-grid cells from 620 to 627 ft. The rock outcrop on the right (south) bank indicated no signs of substantial change except for minor localized scour, likely of previously deposited sediment (fig. 27). As with all difference maps in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The difference between the survey on May 24, 2017, and the previous survey on July 21, 2011 (fig. 28), also indicates minor deposition between 2011 and 2017, as indicated by an average difference of +0.68 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from 2011 to 2017 was about 58,400 yd³, and the net volume of fill was about 105,700 yd³, resulting in a net gain of about 47,300 yd³ of sediment between 2011 and 2017. Near the spur dike on the upstream left (north) bank, there was an area of moderate

scour upstream and an area of substantial scour of more than 20 ft immediately downstream, with a commensurate area of deposition continuing downstream along the left (north) bank (fig. 28). Areas of alternating scour and deposition were present along the channel thalweg (fig. 28). The cross sections from these two surveys also were similar to one another except in the channel thalweg and near the toe of the left (north) bank (fig. 26). The rock outcrop on the right (south) bank indicated no signs of substantial change except for minor localized scour, likely of previously deposited sediment, and some deposition behind the downstream longitudinal spur dikes (fig. 28). As with all difference maps in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The vertically averaged velocity vectors indicate mostly uniform flow throughout most of the reach, ranging from about 2 to 9 ft/s (fig. 29). Exceptions to uniform conditions include substantial variation in velocities on the left (north) bank downstream from the spur dike, and moderate turbulence observed in the downstream transects near the longitudinal spur dikes (fig. 29). All the piers were aligned with flow, as indicated by little to no turbulence observed downstream that can be directly attributed to the piers (fig. 29).

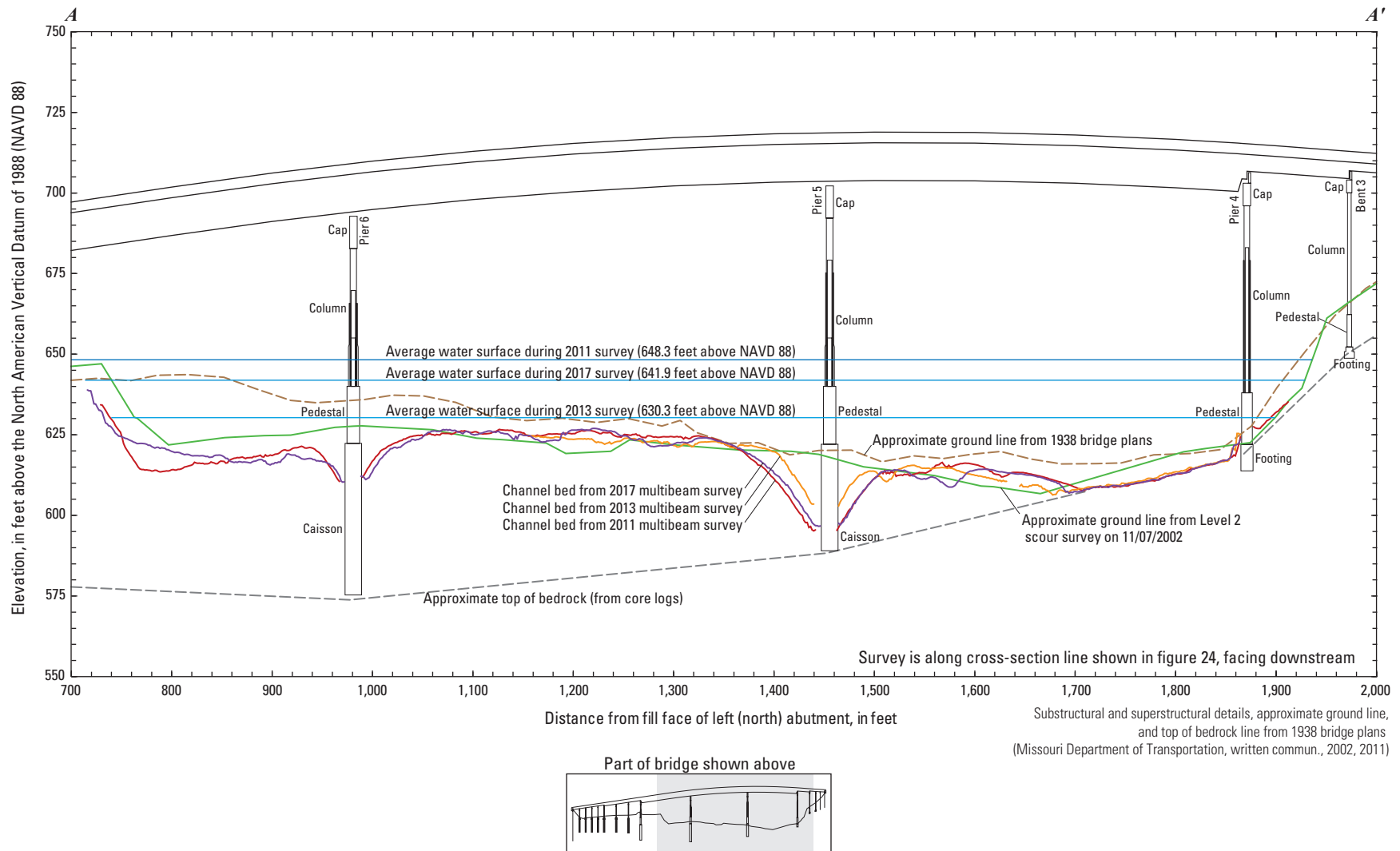
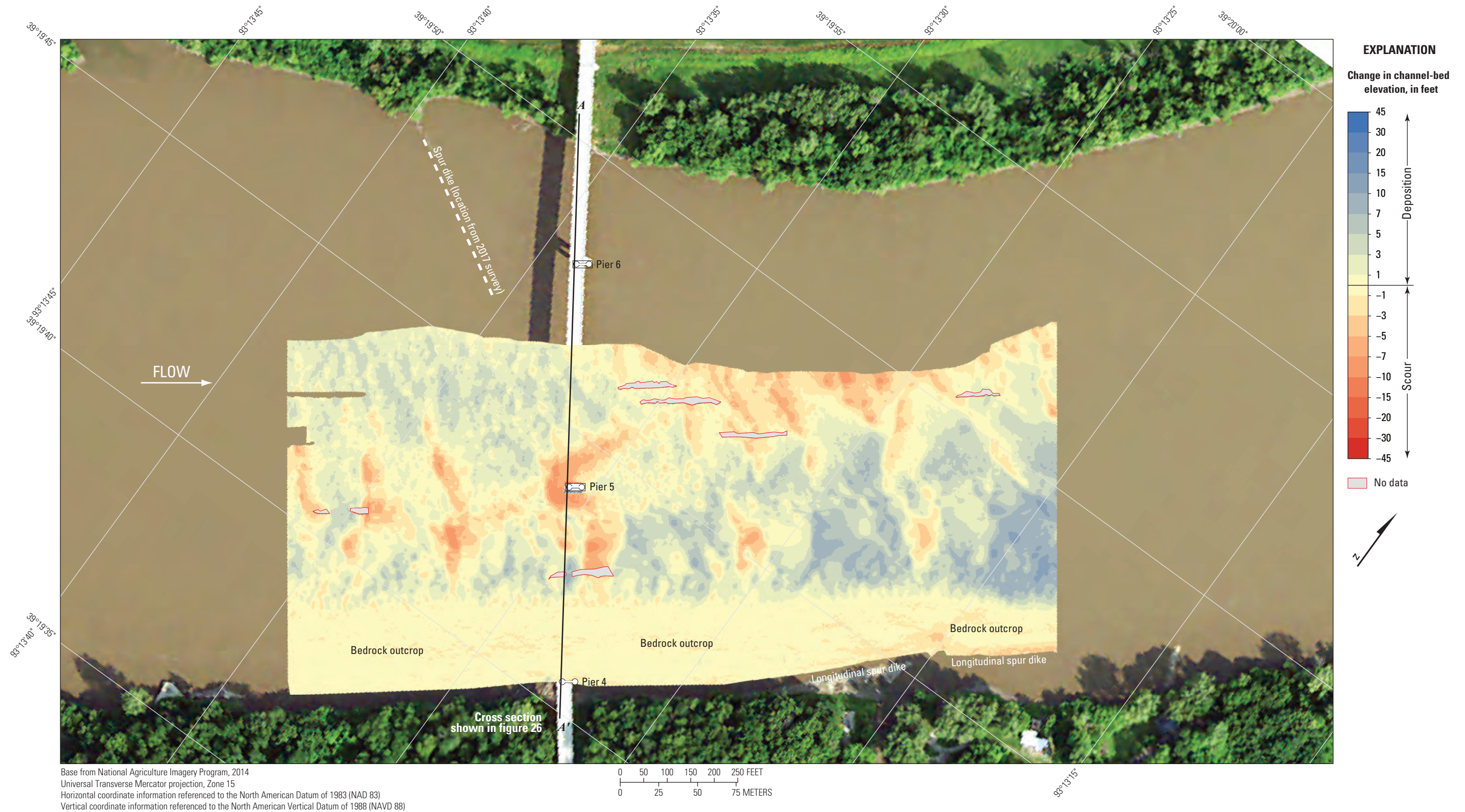


Figure 26. Key features, substructural and superstructural details, and surveyed channel bed of structure K0999 on Missouri State Highway 41 crossing the Missouri River at Miami, Missouri.



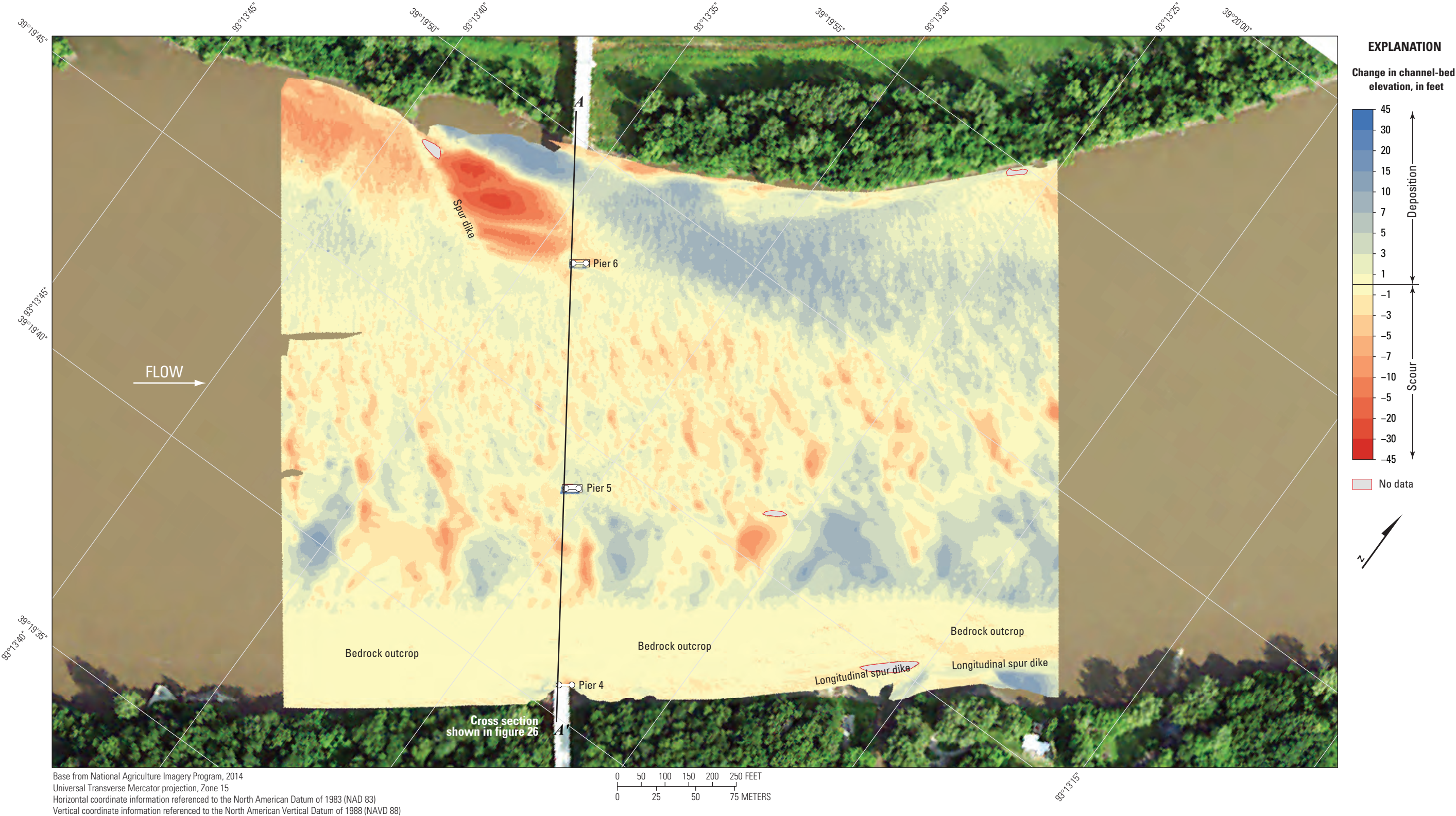


Figure 28. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure K0999 on Missouri State Highway 41 at Miami, Missouri, on May 24, 2017, and July 21, 2011.

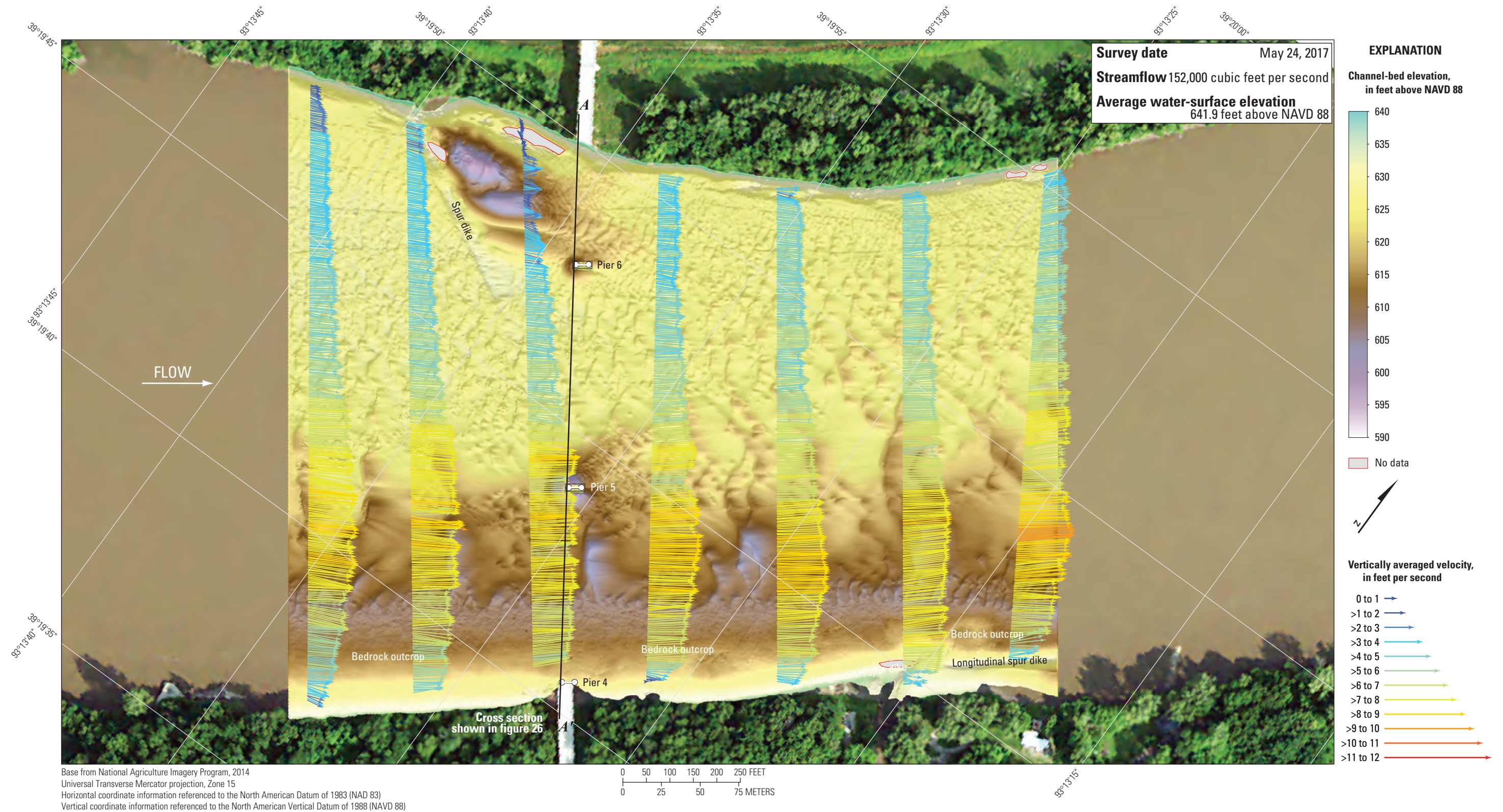


Figure 29. Bathymetry and vertically averaged velocities of the Missouri River channel near structure K0999 on Missouri State Highway 41 at Miami, Missouri.

Structure G0069 on Missouri State Highway 240 at Glasgow, Missouri

Structure G0069 (site 17) on Missouri State Highway 240 crosses the Missouri River at RM 226.3 at Glasgow, Mo., southeast of Miami and about halfway between Kansas City and St. Louis, Mo. (fig. 1). The site was surveyed on May 24, 2017, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 610.8 ft (table 5). Streamflow on the Missouri River was about 167,000 ft³/s during the survey (table 5).

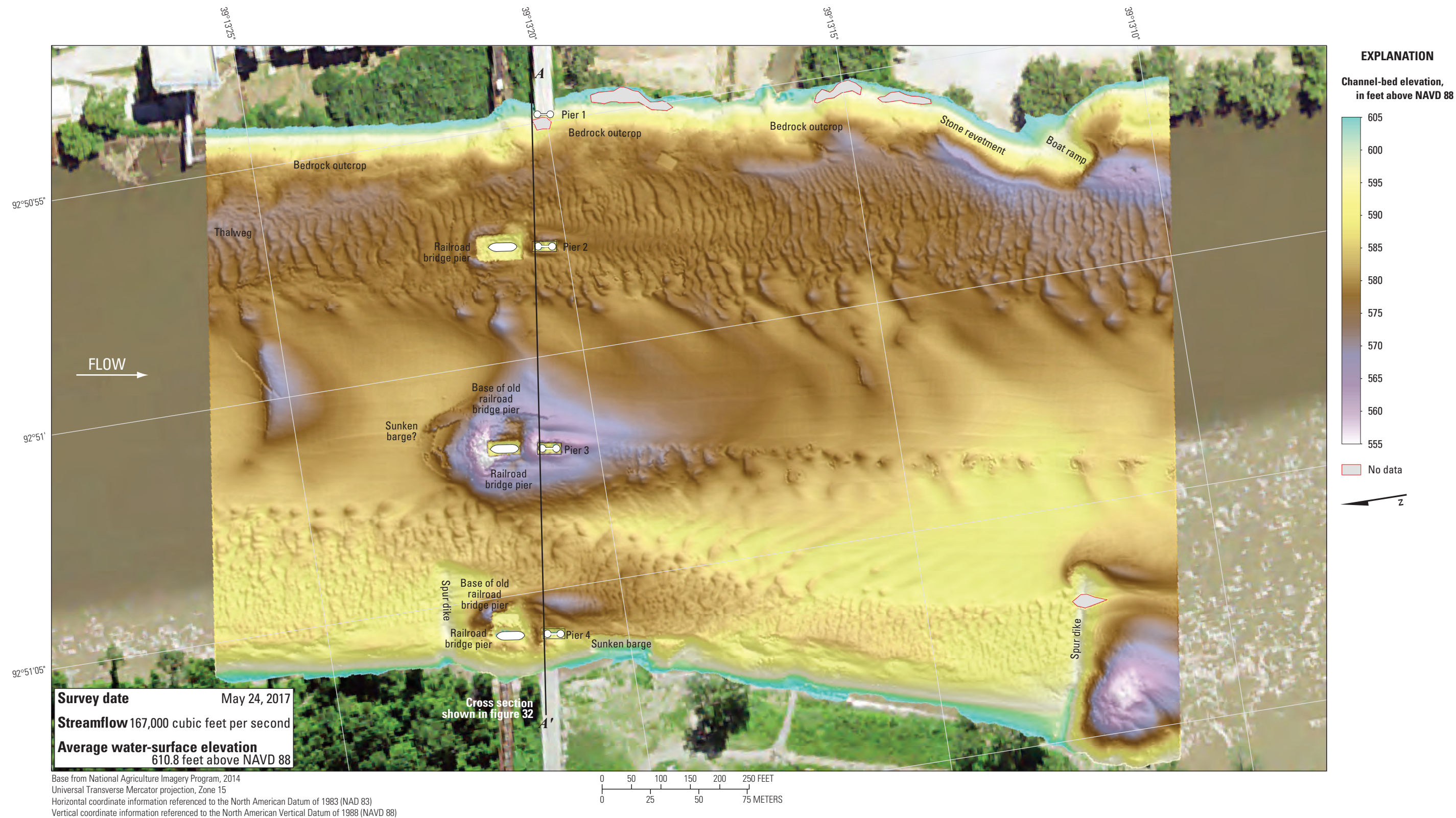
The survey area was about 1,640 ft long and varied from about 940 ft wide at the upstream end to about 1,160 ft wide near the downstream end, extending from bank to bank in the main channel (fig. 30). The upstream end of the survey area was about 590 ft upstream from the centerline of structure G0069, and piers 2, 3, and 4 were in the water and away from the banks (fig. 30). The approximate channel-bed elevations ranged from about 574 to 596 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 31), except near the piers and downstream from the spur dike on the downstream right (west) bank (fig. 30). A poorly defined thalweg was present along the left (east) bank and deepened in the downstream reach (fig. 30). The thalweg was about 13 to 15 ft deeper than the channel bed in the middle of the downstream reach (fig. 30). Two spur dikes, and a sunken barge observed during the previous surveys, were present on the right (west) bank (fig. 30). Two large dune features were present in the upstream reach, and numerous medium and small dunes and ripples were present along the left and right sides throughout the channel (fig. 30). The bed was generally smooth in the middle of the channel downstream from the bridge, except for small features likely caused by wake vortices downstream from pier 3 (fig. 30).

A small scour hole was observed near pier 2 (fig. 30), which is founded on a footing on bedrock according to bridge plans (fig. 32; table 6). The ground line from the bathymetric survey indicated that the right side of the footing seemed to be undermined in previous surveys but was partially buried in bed sediments in the 2017 survey (fig. 32). The details of the footing of pier 2 in the bridge plans for structure G0069 are not sufficient to tell if it was entrenched in the bedrock in any way, particularly if the top of the bedrock was not level, as indicated by previous surveys (Huizinga, 2014; fig. 32). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (Brown and others, 2010; American Association of State Highway Transportation Officials, 2012), but full exposure of usually buried substructural elements warrants special consideration and observation, particularly at an older bridge such as structure G0069 (built in 1922).

A substantial scour hole was observed near main channel pier 3, and a smaller scour hole was observed near pier 4. Near pier 3 (fig. 30), the scour hole had a minimum channel-bed elevation of about 560 ft (table 6), which is about 20 ft below the average channel bed immediately upstream from the pier (figs. 30, 32; table 6). The scour hole was substantially larger in 2017 than in the previous surveys. Near pier 4, the scour hole had a minimum channel-bed elevation of about 572 ft (figs. 30, 32; table 6). Information from bridge plans indicates that piers 3 and 4 are caissons founded on bedrock; the bedrock is exposed at pier 3, and there is about 15 ft of bed material between the bottom of the scour hole and bedrock at pier 4 (fig. 32; table 6). The scour observed near all the highway bridge piers was substantially affected by the upstream railroad bridge piers (fig. 30). The surveyed bed was similar to the previous multibeam surveys between the left bank and pier 2, alternated from 5 to 10 ft above to 5 to 15 ft below the

Structure G0069 on Missouri State Highway 240





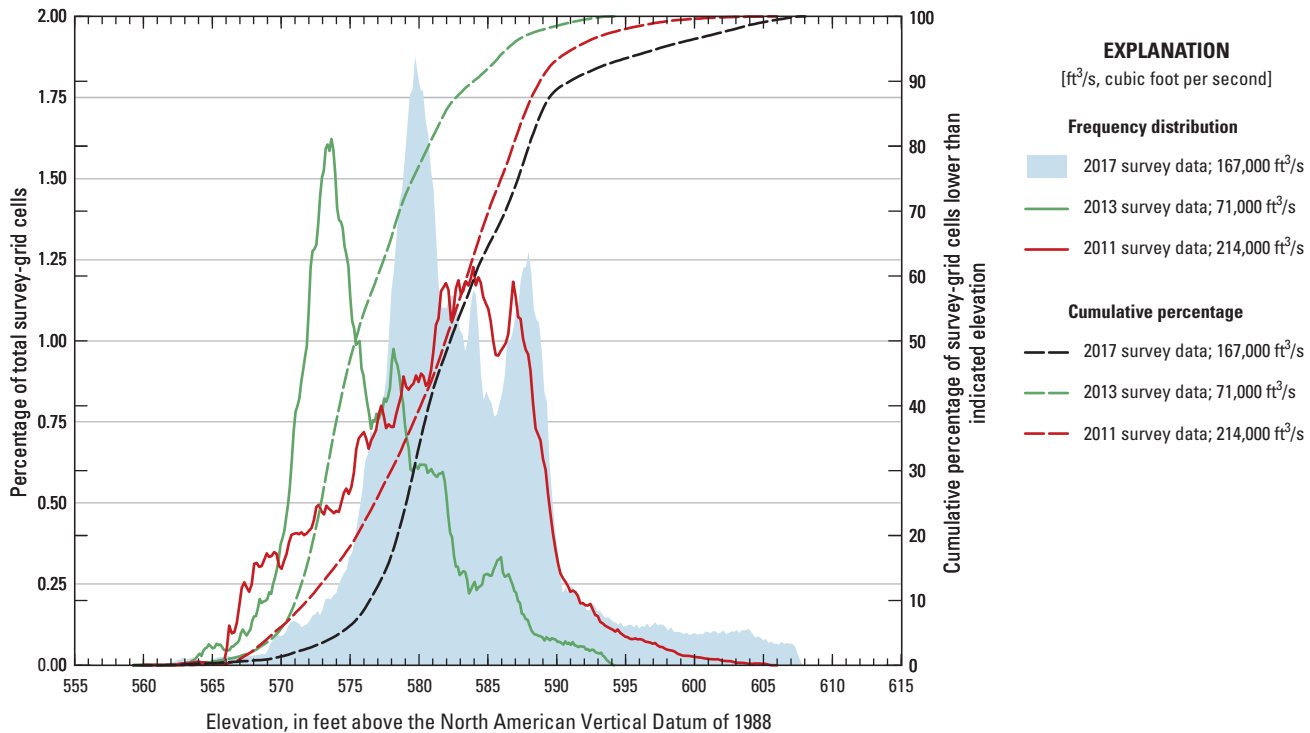


Figure 31. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure G0069 on Missouri State Highway 240 at Glasgow, Missouri, on May 24, 2017, compared to previous surveys.

previous multibeam surveys between piers 2 and 3, and was similar to the 2011 survey between piers 3 and 4 except near pier 3 (fig. 32). The approximate top of bedrock confirmed in the previous multibeam surveys seems to have a thin layer of fluvial material near the left bank in the 2017 survey (fig. 32), with further evidence from small dunes and ripples in that area (fig. 30). The base of an old railroad bridge pier was clearly evident in the scour hole near pier 3 (fig. 30). A differential bed at the upstream face of the scour hole near pier 3 may indicate the presence of a sunken barge but also may result from bed-material movement between the parts of the survey obtained with the untilted and tilted sonar head at this site (fig. 30).

The difference between the survey on May 24, 2017, and the previous nonflood survey on April 26, 2013 (fig. 33), indicates minor deposition (an average difference of +0.43 ft between the bathymetric surfaces) throughout the reach between 2013 and 2017 (table 7). The net volume of cut in the reach from 2013 to 2017 was about 65,500 yd³, and the net volume of fill was about 89,500 yd³, resulting in a net gain of about 24,000 yd³ of sediment. Scour was observed in the upstream right and downstream left sides of the channel, and near pier 3 and downstream from the downstream spur dike (fig. 33). Deposition was observed on the bedrock outcrop on the upstream left side of the channel, around pier 2, and in the downstream middle of the channel (fig. 33). The frequency distribution of bed elevations was of a similar shape but at a

higher elevation in 2017 than in 2013; a greater percentage of survey-grid cells was at elevations above 575 ft (fig. 31).

The difference between the survey on May 24, 2017, and the previous flood survey on July 22, 2011 (fig. 34), indicates moderate deposition (an average difference of +1.41 ft between the bathymetric surfaces) throughout the reach between 2011 and 2017 (table 7). The net volume of cut in the reach from 2011 to 2017 was about 55,200 yd³, and the net volume of fill was about 136,600 yd³, resulting in a net gain of about 81,400 yd³ of sediment. There was an area of moderate to substantial scour of more than 15 ft in the upstream middle of the channel, near pier 3, and downstream from the spur dike on the downstream right (west) bank (fig. 34). However, there was substantial deposition of more than 15 ft on the left (east) side of the channel throughout the reach and moderate deposition on the right side of the channel downstream from the bridge. The frequency distribution of bed elevations in 2017 had higher peak percentages and a narrower shape than in 2011, but the cumulative percentage curves for 2017 and 2011 are remarkably similar (fig. 31).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 2 to 10 ft/s (fig. 35). Exceptions to uniform flow include angled flows near the constriction at the bridges, minor turbulence downstream from the downstream spur dike and the piers, and flow reversal and recirculation downstream from the boat ramp on the downstream left bank (fig. 35).

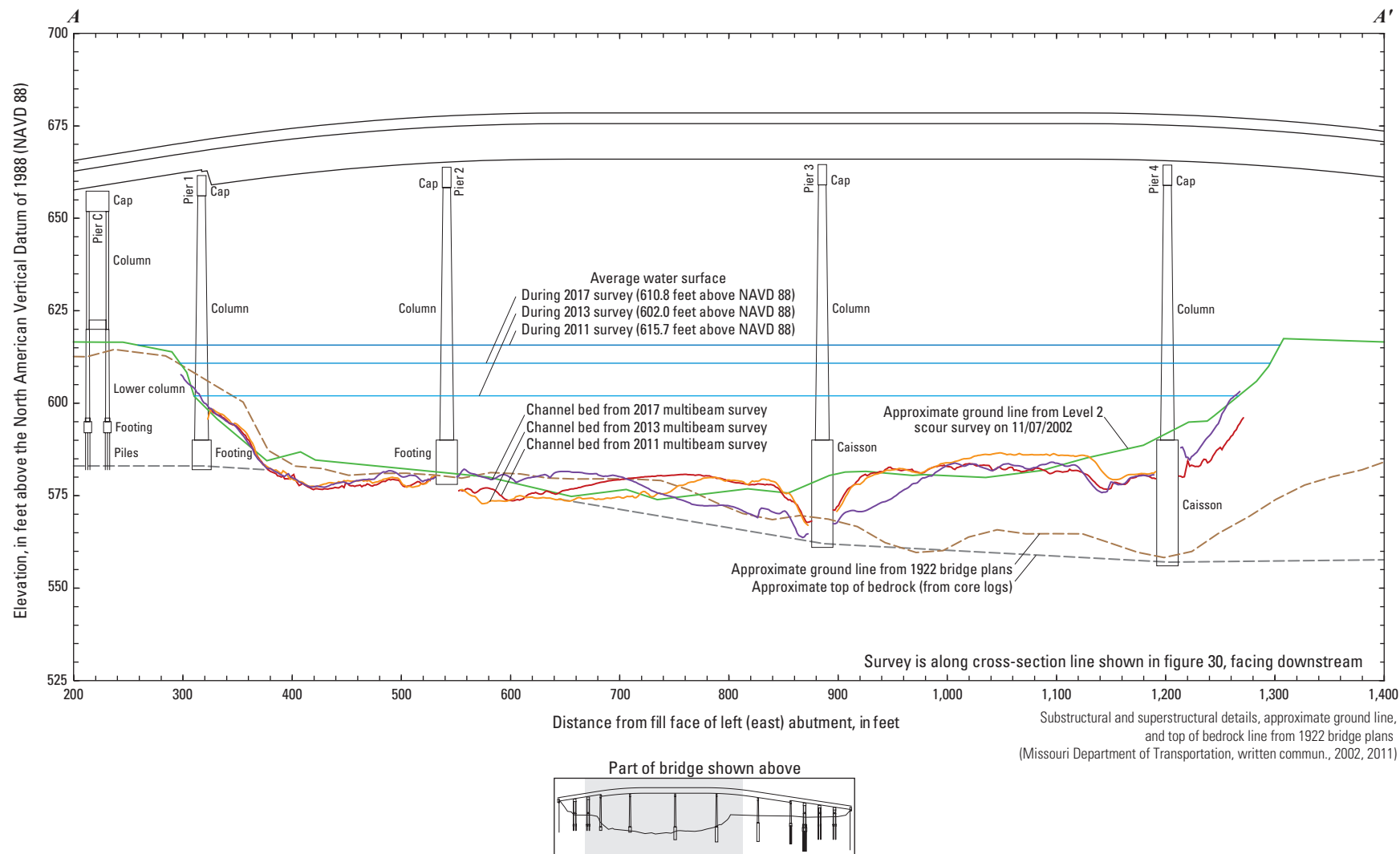


Figure 32. Key features, substructural and superstructural details, and surveyed channel bed of structure G0069 on Missouri State Highway 240 crossing the Missouri River at Glasgow, Missouri.

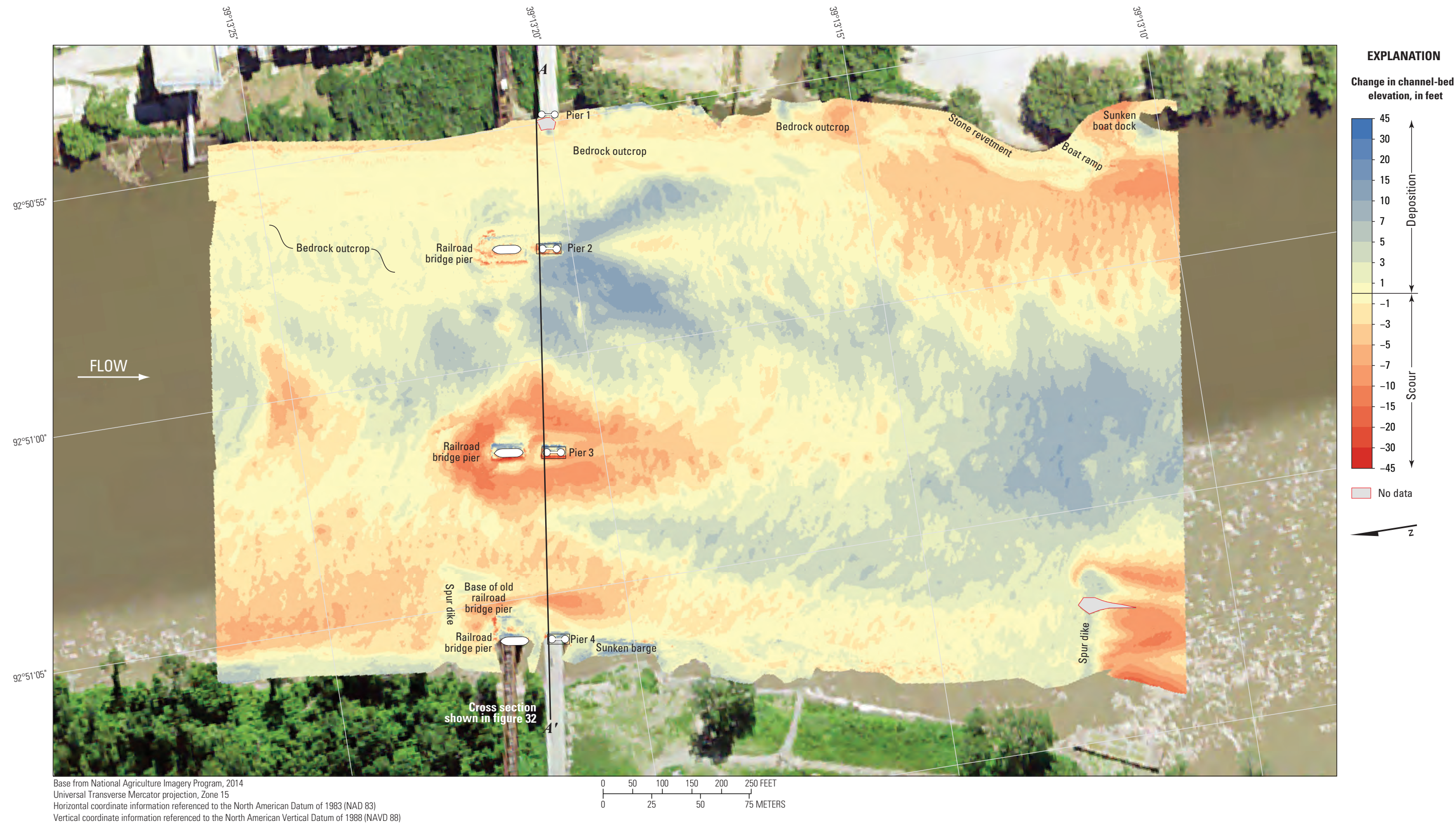


Figure 33. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure G0069 on Missouri State Highway 240 at Glasgow, Missouri, on May 24, 2017, and April 26, 2013.

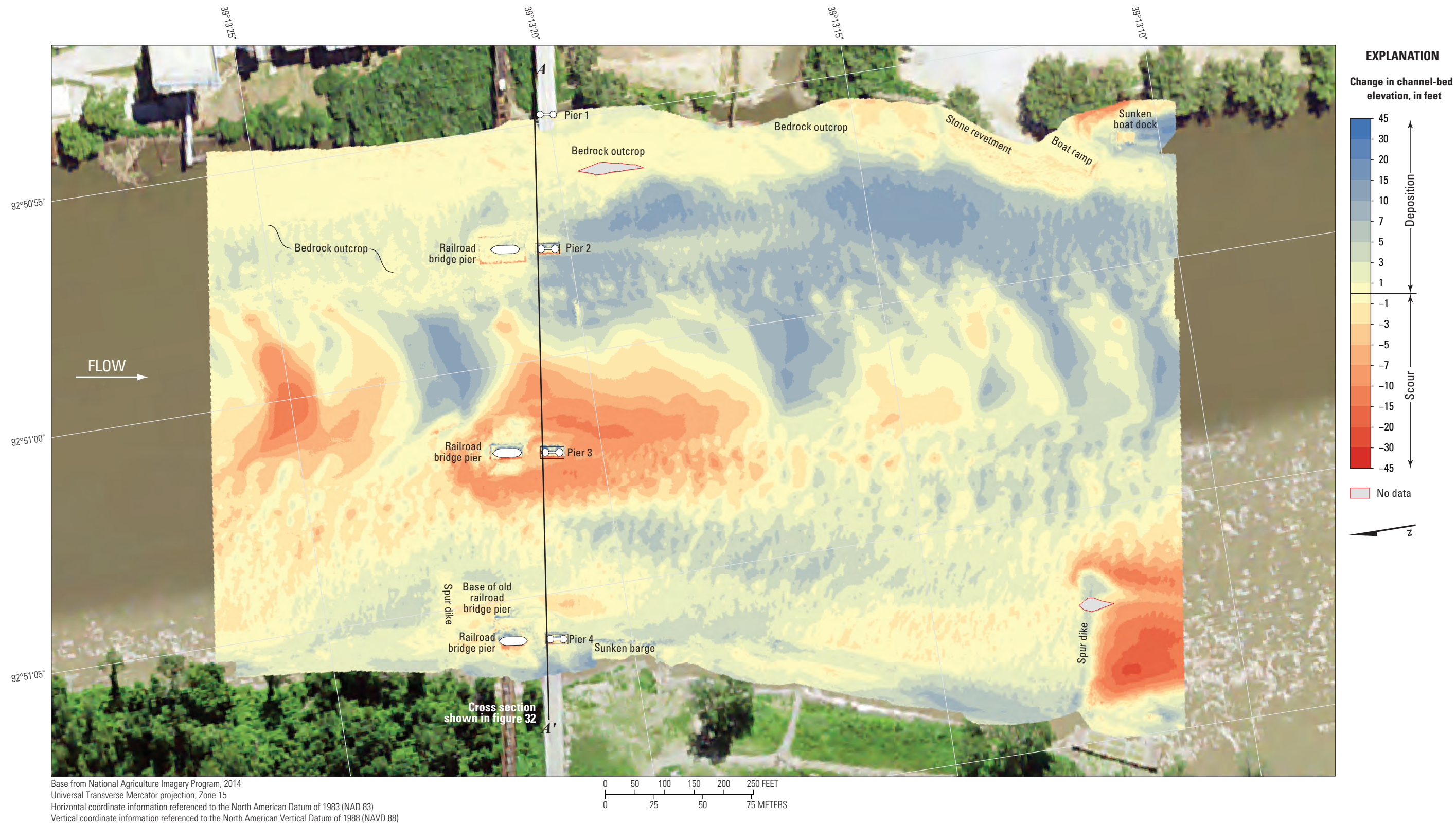
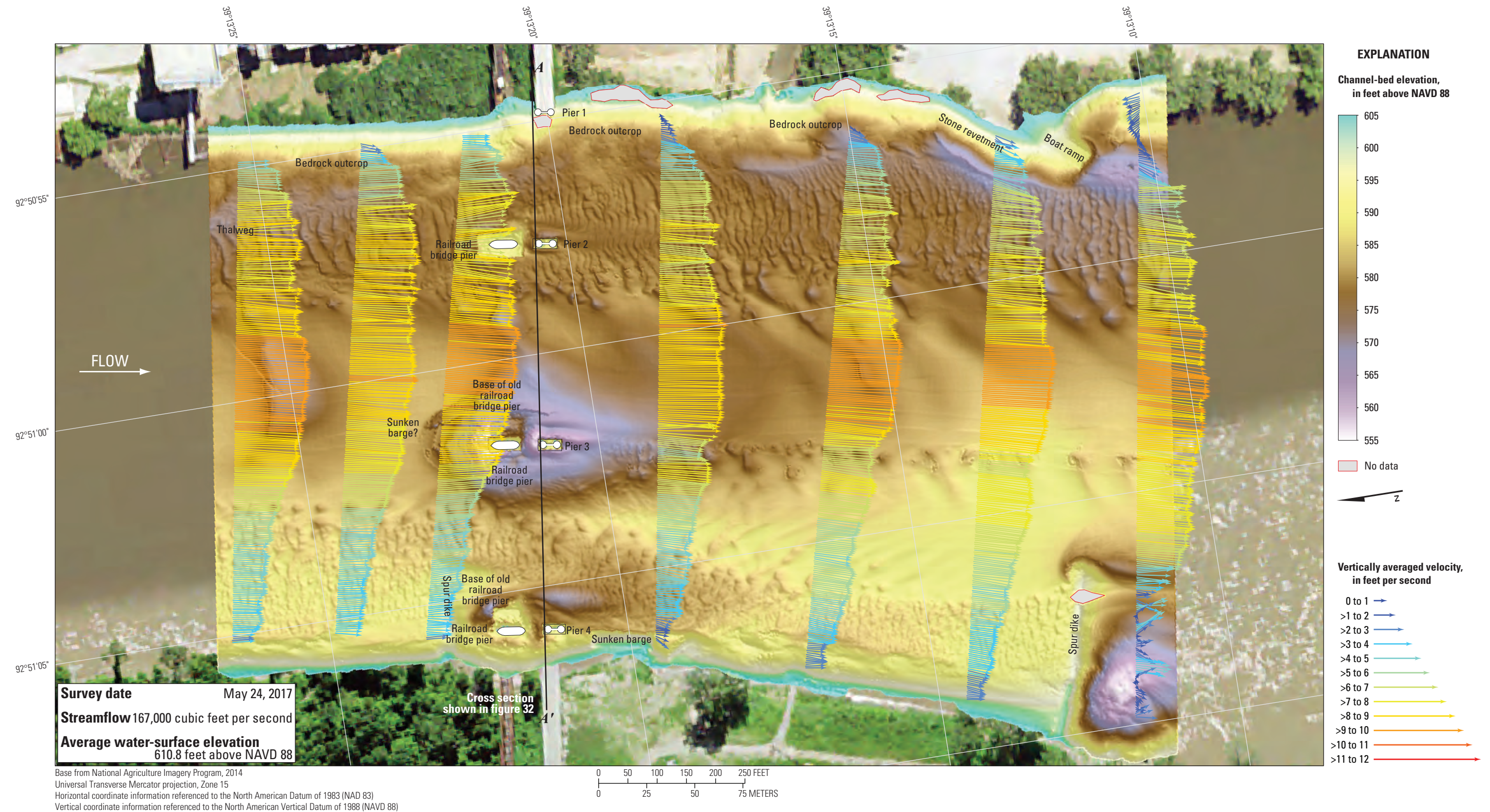


Figure 34. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure G0069 on Missouri State Highway 240 at Glasgow, Missouri, on May 24, 2017, and July 22, 2011.



Structure A4574 on Missouri State Highway 5 at Boonville, Missouri

Structure A4574 (site 18) on Missouri State Highway 5 crosses the Missouri River at RM 196.6 at Boonville, Mo., south of Glasgow and about halfway between Kansas City and St. Louis, Mo. (fig. 1). The site was surveyed on May 25, 2017, and the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 584.7 ft (table 5). Streamflow on the Mississippi River was about 153,000 ft³/s during the survey (table 5).

The survey area was about 1,640 ft long and about 1,300 ft wide, extending from bank to bank in the main channel (fig. 36). The upstream end of the survey area was about 620 ft upstream from the centerline of structure A4574 (fig. 36), and piers 5 through 8 were in the water, although piers 5 and 8 were on the extreme edges of the surveyed area (fig. 36). The approximate channel-bed elevations ranged from about 554 to 569 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 37), reaching a minimum elevation of 547 ft in the channel thalweg along the toe of the left (north) bank (table 5, fig. 36). The well-defined thalweg was present along the left (north) bank throughout the surveyed area and was about 8 to 12 ft deeper than the channel bed in the middle of the channel. Medium dune features with superimposed small dunes and ripples were present in the left (north) side of the channel, and numerous other small dunes and ripples were detected throughout the channel (fig. 36).

Minor scour holes were observed near central main channel piers 6 and 7. Near main channel pier 7 (fig. 36), the scour hole had a minimum channel-bed elevation of about 553 ft

(table 6), about 20 ft above the elevation of the bottom of the pier seal course of 533.00 ft (fig. 38; table 6). The minor scour hole near pier 6 (fig. 36) had a minimum channel-bed elevation of about 560 ft (table 6). Both scour holes were difficult to discern from nearby dunes and ripples, but the upstream edges of the footing of pier 7 were visible during the survey (figs. 36, 38). Information from bridge plans indicates that pier 7 is founded on shafts drilled 39 ft into bedrock, having about 39 ft of bed material between the bottom of the scour hole and bedrock (fig. 38; table 6). Pier 6 is founded on a footing on bedrock, having about 9 ft of bed material between the bottom of the scour hole and bedrock (fig. 38; table 6). The surveyed bed was similar to the two previous multibeam surveys in 2011 and 2013, with the 2017 bed oscillating between the bed in the previous surveys except near pier 7 where the bed was 5 to 7 ft lower in 2017 than in either previous survey (fig. 38).

Main channel piers 5 and 8 were along the edges of the surveyed area. Pier 8 is immediately downstream from a longitudinal spur dike and seems to be embedded in the stone revetment along the left bank (fig. 36). A scour hole near the upstream toe of the revetment near the pier reached a minimum channel-bed elevation of about 547 ft (table 6), the minimum of the survey, which is about 20 ft above the elevation of the bottom of the pier seal course of 527.00 ft (fig. 38; table 6). The minimum elevation surveyed near pier 5 was about 560 ft (figs. 36, 38), which is equal to the elevation of bedrock near the pier; pier 5 is founded on a footing on bedrock according to bridge plans (fig. 38; table 6). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (Brown and others, 2010; American Association of State Highway Transportation Officials, 2012),

Structure A4574 on Missouri State Highway 5



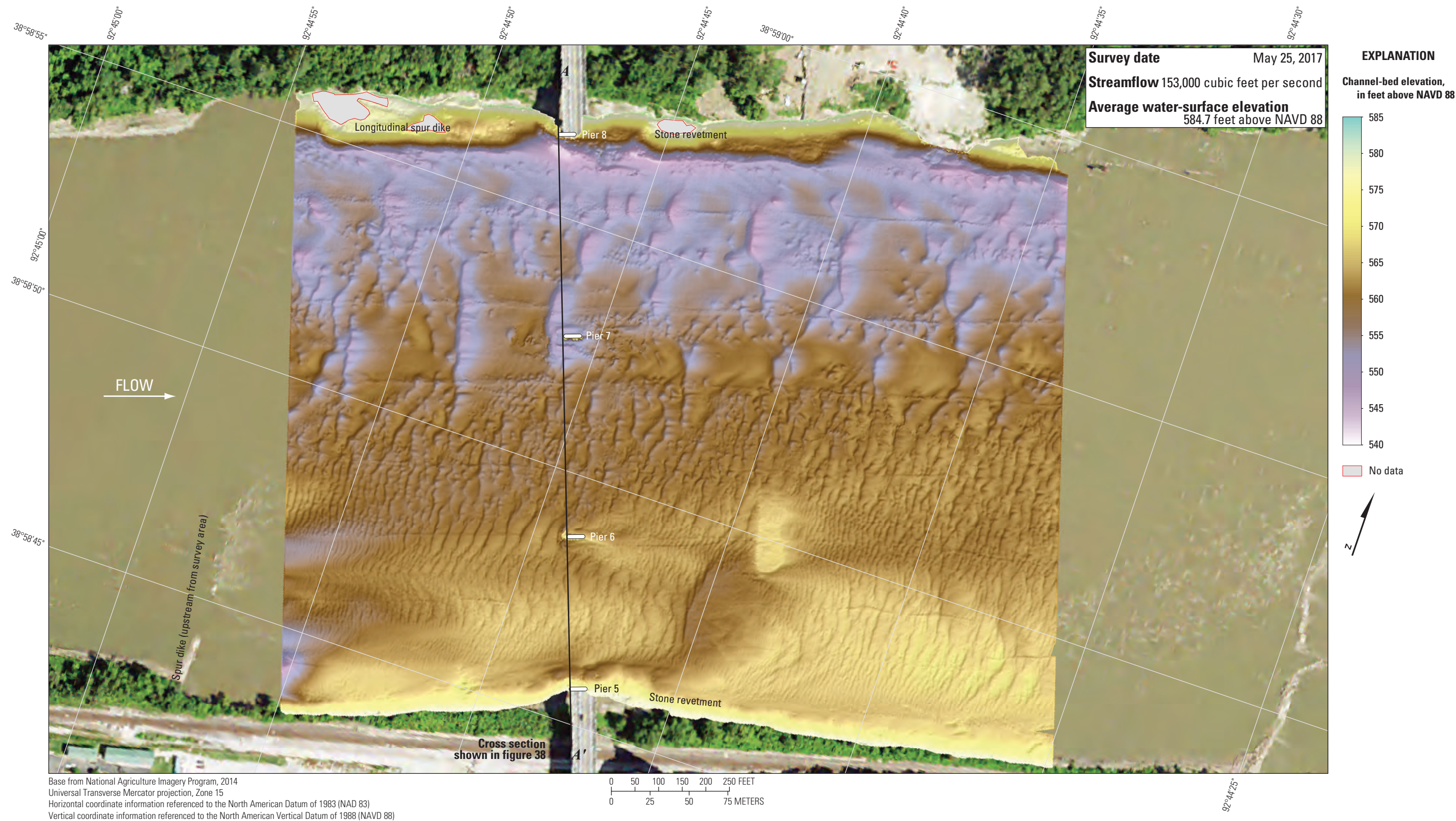


Figure 36. Bathymetric survey of the Missouri River channel near structure A4574 on Missouri State Highway 5 at Boonville, Missouri.

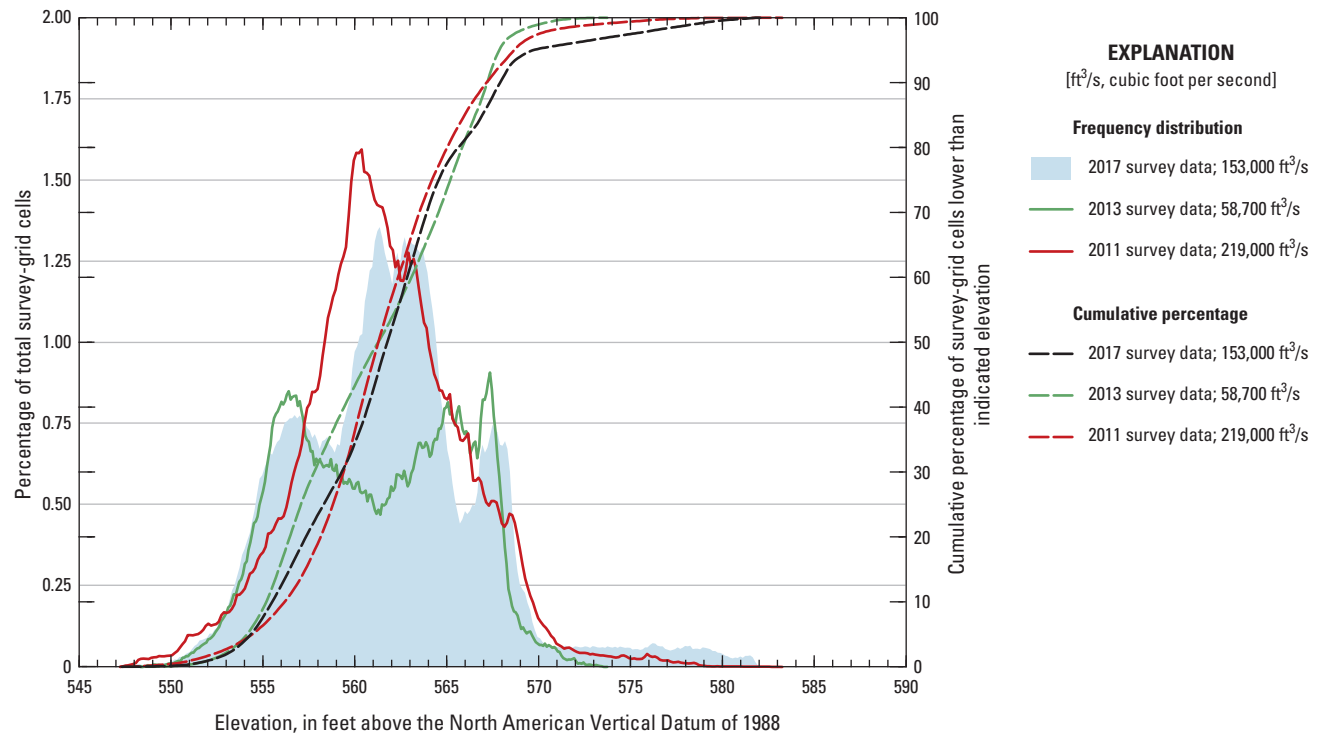


Figure 37. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A4574 on Missouri State Highway 5 at Boonville, Missouri, on May 25, 2017, compared to previous surveys.

but full exposure of usually buried substructural elements warrants special consideration and observation.

The difference between the survey on May 25, 2017, and the previous nonflood survey on April 29, 2013 (fig. 39), indicates an approximate balance between scour and deposition throughout the reach between 2013 and 2017 (table 7). The net volume of cut in the reach from 2013 to 2017 was about 67,100 yd³, and the net volume of fill was about 54,800 yd³, resulting in a net loss of only about 12,300 yd³ of sediment. Minor to moderate scour of as much as 10 ft is balanced with deposition in the area downstream from the spur dike on the right (south) bank just upstream from the surveyed reach (fig. 39). Scour balanced with deposition is present throughout the left (north) side of the channel as well (fig. 39). The average difference between the April 2013 and May 2017 bathymetric surfaces (−0.18 ft; table 7) indicates essentially zero net change overall, as evident in the difference map (fig. 39). The frequency distributions and cumulative percentage curves were remarkably similar between the various surveys at this site (fig. 37).

The difference between the survey on May 25, 2017, and the previous flood survey on July 25, 2011 (fig. 40), also indicates an approximate balance between scour and deposition

throughout the reach between 2011 and 2017 (table 7). The net volume of cut in the reach from 2011 to 2017 was about 79,200 yd³, and the net volume of fill was about 76,500 yd³, resulting in a net loss of only about 2,700 yd³ of sediment. Moderate to major scour of as much as 20 ft along the upstream thalweg and in the area downstream from the spur dike on the upstream right (south) bank is balanced with deposition of as much as 15 ft farther downstream (fig. 40). Large dune features present in the thalweg in the 2011 survey were replaced with medium dunes, resulting in an alternating scour/deposition pattern in the thalweg (fig. 40); however, the average difference between the July 2011 and May 2017 bathymetric surfaces was −0.04 ft (table 7), which indicates essentially zero net change overall.

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 2 to 8 ft/s (fig. 41). Exceptions to uniform flow include moderate turbulence and flow reversal downstream from the upstream right spur dike and the longitudinal dikes on the left bank (fig. 41). All the piers were aligned with flow, as indicated by little to no turbulence observed downstream that can be directly attributed to the piers (fig. 41).

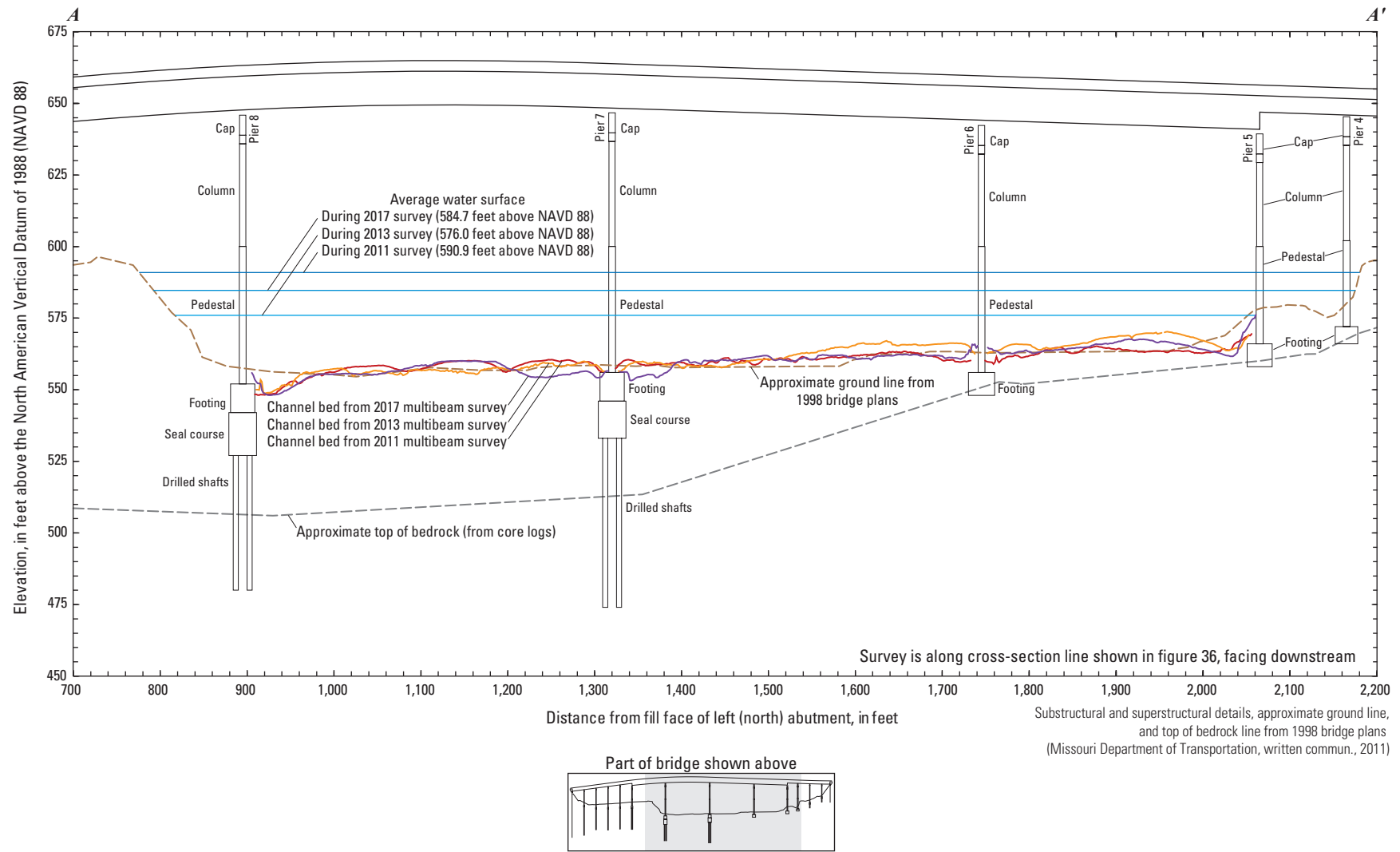


Figure 38. Key features, substructural and superstructural details, and surveyed channel bed of structure A4574 on Missouri State Highway 5 crossing the Missouri River at Boonville, Missouri.

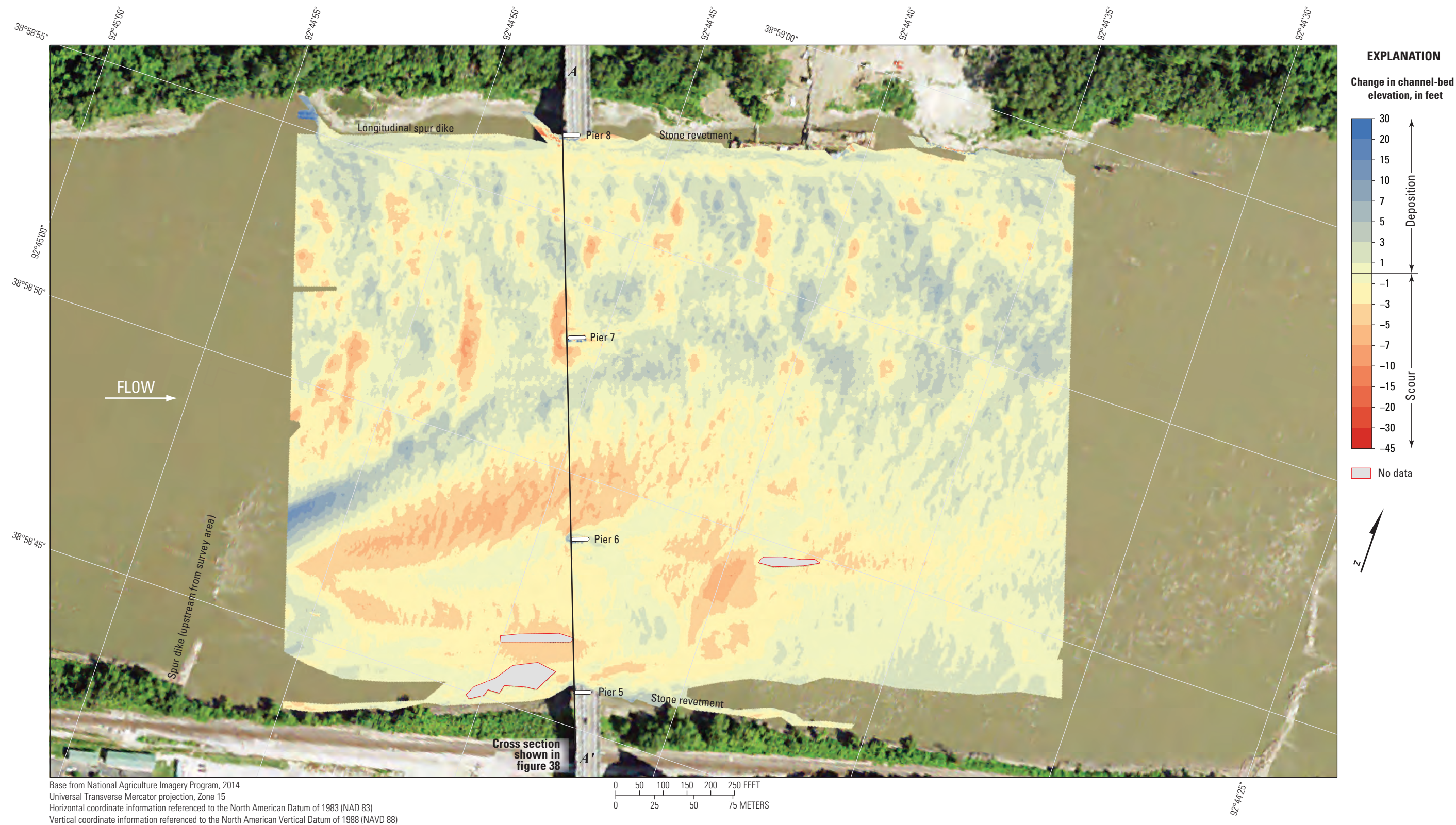


Figure 39. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4574 on Missouri State Highway 5 at Boonville, Missouri, on May 25, 2017, and April 29, 2013.

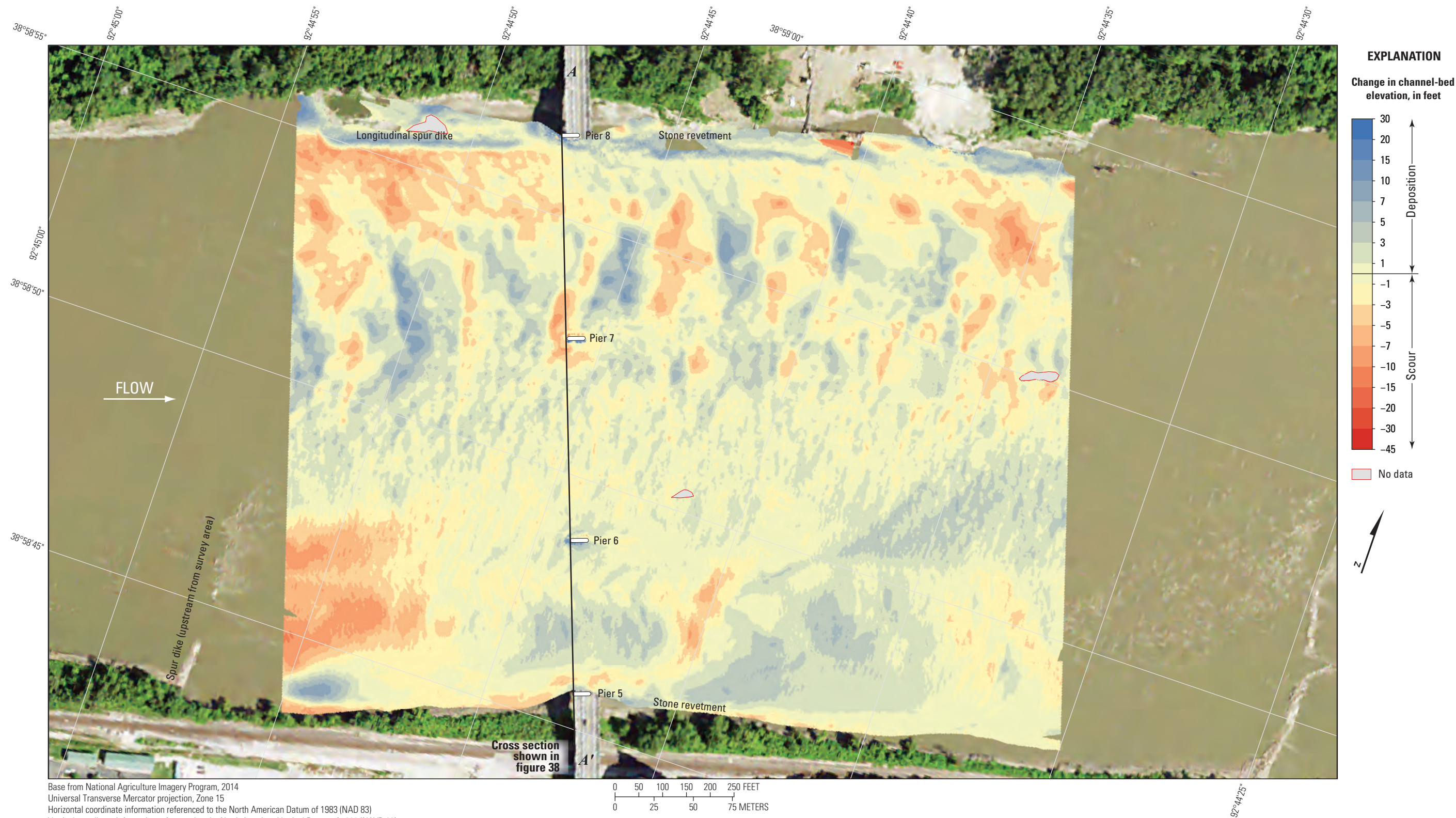


Figure 40. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4574 on Missouri State Highway 5 at Boonville, Missouri, on May 25, 2017, and July 25, 2011.

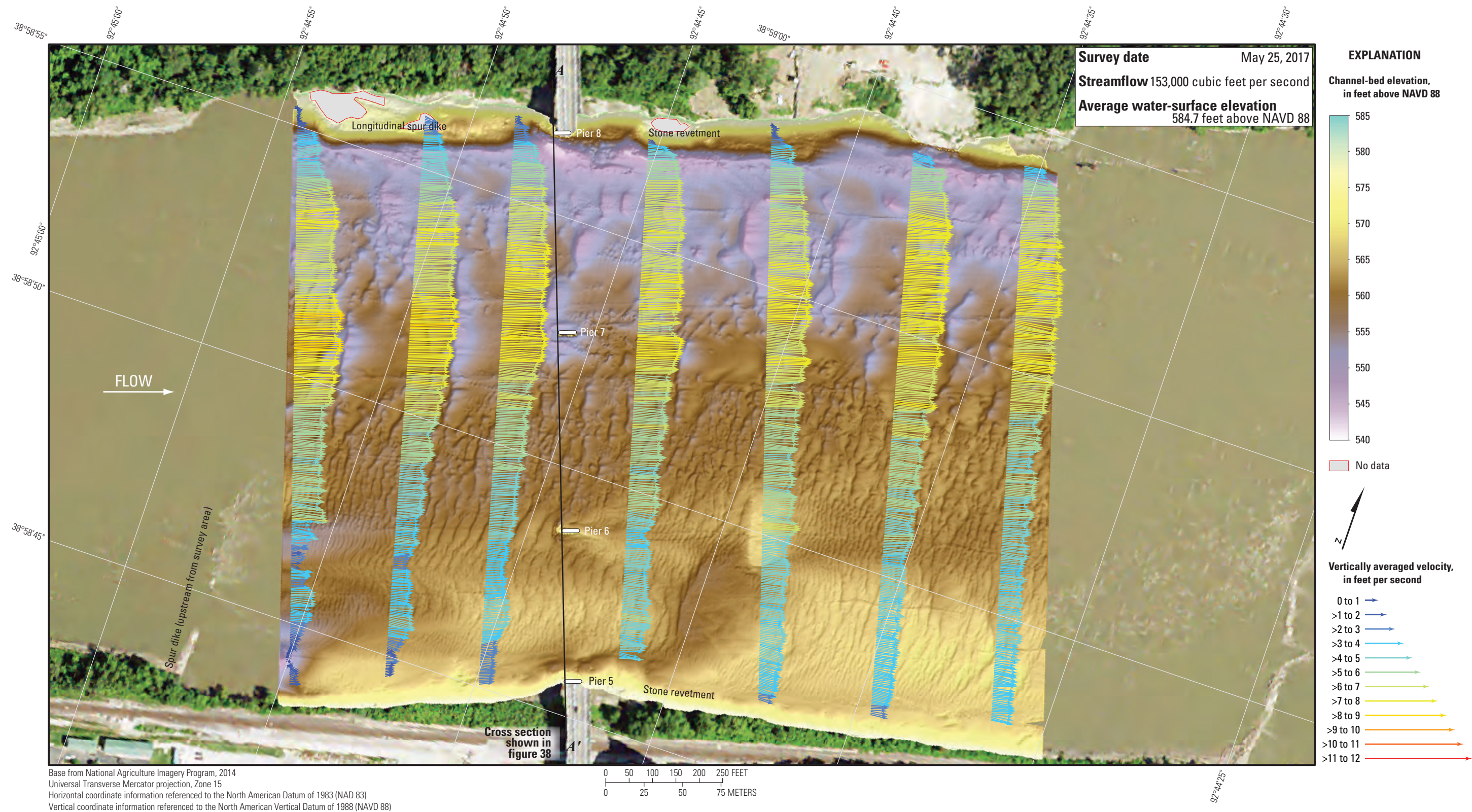


Figure 41. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A4574 on Missouri State Highway 5 at Boonville, Missouri.

Structure L0962 on Interstate 70 near Rocheport, Missouri

Structure L0962 (site 19) on Interstate 70 crosses the Missouri River at RM 185.1 near Rocheport, Mo., east of Boonville and west of St. Louis, Mo. (fig. 1). The site was surveyed on May 25, 2017, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 574.7 ft (table 5). Streamflow on the Missouri River was about 155,000 ft³/s during the survey (table 5).

The survey area was about 1,640 ft long and about 1,200 ft wide, generally extending from bank to bank in the main channel (fig. 42). The upstream end of the survey area was about 580 ft upstream from the centerline of structure L0962 (fig. 42), and piers 14 and 15 were in the water; bent 16 was embedded in a debris raft island near the left (northeast) bank. The channel-bed elevations ranged from about 538 to 562 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 43). A poorly defined thalweg was present along the left bank, and a nearly planar bed in the middle of the channel at the upstream end of the reach became progressively more broken with small dunes and ripples as one progressed downstream (fig. 42). The water depth during the 2017 survey was sufficiently high to permit surveying behind and over the longitudinal spur dikes on the left (northeast) bank (fig. 42). The minimum channel-bed elevation of 513 ft (table 5) occurred downstream from the longitudinal spur dike on the downstream left (northeast) side (fig. 42).

A substantial scour hole near main channel pier 14 (fig. 42) had a minimum channel-bed elevation of about 522 ft (table 6), which is about 23 ft below the average channel

elevation upstream from the bridge (fig. 44; table 6). Information from bridge plans indicates that pier 14 is founded on a caisson on bedrock, having about 24 ft of bed material between the bottom of the scour hole and bedrock (fig. 44; table 6). Pier 15 is embedded in the longitudinal spur dike, and the minimum channel elevation at the toe of the dike near the pier was about 534 ft (figs. 42, 44; table 6). Pier 15 also is founded on a caisson on bedrock, having about 15 ft of material between the minimum channel elevation and bedrock (fig. 44; table 6); however, the rock of the spur dike will limit or prevent a local scour hole near pier 15. Bent 16 was completely surrounded by an island, resulting from a persistent debris raft between pier 15 and bent 16 downstream from the lateral part of the spur dike near those piers/bents (fig. 42). The surveyed bed generally was higher than the previous multibeam survey in 2011, with 15 to 20 ft of deposition in the middle, between piers 14 and 15, and about 5 to 10 ft of deposition between pier 14 and the right bank (fig. 44).

The difference between the survey on May 25, 2017, and the previous nonflood survey on April 29, 2013 (fig. 45), indicates an approximate balance of scour and deposition throughout the reach between 2013 and 2017; however, the average difference of -0.56 ft between the bathymetric surfaces indicates minor scour between the surveys (table 7). The net volume of cut in the reach from 2013 to 2017 was about 72,500 yd³, and the net volume of fill was about 40,700 yd³, resulting in a net loss of about 31,800 yd³ of sediment between 2013 and 2017. There was minor to moderate deposition of as much as 10 ft in the upstream left part of the channel and downstream from the spur dike on the right (southwest) part of the channel downstream from the bridge (fig. 45); however, moderate to substantial scour of as much as 15 ft was observed near pier 14 and along the toe of the longitudinal spur dikes along the left (northeast) side of the channel (fig. 45). The

Structure L0962 on Interstate 70



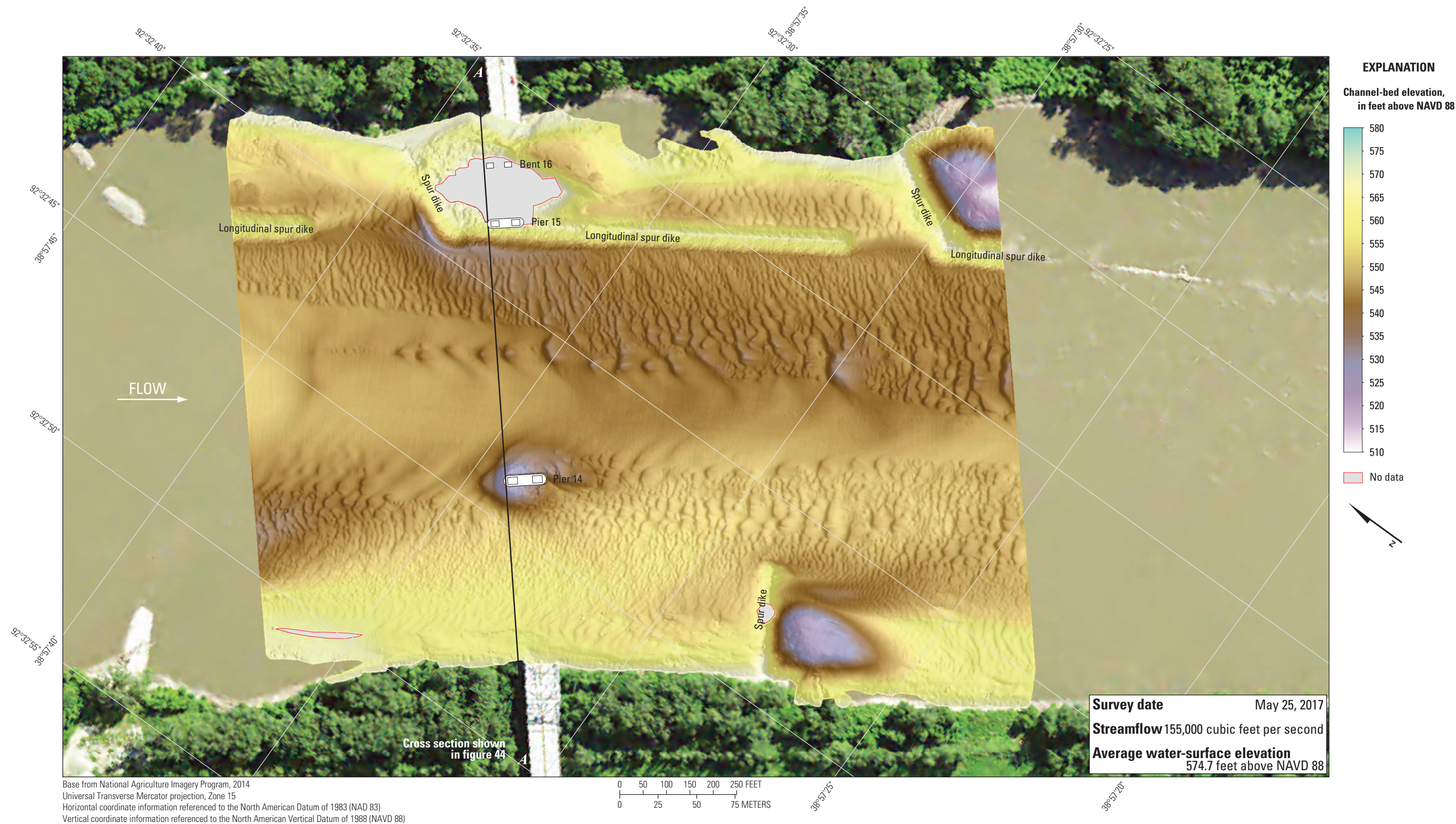


Figure 42. Bathymetric survey of the Missouri River channel near structure L0962 on Interstate 70 near Rocheport, Missouri.

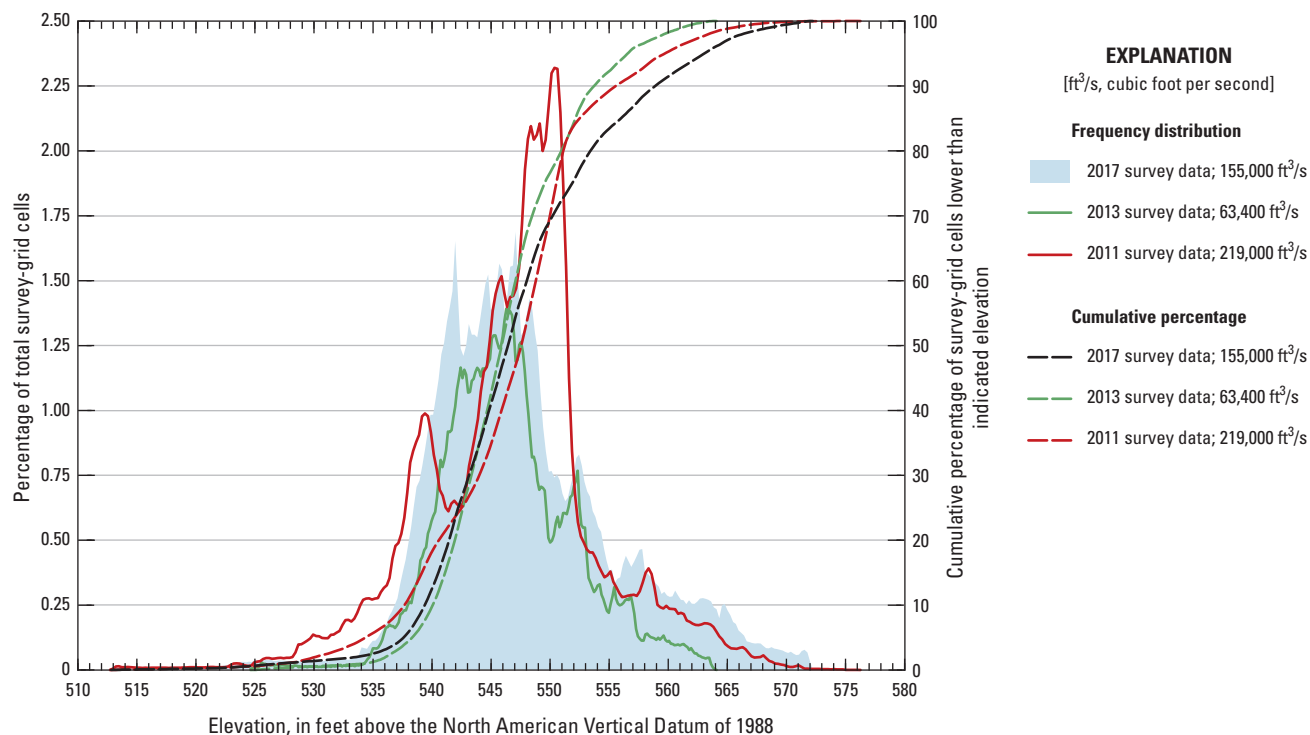


Figure 43. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure L0962 on Interstate 70 near Rocheport, Missouri, on May 25, 2017, compared to previous surveys.

cross section from the 2017 survey is generally similar to the 2013 survey, except near pier 14 where the 2017 survey section is below the 2011 survey (fig. 44). The frequency distribution of bed elevations in 2017 was similar to but wider than in 2013, with a higher percentage of survey-grid cells at higher elevations than in 2013 because of the higher water-surface elevation (fig. 44). Minor scour indicated along the longitudinal spur dikes on the left (northeast) bank may be the result of minor positional variations between the surveys (figs. 44, 45). As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The difference between the survey on May 25, 2017, and the previous flood survey on July 26, 2011 (fig. 46), also indicated an approximate balance of scour and deposition throughout the reach between 2011 and 2017. The net volume of cut in the reach from 2011 to 2017 was about 108,400 yd³, and the net volume of fill was about 122,900 yd³, resulting in a net gain of only about 14,500 yd³ of sediment. However, the apparent balance of scour and deposition (an average difference of +0.22 ft between the bathymetric surfaces; table 7) was the result of moderate to substantial scour of as much as 45 ft balanced with moderate to substantial deposition of as much as 45 ft in various locations throughout the reach

(fig. 46). The cross section from the 2017 survey is generally similar to the 2011 survey between pier 14 and the right (southwest) bank, but the cross sections alternate as to which is at a higher elevation between piers 14 and 15 (fig. 44). The frequency distribution of bed elevations in 2011 was different from both 2013 and 2017, with a substantially higher percentage of survey-grid cells at elevations between 545 and 555 ft (fig. 44). Minor scour was again indicated along the longitudinal spur dikes on the left (northeast) bank (figs. 44, 46) but may be the result of minor positional variations between the surveys. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 1 to 10 ft/s (fig. 47), with locally lower velocities and flow reversal along the banks, particularly downstream from the various spur dikes in the reach (fig. 47). Pier 14 was mostly aligned with flow, causing minimal turbulence downstream (fig. 47); however, flow approached pier 14 from the left side, causing an asymmetric scour hole that is longer and slightly deeper on the left side, similar to observations from previous surveys (fig. 47).

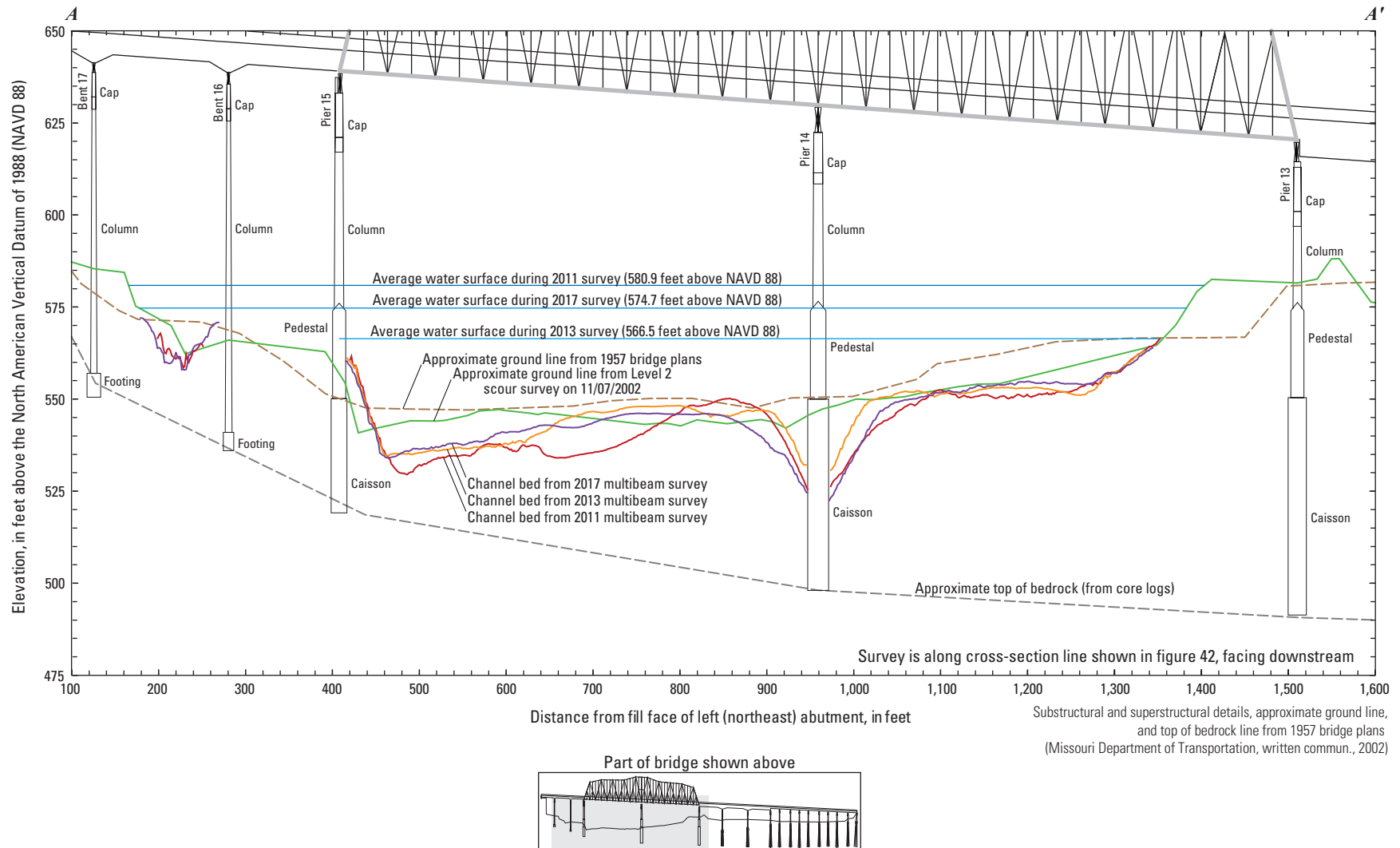


Figure 44. Key features, substructural and superstructural details, and surveyed channel bed of structure L0962 on Interstate 70 crossing the Missouri River near Rocheport, Missouri.

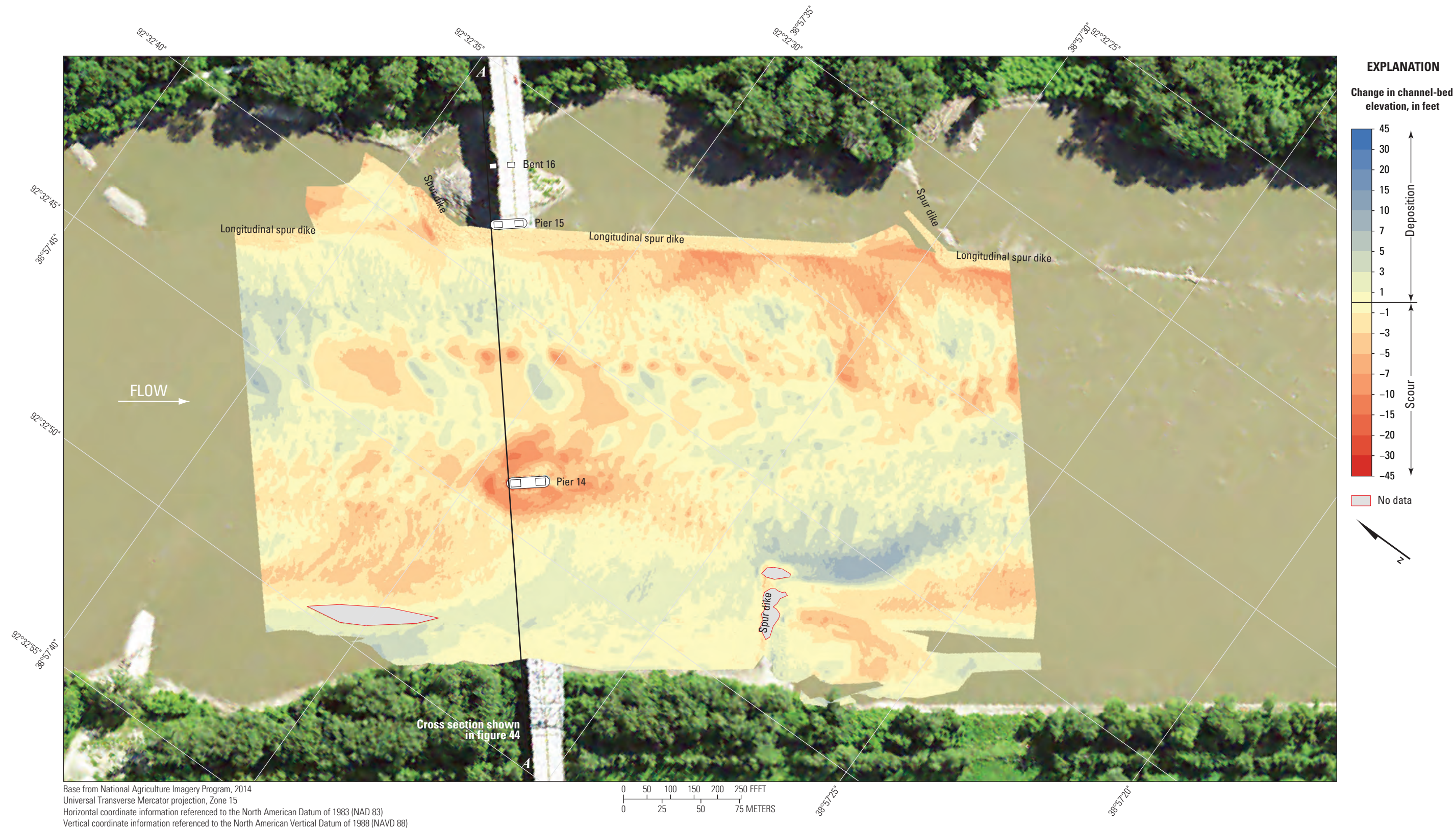
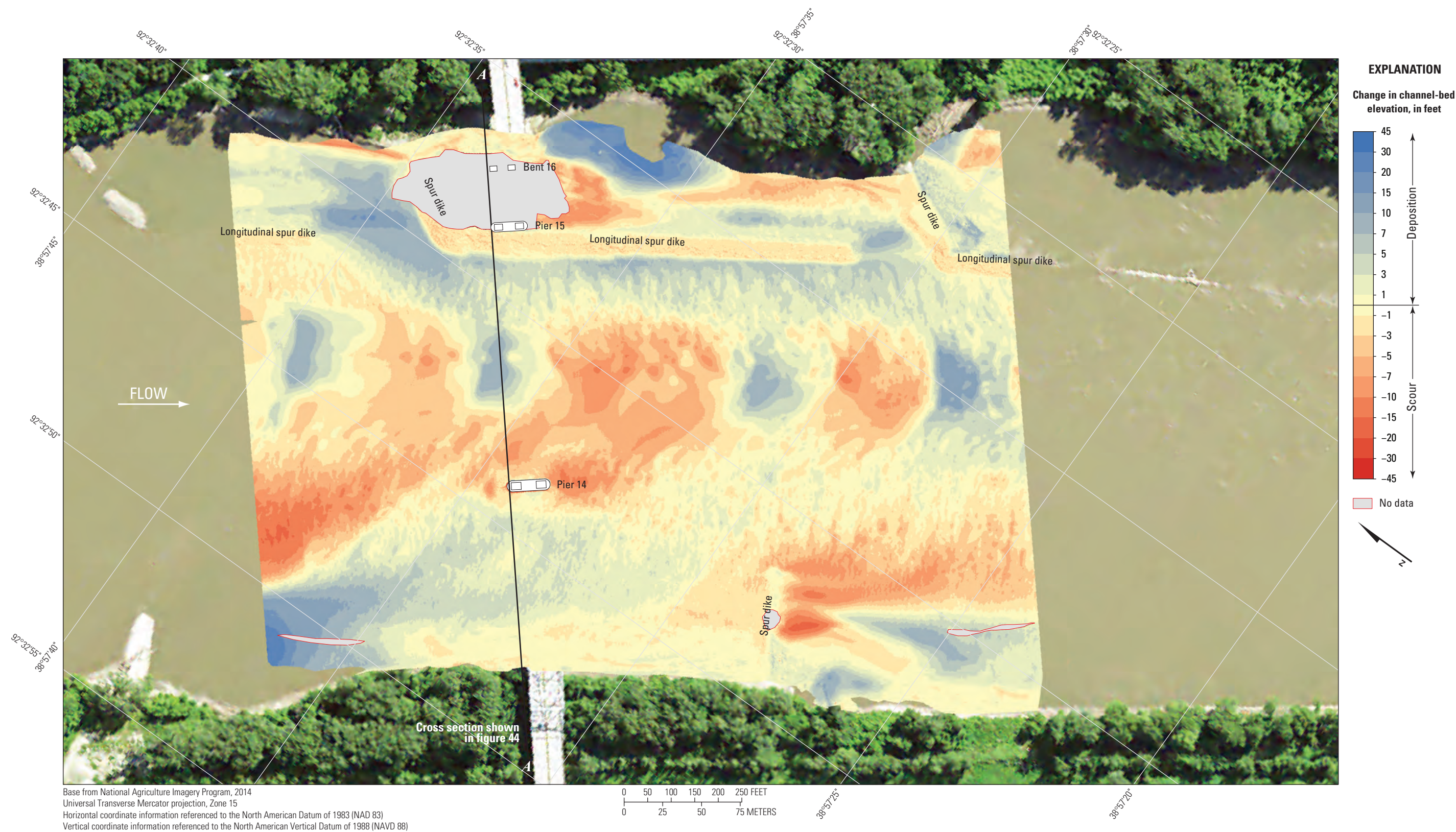


Figure 45. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure L0962 on Interstate 70 near Rocheport, Missouri, on May 25, 2017, and April 29, 2013.



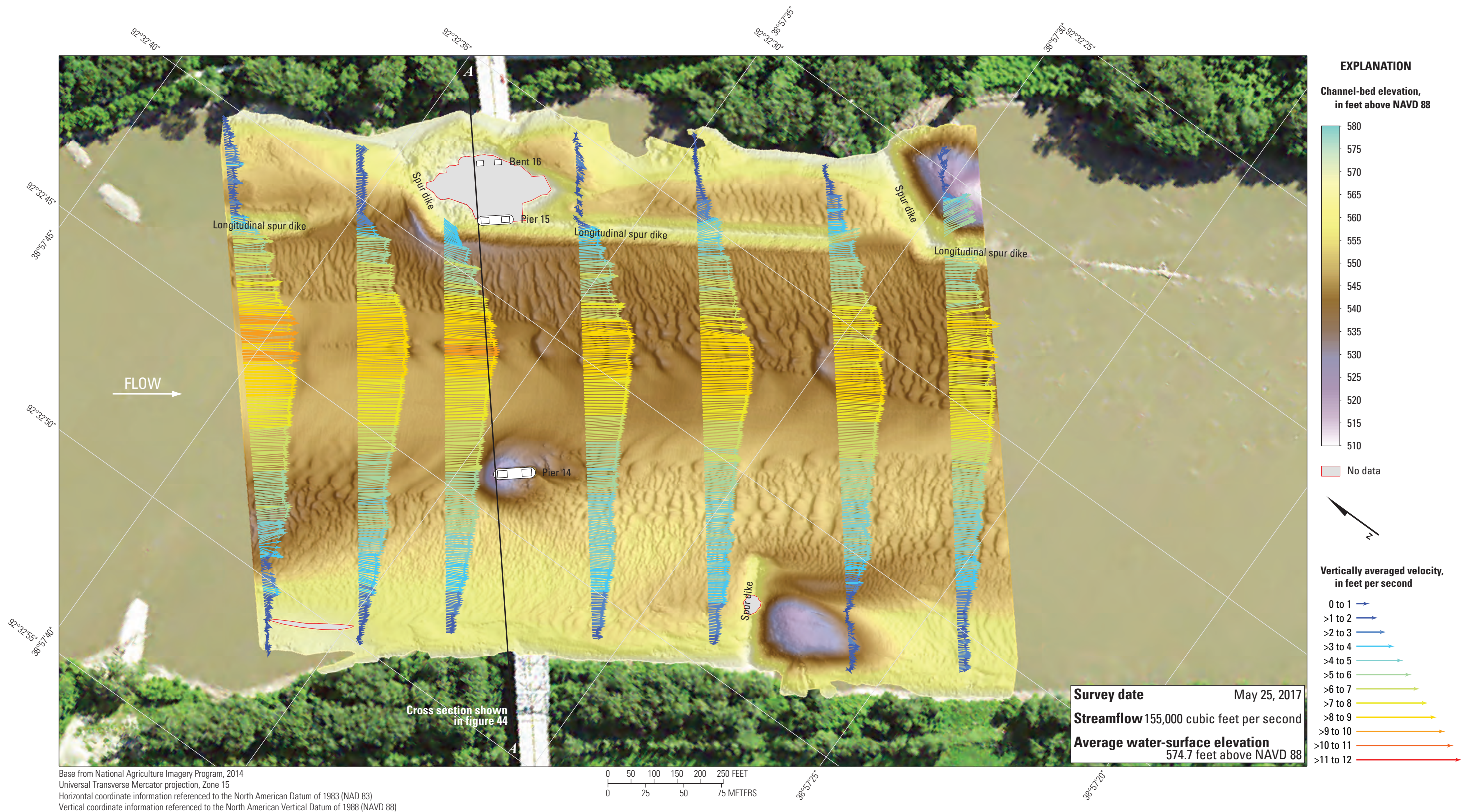


Figure 47. Bathymetry and vertically averaged velocities of the Missouri River channel near structure L0962 on Interstate 70 near Rocheport, Missouri.

Structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri

Structures L0550 and A4497 (site 20) are dual bridges on U.S. Highway 54 crossing the Missouri River at RM 143.9 at Jefferson City, Mo., southeast of Rocheport and west of St. Louis, Mo. (fig. 1). The site was surveyed on May 31, 2017, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 537.0 ft (table 5). Streamflow on the Missouri River was about 125,000 ft³/s during the survey (table 5). This site has been the subject of several multibeam surveys (Huizinga, 2014) that provide bathymetry at a variety of flow conditions for comparison. Furthermore, scour countermeasures in the form of a riprap blanket were placed around pier 4 of structures L0550 and A4497 in 2015, and the site near the piers was surveyed before and after the installation of these countermeasures.

The survey area in 2017 was about 1,640 ft long and about 970 ft wide from bank to bank in the main channel (fig. 48). The upstream end of the survey area was about 630 ft upstream from the centerline between structures L0550 and A4497, and piers 3 and 4 of both structures were in the water, although pier 3 was on the extreme edges of the surveyed area on the right (south) bank (fig. 48). The channel-bed elevations ranged from about 504 to 525 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5; fig. 49), except along the toe of the right (south) bank, on the upper banks, and near the spur dikes on the left and right sides of the channel (fig. 48). A shallow thalweg was present along the right (south) bank throughout the reach and was about 5 to 7 ft deeper than the channel bed in the middle of the channel (fig. 48). Small dunes and ripples were present throughout the survey reach (fig. 48). As in previous surveys (Huizinga, 2012; 2014), stone revetment was present on the right (south) bank throughout the reach (fig. 48).

The scour holes that historically have been observed near pier 4 of both structures (see fig. 31 in Huizinga, 2014) were conspicuously absent in the 2017 survey, having been

effectively mitigated by the scour countermeasures installed around the piers (figs. 48, 50–52). The top of the riprap blanket countermeasure was evident around both piers in 2017, except along the upstream edge of the blanket where migrating medium dune features have deposited material and covered the riprap (fig. 48). As would be expected, the change from before to after the installation of countermeasures indicates as much as 30 ft of deposition near the upstream face of pier 4 of upstream structure L0550 (fig. 53); other minimal changes occurred between the before and after surveys. Information from bridge plans indicates that pier 4 of upstream structure L0550 is founded on a caisson on bedrock, having about 49 ft of bed material between the channel bed near the pier and bedrock (fig. 50; table 6). Pier 4 of structure A4497 is founded on shafts drilled 11 ft into bedrock, having about 50 ft of bed material between the channel bed near the pier and bedrock (fig. 51; table 6). Away from the piers, the surveyed bed generally was similar to the various other multibeam surveys, but most similar to the July 2011 survey, and lower than the January 2010 survey (figs. 50, 51).

As with the other sites in this (2017) study, this site was surveyed with the other July–August 2011 flood surveys and the previous surveys of the mid-Missouri sites in 2013, as detailed in Huizinga (2012) and Huizinga (2014). Furthermore, real-time monitoring of the scour hole at pier 4 happened at this site from 2010 to 2013 using fixed, single-beam acoustic transducers attached to the upstream nose of pier 4 of both structures, and several bathymetric surveys of the area were completed as part of that study, also detailed in previous reports for this site (Huizinga, 2012, 2014). Finally, as mentioned previously, partial surveys of the channel bed near pier 4 of structures L0550 and A4497 were surveyed before and after installation of the scour countermeasures near those piers (fig. 52). As in the preceding discussions at each site between Kansas City and St. Louis, the differences between the current (2017) survey at this site and all the previous surveys will be examined and discussed in reverse chronological order from most recent to earliest.

Structures L0550 and A4497 on U.S. Highway 54





Figure 48. Bathymetric survey of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri.

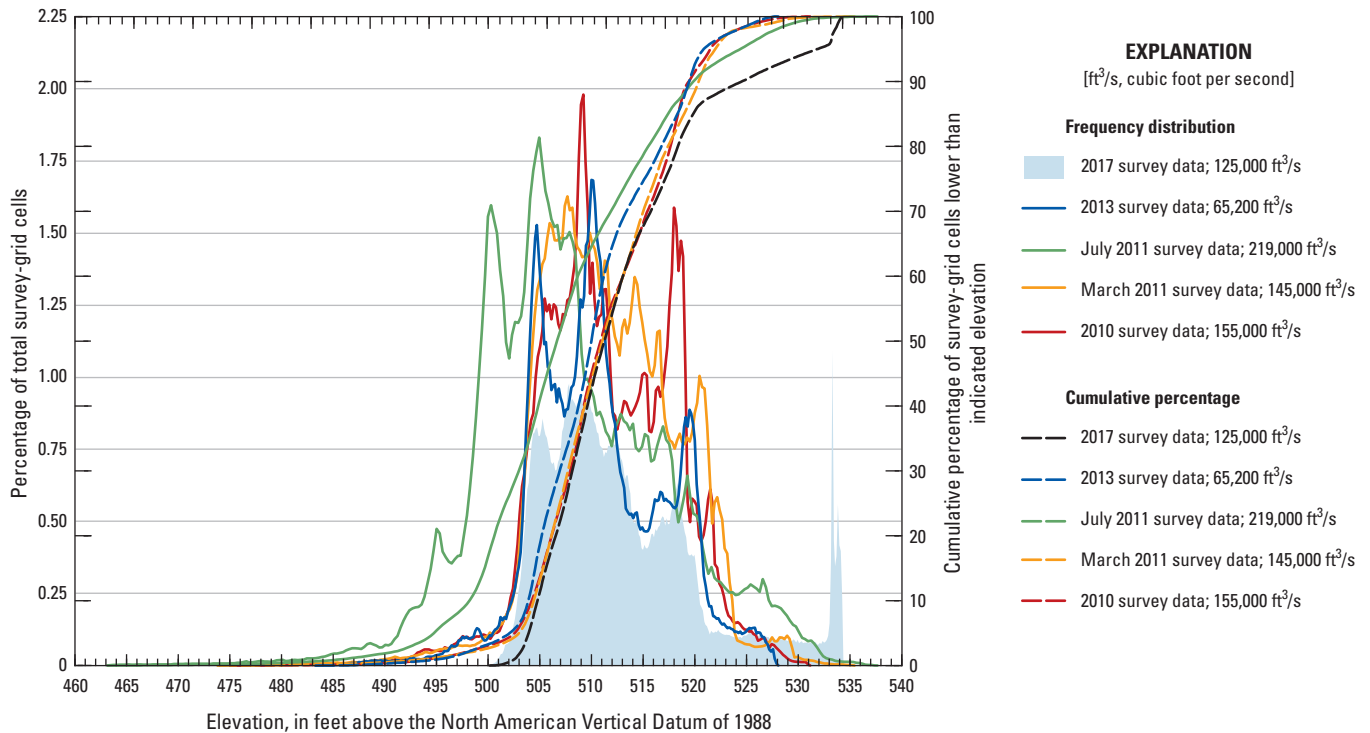


Figure 49. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 31, 2017, compared to previous surveys.

The difference between the survey on May 31, 2017, and the partial surveys on September 22 and October 29, 2015, clearly indicate the changes resulting from the installation of the riprap blanket countermeasures around pier 4 (fig. 54). The scour hole near pier 4 of both structures before the installation experienced deposition of as much as 20 ft (fig. 54A). Minor scour of 7 to 10 ft was observed throughout the partial reach in the areas away from the riprap blanket (fig. 54). Additionally, settling of the riprap blanket seems to have occurred along the upstream edge and along both sides of the blanket, with as much as 10 ft of scour indicated in those areas (fig. 54B), particularly near pier 4 of structure L0550. The cross sections from the 2017 survey compared to the postinstallation survey indicate the pattern of settling of the blanket along the edges (figs. 50, 51). Cut and fill volumes were not computed for the partial reaches of the before- and after-installation surveys.

The difference between the survey on May 31, 2017, and the previous nonflood survey on April 30, 2013 (fig. 55), indicates an approximate balance of scour and deposition (an average difference of +0.47 ft between the bathymetric surfaces) throughout the reach between 2013 and 2017 (table 7). The net volume of cut in the reach from 2013 to 2017 was about 46,500 yd³, and the net volume of fill was about 73,900 yd³, resulting in a net gain of about 27,400 yd³ of sediment. There was substantial deposition of as much as 45 ft in the scour holes upstream from pier 4 of both structures with the installation of the countermeasures, and moderate deposition of as

much as 10 ft in the wake zone on either side and downstream from the piers (fig. 55). Elsewhere throughout the reach, scour of as much as 15 ft was balanced by deposition of as much as 10 ft (fig. 55). The frequency distribution of bed elevations was of a similar shape in 2017 compared to 2013, albeit with a lower peak percentage of survey-grid cells in 2017 than 2013 (fig. 49). The resulting cumulative percentage curve is shifted to the left in 2013 compared to the 2017 curve (fig. 49). The rock outcrops on the right (south) bank seem to have experienced localized scour (fig. 55), but it is uncertain how much of this apparent difference is a function of positional variations between the surveys. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers likely results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The difference between the survey on May 31, 2017, and the previous flood survey on July 27, 2011 (fig. 56), indicates widespread deposition throughout the reach between July 2011 and 2017, with an average difference of +3.88 ft between the bathymetric surfaces (table 7). The net volume of cut in the reach from July 2011 to 2017 was about 14,300 yd³, and the net volume of fill was about 249,000 yd³, resulting in a net gain of about 234,700 yd³ of sediment. There was substantial deposition of as much as 60 ft in the scour holes upstream from pier 4 of both structures with the installation of the countermeasures, and moderate deposition of as much as

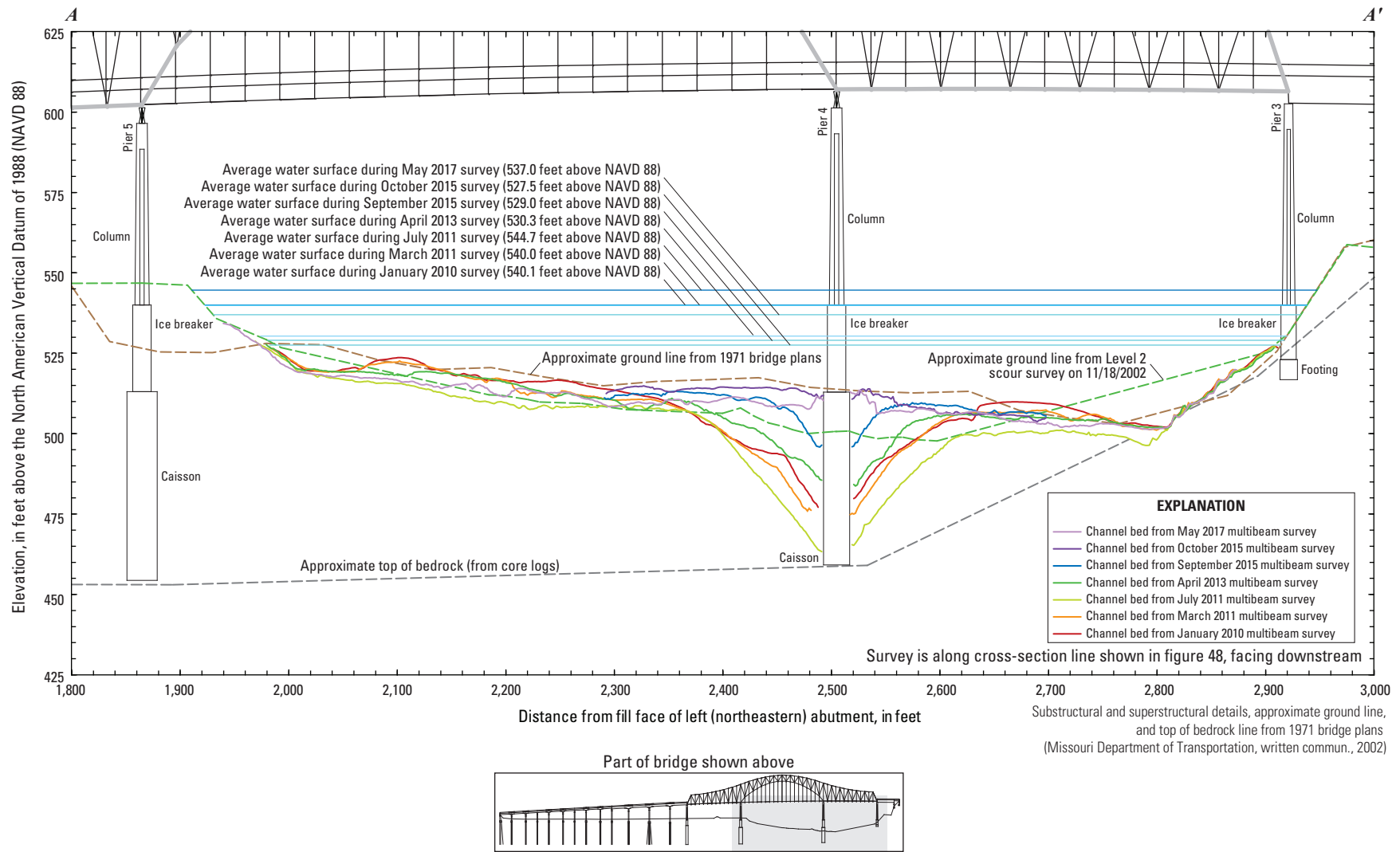


Figure 50. Key features, substructural and superstructural details, and surveyed channel bed of structure L0550 on U.S. Highway 54 crossing the Missouri River at Jefferson City, Missouri.

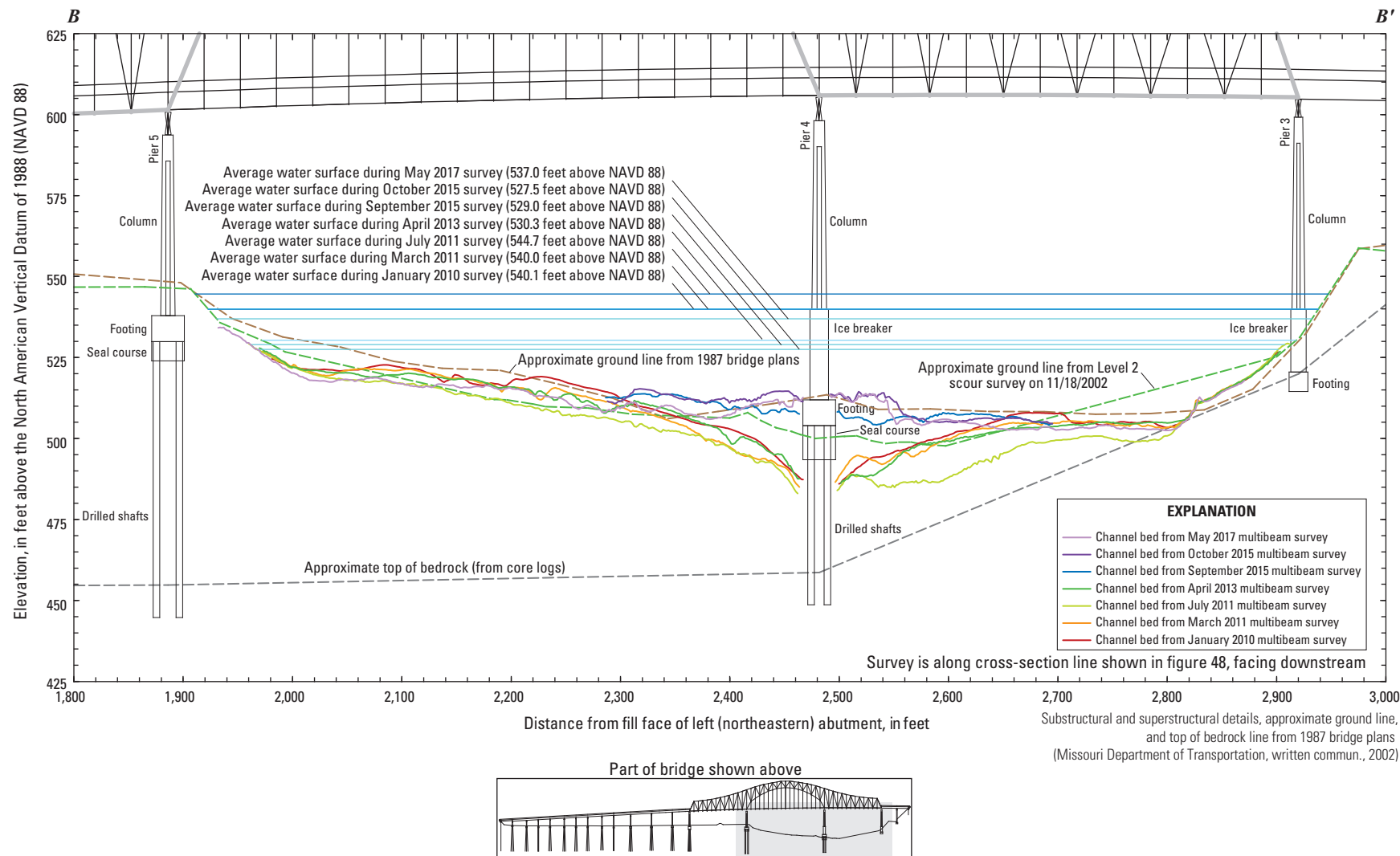


Figure 51. Key features, substructural and superstructural details, and surveyed channel bed of structure A4497 on U.S. Highway 54 crossing the Missouri River at Jefferson City, Missouri.



Figure 52. Bathymetric survey of the Missouri River channel near the main channel piers of structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri. *A*, on September 22, 2015, before installation of scour countermeasures; *B*, on October 29, 2015, after installation of scour countermeasures.

15 ft in the wake zone on either side from the piers (fig. 56). Elsewhere throughout the reach, deposition of as much as 10 ft was balanced by localized scour of as much as 15 ft along the left (north) bank (fig. 56). The frequency distribution of bed elevations was unique in July 2011, with a substantial percentage of survey-grid cells at elevations below 500 ft compared to 2017 (fig. 49). The cumulative percentage curve is substantially shifted to the left in July 2011 compared to the 2017 curve (fig. 49). Again, the rock outcrops on the right (south) bank seem to have experienced localized scour (fig. 56), but it is uncertain how much of this apparent difference is a function of positional variations between the surveys. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers likely results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The difference between the survey on May 31, 2017, and a previous survey on March 1, 2011 (fig. 57), indicates moderate deposition (an average difference of +0.76 ft between the bathymetric surfaces) throughout the reach between March 2011 and 2017 (table 7). The net volume of cut in the reach from March 2011 to 2017 was about 43,000 yd³, and the net volume of fill was about 81,200 yd³, resulting in a net gain of about 38,200 yd³ of sediment. Once again, there was substantial deposition of as much as 45 ft in the scour holes upstream from pier 4 of both structures with the installation of the countermeasures, and moderate deposition of as much as 15 ft in the wake zone on either side and downstream from the piers, balanced with scour of as much as 15 ft elsewhere throughout the reach (fig. 57). The frequency distribution of bed elevations was similar in March 2011 and 2017, albeit with a lower peak percentage of survey-grid cells in 2017 compared to March 2011 and with a larger percentage of survey-grid cells at higher elevations in 2017 (fig. 49). The cumulative percentage curves in March 2011 and 2017 are similar, except where greater than 90 percent because of the higher percentage of survey-grid cells at a higher elevation than in March 2011 (fig. 49). Again, the rock outcrops on the right (south) bank seem to have experienced localized scour (fig. 57), but it is uncertain how much of this apparent difference is a function of positional variations between the surveys. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers likely results from

minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

The difference between the survey on May 31, 2017, and the first survey at this site on January 26, 2010 (fig. 58), indicates moderate scour (an average difference of -0.63 ft between the bathymetric surfaces) throughout the reach between 2010 and 2017 (table 7). The net volume of cut in the reach from 2010 to 2017 was about 83,900 yd³, and the net volume of fill was about 51,700 yd³, resulting in a net loss of about 32,200 yd³ of sediment between 2010 and 2017. Once again, there was substantial deposition of as much as 45 ft in the scour holes upstream from pier 4 of both structures with the installation of the countermeasures, and moderate deposition of as much as 15 ft in the wake zone on either side and downstream from the piers; however, moderate scour of as much as 15 ft was present elsewhere throughout most of the reach (fig. 58). The frequency distribution of bed elevations in 2010 was similar to March 2011 and 2017, albeit with a lower percentage of survey-grid cells in 2017 than either March 2011 or 2010 and with a larger percentage of survey-grid cells at higher elevations in 2017 (fig. 49). The cumulative percentage curves in 2010 and 2017 are similar, except where greater than 90 percent because of the higher percentage of survey-grid cells at a higher elevation, as in March 2011 (fig. 49). Again, the rock outcrops on the right (south) bank seem to have experienced localized scour (fig. 58), but it is uncertain how much of this apparent difference is a function of positional variations between the surveys. Position information for surveys before mid-2010 were not processed through POSPac MMS and, therefore, have more questionable positional accuracy, particularly near the bridges where the GNSS signal might be lost. As with all difference maps presented in this report, substantial deposition or scour apparent at the faces of the piers likely results from minor horizontal positional variances between the surveys (see the “Uncertainty Estimation” section).

Although velocity transects were obtained during the survey on May 31, 2017, the data from those transects were somehow lost. Streamflow of the Missouri River at the site was available from a set of four transects measured upstream from the bridge by another USGS crew at approximately the same time as the bathymetric survey; however, velocity vector information is not available for the 2017 survey.

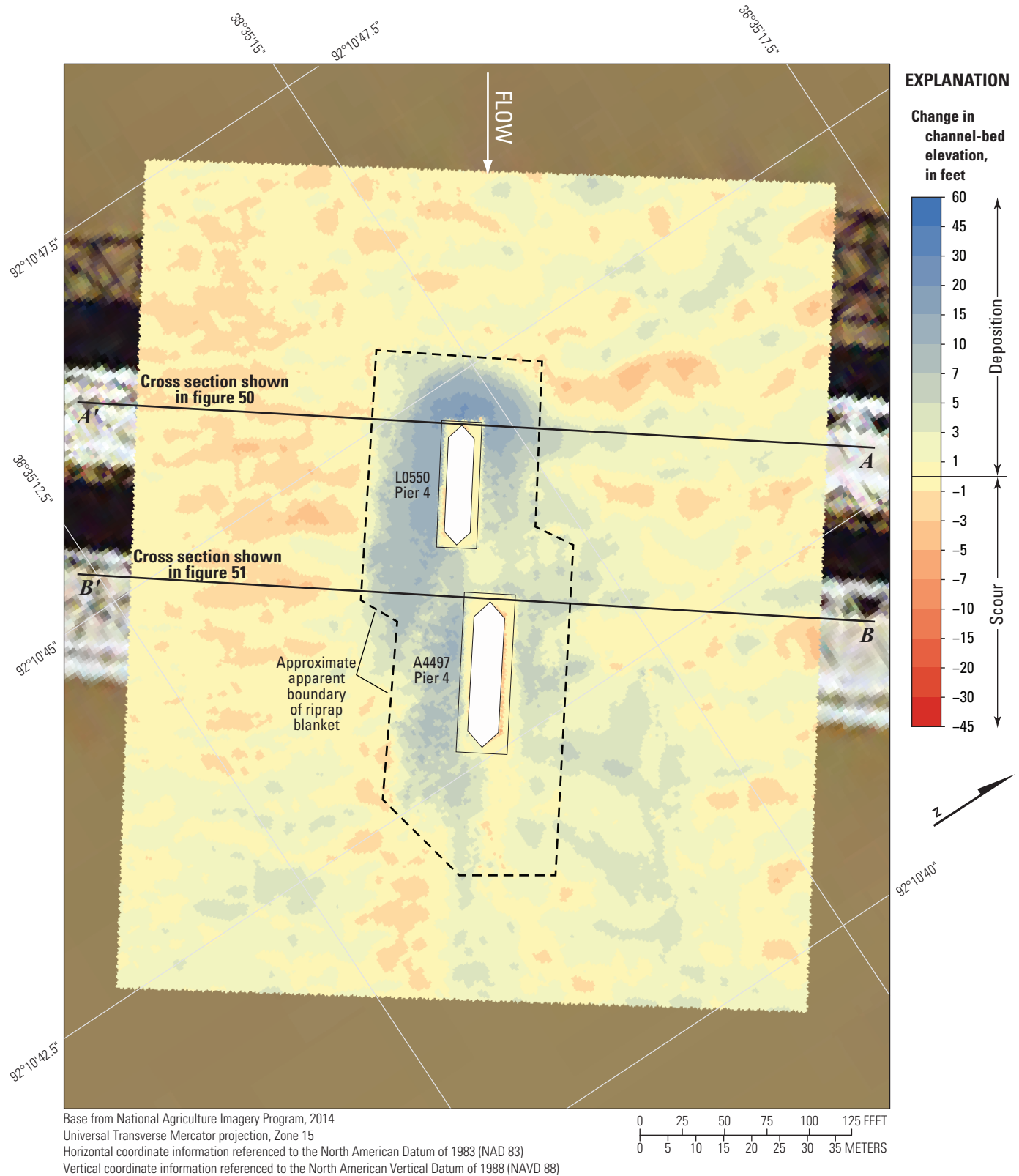


Figure 53. Difference between surfaces created from bathymetric surveys of the Missouri River channel near the main channel piers of structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on September 22 and October 29, 2015, before and after installation of scour countermeasures.

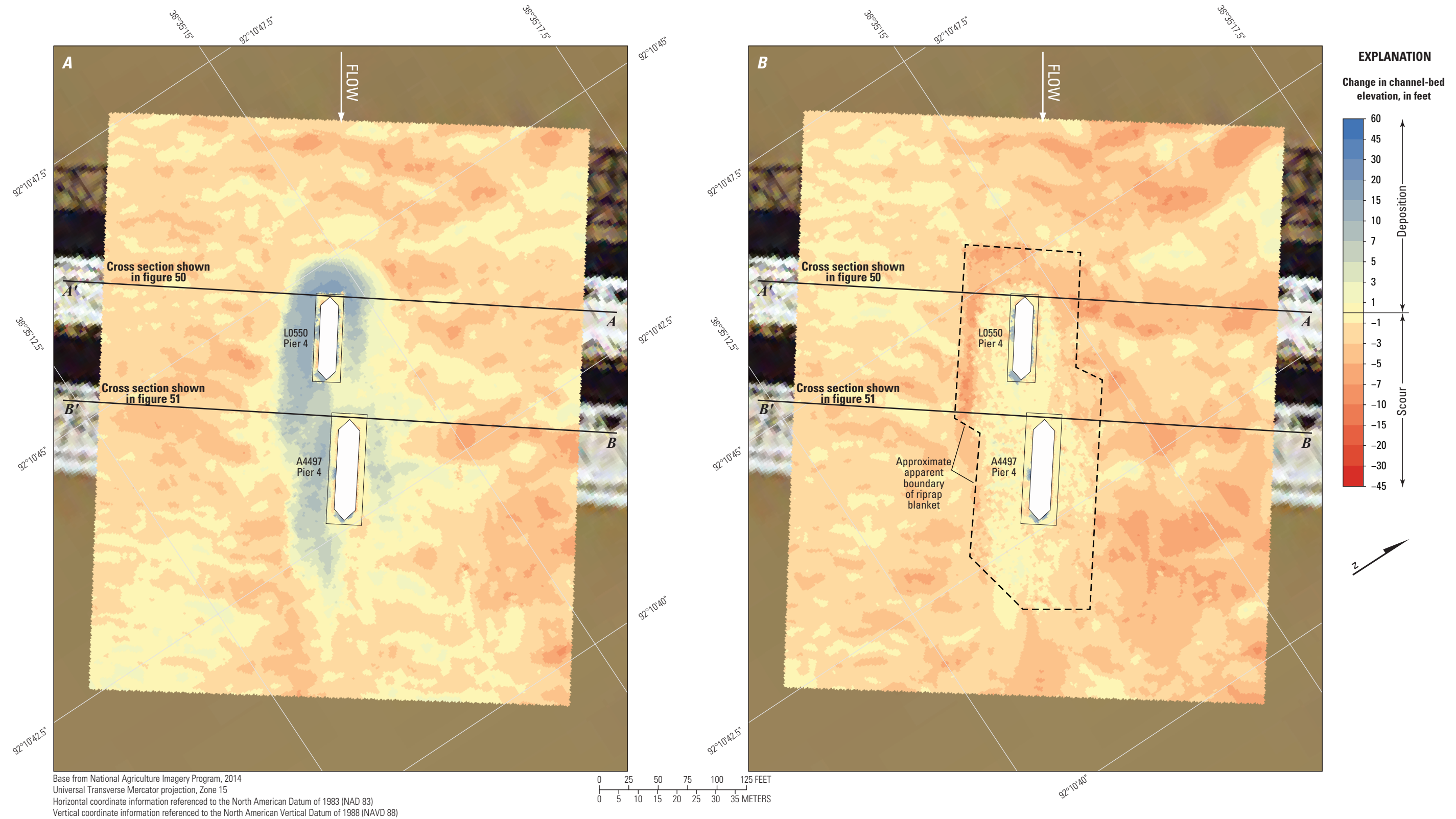


Figure 54. Difference between surfaces created from bathymetric surveys of the Missouri River channel near the main channel piers of structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 31, 2017, and before and after the installation of scour countermeasures. *A*, September 22, 2015, before installation of scour countermeasures; *B*, October 29, 2015, after installation of scour countermeasures.

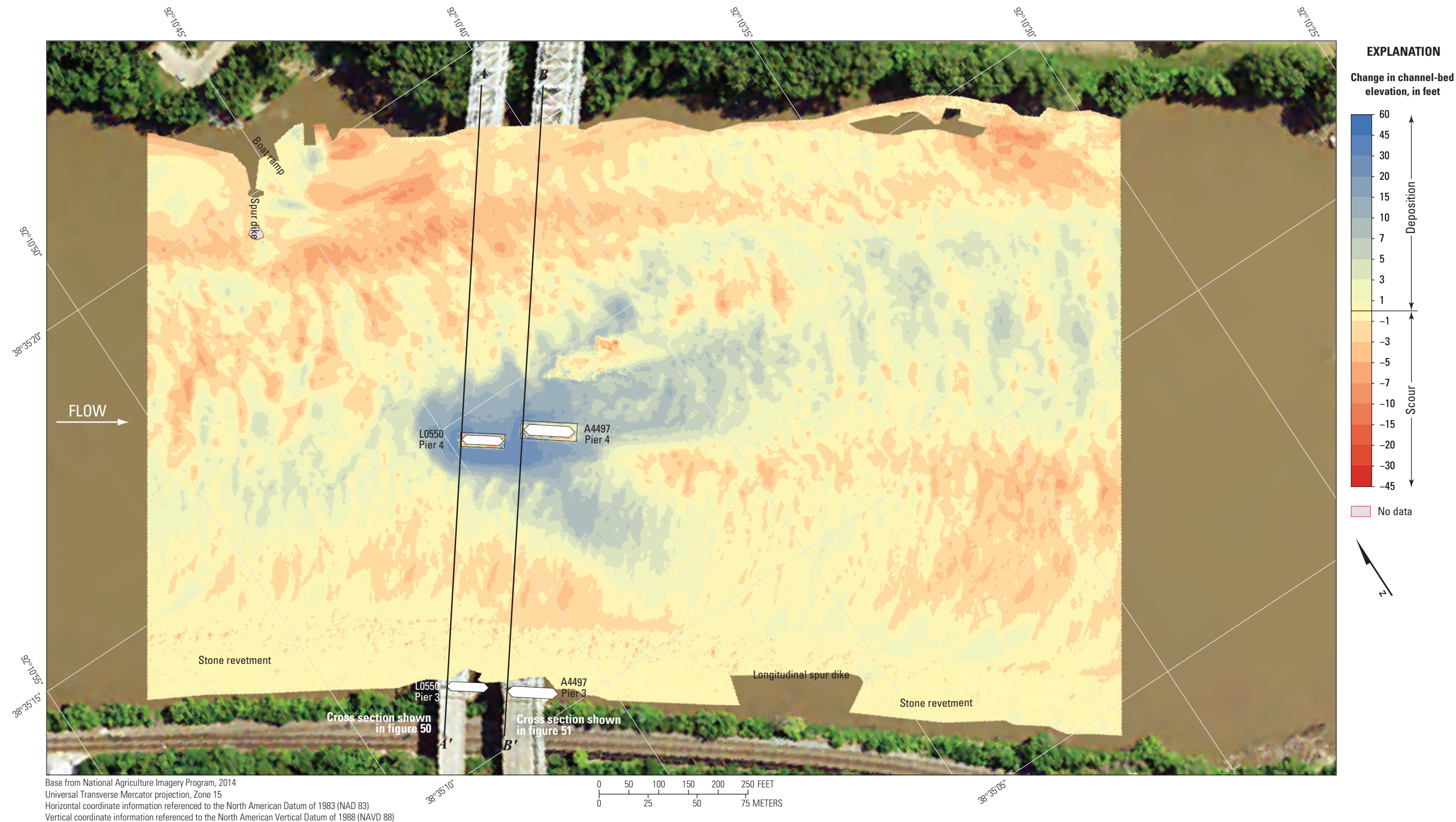
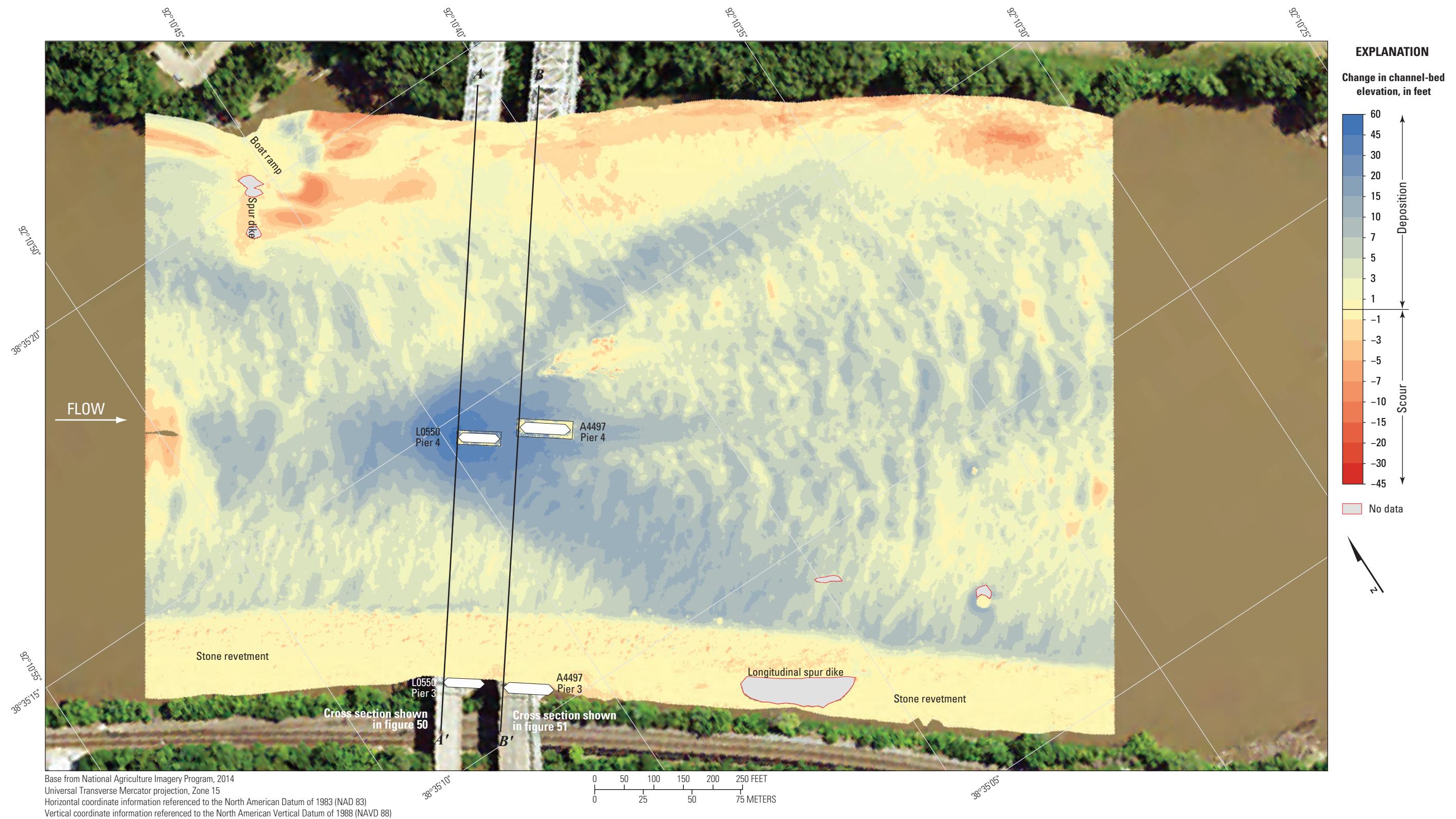


Figure 55. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 31, 2017, and April 30, 2013.



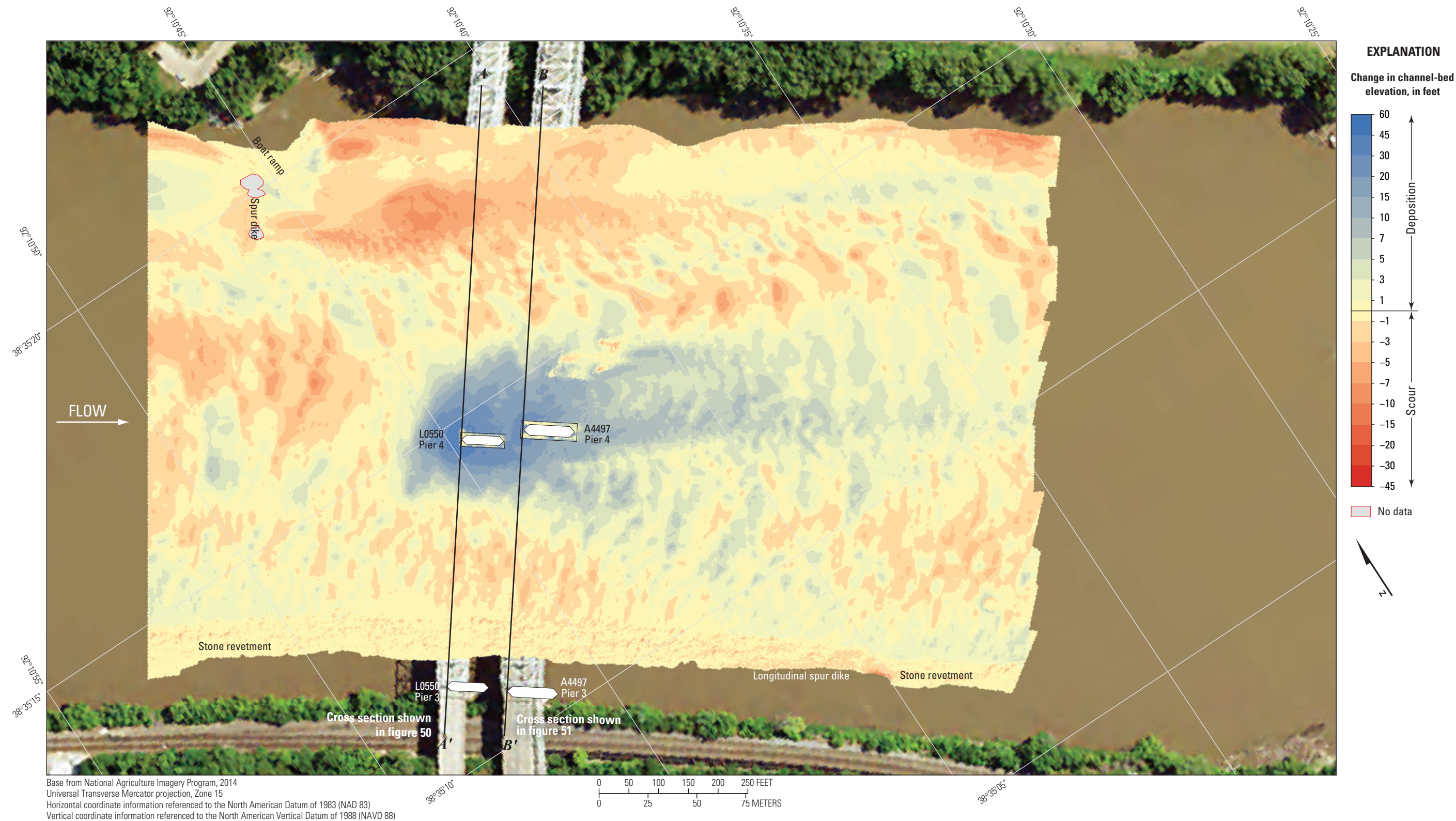


Figure 57. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 31, 2017, and March 1, 2011.

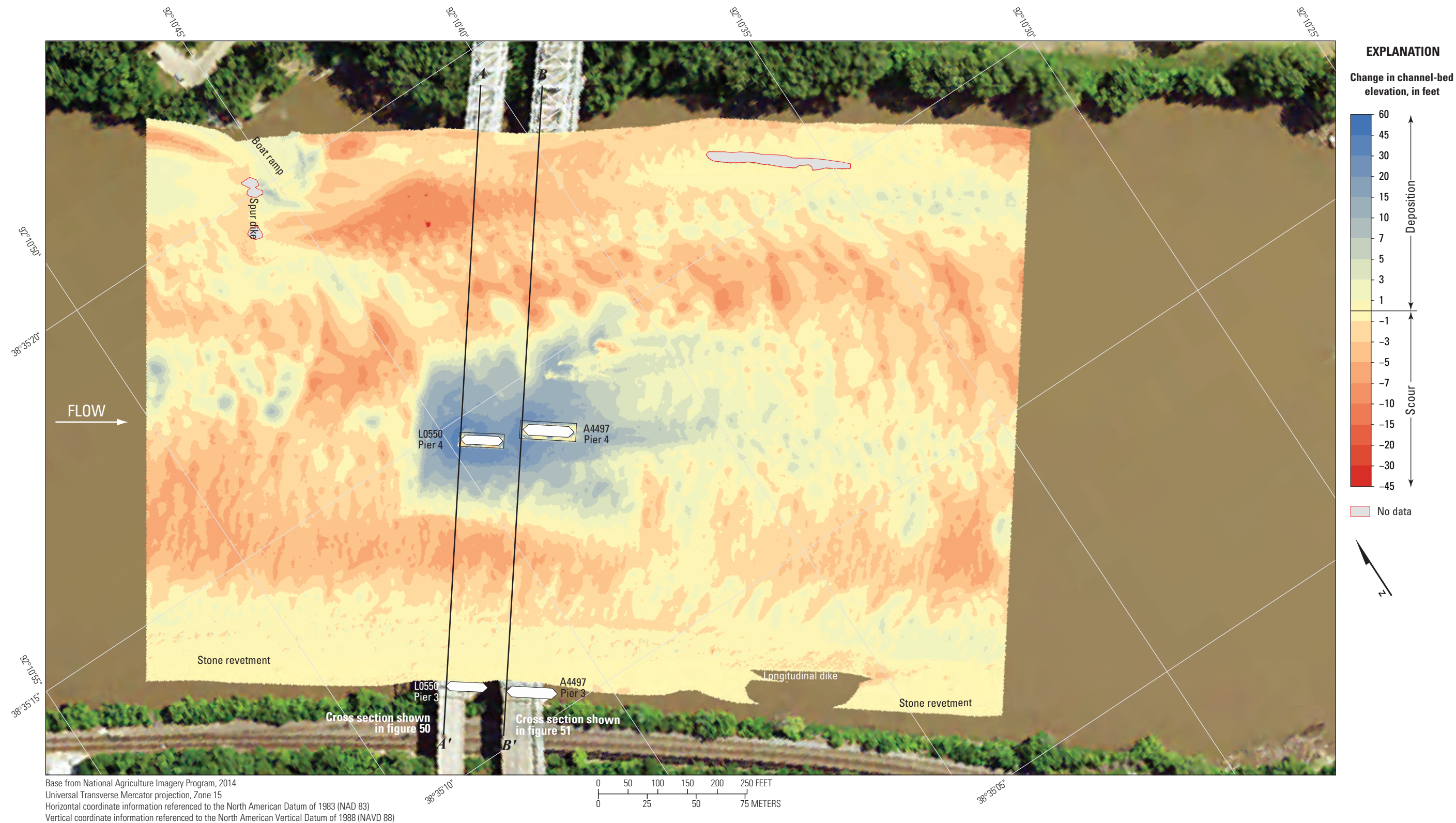


Figure 58. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 31, 2017, and January 26, 2010.

Structure A6288 on Missouri State Highway 19 at Hermann, Missouri

Structure A6288 (site 21) on Missouri State Highway 19 crosses the Missouri River at RM 97.9 at Hermann, Mo., east of Jefferson City and west of St. Louis, Mo. (fig. 1). The site was surveyed on May 31, 2017, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 501.1 ft (table 5). Streamflow on the Missouri River was about 192,000 ft³/s during the survey (table 5).

The survey area was about 1,840 ft long and about 1,450 ft wide, generally extending from bank to bank in the main channel (fig. 59). The upstream end of the survey area was about 690 ft upstream from the centerline of structure A6288 at pier 5 (fig. 59), and piers 4 through 6 were in the water; pier 3 was on the edge of water at the right (south) bank. The channel-bed elevations ranged from about 464 to 487 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 5, fig. 60), except inside the upstream left (north) longitudinal spur dike where a local minimum channel-bed elevation of 444 ft was observed (fig. 59; table 5). A poorly defined thalweg was present along the toe of the left longitudinal spur dikes that deepened as one progressed downstream, and numerous small to medium dunes and ripples were present throughout the channel (fig. 59).

Minor scour holes were observed near both of the piers in the main channel, and near pier 6 behind the longitudinal spur dike on the left (north) side (fig. 59). The minor scour hole near pier 6 had a minimum channel-bed elevation of about 465 ft (table 6), which is about 23 ft above the elevation of the bottom of the pier seal course of 442.00 ft (fig. 61; table 6). The minor scour hole near pier 5 had a minimum channel-bed elevation of about 465 ft (table 6), which is about 21 ft above

the elevation of the bottom of the pier seal course of 444.50 ft (fig. 61; table 6). The minor scour hole near pier 4 had a minimum channel-bed elevation of about 463 ft (table 6), which is about 12 ft above the elevation of the bottom of the pier seal course of 451.50 ft (fig. 61; table 6). Both scour holes near main channel piers 4 and 5 were difficult to discern from nearby dunes and ripples, but the upstream edges of the footing of pier 4 were visible during the survey (figs. 59, 61). Information from bridge plans indicates that piers 4, 5, and 6 are founded on shafts drilled as much as 27 ft into bedrock, having about 64 ft of bed material between the bottom of the scour hole and bedrock at pier 6, about 51 ft of material at pier 5, and about 20 ft of material at pier 4 (fig. 61; table 6). The surveyed bed in 2017 generally was similar to both previous multibeam surveys in 2011 and 2013, which in turn, were similar to the original ground line in 2001 from bridge plans, except between pier 4 and the right (south) bank and to the left of the spur dike on the left (north) side (fig. 61).

The difference between the survey on May 31, 2017, and the previous nonflood survey on May 2, 2013 (fig. 62), indicates minor to moderate scour has occurred throughout the reach between 2013 and 2017, with an average difference between the May 2013 and May 2017 bathymetric surfaces of -1.95 ft (table 7). The net volume of cut in the reach from 2013 to 2017 was about 176,900 yd³, and the net volume of fill was about 23,000 yd³, resulting in a net loss of about 153,900 yd³ of sediment between 2013 and 2017. Minor to moderate scour of as much as 10 ft throughout most of the reach is partially balanced with deposition in the area downstream from the spur dike on the left (north) bank and across the upstream center of the reach (fig. 62). The frequency distributions and cumulative percentage curves were remarkably similar in shape between the various surveys at this site (fig. 60), with a slightly higher percentage of survey-grid cells at a slightly lower elevation than in 2011.

Structure A6288 on Missouri State Highway 19



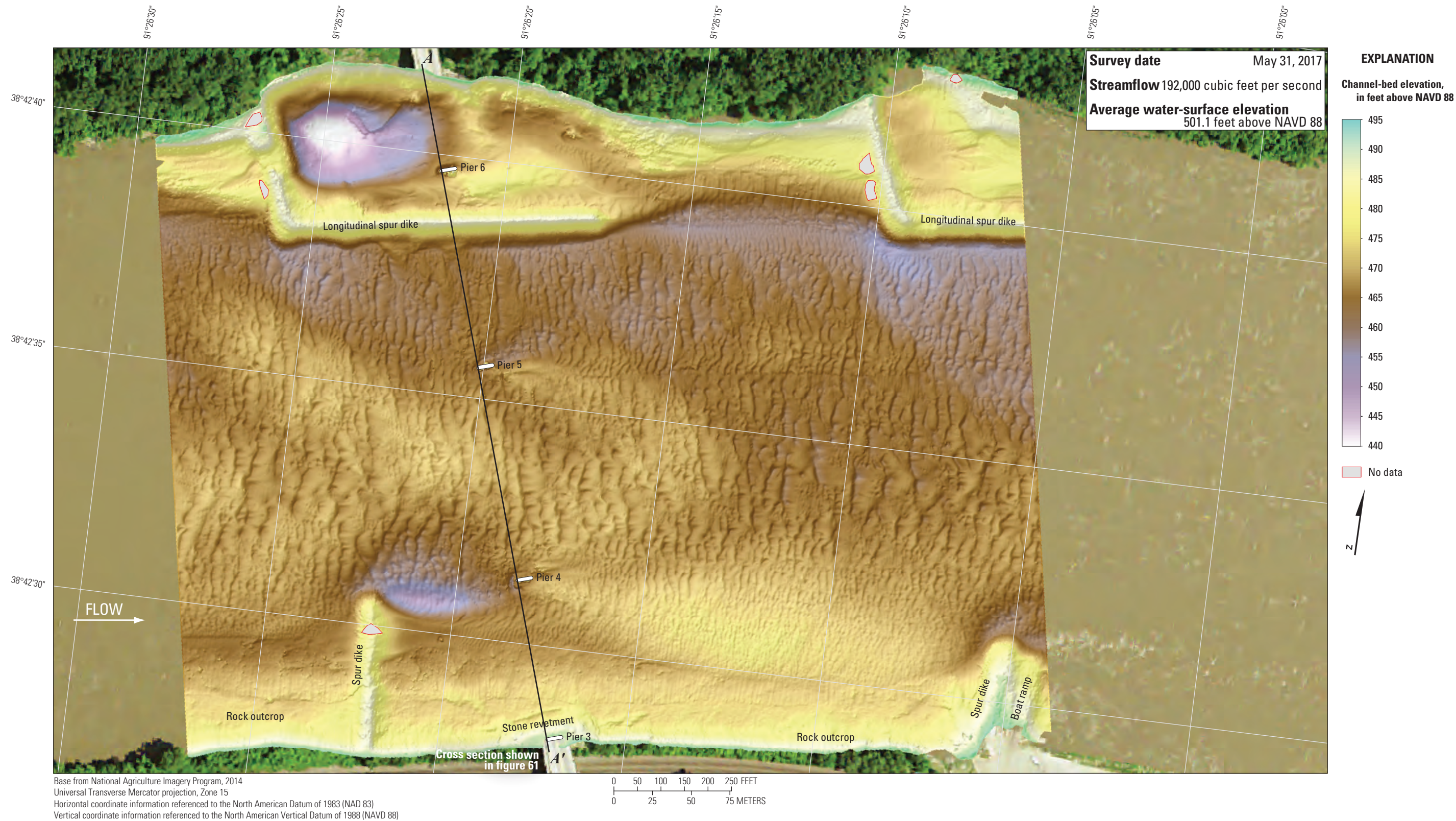


Figure 59. Bathymetric survey of the Missouri River channel near structure A6288 on Missouri State Highway 19 at Hermann, Missouri.

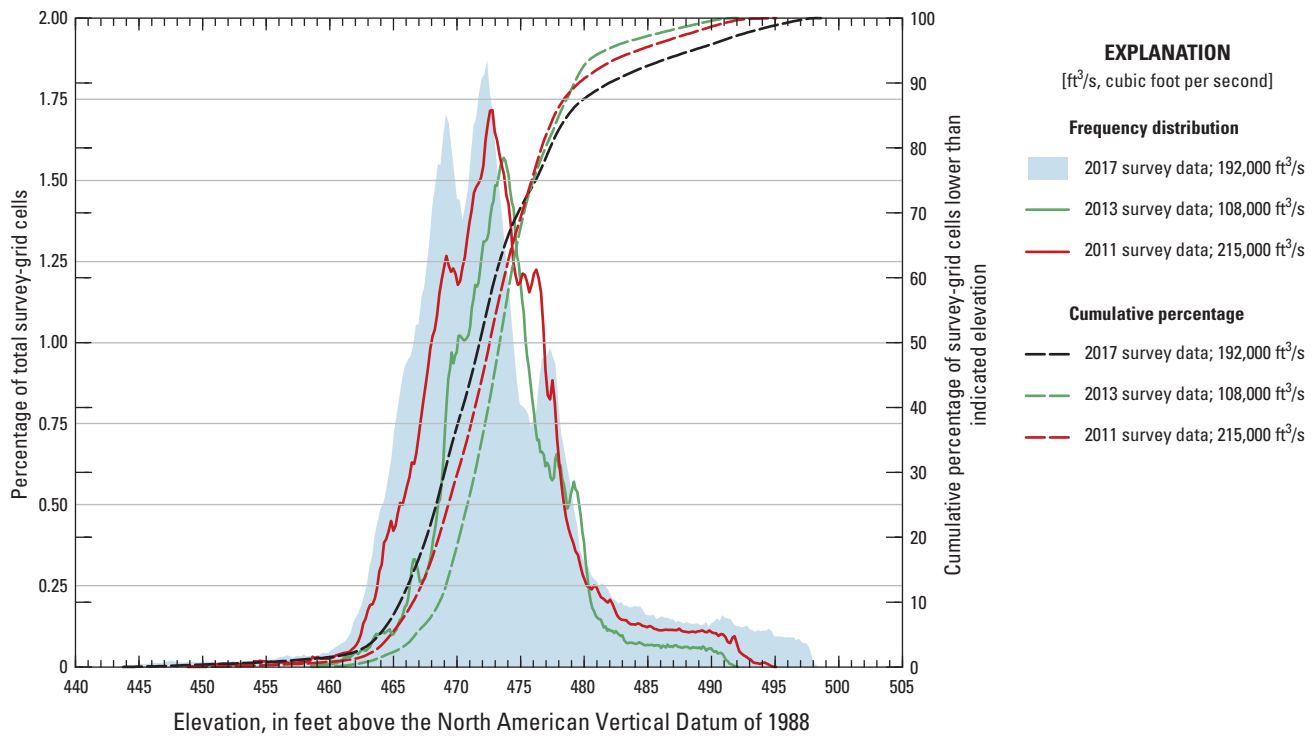


Figure 60. Frequency distribution of bed elevations for bathymetric survey-grid cells on the Missouri River near structure A6288 on Missouri State Highway 19 at Hermann, Missouri, on May 31, 2017, compared to previous surveys.

The difference between the survey on May 31, 2017, and the previous flood survey on July 28, 2011 (fig. 63), indicates an approximate balance between scour and deposition throughout the reach between 2011 and 2017, with a tendency towards minor scour (the average difference between the July 2011 and May 2017 bathymetric surfaces was -0.73 ft; table 7). The net volume of cut in the reach from 2011 to 2017 was about 133,200 yd³, and the net volume of fill was about 66,700 yd³, resulting in a net loss of about 66,500 yd³ of sediment between 2011 and 2017. Moderate scour of as much as 15 ft in the center part of the channel, and moderate to major scour of as much as 20 ft inside the longitudinal spur dike on the left (north) side near the bridge

is balanced with localized deposition of as much as 30 ft in other areas of the channel (fig. 63). Large dune features present in the middle of the channel in the 2011 survey were replaced with medium to small dunes, resulting in an alternating scour/deposition pattern in that area (fig. 63).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 1 to 8 ft/s (fig. 64). Exceptions to uniform flow include moderate turbulence and flow reversal downstream from the upstream right spur dike and the longitudinal dikes on the left bank (fig. 64). The bridge piers were skewed to flow but caused only minor turbulence downstream (fig. 64).

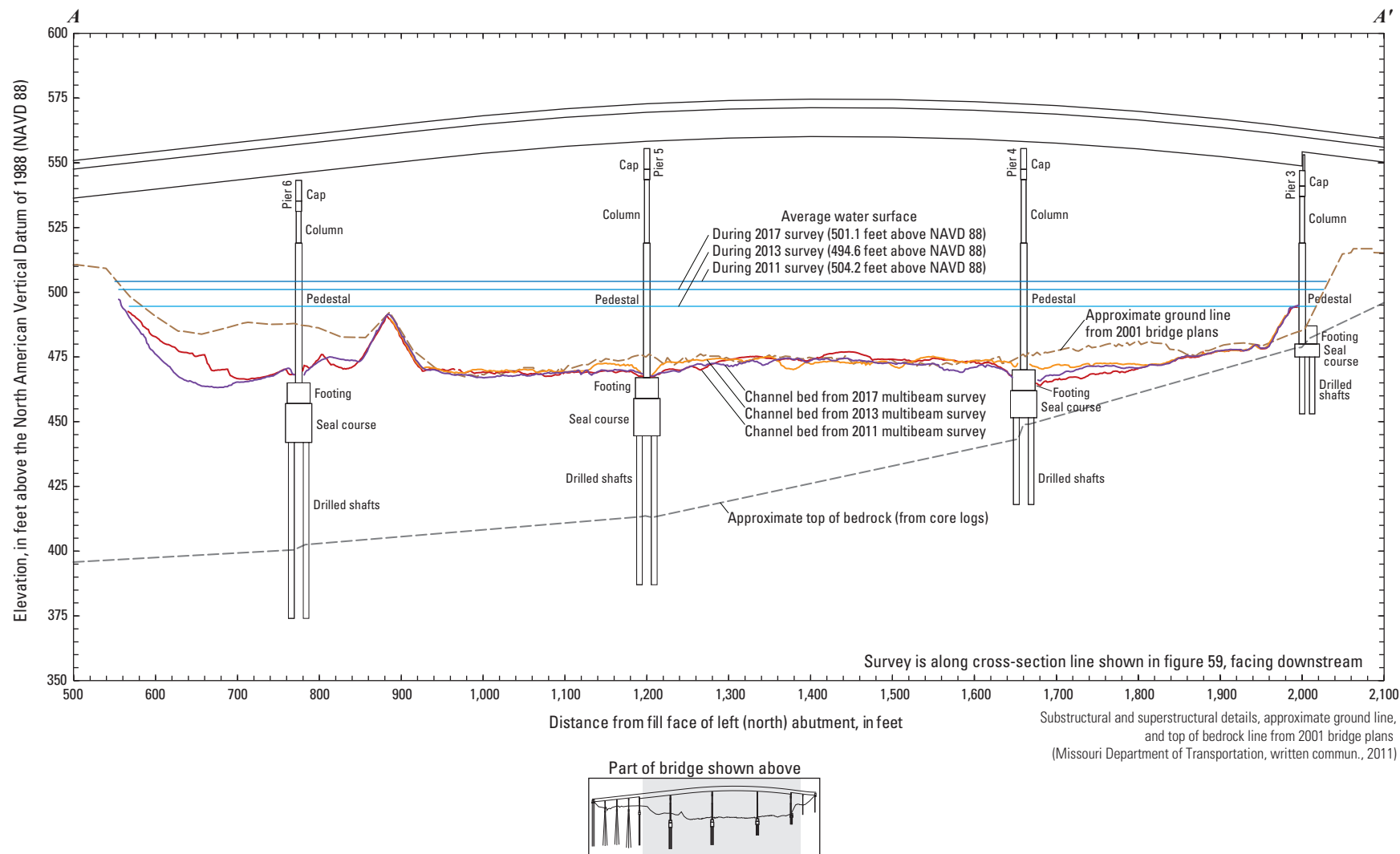


Figure 61. Key features, substructural and superstructural details, and surveyed channel bed of structure A6288 on Missouri State Highway 19 crossing the Missouri River at Hermann, Missouri.

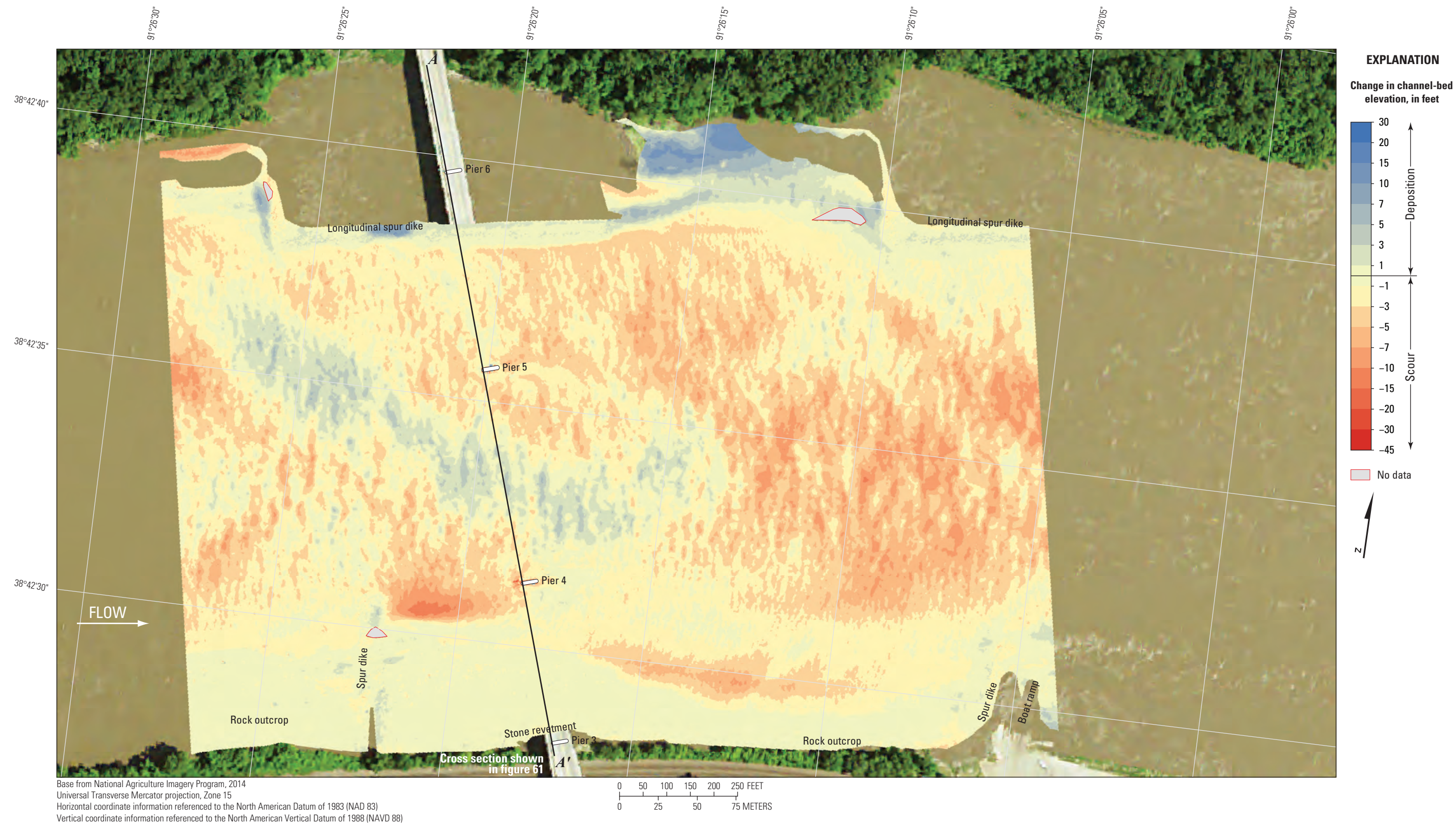


Figure 62. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A6288 on Missouri State Highway 19 at Hermann, Missouri, on May 31, 2017, and May 2, 2013.

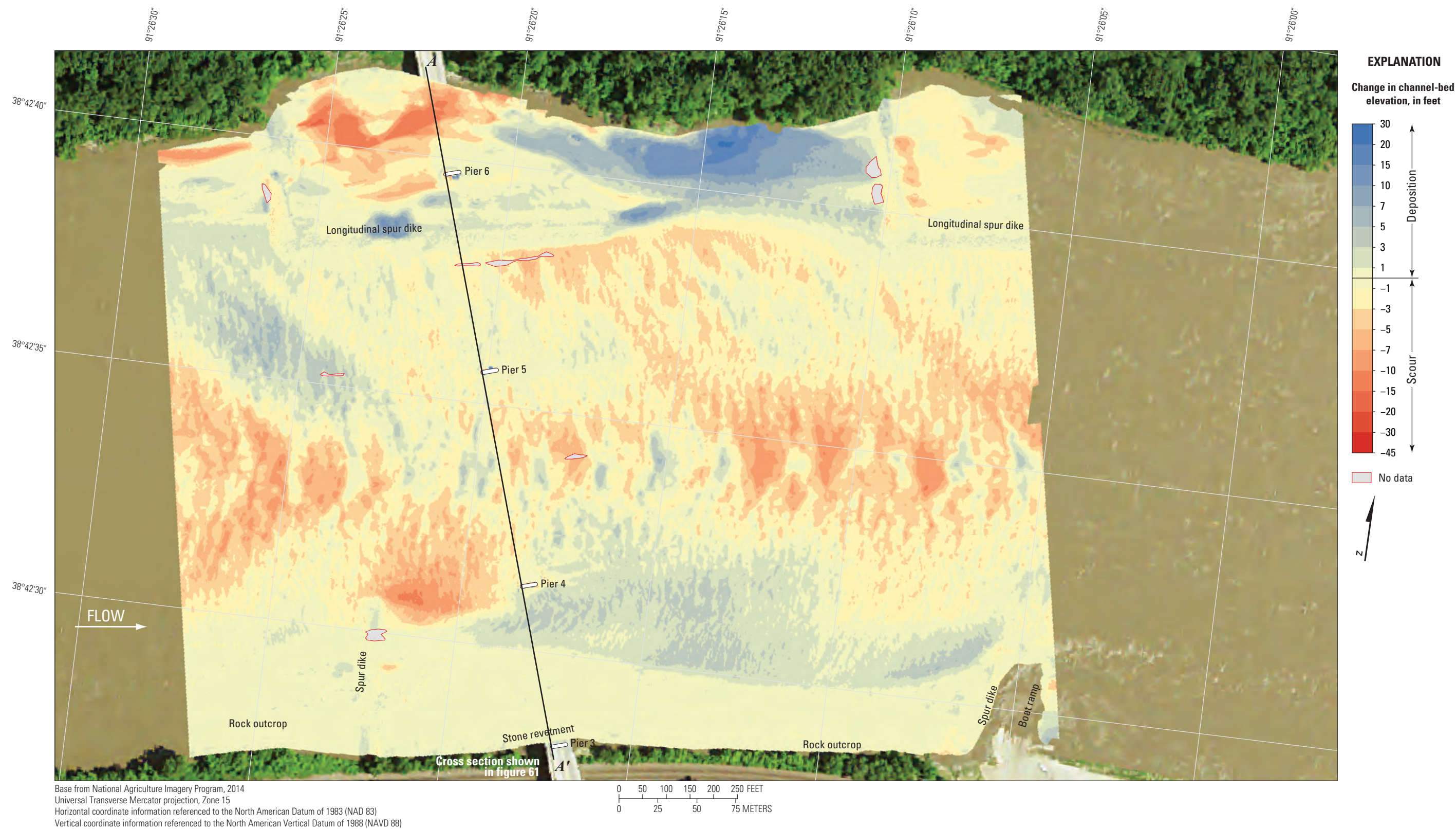


Figure 63. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A6288 on Missouri State Highway 19 at Hermann, Missouri, on May 31, 2017, and July 28, 2011.

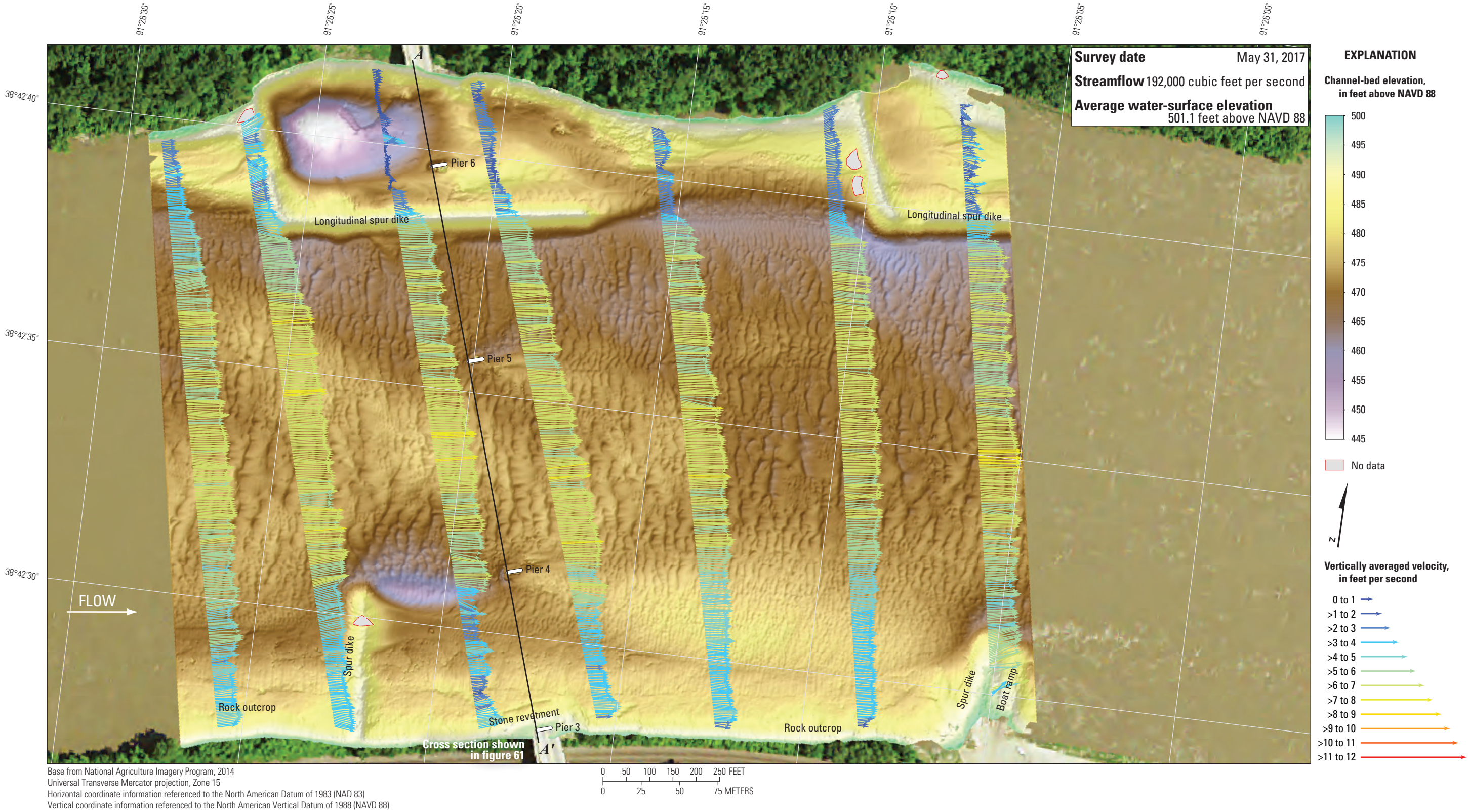


Figure 64. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A6288 on Missouri State Highway 19 at Hermann, Missouri.

General Findings and Implications

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

Effects of Moderate Flooding Compared to Previous Surveys

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

Because of the myriad number and interactions of factors affecting sediment transport conditions and the resultant bed configuration, it is simplistic to assume that the configuration and size of bed forms observed during the current (2017) surveys between Kansas City and St. Louis (fig. 1) are dependent only upon the instantaneous streamflow at a given site. Although it is beyond the scope of the current (2017) study to examine all the antecedent conditions that created the observed channel-bed configuration, the following discussion attempts to draw conclusions based on the conditions observed at each site during the current (2017) and previous surveys.

A comparison of the dune sizes at the various sites is indicative of the slightly different flow regimes between 2011 and 2017 at the surveyed sites. Several of the surveys in 2011 had large to very large dune features, whereas the 2017 surveys were filled throughout with mostly medium to large dune features and ripples. However, in both sets of surveys (2011 and 2017), the largest dune features were observed at the upstream-most sites (figs. 6, 12, 18, 24, 30), and they diminished as one progressed downstream (figs. 36, 42, 48, 59). In 2017, the streamflow generally was decreasing from an earlier crest as one progressed downstream (fig. 2), and a similar kind of flow condition existed in 2011 (see fig. 2 in Huizinga, 2012). Nonetheless, streamflows in 2011 were higher than in 2017 (table 7), and the smaller size and amplitude of the dune features in 2017 compared to 2011 indicate less bed-material and bedload transport because of the lower streamflows (Simons and others, 1965). Dune sizes at the surveyed sites in 2013 were predominantly small to medium dunes and ripples,

indicative of the substantially lower flow regime in 2013 (table 7).

Streamflows at the sites during the 2017 surveys ranged from about 1.8 to 3.9 times greater than the 2013 streamflows, and water-surface elevations were 6.5 to 12.4 ft higher in 2017 than in 2013 (table 7). The average difference between the bathymetric surfaces varied from 1.9 ft lower to 1.0 ft higher in 2017 than 2013 and is generally negative, indicating scour (table 7). Alternatively, streamflows at the Missouri River sites during the 2017 surveys ranged from about 60 to 90 percent of the 2011 streamflows, with water-surface elevations about 3 to 8 ft lower in 2017 than in 2011 (table 7), and the average difference between the bathymetric surfaces varied from about 0.7 ft lower to about 3.9 ft higher in 2017 than 2011, tending towards positive values, which indicates deposition (table 7). Some of the smaller average differences between surveys might be considered equivocal, based on the uncertainty associated with points as indicated by the TPU values recorded for the surveys (table 4). Nevertheless, these patterns are generally in keeping with what might be expected for scour and deposition based purely on streamflow. However, when the average channel-bed elevation is examined looking downstream with time (fig. 65), there generally seems to be only small variation in the average channel-bed elevations at a given site, and the average channel-bed elevation of the 2017 surveys was higher than the two previous surveys at all but structure A6288 (site 21; fig. 65; see also table 2 in the 2013 survey report [Huizinga, 2014] and table 5 in the 2011 flood survey report [Huizinga, 2012]). The average channel-bed elevation is affected by the area of the channel that was surveyed; therefore, the 2013 average channel-bed elevations may have been skewed low because less area could be surveyed at several sites during those lower flow conditions. Nonetheless, this configuration of average channel-bed elevations and average differences indicates that greater streamflow alone does not necessarily result in more scour at a site (as might be evidenced by lower average channel-bed elevations with increased streamflow).

The average channel-bed elevation at structure A4574 (site 18) was remarkably similar in all three surveys (0.5-ft overall variation in all three surveys) and higher than what might be implied by a trendline along the reach between Kansas City and St. Louis (fig. 65). This lack of variability may indicate this site is at or near a local feature that controls sediment deposition and scour. The Missouri River flood plain is somewhat narrower downstream, and the transition in physiographic province from the Central Lowlands to the Ozark Plateau occurs near this area (Missouri Department of Natural Resources, 2002).

For the earliest surveys at structures L0550/A4997 (site 20), the streamflows were both greater than the 2017 streamflow (by 24 and 16 percent, respectively; table 7), and the water-surface elevation was about 3 ft higher in both surveys (table 7). However, the average difference between the bathymetric surfaces was about 0.6 ft lower and 0.8 ft higher in 2017 than in 2010 and March 2011, respectively (table 7).

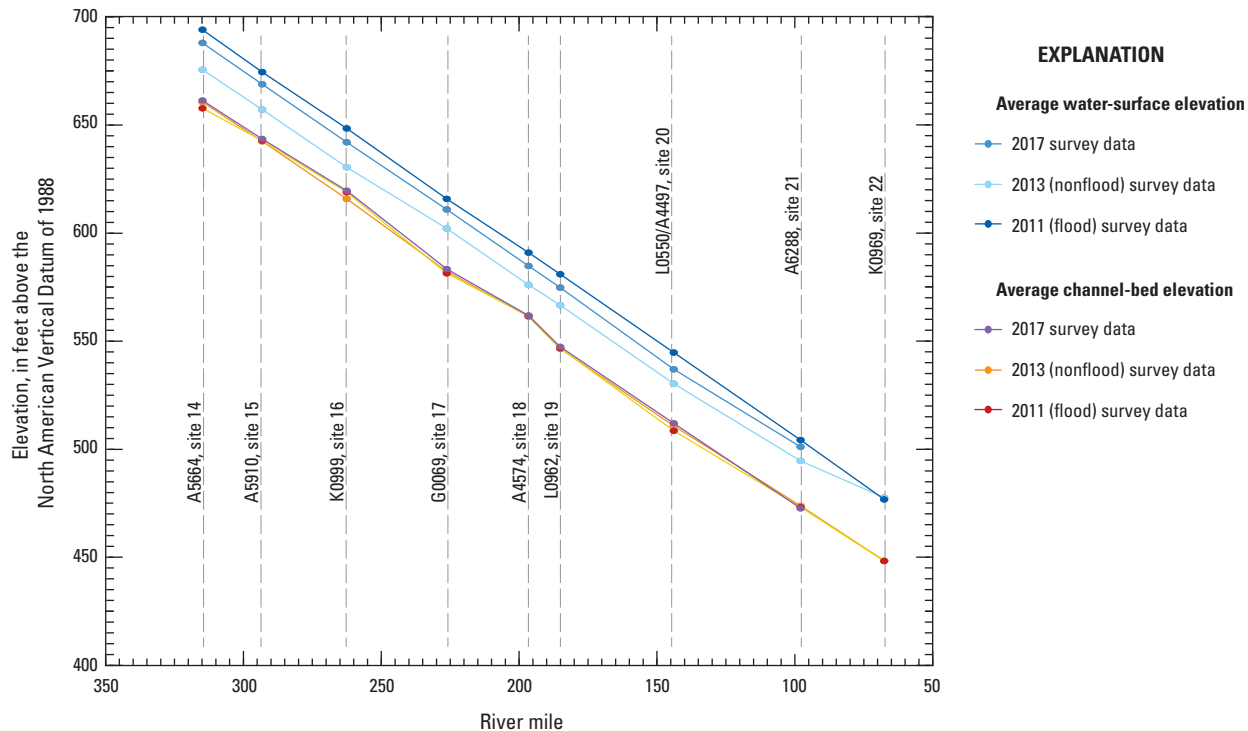


Figure 65. Average channel-bed and water-surface elevations near bridges on the Missouri River between Kansas City and St. Louis, Missouri, from surveys in 2011, 2013, and 2017.

Most of the surveys at this site had a positive average difference, likely affected by the placement of the scour countermeasures around pier 4 of both structures. However, the negative average difference between the surfaces from 2010 to 2017 may have been the result of the timing of the first survey in January 2010. Although the streamflow was higher in 2010 than 2017, colder water temperatures during the winter months and generally lower streamflows before the 2010 survey might have allowed sediment to deposit in the reach just before the 2010 survey. On the other hand, the March 2011 survey was after a previous rise in February 2011 and sustained higher flow, which might have removed sediment until the March 2011 survey.

An examination of the frequency distributions of bed elevations in the 2017 surveys compared to the previous surveys reveals additional differences (fig. 66). The frequency distributions generally were narrower in the 2013 and 2017 surveys than in the 2011 survey at each site, with a higher percentage of survey-grid cells in a particular elevation range (fig. 66.4).

The narrower distribution curves result in generally steeper cumulative percentage curves in 2013 and 2017 than in 2011 (fig. 66B). A notable exception is the 2011 cumulative percentage curve at structure A5664, site 14 (fig. 66B); however, this site was somewhat unique in all three surveys, having much higher percentages of survey-grid cells in a particular elevation range than all the other sites (fig. 66.4). Cumulative percentage curves that are steep indicate a channel bed with a narrower range of elevations (more level throughout the reach), whereas those that are less steep indicate a wider variation of elevations. Cumulative percentage curves with “steps” indicate a channel with distinct groups of elevations, such as thalweg on one side and a shallow area on the opposite side of the channel (such as structure A5910, site 15; figs. 18, 19); however, all the surveys in 2017 had steps in the cumulative percentage curves at the upper end and are the result of collecting more information higher on the banks with the tilted MBES head than was done in the prior surveys.

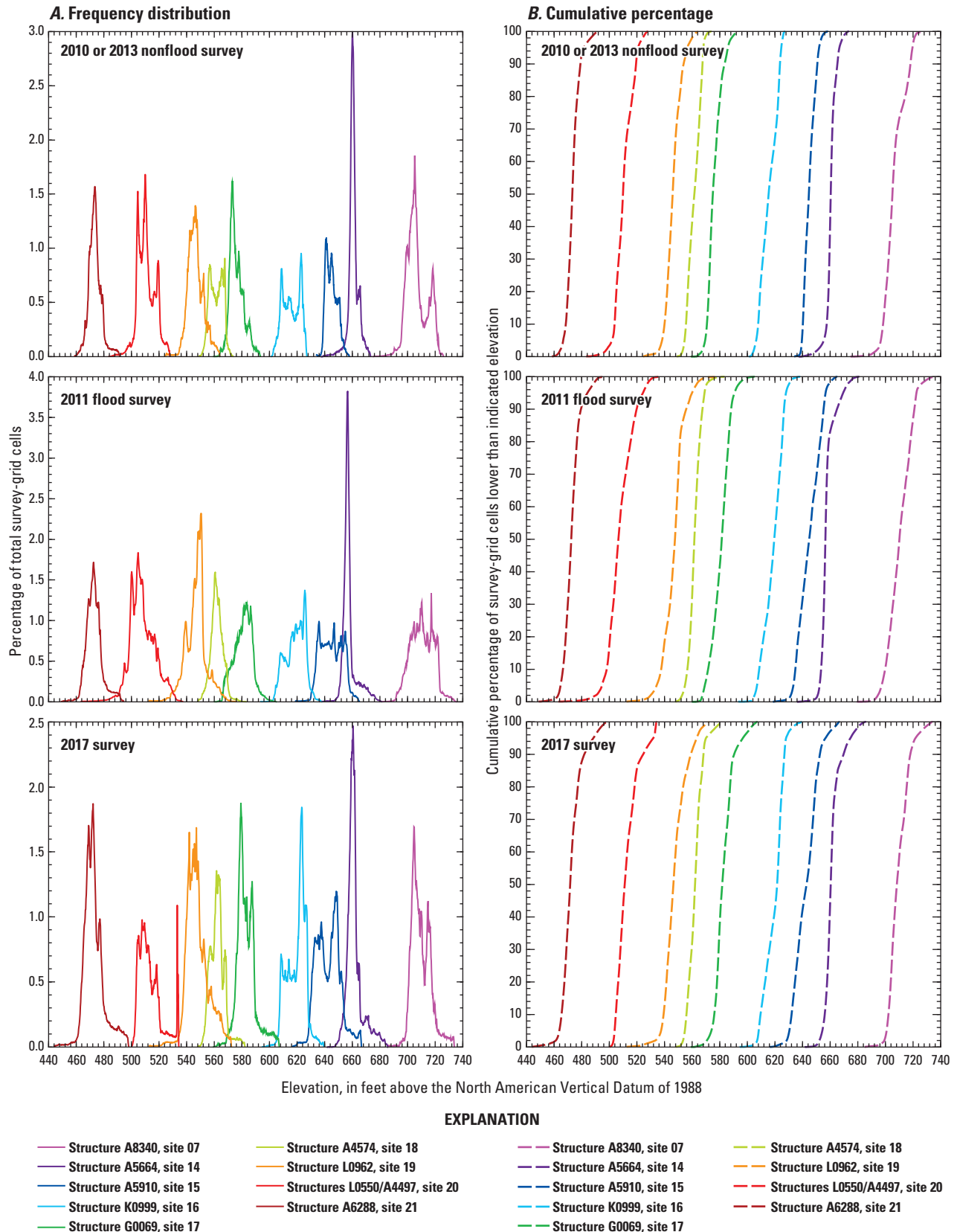


Figure 66. Comparison of frequency distribution and cumulative percentage of bed elevations for bathymetric survey-grid cells from various surveys on the Missouri River between Kansas City and St. Louis, Missouri. *A*, frequency distribution; *B*, cumulative percentage.

Size and Shape of Scour Holes

Generally, every pier in the main channel area for which bathymetry could be obtained had some sort of scour hole, except those on banks or embedded in spur dikes; however, the size and shape of these holes were different from one bridge to the next and occasionally even at the same bridge site. The factors affecting the size and shape of the pier scour holes have been discussed in previous survey reports (Huizinga, 2012, 2014, 2015, 2016, 2017a), and the frontal slope of the various scour holes has been determined in several of the previous reports. Frontal slopes were not computed for the sites in this (2017) study; however, the factors that affect the local pier scour equation in Richardson and Davis (2001), 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, are discussed in this section.

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, which is consistent with previous surveys. 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, 17, 23, 30, 35, 47, and 64). 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 was 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. 9, 17, 29, and 35) in the absence of a spur dike or rock outcrop that might limit local scour (pier 15 in fig. 47). Similar findings have been observed during the various studies using the MBMS in Missouri (Huizinga, 2010, 2011, 2012, 2014, 2015, 2016, 2017a).

Also consistent with the local pier scour equation in Richardson and Davis (2001), piers having wide or blunt noses resulted in larger, deeper scour holes than those having narrow, round, or sharp noses. In fact, narrow piers having round or sharp noses that were aligned with flow often had scour holes that were difficult to discern from nearby small dunes and ripples (figs. 12, 18, and 36), whereas the scour hole generally was substantial near piers having blunt noses (figs. 24 and 30) and those that were rounded but wide relative to their length (fig. 27). When the channel bed immediately upstream from a pier was above the top of a footing, the scour holes near that pier occasionally did not penetrate below the top of the footing (pier 11, figs. 18, 20; pier 5, figs. 59, 61); the footing was an effective scour limiter at these piers. However, if the upstream edge of the top of the footing was exposed, the substantial extra width of the footing tended to widen the scour hole (pier 21, figs. 12, 14; pier 7, figs. 36, 38; pier 4, figs. 59, 61). Similar findings have been observed during the various studies using the MBMS in Missouri (Huizinga, 2010,

2011, 2014, 2015, 2016, 2017a), particularly during the 2011 flood (Huizinga, 2012).

Several of the surveyed bridges had piers that were skewed to approach flow, resulting in asymmetric scour holes at those bridges: pier 14 of structure L0962 on Interstate 70 near Rocheport, Mo. (fig. 42), and pier 5 of structure A6288 on Missouri State Highway 19 at Hermann, Mo. (fig. 59). 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.

Bed material deposited on previously exposed bedrock around pier 2 of structure G0069 (site 17) resulted in a scour hole near that pier and the upstream railroad bridge (fig. 30); however, that scour was limited by the bedrock present around those piers (note the area of no scour/deposition in a horseshoe shape around the piers in figures 33 and 34). Additional bed armoring on either side of the railroad bridge upstream from pier 3 also limited scour/deposition there (figs. 33, 34).

The riprap blanket installed around pier 4 of structures L0550/A4497 (site 20) as a scour countermeasure has effectively mitigated the scour hole typically observed at these piers in previous surveys (figs. 54A, 55–58). The apparent settling around the edges of the blanket since it was installed in 2015 (fig. 54B) warrants monitoring in future surveys for any further settling, but this likely will not adversely affect the scour mitigating effect of the countermeasure.

Summary and Conclusions

Bathymetric and velocimetric data were collected on the Missouri River near 10 highway bridges at 9 crossings between Kansas City and St. Louis, Missouri, by the U.S. Geological Survey in cooperation with the Missouri Department of Transportation from May 22 to 31, 2017. A multibeam echosounder mapping system was used to obtain channel-bed elevations for areas ranging from 1,550 to 1,840 feet (ft) longitudinally and generally extending across the active channel from bank to bank in the Missouri River during moderate flood flow conditions. These surveys document the channel-bed conditions and velocity distribution at the time of the surveys and provide characteristics of scour holes that may be useful in the development of predictive guidelines or equations for scour holes. These data also may be used by the Missouri Department of Transportation as a moderate flow comparison to help assess the bridges for stability and integrity issues with respect to bridge scour during floods.

The estimated total propagated uncertainty for the bathymetric surface of each survey area was computed as an estimate of the accuracy to be expected for each point with all relevant error sources taken into account. An analysis of the surveys indicated that more than 97 percent of the bathymetric data at all the sites have a total propagated uncertainty of less than 0.50 ft, and more than three-quarters (80 percent or more)

of the channel-bed elevations at the sites have a total propagated uncertainty of 0.25 ft or less.

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

Bathymetric data were collected around every pier that was in water, except those at the edge of water, and scour holes were observed at most surveyed piers. Scour holes were present at most piers for which bathymetry could be obtained, except at piers on channel banks, those near or embedded in lateral or longitudinal spur dikes, and those on exposed bedrock outcrops. Occasionally, the scour hole near a pier was difficult to discern from nearby bed features. The observed scour holes at the surveyed bridges were generally examined with respect to shape and depth.

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 4 and 5 at structure K0999 on Missouri State Highway 41 at Miami, Mo.; piers 2 and 3 at structure G0069 on Missouri State Highway 240 at Glasgow, Mo.; and pier 5 at structure A4574 on Missouri State Highway 5 at Boonville, Mo. At these structures, the bed-material thickness between the bottom of the scour hole and bedrock was less than 6 ft. 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.

Streamflow at the sites during the 2017 surveys was 1.8 to 3.9 times greater than the 2013 streamflows, and water-surface elevations were 6.5 to 12.4 ft higher in 2017 than in 2013. Alternatively, streamflows at the Missouri River sites during the 2017 surveys ranged from about 60 to 90 percent of the 2011 streamflows, with water-surface elevations about 3 to 8 ft lower in 2017 than in 2011. The average difference between the bathymetric surfaces varied from 1.9 ft lower to 1.0 ft higher in 2017 than 2013 and varied from 0.7 ft lower to 3.9 ft higher in 2017 than 2011. The average channel-bed elevation indicates only small variation with time at the surveyed sites, and generally, the average channel-bed elevation of the 2017 surveys fell between the two previous surveys, as might be expected given the streamflow ratios of the 2017 surveys compared to the previous surveys. However, the average channel-bed elevation at structure A4574 (site 18) was remarkably similar in all three surveys and higher than what might be implied by a trendline along the reach between Kansas City and St. Louis, which may indicate this site is at or near a local feature that controls sediment deposition and scour.

Pier size, nose shape, and alignment to flow had a profound effect on the size of the scour hole observed for a given pier. Narrow piers having round or sharp noses that were

aligned with flow often had scour holes that were difficult to discern from nearby bed features, whereas piers having wide or blunt noses resulted in larger, deeper scour holes. Several of the structures had piers that were skewed to primary approach flow, and scour holes near these piers generally indicated deposition on the leeward side of the pier and greater scour on the side of the pier with impinging flow. A riprap blanket constructed in 2015 around pier 4 of structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Mo., effectively mitigates the scour observed near those piers in previous surveys.

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Appendix 1. Shaded Triangulated Irregular Network Images of the Channel and Side of Pier for Each Surveyed Pier

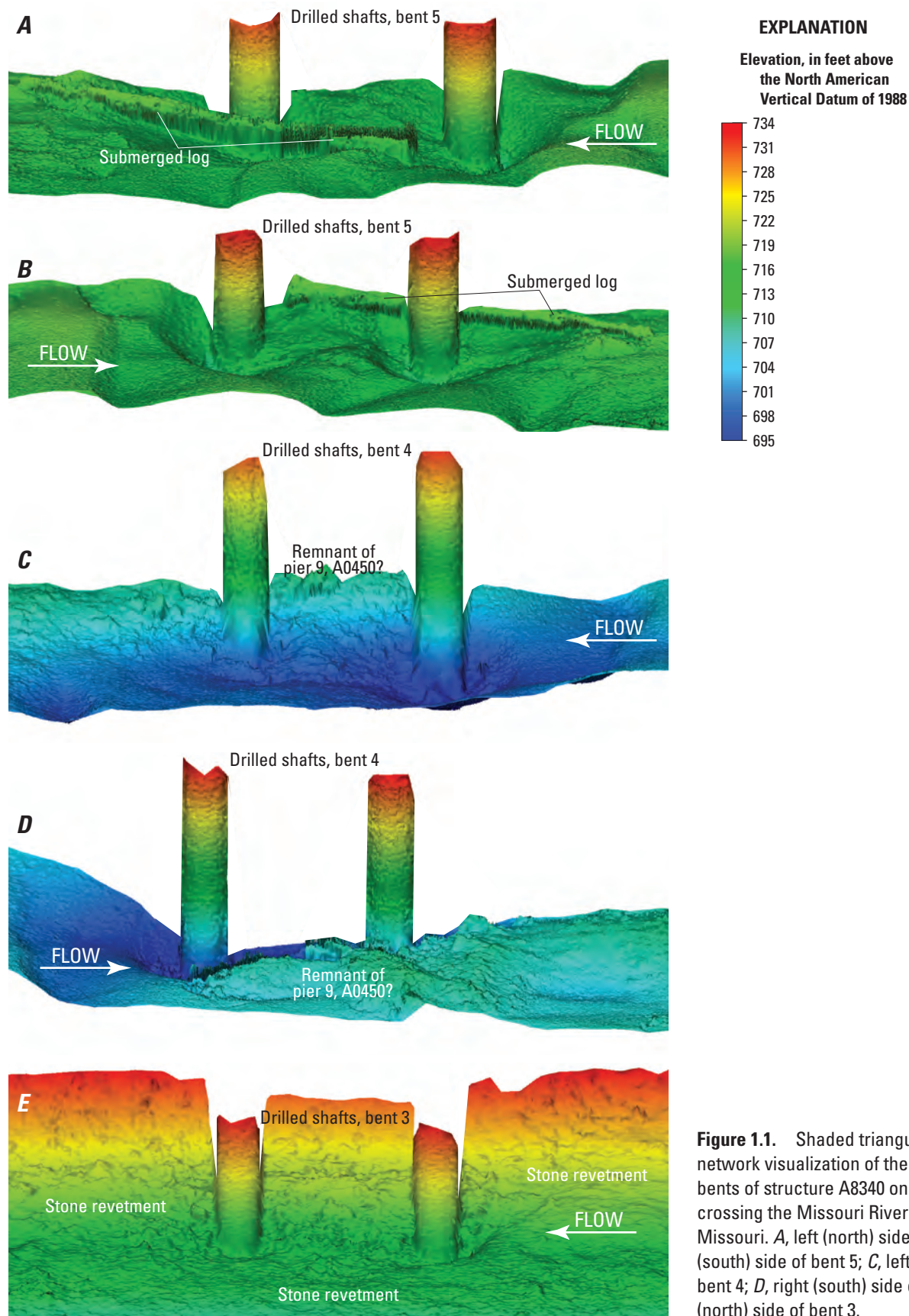


Figure 1.1. Shaded triangulated irregular network visualization of the channel bed and bents of structure A8340 on U.S. Highway 69 crossing the Missouri River in Kansas City, Missouri. *A*, left (north) side of bent 5; *B*, right (south) side of bent 5; *C*, left (north) side of bent 4; *D*, right (south) side of bent 4; *E*, left (north) side of bent 3.

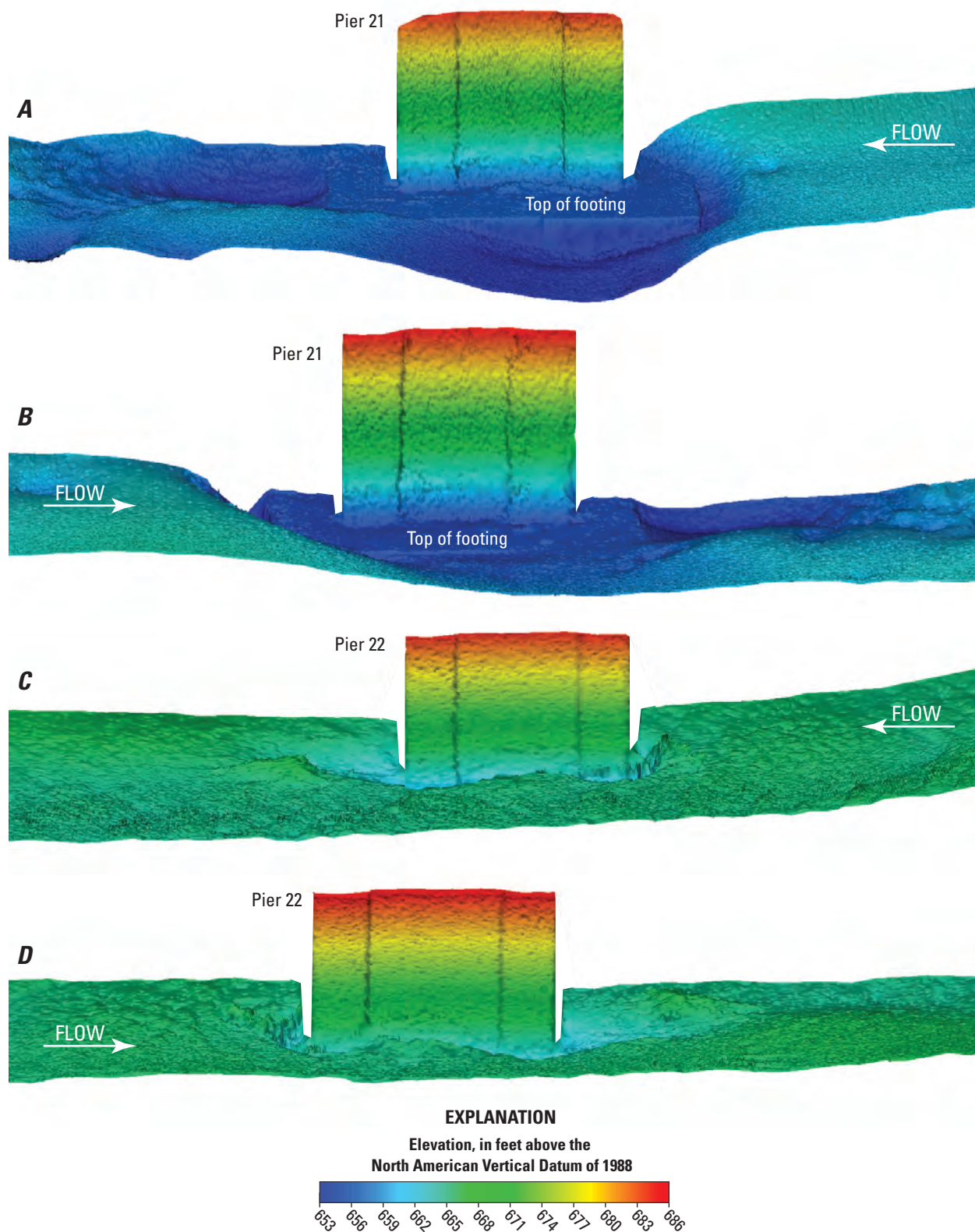


Figure 1.2. Shaded triangulated irregular network visualization of the channel bed and piers of structure A5664 on Missouri State Highway 13 crossing the Missouri River at Lexington, Missouri. *A*, left (north) side of pier 21; *B*, right (south) side of pier 21; *C*, left (north) side of pier 22; *D*, right (south) side of pier 22.

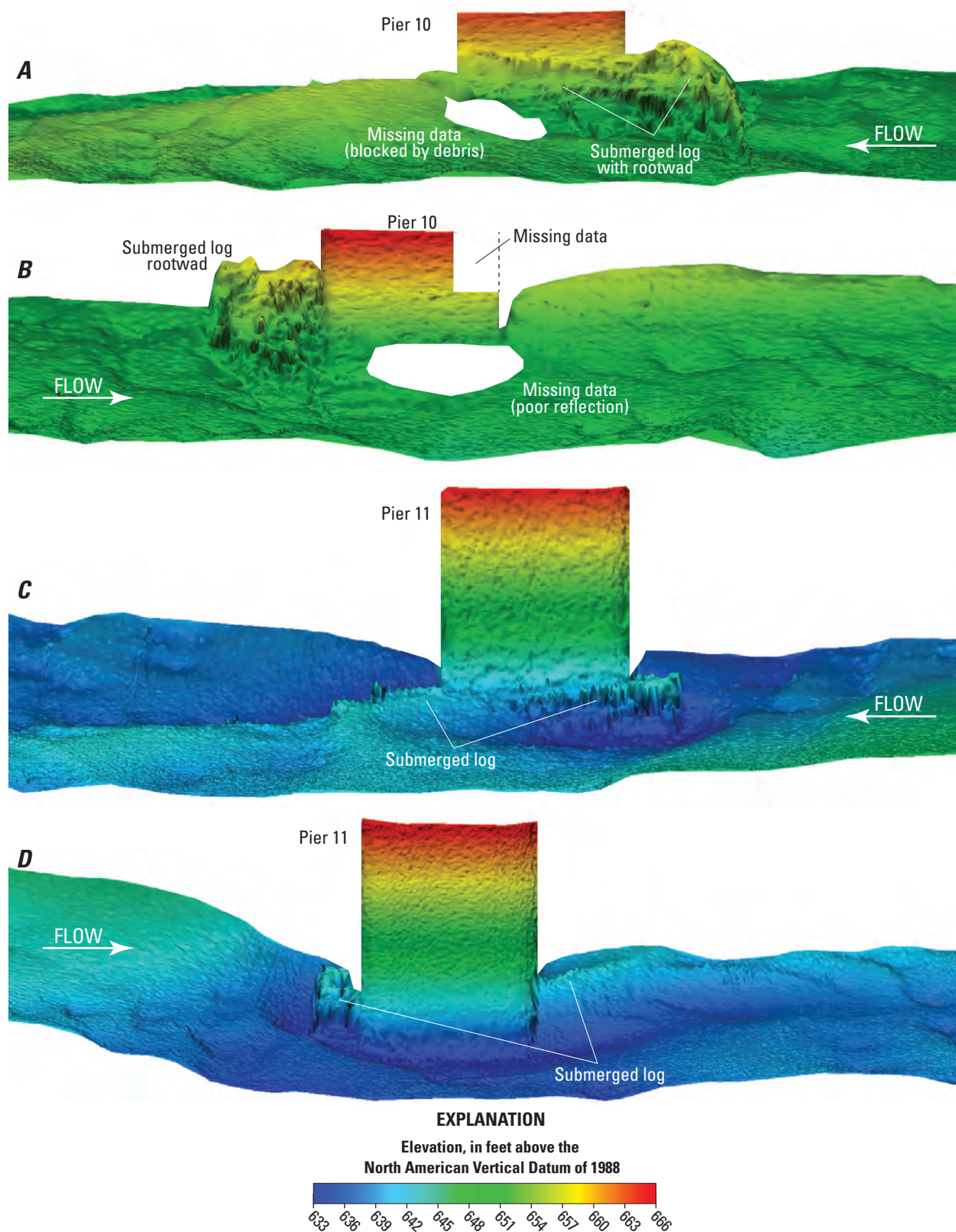


Figure 1.3. Shaded triangulated irregular network visualization of the channel bed and piers of structures A5910 on U.S. Highway 24 crossing the Missouri River at Waverly, Missouri. *A*, left (north) side of pier 10; *B*, right (south) side of pier 10; *C*, left (north) side of pier 11; *D*, right (south) side of pier 11.

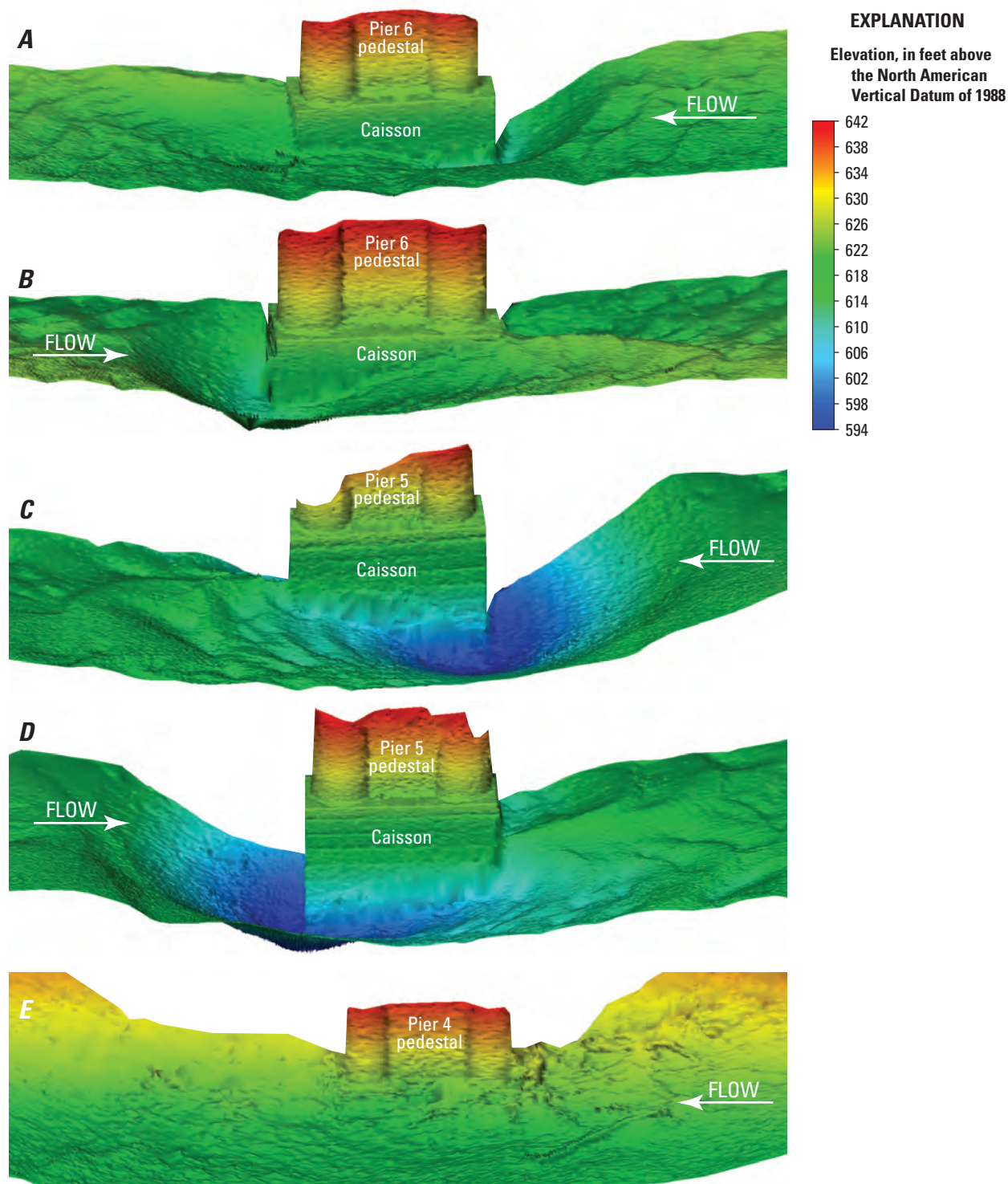


Figure 1.4. Shaded triangulated irregular network visualization of the channel bed and piers of structure K0999 on Missouri State Highway 41 crossing the Missouri River at Miami, Missouri. *A*, left (north) side of pier 6; *B*, right (south) side of pier 6; *C*, left (north) side of pier 5; *D*, right (south) side of pier 5; *E*, left (north) side of pier 4.

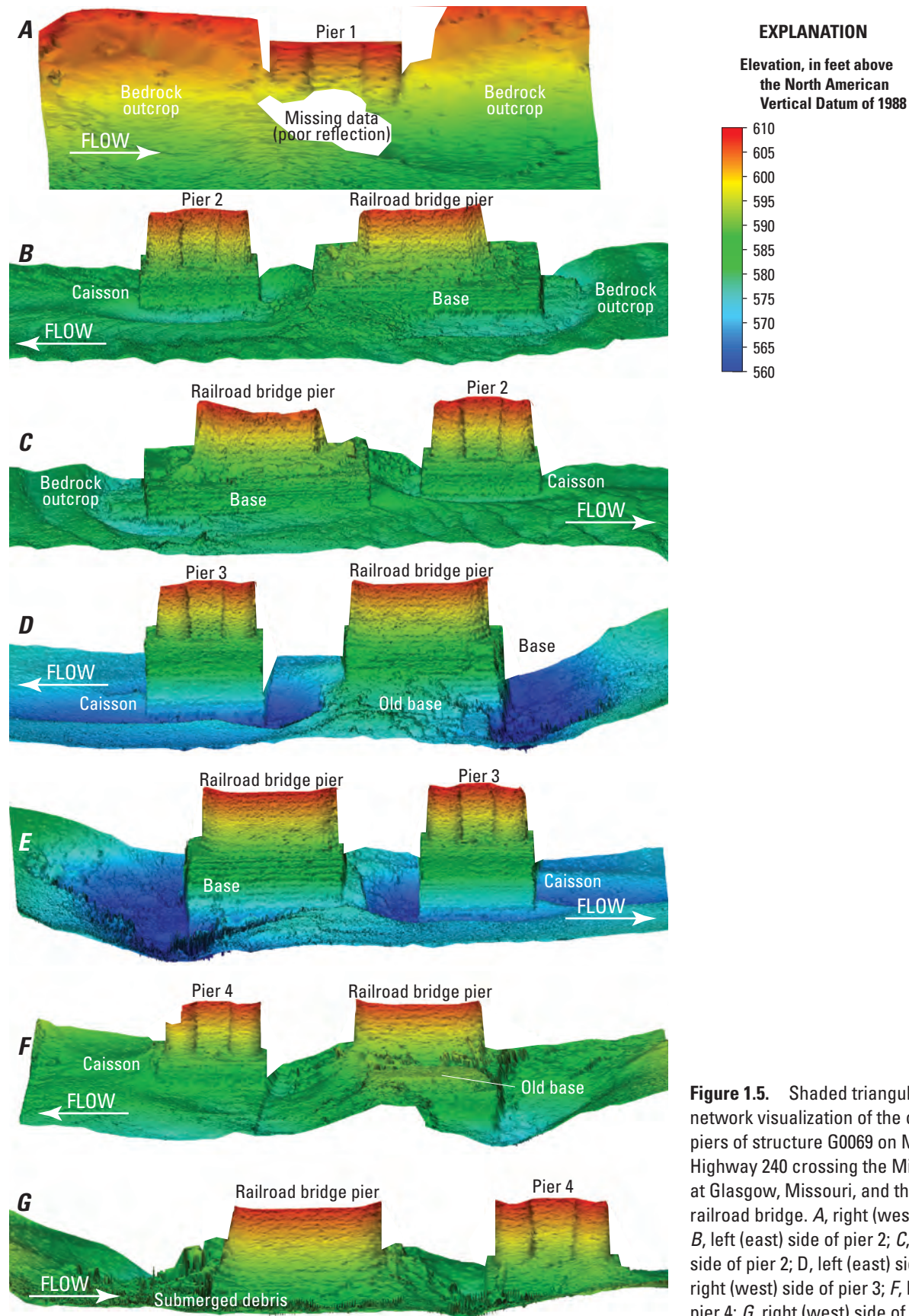


Figure 1.5. Shaded triangulated irregular network visualization of the channel bed and piers of structure G0069 on Missouri State Highway 240 crossing the Missouri River at Glasgow, Missouri, and the upstream railroad bridge. A, right (west) side of pier 1; B, left (east) side of pier 2; C, right (west) side of pier 2; D, left (east) side of pier 3; E, right (west) side of pier 3; F, left (east) side of pier 4; G, right (west) side of pier 4.

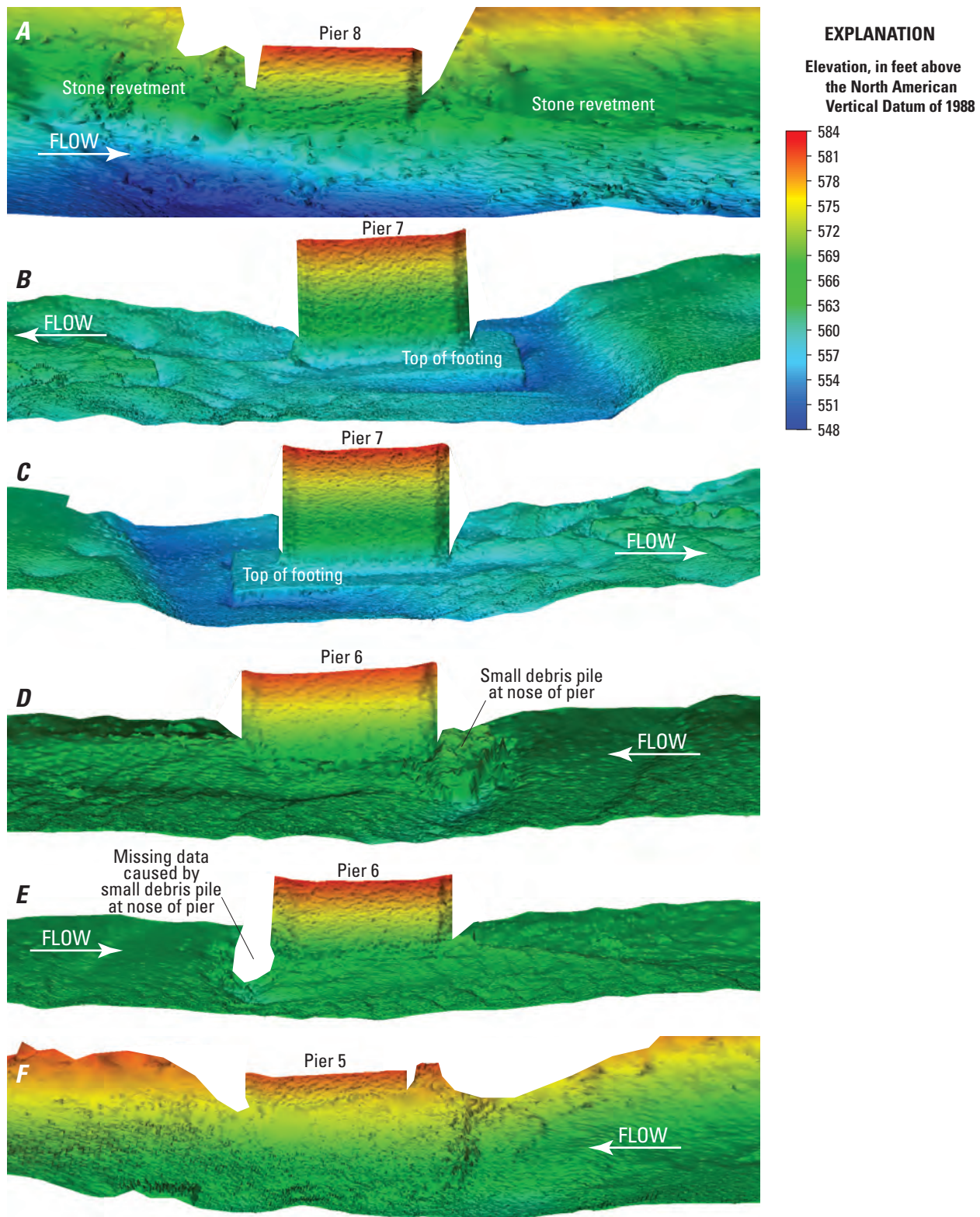


Figure 1.6. Shaded triangulated irregular network visualization of the channel bed and piers of structure A4574 on Missouri State Highway 5 crossing the Missouri River at Boonville, Missouri. *A*, right (south) side of pier 8; *B*, left (north) side of pier 7; *C*, right (south) side of pier 7; *D*, left (north) side of pier 6; *E*, right (south) side of pier 6; *F*, left (north) side of pier 5.

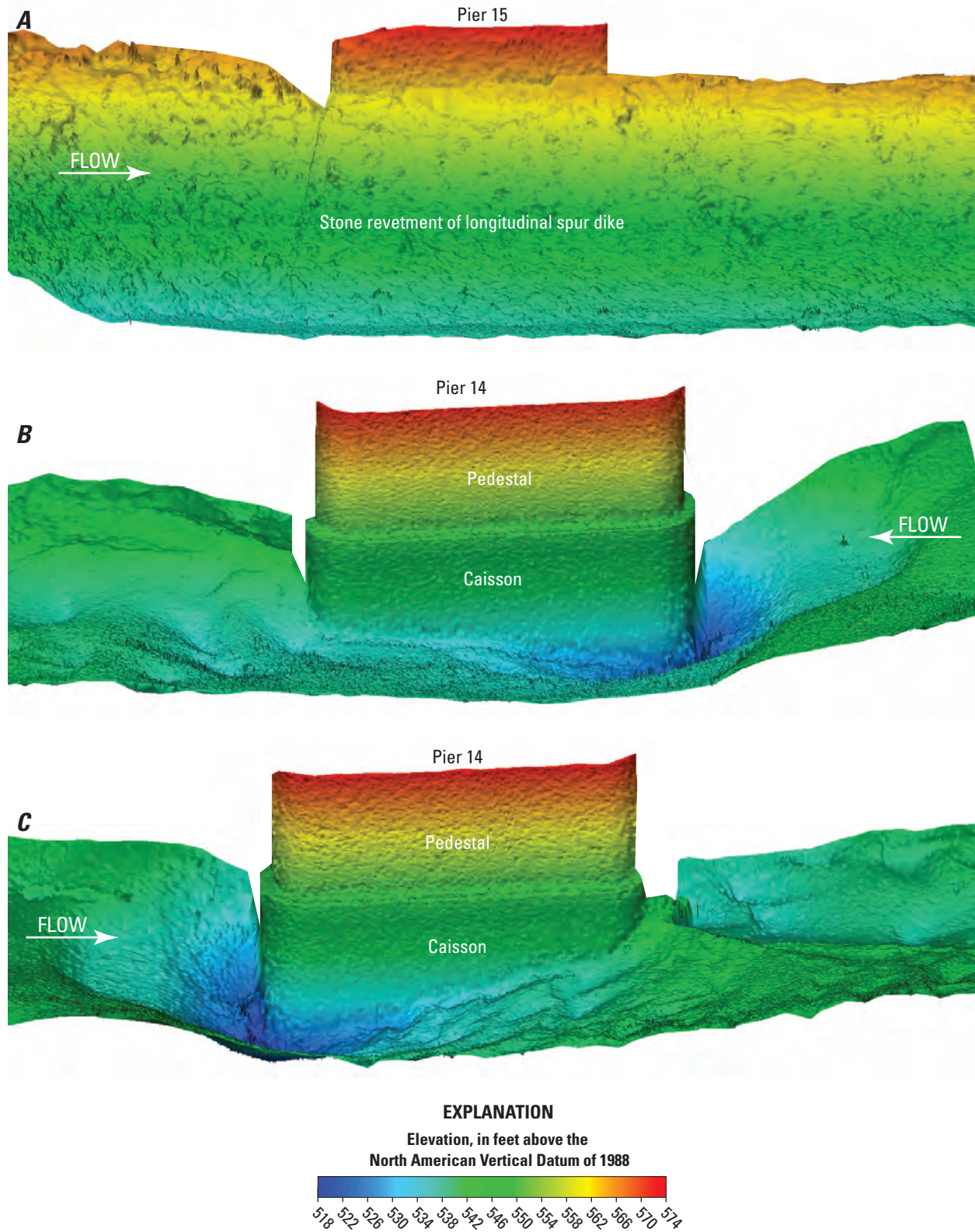


Figure 1.7. Shaded triangulated irregular network visualization of the channel bed and piers of structure L0962 on Interstate 70 crossing the Missouri River near Rocheport, Missouri. A, right (west) side of pier 15; B, left (east) side of pier 14; C, right (west) side of pier 14.

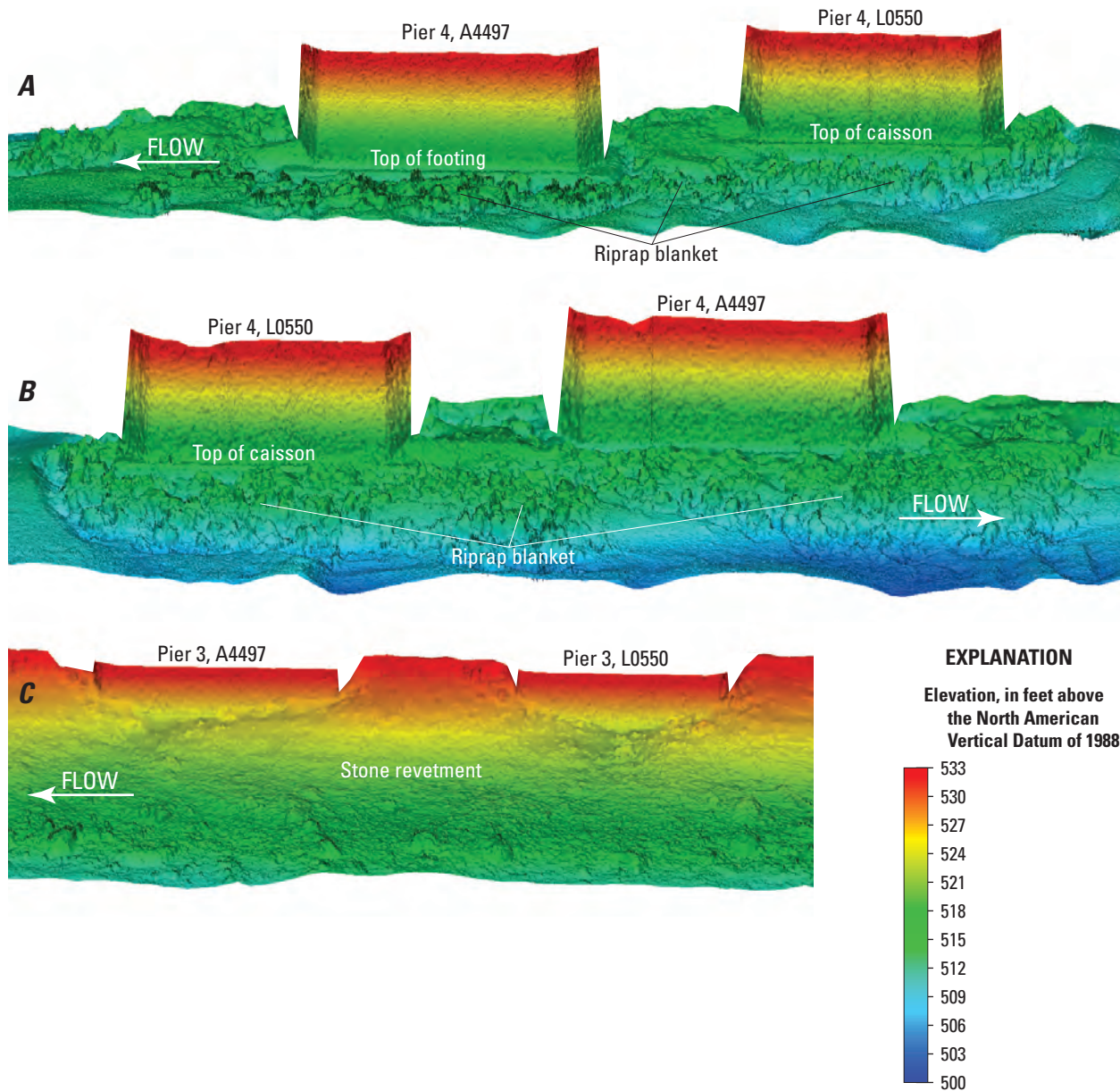


Figure 1.8. Shaded triangulated irregular network visualization of the channel bed and piers of structures L0550 and A4497 on U.S. Highway 54 crossing the Missouri River at Jefferson City, Missouri. *A*, left (northeast) side of pier 4 of both structures; *B*, right (southwest) side of pier 4 of both structures; *C*, left (northeast) side of pier 3 of both structures.

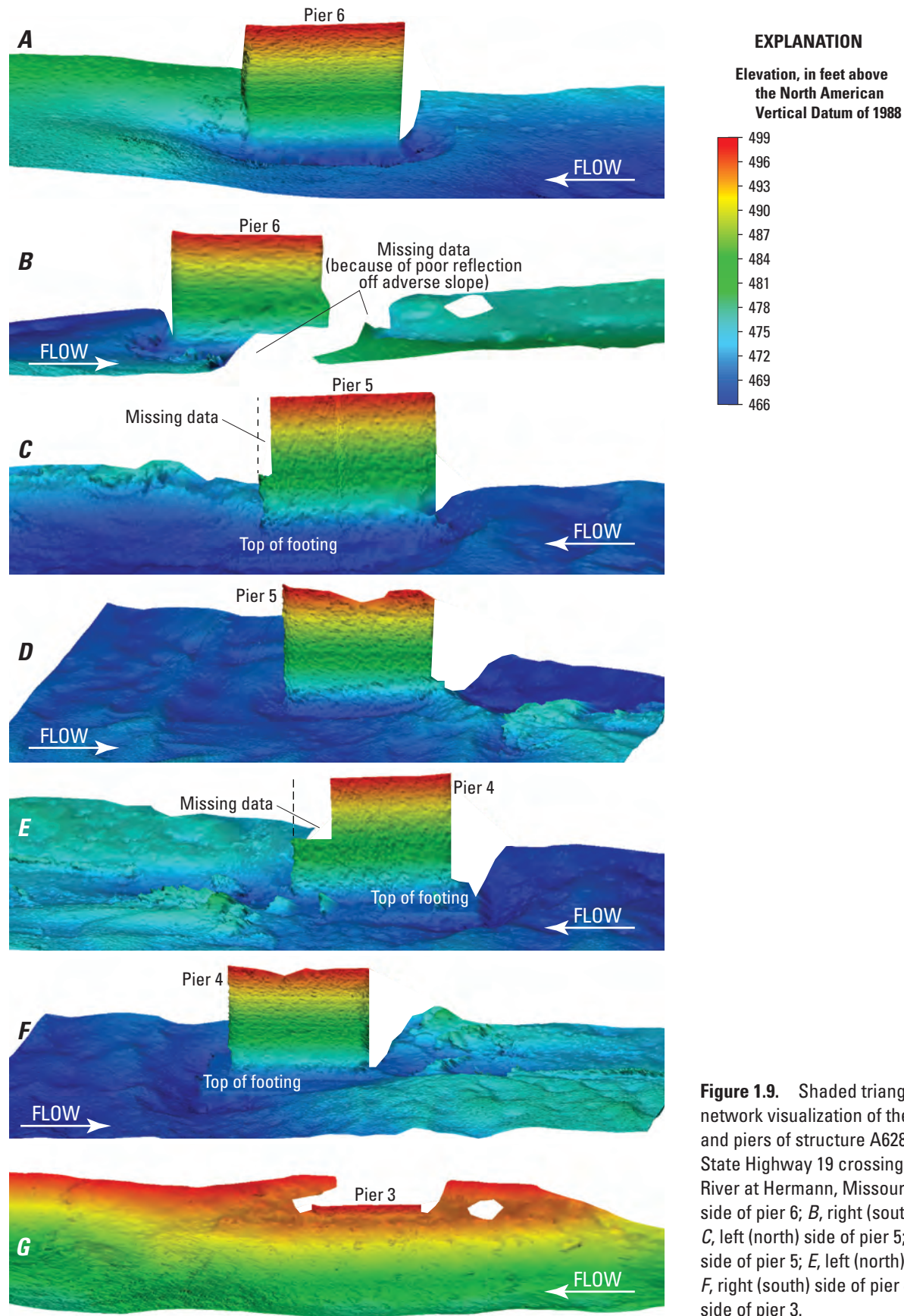


Figure 1.9. Shaded triangulated irregular network visualization of the channel bed and piers of structure A6288 on Missouri State Highway 19 crossing the Missouri River at Hermann, Missouri. *A*, left (north) side of pier 6; *B*, right (south) side of pier 6; *C*, left (north) side of pier 5; *D*, right (south) side of pier 5; *E*, left (north) side of pier 4; *F*, right (south) side of pier 4; *G*, left (north) side of pier 3.

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