USGS
science for a changing world

Prepared in cooperation with Missouri Department of Transportation

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri River between Kansas City and St. Louis, Missouri, May 19–26, 2021

Scientific Investigations Report 2024–5021

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

Cover: Structure A6288 on State Highway 19 at Hermann, Missouri.
Photograph by Richard J. Huizinga, U.S. Geological Survey.

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri River between Kansas City and St. Louis, Missouri, May 19–26, 2021

By Richard J. Huizinga

Prepared in cooperation with Missouri Department of Transportation

Scientific Investigations Report 2024–5021

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

U.S. Geological Survey, Reston, Virginia: 2024

Suggested citation:
Huizinga, R.J., 2024, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River between Kansas City and St. Louis, Missouri, May 19–26, 2021: U.S. Geological Survey Scientific Investigations Report 2024–5021, 101 p., https://doi.org/10.3133/sir20245021.

Associated data for this publication:
Huizinga, R.J., and Rivers, B.C., 2023, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri River between Kansas City and St. Louis, Missouri, May 19–26, 2021 (ver. 2.0, August 2023): U.S. Geological Survey data release, https://doi.org/10.5066/P9ULGQ4W.

U.S. Geological Survey, 2023, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN.

ISSN 2328-0328 (online)

Acknowledgments

The author would like to acknowledge Dennis Heckmann (retired), Bryan Hartnagel, Travis Stump, and Jennifer Harper at the Missouri Department of Transportation for their role in funding and supporting the work of the project detailed in this report.

The author also wishes to gratefully acknowledge Benjamin C. Rivers and Aaron L. Walsh of the U.S. Geological Survey for their assistance in collecting and processing the data for this project.

Contents

Figures

Tables

Conversion Factor

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
	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)

Datums

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” 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 river mile 0 at 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 maps at the request and for the convenience of the cooperator.

Abbreviations

ADCP	acoustic Doppler current profiler
AEP	annual exceedance probability
CUBE	Combined Uncertainty and Bathymetry Estimator
DEM	digital elevation model
DoD	digital elevation model of difference
GCD	Geomorphic Change Detection
GNSS	Global Navigation Satellite System
IHO	International Hydrographic Organization
IMU	inertial measurement unit
INS	inertial navigation system
MBES	multibeam echosounder
MBMS	multibeam echosounder mapping system
MMS	Mobile Mapping Suite
MoDOT	Missouri Department of Transportation
NAVD 88	North American Vertical Datum of 1988
POS MV	Position Orientation Solution for Marine Vessels
RM	river mile
RTK	real-time kinematic
SBET	smoothed best estimate of trajectory
TIN	triangulated irregular network
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Bathymetric and Velocimetric Surveys at Highway Bridges Crossing the Missouri River between Kansas City and St. Louis, Missouri, May 19–26, 2021

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 nine bridges at eight highway crossings of the Missouri River between Kansas City and St. Louis, Missouri, from May 19 to 26, 2021. A multibeam echosounder mapping system was used to obtain channel-bed elevations for river reaches about 1,640 to 1,840 feet (ft) longitudinally and generally extending laterally across the active channel from bank to bank during low to moderate flood-flow conditions. These surveys provided channel geometry and hydraulic conditions at the time of the surveys and provided characteristics of scour holes that may be useful in developing or verifying predictive guidelines or equations for computing potential scour depth. These data also may be useful to the Missouri Department of Transportation as a low to moderate flood-flow assessment of the bridges for stability and integrity issues with respect to bridge scour during floods.

Bathymetric data were collected around every in-channel pier. Scour holes were present at most piers for which bathymetry could be obtained, except those on banks or surrounded by riprap. Occasionally, scour holes were minor and difficult to discern from nearby dunes and ripples. All the bridge sites in this study were previously surveyed and documented in previous studies. Comparisons between bathymetric surfaces from the previous surveys and those of the current (2021) study do not indicate any consistent correlation between channel-bed elevations and streamflow conditions. The average difference between the bathymetric surfaces varied from 1.59 ft higher to 0.95 ft lower in 2021 than 2017, which corresponds to a gain of 100,200 cubic yards and a loss of 55,800 cubic yards, respectively. The average difference between the bathymetric surfaces varied from 2.74 ft higher to 3.05 ft lower in 2021 than 2013, which corresponds to a gain of 111,500 cubic yards and a loss of 169,200 cubic yards, respectively. The average difference between the bathymetric surfaces varied from 4.52 ft higher to 1.38 ft lower in 2021 than 2011, which corresponds to a gain of 221,100 cubic yards and a loss of 90,300 cubic yards, respectively. The most substantial overall net gain was 221,100 cubic yards between 2011 and 2021 at structures L0550 and A4497 at Jefferson City (site 20). The large net gain likely results from a combination of the mitigation of the scour holes near pier 4 of both bridges and the substantially lower flow in 2021 than in 2011. Alternatively, the most substantial overall net loss was 169,200 cubic yards between 2013 and 2021 at structure A6288 at Hermann (site 21), despite comparable streamflows.

Pier size, nose shape, and skew to approach flow had a substantial effect on the size of the scour hole observed at a given pier. Larger and deeper scour holes were present at piers with wide or blunt noses caused by exposed footings or caissons. When a pier was skewed to primary approach flow, the scour hole was generally deeper and larger than at a similar pier without skew; furthermore, the shape of the scour hole near skewed piers in this study generally was longer and deeper on the side with impinging flow. At structure A6288 at Hermann (site 21), the scour hole near pier 5 was difficult to discern from nearby dunes and ripples, whereas the upstream edge of the footing was visible at pier 4, which likely contributes to the larger scour hole near that pier; the top of the footing may blunt the horseshoe vortex at pier 5, but the exposed front of the footing may exacerbate the vortex at pier 4.

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 (Arneson and others, 2012). Scour at a bridge site is caused by short- and long-term geomorphic processes and the local effects from elements of the structure in or next to the waterway (Huizinga and Rydlund, 2004; Arneson and others, 2012). 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 increase with increased streamflow.

The Missouri Department of Transportation (MoDOT) manages most of the transportation infrastructure within Missouri. A part of their 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 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, inspecting the submerged part of the bridge requires a different approach.

The U.S. Geological Survey (USGS), in cooperation with MoDOT, began assessing scour at selected waterway crossings in Missouri in 1988 (Becker, 1994) and at waterway crossings throughout the State in 1991 (Huizinga and Rydlund, 2004). In 2007, the USGS, in cooperation with MoDOT, began monitoring scour at bridges using single-beam echosounders (Rydlund, 2009) and surveying channel bathymetry using a multibeam echosounder mapping system (MBMS; Huizinga and others, 2010; Huizinga, 2012, 2013; also refer to report references listed in table 1). The MBMS is a useful tool not only in surveying channel bathymetry but also in providing a medium- to high-resolution representation of submerged bridge structural elements. In 2010, the first round of periodic surveys at waterway crossings across the Missouri and Mississippi Rivers throughout Missouri began with bridges in the Kansas City, Missouri, area and were followed by bridges in the St. Louis, Mo., area, bridges on the Missouri River between Kansas City and St. Louis, and those on the periphery of Missouri (table 1). During high-flow conditions in June–August 2011, many of the highway bridges and several of the railroad bridges along the length 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) over the Missouri River in and into Missouri (Huizinga, 2012). These surveys help MoDOT fulfill the need for underwater inspection of bridges over the Missouri and Mississippi Rivers and provide a valuable snapshot in time of the channel bed elevations and velocities in the area near the bridge crossings, which can be used for developing or modifying tools for predicting bridge scour and other geomorphologic processes.

The study detailed in this report covers the surveys at the highway bridges across the Missouri River between Kansas City and St. Louis, Mo. (fig. 1), except for the new bridge over the Missouri River at Washington, Mo. (fig. 1, site number 22), which was under construction at the time of the previous surveys in that area (May 2017) and was surveyed with the St. Louis area bridges in August 2020 (tables 1 and 2). Therefore, this study details surveys at nine bridges at eight crossings (table 2).

Purpose and Scope

The purpose of this report is to describe the equipment and methods used and to document results of bathymetric and velocimetric surveys completed on May 19–26, 2021, of the Missouri River channel near nine highway bridges at eight crossings between Kansas City and St. Louis, Mo. (fig. 1; table 2). The results obtained from the bathymetric and velocimetric surveys of the channels document the channel-bed geometry and velocity distribution at the time of the surveys and provide characteristics of scour holes that may be useful in developing or modifying predictive guidelines or equations for computing potential scour depth. 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. Results are also compared to previous surveys at the sites (Huizinga, 2012, 2014, 2020a).

Table 1. Routine periodic surveys of bridges crossing the Missouri and Mississippi Rivers in and into Missouri.

Dates of routine surveys	Report references	Data references	Special notes
		Kansas City area	
March 2010	Huizinga (2010)	Huizinga (2020b)	Excluded L0734, A7650 not yet built.
June 2015	Huizinga (2016)	Huizinga (2020b)	Excluded K0456/A0450.
August 2019	Huizinga (2022a)	Huizinga (2021)	None.
		St. Louis area	
October 2010	Huizinga (2011)	Huizinga (2017b)	A6500 not yet built.
May 2016	Huizinga (2017a)	Huizinga (2017b)	None.
August 2020	Huizinga (2023)	Huizinga (2022b)	Included new bridges A8141 at Washington and A8504 at Louisiana, Mo.
		Mid-Missouri	
April–May 2013	Huizinga (2014)	Huizinga (2020c)	None.
May 2017	Huizinga (2020a)	Huizinga (2020c)	Excluded K0969, included A8340 in Kansas City.
		Periphery of Missouri	
June 2014	Huizinga (2015)	Huizinga (2020d)	None.
July–August 2018	Huizinga (2020e)	Huizinga (2020d)	Excluded K0932.

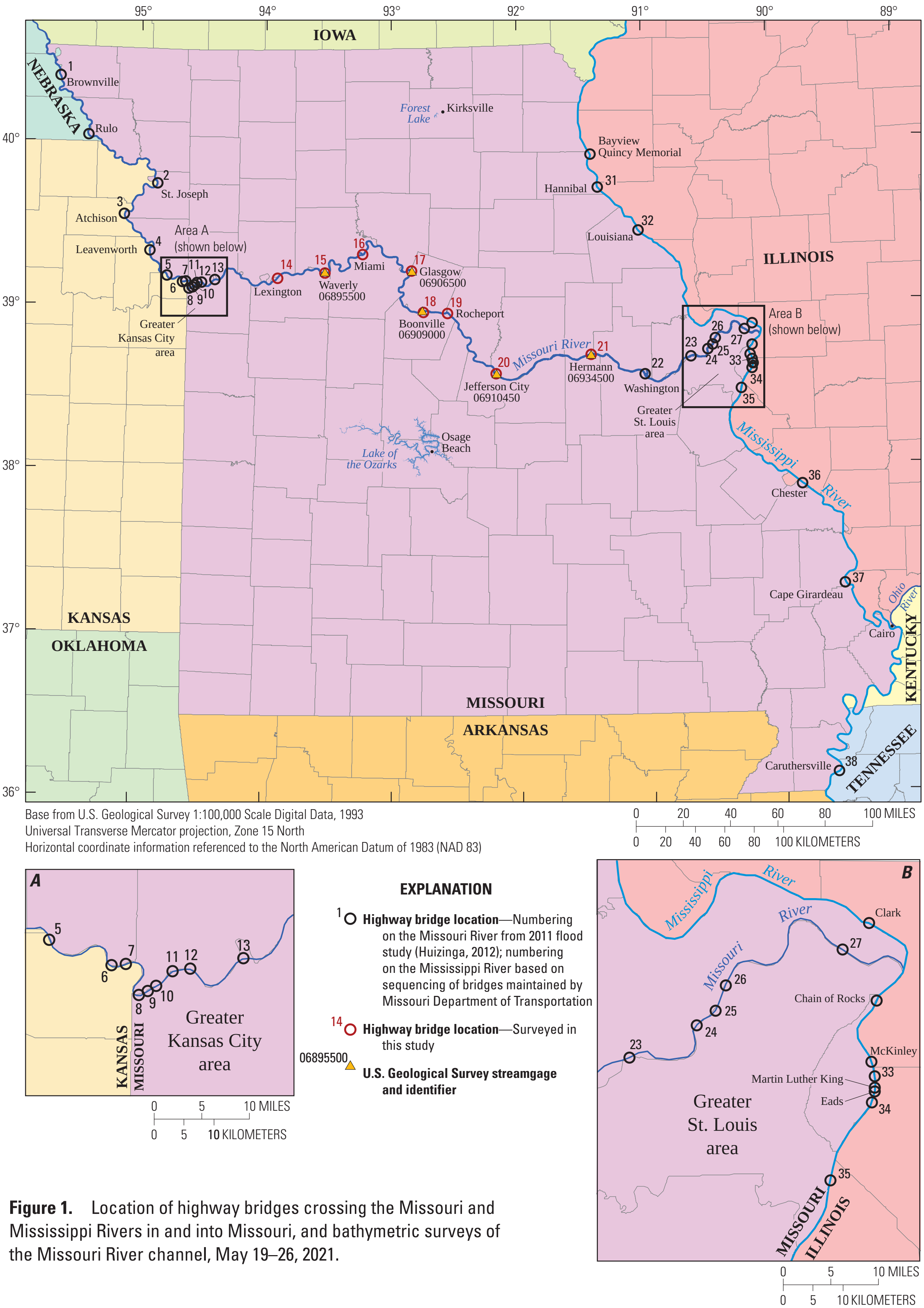


Figure 1. Location of highway bridges crossing the Missouri and Mississippi Rivers in and into Missouri, and bathymetric surveys of the Missouri River channel, May 19–26, 2021.

Table 2. Highway bridges crossing the Missouri River between Kansas City and St. Louis, Missouri.

[Bridges are listed in downstream order. MO, State highway; --, not applicable; US, U.S. highway; IS, Interstate highway; S, southbound; N, northbound]

Site number (fig. 1)	Structure number	Local name	County, State	Route	River mile[a]	Surveyed as part of this study	Remarks	Figures
14	A5664	Lexington	Ray, Mo.	MO 13	314.9	Yes	--	1, 6, 7, 8, 9, 10, 11, 1.1
15	A5910	Waverly	Lafayette, Mo.	US 24	293.2	Yes	--	1, 12, 13, 14, 15, 16, 17,18, 1.2
16	K0999	Miami	Carroll, Mo.	MO 41	262.6	Yes	--	1, 19, 20, 21, 22, 23, 24, 25, 1.3
17	G0069	Glasgow	Saline, Mo.	MO 240	226.3	Yes	--	1, 5, 26, 27, 28, 29, 30, 31, 32, 1.4
18	A4574	Boonville	Cooper, Mo.	MO 5	196.6	Yes	--	1, 33, 34, 35, 36, 37, 38, 39, 1.5
19	L0962	Rocheport	Boone, Mo.	IS 70	185.1	Yes	--	1, 40, 41, 42, 43, 44, 45, 46, 1.6
20	L0550	Jefferson City	Callaway, Mo.	US 54 S	143.9	Yes	Dual bridge crossing with A4497	1, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 1.7
	A4497		Cole, Mo.	US 54 N		Yes	Dual bridge crossing with L0550	
21	A6288	Hermann	Montgomery, Mo.	MO 19	97.9	Yes	--	1, 57, 58, 59, 60, 61, 62, 63, 1.8
22	K0969/ A8141	Washington	Franklin, Mo.	MO 47	67.6	No	Replaced in 2018, surveyed in 2020	1

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

Description of Study Area

The study area for this report is the Missouri River between Kansas City and St. Louis, Mo., but excludes the new bridge at Washington, Mo., surveyed in 2020 (Huizinga, 2023; fig. 1). 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; nine bridges at eight crossings) were examined as part of this study. The site numbering sequence used in previous studies on the Missouri River (Huizinga, 2012, 2014) is used in this report for consistency and comparability.

Description of Streamflow Conditions

Data from the selected streamflow-gaging stations (hereinafter referred to as “streamgages”) on the Missouri River at Waverly, Mo. (USGS station 06895500; hereafter referred to as the “Waverly streamgage”); Missouri River at Glasgow, Mo. (USGS station 06906500); Missouri River at Boonville, Mo. (USGS station 06909000); Missouri River at Jefferson City, Mo. (USGS station 06910450); and Missouri River at Hermann, Mo. (USGS station 06934500; hereinafter referred to as the “Hermann streamgage;” U.S. Geological Survey [USGS], 2023a; fig. 1), indicated the Missouri River was on or between minor to moderate flood rises when the sites on the Missouri River were surveyed on May 19–26, 2021 (fig. 2*A*); furthermore, this rise happened during generally higher late-spring flows (fig. 2*B*).

Streamflow on the Missouri River as measured at the Waverly streamgage was about 74,500 cubic feet per second (ft^3/s) during the survey at the U.S. Highway 24 crossing at Waverly on May 20, 2021 (the lowest measured value), whereas streamflow on the Missouri River as measured at the Hermann streamgage was about 148,000 ft^3/s during the survey at the Missouri State Highway 19 crossing at Hermann on May 26, 2021 (the highest measured value). The streamflow of 74,500 ft^3/s at the Waverly streamgage has a daily exceedance probability of about 24 percent (the probability that the indicated streamflow value would be equaled or exceeded on any given day at that streamgage; USGS, 2023b) and is less than the 90-percent annual exceedance probability (AEP; the probability that the indicated streamflow value would be equaled or exceeded within a period of one year; also known as the 1-year recurrence interval) flood discharge of 93,200 ft^3/s (U.S. Army Corps of Engineers [USACE], 2003, plate E–20). The streamflow of 148,000 ft^3/s at the Hermann streamgage has a daily exceedance probability of about 15 percent (USGS, 2023c) and is greater than the 90-percent AEP (the 1-year recurrence interval) flood discharge of 134,000 ft^3/s but less than the 50-percent AEP (the 2-year recurrence interval) flood discharge of 248,000 ft^3/s (USACE, 2003, plate E–20). Daily exceedance probabilities for the Waverly and Hermann streamgages were computed using daily streamflow from 1957 to 2022 (USGS, 2023b, c).

Streamflow conditions during the dates of each survey were in the low to moderate flood-flow regime. In an analysis of real-time scour monitoring data at Jefferson City, Mo., Huizinga (2014) noted that substantial pier scour generally 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 (refer to fig. 35 in Huizinga, 2014). Several peaks were observed earlier in the year (fig. 2*B*), and streamflow was substantially higher than base flow based on the daily exceedance values despite the lack of peak streamflow conditions during the study. Although the scour conditions captured in this study may not represent the maximum scour potential at the sites, the cumulative information gathered during multiple surveys from 2011 to 2021 remains useful for determining scour for a variety of flow conditions, particularly when combined with, or compared to, a scour scenario captured at high flood-flow conditions.

Description of Equipment and Basic Processing

The bathymetry of the Missouri River at each of the bridges was determined using a high-resolution MBMS. The various components of the MBMS used for this study are described in previous studies on the Missouri and Mississippi Rivers in Missouri (refer to report references listed in table 1) and on the Missouri and Yellowstone Rivers in North Dakota (Densmore and others, 2013). MBMS survey methods and data quality checks were similar to these previous studies. A brief description of the equipment follows; a more-complete description of the various system components and methods used in this study are available in the previous reports by Huizinga (2010), Huizinga and others (2010), and Densmore and others (2013).

An MBMS is an integration of several individual components: the multibeam echosounder (MBES), a sound-velocity probe, an inertial navigation system (INS), and a data-collection and data-processing computer. The MBES used in this study is the Norbit iWBMSh (fig. 3), operated at a frequency of 400 kilohertz (kHz). The iWBMSh is similar in operation to the MBES systems used in previous studies in the mid-Missouri area, except that it has a curved piezoceramic receiver array, which enables bathymetric data to be collected throughout a swath range of 210 degrees. Optimum data usually are collected in a swath of less than 160 degrees (80 degrees on each side of nadir, or straight down below the MBES); nevertheless, the swath can be electronically rotated to either side of nadir, enabling data collection along sloping banks up to a depth just below the water surface. The sound-velocity probe provides real-time measurements of the speed of sound at the MBES to accurately determine the depth readings of the MBES (Hughes Clarke and others, 1996). The

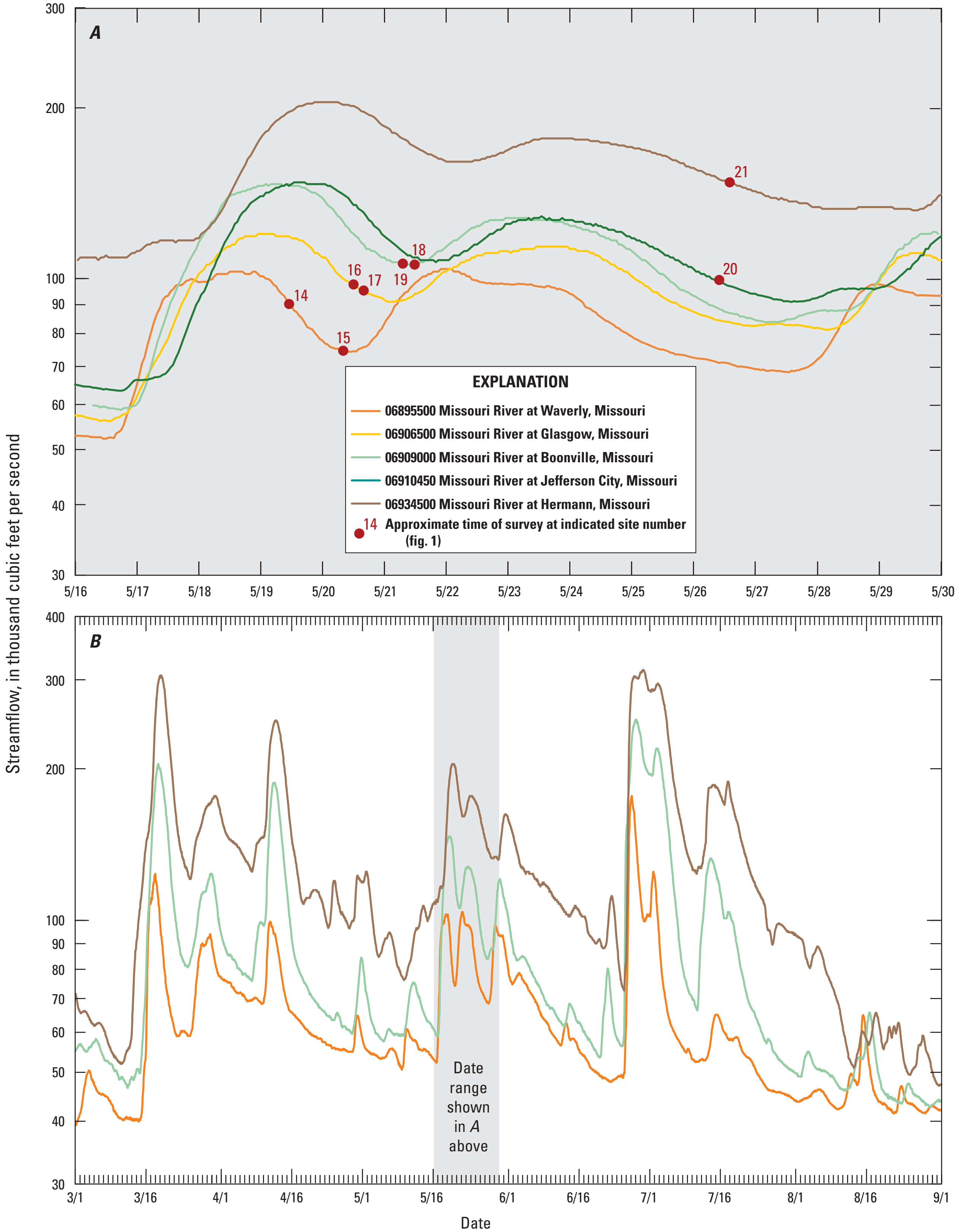


Figure 2. Hourly streamflow at selected streamgages in the study area on the Missouri River between Kansas City and St. Louis, Missouri (U.S. Geological Survey, 2023a). *A*, May 16–30, 2021. *B*, March 1–September 1, 2021.

Figure 3. The multibeam echosounder. Photographs by Richard J. Huizinga, U.S. Geological Survey (USGS). *A*, Viewed from the side. *B*, Mounted on the port side of the U.S. Geological Survey boat.

river environment tends to be well mixed, such that the sound velocity at the MBES is sufficiently representative of a sound-velocity profile of the full water column. The Norbit iWBMSh uses the Applanix Position Orientation Solution for Marine Vessels (POS MV) OceanMaster INS system, consisting of an inertial measurement unit (IMU) attached directly to the MBES mount in a “tightly coupled” configuration (fig. 3*A*) and two Global Navigation Satellite System (GNSS) antennae. The INS provides position in three-dimensional space and measures the attitude of the vessel (pitch, roll, yaw, and heading) 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 GNSS real-time network for the navigation and tide solution during the 2021 surveys.

Similar to all previous surveys after 2010 (refer to report references listed in table 1), the navigation information from the 2021 surveys was postprocessed using the POSPac Mobile Mapping Suite (MMS) software (version 8.0; Applanix Corporation, 2021) to mitigate the effects of degraded positional accuracy of the vessel while near or under a bridge resulting from GNSS outages. The POSPac MMS software provides tools to identify and compensate for sensor and environmental errors to compute an optimally blended navigation solution from the GNSS and raw IMU 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. Because of advances in technology, surveys before 2010 do not have an SBET file and are more likely to have artifacts resulting from minor positional variations between surveys.

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 (version 2020; HYPACK, Inc., 2020) that was used to prepare for and do bathymetric surveys. 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 and visualized in HYPACK/HYSWEEP as a gridded bathymetric surface or a point cloud.

Information about the velocity of the river at various points throughout each study reach was collected using an acoustic Doppler current profiler (ADCP), similar to previous studies since 2011 by Huizinga (for example, refer to Huizinga, 2012, 2022a). 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 ADCP operates in depths from 2.3 to 230 ft to determine the velocity of water by measuring the Doppler shift of an acoustic signal reflected from various particles suspended in the water (Mueller and others, 2013). By measuring the Doppler shift in four different beam directions, the velocity of the water in each bin can be determined in three dimensions. The depth-averaged velocities from the two traverses of a given section line were computed using averaging algorithms from the Velocity Mapping Toolbox (version 4.09; Parsons and others, 2013).

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 any differences from—these methods are highlighted below.

Surveying Methods

Generally, the surveyed area extended across the active channel from bank to bank, just like the previous studies on the Missouri and Mississippi Rivers (Huizinga and others, 2010; Huizinga, 2012; also refer to references listed in table 1). The survey extent ranged from 1,550 to 1,840 ft long in the longitudinal (streamwise) direction and was positioned so that the surveyed highway bridges were about one-third to one-half of the total length from the upstream extent, generally using the same upstream and downstream extents as were used in the 2011 flood study (Huizinga, 2012). The upstream and downstream boundaries of the surveyed areas were assumed to capture all the substantial hydraulic effects (wake vortices and shear flow) of the bridge structures.

Like in previous studies, bathymetric data were obtained along longitudinal transect lines, and each survey was designed such that the survey swaths overlapped to attempt to ensure complete coverage of the channel bed and minimize sonic “shadows” (Huizinga and others, 2010). Many of the surveyed swaths had substantial overlap, except in shallow areas near the channel banks or spur dikes and near in-flow structures or debris rafts. Areas near bridge piers and along the banks also were surveyed in an upstream direction with the MBES swath electronically tilted to port or starboard to increase the acquisition of bathymetric data higher on the banks and sides of the piers. The electronically tilted swath generally was 120 to 160 degrees wide, extending from 10 degrees above horizontal on the bank-ward or pier-ward side of the survey vessel, and 20 to 60 degrees past nadir below the vessel.

After completing the bathymetric survey at a given site, velocity data were obtained with the ADCP on seven transections spanning the channel within the study area. The position and speed of the boat was determined using a differential GNSS receiver mounted on a pole directly above the ADCP. The bottom-track reference method for determining boat speed was anticipated to be unusable because of moving channel-bed material, so the boat velocity was determined using the GNSS essential fix data string (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 being surveyed. Each section line was traversed in each direction across the river, and the reported velocity values were the average from the two traverses of a given section line. 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 Measures

For the MBMS, the principal quality-assurance measures were assessed in real time during the survey. The MBMS operator assessed the quality of the collected data in real time by making visual observations of cross-track swath shape (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, beam angle checks and a suite of patch tests were done to ensure quality data were acquired from the MBMS for the 2021 surveys. An initial patch test was completed on May 5, 2021, at Forest Lake near Kirksville, Mo. (fig. 1). The beam angle check and an additional patch test were completed at Lake of the Ozarks near Osage Beach, Mo. (fig. 1) on November 18, 2021. The results of the beam angle check (table 3) were within the recommended performance standards used by the USACE for hydrographic surveys for all the representative angles below 70 degrees (USACE, 2013). Points acquired outside of the central 100–110 degrees of the swath generally had overlap with adjacent swaths, which increases the quality of the survey in the overlapped areas because of duplication.

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 (Huizinga, 2023), and primarily are used to determine angular offsets to roll, pitch, and yaw caused by the alignment of the transducer head relative to the INS (fig. 4). These offsets have been observed to be essentially constant for a given equipment configuration and survey season, barring an event that causes the mount to change such as striking a floating or submerged object (refer to report references listed in table 1; Huizinga and others, 2023; Rivers and others, 2023).

Although the MBES had several minor strikes of floating or submerged debris at various times during the 2021 survey season, no changes to the roll or pitch angles were apparent from the beginning to the end of the river surveys in May (table 4). The tightly coupled configuration of the Norbit iWBMSh, wherein the IMU of the INS is mounted on the same mounting bracket as the MBES (fig. 3*A*) results in no measured timing offset and no measured angular offset for pitch (table 4). The yaw is a measure of the alignment of the GNSS receivers relative to the IMU of the INS on the echosounder head, and the measured offset for yaw changed

Table 3. Results of a beam angle check from two check lines over a reference surface at Lake of the Ozarks near Osage Beach, Missouri, on November 18, 2021.

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

Beam angle limit, in degrees	Maximum outlier, in feet	Mean difference, in feet	Standard deviation, in feet	95-percent confidence, in feet
0	0.24	−0.09	0.04	0.07
5	0.28	−0.09	0.03	0.07
10	0.23	−0.08	0.04	0.07
15	0.22	−0.08	0.04	0.07
20	0.23	−0.08	0.04	0.08
25	0.23	−0.07	0.04	0.08
30	0.27	−0.07	0.04	0.08
35	0.27	−0.07	0.05	0.09
40	0.23	−0.05	0.04	0.08
45	0.21	−0.04	0.04	0.09
50	0.22	−0.04	0.05	0.09
55	0.23	−0.03	0.05	0.10
60	0.21	−0.01	0.05	0.10
65	0.25	0.02	0.06	0.12
70	0.30	0.03	0.06	0.12
		Performance standards[1]		
Threshold	1.00	<0.20	--	<0.80
Result	Met	Met	--	Met

[1]Performance standard check values are from U.S. Army Corps of Engineers (2013, table 3-1) for soft sand/silt bottoms.

from –2.5 to –1.5 between the two patch tests (table 4). The variable angular offset for yaw observed in the 2021 surveys is believed to be the result of a combination of a loose connection on the T-pole on which the GNSS receivers were mounted (fig. 3*B*) and an incorrectly applied magnetic variation or grid convergence parameter in the post-processing of the survey data (Rivers and others, 2023). The measured angular offset for roll remained a constant −0.10 (table 4), which is different from previous results for this equipment configuration in other recent surveys (Huizinga, 2022a; Huizinga and others, 2023); however, the MBES had undergone calibration testing in January 2021, which is the likely source of the change. Furthermore, the roll offset of −0.10 is consistent with other data collected since the calibration testing in 2021 (Rivers and others, 2023). It was noted in the earliest work with the MBMS in Missouri (Huizinga, 2010) that a sensitivity analysis of the four offsets indicated 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. Processing all the data for the bridge surveys detailed in this report with an angular offset of roll of –0.10 degree, no angular offset for pitch, and an angular offset for yaw of –2.0 degrees generally yielded good results with no noticeable artifacts caused by incorrect offsets.

Angular offsets were applied to the bathymetric data before removing 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 MBMax processing package of the HYPACK/HYSWEEP software (HYPACK, Inc., 2020) and used to generate a gridded raster surface of the channel bed (and associated uncertainty) near each bridge (hereinafter referred to as a “bathymetric surface”) using ArcMap (version 10.8.1; Esri, 2022).

A quality-assurance plan has been established for streamflow and velocity measurements using ADCPs that includes several instrument diagnostics checks and calibrations. These standard operating procedures were followed when acquiring the velocity profile data for these surveys. For a detailed description of these procedures, refer to Mueller and others (2013).

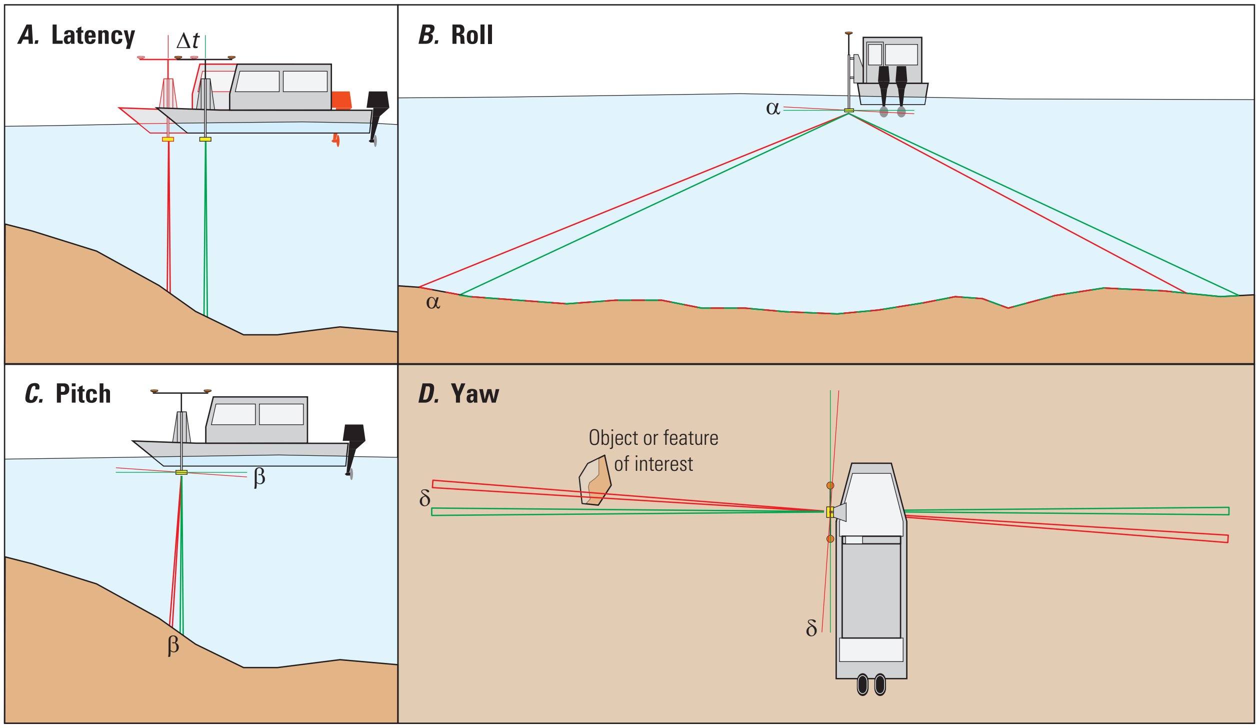


Figure 4. Generalized effects on data from a multibeam echosounder (from Huizinga, 2022a). *A*, Timing offset for latency. *B*, Angular offset for roll. *C*, Angular offset for pitch. *D*, Angular offset for yaw.

Table 4. Patch test results at two locations on May 4 and November 18, 2021.

Date of test	Timing offset, in seconds	Angular offset for roll, in degrees	Angular offset for pitch, in degrees	Angular offset for yaw, in degrees	Location (fig. 1)
05/04/2021	0	−0.10	0.00	−2.50	Forest Lake near Kirksville, Missouri
11/18/2021	0	−0.10	0.00	−1.50	Lake of the Ozarks near Osage Beach, Missouri

Uncertainty Estimation

Similar to recent bathymetry studies in Missouri (refer to report references listed in table 1; Huizinga and others, 2023; Rivers and others, 2023), uncertainty in each survey was estimated by computing the uncertainty for each survey-grid cell in the bathymetric surface of the survey area using the CUBE method (Calder and Mayer, 2003). The gridded uncertainty is a measure of the variability of the individual points in the cell used to determine the CUBE-derived elevation for the cell. Statistics of gridded uncertainty for each of the survey areas are shown in table 5. An example of the spatial distribution of gridded uncertainty typically observed in the survey data at structure G0069 on State Highway 240 is shown in figure 5. The uncertainty data were output and combined with the three-dimensional bathymetry data and are included with metadata in the USGS data release associated with this study (Huizinga and Rivers, 2023).

More than 99 percent of the uncertainty values at all the sites were less than 0.50 ft (table 5), which is within the specifications for a “Special Order” survey, the second-most-stringent survey standard of the International Hydrographic Organization (IHO; International Hydrographic Organization, 2020). More than 97 percent of the uncertainty values were less than 0.25 ft, and more than 82 percent of the uncertainty values were less than 0.10 ft at all the sites (table 5). The

Table 5. Total gridded 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, May 19–26, 2021.

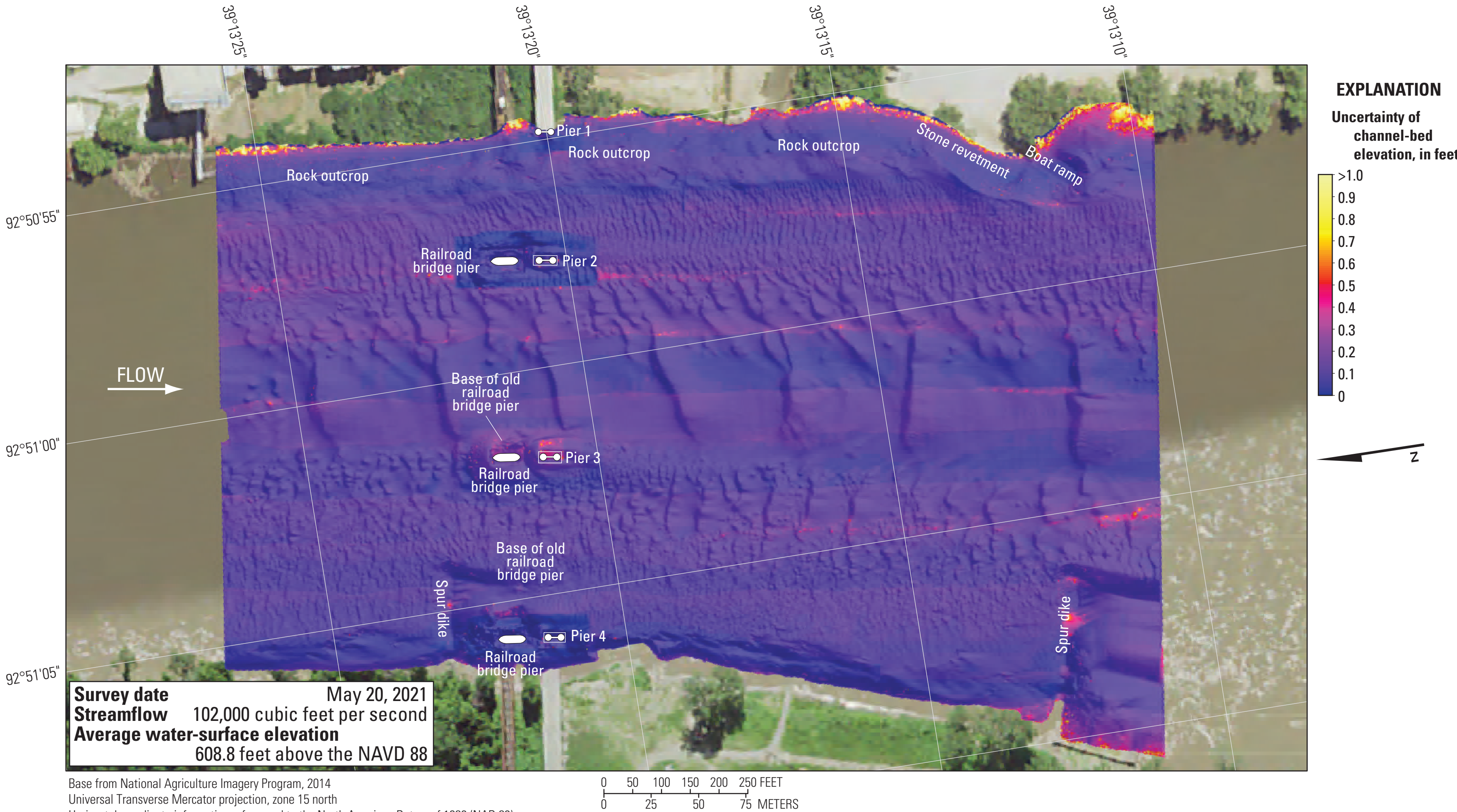
[Data are summarized from Huizinga and Rivers (2023)]

Site number (fig. 1)	Structure number	Uncertainty, in feet				Percentage of bathymetry points with uncertainty value less than a given threshold			
		Maximum	Mean	Median	Standard deviation	1.00 foot	0.50 foot	0.25 foot	0.10 foot
14	A5664	2.89	0.07	0.07	0.08	99.9	99.2	97.5	91.6
15	A5910	3.25	0.07	0.07	0.07	99.9	99.5	98.2	91.1
16	K0999	3.02	0.07	0.07	0.07	99.9	99.5	97.8	90.4
17	G0069	3.25	0.09	0.10	0.06	100.0	99.7	98.5	83.3
18	A4574	3.25	0.08	0.07	0.06	99.9	99.6	98.6	87.6
19	L0962	3.18	0.09	0.07	0.08	99.9	99.3	97.2	83.6
20	L0550/A4497	1.12	0.08	0.07	0.04	100.0	100.0	99.6	91.5
21	A6288	1.44	0.09	0.07	0.05	100.0	99.9	99.0	82.2

tops of bridge substructural elements (pier footings and seal courses) typically had uncertainty values of less than 0.10 ft. Similar to previous surveys with this type of equipment (refer to, for example, Huizinga, 2012, 2016), the uncertainty values were larger near moderate-relief features (banks, spur dikes, rock riprap and outcrops, and scour holes near piers). The largest uncertainty in this group of surveys was 3.25 ft (table 5); however, as noted in previous studies, uncertainty values of this magnitude typically happened near high-relief features, such as the front or side of a pier footing. Occasionally, the uncertainty values also were larger (1.00 ft or greater) in the outermost beams of the multibeam swath where overlap existed with an adjacent swath, particularly when the MBES head was electronically tilted for the survey lines along the banks or near the piers. Overlapping adjacent swaths in the channel thalweg (the line of maximum depth in the channel) also can display larger uncertainty values because substantial bed movement can happen between survey passes (fig. 5).

The uncertainty of the gridded data computed using the CUBE method has been decreasing with time compared to previous surveys (refer to table 4 in Huizinga, 2012, 2014, 2020a). The decrease in uncertainty primarily is the result of improvements in data-collection equipment and methods. The tightly coupled configuration of the Norbit iWBMSh used in these surveys decreases some of the uncertainty by substantially reducing the lever arm length (and therefore the potential movement) between the MBES and IMU. The ability to electronically tilt the swath substantially reduces the time between when unrotated, down-looking data and rotated, side-looking data are collected, which reduces the uncertainty of the data in the swath overlap zone that might otherwise experience more substantial bed movement.

The survey at structure G0069 on Missouri State Highway 240 at Glasgow had the highest maximum value (3.25 ft) and the highest median value (0.10 ft) of gridded uncertainty, as well as a lower percentage of bathymetry points with a gridded uncertainty of less than the various thresholds (table 5). The survey at this site was obtained with relatively smooth longitudinal swaths (fig. 5), which was the case at nearly all the sites surveyed in this study. The primary anomalies at this site were observed along the banks and near the piers, where the MBES was used in an electronically tilted configuration to extend the potential coverage in these areas, resulting in higher uncertainty values. Generally, the magnitude and distribution of uncertainty observed at this site are representative of those observed at all the sites.



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

Figure 5. Uncertainty of gridded bathymetric data from the Mississippi River channel near structure G0069 on Missouri State Highway 240 at Glasgow, Missouri.

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 and progressing downstream on the Missouri River. The range of bed elevations, described as “the channel-bed elevations,” for each survey was based on statistical analyses of the bathymetric surface at each site and covers the 5th to 95th percentile range of the data. Because the surveys generally were limited to the active channel from bank-to-bank excluding overbank areas, this percentile range generally covered the channel bed but excluded the banks and localized high or low spots, such as spur dikes or scour holes near piers or spur dikes. 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.

All the bridge sites in this study were previously surveyed (Huizinga, 2012, 2014, 2020a), and bathymetry data from earlier surveys at all eight crossings are included with metadata in Huizinga (2020c). A map showing the difference in channel-bed elevation for the area common to the comparison 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 using the Geomorphic Change Detection (GCD; version 7) add-in tool for ArcGIS available through the Riverscapes Consortium (2022). The GCD program computes elevation difference and volumetric change in storage between two gridded raster surfaces (each as a digital elevation model [DEM] of the surface) derived from repeat topographic or bathymetric surveys. The GCD program provides a suite of tools to associate the uncertainties for points in the various surveys (using the uncertainty values associated with each point, or an average uncertainty of the survey when point-specific uncertainty data were not available [survey data from 2011 or before]) and propagates those uncertainties through the DEM of difference (DoD) map. The GCD program also provides a way to segregate the best estimates of change using threshold masks. A threshold mask of 95-percent confidence was used for comparisons in the current study, and summary statistics (maximum, minimum, and average) of the DoD maps were determined. Sediment volumes for cut (scour) and fill (deposition) between the 2021 survey and any previous surveys between 2011 and 2017 also were determined. The surveys are broadly compared based on their timing and the streamflow at the time of the survey. Additionally, shaded triangulated irregular network (TIN) images of the channel and side of pier were prepared for each surveyed pier. These visualizations are shown in figures 1.1 to 1.8.

Although the configuration of the channel bed and the underlying sediment transport conditions at a site are associated with an instantaneous streamflow in the discussions that follow, a given bathymetric surface actually reflects more than those instantaneous transport conditions. A wide variety of factors affect the channel-bed configuration of a reach for a specific streamflow, including magnitude of flow velocities and velocity distribution; the number, size, and timing of previous flood rises; whether the stage currently is rising or falling; and other local hydraulic conditions (Gilbert and Murphy, 1914; Simons and Richardson, 1966). Furthermore, the channel-bed configuration at a site is affected by upstream and local sediment conditions (size and spatial distribution) and contributions, as well as water temperature and other seasonal variations (Simon, Li and Associates, 1985). Because of the myriad number and interactions between factors affecting sediment transport conditions and the resulting bed conditions, it was assumed that the configuration and size of bed forms observed during the current (2021) surveys in the mid-Missouri area depended on more than the instantaneous streamflow at a given site. Although it is beyond the scope of the current (2021) study to examine all the antecedent conditions that created the observed channel-bed configuration, the comparisons with previous surveys under different streamflow conditions nevertheless contributes to understanding the many complexities of sediment transport and resulting channel-bed net conditions.

As in recent previous studies (refer to report references listed in table 1), when discussing the vertically averaged velocity values obtained during the surveys in the sections that follow, neighboring vectors having random variations in direction and magnitude were taken as an indication of nonuniform flow in the section resulting from shear and wake vortices. Conversely, neighboring vectors having gradual and systematic variations were assumed to indicate 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.

Structure A5664 on State Highway 13 at Lexington, Missouri

Structure A5664 (site 14; table 2) on State Highway 13 crosses the Missouri River at river mile (RM) 314.9 at Lexington, Mo., east of and downstream from Kansas City, Mo. (fig. 1). The site was surveyed on May 19, 2021, and the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 681.3 ft (table 6; fig. 6). Streamflow on the Missouri River was about 82,200 ft^3/s, as determined from the rated streamflow measured at Waverly (streamgage 06895500) 6 hours after the survey (table 6, especially note “e”). Velocity data were not collected at this site owing to a faulty ADCP unit.

The survey area was about 1,640 ft long and about 1,000 ft wide, extending across the active channel from bank to bank (fig. 6). The survey area extended 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. 6). The channel-bed elevations ranged from about 653 to 668 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; fig. 7), except near the spur dikes on the right (south) bank (fig. 6; table 6). The channel bed between the left (north) bank and the spur dikes was filled with medium 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. 6). Localized scour holes were present downstream from and off the ends of the spur dikes on the right (south) side (fig. 6). As in previous surveys (Huizinga, 2012, 2014, 2022a), stone revetment was present on the left (north) bank throughout the reach, and spur dikes were present on the right (south) bank (fig. 6).

The minor scour holes near main channel piers 21 and 22 were difficult to discern from nearby dunes and ripples (figs. 6 and 1.1). Information from bridge plans indicates that piers 21 and 22 are founded on shafts drilled 28 to 50 ft into bedrock, having about 52 ft of bed material between the channel bottom and bedrock at pier 21 and about 27 ft of material at pier 22 (fig. 8; difference between “Approximate minimum elevation in scour hole near pier/bent” and “Approximate elevation of bedrock near pier/bent” in table 7). The surveyed bed generally was similar to the previous multibeam surveys in 2013 and 2017, except on the left side of pier 21 (fig. 8). The scour hole near pier 21 appears to penetrate to the top of the pier footing (figs. 6, 8, 1.1*A*, 1.1*B*), which might provide some mitigation to the scour hole at this pier as the downward flow of the horseshoe vortex at the pier column face is blunted by the footing (Arneson and others, 2012).

The computed difference between the survey DEMs with a probabilistic threshold mask of 95-percent confidence based on uncertainty (hereinafter referred to simply as “the difference”) from the survey on May 19, 2021, and the previous survey on May 23, 2017 (fig. 9), indicates about 92 percent of the joint area of interest had change greater than the 95-percent confidence interval of uncertainty (hereinafter referred to as “detectable change”), which means about 8 percent of the differences in the joint area of interest are equivocal and within the 95-percent confidence bounds of uncertainty of detectable change (hereinafter referred to as “within the bounds of uncertainty”; table 8). Bed variation seemed about equal between scour and deposition in most of the channel from 2017 to 2021 in the DoD (fig. 9); however, deposition is dominant in the thalweg along the left (north) bank throughout the reach, whereas substantial scour is apparent downstream from the spur dikes on the right (south) bank (fig. 9). The average difference between the bathymetric surfaces (the statistical mean value of the gridded raster surface [fig. 9] created from the thresholded difference between the 2021 and 2017 gridded raster bathymetric surfaces) was –0.52 ft (table 8), indicating minor to moderate channel degradation between the 2017 and 2021 surveys. The net volume of cut in the reach from 2017 to 2021 was about 89,700 cubic yards (yd^3), and the net volume of fill was about 61,200 yd^3, resulting in a net loss of about 28,500 yd^3 of sediment between 2017 and 2021 (table 8). The cross sections from the two surveys along the upstream face of the bridge are not substantially different from one another for most of the section, except on the left side of pier 21 where the 2017 section is 5 to 10 ft lower than the 2021 section (fig. 8). The frequency distribution of bed elevations in 2021 also was similar to 2017 (fig. 7). The stone revetement on the left (north) bank showed areas of minor scour and deposition, and the spur dike on the right (south) bank downstream from the bridge showed minor erosion on one side and deposition on the other (fig. 9); however, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 19, 2021, and the survey on Aril 24, 2013, (fig. 10), indicates about 61 percent of the joint area of interest had detectable change, which means about 39 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Scour and deposition are roughly balanced throughout most of the reach between 2013 and 2021 in the DoD, except along the right (south) bank, particularly downstream from the spur dikes (fig. 10). The average difference between the bathymetric surfaces was –1.14 ft (table 8), indicating moderate channel degradation between the 2013 and 2021 surveys. However, the net loss of sediment between 2013 and 2021 was about 32,100 yd^3, which is similar to the net loss of sediment between 2017 and 2021 (table 8). The cross-section from the 2021 survey along is very similar to the 2013 section (fig. 8), and the frequency distribution of bed elevations in 2021appears very similar to 2013 (fig. 7). The stone revetment on the left (north) bank is within the bounds of uncertainty (fig. 10). A substantial part of the channel on the right (south) side was not surveyed in 2013 because of generally lower flows (table 8) and shallow depths in that area. As with the previous DoD, deposition or scour apparent on opposing faces of a feature (such as a pier or spur dike) likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

Table 6. Bridge and survey information, and selected channel-bed elevations from surveys on the Missouri River between Kansas City and St. Louis, Missouri, August 19–26, 2021.

[Data are summarized from Huizinga and Rivers (2023). Sites are shown on figure 1. Dates are given in month/day/year. All elevations are in feet above the North American Vertical Datum of 1988. ADCP, acoustic Doppler current profiler; MO, State highway; US, U.S. highway; IS, Interstate highway]

Site number (fig. 1)	Structure number	Survey date	Route	River mile[a]	Streamflow from ADCP measurements,[b] in cubic feet per second	Average water-surface elevation near the bridge, in feet	Average channel-bed elevation,[c] in feet	Approximate elevation of the indicated percentile of the bathymetric data, in feet		Approximate local minimum channel elevation,[d] in feet
								5th percentile	95th percentile	
14	A5664	05/19/21	MO 13	314.9	82,200[e]	681.3	660.2	652.8	668.1	637
15	A5910	05/20/21	US 24	293.2	75,500	661.7	642.4	634.9	651.7	618
16	K0999	05/20/21	MO 41	262.6	79,800	634.5	618.4	607.0	626.4	595
17	G0069	05/20/21	MO 240	226.3	102,000	605.1	582.9	575.4	592.7	562
18	A4574	05/21/21	MO 5	196.6	112,000	580.9	561.3	554.7	566.8	548[f]
19	L0962	05/21/21	IS 70	185.1	110,000	571.1	549.0	541.1	559.2	515
20	L0550/A4497	05/26/21	US 54	143.9	95,700	534.2	511.3	504.3	520.9	499
21	A6288	05/26/21	MO 19	97.9	132,000	497.7	472.1	462.8	484.1	442

[a]River 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.

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

[c]The statistical average of the gridded raster surface of channel-bed elevations.

[d]The minimum channel-bed elevation of the gridded raster surface, not necessarily in any scour holes near the bridge.

[e]Velocity data were not collected at this site owing to a faulty ADCP unit. Streamflow value is from the streamgage at Waverly (streamgage 06895500) 6 hours after the time of the survey to account for the time of travel between Lexington and Waverly.

[f]The minimum channel-bed elevation is in a scour hole near a substructural element at this site.

Figure 6. Bathymetric survey of the Missouri River channel near structure A5664 on State Highway 13 at Lexington, Missouri.

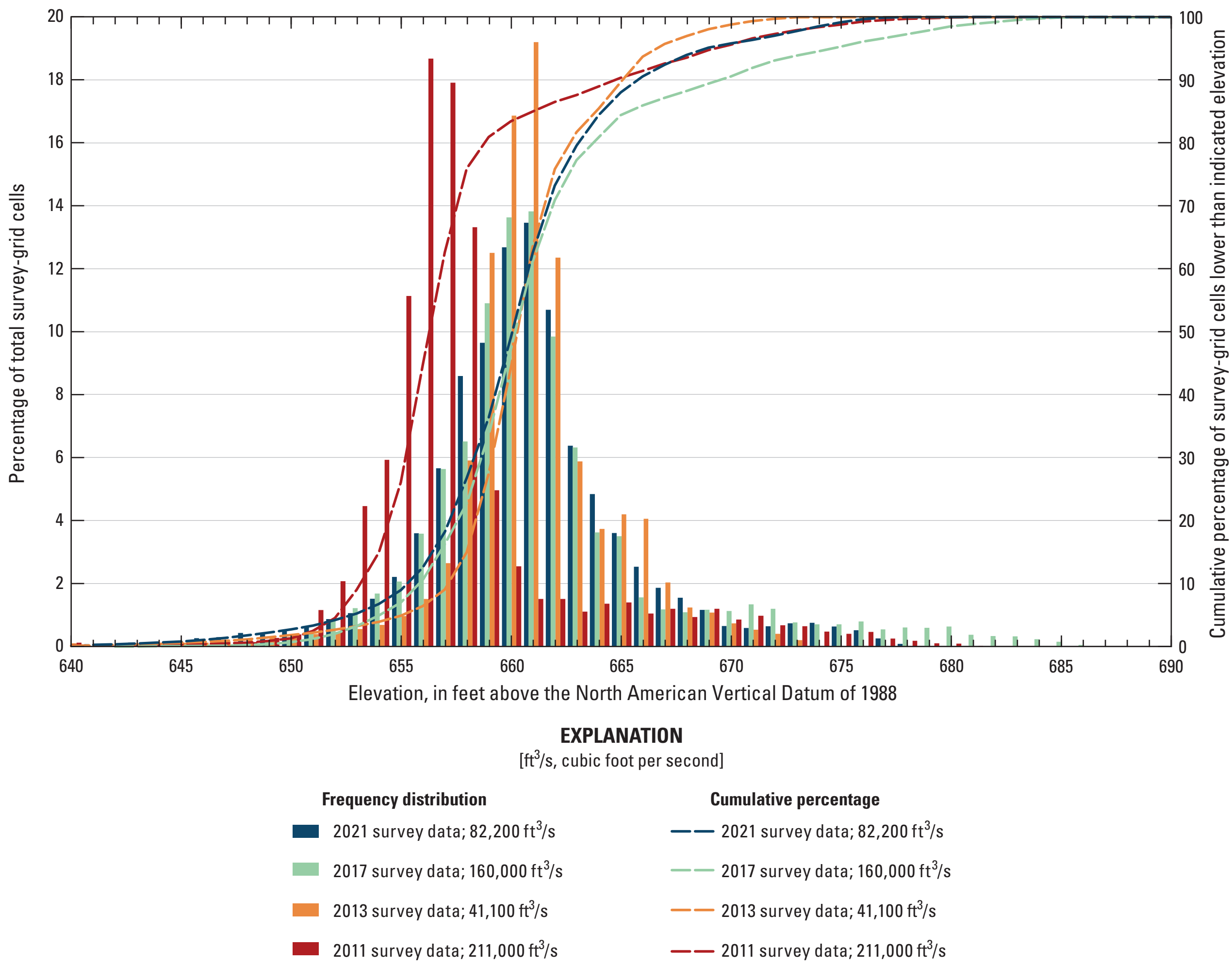


Figure 7. Frequency distribution of bed elevations for bathymetric survey-grid cells in 1-foot elevation bins on the Missouri River near structure A5664 on State Highway 13 at Lexington, Missouri, on May 19, 2021, compared to previous surveys in 2011, 2013, and 2017 (Huizinga, 2012, 2014, and 2020a, respectively).

The difference between the survey on May 19, 2021, and the earliest survey during flooding on July 20, 2011 (fig. 11), indicates about 88 percent of the joint area of interest had detectable change, which means about 12 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition is dominant throughout most of the reach between 2011 and 2021 in the DoD, except along the right (south) bank, and near the spur dikes near the right bank (fig. 11). The average difference between the bathymetric surfaces was +3.22 ft (table 8), indicating substantial channel aggradation between the 2011 and 2021 surveys. The net gain of sediment in the reach between 2011 and 2021 was about 167,600 yd^3, which is the second-largest net gain shown in table 8. The cross section from the 2011 survey along the upstream face of the bridge varies from 5 to 15 ft below the other survey sections, except near the banks (fig. 8). The frequency distribution of bed elevations in 2011 is unique compared to the other distributions at this site, with a substantially higher percentage of cells at lower channel-bed elevations (fig. 7). The stone revetment on the left (north) bank showed signs of localized substantial deposition, whereas the spur dikes on the right (south) bank showed minor scour (fig. 11). As with the previous DoD, deposition or scour apparent on opposing faces of a feature (such as a pier or spur dike) likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

Table 7. Results near piers and bents from surveys on the Missouri River between Kansas City and St. Louis, Missouri, May 19–26, 2021.

[Data are summarized from Huizinga and Rivers (2023). Sites are shown on figure 1. All elevations are in feet above the North American Vertical Datum of 1988. MoDOT, Missouri Department of Transportation; --, not known/applicable]

Site number (fig. 1)	Structure number	MoDOT pier/bent number	Foundation Information				Approximate minimum elevation in scour hole near pier/bent,[a] in feet	Approximate elevation of scour hole at upstream pier/bent face, in feet	Approximate elevation of bedrock near pier/bent, in feet	Approximate distance between bottom of scour hole and bedrock, in feet	Depth of scour hole from average upstream channel bed, in feet
			Type	Width, in feet	Penetration into bedrock, in feet	Bottom of seal course elevation, in feet					
14	A5664	21	Drilled shaft	49.2	28	631.55	656	656	604	52	4
		22	Drilled shaft	31.2	50	634.83	659	659	632	27	4
15	A5910	10	Drilled shaft	32	30	628.00	646	648	605	41	2
		11	Drilled shaft	32	42	614.00	635	635	600	35	5
16	K0999	6	Caisson	16.5	0	--	617	617	574	43	9
		5	Caisson	16.5	0	--	597	597	588	9	20
		4	Footing	12	6	--	623	623	620	3	0
17	G0069	2	Footing	19.5	1	--	576	579	576	0[b]	4[b]
		3	Caisson	19.5	1	--	566	566	562	4	12[b]
		4	Caisson	19.5	1	--	579	579	557	22	9[b]
18	A4574	8	Drilled shaft	32	26	527.00	548	548	506	42	2[c]
		7	Drilled shaft	32	39	533.00	556	556	513	43	2
		6	Footing	30	2	--	563	563	551	12	3
		5	Footing	29	2	--	559[c]	559	560	0[c]	0[c]
19	L0962	16	Footing	12	2	--	538	538	536	2	5
		15	Caisson	18	3	--	538	([c])	519	19[c]	([c])
		14	Caisson	24	1	--	531	531	498	33	17
20	L0550	4	Caisson	24	1	--	503[d]	503[d]	459	44	0[d]
	A4497	4	Drilled shaft	29.9	11	493.50	509[d]	509[d]	459	50	0[d]
21	A6288	6	Drilled shaft	32	27	442.00	469	469	401	68	7
		5	Drilled shaft	32	26	444.50	464	467	413	51	3
		4	Drilled shaft	32	25	451.50	460	460	443	17	10

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

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

[c]Scour hole is substantially affected by adjacent spur dike.

[d]Scour hole mitigated by riprap blanket around pier(s).

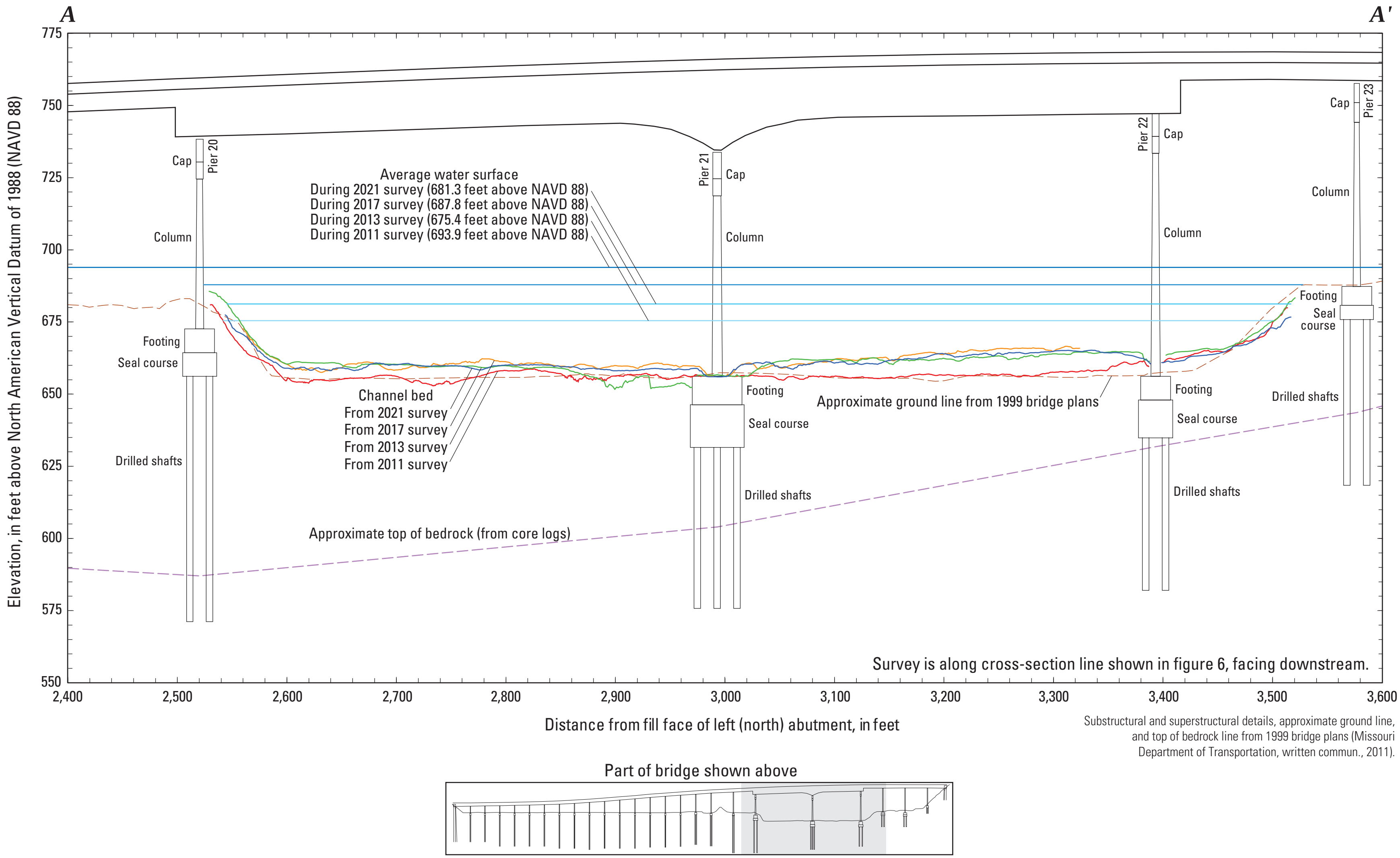


Figure 8. Key features, substructural and superstructural details, and surveyed channel bed of structure A5664 on State Highway 13 crossing the Missouri River at Lexington, Missouri.

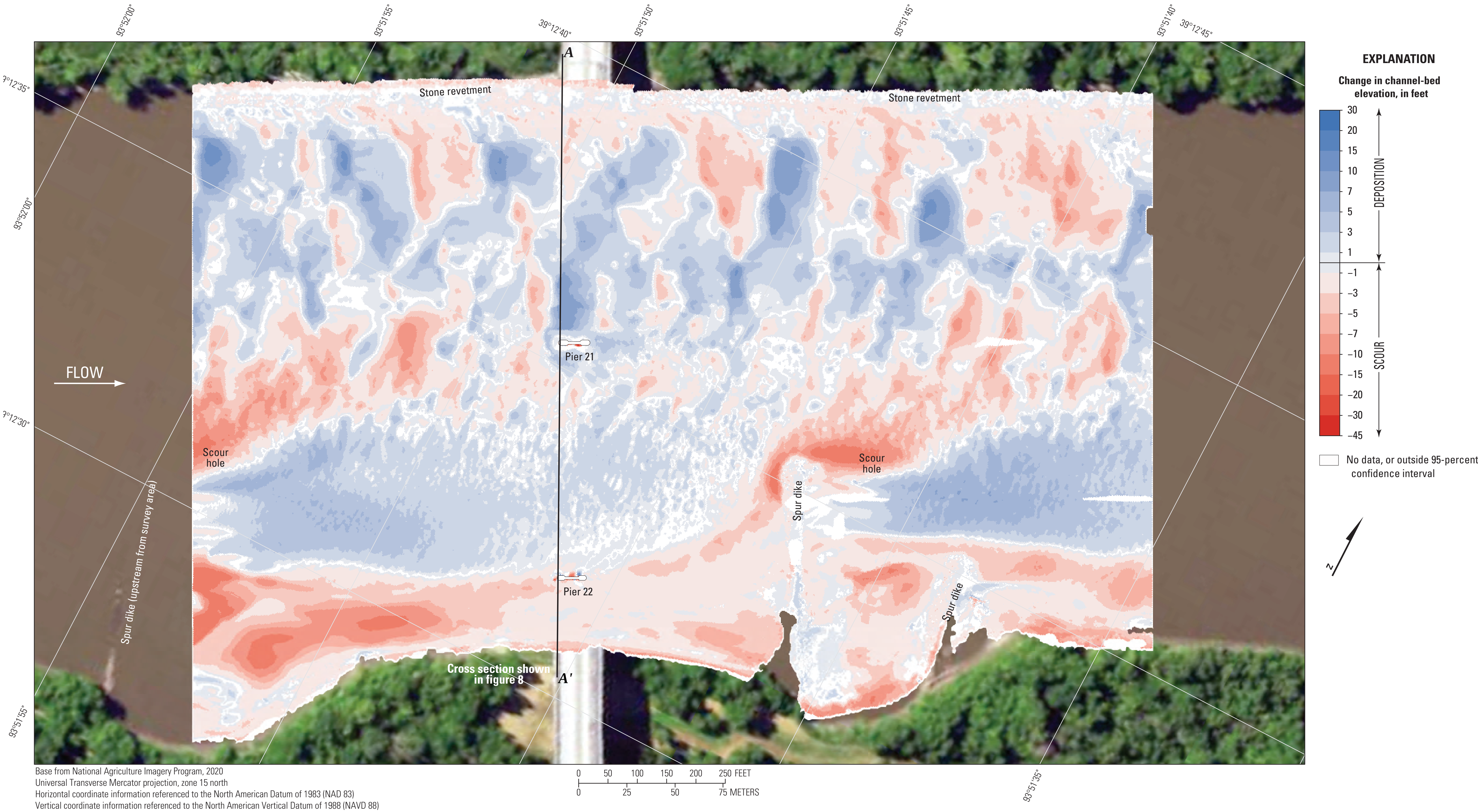


Figure 9. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5664 on State Highway 13 at Lexington, Missouri, on May 19, 2021, and May 23, 2017, with probabilistic thresholding.

Preparing for a survey with the multibeam echosounder mapping system.
Photograph by Richard J. Huizinga, U.S. Geological Survey.

Table 8. Summary information and bathymetric surface difference statistics from surveys on the Missouri River between Kansas City and St. Louis, Missouri, from May 19–26, 2021, and previous surveys (Huizinga, 2012, 2014, 2020a).

[Dates are shown as month/day/year. All elevations are referenced to the North American Vertical Datum of 1988. MoDOT, Missouri Department of Transportation; Min, minimum; Max, maximum; A, Huizinga (2012); B, Huizinga (2014); C, Huizinga (2020a)]

Site number (fig. 1)	MoDOT structure number	Previous survey					Difference between 2021 survey and previous survey[a]		
		Source of data	Date	Streamflow, in cubic feet per second	Surveyed area, in 1×10^6 square feet	Average water-surface elevation, in feet	Streamflow, in cubic feet per second	Surveyed area, in 1×10^6 square feet	Average water-surface elevation, in feet
14	A5664	A	07/20/11	211,000	1.630	693.9	−128,800	0.003	−12.6
		B	04/24/13	41,100	1.263	675.4	41,100	0.370	5.8
		C	05/23/17	160,000	1.683	687.8	−77,800	−0.050	−6.5
15	A5910	A	07/21/11	213,000	1.700	674.3	−137,500	−2.484	−12.6
		B	04/25/13	41,100	1.185	657.0	34,400	0.498	4.7
		C	05/23/17	160,000	1.754	668.8	−84,500	−0.071	−7.1
16	K0999	A	07/21/11	213,000	1.890	648.3	−133,200	0.001	−13.8
		B	04/25/13	44,600	1.131	630.3	35,200	0.760	4.2
		C	05/24/17	152,000	1.930	641.9	−72,200	−0.039	−7.4
17	G0069	A	07/22/11	214,000	1.570	615.7	−112,000	0.034	−10.6
		B	04/26/13	71,000	1.524	602.0	31,000	0.080	3.1
		C	05/24/17	167,000	1.635	610.8	−65,000	−0.031	−5.7
18	A4574	A	07/25/11	219,000	2.034	590.9	−107,000	0.031	−10.0
		B	04/29/13	58,700	1.889	576.0	53,300	0.176	4.9
		C	05/25/17	153,000	2.088	584.7	−41,000	−0.023	−3.8
19	L0962	A	07/26/11	219,000	1.851	580.9	−109,000	0.124	−9.8
		B	04/29/13	63,400	1.527	566.5	46,600	0.448	4.6
		C	05/25/17	155,000	1.868	574.7	−45,000	0.107	−3.6
20	L0550/ A4497	A	01/26/10	155,000	1.526	540.1	−59,300	0.091	−5.9
		A	03/01/11	145,000	1.537	540.0	−49,300	0.080	−5.8
		A	07/27/11	219,000	1.651	544.7	−123,300	−0.034	−10.5
		B	04/30/13	62,500	1.578	530.3	33,200	0.039	3.9
		C	05/31/17	125,000	1.673	537.0	−29,300	−0.056	−2.8
21	A6288	A	07/28/11	215,000	2.475	504.2	−83,000	0.003	−6.5
		B	05/02/13	108,000	2.145	494.6	24,000	0.333	3.1
		C	05/31/17	192,000	2.545	501.1	−60,000	−0.067	−3.4

Table 8. Summary information and bathymetric surface difference statistics from surveys on the Missouri River between Kansas City and St. Louis, Missouri, from May 19–26, 2021, and previous surveys (Huizinga, 2012, 2014, 2020a).—Continued

[Dates are shown as month/day/year. All elevations are referenced to the North American Vertical Datum of 1988. MoDOT, Missouri Department of Transportation; Min, minimum; Max, maximum; A, Huizinga (2012); B, Huizinga (2014); C, Huizinga (2020a)]

Site number (fig. 1)	Statistics of differences between 2021 and previous bathymetric survey surfaces, in feet				Max difference near upstream pier face(s),[c,d] in feet	Joint area of interest with detectable change, in percent	Net volume of cut, in cubic yards	Net volume of fill, in cubic yards	Net change in sediment volume, in cubic yards
	Min[b,c]	Max[b,c]	Average[c]	Standard deviation					
14	−17.8	20.3	3.22	4.63	3.0	88	43,400	211,000	167,600
	−15.8	14.3	−1.14	2.51	1.1	61	49,000	16,900	−32,100
	−25.1	14.6	−0.52	3.42	4.2	92	89,700	61,200	−28,500
15	−33.9	19.5	0.44	6.00	1.9	86	104,000	127,000	23,000
	−22.5	13.0	−1.55	3.31	−3.7	64	63,200	20,200	−43,000
	−25.4	15.9	−0.33	3.85	2.8	91	95,900	77,600	−18,300
16	−28.1	36.6	−0.09	4.79	11.9	73	94,500	90,100	−4,400
	−18.9	20.8	−0.70	2.71	−4.8	58	37,800	20,900	−16,900
	−26.0	13.0	−0.95	2.88	11.8	85	97,800	42,000	−55,800
17	−21.7	16.0	1.84	4.95	8.8	76	51,200	131,000	79,800
	−27.9	16.5	0.66	4.12	5.3	71	55,800	81,900	26,100
	−36.4	20.8	−0.09	3.24	7.8	87	64,400	59,900	−4,500
18	−21.7	17.8	−0.53	3.18	5.8	76	91,900	62,200	−29,700
	−16.1	16.1	−0.54	2.79	−3.8	64	67,900	44,100	−23,800
	−25.2	12.3	−0.44	2.34	5.2	85	77,500	48,800	−28,700
19	−34.9	38.6	2.47	5.88	8.2	82	72,200	209,400	137,200
	−27.2	26.5	2.74	4.00	4.1	72	28,900	140,400	111,500
	−33.3	38.4	1.59	5.00	11.3	91	77,300	177,500	100,200
20	−12.8	35.4	−1.21	4.65	32.5	73	94,200	49,000	−45,200
	−16.4	39.5	1.27	5.10	39.5	72	46,700	92,100	45,400
	−12.4	47.0	4.52	5.37	47.0	83	25,700	246,800	221,100
	−12.9	33.8	0.49	4.68	24.2	62	57,900	75,300	17,400
	−21.9	16.8	−0.35	2.34	−7.8	77	50,400	34,300	−16,100
21	−20.4	23.4	−1.38	3.82	−9.9	73	146,700	56,400	−90,300
	−26.2	20.4	−3.05	2.11	−11.0	71	177,700	8,500	−169,200
	−26.7	26.4	−0.39	2.69	−10.1	76	85,500	58,100	−27,400

[a]A positive value of difference means the 2021 value was larger than previous value, whereas a negative value means the 2021 value was smaller than the previous value.

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

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

[d]The maximum difference near the upstream pier face was taken near the location of the "approximate elevation of scour hole at upstream pier face" in table 7.

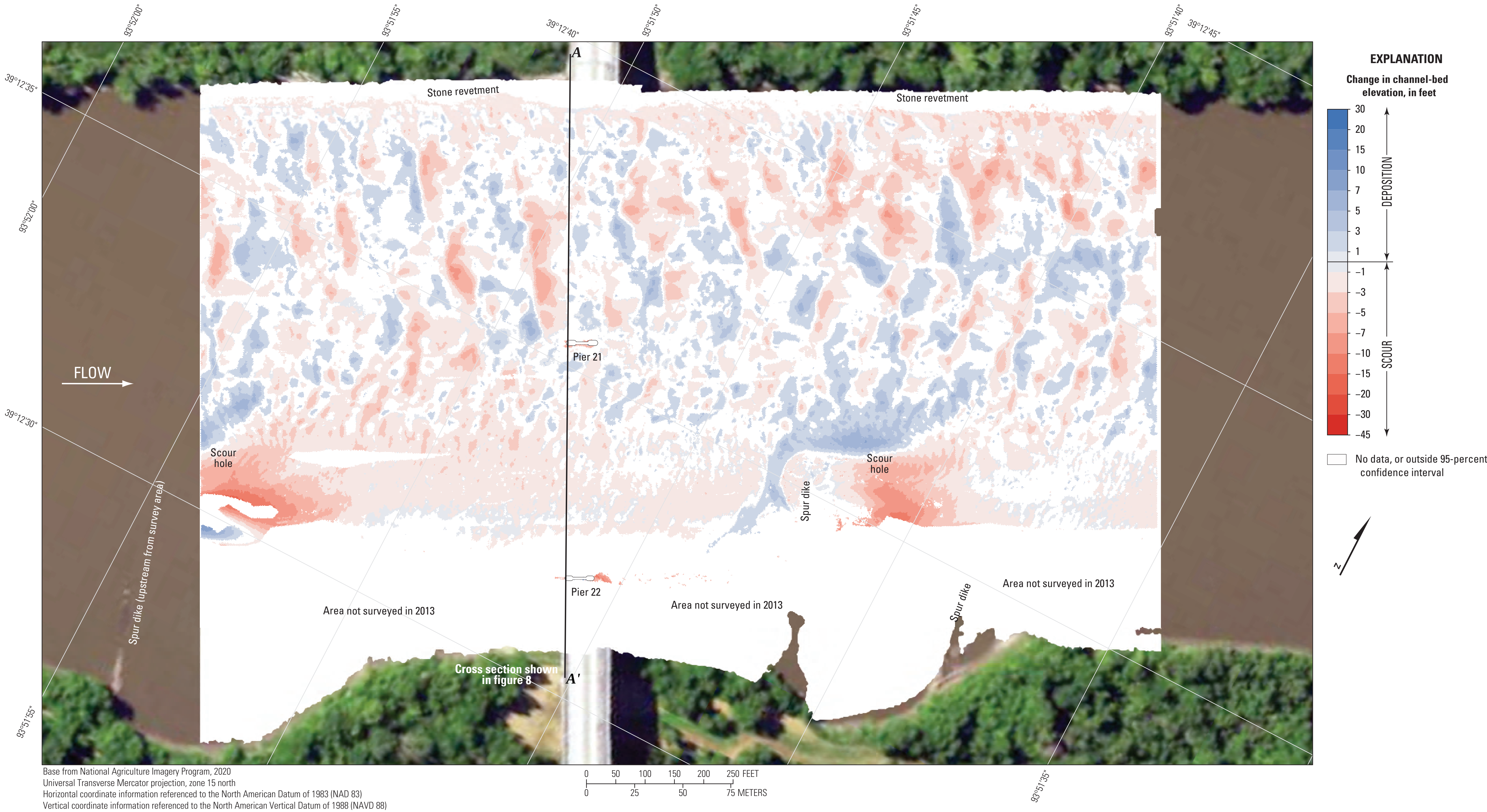


Figure 10. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5664 on State Highway 13 at Lexington, Missouri, on May 19, 2021, and April 24, 2013, with probabilistic thresholding.

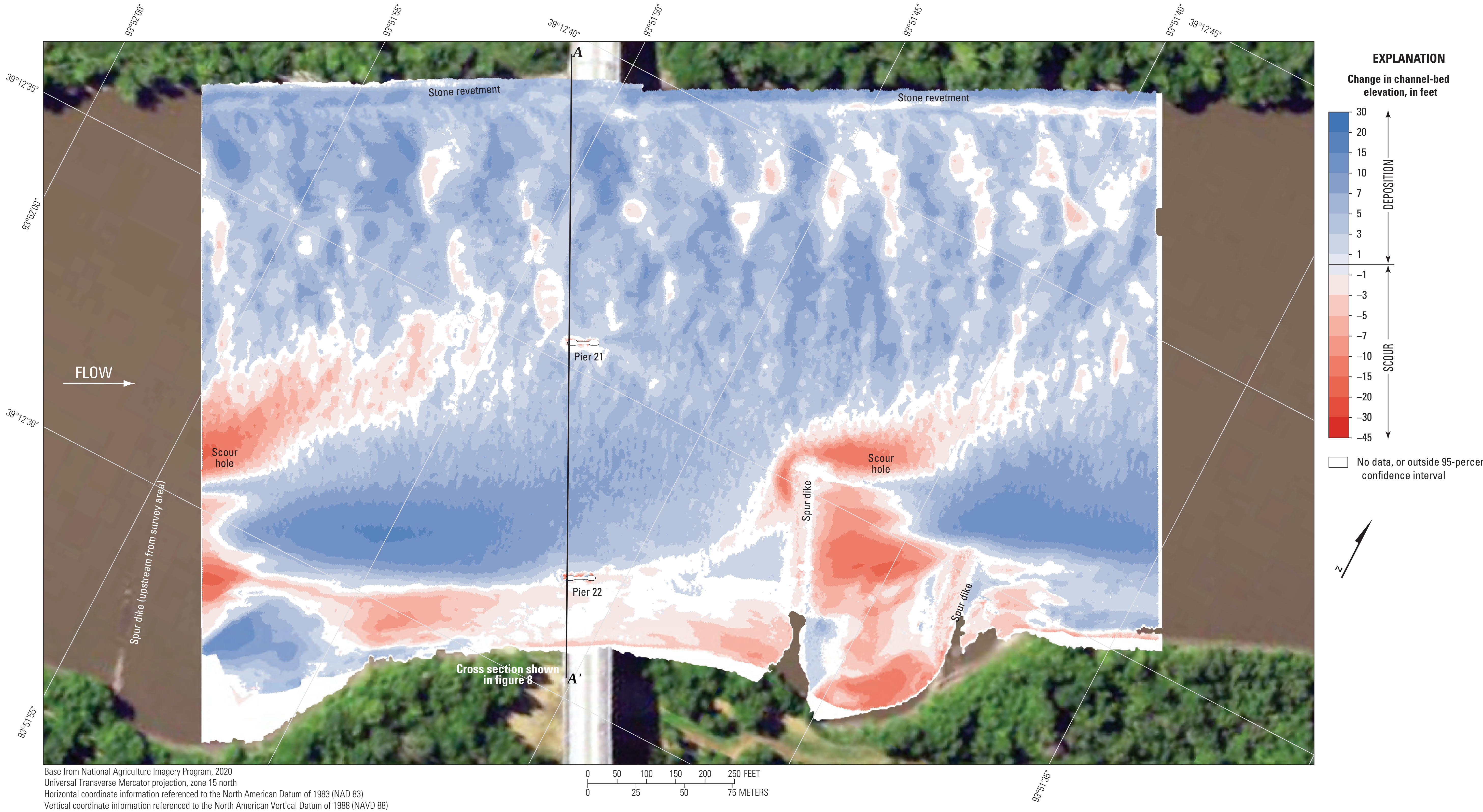


Figure 11. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5664 on State Highway 13 at Lexington, Missouri, on May 19, 2021, and July 20, 2011, with probabilistic thresholding.

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

Structure A5910 (site 15; table 2) 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). The site was surveyed on May 20, 2021, when the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 661.7 ft (table 6; fig. 12) and streamflow was about 75,500 ft^3/s during the survey (table 6).

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. 12). The survey area extended about 650 ft upstream from the centerline of structure A5910 (fig. 12). The channel-bed elevations ranged from about 635 to 652 ft throughout the survey area (5th to 95th percentile range of the bathymetric data; fig. 13), 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. 12; table 6). The thalweg was about 10 to 15 ft deeper than the channel bed in the middle of the channel (fig. 12). A line of small to medium 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. 12). A localized deep scour hole downstream from the downstream spur dike on the left bank had a minimum channel-bed elevation of about 618 ft (table 6; fig. 12). As in previous surveys (Huizinga, 2012, 2014, 2022a), a rock outcrop was evident on the right (south) bank at 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. 12).

The minor scour holes near piers 10 and 11 were difficult to discern from nearby dunes and ripples (figs. 12, 1.2). Information from bridge plans indicates that piers 10 and 11 are founded on shafts drilled 30 to 42 ft into bedrock, and the thickness of bed material between the bottom of the scour hole and bedrock at pier 11 is 35 ft (table 7; fig. 14). Along the upstream bridge face, the surveyed bed from 2021 generally falls within the fluctuating range of elevations seen in previous multibeam surveys (fig. 14).

The difference between the survey on May 20, 2021, and the previous survey on May 23, 2017 (fig. 15), indicates about 91 percent of the joint area of interest had detectable change, which means about 9 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition appears dominant in the thalweg along the right (south) bank throughout the reach between 2017 and 2021 in the DoD, whereas scour is evident in the area along a line between the southern tips of the spur dikes (fig. 15). The average difference between the bathymetric surfaces was –0.33 ft (table 8), indicating minor channel degradation between the 2017 and 2021 surveys. The net volume of cut in the reach from 2017 to 2021 was about 95,900 yd^3, and the net volume of fill was about 77,600 yd^3, resulting in a net loss of about 18,300 yd^3 of sediment between 2017 and 2021 (table 8). The cross section from the 2021 survey along the upstream face of the bridge is similar to the 2017 survey section between the left bank and pier 10, is 5 to 12 ft below the 2017 survey section between piers 10 and 11 and is 5 to 12 ft above the 2017 survey section between pier 11 and the right bank (fig. 14). The frequency distribution of bed elevations in 2021 is similar to the 2017 distribution above an elevation of 644 ft, but the 2017 distribution has a higher percentage of cells at a lower channel-bed elevation than 2021 (fig. 13). The rock outcrop, stone revetment, and longitudinal spur dike on the right (south) bank showed localized signs of minor scour and deposition, and the various spur dikes throughout the channel showed minor scour on one face and deposition on the other (fig. 15). As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 20, 2021, and the survey on April 25, 2013 (fig. 16), indicates about 64 percent of the joint area of interest had detectable change, which means about 36 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Minor erosion and deposition appear nearly balanced throughout the reach between 2013 and 2021 in the DoD, with scour slightly more dominant and with localized substantial erosion and deposition downstream from the spur dikes (fig. 16). However, the average difference between the bathymetric surfaces was –1.55 ft (table 8), indicating moderate channel degradation between the 2013 and 2021 surveys, and the net loss of sediment between 2013 and 2021 was about 43,000 yd^3, which is more than double the net loss of sediment between 2017 and 2021 (table 8). The cross section from the 2021 survey along the upstream face of bridge is roughly similar to the 2013 survey section, varying 5 to 10 ft above and below the 2013 section (fig. 14). The frequency distribution of bed elevations in 2021 appears similar in shape to 2013, but with a lower percentage of cells in the middle range of channel-bed elevations (fig. 13). The rock outcrop, stone revetment, and longitudinal spur dike on the right (south) bank are within the bounds of uncertainty (fig. 16). A substantial part of the channel on the left (north) side was not surveyed in 2013 because of generally lower flows (table 8) and shallow depths in that area. As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 20, 2021, and the earliest survey during flooding on July 21, 2011 (fig. 17), indicates about 86 percent of the joint area of interest had detectable change, which means about 14 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition is dominant in the thalweg along the right (south) bank between 2011 and 2021 in the DoD, and substantial deposition is balanced with moderate to substantial erosion downstream from the upstream spur dike, whereas the scour hole downstream from the downstream spur dike is substantially larger in 2021 than

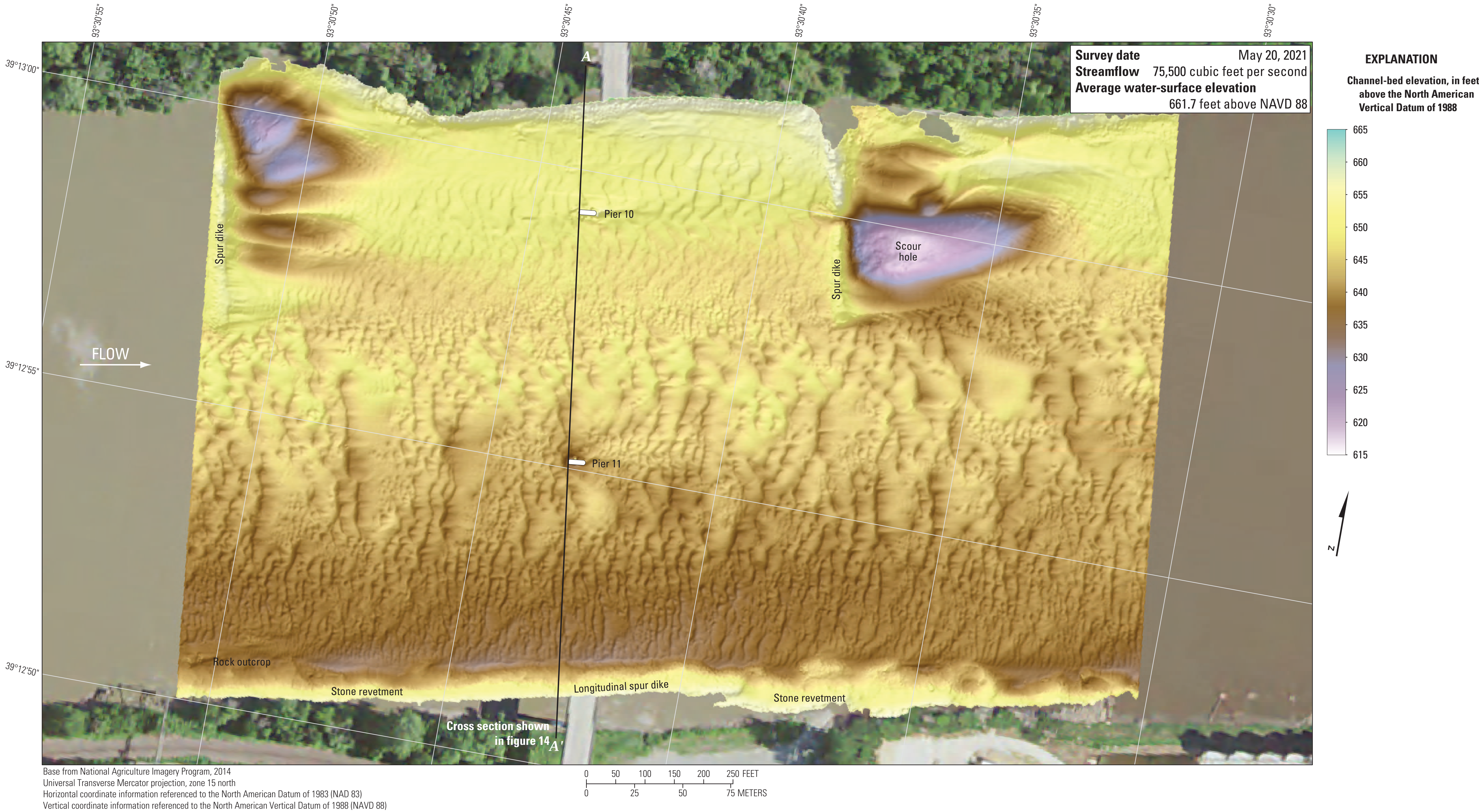


Figure 12. Bathymetric survey of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri.

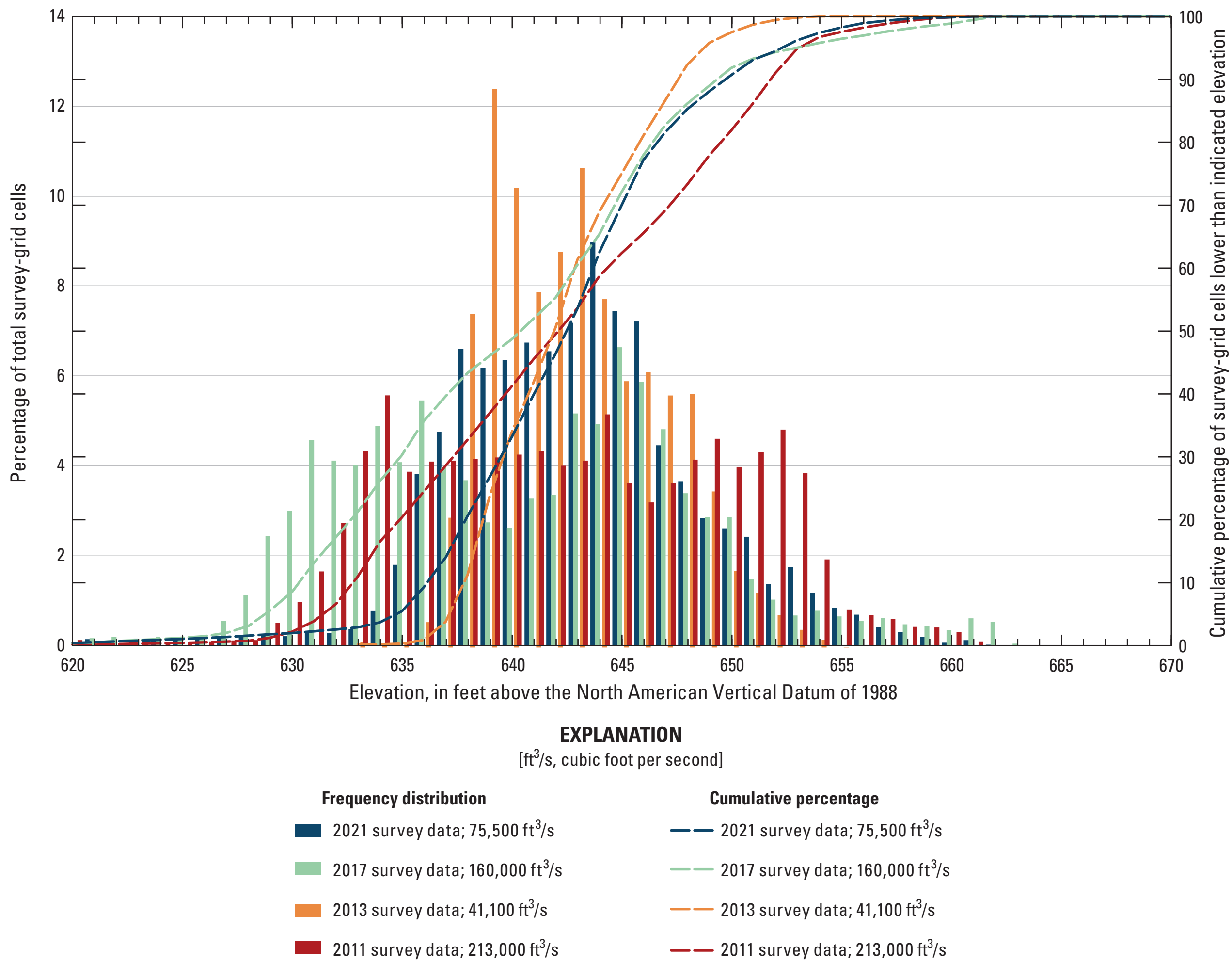


Figure 13. Frequency distribution of bed elevations for bathymetric survey-grid cells in 1-foot elevation bins on the Missouri River near structure A5910 on U.S. Highway 24 at Waverly, Missouri, on May 20, 2021, compared to previous surveys in 2011, 2013, and 2017 (Huizinga, 2012, 2014, and 2020a, respectively).

2011 (fig. 17). The average difference between the bathymetric surfaces was +0.44 ft (table 8), indicating minor to moderate deposition between the 2011 and 2021 surveys, with a net gain of sediment of about 23,000 yd³ (table 8). The frequency distribution of bed elevations in 2011 was wider and lower than 2021, with a lower percentage of cells at a wider range of channel-bed elevations (fig. 13). The rock outcrop, stone revetment, and longitudinal spur dike on the right (south) bank showed localized signs of minor scour and deposition, and the various spur dikes throughout the channel showed minor scour on one face and deposition on the other (fig. 17). As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to "Uncertainty Estimation" section).

The vertically averaged velocity vectors indicate mostly uniform flow in the middle of the channel, with velocities ranging from about 3 to 9 feet per second (ft/s; fig. 18). Local lower velocities and turbulence were observed downstream from the various spur dikes on the left (north) bank (fig. 18). The wake vortices downstream from the main channel piers were not pronounced and seemed to be no greater than the general nonuniformity of flow observed in the channel (fig. 18). Minor localized turbulence was present in all the sections (fig. 18).

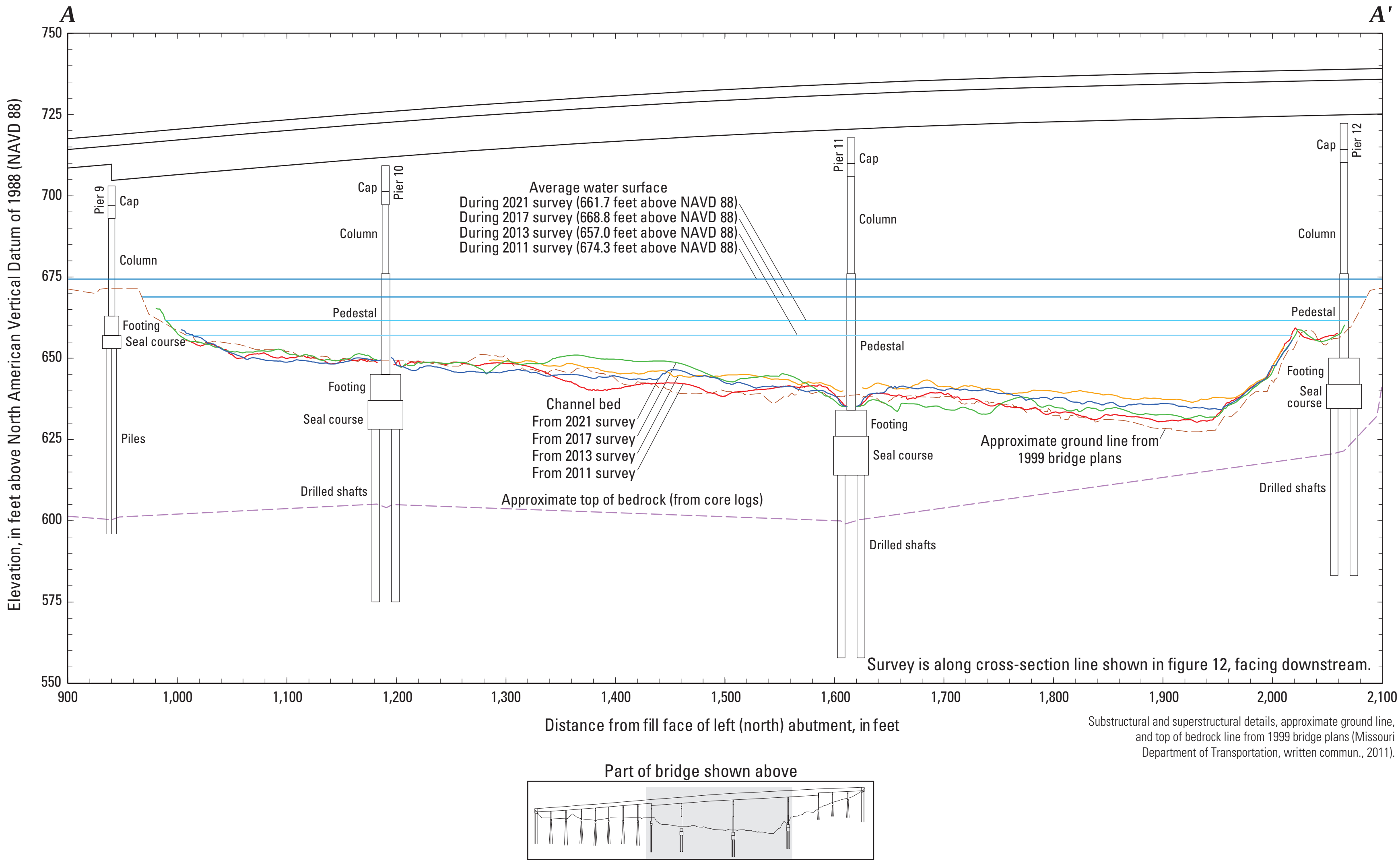


Figure 14. Key features, substructural and superstructural details, and surveyed channel bed of structure A5910 on U.S. Highway 24 crossing the Missouri River at Waverly, Missouri.

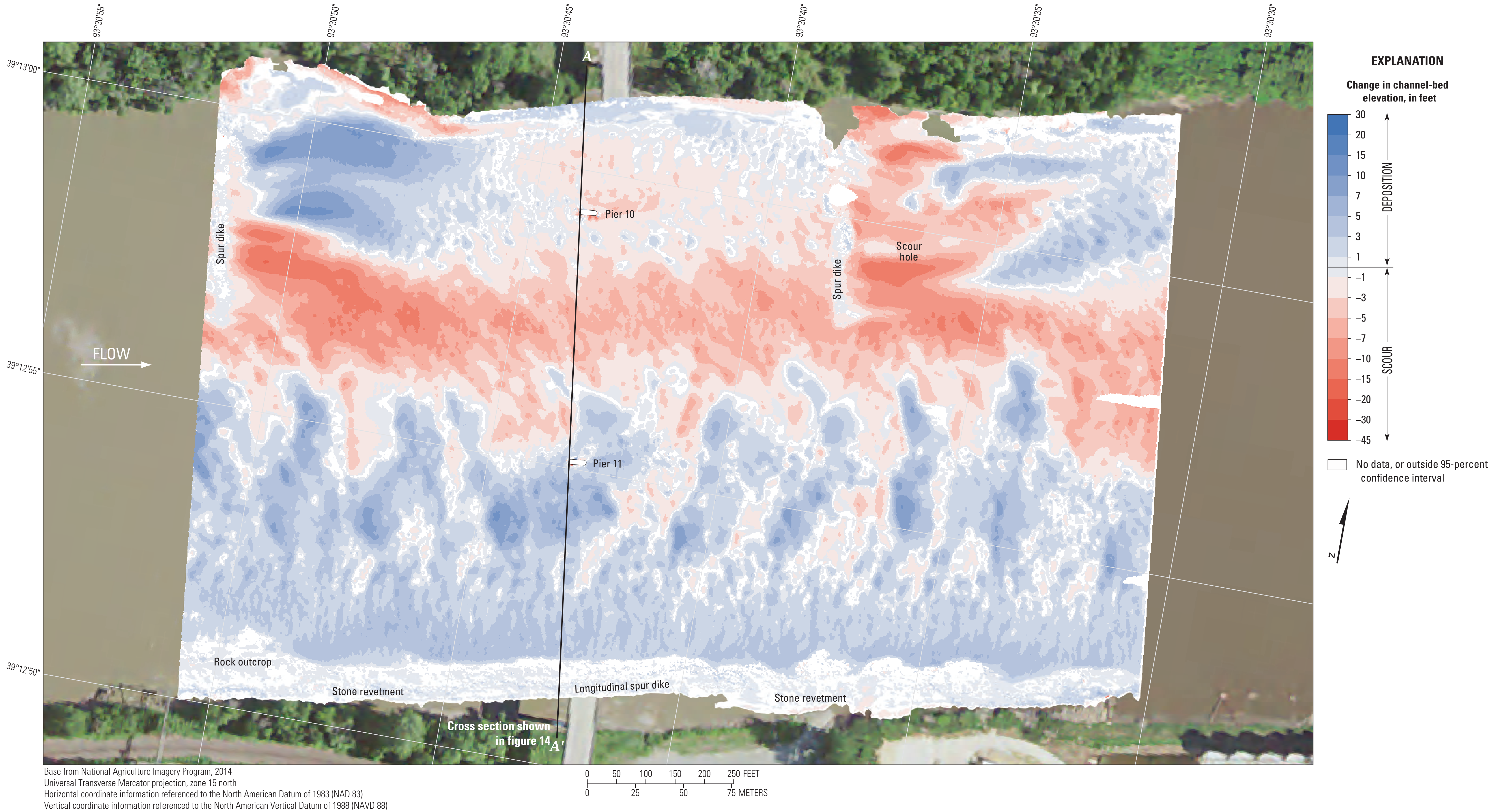


Figure 15. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri, on May 20, 2021, and May 23, 2017, with probabilistic thresholding.

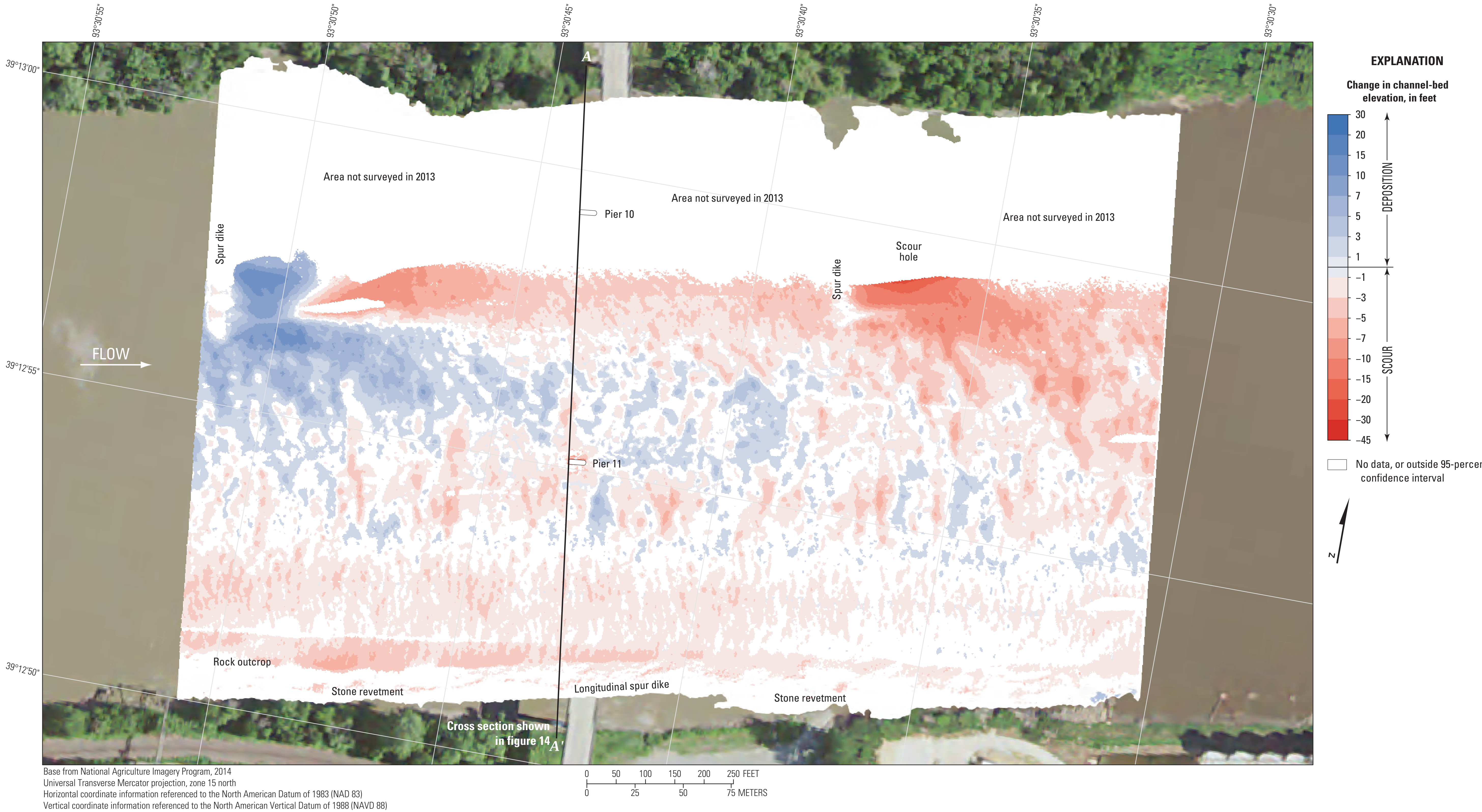


Figure 16. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri, on May 20, 2021, and April 25, 2013, with probabilistic thresholding.

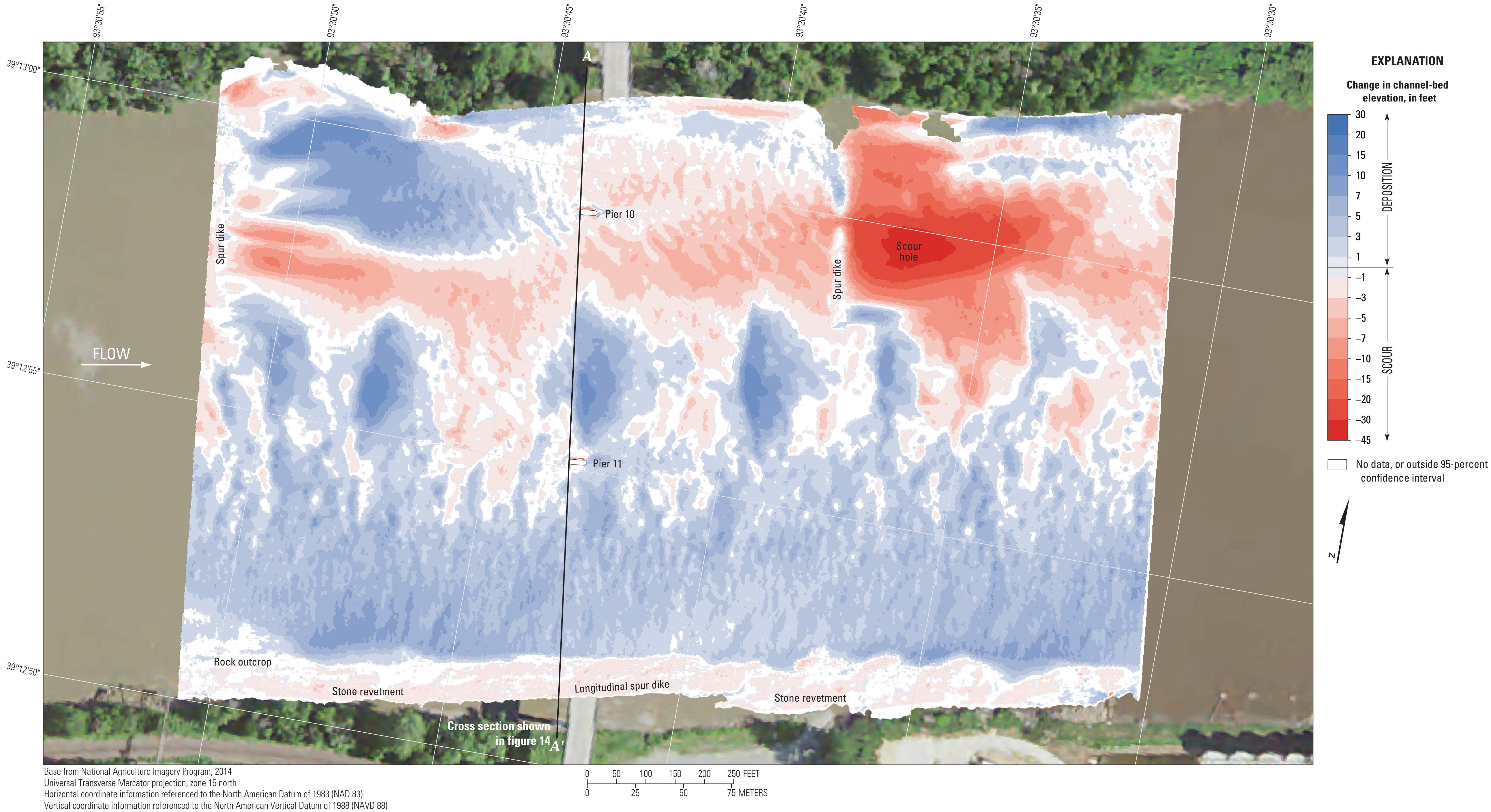


Figure 17. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri, on May 20, 2021, and July 21, 2011, with probabilistic thresholding.

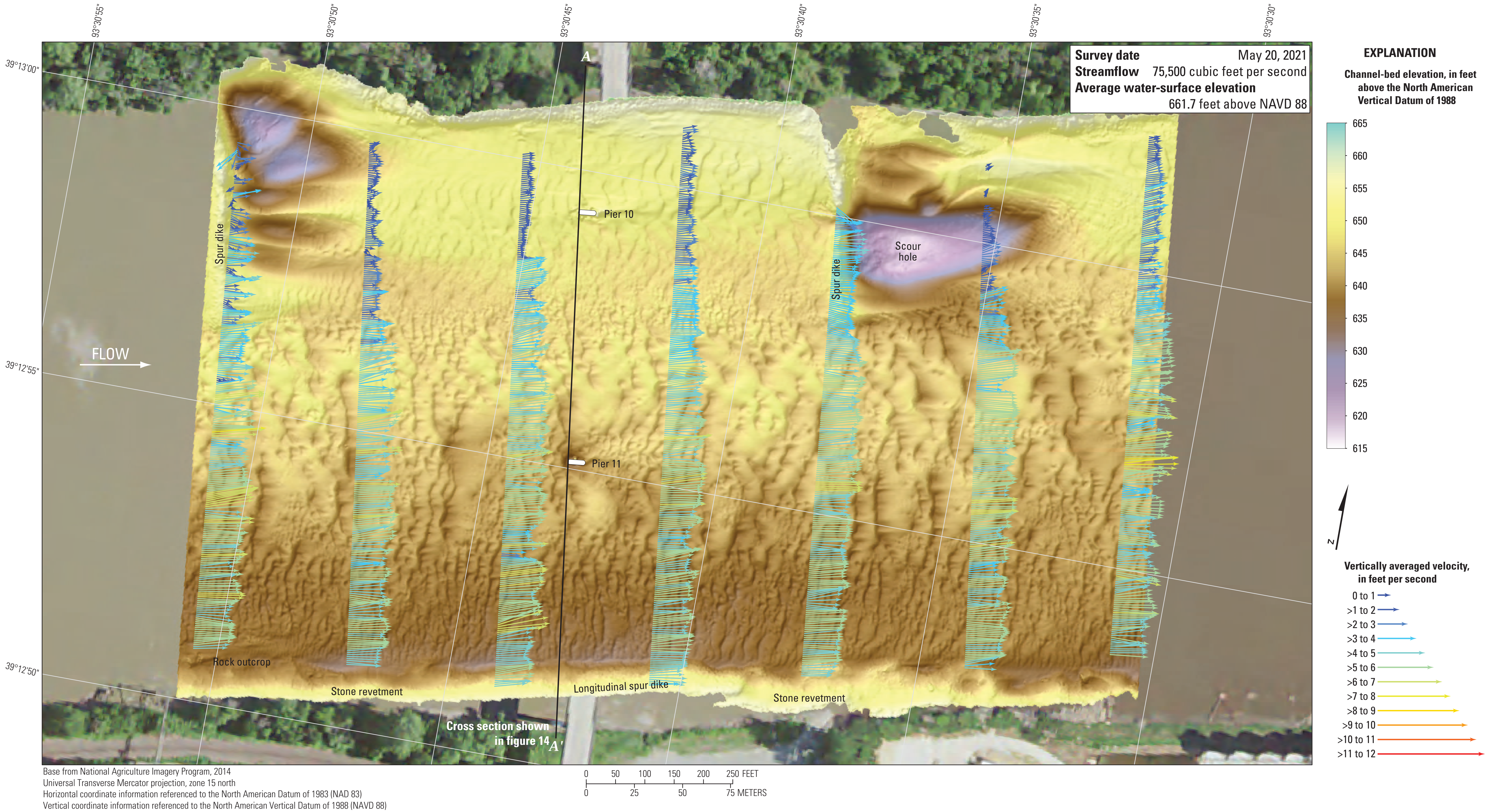


Figure 18. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A5910 on U.S. Highway 24 at Waverly, Missouri.

Structure K0999 on State Highway 41 at Miami, Missouri

Structure K0999 (site 16; table 2) on 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 20, 2021, when the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 634.5 ft (table 6; fig. 19) and streamflow was measured at about 79,800 ft^3/s during the survey (table 6).

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. 19). The survey area extended about 625 ft upstream from the centerline of structure K0999 (fig. 19). The approximate channel-bed elevations ranged from about 607 to 626 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 6; fig. 20) except near pier 5, in the scour hole downstream from the spur dike on the left (north) bank, and in the troughs of the medium dune features in the thalweg along the toe of the rock outcrop along the right (south) side of the channel (fig. 19; table 6). The thalweg was along the outside of the river bend on the right (south) bank and was about 10 to 15 ft deeper than the bed in the middle of the channel (fig. 19). Numerous superimposed small to medium dunes and ripples were present throughout the channel (fig. 19). As in previous surveys (Huizinga, 2012, 2014, 2020a), a rock outcrop was present on the right (south) bank throughout the reach (fig. 19).

A substantial scour hole was observed near pier 5 of structure K0999 (figs. 19, 1.3*C*, 1.3*D*), and was about 20 ft below the average channel-bed elevation upstream from the scour hole (table 7). Information from bridge plans indicates that piers 5 and 6 are caissons founded on bedrock, with about 43 ft of bed material between the bottom of the scour hole and bedrock at pier 6 but only about 9 ft of bed material between the bottom of the scour hole and bedrock at pier 5 (table 7; fig. 21). Pier 4 is founded on a footing on bedrock according to bridge plans (fig. 21), and no scour hole was observed near the pier (fig. 19; table 7). The surveyed bed along the cross section generally was similar to previous multibeam surveys (fig. 21), but as much as 15 ft higher than previous surveys between the left bank and pier 6. 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. 21). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (Brown and others, 2018; American Association of State Highway Transportation Officials, 2020), but full exposure of usually buried substructural elements warrants special consideration and observation.

The difference between the survey on May 20, 2021, and the previous survey on May 24, 2017 (fig. 22), indicates about 85 percent of the joint area of interest had detectable change, which means about 15 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Scour appears dominant throughout most of the reach between 2017 and 2021 in the DoD, except downstream from the spur dike on the left (north) bank and in the troughs of the medium dunes near the thalweg (fig. 22). The average difference between the bathymetric surfaces was –0.95 ft (table 8), indicating moderate channel degradation between the 2017 and 2021 surveys. The net volume of cut in the reach from 2017 to 2021 was about 97,800 yd^3, and the net volume of fill was about 42,000 yd^3, resulting in a net loss of about 55,800 yd^3 of sediment between 2017 and 2021 (table 8). The cross section from the 2021 survey along the upstream face of the bridge generally varies above and below the 2017 survey section (fig. 21). The frequency distribution of bed elevations in 2021 appears similar in shape to 2017, but with a slightly higher percentage of cells at a lower channel-bed elevations (fig. 20). The rock outcrop on the right (south) bank showed localized signs of minor deposition and scour, but most of the rock outcrop indicated changes within 1 ft of the 2017 elevation, or changes outside the 95-percent confidence interval (fig. 22).

The difference between the survey on May 20, 2021, and the survey on April 25, 2013 (fig. 23), indicates about 58 percent of the joint area of interest had detectable change, which means about 42 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). A substantial part of the channel on the left (north) side was not surveyed in 2013 because of generally lower flows (table 8) and shallow depths in that area. Erosion again appears dominant throughout most of the joint reach between 2013 and 2021 in the DoD, except localized minor deposition throughout the downstream channel thalweg (fig. 23). The average difference between the bathymetric surfaces was –0.70 ft (table 8), again indicating moderate channel degradation between the 2013 and 2021 surveys, but the net loss of sediment between 2013 and 2021 was about 16,900 yd^3, which is less than the net loss of sediment between 2017 and 2021 (table 8). The cross section from the 2021 survey along the upstream face of bridge generally is similar to but 5 to 10 ft lower than the 2013 survey section (fig. 21). The frequency distribution of bed elevations in 2013 has a substantially higher percentage of cells at lower channel-bed elevations than 2021 (fig. 20). The difference in the distribution may be the result of the substantially narrower survey area in 2013, and general lack of bank information (fig. 23). The rock outcrop on the right (south) bank showed localized signs of minor scour (fig. 23); however, the differences of most of the channel near the rock outcrop were equivocal. As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to "Uncertainty Estimation" section).

The difference between the survey on May 20, 2021, and the earliest survey during flooding on July 21, 2011 (fig. 24), indicates about 73 percent of the joint area of interest had detectable change, which means about 27 percent of the differences in the joint area of interest are equivocal and within the

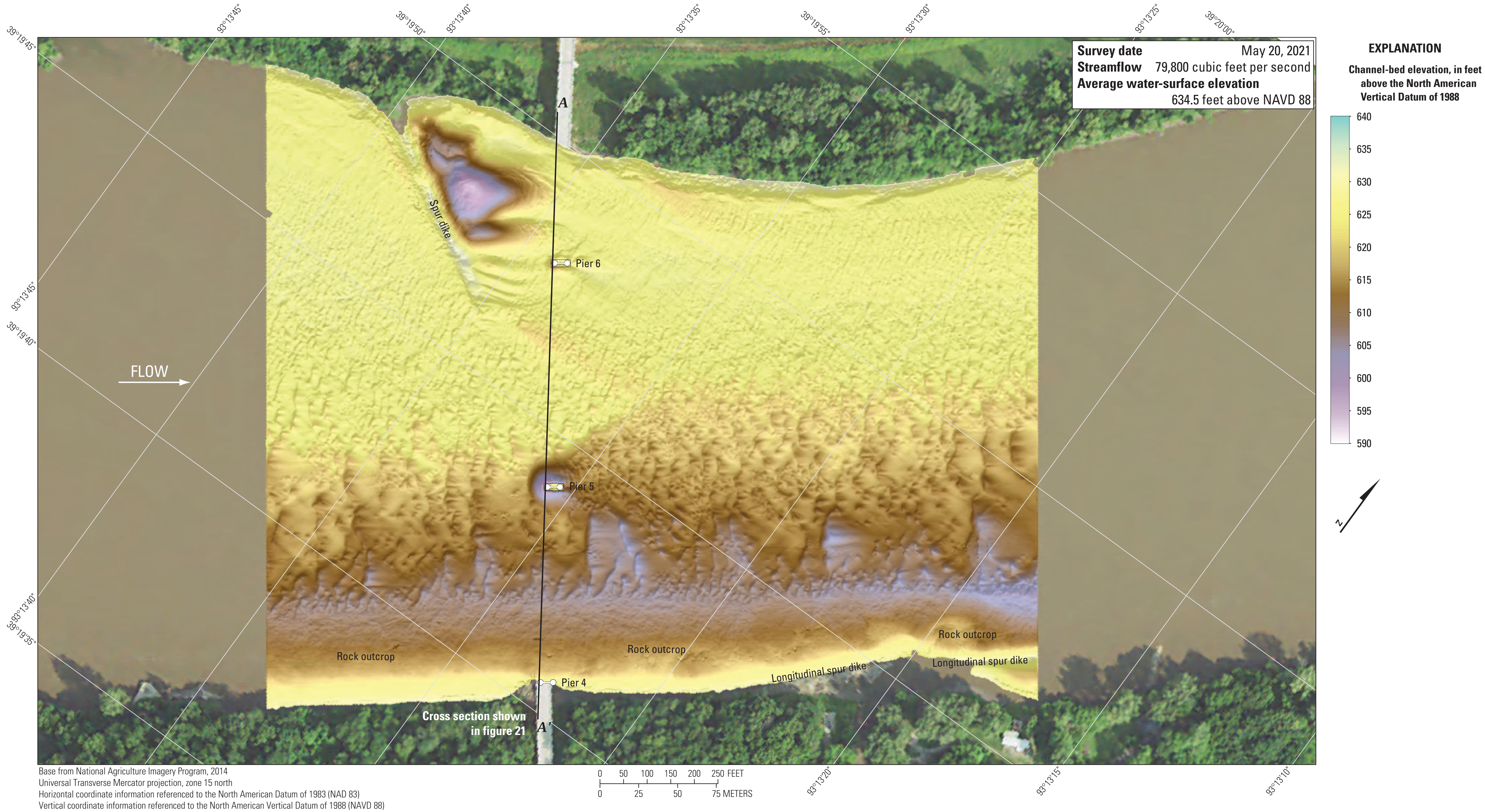


Figure 19. Bathymetric survey of the Missouri River channel near structure K0999 on State Highway 41 at Miami, Missouri.

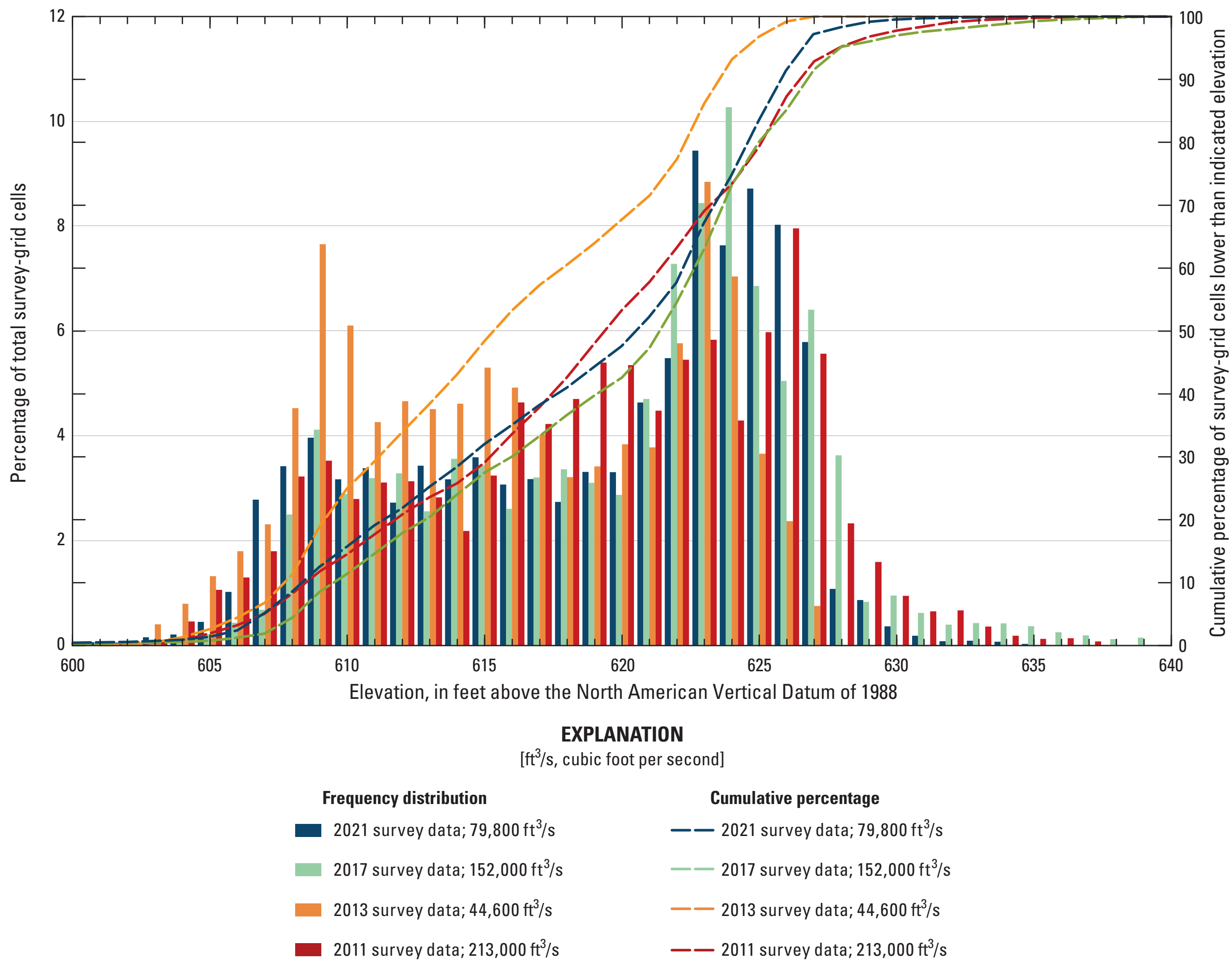


Figure 20. Frequency distribution of bed elevations for bathymetric survey-grid cells in 1-foot elevation bins on the Missouri River near dual bridge structure K0999 on State Highway 41 at Miami, Missouri, on May 20, 2021, compared to previous surveys in 2011, 2013, and 2017 (Huizinga, 2012, 2014, and 2020a, respectively).

bounds of uncertainty (table 8). Scour and deposition appear approximately balanced throughout the reach between 2011 and 2021 in the DoD, with substantial scour near the spur dike on the left (north) bank balanced with deposition downstream, and alternating scour and deposition in the thalweg (fig. 24). The average difference between the bathymetric surfaces was –0.09 ft (table 8), indicating a rough balance between aggradation and degradation between the 2011 and 2021 surveys. There was a net loss of sediment between 2011 and 2021 of only 4,400 yd^3 (table 8). The frequency distribution of bed elevations in 2011 is remarkably similar to 2021 (fig. 20). The rock outcrop on the right (south) bank showed localized signs of minor scour, particularly higher on the bank (fig. 24); however, the differences of most of the channel near the rock outcrop were equivocal. As with the previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The vertically averaged velocity vectors indicate mostly uniform flow in the middle of the channel, with velocities ranging from about 2 to 8 ft/s (fig. 25). Lower velocities and turbulence were observed downstream from the spur dike on the left (north) side of the channel (fig. 25). The wake vortices downstream from piers 5 and 6 were not pronounced and seemed to be no greater than the general nonuniformity of flow observed in the channel (fig. 25). Minor localized turbulence again was present in all the sections (fig. 25).

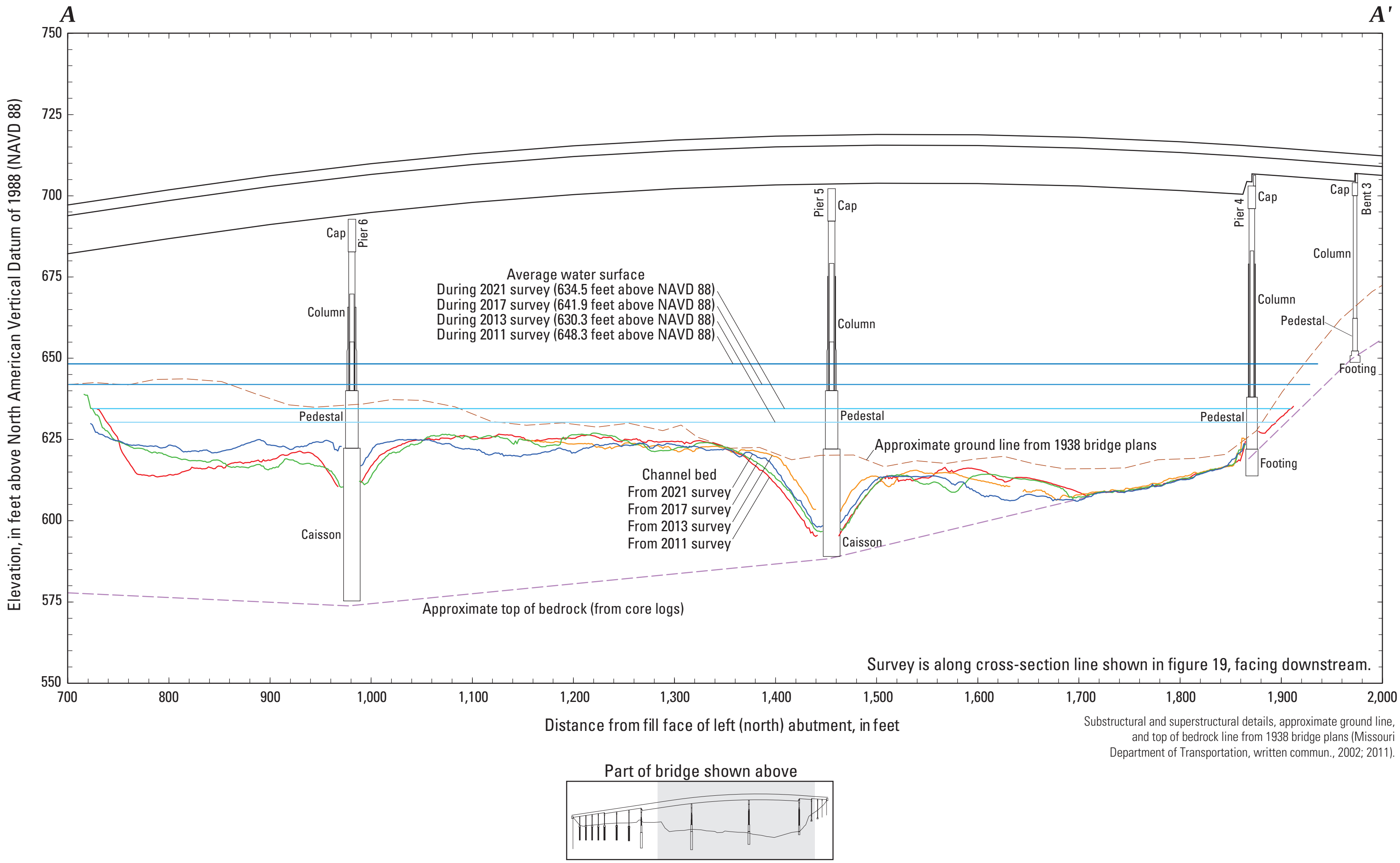


Figure 21. Key features, substructural and superstructural details, and surveyed channel bed of structure K0999 on State Highway 41 crossing the Missouri River at Miami, Missouri.

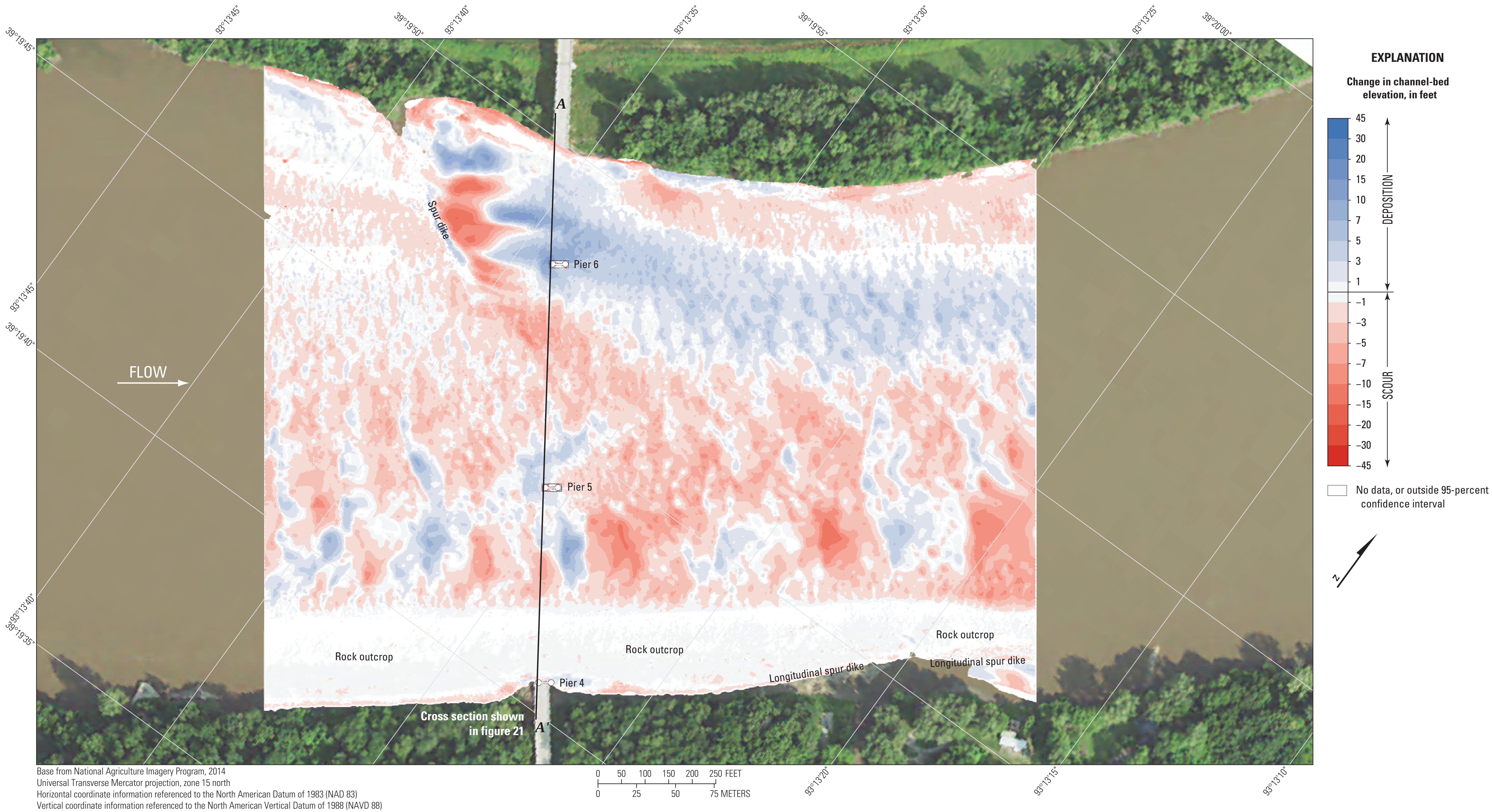


Figure 22. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure K0999 on State Highway 41 at Miami, Missouri, on May 20, 2021, and May 24, 2017, with probabilistic thresholding.

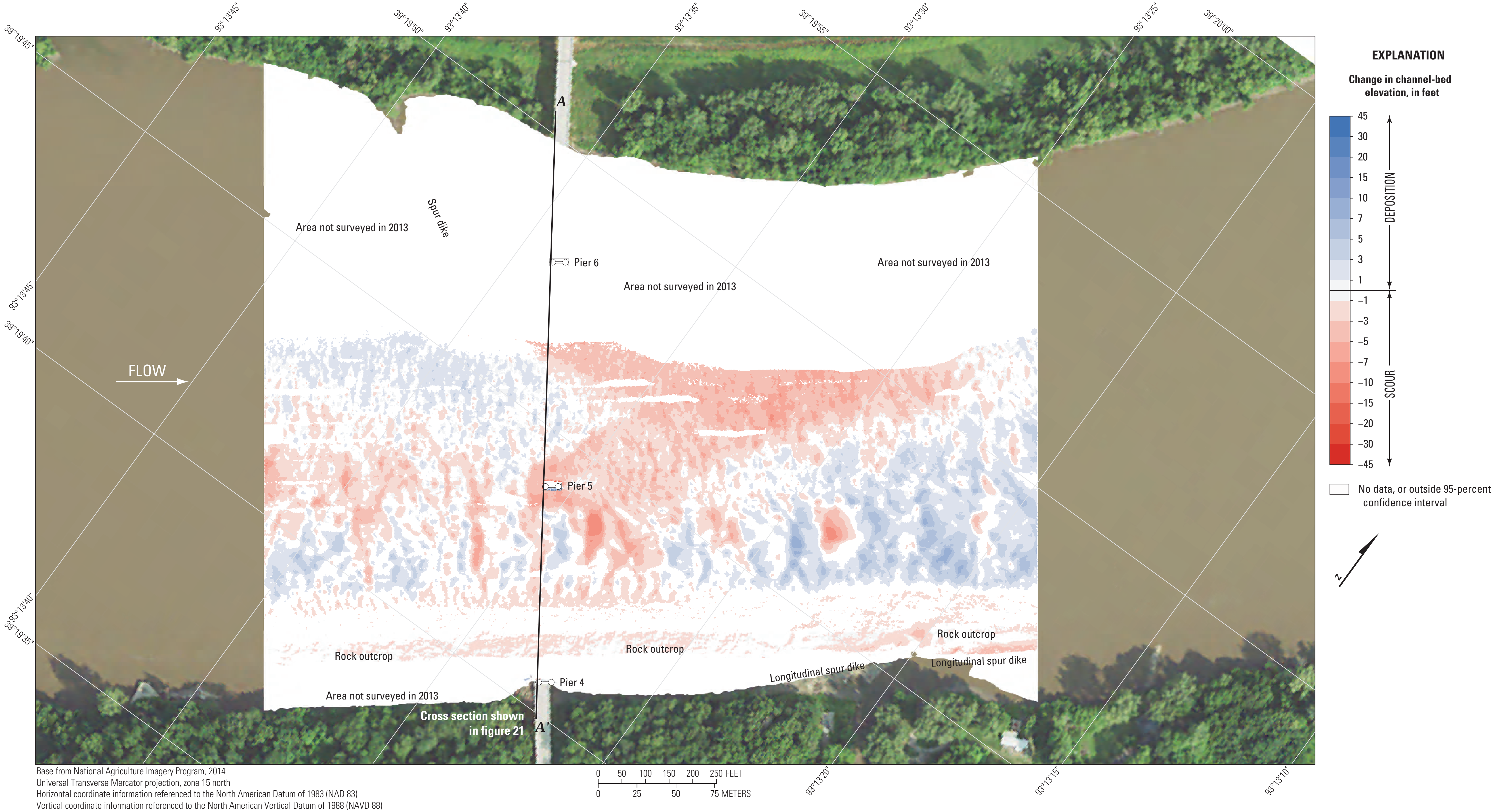


Figure 23. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure K0999 on State Highway 41 at Miami, Missouri, on May 20, 2021, and April 25, 2013, with probabilistic thresholding.

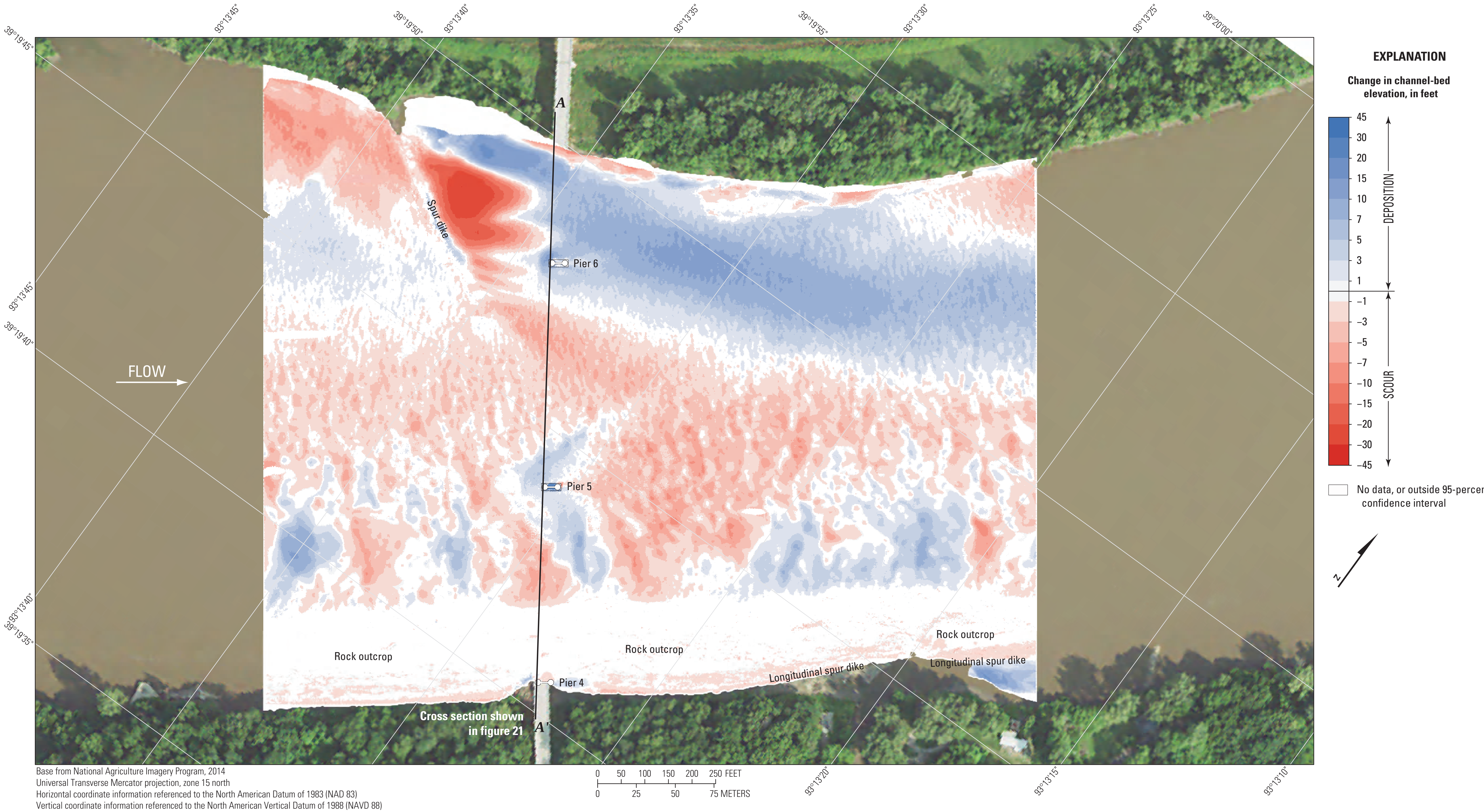


Figure 24. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure K0999 on State Highway 41 at Miami, Missouri, on May 20, 2021, and July 21, 2011, with probabilistic thresholding.

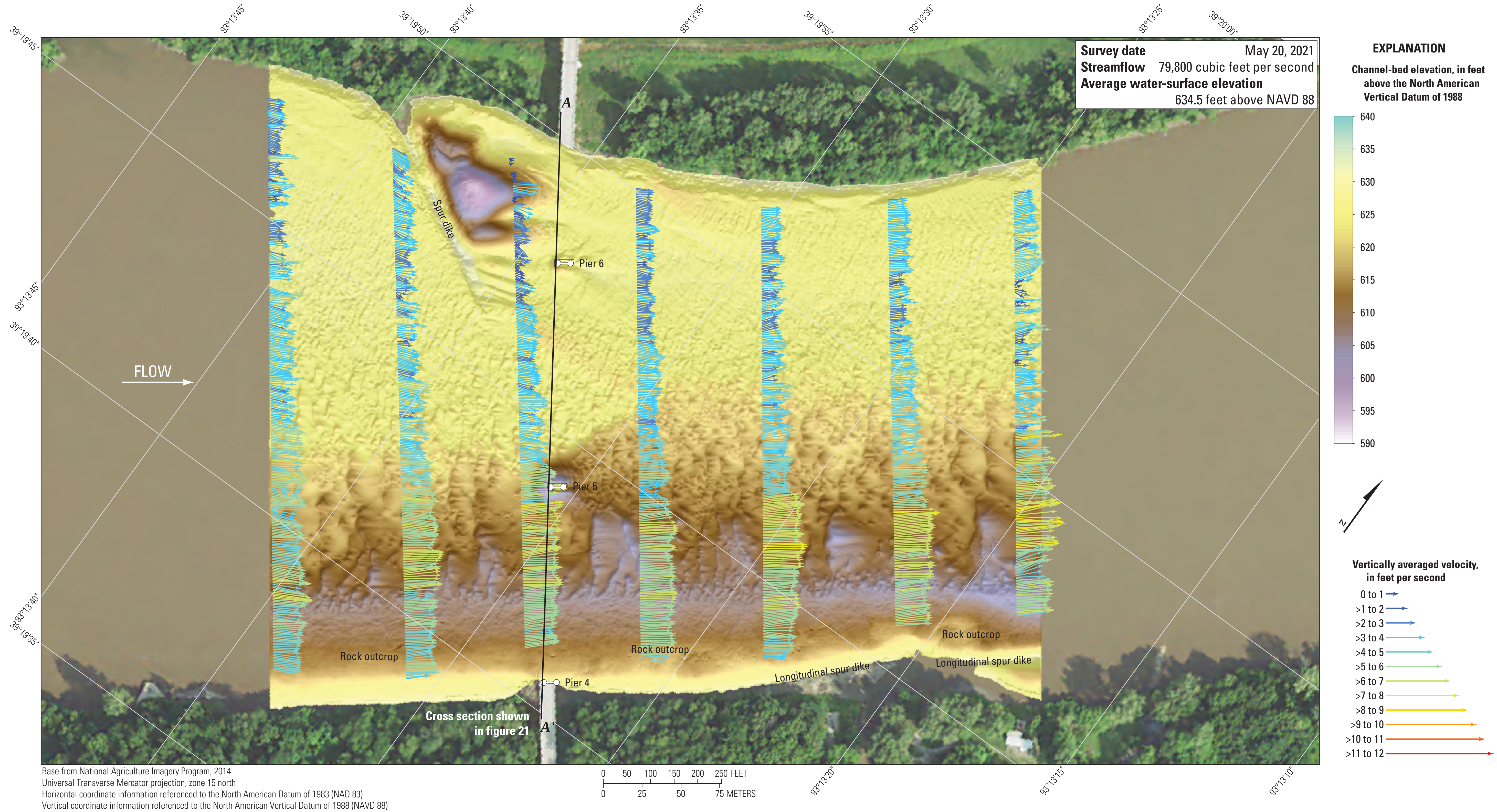


Figure 25. Bathymetry and vertically averaged velocities of the Missouri River channel near structure K0999 on State Highway 41 at Miami, Missouri.

Structure G0069 on State Highway 240 at Glasgow, Missouri

Structure G0069 (site 17; table 2) on 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 20, 2021, when the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 605.1 ft (table 6; fig. 26) and streamflow on the Missouri River was about 102,000 ft^3/s during the survey (table 6).

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. 26). 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. 26). The channel-bed elevations ranged from about 575 to 593 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 6; fig. 27), except near the piers and downstream from the spur dike on the downstream right (west) bank (fig. 26; table 6). A poorly defined thalweg was present along the left (east) bank and deepened in the downstream reach (fig. 26). The thalweg was about 13 to 15 ft deeper than the channel bed in the middle of the downstream reach (fig. 26). Two spur dikes, and a sunken barge observed during the previous surveys, were present on the right (west) bank (fig. 26). A series of medium to large dunes were present in the middle of the channel throughout the reach, and numerous small dunes and ripples were present throughout the rest of the channel (fig. 26).

A small scour hole was observed near pier 2 (fig. 26), which is founded on a footing on bedrock according to bridge plans (fig. 28; table 6). The ground line from the bathymetric survey indicated that the right side of the footing seemed to be undermined in previous surveys in 2011 and 2013 but was partially buried in bed sediments in the 2017 and 2021 surveys (figs. 28, 1.4*B*, 1.4*C*). 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. 28). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (Brown and others, 2018; American Association of State Highway Transportation Officials, 2020), 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 (figs. 26, 1.4*D*, 1.4*E*), and a smaller scour hole was observed near pier 4 (fig. 26). Near pier 3, the scour hole had a minimum channel-bed elevation of about 566 ft (table 7), which is about 12 ft below the average channel bed immediately upstream from the pier (figs. 26, 28; table 7). Near pier 4, the scour hole had a minimum channel-bed elevation of about 579 ft (figs. 26, 28; table 7). Information from bridge plans indicates that piers 3 and 4 are caissons founded on bedrock, and there is about 4 ft of bed material between the bottom of the scour hole and bedrock at pier 3 and about 22 ft at pier 4 (fig. 28; table 7). The scour observed near all the highway bridge piers was substantially affected by the upstream railroad bridge piers (fig. 26). The 2021 surveyed bed generally was most similar to the 2011 multibeam survey (fig. 28). 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 2021 survey (fig. 28), with further evidence from small dunes and ripples in that area (fig. 26).

The difference between the survey on May 20, 2021, and the previous survey on May 24, 2017 (fig. 29), indicates about 87 percent of the joint area of interest had detectable change, which means about 13 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Scour and deposition appear roughly balanced throughout the reach between 2017 and 2021 in the DoD, with scour and deposition alternating in the troughs of the medium to large dune features in the middle of the channel and lengthwise throughout the right (west) side of the reach (fig. 29). The average difference between the bathymetric surfaces was –0.09 ft (table 8), indicating a rough balance between aggradation and degradation between the 2017 and 2021 surveys. The net volume of cut in the reach from 2017 to 2021 was about 64,400 yd^3, and the net volume of fill was about 59,900 yd^3, resulting in a net loss of only about 4,500 yd^3 of sediment between 2017 and 2021 (table 8). The scour holes near piers 3 and 4 were narrower and shallower in 2021 and in 2017 (fig. 28). The frequency distribution of bed elevations in 2021 appears similar in shape to 2017, with a slightly higher percentage of cells in the middle range of channel-bed elevations than 2017 (fig. 27). The rock outcrop and stone revetment along the left (east) bank showed localized signs of minor to moderate scour, but most of the rock outcrop indicated changes within 1 ft of the 2017 elevation, or changes outside the 95-percent confidence interval (fig. 29).

The difference between the survey on May 20, 2021, and the survey on April 26, 2013 (fig. 30), indicates about 71 percent of the joint area of interest had detectable change, which means about 29 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition appears dominant throughout most of the reach between 2013 and 2021 in the DoD, except for localized erosion in the troughs of the medium to large dunes in the middle of the channel, and erosion along the upstream right (west) bank and downstream left (east) bank (fig. 30). The average difference between the bathymetric surfaces was +0.66 ft (table 8), indicating moderate channel aggradation between the 2013 and 2021 surveys, and the net gain of sediment between 2013 and 2021 was about 26,100 yd^3 (table 8). The scour holes near piers 3 and 4 are nearly identical in 2013 and 2021 (fig. 28). However, the frequency distribution of bed elevations in 2013 has a substantially higher percentage of cells at lower channel-bed elevations than 2021 (fig. 27). The stone revetment along the right (southeast) bank showed

Figure 26. Bathymetric survey of the Missouri River channel near structure G0069 on State Highway 240 at Glasgow, Missouri.

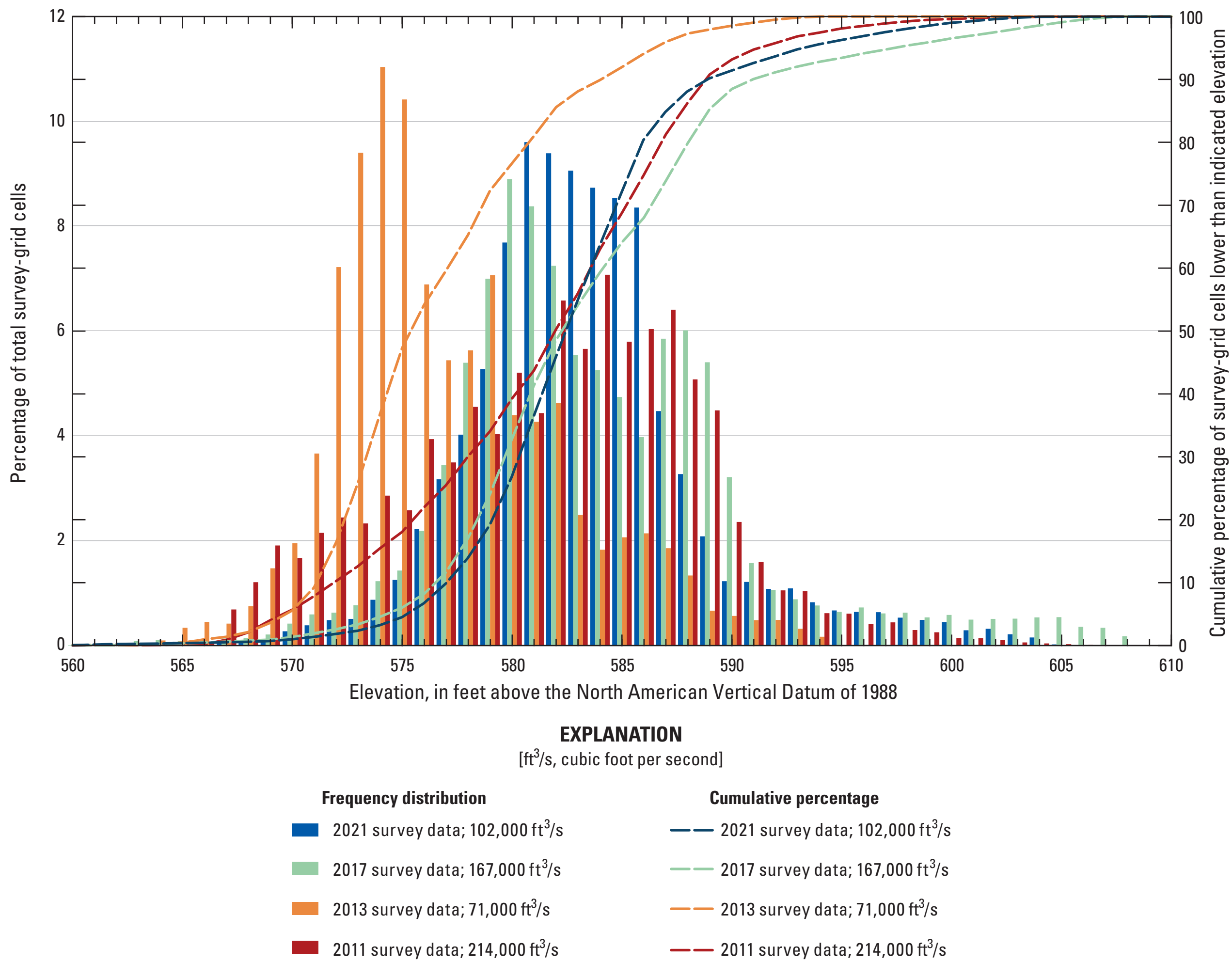


Figure 27. Frequency distribution of bed elevations for bathymetric survey-grid cells in 1-foot elevation bins on the Missouri River near structure G0069 on State Highway 240 at Glasgow, Missouri, on May 20, 2021, compared to previous surveys in 2011, 2013, and 2017 (Huizinga, 2012, 2014, and 2020a, respectively).

localized signs of scour and deposition downstream from the bridge and moderate deposition upstream from the bridges (fig. 30). The bedrock outcrop and stone revetment along the left (east) bank showed localized signs of minor to moderate scour (fig. 30); however, the differences of most of the channel near the rock outcrop were equivocal. As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 20, 2021, and the earliest survey during flooding on July 22, 2011 (fig. 31), indicates about 76 percent of the joint area of interest had detectable change, which means about 24 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition appears dominant throughout the reach between 2011 and 2021 in the DoD, with substantial localized erosion in the troughs of the medium to large dunes in the middle of the channel and downstream from the spur dike on the downstream right (west) bank (fig. 31). The average difference between the bathymetric surfaces was +1.84 ft, and a net gain of sediment between 2011 and 2021 of about 79,800 yd^3 further indicates substantial deposition in the reach between 2011 and 2021 (table 8). Nevertheless, the frequency distribution of bed elevations in 2021 appears similar in shape to 2011 above 585 ft; however, below about 585 ft, the 2011 distribution has a substantially higher percentage of cells for a given elevation (fig. 27).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the reach, ranging from about 4 to 9 ft/s, except downstream from the spur dikes on the right (west) bank and the boat ramp on the left (east) bank (fig. 32). The wake vortices downstream from piers 2 and 3 were not pronounced and seemed to be no greater than the general nonuniformity of flow observed in the channel (fig. 32). Minor localized turbulence again was present in all the sections (fig. 32).

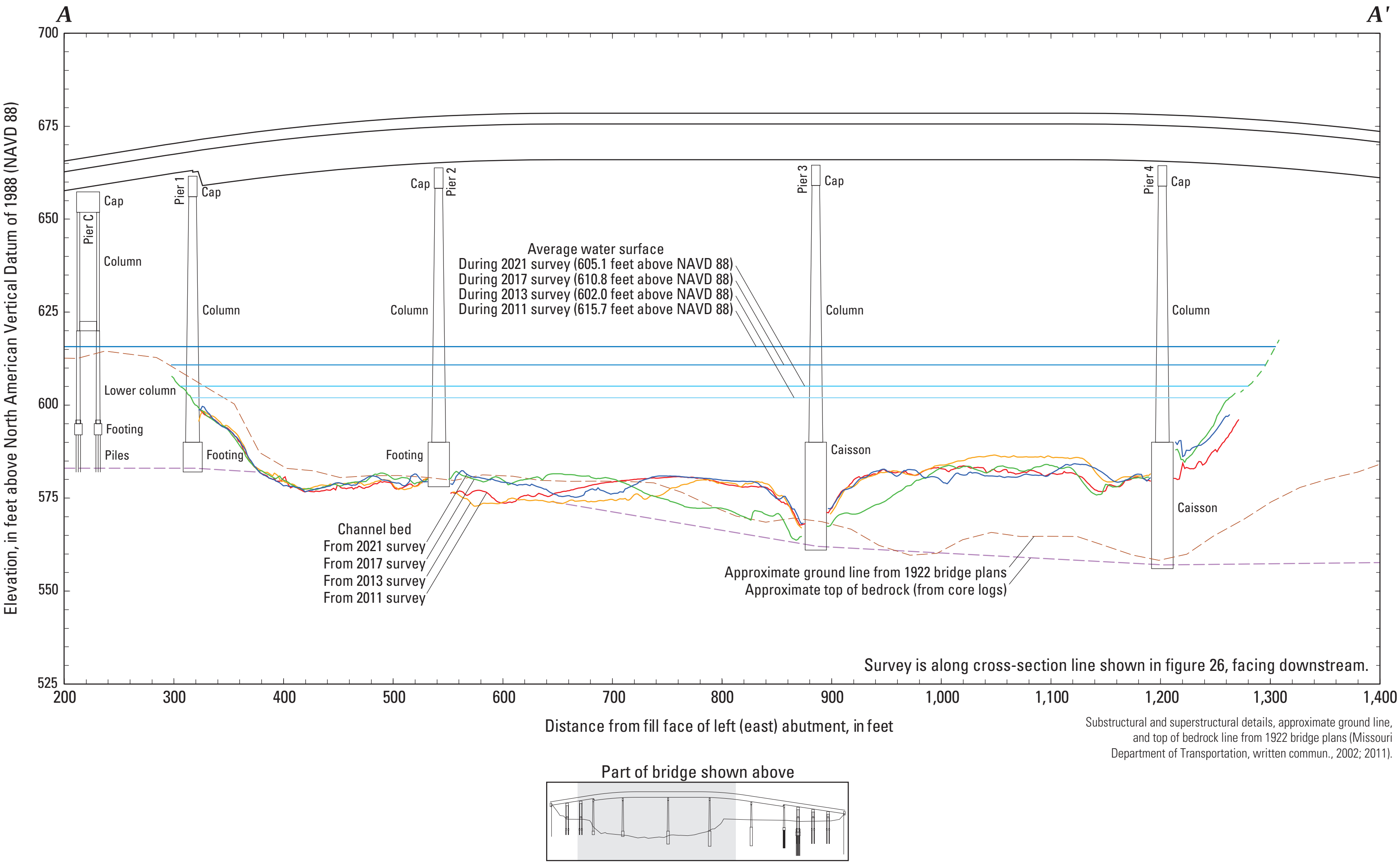


Figure 28. Key features, substructural and superstructural details, and surveyed channel bed of structure A3292 on State Highway 240 crossing the Missouri River at Glasgow, Missouri.

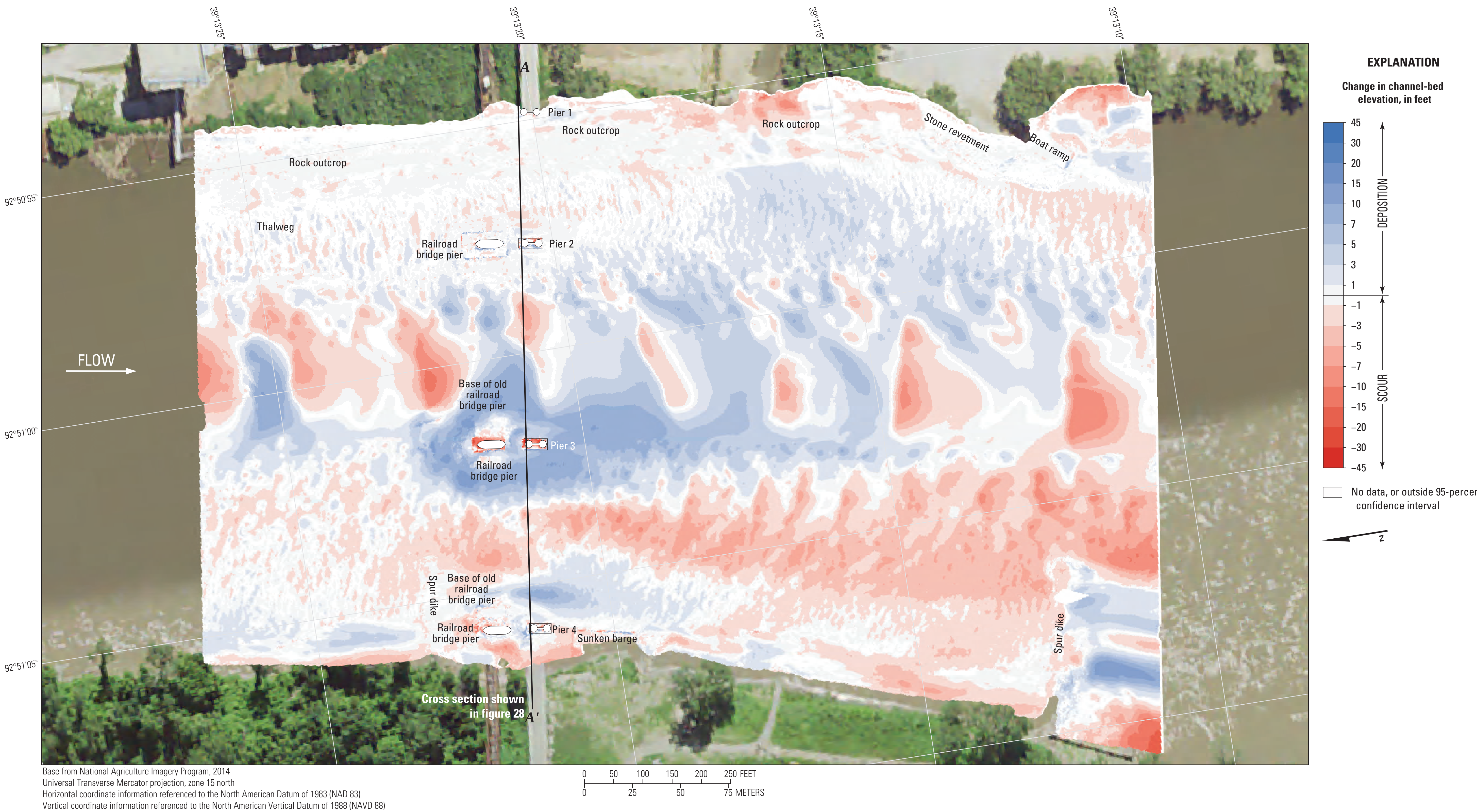


Figure 29. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure G0069 on State Highway 240 at Glasgow, Missouri, on May 20, 2021, and May 24, 2017, with probabilistic thresholding.

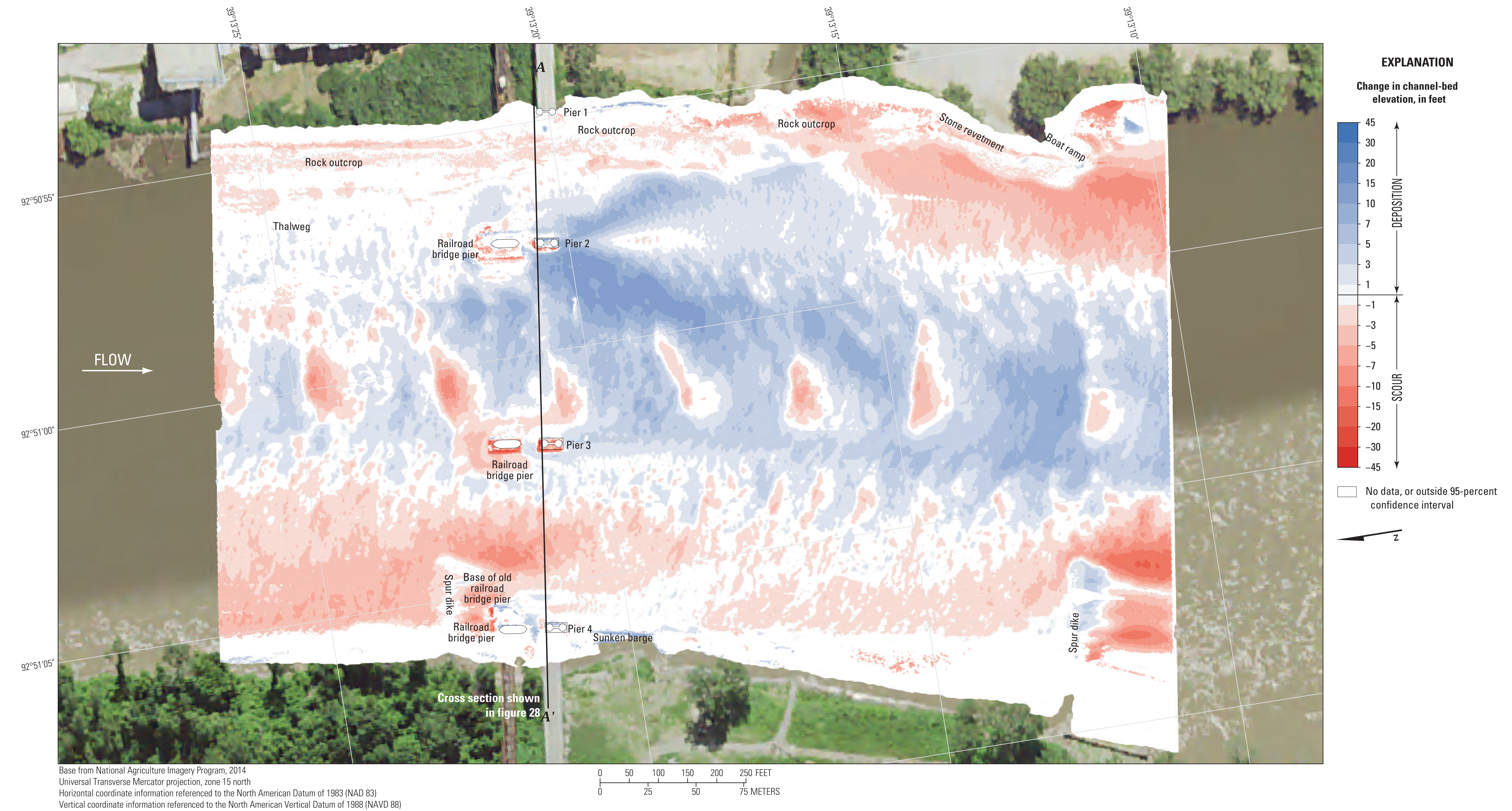


Figure 30. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure G0069 on State Highway 240 at Glasgow, Missouri, on May 20, 2021, and April 26, 2013, with probabilistic thresholding.

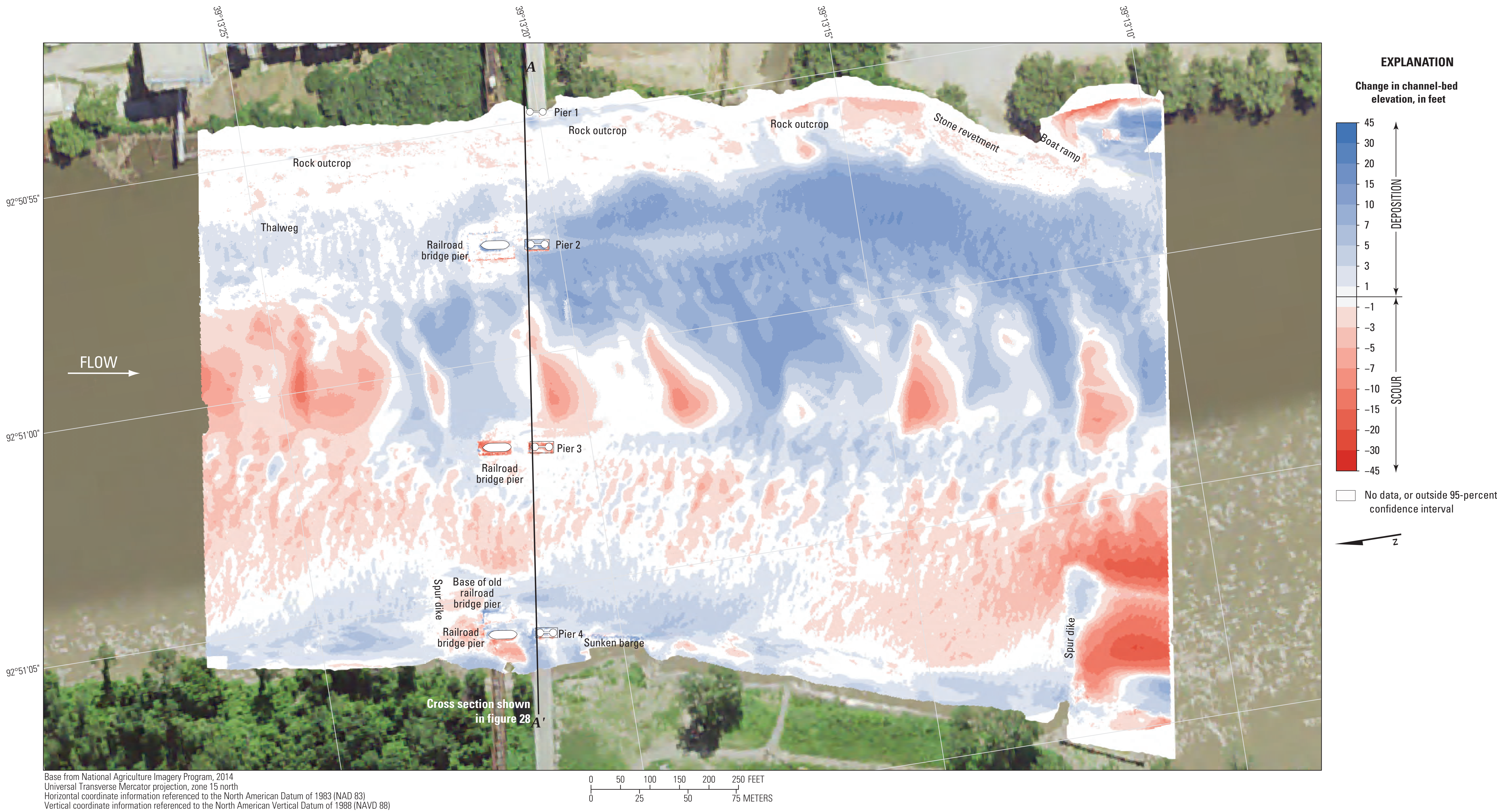


Figure 31. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure G0069 on State Highway 240 at Glasgow, Missouri, on May 20, 2021, and July 22, 2011, with probabilistic thresholding.

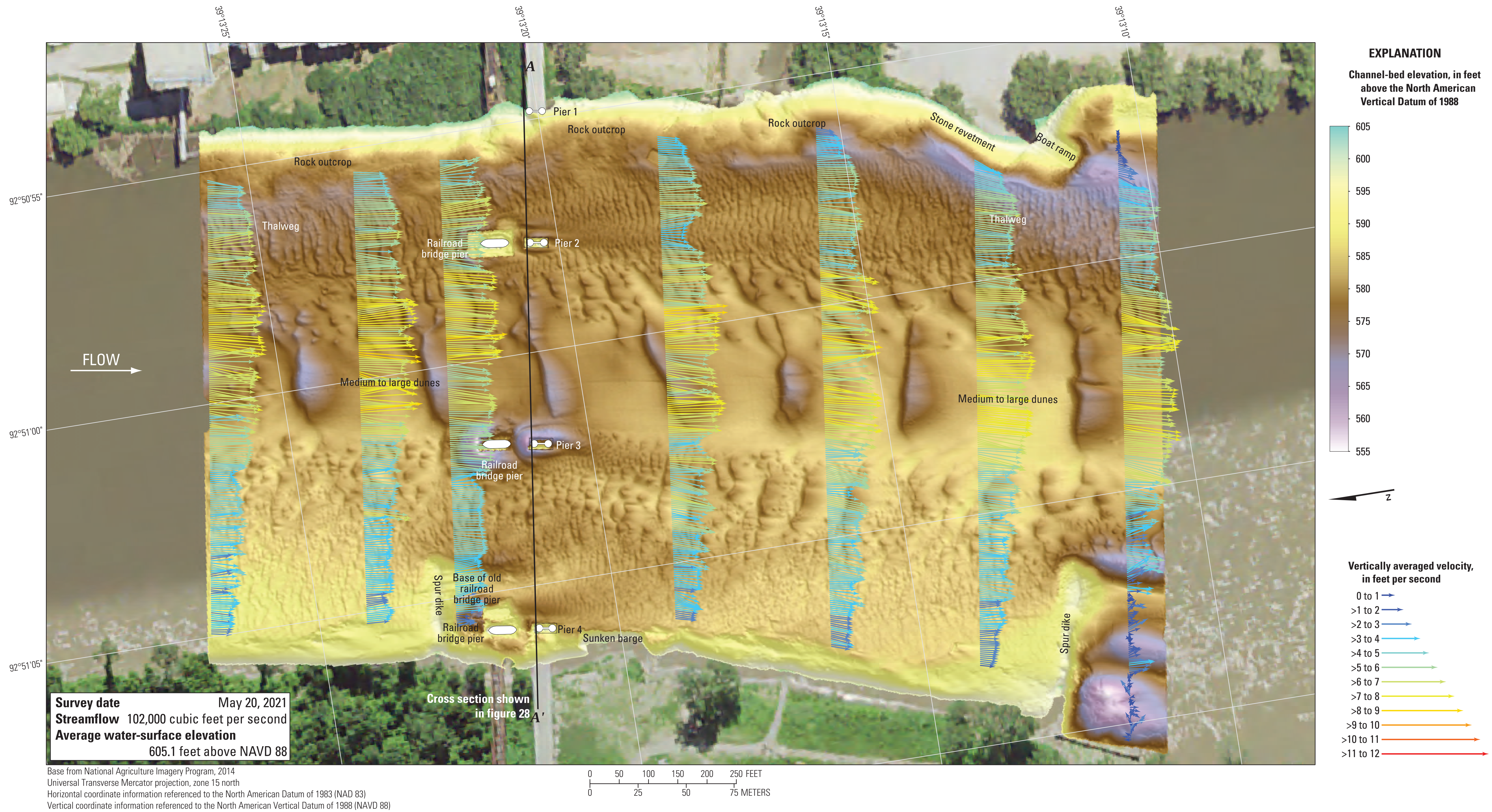


Figure 32. Bathymetry and vertically averaged velocities of the Missouri River channel near structure G0069 on State Highway 240 at Glasgow, Missouri.

Structure A4574 on State Highway 5 at Boonville, Missouri

Structure A4574 (site 18; table 2) on 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 21, 2021, when the average water-surface elevation near the bridge, determined by the RTK GNSS tide solution, was 580.9 ft (table 6; fig. 33) and streamflow on the Missouri River was about 112,000 ft^3/s during the survey (table 6).

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. 33). The upstream end of the survey area was about 620 ft upstream from the centerline of structure A4574, and piers 5 through 8 were in the water, although piers 5 and 8 were on the extreme edges of the surveyed area (fig. 33). The approximate channel-bed elevations ranged from about 555 to 567 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; table 6; fig. 34) reaching a minimum elevation of 548 ft in the channel thalweg along the toe of the left (north) bank (fig. 33; table 6). The well-defined thalweg was present along the left (north) bank throughout the surveyed area and was about 8 to 10 ft deeper than the channel bed in the middle of the channel. Small to medium dune features with superimposed small dunes and ripples were present throughout the channel (fig. 33).

The minor scour holes near piers 6 and 7 were difficult to discern from nearby dunes and ripples (figs. 33, 1.5*B*, 1.5*C*, 1.5*D*, 1.5*E*). Near pier 7, the scour hole had a minimum channel-bed elevation of about 556 ft (table 7), about 23 ft above the elevation of the bottom of the pier seal course of 533.00 ft and about 43 ft above the level of bedrock near that pier (fig. 35; table 7). The minor scour hole near pier 6 had a minimum channel-bed elevation of about 563 ft (table 7). Information from bridge plans indicates that pier 7 is founded on shafts drilled 39 ft into bedrock (fig. 35; table 7), whereas pier 6 is founded on a footing on bedrock, having about 12 ft of bed material between the bottom of the scour hole and bedrock (fig. 35; table 7). The surveyed bed was similar to the previous multibeam surveys in 2011, 2013, and 2017, with the 2021 bed oscillating between the bed in the previous surveys except between piers 7 and 8 where the bed was 5 to 7 ft lower in 2021 than in the previous surveys (fig. 35). The scour hole near pier 7 appears to penetrate to the top of the pier footing (figs. 33 and 35), which might provide some mitigation to the scour hole at this pier as the downward flow of the horseshoe vortex at the pier column face is blunted by the footing (Arneson and others, 2012).

The difference between the survey on May 21, 2021, and the previous survey on May 25, 2017 (fig. 36), indicates about 85 percent of the joint area of interest had detectable change, which means about 15 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition and erosion appear roughly balanced throughout the reach between 2017 and 2021 in the DoD, except near the right (south) bank where erosion is more dominant (fig. 36). The average difference between the bathymetric surfaces was –0.44 ft (table 8), indicating minor channel degradation between the 2017 and 2021 surveys. The net volume of cut in the reach from 2017 to 2021 was about 77,500 yd^3, and the net volume of fill was about 48,800 yd^3, resulting in a net loss of about 28,700 yd^3 of sediment between 2017 and 2021 (table 8). As indicated in the previous paragraph, the cross section from the 2021 survey along the upstream face of the bridge generally varies above and below the 2017 survey section (fig. 35). The frequency distribution of bed elevations in 2021 is remarkably similar in shape to all the previous surveys, with a slightly higher percentage of cells in the mid-range of channel-bed elevations (fig. 34). The stone revetment on the left (north) bank showed localized areas of erosion and deposition, but nearly all the indicated changes are within 1 ft of the 2017 elevation, or outside the 95-percent confidence interval (fig. 36).

The difference between the survey on May 21, 2021, and the survey on April 29, 2013 (fig. 37), indicates only 64 percent of the joint area of interest had detectable change, which means about 36 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Areas of moderate deposition are balanced with areas of moderate erosion throughout most of the reach between 2013 and 2021 in the DoD, with erosion dominant on the right (south) side and deposition dominant near the tip of the upstream spur dike and in the downstream left (north) side of the channel (fig. 37). The average difference between the bathymetric surfaces was –0.54 ft (table 8), again indicating minor to moderate channel degradation between the 2013 and 2021 surveys, and the net loss of sediment between 2013 and 2021 was about 23,800 yd^3, which is less than but consistent with the net loss of sediment between 2017 and 2021 (table 8). As mentioned in the previous paragraph, the frequency distribution of bed elevations in 2021 is remarkably similar in shape to the other surveys, but the 2013 survey distribution is spread over a slightly larger range of channel-bed elevations (fig. 34). The stone revetment on the left (north) bank showed localized areas of erosion and deposition (fig. 37); however, most of the area was equivocal, and the moderate apparent deposition likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 21, 2021, and the earliest survey during flooding on July 25, 2011 (fig. 38), indicates about 76 percent of the joint area of interest had detectable change, which means about 24 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). As with the other comparisons, scour and deposition appear approximately balanced throughout the reach between 2011 and 2021 in the DoD, with more scour in the upstream part of the reach, and deposition in the downstream part of the reach (fig. 38). The average difference between the bathymetric surfaces was –0.53 ft (table 8), again indicating minor degradation between the 2011 and

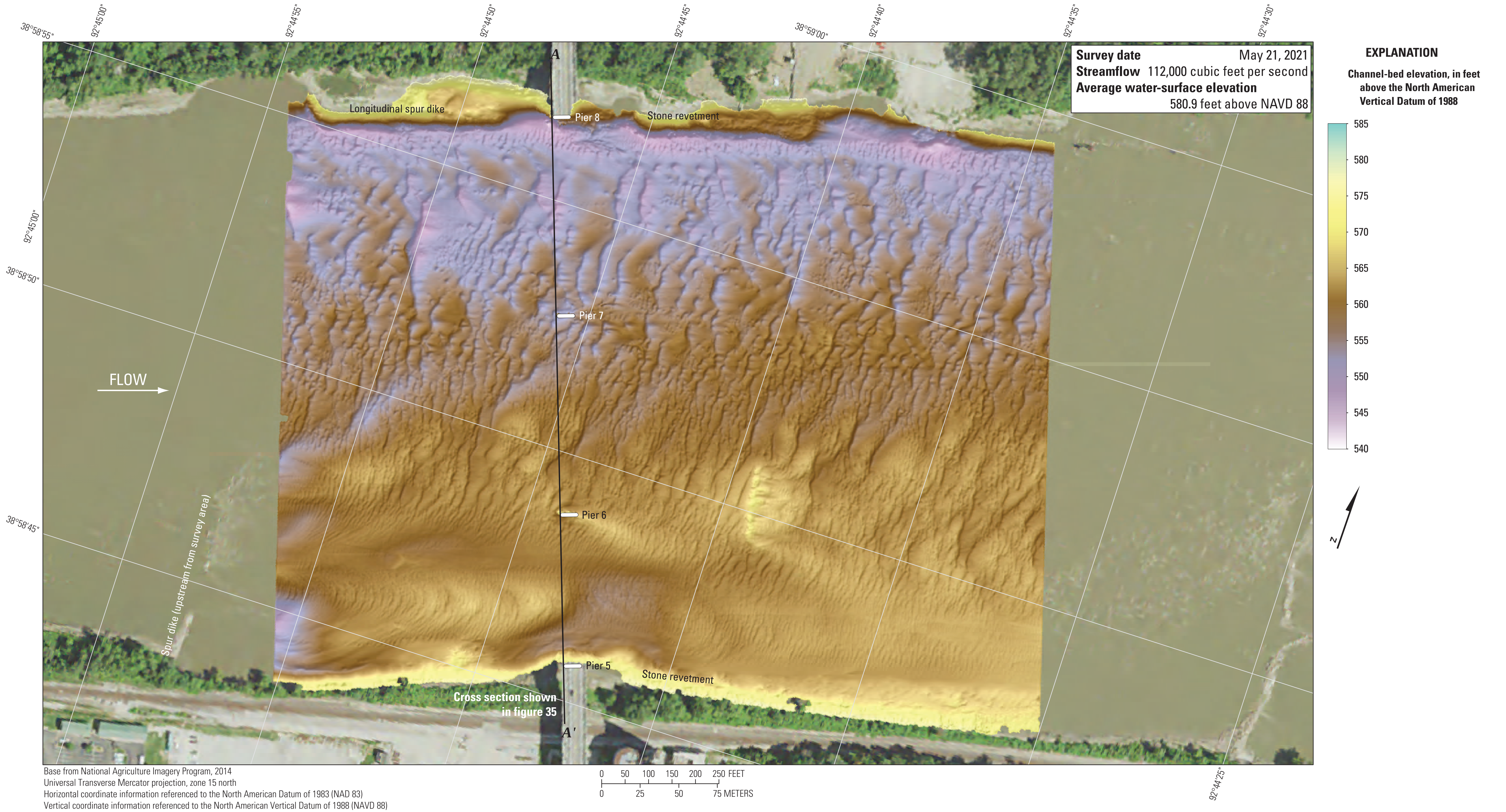


Figure 33. Bathymetric survey of the Missouri River channel near structure A4574 on State Highway 5 at Boonville, Missouri.

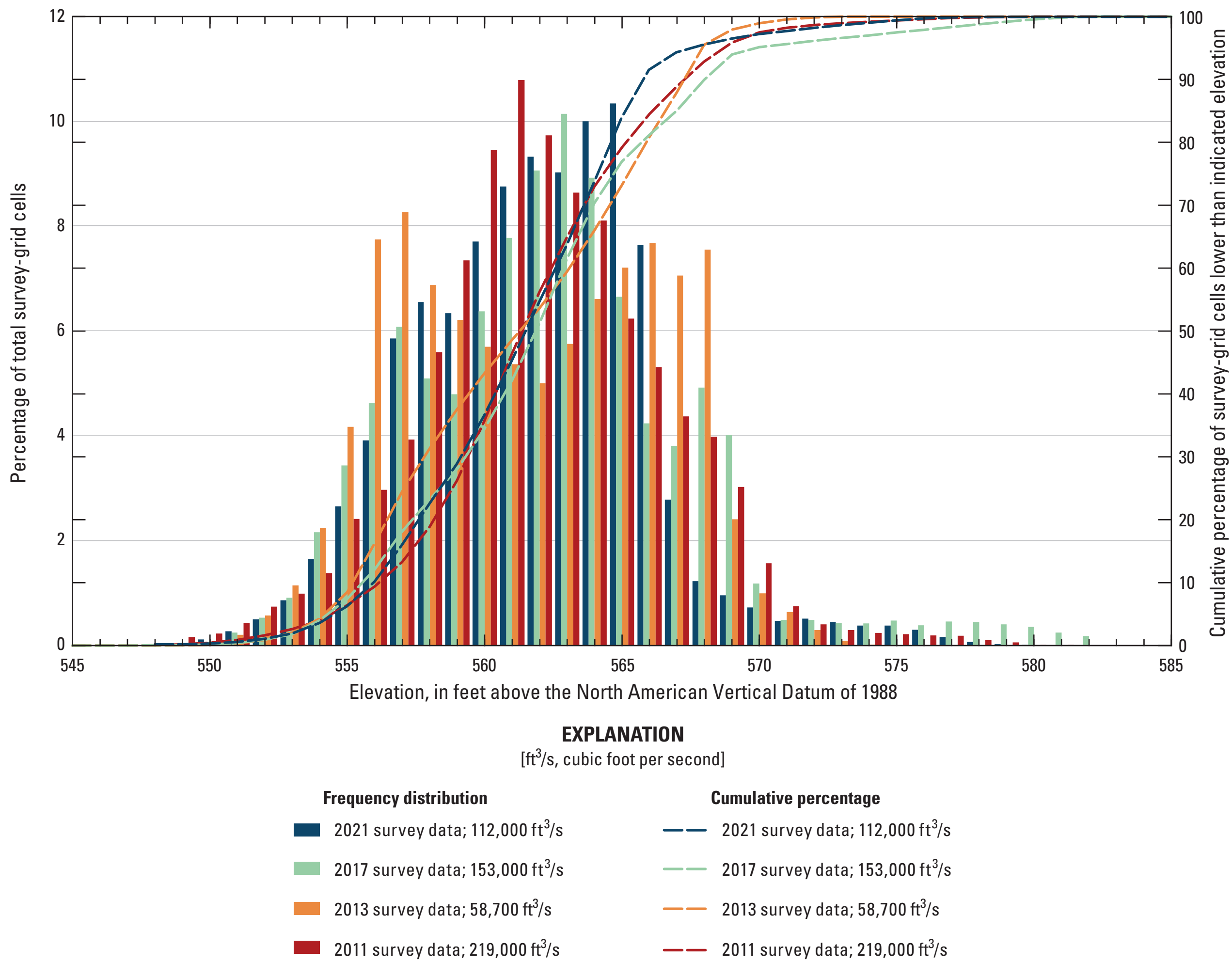


Figure 34. Frequency distribution of bed elevations for bathymetric survey-grid cells in 1-foot elevation bins on the Missouri River near structure A4574 on State Highway 5 at Boonville, Missouri, on May 21, 2021, compared to previous surveys in 2011, 2013, and 2017 (Huizinga, 2012, 2014, 2020a, respectively).

2021 surveys. There was a net loss of sediment between 2011 and 2021 of about 29,700 yd^3 (table 8). The stone revetment and longitudinal spur dike on the left (north) bank showed substantial deposition (fig. 38), which may be the result of these features being repaired or otherwise built up after the 2011 flood. As with several previous DoDs, some of this apparent deposition may result from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The vertically averaged velocity vectors indicate mostly uniform flow with localized moderate turbulence throughout most of the reach, ranging from about 3 to 9 ft/s (fig. 39). Other exceptions to uniform conditions include variable velocities and flow reversal on the right (south) bank downstream from the upstream spur dike (fig. 39). 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. 39).

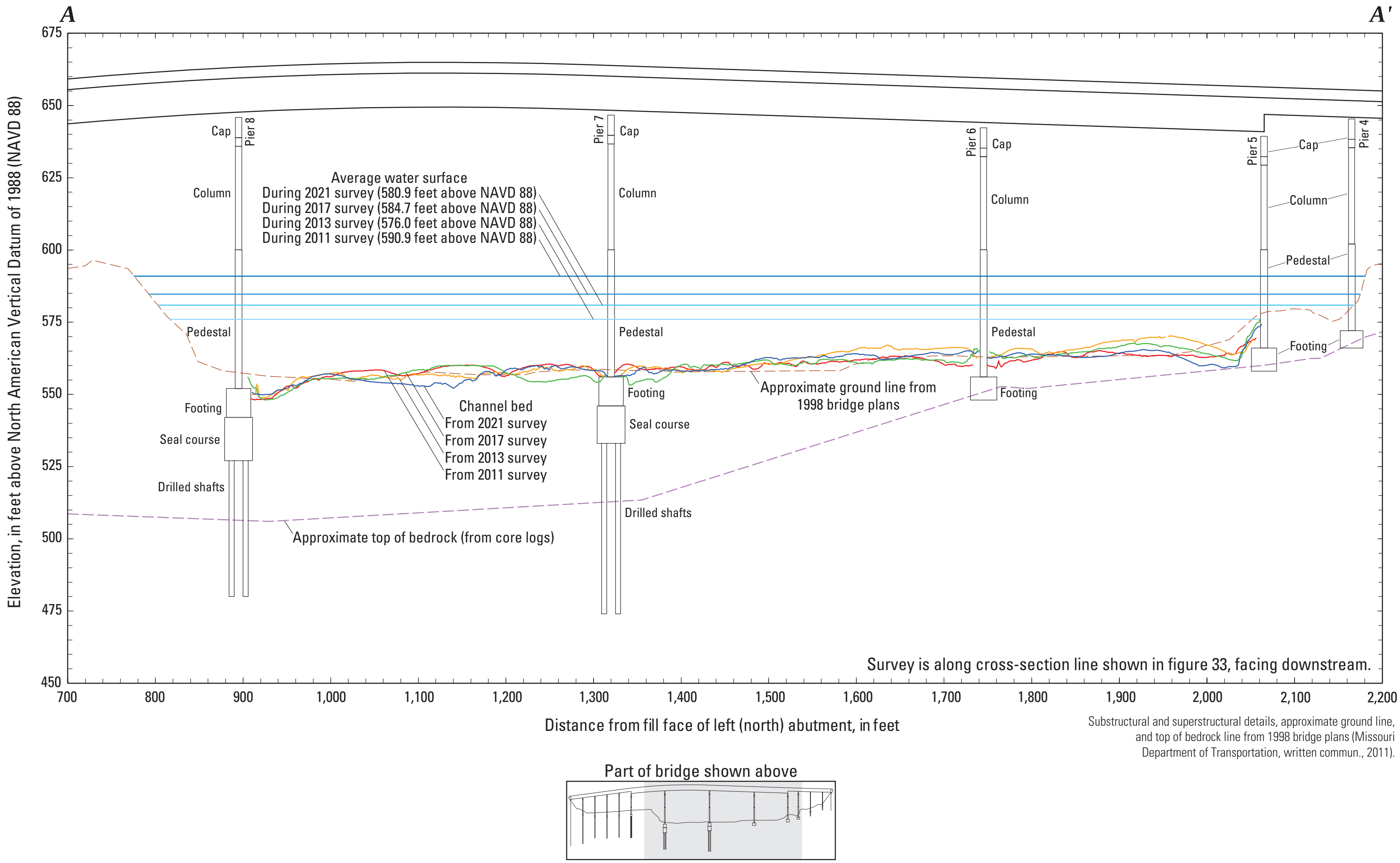


Figure 35. Key features, substructural and superstructural details, and surveyed channel bed of structure A4574 on State Highway 5 crossing the Missouri River at Boonville, Missouri.

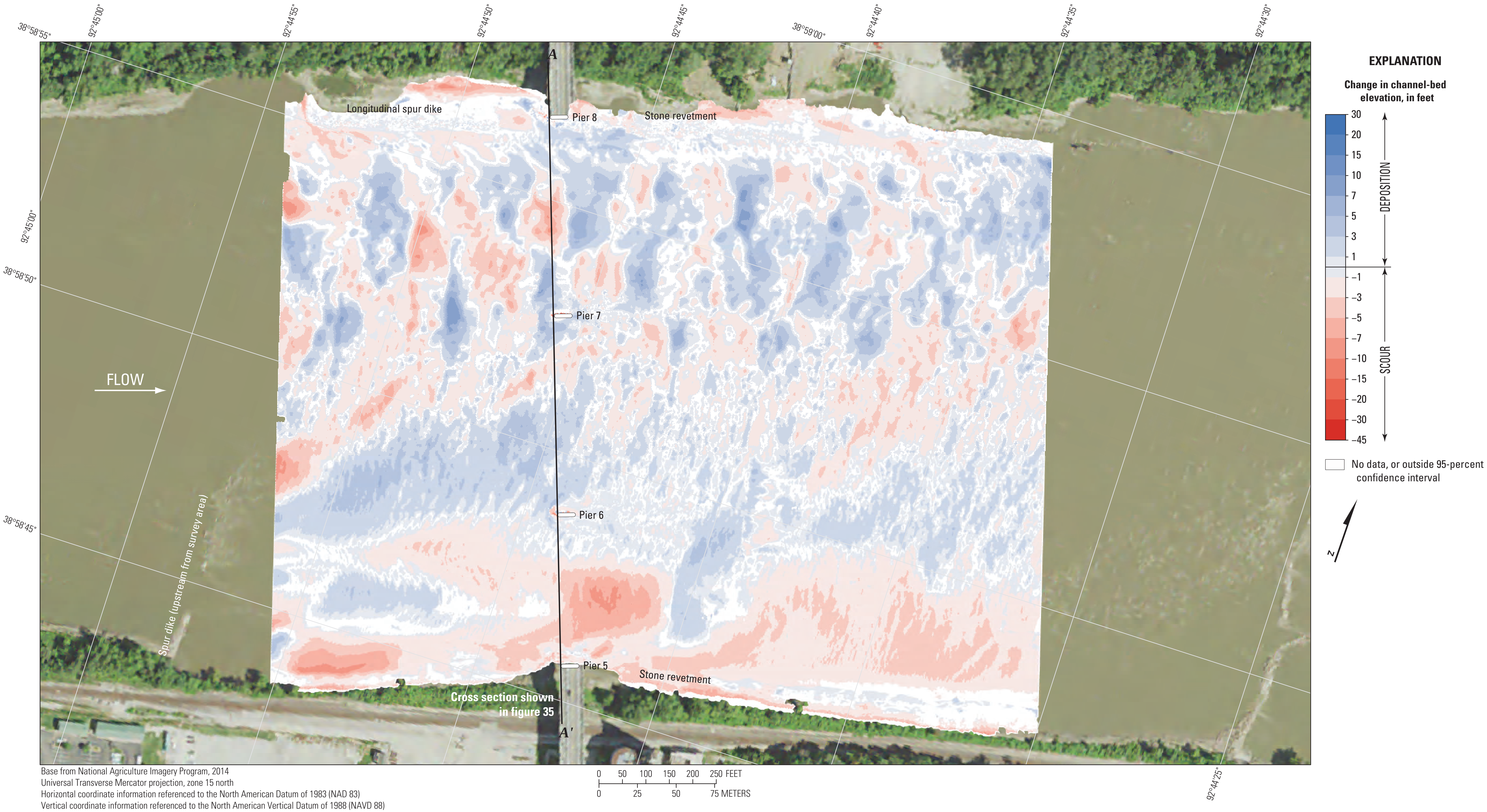


Figure 36. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4574 on State Highway 5 at Boonville, Missouri, on May 21, 2021, and May 25, 2017, with probabilistic thresholding.

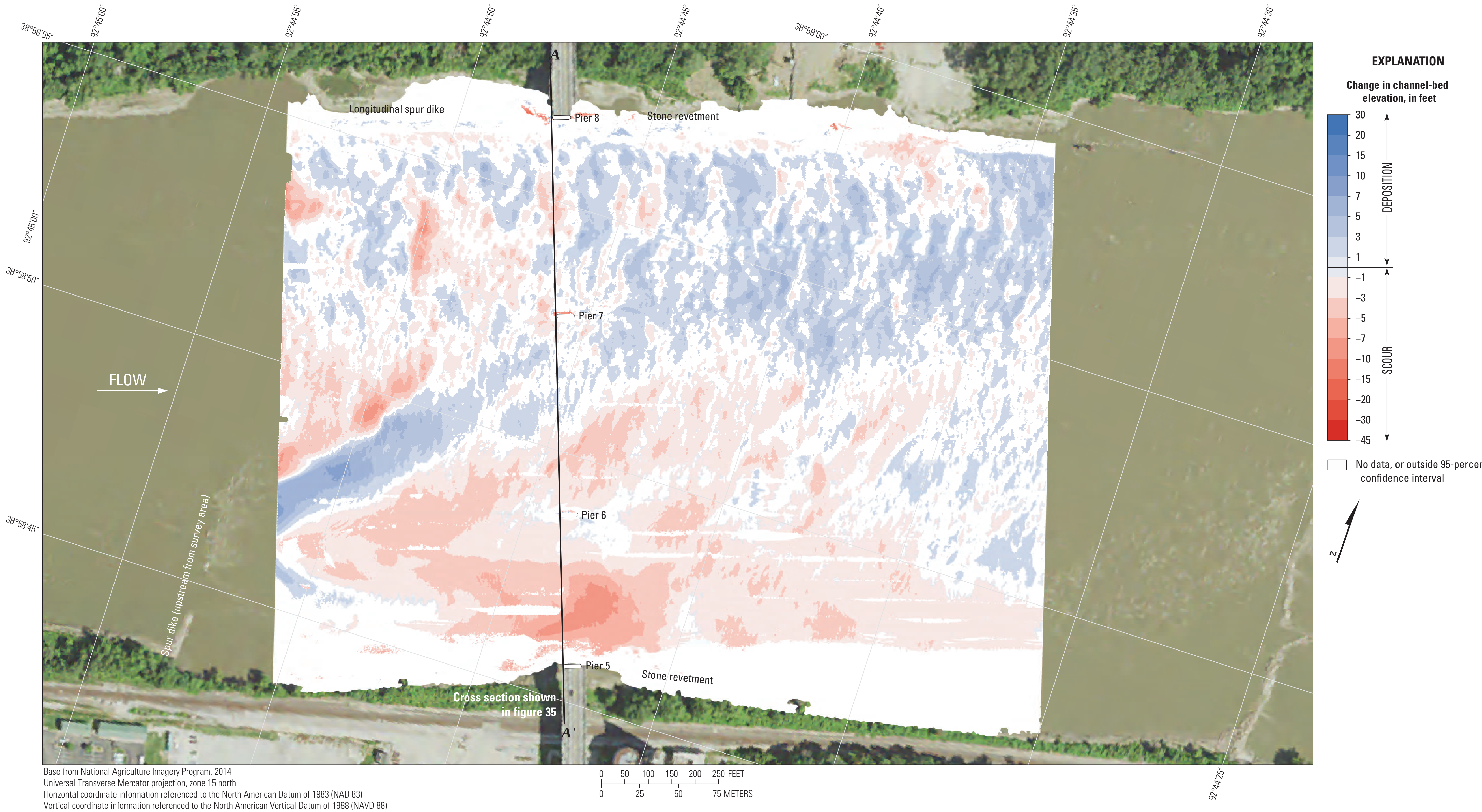


Figure 37. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4574 on State Highway 5 at Boonville, Missouri, on May 21, 2021, and April 29, 2013, with probabilistic thresholding.

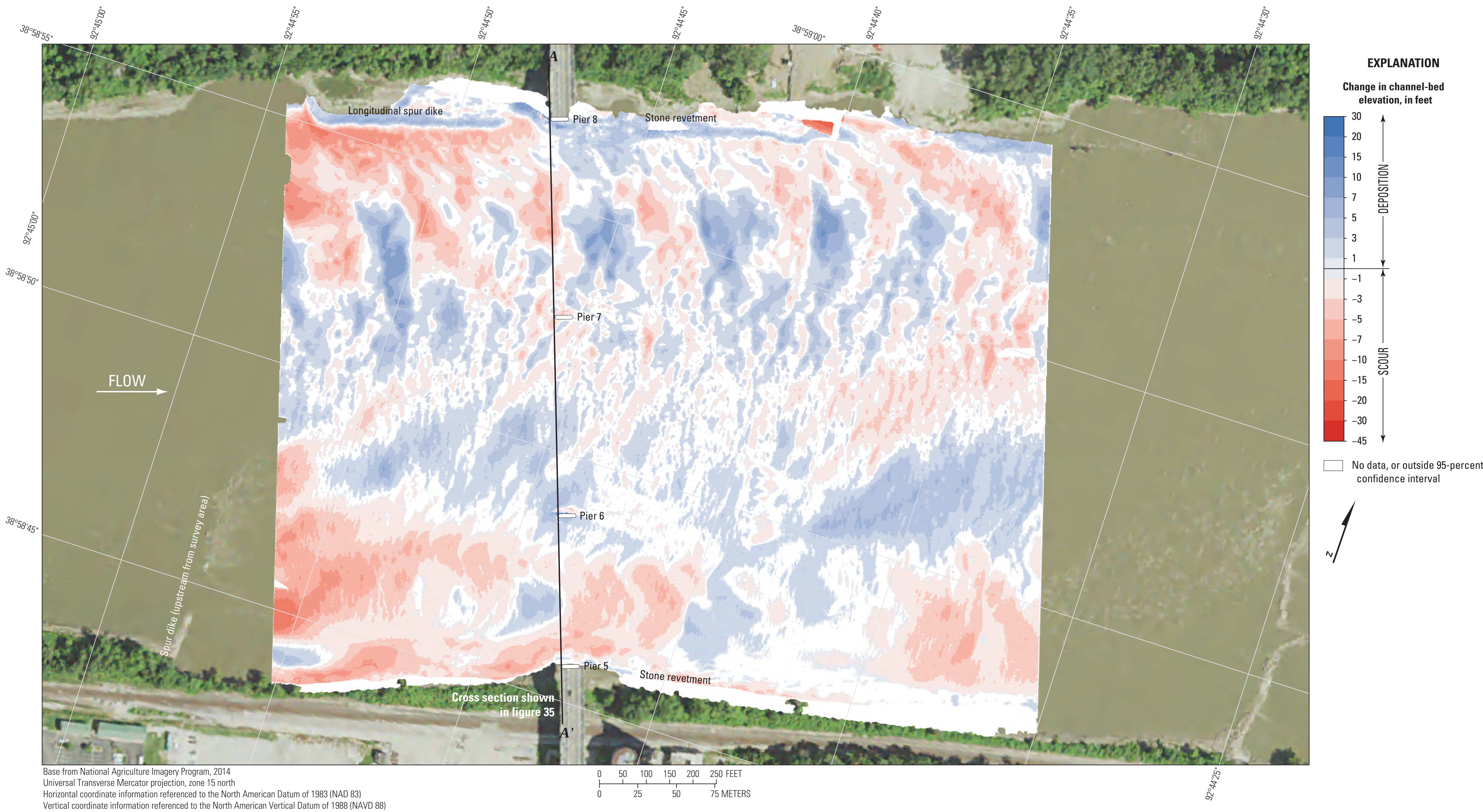


Figure 38. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A4574 on State Highway 5 at Boonville, Missouri, on May 21, 2021, and July 25, 2011, with probabilistic thresholding.

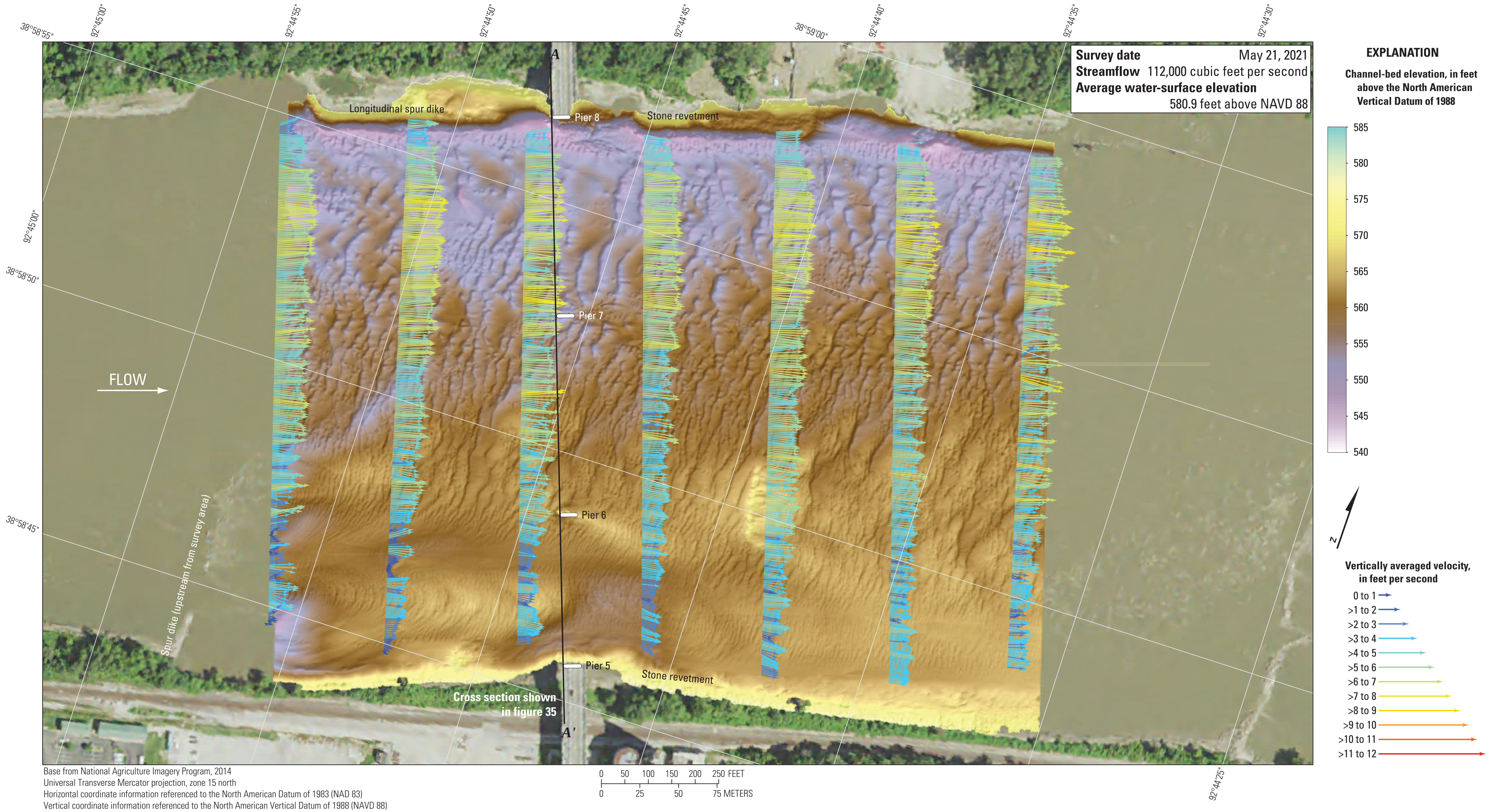


Figure 39. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A4574 on State Highway 5 at Boonville, Missouri.

Structure L0962 on Interstate 70 near Rocheport, Missouri

Structure L0962 (site 19; table 2) 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 21, 2021, when the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 571.1 ft (table 6; fig. 40) and streamflow on the Missouri River was about 110,000 ft^3/s during the survey (table 6).

The survey area was about 1,640 ft long and about 1,200 ft wide, extending essentially from bank to bank in the main channel (fig. 40). The upstream end of the survey area was about 580 ft upstream from the centerline of structure L0962 (fig. 40), and piers 13 and 14 as well as bent 16 were in the water. The channel-bed elevations ranged from about 541 to 559 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; fig. 41; table 6). A poorly defined thalweg was present along the left (northeast) bank, and a series of medium dunes were detected along the middle of the channel, with numerous small dunes and ripples throughout the rest of the channel (fig. 40). The persistent debris raft near bent 16 in previous surveys was not present in 2021, which permitted bathymetric data to be collected near that bent (fig. 40).

A moderate scour hole near pier 14 had a minimum channel-bed elevation of about 531 ft (fig. 40; table 7), which is about 17 ft below the average channel-bed elevation upstream from the bridge (figs. 42, 1.6*E*, 1.6*F*; table 7). Information from bridge plans indicates that pier 14 is founded on a caisson on bedrock, having about 33 ft of bed material between the bottom of the scour hole and bedrock (fig. 42; table 7). The surveyed bed in 2021 generally was similar to the previous multibeam surveys between pier 14 and the right (southwest) bank, but there was substantial erosion between the left (northeast) bank and pier 15, and substantial deposition of as much as 20 ft between piers 14 and 15 (fig. 42).

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 538 ft (figs. 42, 1.6*C*, 1.6*D*; table 7). Pier 15 also is founded on a caisson on bedrock, having about 19 ft of material between the minimum channel-bed elevation and bedrock (fig. 42; table 7); however, the rock of the spur dike will limit or prevent a local scour hole near pier 15. Near bent 16, the minimum channel-bed elevation also was about 538 ft (figs. 42, 1.6*B*; table 7), about 5 ft below the average channel bed upstream from the scour hole, and only about 2 ft above the elevation of bedrock near that bent (fig. 42; table 7). Information from bridge plans indicates that bent 16 is founded on a footing on bedrock (fig. 42; table 7). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (Brown and others, 2018; American Association of State Highway Transportation Officials, 2020), but full exposure of usually buried substructural elements warrants special consideration and observation.

The difference between the survey on May 21, 2021, and the previous survey on May 25, 2017 (fig. 43), indicates about 91 percent of the joint area of interest had detectable change, which means only about 9 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition appears dominant throughout most of the reach between 2017 and 2021 in the DoD, except in localized troughs in the medium dune features in the upstream part of the reach and downstream from the spur dikes on both banks (fig. 43). Substantial erosion of as much as 45 ft was observed near pier 15 and bent 16 (fig. 43). The average difference between the bathymetric surfaces was +1.59 ft (table 8), indicating moderate channel aggradation between the 2017 and 2021 surveys. The net volume of cut in the reach from 2017 to 2021 was about 77,300 yd^3, and the net volume of fill was about 177,500 yd^3, resulting in a net gain of about 100,200 yd^3 of sediment between 2017 and 2021 (table 8). The frequency distribution of bed elevations in 2021 is somewhat unique (fig. 41); similar in overall shape to 2017 (and the others), but with a 3–5-ft shift towards higher elevations at the centroid of the elevation distribution. The longitudinal spur dikes along the left (northeast) bank showed minor to moderate scour on one side and deposition on the other (fig. 43); however, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 21, 2021, and the survey on April 29, 2013 (fig. 44), indicates about 72 percent of the joint area of interest had detectable change, which means about 28 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition again appears dominant throughout most of the reach between 2013 and 2021 in the DoD, except for localized substantial erosion downstream from the longitudinal spur dikes on the left (northeast) bank and in the troughs in the medium dune features along the upstream middle of the channel (fig. 44). The average difference between the bathymetric surfaces was +2.74 ft (table 8), indicating moderate to substantial channel aggradation between the 2013 and 2021 surveys with a net gain of sediment between 2013 and 2021 of about 111,500 yd^3 (table 8). As with 2017, the frequency distribution of bed elevations in 2021 has an almost 5-ft shift towards higher elevations at the centroid of the elevation distribution compared to 2013 (fig. 41). The difference in the distribution likely is the result of the substantially narrower survey area in 2013, and general lack of bank information (fig. 44). The longitudinal spur dikes along the left (northeast) bank showed minor scour on the side that could be surveyed in 2013, but much of the difference is equivocal, and substantial areas behind the spur dikes were not surveyed in 2013 (fig. 44).

The difference between the survey on May 21, 2021, and the earliest survey during flooding on July 26, 2011 (fig. 45), indicates about 82 percent of the joint area of interest had detectable change, which means about 18 percent of the differences in the joint area of interest are equivocal and within the

Figure 40. Bathymetric survey of the Missouri River channel near structure L0962 on Interstate 70 near Rocheport, Missouri.

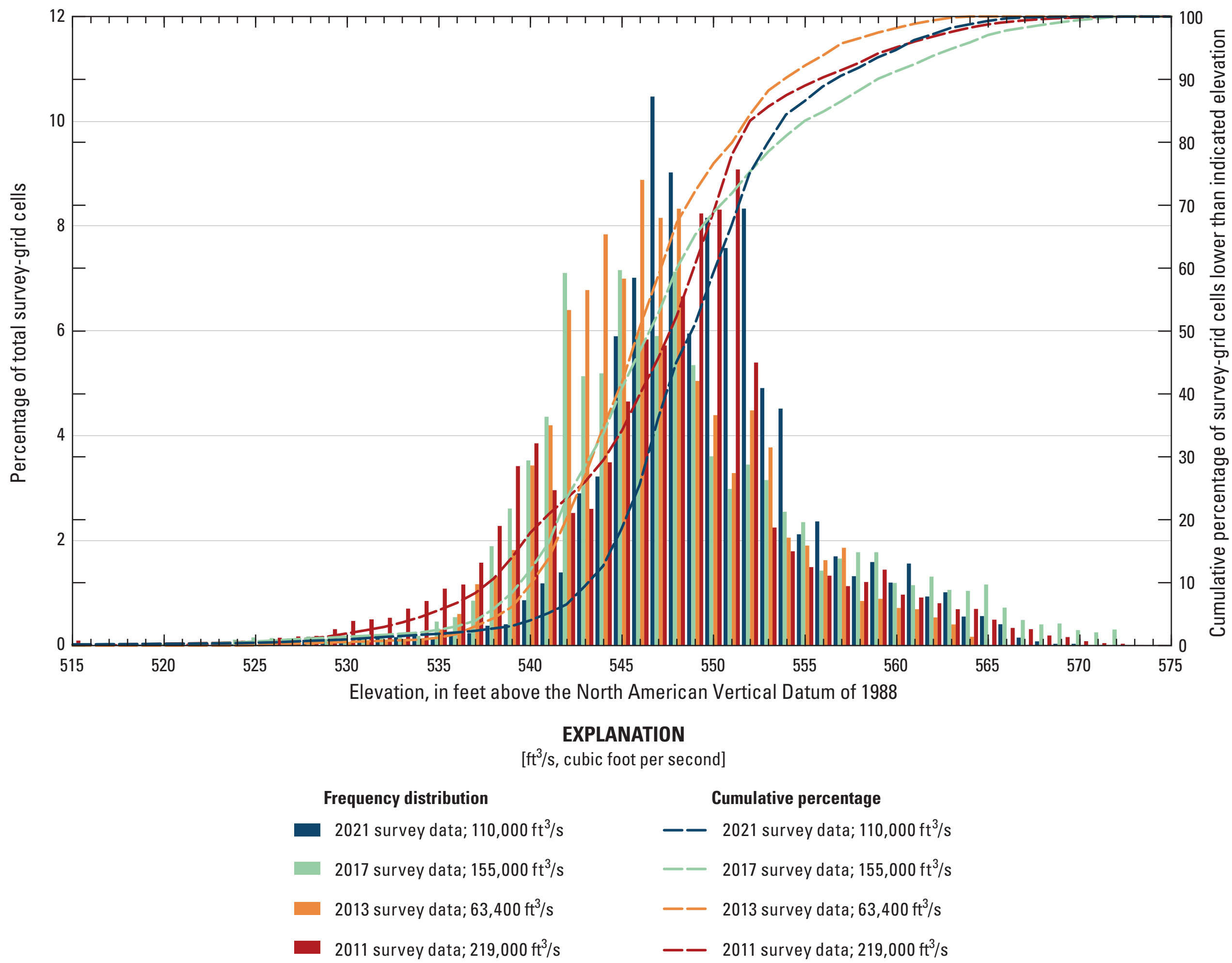


Figure 41. Frequency distribution of bed elevations for bathymetric survey-grid cells in 1-foot elevation bins on the Missouri River near structure L0962 on Interstate 70 near Rocheport, Missouri, on May 21, 2021, compared to previous surveys in 2011, 2013, and 2017 (Huizinga, 2012, 2014, 2020a, respectively).

bounds of uncertainty (table 8). Scour and deposition appear approximately balanced in the reach between 2011 and 2021 in the DoD (fig. 45), with substantial deposition in the thalweg and some areas downstream from the spur dikes on both banks balanced by substantial erosion in the upstream middles of the channel and near pier 15 and bent 16. However, the average difference between the 2011 and 2021 bathymetric surfaces was +2.47 ft (table 8), indicating moderate to substantial channel aggradation with a net gain of sediment between 2011 and 2021 of about 137,200 yd^3 (table 8). The frequency distribution of bed elevations in 2021 is most similar to the 2011 distribution above 547 ft, but the 2011 distribution has a higher percentage of cells at a lower channel-bed elevation, particularly below about 545 ft (fig. 41). The longitudinal spur dikes along the left (northeast) bank again showed minor to moderate scour on one side and deposition on the other, as does pier 14 (fig. 45); however, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to "Uncertainty Estimation" section).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the channel, ranging from about 3 to 10 ft/s (fig. 46), with locally lower velocities and flow reversal along the banks, particularly downstream from the various spur dikes in the reach. Pier 14 was mostly aligned with flow, causing minimal turbulence downstream (fig. 46); however, flow approached pier 14 from the left side (fig. 46), causing an asymmetric scour hole that is longer and slightly deeper on the left side, similar to observations from previous surveys (fig. 40).

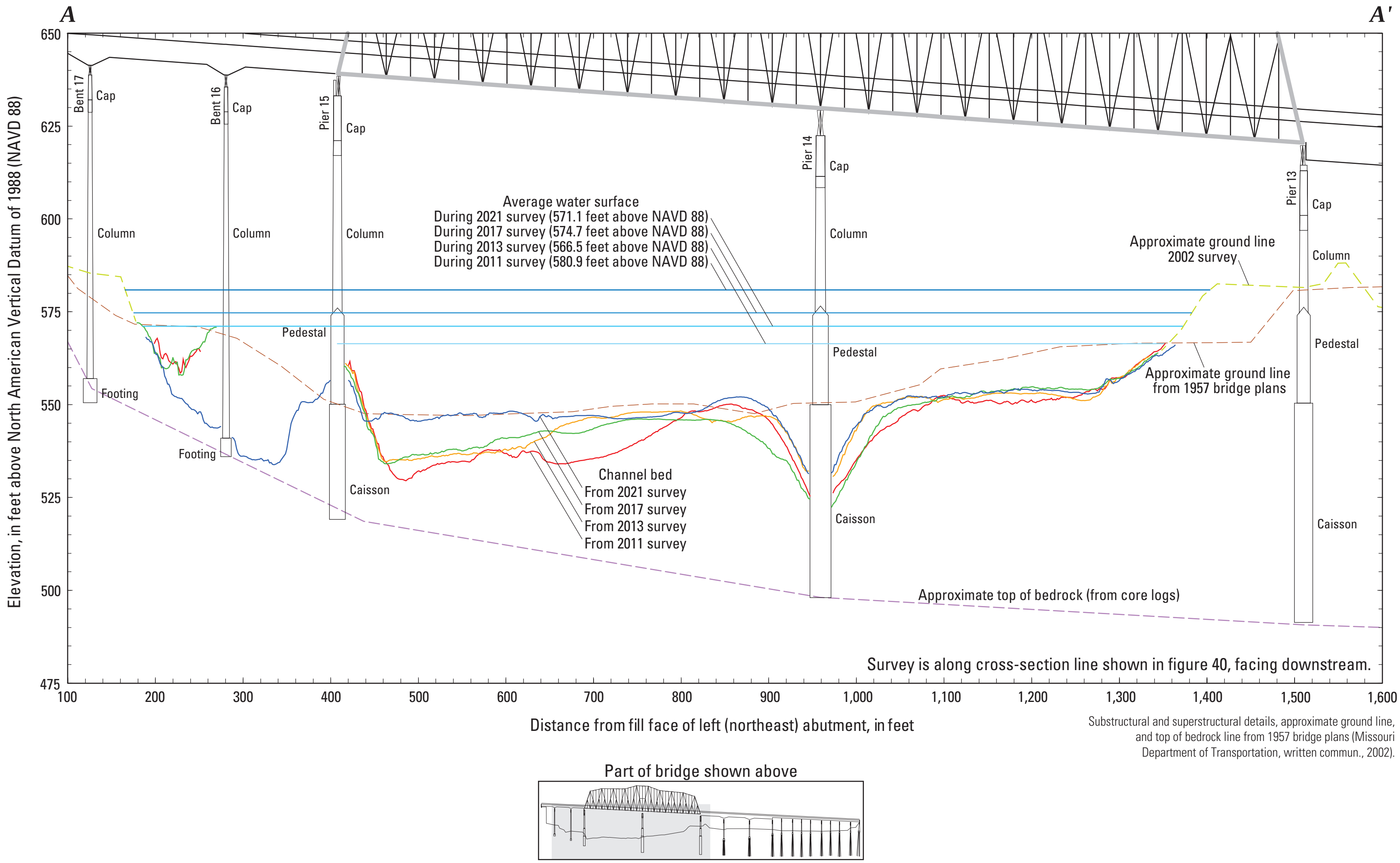


Figure 42. Key features, substructural and superstructural details, and surveyed channel bed of structure L0962 on Interstate 70 crossing the Missouri River near Rocheport, Missouri.

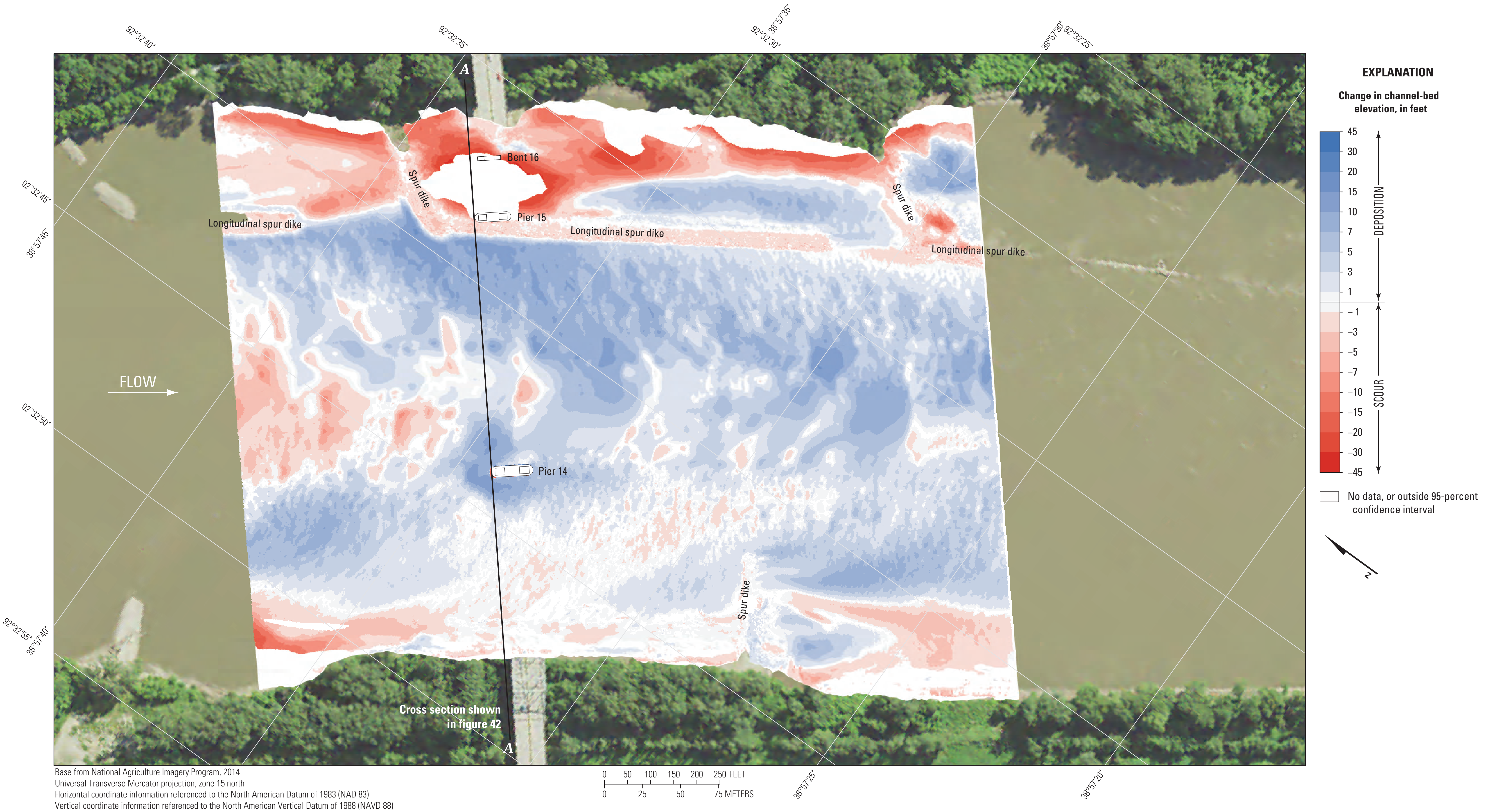


Figure 43. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure L0962 on Interstate 70 near Rocheport, Missouri, on May 21, 2021, and May 25, 2017, with probabilistic thresholding.

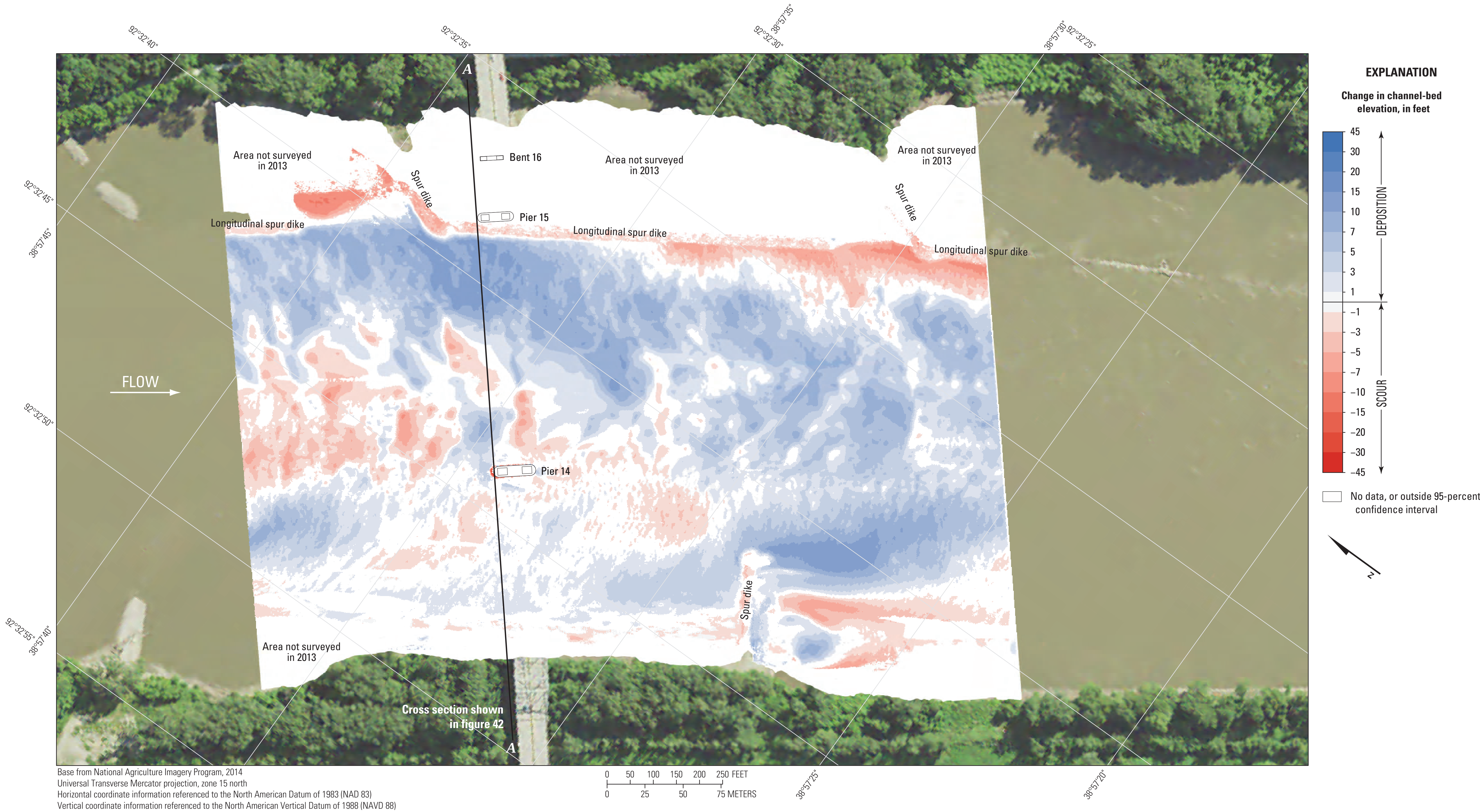


Figure 44. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure L0962 on Interstate 70 near Rocheport, Missouri, on May 21, 2021, and April 29, 2013, with probabilistic thresholding.

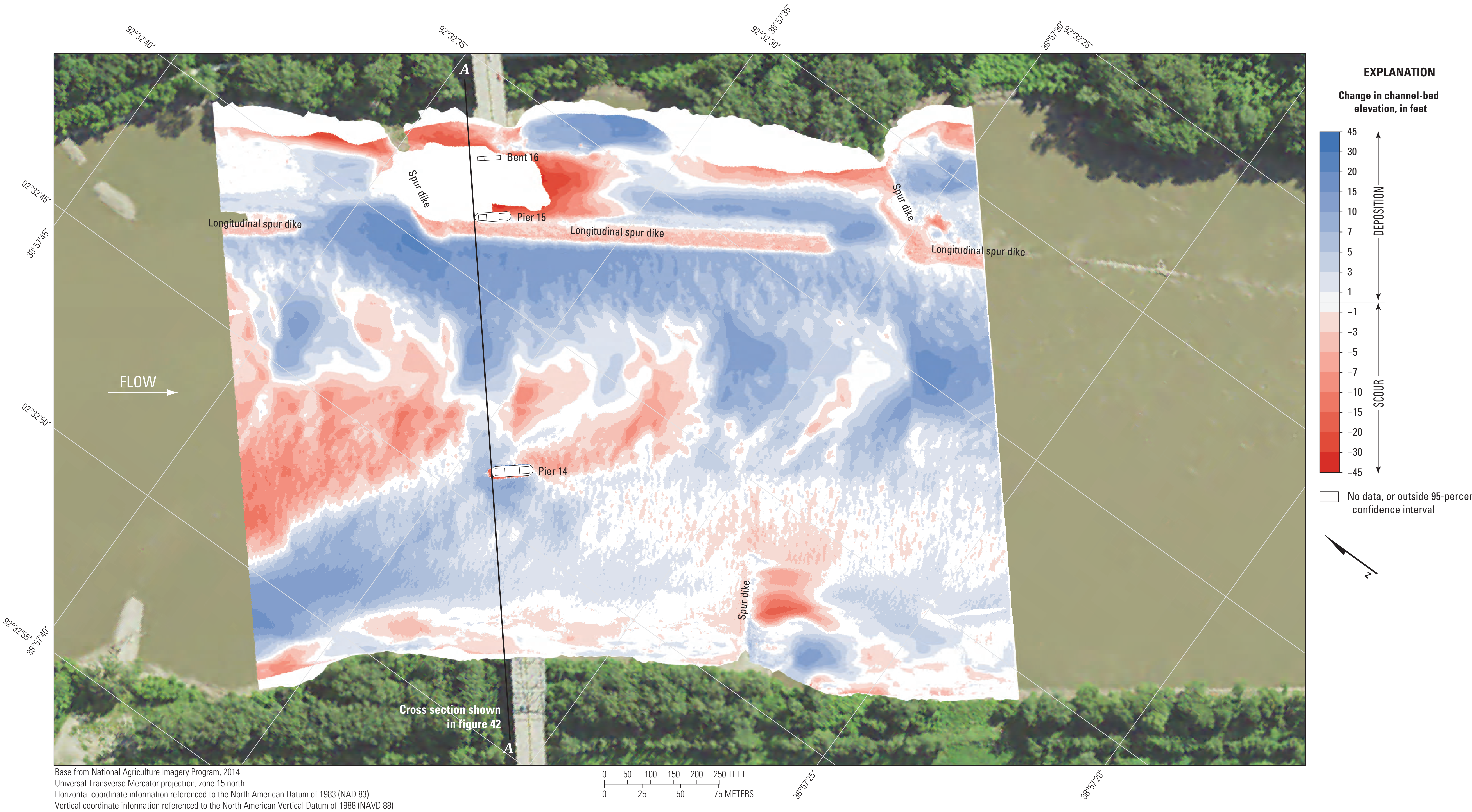


Figure 45. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure L0962 on Interstate 70 near Rocheport, Missouri, on May 21, 2021, and July 26, 2011, with probabilistic thresholding.

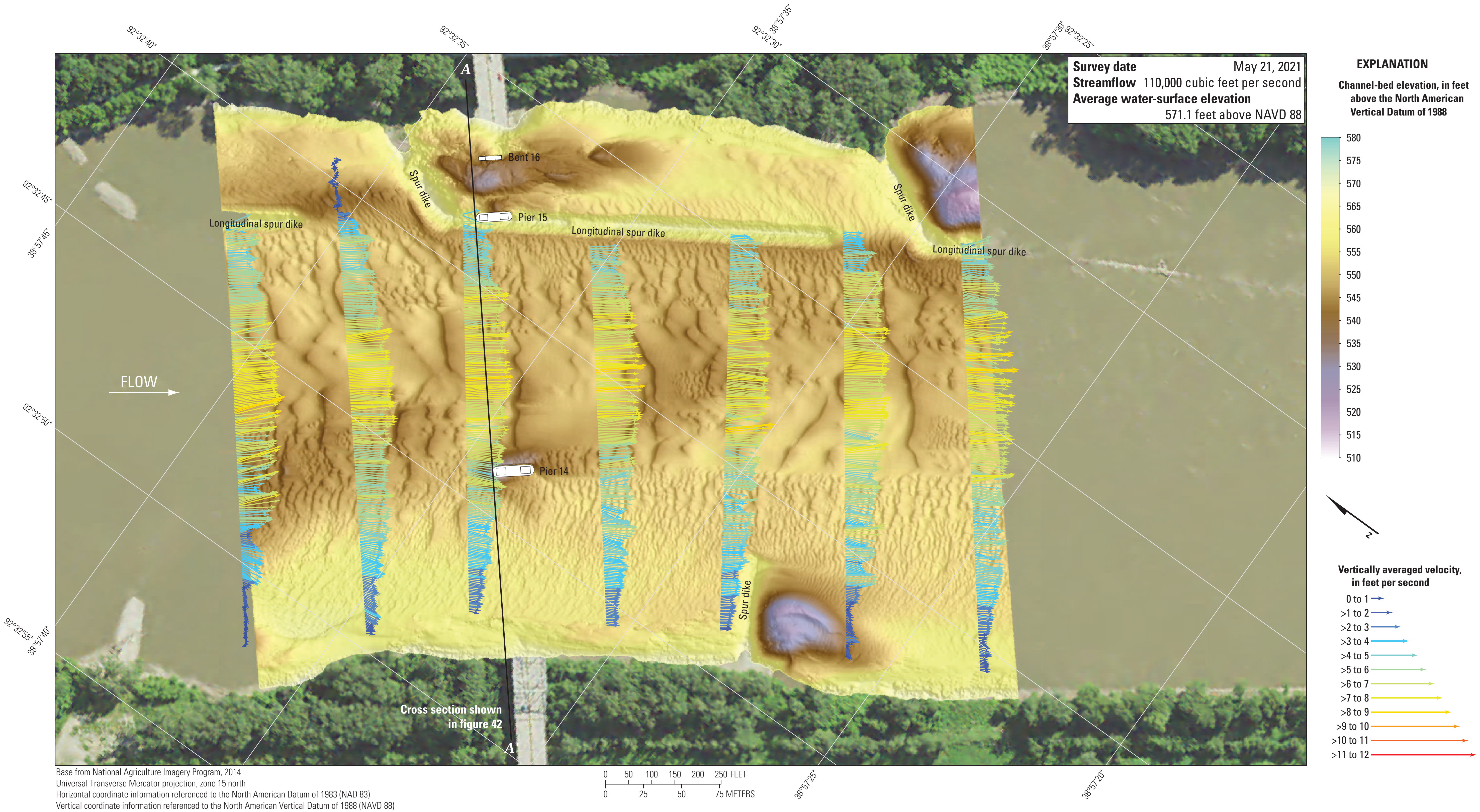


Figure 46. Bathymetry and vertically averaged velocities of the Missouri River channel near structure L0962 on Interstate 70 near Rocheport, Missouri.

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

Structures L0550 and A4497 (site 20; table 2) 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 26, 2021, when the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 534.2 ft (table 6; fig. 47) and streamflow on the Missouri River was about 95,700 ft^3/s during the survey (table 6). 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 (Huizinga, 2020a).

The survey area was about 1,640 ft long and about 970 ft wide from bank to bank in the main channel (fig. 47). 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 edge of the surveyed area on the right (south) bank (fig. 47). The channel-bed elevations ranged from about 504 to 521 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; fig. 48; table 6), 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. 47; table 6). A shallow thalweg was present along the right (south) bank throughout the reach and was about 5 to 8 ft deeper than the channel bed in the middle of the channel (fig. 47). Small dunes and ripples were present throughout the survey reach (fig. 47). As in previous surveys (Huizinga, 2012, 2014, 2022a), stone revetment was present on the right (south) bank throughout the reach (fig. 47).

The scour holes that historically had been observed near pier 4 of both structures before 2015 (refer to fig. 31 in Huizinga, 2014) were conspicuously absent in the 2021 survey, having been effectively mitigated by the scour countermeasures installed around the piers in 2015 (figs. 47, 1.7*A*, 1.7*B*). The top of the riprap blanket countermeasure was evident around both piers in 2021 but appeared to have settled by 5 to 10 ft at the upstream end (figs. 47, 49, 1.7*A*, 1.7*B*), resulting in a shallow scour hole with a minimum channel-bed elevation of about 503 ft around the upstream perimeter of the blanket (fig. 47; table 7). Information from bridge plans indicates that pier 4 of upstream structure L0550 is founded on a caisson on bedrock, having about 44 ft of bed material between the channel bed near the pier and bedrock (fig. 49; table 7). 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. 50; table 7). The surveyed bed generally was similar to the previous multibeam survey in 2017 (figs. 49 and 50).

The difference between the survey on May 26, 2021, and the previous survey on May 31, 2017 (fig. 51), indicates about 77 percent of the joint area of interest had detectable change, which means about 23 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Erosion appears dominant throughout most of the reach between 2017 and 2021 in the DoD, except in localized troughs of dune features on the left (northeast) side of the channel, and in the thalweg along the right (southwest) bank (fig. 51). The average difference between the bathymetric surfaces was –0.35 ft (table 8), indicating minor channel degradation between the 2017 and 2021 surveys. The net volume of cut in the reach from 2017 to 2021 was about 50,400 yd^3, and the net volume of fill was about 34,300 yd^3, resulting in a net loss of about 16,100 yd^3 of sediment between 2017 and 2021 (table 8). The frequency distribution of bed elevations in 2021 is similar in shape to 2017, but with a higher percentage of cells in the mid-range of channel-bed elevations between 505 and 515 ft (fig. 48). The upstream and right edges of the riprap blanket around the piers showed erosion of 5 to 10 ft, and other localized erosion was evident on the top of the blanket (fig. 51); furthermore, the stone revetment along the right (southwest) bank also showed localized signs of minor scour and deposition (fig. 51); however, the apparent scour and deposition of the revetement and top of the riprap blanket may be the result of minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 26, 2021, and the survey on April 30, 2013 (fig. 52), indicates about 62 percent of the joint area of interest had detectable change, which means about 38 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition appears dominant throughout most of the reach between 2013 and 2021 in the DoD, except for moderate to substantial erosion along the left (northeast) bank (fig. 52). The average difference between the bathymetric surfaces was +0.49 ft (table 8), indicating minor channel aggradation between the 2013 and 2021 surveys, and there was a net gain of about 17,400 yd^3 of sediment between 2013 and 2021 (table 8). The frequency distribution of bed elevations in 2021 is again similar in shape to 2013, but with a slightly higher percentage of cells in the mid-range of channel-bed elevations between 505 and 515 ft (fig. 48); furthermore, the centroid of the 2013 distribution is shifted about 2 ft lower than the 2021 distribution below 514 ft. The stone revetment along the right (southwest) bank also showed very localized signs of minor scour and deposition (fig. 52); however, the differences of most of the channel near the revetment were equivocal. As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 21, 2021, and the survey during flooding on July 27, 2011 (fig. 53), indicates about 83 percent of the joint area of interest had detectable change, which means about 17 percent of the differences in

Figure 47. Bathymetric survey of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri.

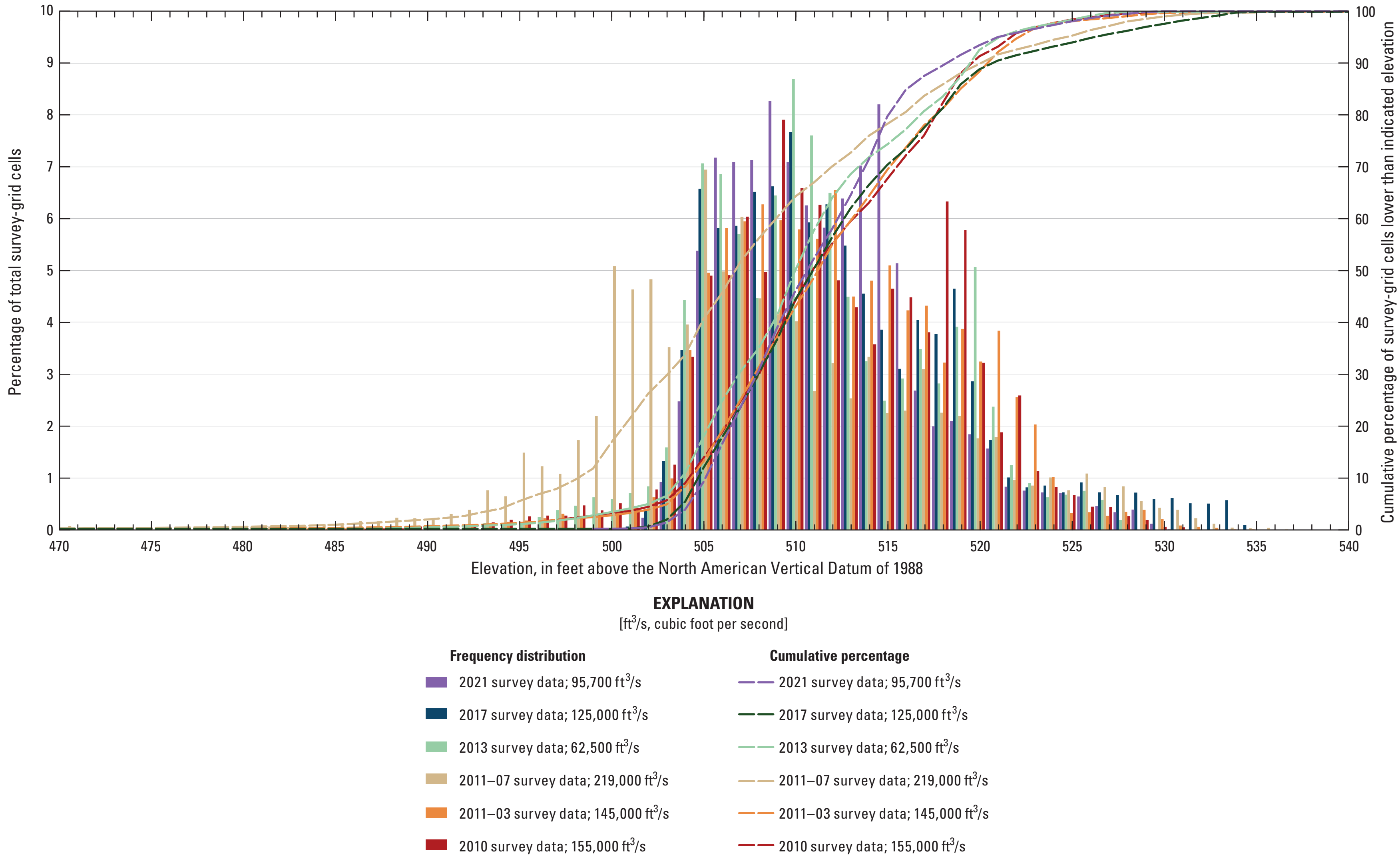


Figure 48. Frequency distribution of bed elevations for bathymetric survey-grid cells in 1-foot elevation bins on the Missouri River near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 26, 2021, compared to previous surveys in 2010, 2011, 2013, and 2017 (Huizinga, 2012, 2014, 2020a, respectively).

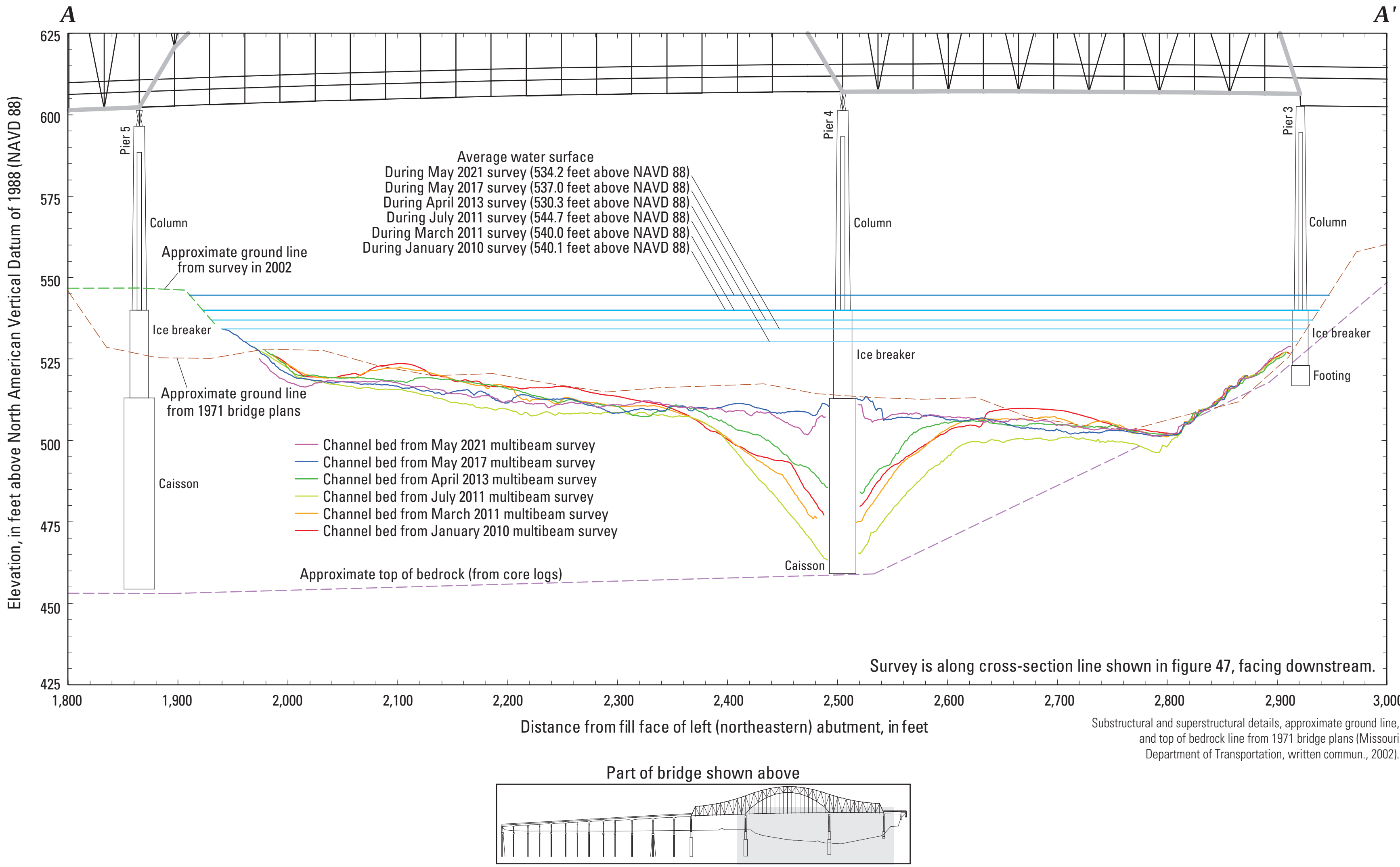


Figure 49. Key features, substructural and superstructural details, and surveyed channel bed of upstream structure L0550 on U.S. Highway 54 crossing the Missouri River at Jefferson City, Missouri.

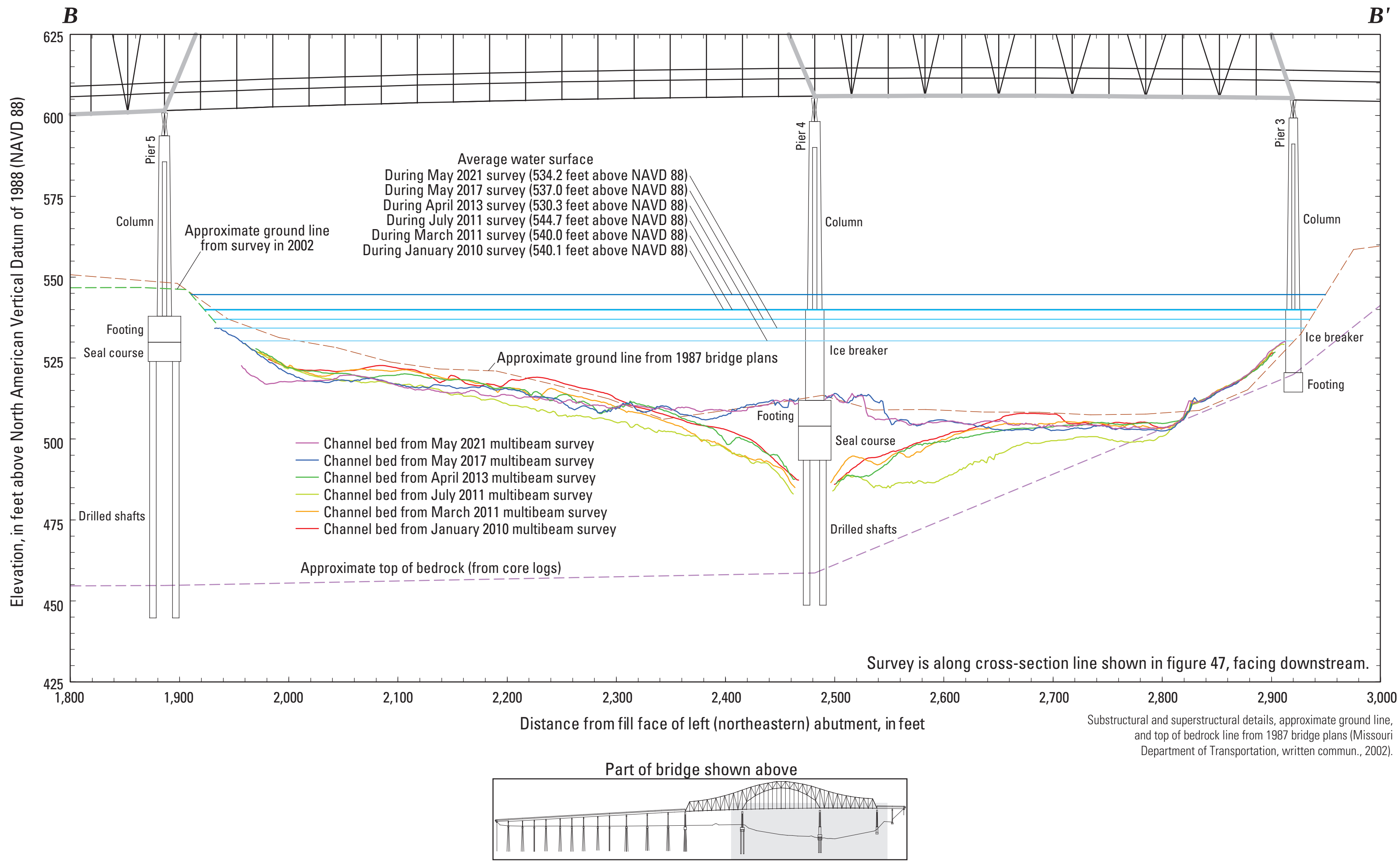


Figure 50. Key features, substructural and superstructural details, and surveyed channel bed of downstream structure A4497 on U.S. Highway 54 crossing the Missouri River at Jefferson City, Missouri.

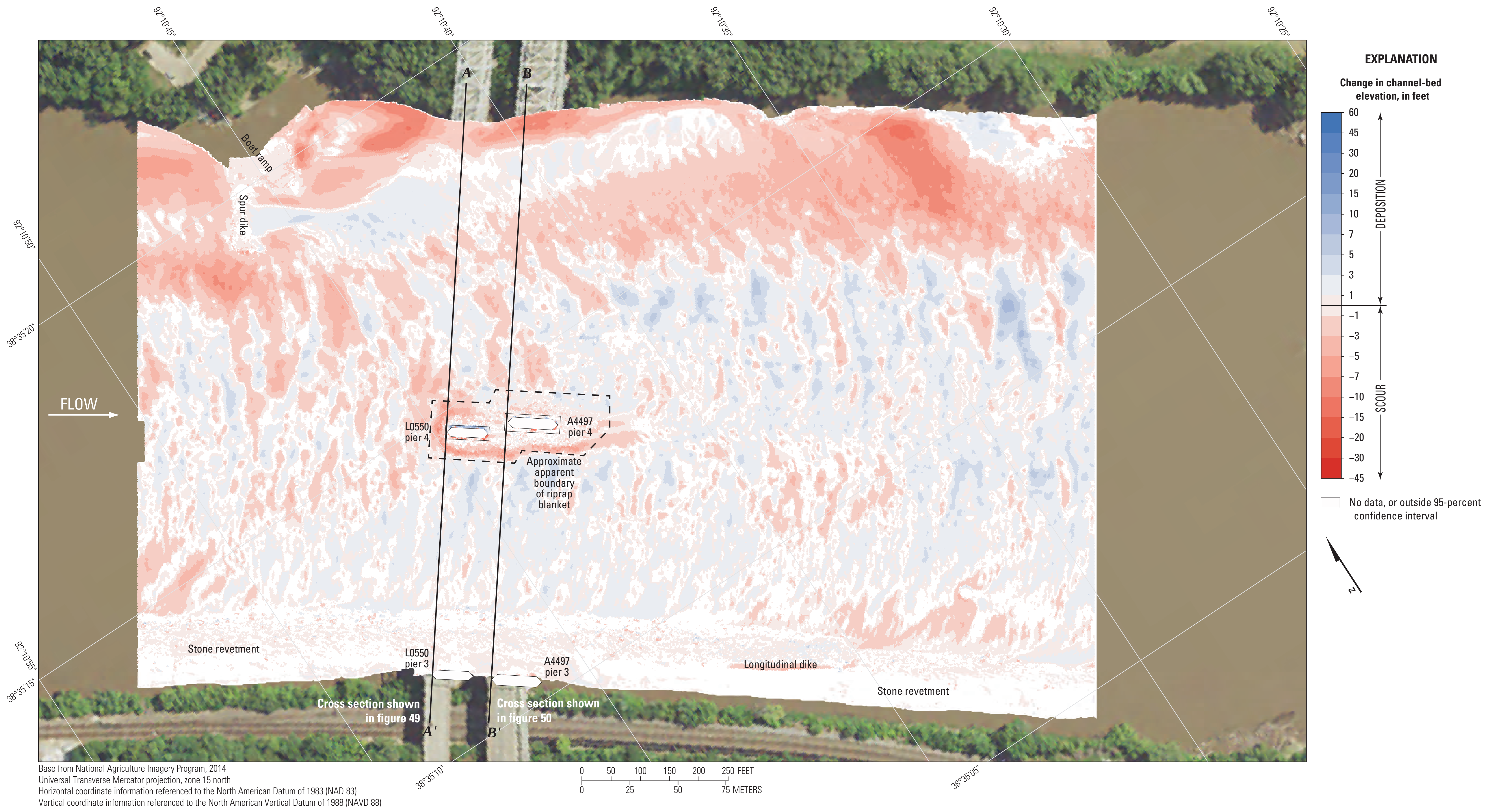
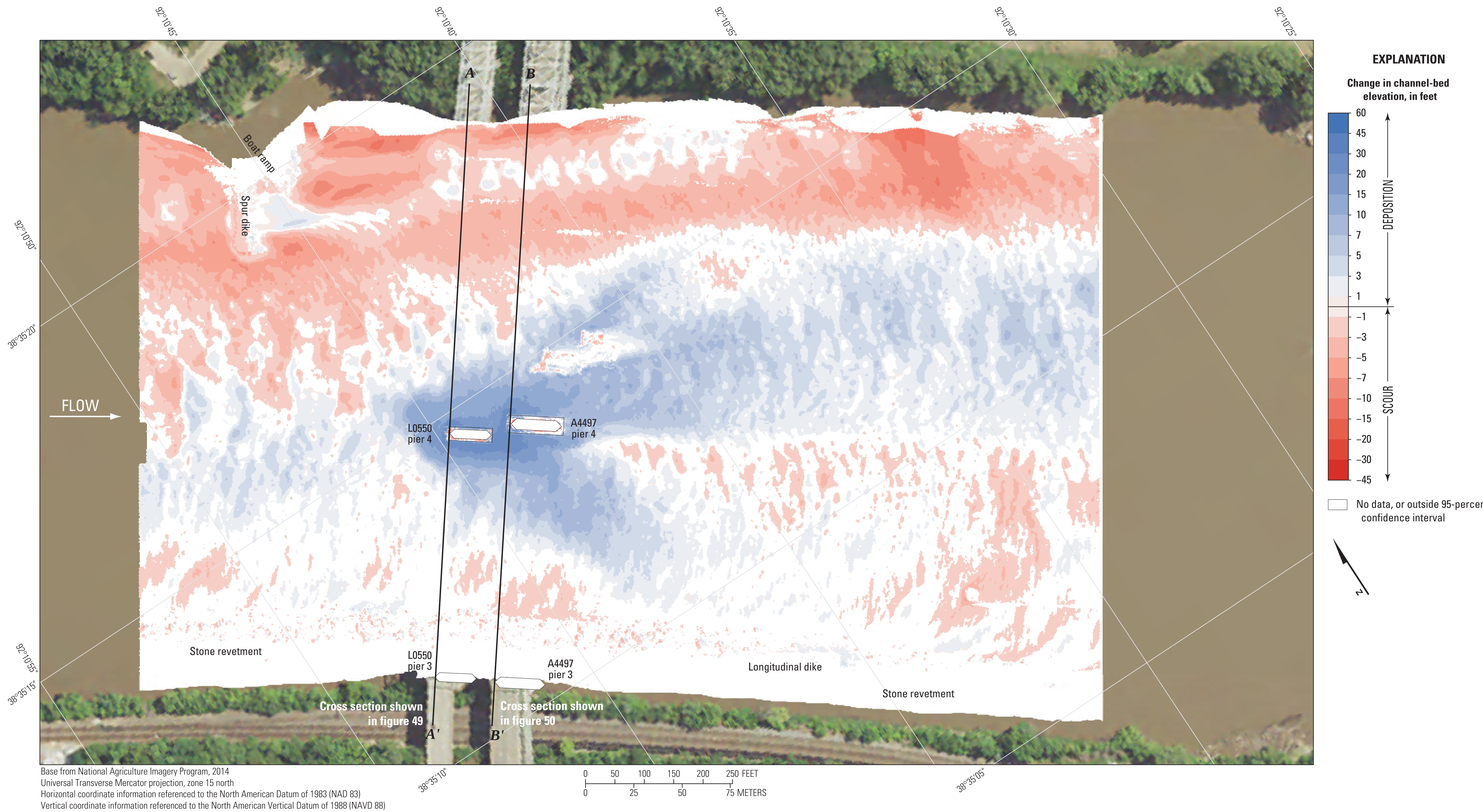


Figure 51. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 26, 2021, and May 31, 2017, with probabilistic thresholding.



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

Figure 52. 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 26, 2021, and April 30, 2013, with probabilistic thresholding.

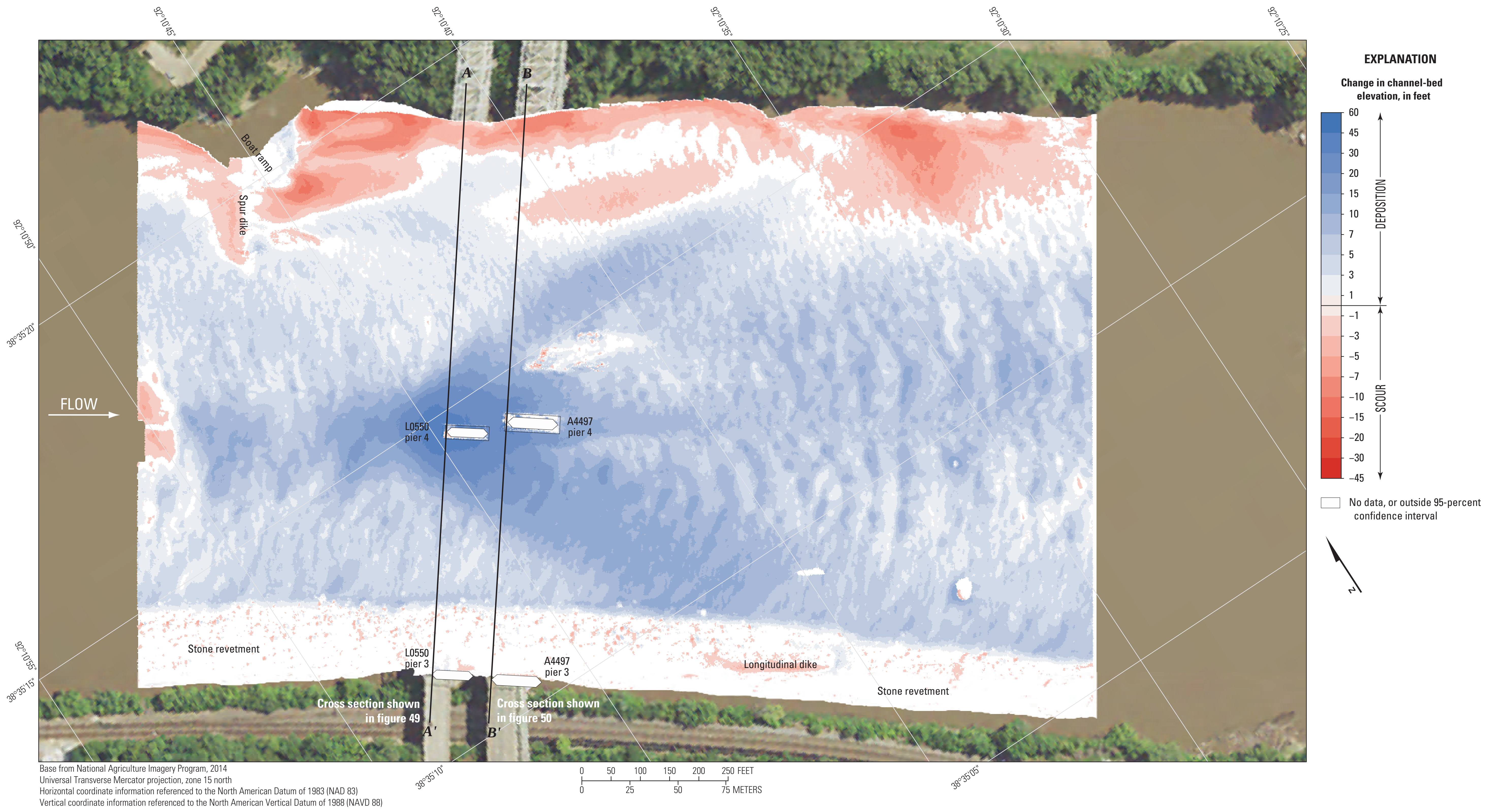


Figure 53. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 26, 2021, and July 27, 2011, with probabilistic thresholding.

the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition appears dominant in the reach between 2011 and 2021 in the DoD (fig. 53), with substantial deposition of as much as 45 ft in the historical scour hole near pier 4 of both structures. Alternatively, substantial erosion of as much as 20 ft was apparent along the left (northeast) bank (fig. 53). Nevertheless, the average difference between the 2011 and 2021 bathymetric surfaces was +4.52 ft (table 8) with a net gain of sediment between 2011 and 2021 of about 221,100 yd^3 (table 8), both of which are by far the largest positive changes observed in the 2021 surveys compared to previous surveys. The frequency distribution of bed elevations in 2011 is unique compared to the other distributions at this site, with a substantially higher percentage of cells at lower channel-bed elevations (fig. 48). The stone revetment along the right (southwest) bank again showed very localized signs of minor scour and deposition (fig. 53); however, the differences of most of the channel near the revetment were equivocal. As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to "Uncertainty Estimation" section).

The difference between the survey on May 21, 2021, and an earlier survey on March 1, 2011 (fig. 54), indicates about 72 percent of the joint area of interest had detectable change, which means about 28 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition appears dominant in the reach between March 2011 and 2021 in the DoD (fig. 54), with substantial deposition of as much as 45 ft in the historical scour hole near pier 4 of both structures, but moderate erosion of as much as 15 ft along the left (northeast) bank. However, the average difference between the March 2011 and 2021 bathymetric surfaces was +1.27 ft (table 8), indicating moderate channel aggradation with a net gain of sediment between March 2011 and 2021 of about 45,400 yd^3 (table 8). As in the other comparisons at this site, the stone revetment along the right (southwest) bank again showed very localized signs of minor scour and deposition (fig. 54); however, the differences of most of the channel near the revetment were equivocal. As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to "Uncertainty Estimation" section).

The difference between the survey on May 21, 2021, and the earliest survey on January 16, 2010 (fig. 55), indicates about 73 percent of the joint area of interest had detectable change, which means about 27 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Despite substantial deposition of as much as 60 ft in the historical scour hole near pier 4 of both bridges, erosion appears dominant in the reach between 2010 and 2021 in the DoD (fig. 55). The average difference between the 2010 and 2021 bathymetric surfaces was –1.21 ft (table 8), indicating moderate channel degradation with a net loss of sediment between 2010 and 2021 of about 45,200 yd^3 (table 8). Once again, the stone revetment along the right (southwest) bank again showed very localized signs of minor scour and deposition (fig. 54); however, the differences of most of the channel near the revetment were equivocal. As with previous DoDs, deposition or scour apparent on opposing faces of a feature likely results from minor horizontal positional variances between the surveys (refer to "Uncertainty Estimation" section).

The vertically averaged velocity vectors indicate mostly uniform flow throughout the channel, ranging from about 3 to 9 ft/s (fig. 56), with locally lower velocities and flow reversal along the banks downstream from the various spur dikes in the reach. Pier 4 of both structures are mostly aligned with flow but cause moderate turbulence downstream (fig. 56). However, flow velocities seemed unusually variable in all the transects (fig. 56), which is unusual given the general lack of spur dikes and substantial dune features that might cause flow divergence or upwelling in the reach (Best, 2005).

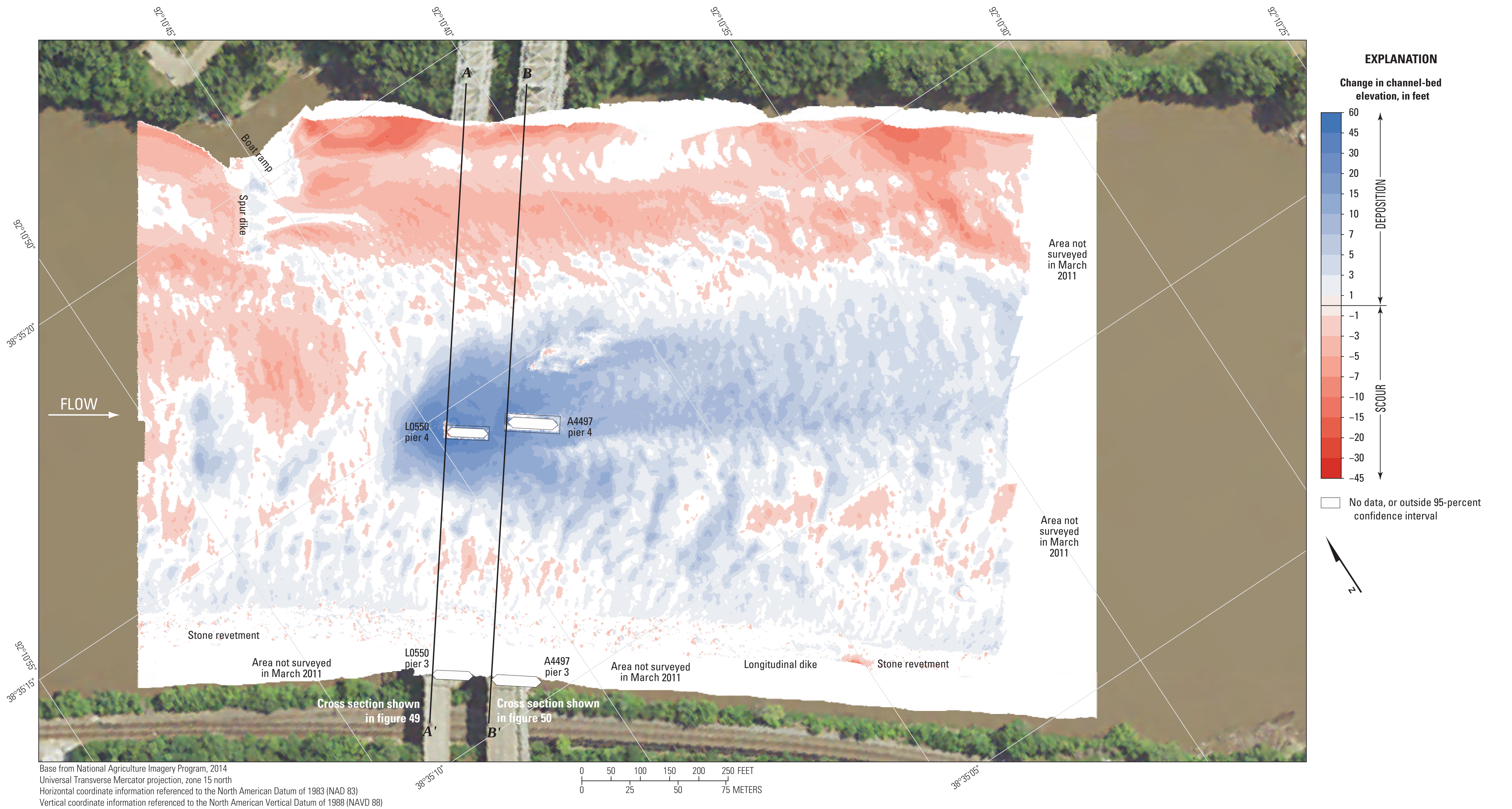


Figure 54. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 26, 2021, and March 1, 2011, with probabilistic thresholding.

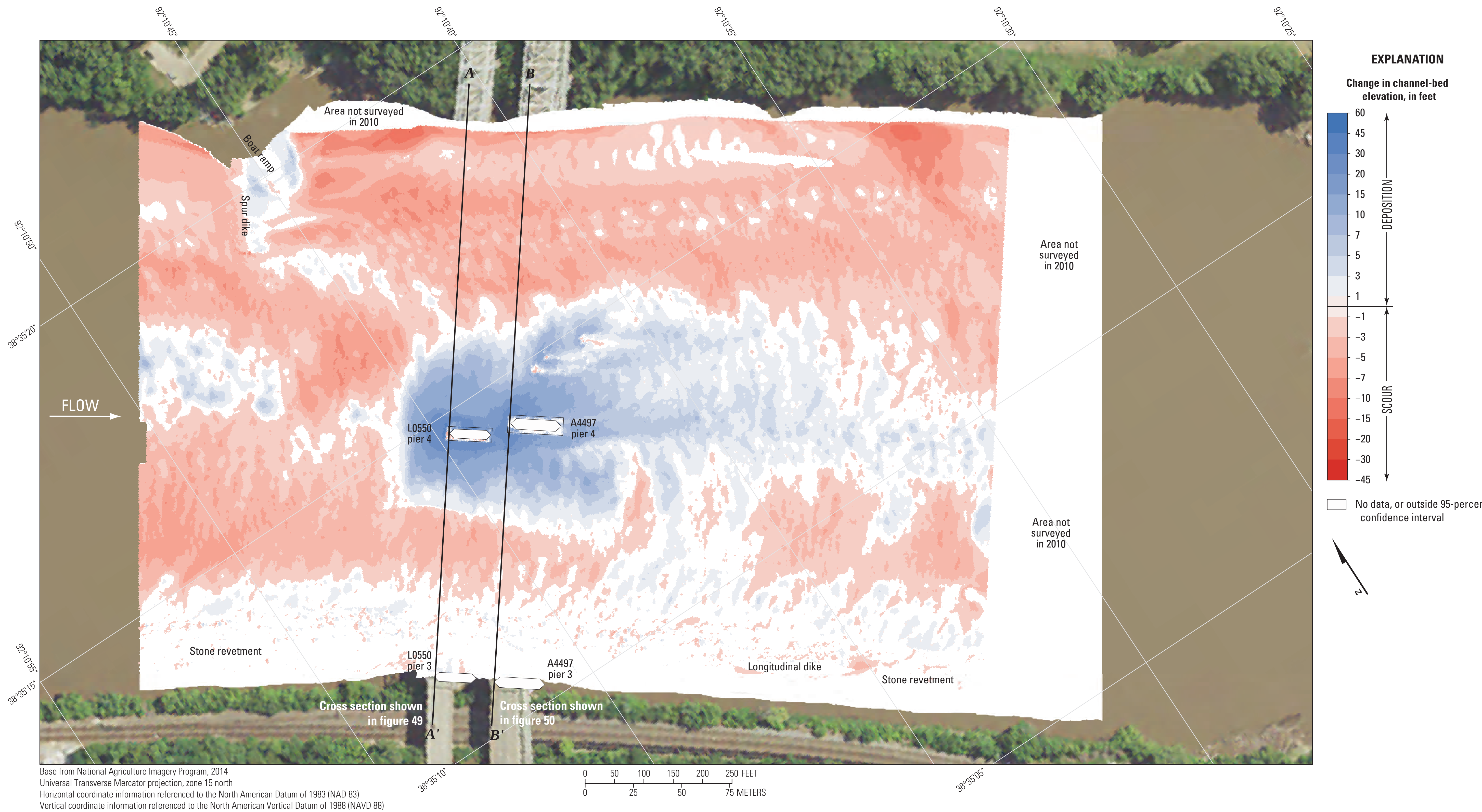


Figure 55. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri, on May 26, 2021, and January 26, 2010, with probabilistic thresholding.

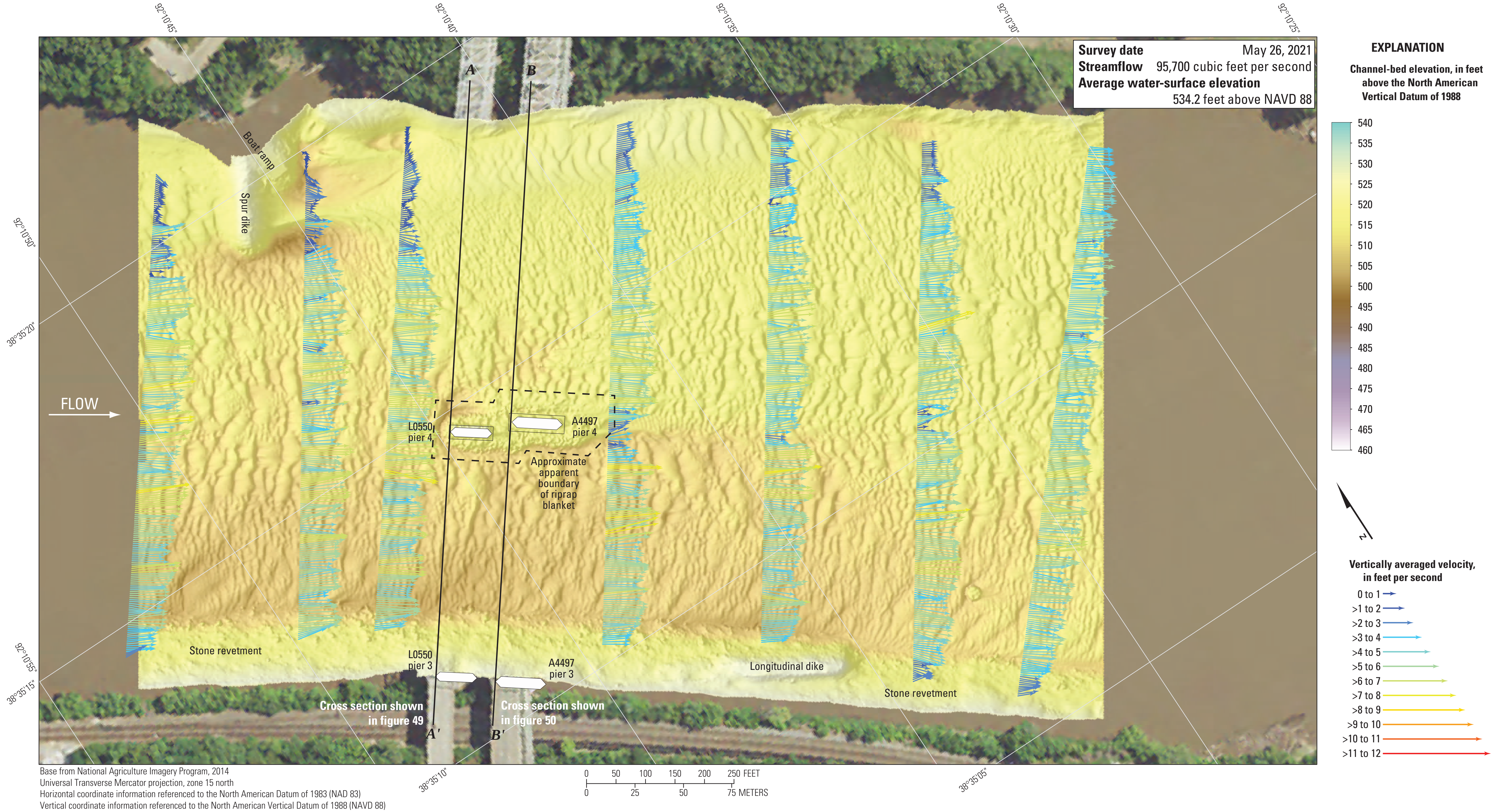


Figure 56. Bathymetry and vertically averaged velocities of the Missouri River channel near structures L0550 and A4497 on U.S. Highway 54 at Jefferson City, Missouri.

Structure A6288 on State Highway 19 at Hermann, Missouri

Structure A6288 (site 21; table 2) on 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 26, 2021, when the average water-surface elevation of the river in the survey area, determined by the RTK GNSS tide solution, was 497.7 ft (table 6; fig. 57) and streamflow on the Missouri River was about 132,000 ft^3/s during the survey (table 6).

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. 57). The upstream end of the survey area was about 690 ft upstream from the centerline of structure A6288 at pier 5 (fig. 57), and piers 4 through 6 were in the water. The channel-bed elevations ranged from about 463 to 484 ft for most of the surveyed area (5th to 95th percentile range of the bathymetric data; fig. 58; table 6) except inside the upstream left (north) longitudinal spur dike where a local minimum channel-bed elevation of 442 ft was observed (table 6; fig. 57). A poorly defined thalweg was present along the left (north) bank throughout the length of the surveyed area. Numerous small to medium dunes and ripples were detected throughout the channel (fig. 57). As in previous surveys (Huizinga, 2012, 2014, 2022a), rock outcrops and stone revetment were present on the right (south) bank throughout the reach, and spur dikes were present on both banks (fig. 57).

Minor scour holes were observed near both piers in the main channel, and near pier 6 behind the longitudinal spur dike on the left (north) side (fig. 57). The minor scour hole near pier 6 had a minimum channel-bed elevation of about 469 ft (table 7), which is about 27 ft above the elevation of the bottom of the pier seal course of 442.00 ft (fig. 59; table 7). The minor scour hole near pier 5 had a minimum channel-bed elevation of about 464 ft (table 7), which is about 20 ft above the elevation of the bottom of the pier seal course of 444.50 ft (fig. 59; table 7). The moderate scour hole near pier 4 had a minimum channel-bed elevation of about 460 ft (table 7), which is about 9 ft above the elevation of the bottom of the pier seal course of 451.50 ft (fig. 59; table 7). The scour hole near pier 5 was difficult to discern from nearby dunes and ripples, but the downstream left edge of the footing was visible during the survey (fig. 1.8*C*). The upstream edge of the footing for pier 4 also was visible during the survey (figs. 57, 59, 1.8*E*, 1.8*F*), which likely contributes to the larger scour hole near that pier. The top of the footing may blunt the horseshoe vortex at pier 5, but the exposed front of the footing may exacerbate the vortex at pier 4. 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 68 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 17 ft of material at pier 4, owing to the sloping nature of the bedrock (fig. 59; table 7). The surveyed bed in 2021 generally was similar to the previous multibeam surveys but tended to fall towards the bottom of the fluctuating range of elevations seen in previous surveys between the longitudinal spur dike on the left (north) side of the channel and pier 4 (fig. 59).

The difference between the survey on May 26, 2021, and the previous survey on May 31, 2017 (fig. 60), indicates about 76 percent of the joint area of interest had detectable change, which means about 24 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Deposition and erosion appear roughly balanced throughout most of the reach between 2017 and 2021 in the DoD, including areas of substantial erosion and deposition behind the longitudinal spur dike on the left (north) bank near the bridge (fig. 60). The scour hole near pier 4 was wider and deeper in 2021 than in 2017 (figs. 59, 60), despite the lower streamflow in 2021 (table 8). The average difference between the bathymetric surfaces was –0.39 ft (table 8), indicating minor channel degradation between the 2017 and 2021 surveys. The net volume of cut in the reach from 2017 to 2021 was about 85,500 yd^3, and the net volume of fill was about 58,100 yd^3, resulting in a net loss of about 27,400 yd^3 of sediment between 2017 and 2021 (table 8). The frequency distribution of bed elevations in 2021 is similar to 2017, but with a 2–3-ft shift of the centroid towards lower elevations (fig. 58). The rock outcrop and stone revetment along the right (south) bank and the longitudinal spur dikes on the left (north) side showed localized signs of minor scour and deposition (fig. 60); however, the apparent scour or deposition may be the result of minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section).

The difference between the survey on May 26, 2021, and the survey on May 2, 2013 (fig. 61), indicates about 71 percent of the joint area of interest had detectable change, which means about 29 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Erosion appears dominant throughout most of the reach between 2013 and 2021 in the DoD, except in localized areas near and downstream from spur dikes on both banks (fig. 61). The average difference between the bathymetric surfaces was –3.05 ft (table 8), which is the largest negative change observed in the 2021 surveys compared to previous surveys. The average difference indicates substantial channel degradation between the 2013 and 2021 surveys, and the net loss of sediment between 2013 and 2021 was about 169,200 yd^3 (table 8), which is the most substantial loss between the surveys detailed in this report. The cross section from the 2021 survey along the upstream face of the bridge is about 5–8 ft below the 2013 survey section, except near pier 4 where the difference is near 20 ft (fig. 59). The frequency distribution of bed elevations in 2013 has a higher percentage of cells in a narrower range of channel-bed elevations, causing a shift of the centroid of 4–5 ft higher than 2021 (fig. 58). The rock outcrop and stone revetment on the right (south) bank is within the bounds of uncertainty (fig. 61). A substantial part of the channel on the left (north) side was not surveyed in 2013 because of generally lower flows (table 8) and shallow depths in that area. As with the previous DoDs, deposition or scour

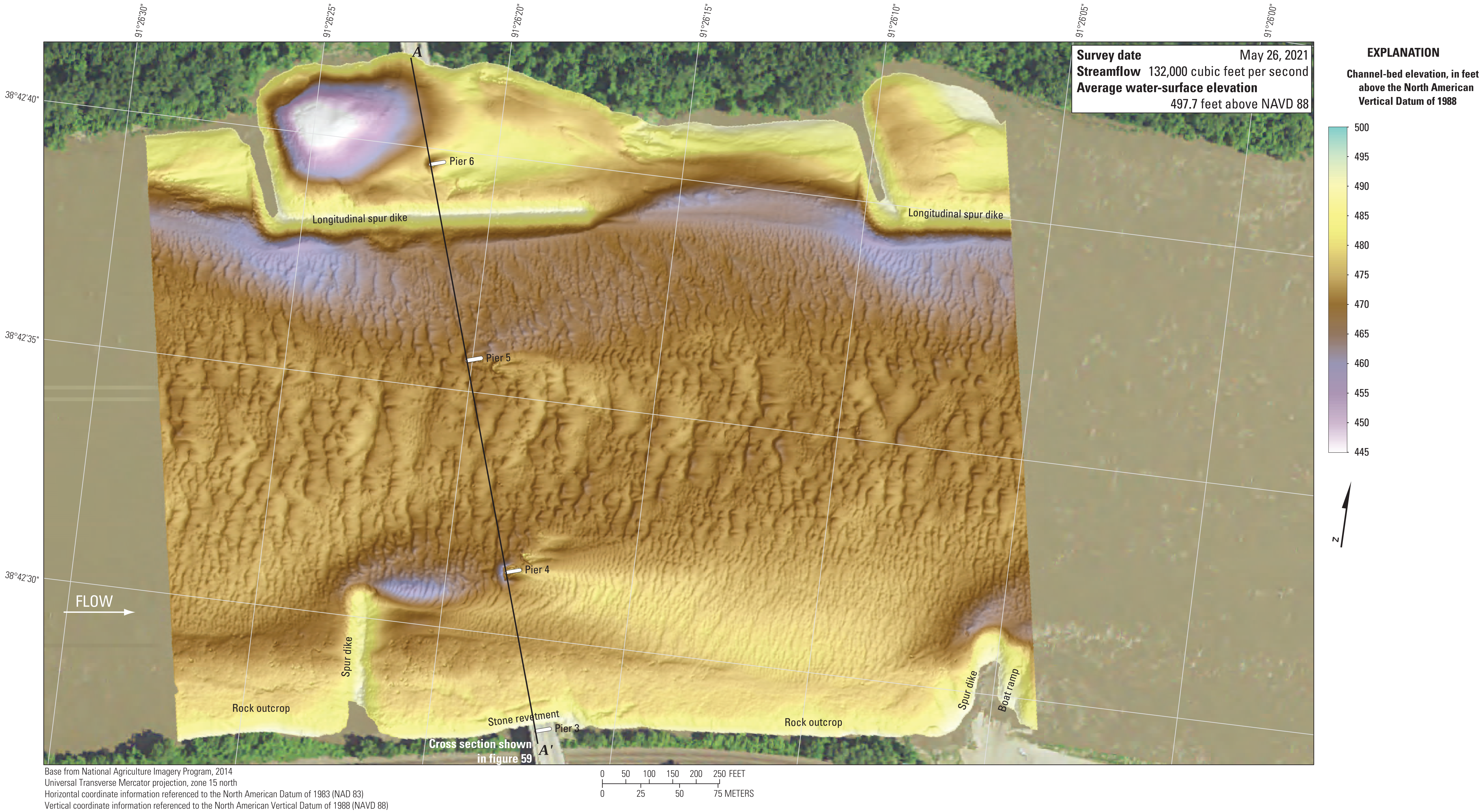


Figure 57. Bathymetric survey of the Missouri River channel near structure A6288 on State Highway 19 at Hermann, Missouri.

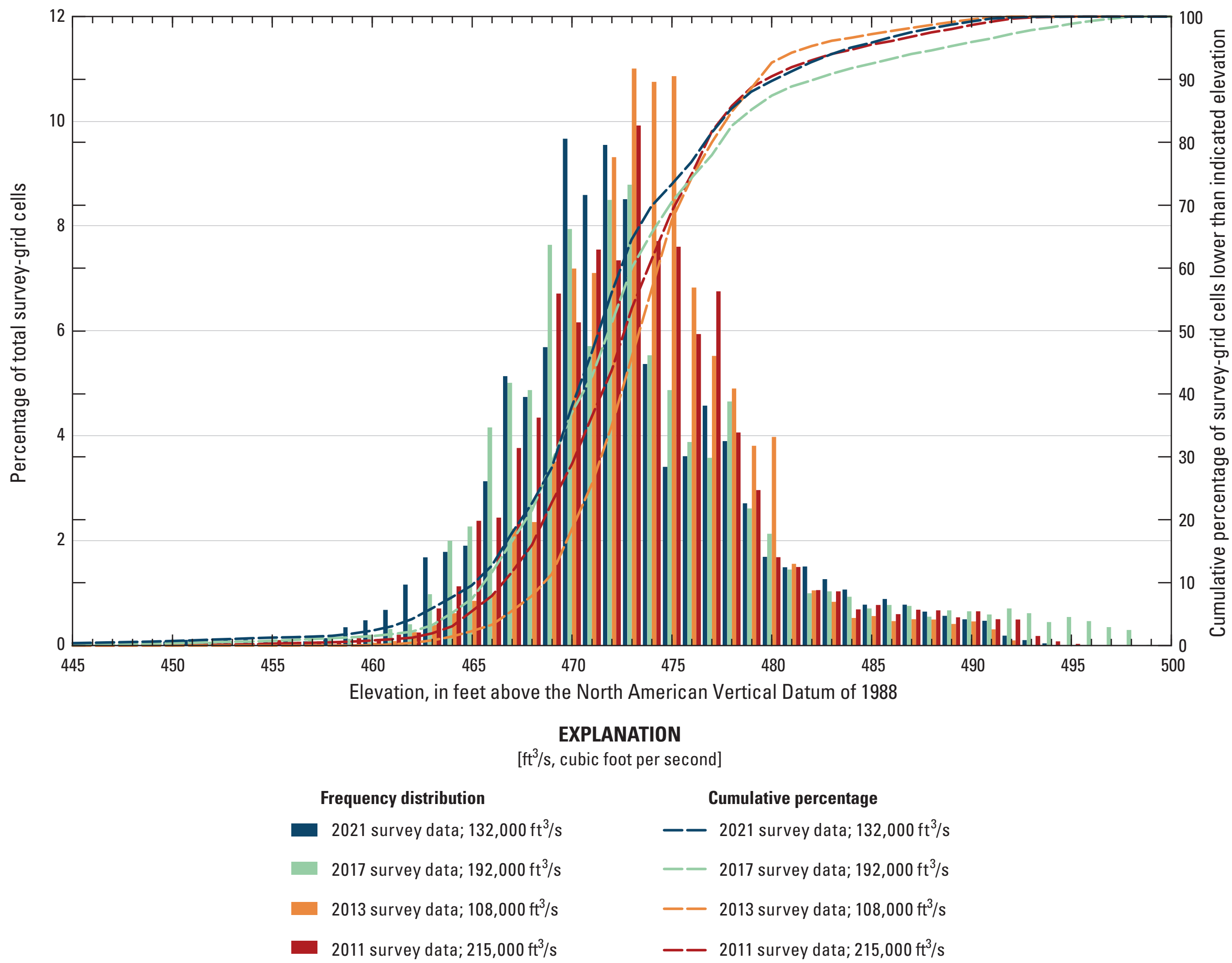


Figure 58. Frequency distribution of bed elevations for bathymetric survey-grid cells in 1-foot elevation bins on the Missouri River near structure A6288 on State Highway 19 at Hermann, Missouri, on May 26, 2021, compared to previous surveys in 2011, 2013, and 2017 (Huizinga, 2012, 2014, 2020a, respectively).

apparent on opposing faces of a feature (such as a pier or spur dike) likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section). Nevertheless, the substantial deposition on the longitudinal spur dike just upstream from the bridge (fig. 61) likely is the result of repairs made to the dike between 2013 and 2017, because a similar indication of deposition was not apparent in the comparison between 2017 and 2021 (fig. 60).

The difference between the survey on May 26, 2021, and the survey during flooding on July 28, 2011 (fig. 62), indicates about 73 percent of the joint area of interest had detectable change, which means about 27 percent of the differences in the joint area of interest are equivocal and within the bounds of uncertainty (table 8). Erosion appears dominant throughout most of the reach between 2011 and 2021 in the DoD, except for substantial deposition in localized areas near and downstream from spur dikes on both banks (fig. 62). The average difference between the bathymetric surfaces was –1.38 ft (table 8), which is the third-largest negative change observed in the 2021 surveys compared to previous surveys. The average difference indicates moderate channel degradation between the 2011 and 2021 surveys, and the net loss of sediment between 2011 and 2021 was about 90,300 yd^3 (table 8), which is the second-most substantial loss between the surveys detailed in this report. The rock outcrop and stone revetment along the right (south) bank and the longitudinal spur dikes on the left (north) side showed localized signs of minor scour and deposition (fig. 62); however, as with the previous

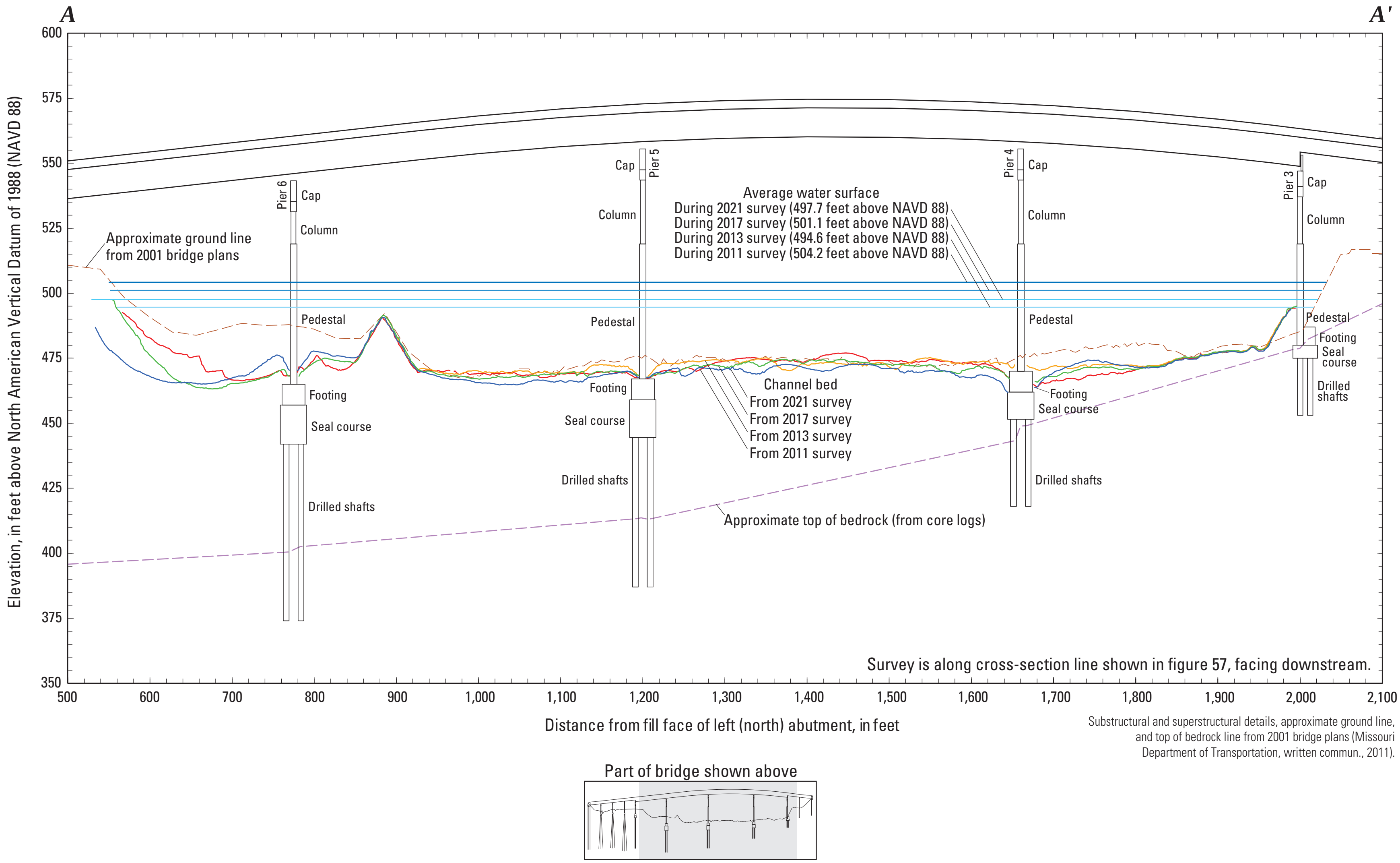


Figure 59. Key features, substructural and superstructural details, and surveyed channel bed of structure A6288 on State Highway 19 crossing the Missouri River at Hermann, Missouri.

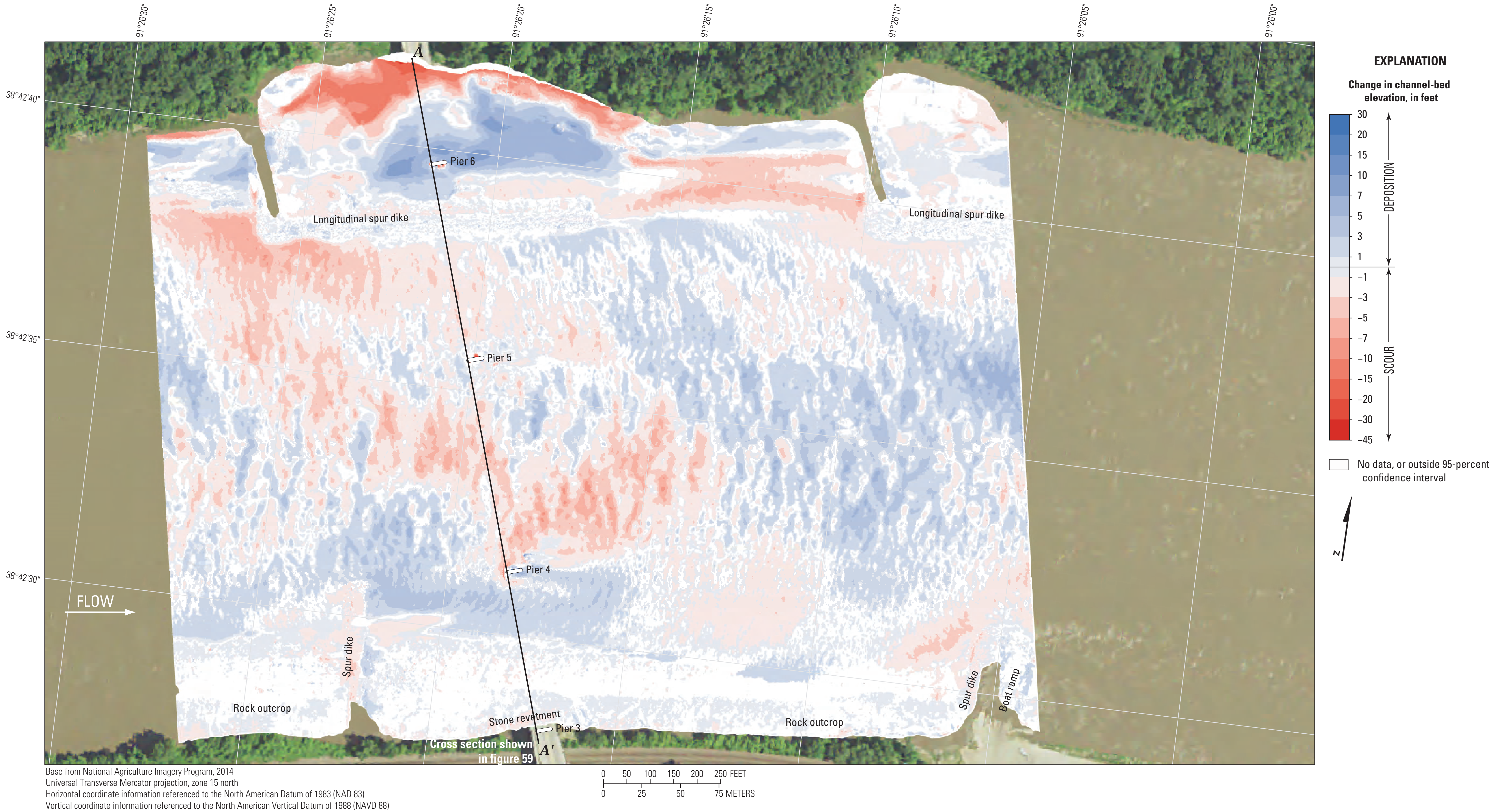


Figure 60. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A6288 on State Highway 19 at Hermann, Missouri, on May 26, 2021, and May 31, 2017, with probabilistic thresholding.

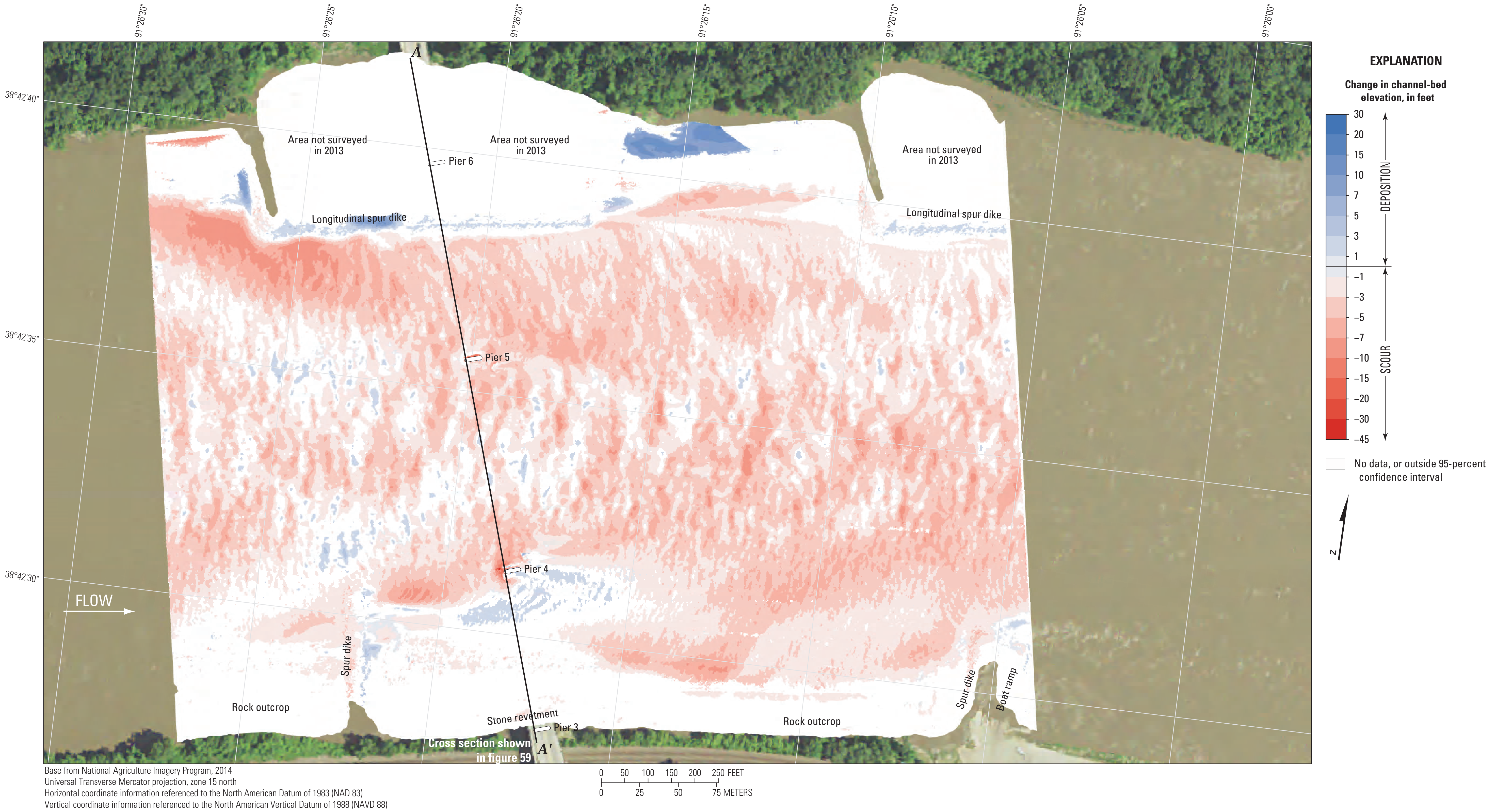


Figure 61. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A6288 on State Highway 19 at Hermann, Missouri, on May 26, 2021, and May 2, 2013, with probabilistic thresholding.

DoDs, deposition or scour apparent on opposing faces of a feature (such as a pier or spur dike) likely results from minor horizontal positional variances between the surveys (refer to “Uncertainty Estimation” section). The substantial deposition on the longitudinal spur dike just upstream from the bridge observed in the 2013 to 2021 comparison (fig. 61) appears again in the 2011 to 2021 comparison (fig. 62), and likely is the result of repairs made to the dike between 2013 and 2017.

The vertically averaged velocity vectors indicate mostly uniform flow throughout the channel, ranging from about 2 to 9 ft/s (fig. 63), with locally lower velocities and flow reversal along the banks downstream from the various spur dikes in the reach. Flow velocities seemed unusually variable in all the transects (fig. 63), which might be the result of flow divergence and upwelling caused by the spur dikes and small to medium dune features in the reach (Best, 2005).

The end of a survey day on the Missouri River.

Photograph by Richard J. Huizinga, U.S. Geological Survey.

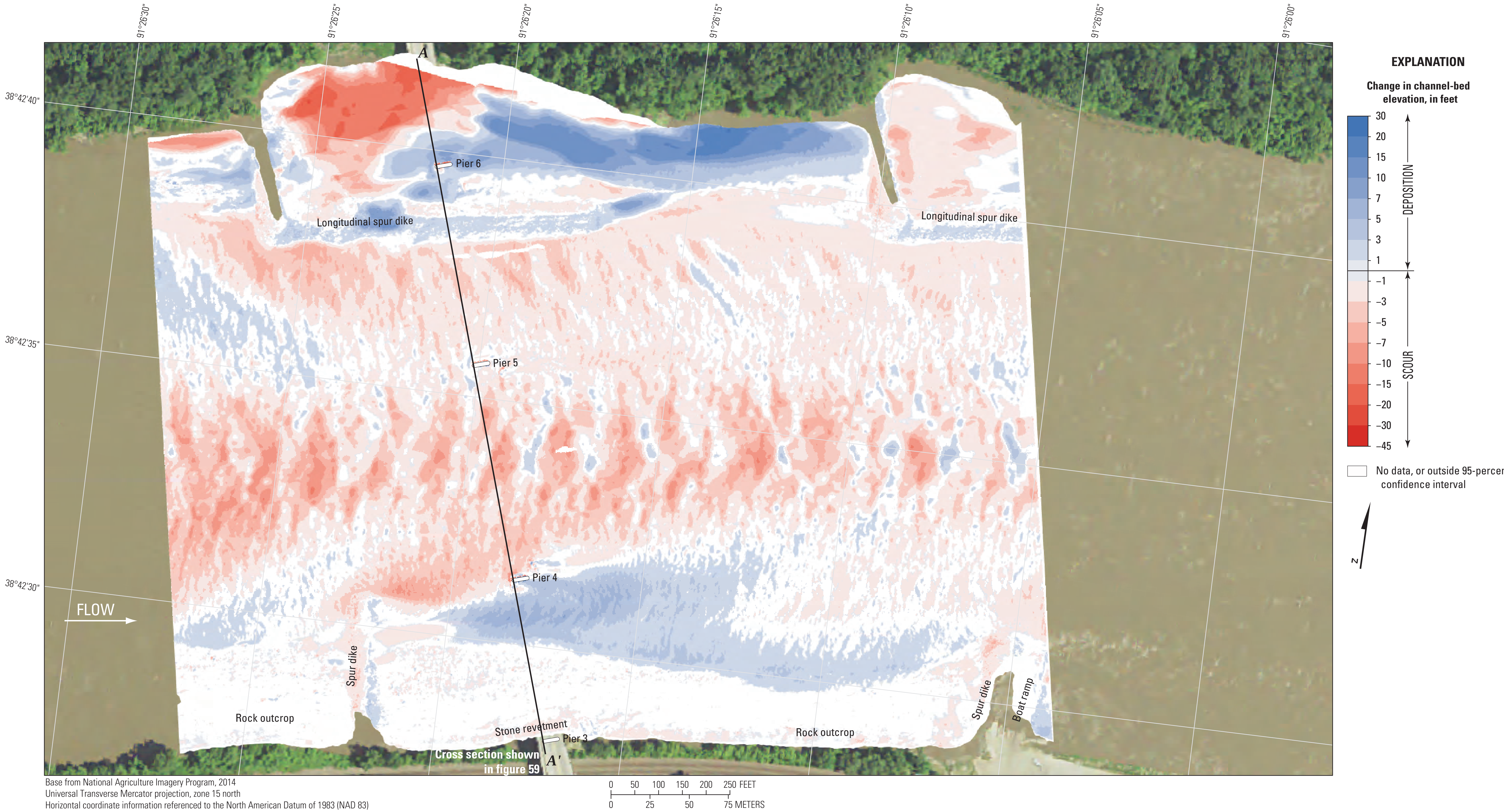


Figure 62. Difference between surfaces created from bathymetric surveys of the Missouri River channel near structure A6288 on State Highway 19 at Hermann, Missouri, on May 26, 2021, and July 28, 2011, with probabilistic thresholding.

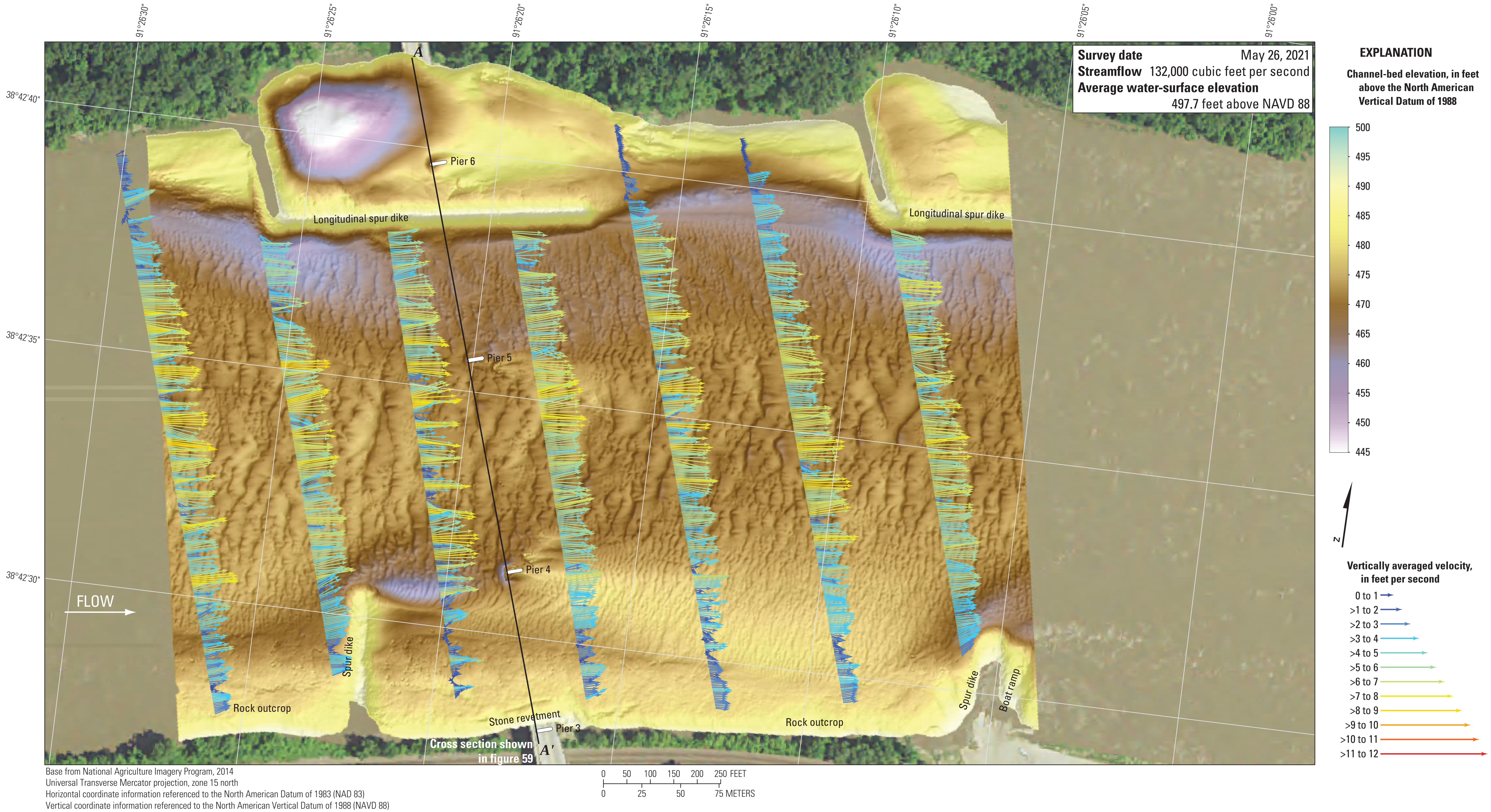


Figure 63. Bathymetry and vertically averaged velocities of the Missouri River channel near structure A6288 on State Highway 19 at Hermann, Missouri.

Summary and Conclusions

Bathymetric and velocimetric data were collected by the U.S. Geological Survey, in cooperation with the Missouri Department of Transportation, near nine bridges at eight highway crossings between Kansas City and St. Louis, Missouri, on May 19–26, 2021. A multibeam echosounder mapping system was used to obtain channel-bed elevations for river reaches extending 1,640 to 1,840 feet (ft) longitudinally and generally extending laterally across the active channel from bank to bank during low to moderate flood-flow conditions. These surveys indicated the channel conditions at the time of the surveys and provided characteristics of scour holes that may be useful in developing 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 assessment of the bridges for stability and integrity issues with respect to bridge scour during floods.

The estimated gridded 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 sources of error considered. An analysis of the surveys indicated that more than 99 percent of the bathymetric data at all the sites have a gridded uncertainty of less than 0.50 ft, and more than 97 percent of the channel-bed elevations at the sites have a gridded uncertainty of less than 0.25 ft. The gridded uncertainty of the data has been decreasing with time compared to previous surveys attributed to improvements in data-collection equipment and methods.

A variety of fluvial geomorphic features were detected in the channel, ranging from small ripples to large dunes that indicate moderate transport of bedload were present at all the surveyed bridges. Rock outcrops also were detected along one bank at several sites where the alluvial material of the channel bed had been washed away, consistent with previous surveys. Bathymetric data were collected around every pier that was in water. Scour holes were present at most piers for which bathymetry could be obtained, except those on banks or surrounded by riprap. Occasionally, scour holes were minor and difficult to discern from nearby dunes and ripples, such as structure A5664 at Lexington (site 14), structure A5910 at Waverly (site 15), structure A4574 at Boonville (site 18), and pier 5 of structure A6288 at Hermann (site 21).

All the bridge sites in this study were previously surveyed. Comparisons between bathymetric surfaces from the previous surveys and those of the current (2021) study do not indicate any consistent correlation between channel-bed elevations and streamflow conditions. Most of the sites in the current (2021) study were surveyed when the Missouri River was on or between minor to moderate flood rises during generally higher late-spring streamflows. The average difference between the bathymetric surfaces varied from 1.59 ft higher to 0.95 ft lower in 2021 than 2017, which corresponds to a gain of 100,200 cubic yards (yd^3) and a loss of 55,800 yd^3, respectively. The average difference between the bathymetric surfaces varied from 2.74 ft higher to 3.05 ft lower in 2021 than 2013, which corresponds to a gain of 111,500 yd^3 and a loss of 169,200 yd^3, respectively. The average difference between the bathymetric surfaces varied from 4.52 ft higher to 1.38 ft lower in 2021 than 2011, which corresponds to a gain of 221,100 yd^3 and a loss of 90,300 yd^3, respectively. The most substantial overall net gain was between 2011 and 2021 at structures L0550 and A4497 at Jefferson City (site 20), and likely is a combination of the mitigation of the scour holes near pier 4 of both bridges by the riprap blanket scour countermeasures installed in 2015, and the substantially lower flow in 2021 than in 2011. Alternatively, the most substantial overall net loss was between 2013 and 2021 at structure A6288 at Hermann (site 21), despite comparable streamflows. Furthermore, all the changes at structure A6288 at Hermann were a net loss of sediment between 2021 and previous surveys.

Pier size, nose shape, and skew to approach flow affected the size of the scour hole observed at a given pier. Piers with wide or blunt noses caused by exposed footings or caissons usually resulted in larger, deeper scour holes at those piers. When a pier was skewed to primary approach flow, generally the scour hole was deeper and longer than at a similar pier without skew. For example, the exposed caissons of pier 5 of structure K0999 at Miami (site 16) and pier 14 of structure L0962 near Rocheport (site 19) likely contributes to the shape and depth of the scour holes near these piers and the similarity to previous surveys, despite the generally lower flow in 2021 compared to previous surveys. Furthermore, the skew of pier 14 of structure L0962 (site 19) was longer and deeper on the side with impinging flow, similar to the general shape of scour holes for skewed piers. At structure A6288 at Hermann (site 21), the scour hole near pier 5 was difficult to discern from nearby dunes and ripples, whereas the upstream edge of the footing was visible at pier 4, which likely contributes to the larger scour hole near that pier; the top of the footing may blunt the horseshoe vortex at pier 5, but the exposed front of the footing may exacerbate the vortex at pier 4.

A riprap blanket surrounds pier 4 of structures L0550 and A4497 (site 20) and limits scour near those piers. The mitigation of the scour hole by the riprap blanket had been noted in the previous survey in 2017. The upstream end of the blanket appeared to have settled by 5 to 10 ft.

References Cited

American Association of State Highway Transportation Officials, 2020, AASHTO LRFD bridge design specifications (9th ed.): Washington, D.C., American Association of State Highway Transportation Officials, 176 p.

Applanix Corporation, 2021, POSPac MMS GNSS-inertial tools software, rev. 17: Richmond Hill, Ontario, Canada, PUBS–MAN–001768, 239 p.

Arneson, L.A., Zevenbergen, L.W., Lagasse, P.F., and Clopper, P.E., 2012, Evaluating scour at bridges (5th ed.): U.S. Federal Highway Administration Publication FHWA–HIF–12–003, Hydraulic Engineering Circular no. 18, 340 p., accessed September 30, 2022, at https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif12003.pdf.

Becker, L.D., 1994, Investigation of bridge scour at selected sites on Missouri streams: U.S. Geological Survey Water-Resources Investigations Report 94–4200, 40 p., accessed September 30, 2022, at https://doi.org/10.3133/wri944200.

Best, J., 2005, The fluid dynamics of river dunes—A review and some future research directions: Journal of Geophysical Research, v. 110, no. F4, F04S02, accessed August 21, 2023, at https://doi.org/10.1029/2004JF000218.

Brown, D.A., Turner, J.P., Castelli, R.J., and Loehr, E.J., 2018, Drilled shafts—Construction procedures and design methods: U.S. Federal Highway Administration Publication FHWA–NHI–18-024, Geotechnical Engineering Circular no. 10, 756 p., accessed August 21, 2023, at https://www.fhwa.dot.gov/engineering/geotech/nhi18024.pdf.

Calder, B.R., and Mayer, L.A., 2003, Automatic processing of high-rate, high-density multibeam echosounder data: Geochemistry, Geophysics, Geosystems (G3), v. 4, no. 6, 22 p., accessed December 8, 2023, at https://doi.org/10.1029/2002GC000486.

Densmore, B.K., Strauch, K.R., and Dietsch, B.J., 2013, Hydrographic surveys of the Missouri and Yellowstone Rivers at selected bridges and through Bismarck, North Dakota, during the 2011 flood: U.S. Geological Survey Scientific Investigations Report 2013–5087, 59 p., accessed September 30, 2022, at https://doi.org/10.3133/sir20135087.

Dietsch, B.J., Densmore, B.K., and Strauch, K.R., 2014, Repeated multibeam echosounder hydrographic surveys of 15 selected bridge crossings along the Missouri River from Niobrara to Rulo, Nebraska during flood of 2011: U.S. Geological Survey Scientific Investigations Report 2014–5062, 53 p., accessed February 1, 2024, at https://doi.org/10.3133/sir20145062.

Esri, 2022, Resources for ArcMap (ver. 10.8): accessed August 29, 2022, at https://www.esri.com/en-us/arcgis/products/arcgis-desktop/resources.

Gilbert, G.K., and Murphy, E.C., 1914, The transportation of debris by running water: U.S. Geological Survey Professional Paper 86, 263 p., accessed September 30, 2022, at https://doi.org/10.3133/pp86.

Hughes Clarke, J.E., Mayer, L.A., and Wells, D.E., 1996, Shallow-water imaging multibeam sonars—A new tool for investigating seafloor processes in the coastal zone and on the continental shelf: Marine Geophysical Researches, v. 18, p. 607–629, accessed November 29, 2022, at https://doi.org/10.1007/BF00313877.

Huizinga, R.J., 2010, Bathymetric surveys at highway bridges crossing the Missouri River in Kansas City, Missouri, using a multibeam echo sounder, 2010: U.S. Geological Survey Scientific Investigations Report 2010–5207, 61 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20105207.

Huizinga, R.J., 2011, Bathymetric surveys at highway bridges crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, 2010: U.S. Geological Survey Scientific Investigations Report 2011–5170, 75 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20115170.

Huizinga, R.J., 2012, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River in and into Missouri during summer flooding, July–August 2011: U.S. Geological Survey Scientific Investigations Report 2012–5204, 166 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20125204.

Huizinga, R.J., 2013, Results of repeat bathymetric and velocimetric surveys at the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas, 2009–2013: U.S. Geological Survey Scientific Investigations Report 2013–5177, 50 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20135177.

Huizinga, R.J., 2014, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River between Kansas City and St. Louis, Missouri, April–May, 2013: U.S. Geological Survey Scientific Investigations Report 2014–5116, 79 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20145116.

Huizinga, R.J., 2015, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri and Mississippi Rivers on the periphery of Missouri, June 2014: U.S. Geological Survey Scientific Investigations Report 2015–5048, 81 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20155048.

Huizinga, R.J., 2016, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River near Kansas City, Missouri, June 2–4, 2015: U.S. Geological Survey Scientific Investigations Report 2016–5061, 93 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20165061.

Huizinga, R.J., 2017a, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, May 23–27, 2016: U.S. Geological Survey Scientific Investigations Report 2017–5076, 102 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20175076.

Huizinga, R.J., 2017b, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, October 2008 through May 2016: U.S. Geological Survey data release, accessed August 24, 2023, at https://doi.org/10.5066/F71C1VCC.

Huizinga, R.J., 2020a, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River between Kansas City and St. Louis, Missouri, May 22–31, 2017: U.S. Geological Survey Scientific Investigations Report 2020–5018, 104 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20205018.

Huizinga, R.J., 2020b, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri River in Kansas City, Missouri, March 2010 through May 2017: U.S. Geological Survey data release, accessed August 24, 2023, at https://doi.org/10.5066/P9L6GW57.

Huizinga, R.J., 2020c, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri River between Kansas City and St. Louis, Missouri, January 2010 through May 2017: U.S. Geological Survey data release, accessed August 24, 2023, at https://doi.org/10.5066/P94M4US7.

Huizinga, R.J., 2020d, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri and Mississippi Rivers on the periphery of Missouri, December 2008 through August 2018: U.S. Geological Survey data release, accessed August 24, 2023, at https://doi.org/10.5066/P9WDI9YF.

Huizinga, R.J., 2020e, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri and Mississippi Rivers on the periphery of Missouri, July–August 2018: U.S. Geological Survey Scientific Investigations Report 2020–5088, 100 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20205088.

Huizinga, R.J., 2021, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri River in Kansas City, Missouri, in August 2019, August 2020, and October 2020: U.S. Geological Survey data release, accessed August 24, 2023, at https://doi.org/10.5066/P96TX8AE.

Huizinga, R.J., 2022a, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri River near Kansas City, Missouri, August 2019, August 2020, and October 2020: U.S. Geological Survey Scientific Investigations Report 2021–5098, 112 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20215098.

Huizinga, R.J., 2022b, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, August 3–10, 2020: U.S. Geological Survey data release, accessed April 25, 2023, at https://doi.org/10.5066/P9F04JC5.

Huizinga, R.J., 2023, Bathymetric and velocimetric surveys at highway bridges crossing the Missouri and Mississippi Rivers near St. Louis, Missouri, August 3–10, 2020 (ver. 1.1, June 2023): U.S. Geological Survey Scientific Investigations Report 2023–5050, 129 p., accessed June 1, 2023, at https://doi.org/10.3133/sir20235050.

Huizinga, R.J., and Rivers, B.C., 2023, Bathymetry and velocity data from surveys at highway bridges crossing the Missouri River between Kansas City and St. Louis, Missouri, May 19–26, 2021 (ver. 2.0, August 2023): U.S. Geological Survey data release, accessed August 14, 2023, at https://doi.org/10.5066/P9ULGQ4W.

Huizinga, R.J., Elliott, C.M., and Jacobson, R.B., 2010, Bathymetric and velocimetric survey and assessment of habitat for pallid sturgeon on the Mississippi River in the vicinity of the proposed Interstate 70 Bridge at St. Louis, Missouri: U.S. Geological Survey Scientific Investigations Report 2010–5017, 28 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20105017.

Huizinga, R.J., Rivers, B.C., Richards, J.M., and Waite, G.J., 2023, Bathymetric contour maps, surface area and capacity tables, and bathymetric change maps for selected water-supply lakes in north-central and west-central Missouri, 2020: U.S. Geological Survey Scientific Investigations Report 2023–5046, 52 p., accessed June 6, 2023, at https://doi.org/10.3133/sir20235046.

Huizinga, R.J., and Rydlund, P.H., Jr., 2004, Potential-scour assessments and estimates of scour depth using different techniques at selected bridge sites in Missouri: U.S. Geological Survey Scientific Investigations Report 2004–5213, 42 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20045213.

HYPACK, Inc., 2020, HYPACK user manual: Middletown, Conn., HYPACK, Inc., 2,602 p., accessed June 28, 2022, at http://www.hypack.com/File%20Library/Resource%20Library/Manuals/2020/2020-HYPACK-User-Manual.pdf.

International Hydrographic Organization, 2020, IHO standards for hydrographic surveys (6th ed.): Monaco, International Hydrographic Bureau, Special publication no. 44, 41 p., accessed February 1, 2024, at https://iho.int/uploads/user/pubs/standards/s-44/S-44_Edition_6.1.0.pdf.

Mueller, D.S., Wagner, C.R., Rehmel, M.S., Oberg, K.A., and Rainville, F., 2013, Measuring discharge with acoustic Doppler current profilers from a moving boat (ver. 2.0, December 2013): U.S. Geological Survey Techniques and Methods, book 3, chap. A22, 95 p., accessed September 30, 2022, at https://doi.org/10.3133/tm3A22.

National Marine Electronics Association, 2002, NMEA 0183—Standard for interfacing marine electronic devices (ver. 3.01). National Marine Electronics Association, 88 p., accessed February 1, 2024, at https://www.plaisance-pratique.com/IMG/pdf/NMEA0183-2.pdf.

Parsons, D.R., Jackson, P.R., Czuba, J.A., Engel, F.L., Rhoads, B.L., Oberg, K.A., Best, J.L., Mueller, D.S., Johnson, K.K., and Riley, J.D., 2013, Velocity Mapping Toolbox (VMT)—A processing and visualization suite for moving-vessel ADCP measurements: Earth Surface Processes and Landforms, v. 38, no. 11, p. 1244–1260, accessed April 27, 2023, at https://doi.org/10.1002/esp.3367.

Rivers, B.C., Huizinga, R.J., Richards, J.M., and Waite, G.J., 2023, Bathymetric contour maps, surface area and capacity tables, and bathymetric change maps for selected water-supply lakes in northeastern Missouri, 2021: U.S. Geological Survey Scientific Investigations Report 2023–5108, 63 p., accessed October 10, 2023, at https://doi.org/10.3133/sir20235108.

Riverscapes Consortium, 2022, Geomorphic change detection software: Riverscapes Consortium, accessed September 2022 at https://gcd.riverscapes.net/.

Rydlund, P.H., Jr., 2009, Real-time river channel-bed monitoring at the Chariton and Mississippi Rivers in Missouri, 2007–09: U.S. Geological Survey Scientific Investigations Report 2009–5254, 27 p., accessed August 24, 2023, at https://doi.org/10.3133/sir20095254.

Simons, D.B., and Richardson, E.V., 1966, Resistance to flow in alluvial channels: U.S. Geological Survey Professional Paper 422–J, 61 p., accessed April 27, 2023, at https://doi.org/10.3133/pp422J.

Simon, Li and Associates, 1985, Seasonal effects of river stage-discharge relations at selected gages, Final Report: Fort Collins, Colo., prepared for U.S. Army Corps of Engineers, Contract No. DACW43–85–D–0017, 96 p.

U.S. Army Corps of Engineers [USACE], 2003, Upper Mississippi River System flow frequency study, appendix E: Rock Island, Ill., U.S. Army Corps of Engineers, accessed April 27, 2023, at https://www.mvr.usace.army.mil/Portals/48/docs/FRM/UpperMissFlowFreq/App.%20E%20Kansas%20City%20Dist.%20Hydrology_Hydraulics.pdf.

U.S. Army Corps of Engineers [USACE], 2013, Engineering and design—Hydrographic surveying: Washington D.C., U.S. Army Corps of Engineers, manual no. EM 1110–2–1003, 560 p., accessed September 25, 2023, at https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1003.pdf?ver=gDGVUj_0XR2sXHiIpQZv2Q%3d%3d.

U.S. Geological Survey [USGS], 2023a, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed April 27, 2023, at https://doi.org/10.5066/F7P55KJN.

U.S. Geological Survey [USGS], 2023b, USGS Streamgage Statistics for station 06895500: U.S. Geological Survey WaterWatch toolkit, accessed April 27, 2023, at https://waterwatch.usgs.gov/index.php?sno=06895500&ds=dv01d_por&btnGo=GO&m=sitempnn.

U.S. Geological Survey [USGS], 2023c, USGS Streamgage Statistics for station 06934500: U.S. Geological Survey WaterWatch toolkit, accessed April 27, 2023, at https://waterwatch.usgs.gov/index.php?sno=06934500&ds=dv01d_por&btnGo=GO&m=sitempnn.

Glossary

bent A vertical, load-bearing, intermediate bridge substructure unit between the ends of a bridge used to support the bridge at intermediate intervals, typically consisting of two or more piles (referred to as a “pile bent”) or columns, each supported by an individual footing, pile, or drilled shaft.

caisson An older type of bridge foundation consisting of a watertight retaining structure used as the foundation of a bridge pier, constructed in such a way that the water can be pumped out, keeping the work environment dry while the ground under the caisson is excavated and the caisson “sunk” into final position below the ground line. Upon reaching its final position, the caisson is backfilled with sand or gravel for added weight and stability.

cap The upper or bearing part of a bridge pier or bent, usually made of concrete or hard stone and designed to distribute concentrated loads from the bridge superstructure evenly over the columns of the pier or bent.

cofferdam A temporary retaining structure used in pier and pylon construction to retain water and support the sides of an excavation where water is present. A cofferdam generally consists of vertical sheet piling around the perimeter of a bracing system and a bottom seal course. Once sealed, the water can be pumped out, keeping the work environment dry while the footing, columns, and other substructural elements are built.

column The primary part of a bridge bent, pier, or pylon used to convey the load of the bridge superstructure to the foundation.

drilled shaft A cylindrical shaft that is drilled into the ground as a bridge foundation, typically extending through the alluvial material into underlying rock and filled with reinforced concrete.

footing A part of the foundation of a bridge bent, pier, or pylon used to transmit the load from the column to the ground, either directly or indirectly through piles or drilled shafts.

pedestal A transitional element occasionally used in a bridge pier or pylon, typically present between the column and a footing or caisson.

pier A vertical, load bearing, intermediate bridge substructure unit between the ends of a bridge used to support the bridge at intermediate intervals, consisting of a single column or shaft, or multiple columns connected with a strut or solid web, and generally supported by a single footing.

pile A long, narrow cylinder or beam made of wood, metal, or concrete used as part of the foundation of a bridge, typically driven into the ground from above and integrated into a seal course or footing of a pier, or the cap of a pile bent.

pylon A tower-like vertical, load bearing substructural unit that usually supports the cables of a suspension bridge or a cable-stayed bridge. A pylon typically extends above the bridge superstructure.

seal course The base of a newer type of bridge foundation, created when a cofferdam used to build the foundation is “sealed” with concrete at the underwater ground level to prevent water from entering the cofferdam from below.

spur dike linear structure usually constructed of piled stone projecting from the bank in a river to redirect the river's own energy to protect the bank from erosion and to direct the axis of flow.

stone revetment A facing of stone, concrete units, or slabs built to protect a bank or other feature against erosion by wave action, currents, and surges.

strut A horizontal intermediate bridge substructure unit used to connect and brace two or more columns or shafts of a pier.

substructure The part of a bridge that supports the superstructure and transmits the load of the superstructure and deck to the ground through the foundations.

superstructure The part of a bridge that supports the bridge deck and connects one substructural element to another and thereby transmits the load of the deck and anything on the deck to the substructure.

water year A continuous 12-month period selected to present data relative to hydrologic or meteorological phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30 and is designated by the year in which it ends.

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

Shaded triangulated irregular network images of the channel and side of pier were prepared for each surveyed pier at structure A5664 at Lexington (fig. 1.1), structure A5910 at Waverly (fig. 1.2), structure K0999 at Miami (fig. 1.3), structure G0069 at Glasgow (fig. 1.4), structure A4574 at Boonville (fig. 1.5), structure L0962 near Rocheport (fig. 1.6), structures L0550 and A4497 at Jefferson City (fig. 1.7), and structure A6288 at Hermann (fig. 1.8).

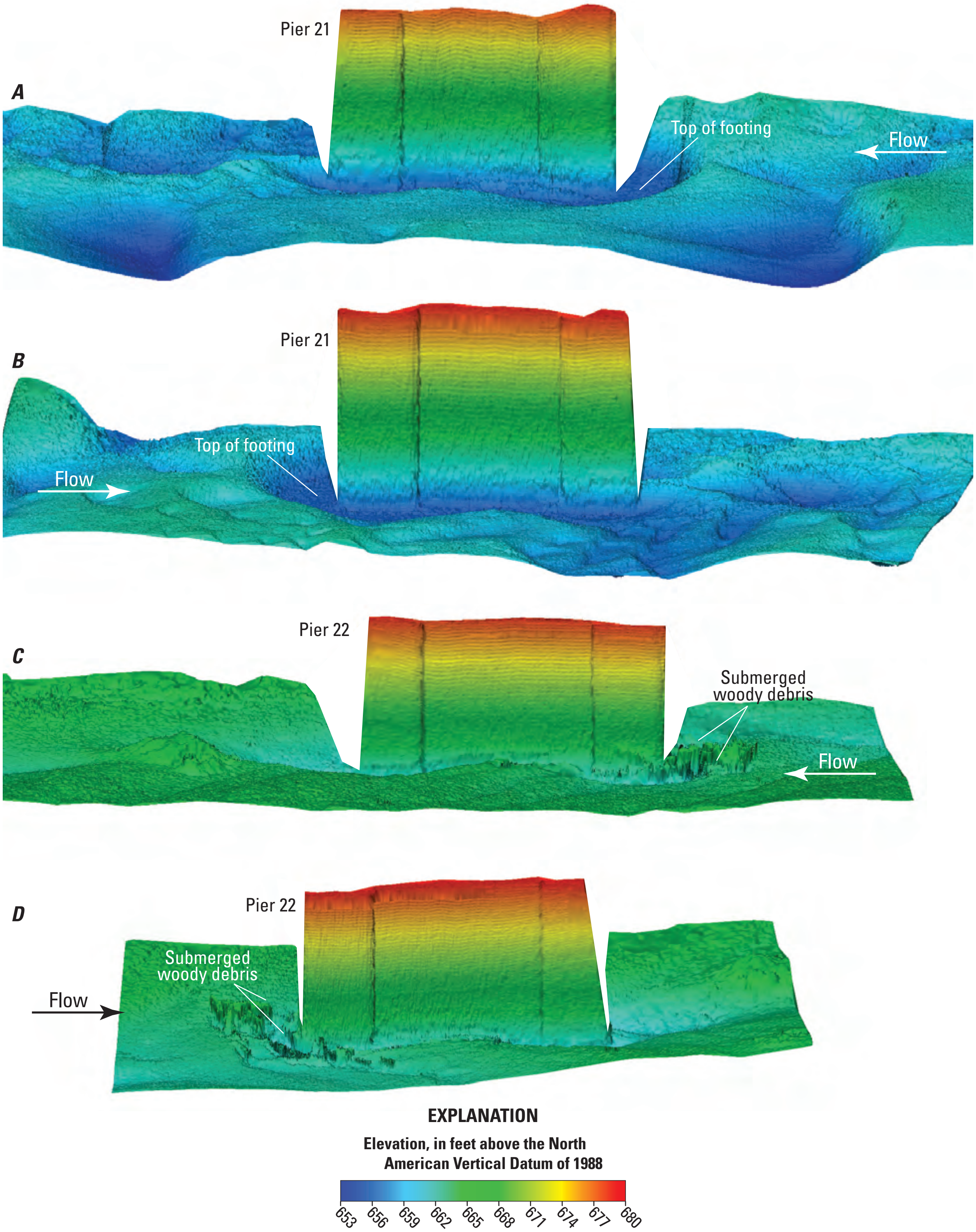


Figure 1.1. Shaded triangulated irregular network visualization of the channel bed and piers of structure A5664 on State Highway 13 over the Missouri River at Lexington, Missouri. *A*, Left (north) side of pier 21. *B*, Right (south) side of pier 21. *C*, Left (north) side of pier 22. *D*, Right (south) side of pier 22.

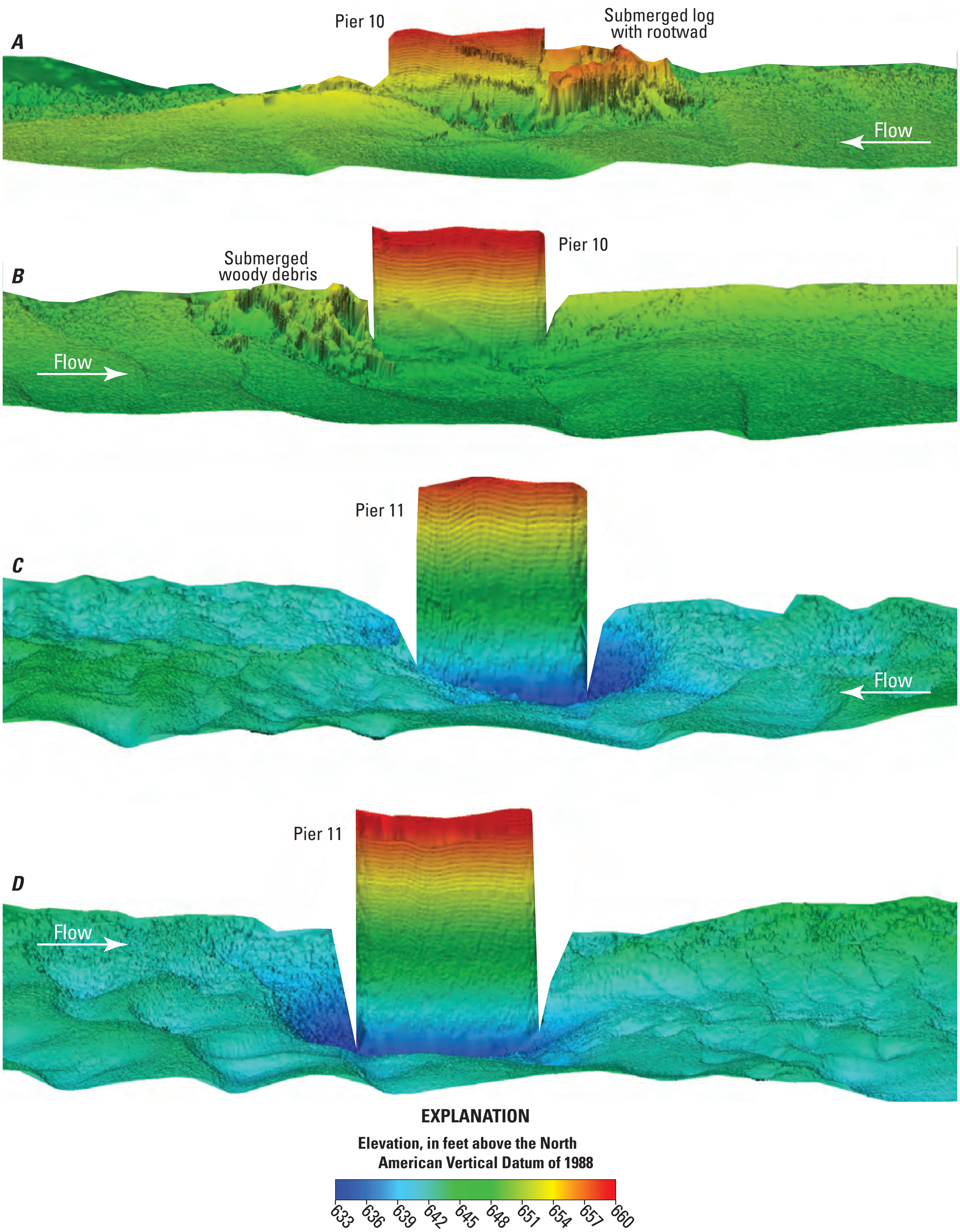


Figure 1.2. Shaded triangulated irregular network visualization of the channel bed and piers of structure A5910 on U.S. Highway 24 over the Missouri River at Waverly, Missouri. *A*, Left (north) side of pier 10. *B*, Right (south) side of pier 10. *C*, Left (north) side of pier 11. *D*, Right (south) side of pier 11.

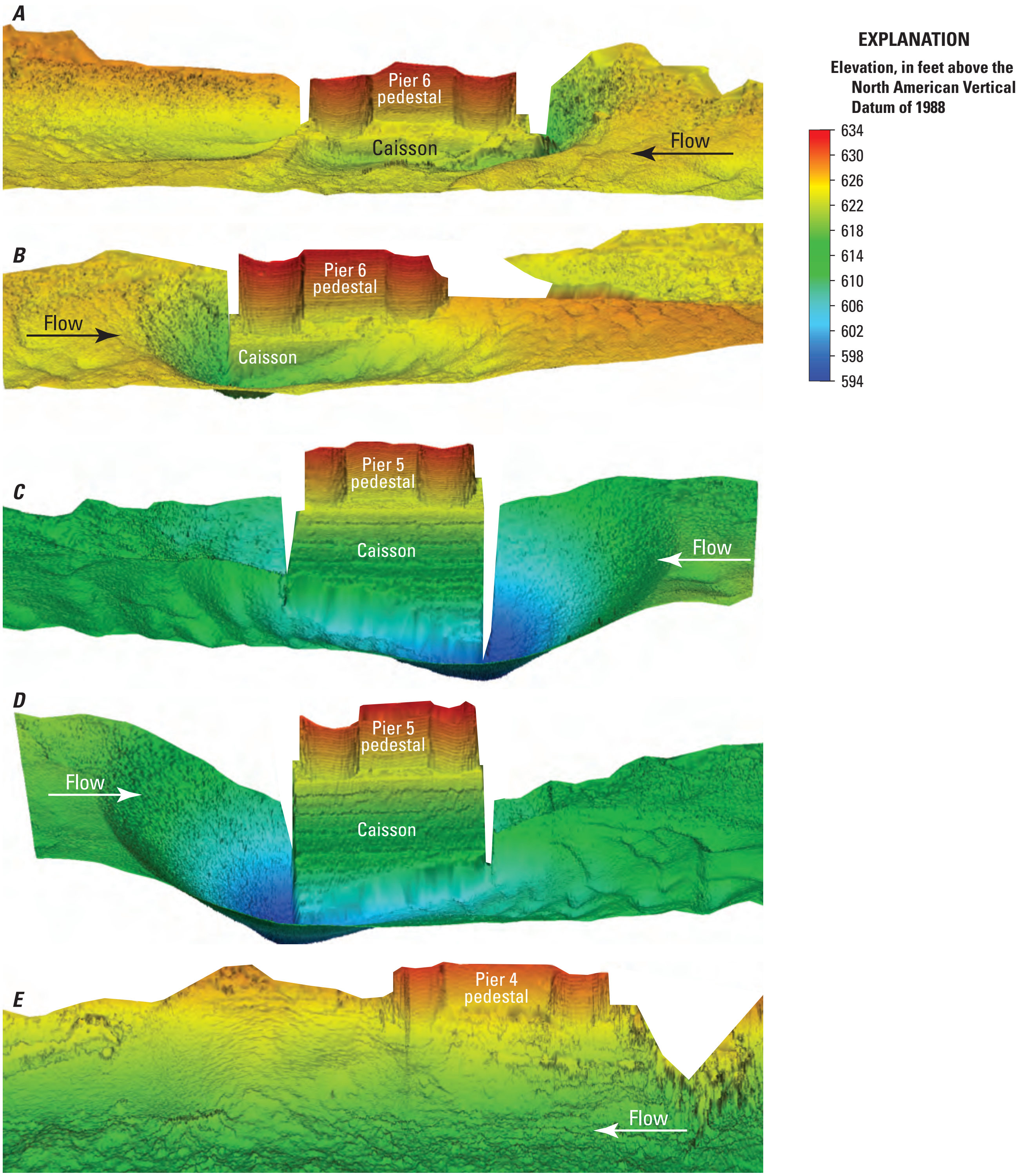
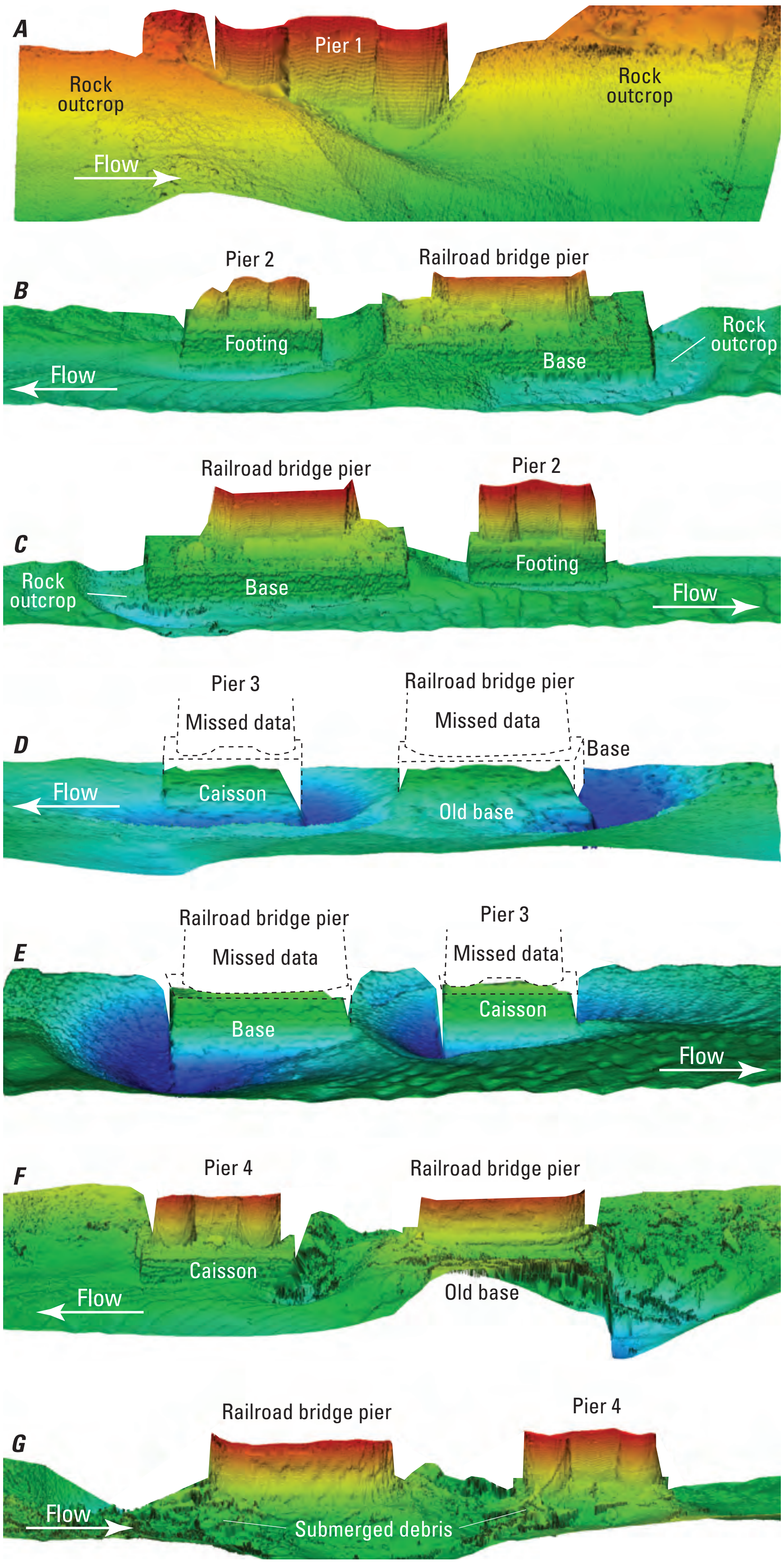


Figure 1.3. Shaded triangulated irregular network visualization of the channel bed and piers of structure K0999 on State Highway 41 over the Missouri River at Miami, Missouri. *A*, Left (north) side of pier 6. *B*, Right (south) side of pier 6. *C*, Left (north) side of pier 5. *D*, Right (south) side of pier 5. *E*, Left (north) side of pier 4.



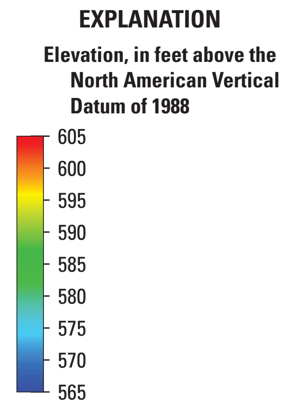


Figure 1.4. Shaded triangulated irregular network visualization of the channel bed and piers of structure G0069 on State Highway 240 over the Missouri River at Glasgow, Missouri. *A*, Right (west) side of pier 1. *B*, Left (east) side of pier 2. *C*, Right (west) side of pier 2. *D*, Left (east) side of pier 3. *E*, Right (west) side of pier 3. *F*, Left (east) side of pier 4. *G*, Right (west) side of pier 4.

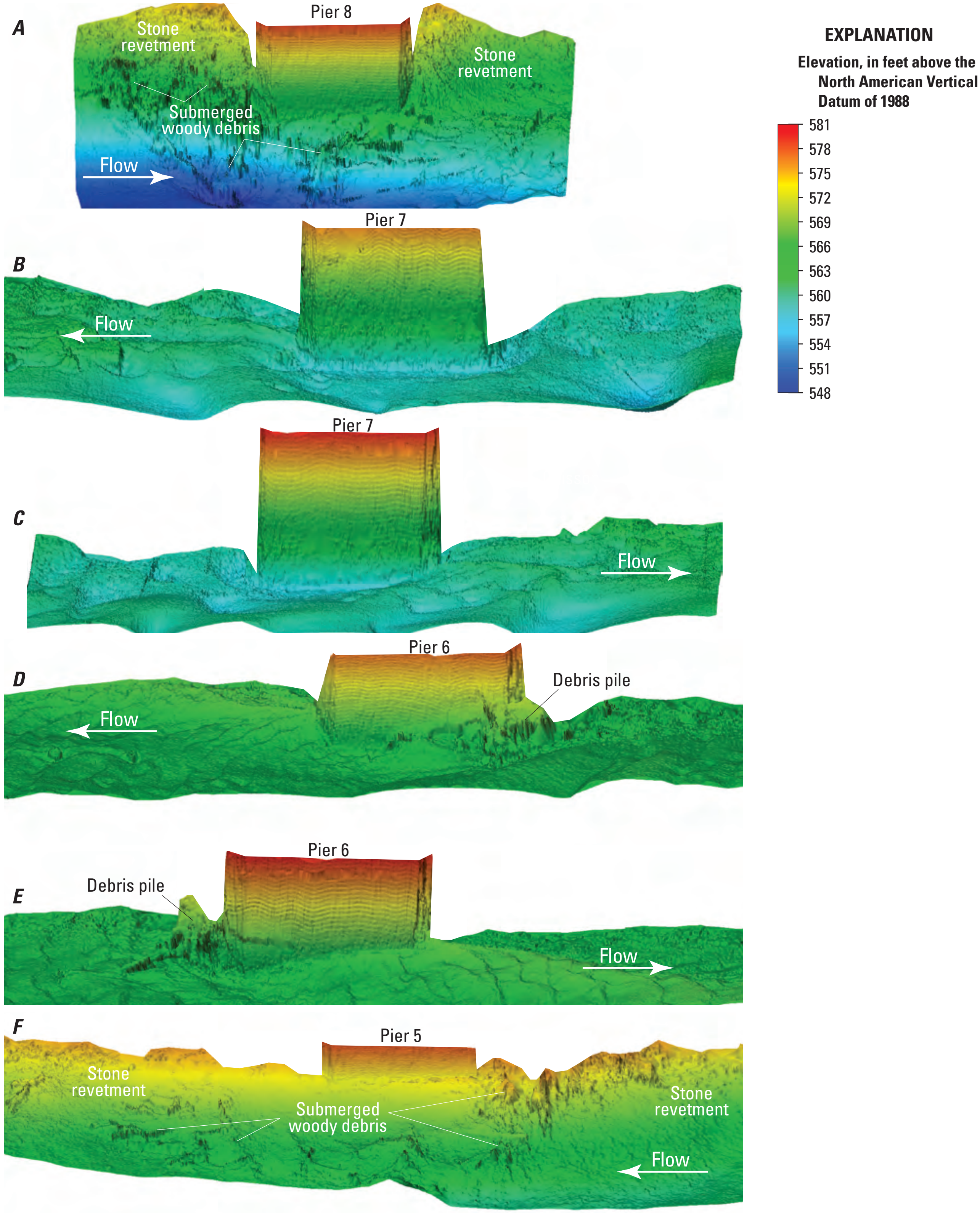


Figure 1.5. Shaded triangulated irregular network visualization of the channel bed and piers of structure A4574 on State Highway 5 over the Missouri River at Boonville, Missouri. *A*, Right (south) side of pier 8. *B*, Left (north) side of pier 7. *C*, Right (south) side of pier 7. *D*, Left (north) side of pier 6. *E*, Right (south) side of pier 6. *F*, Left (north) side of pier 5.

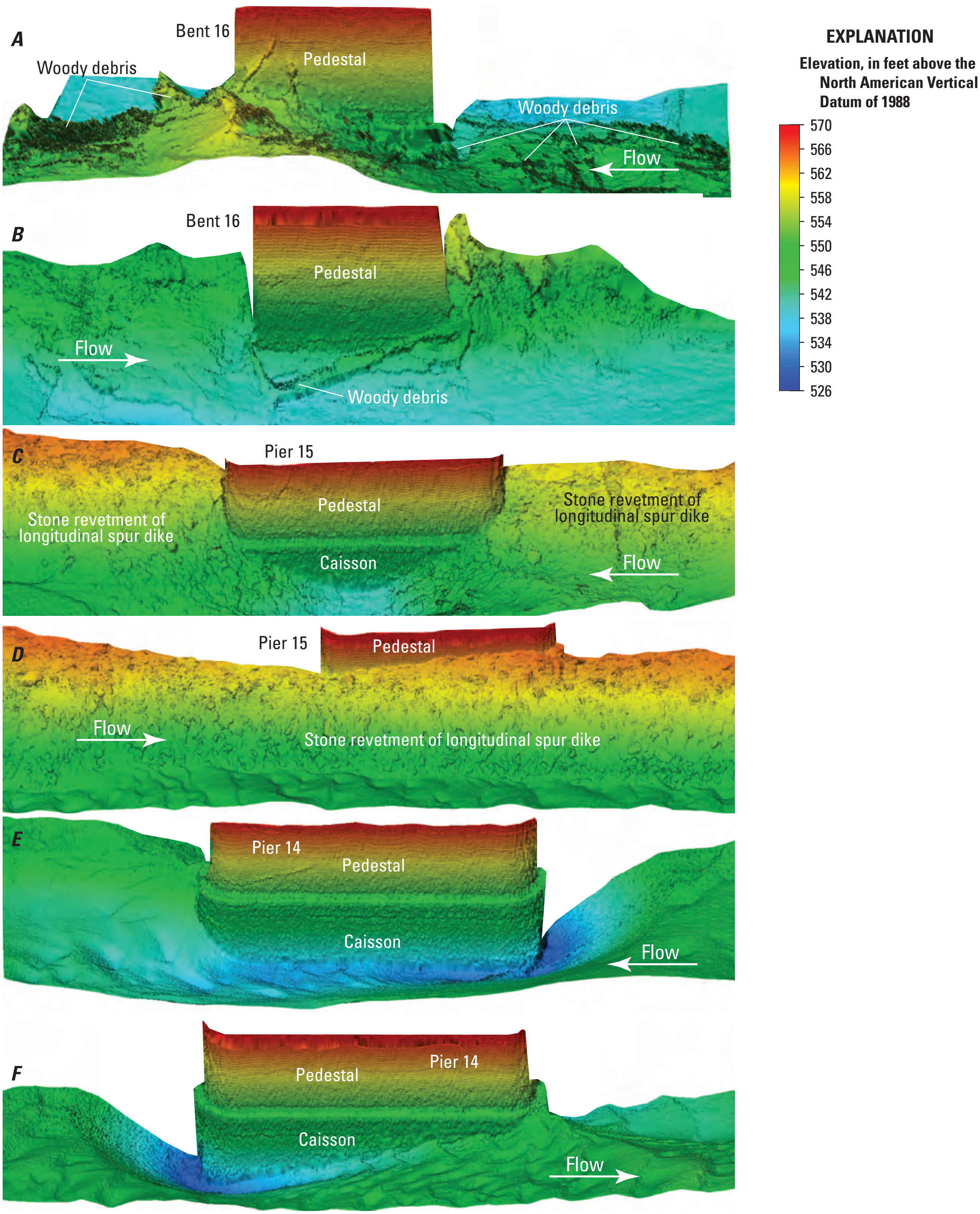


Figure 1.6. Shaded triangulated irregular network visualization of the channel bed and piers of structure L0962 on Interstate 70 over the Missouri River near Rocheport, Missouri. *A*, Left (east) side of bent 16. *B*, Right (west) side of bent 16. *C*, Left (east) side of pier 15. *D*, Right (west) side of pier 15. *E*, Left (east) side of pier 14. *F*, Right (west) side of pier 14.

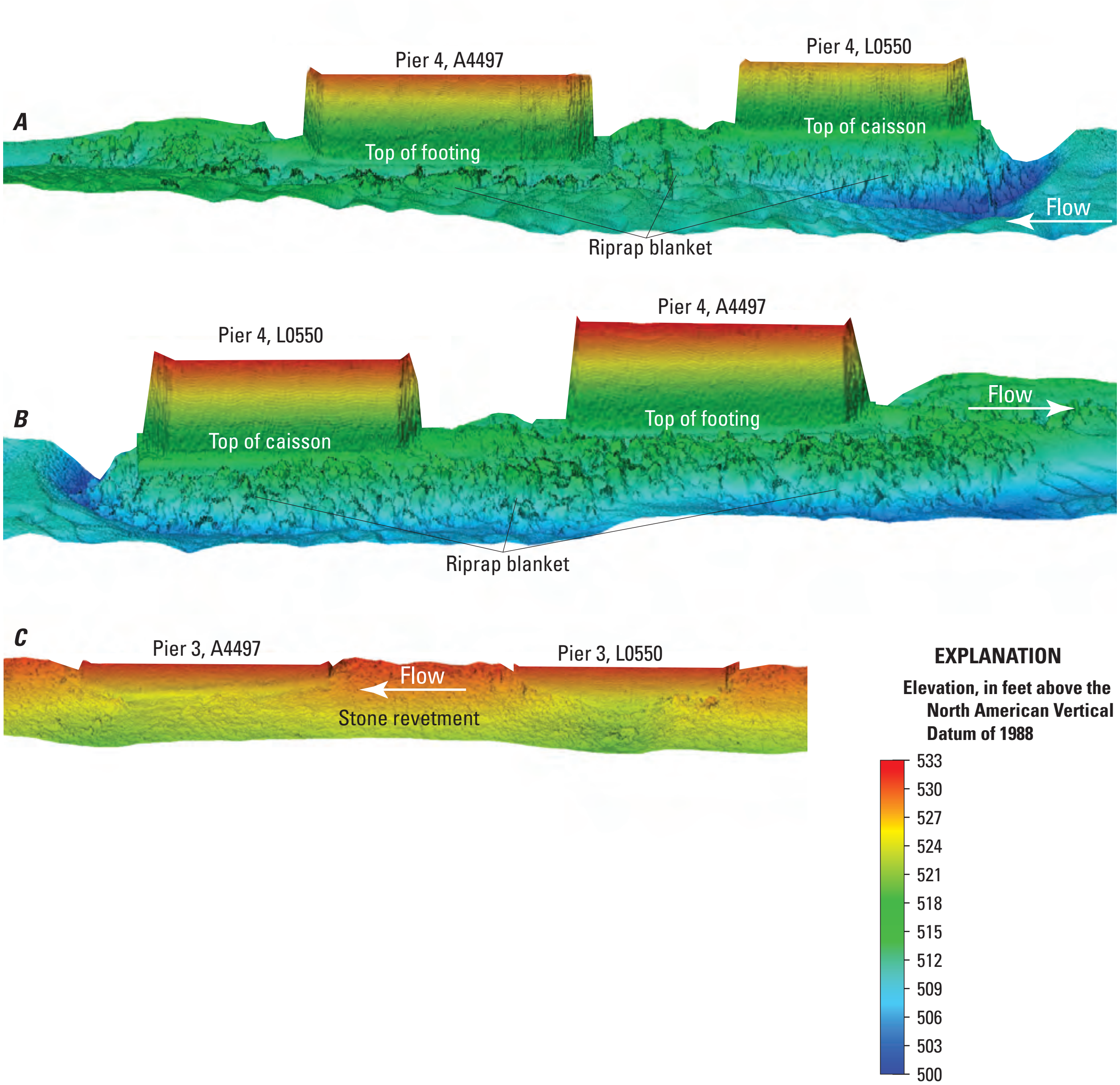


Figure 1.7. Shaded triangulated irregular network visualization of the channel bed and piers of structures L0550 and A4497 on U.S. Highway 54 over the Missouri River at Jefferson City, Missouri. *A*, Left (northeast) side of pier 4 of both structures. *B*, Right (southwest) side of pier 4 of both structures. *C*, Left (northeast) side of pier 3 of both structures.

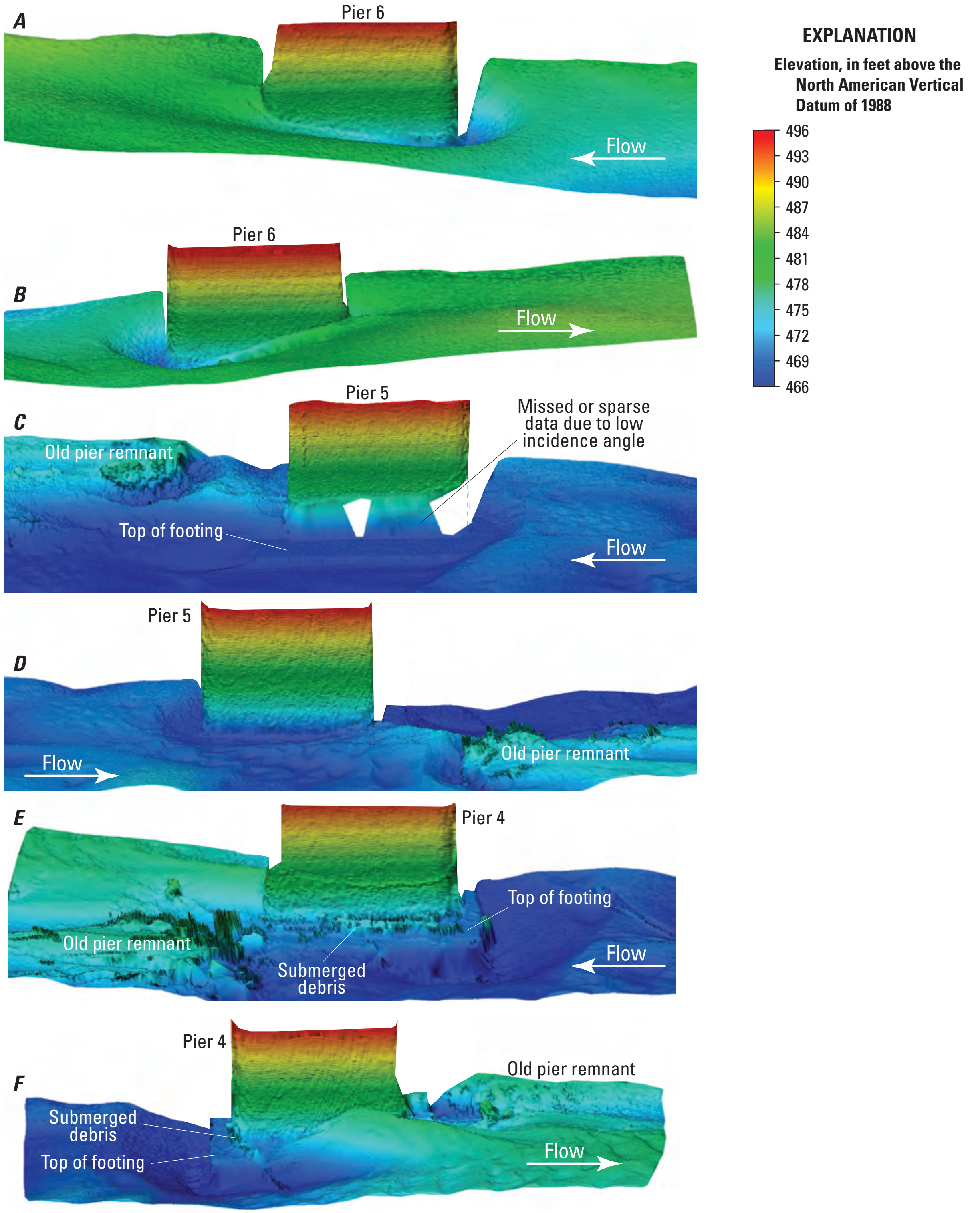


Figure 1.8. Shaded triangulated irregular network visualization of the channel bed and piers of structure A6288 on State Highway 19 over the Missouri River at Hermann, Missouri. *A*, Left (north) side of pier 6. *B*, Right (south) side of pier 6. *C*, Left (north) side of pier 5. *D*, Right (south) side of pier 5. *E*, Left (north) side of pier 4. *F*, Right (south) side of pier 4.

For more information about this publication, contact:
Director, USGS Central Midwest Water Science Center
1400 Independence Road
Rolla, MO 65401
573–308–3667

For additional information, visit: https://www.usgs.gov/centers/cmwater

Publishing support provided by the
Rolla Publishing Service Center

Huizinga—**Bathymetric/Velocimetric Surveys at Highway Bridges Crossing the Missouri River between Kansas City and St. Louis, 2021**—SIR 2024–5021

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20245021