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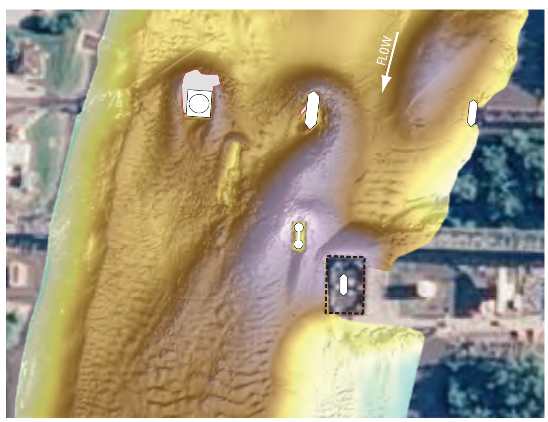
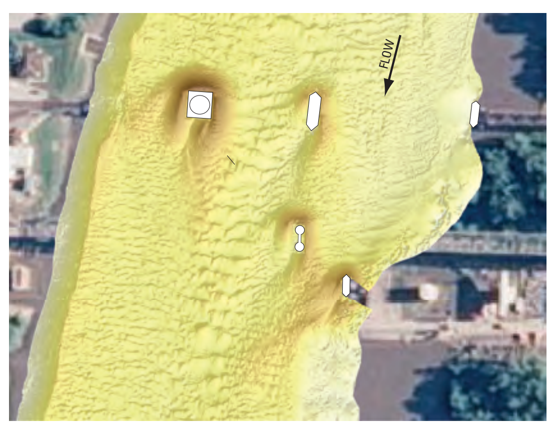
Results of Repeat Bathymetric and Velocimetric Surveys at the Amelia Earhart Bridge on U.S. Highway 59 Over the Missouri River at Atchison, Kansas, 2009–2013





Scientific Investigations Report 2013–5177

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

Cover. Upper Left: Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, before construction of the new U.S. Highway 59 bridge.

Middle: Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, during flooding on June 30, 2010.

Lower Right: Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on April 24, 2013, near the end of construction of the new U.S. Highway 59 bridge.

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

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

U.S. Geological Survey, Reston, Virginia: 2013

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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).

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

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

By Richard J. Huizinga

Abstract

Bathymetric and velocimetric data were collected six times by the U.S. Geological Survey, in cooperation with the Kansas Department of Transportation, in the vicinity of Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas. A multibeam echosounder mapping system and an acoustic Doppler current meter were used to obtain channel-bed elevations and depth-averaged velocities for a river reach approximately 2,300 feet long and extending across the active channel of the Missouri River. The bathymetric and velocimetric surveys provide a “snapshot” of the channel conditions at the time of each survey, and document changes to the channel-bed elevations and velocities during the course of construction of a new bridge for U.S. Highway 59 downstream from the Amelia Earhart Bridge.

The baseline survey in June 2009 revealed substantial scour holes existed at the railroad bridge piers upstream from and at pier 10 of the Amelia Earhart Bridge, with mostly uniform flow and velocities throughout the study reach. After the construction of a trestle and cofferdam on the left (eastern) bank downstream from the Amelia Earhart Bridge, a survey on June 2, 2010, revealed scour holes with similar size and shape as the baseline for similar flow conditions, with slightly higher velocities and a more substantial contraction of flow near the bridges than the baseline. Subsequent surveys during flooding conditions in June 2010 and July 2011 revealed substantial scour near the bridges compared to the baseline survey caused by the contraction of flow; however, the larger flood in July 2011 resulted in less scour than in June 2010, partly because the removal of the cofferdam for pier 5 of the new bridge in March 2011 diminished the contraction near the bridges. Generally, the downstream part of the study reach exhibited varying amounts of scour in all of the surveys except the last when compared to the baseline. During the final survey, velocities throughout the study area were the lowest of all the surveys, resulting in overall deposition throughout the reach compared to the baseline survey—despite the presence of the trestle in the final survey.

The multiple surveys at the Amelia Earhart Bridge document the effects of moderate- to high-flow conditions on scour, compounded by the effects of adding and removing a constriction in the channel. Additional factors such as pier shape and angle of approach flow also were documented.

Introduction

The Amelia Earhart Bridge carries traffic on U.S. Highway 59 (US 59) across the Missouri River between Atchison, Kansas, and Winthrop, Missouri, about 200 feet (ft) downstream from an active railway bridge (fig. 1). Pier 10 of the Amelia Earhart Bridge currently (2013) is the only pier that is in water at all river stages, and is immediately downstream from one of the railway bridge piers. High flow velocities causing the mobilization of sandy bed material in the river have resulted in scour of the channel-bed material around the piers of both bridges (Brian Loving, U.S. Geological Survey, written commun., 2008), potentially affecting their structural integrity. Construction of a new bridge on US 59 immediately downstream from the Amelia Earhart Bridge began in 2009, and a cofferdam and trestle were used to facilitate construction of one of the piers for the new bridge. It was expected that the cofferdam, trestle, and other construction-related activities would have an effect on the flow patterns near pier 10 of the existing Amelia Earhart Bridge.

Scour in alluvial channels is the removal of channel-bed and bank material by flowing water, and is the leading cause of bridge failures in the United States (Richardson and Davis, 2001). Scour at a bridge site is the result of (1) short- and long-term geomorphic processes and (2) the local effects caused by elements of the structure in or adjacent to the waterway (Richardson and Davis, 2001; Huizinga and Rydlund, 2004). When describing scour at a bridge site, Richardson and Davis (2001) further separate long-term aggradation and degradation of a channel from the contraction and local scour observed during floods. Contraction scour is the general change in the channel-bed elevation across a bridge opening resulting from the passage of a flood

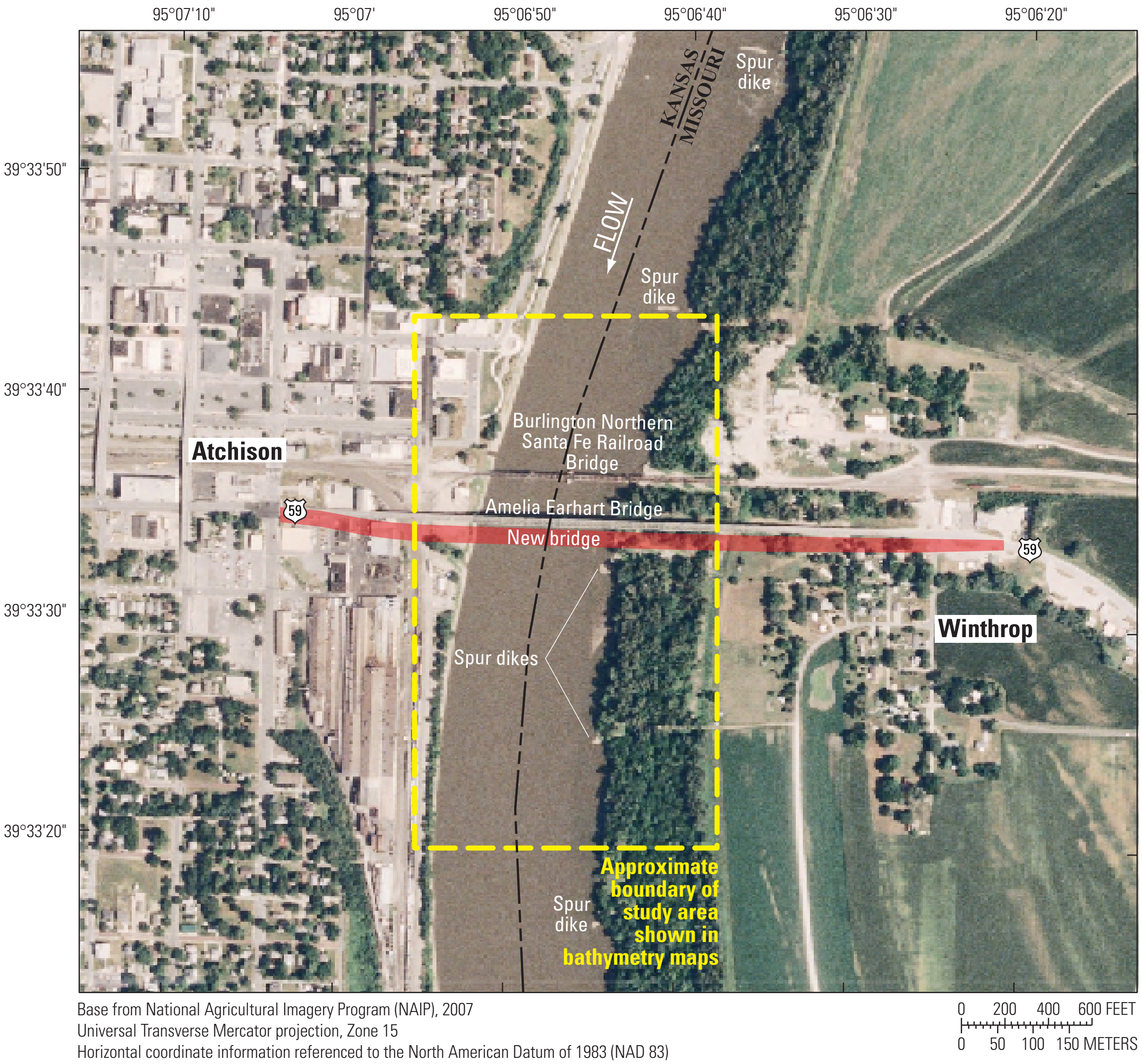


Figure 1. Location of the Amelia Earhart Bridge and proposed new bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas.

through a constriction. Local scour is the localized erosion of material caused by flow vortex action that forms near bridge piers and abutments. Although all of the scour processes (long-term, contraction, and local scour) continually are at work, contraction and local scour generally are cyclic, resulting in a decrease and subsequent increase of the channel-bed elevation during the passage of a flood. Scour processes can be exacerbated during high-flow conditions. Because the effects of scour can be severe and dangerous, bridges and other structures over waterways are routinely assessed and inspected.

Nationwide, the U.S. Geological Survey (USGS) has assisted various state Departments of Transportation with assessing scour at waterway crossings. In 1991, the USGS began assessing scour at waterway crossings in Missouri, in cooperation with the Missouri Department of Transportation (MoDOT; Huizinga and Rydlund, 2004). Starting in 2007, the USGS began determining channel bathymetry and monitoring bridges for scour using single-beam echosounders and a multibeam echosounder mapping system (MBMS; Rydlund, 2009; Huizinga, 2010, 2011, 2012; Huizinga and others, 2010). In particular, the MBMS has proven to be a useful tool not only in determining channel bathymetry, but also in providing medium- to high-resolution imagery of bridge structural elements below the water line.

In 2009, the USGS, in cooperation with Kansas Department of Transportation (KDOT), began a series of six bathymetric and velocimetric surveys for a span of almost 4 years in the vicinity of the Amelia Earhart Bridge on US 59 at Atchison, Kansas. The objective of the bathymetric and velocimetric surveys was to document the effects of construction activities related to the new US 59 bridge on the existing Amelia Earhart Bridge, particularly in the vicinity of pier 10 of the existing bridge. Although these data were not directly useful for the design of the new bridge on US 59, KDOT and others can use the findings from these surveys to assist in designing new bridges, as well as laying out and sequencing construction projects on large rivers.

Purpose and Scope

This report documents the results and findings of six bathymetric and velocimetric surveys of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on US 59 over the Missouri River at Atchison, Kansas, using a multibeam echosounder mapping system (MBMS) and an acoustic Doppler current profiler (ADCP; table 1). Equipment and methods used and results obtained are described. The results obtained from the bathymetric and velocimetric surveys of the channel provide a "snapshot" of the channel-bed conditions at the time of each survey, and provide information about the stability and integrity of the foundations of the Amelia Earhart Bridge with respect to bridge scour during the construction of the new bridge on US 59. Comparison of surveys completed before, during, and after the principal construction-related activities near pier 10 of the Amelia Earhart Bridge during a variety of flow conditions on the Missouri River indicate the effects of the construction activities and flow velocities on the channel and subsequently on the bridge foundations.

Description of Study Area

The Amelia Earhart Bridge (hereinafter referred to as "the Earhart Bridge") [KDOT structure 59-3-16.38 (013)] is located on US 59 over the Missouri River at Atchison, Kansas (fig. 1). The Earhart Bridge crosses the Missouri River at river mile 422.5, on the eastern side of Kansas between St. Joseph, Missouri, and Kansas City, Missouri (fig. 1). The study area is approximately 2,300 ft long, extending approximately 880 ft upstream and 1,420 ft downstream from the centerline of the Earhart Bridge (fig. 2). The upstream and downstream boundaries of the surveyed areas were assumed to be beyond the hydraulic effect of the bridge structures.

The Earhart Bridge is approximately 200 ft downstream from an active railway bridge, operated by the Burlington Northern Santa Fe (BNSF) Railroad (fig. 2). The centerline of the new bridge on US 59 being constructed is approximately 78 ft downstream from the centerline of the existing Earhart Bridge (Mark Hurt, Kansas Department of Transportation, written commun., 2009; fig. 2). The right descending bank (the western, or Kansas bank) is covered with revetment (erosion protection) in the form of large rock cobbles and broken concrete debris. There are several lateral rock "spur" dikes that extend into the channel from the left descending bank (the eastern, or Missouri bank; fig. 1). A construction trestle (fig. 2) was built from the left bank near one of the lateral rock spur dikes (fig. 1) to assist in construction of and access to pier 5 of the new bridge.

Description of Equipment

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

A MBMS is an integration of several individual components: the multibeam echosounder (MBES), a navigation and motion-sensing system, and a data-collection and processing computer. The MBES that was used during the first four

Table 1. Dates and information related to the bathymetric and velocimetric surveys conducted at the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas.

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; ft, feet; --, not applicable; all elevations are in feet above the North American Vertical Datum of 1988]

Survey number	Survey date	Discharge, measured at USGS streamflow-gaging station at St. Joseph, Missouri (ft^3/s)	Change from previous survey (ft^3/s)	Change from base-line on 06/30/09 (ft^3/s)	Average water-surface eleva-tion in vicinity of bridge (ft)	Change from previous survey (ft)	Change from base-line on 06/30/09 (ft)	Average channel-bed eleva-tion (ft)	Change from previous survey (ft)	Change from base-line on 06/30/09 (ft)	Average water depth (ft)	Length of survey area (ft)	Width of survey area (ft)	Figures
1	06/30/09	56,600	--	--	777.4	--	--	755.5	--	--	21.9	2,295	645	8, 9, 10, 11, 14
2	06/02/10	63,000	6,400	6,400	780.1	2.7	2.7	753.3	-2.3	-2.3	26.9	1,970	575	10, 12, 13, 14, 15, 16, 17
3	06/30/10	134,000	71,000	77,400	788.7	8.6	11.3	749.8	-3.5	-5.8	39.0	2,295	645	10, 14, 16, 18, 19, 20, 21
4	10/27/10	70,900	-63,100	14,300	779.5	-9.2	2.1	753.2	3.5	-2.3	26.3	2,295	645	10, 14, 16, 22, 23, 24, 25
5	07/15/11	214,000	143,100	157,400	792.4	12.9	15.0	746.5	-6.7	-9.0	45.9	[a]1,350	660	10, 14, 16, 26, 27, 28, 29, 30
6	04/24/13	36,500	-177,500	-20,100	772.5	-19.9	-4.9	756.6	10.1	1.1	15.9	1,970	570	6, 10, 14, 16, 31, 32, 33, 34

[a]The water-surface elevation during this survey did not permit sufficient clearance under the railroad bridge to permit safely surveying upstream from the railroad bridge.

Figure 2. Study area near the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas, during construction of the new bridge.

surveys is the RESON SeaBat™ 7125 (fig. 3*A*), operated at a frequency of 400 kilohertz (kHz). The RESON SeaBat™ 7125-SV2 (fig. 3*B*) was used in the last two surveys, and is an updated version of the RESON SeaBat™ 7125 used in the earlier surveys and previous studies (Huizinga, 2010, 2011; Huizinga and others, 2010) with similar features and functions, but with a more streamlined sonar head, and stiffer, more compact head tilt bracket (fig. 3*B*). The navigation and motion-sensing system that was used is the Applanix Position Orientation Solution for Marine Vessels (POS MV™) WaveMaster system (hereinafter referred to as "the POS"). The navigation system locates the MBES in three-dimensional space, and the motion-sensing system measures the heave, pitch, roll, and heading of the vessel (and, thereby, the MBES) to accurately position the data received by the MBES.

Two methods were used to provide real-time kinetic (RTK) differential corrections to the POS for the navigation and tide solution during the surveys. For all but the last survey, a Global Positioning System (GPS) base station was set up on the river bank near the bridge, as in previous studies (Huizinga, 2010, 2011, 2012; Huizinga and others, 2010). For the last survey, the Virtual Real-time Station (VRS) network, established and maintained by MoDOT, was used to provide the RTK differential corrections to the POS.

With either method of obtaining differential corrections, the bridge structures blocked a part of or the whole signal from the GPS constellation of satellites when the survey vessel was near or under the bridges, resulting in a GPS outage that had the potential to degrade the positional accuracy of the vessel until such time as an RTK-fixed navigation solution was re-acquired; however, as in the studies in Kansas City and St. Louis (Huizinga, 2010, 2011) and on the Missouri River during the 2011 summer flooding (Huizinga, 2012), the navigation information from all but the first survey was post-processed using the POS-Pac™ Mobile Mapping Suite (MMS™) software (Applanix Corporation, 2009), which provided tools to identify and compensate for sensor and environmental errors, and computes an optimally blended navigation solution from the GPS and inertial motion unit (IMU) raw data. The blended navigation solution (called a "standard best-estimate of travel" or "SBET" file), generated by post-processing the navigation data, was applied to the whole survey for a given date to minimize the effects of the GPS outages when surveying under the bridges.

The data from the MBES and navigation and motion-sensing components were processed and integrated into a cohesive dataset for editing and visualization. A computer onboard the survey boat ran the HYPACK®/HYSWEEP® data acquisition software (HYPACK, Inc., 2011) that was used to prepare the bathymetric surveys and collect the survey data. On completion of the surveys, the acquired depth data were further processed to remove data spikes and other spurious points in the multibeam swath trace. The edited depth data were converted to elevations and georeferenced using the navigation and position solution data from the SBET file from POS-Pac™ MMS™, and were visualized in HYPACK®/HYSWEEP® as a triangulated irregular network (TIN) surface or a point cloud. The finalized, georeferenced elevation data were output to a comma-delimited file either with no data reduction, or filtered and reduced based on a 1.64-ft (0.5-meter) data resolution. These comma-delimited elevation data were compiled into a geographic information system (GIS) database for each survey using the ArcGIS package (Environmental Systems Research Institute, 2013).

Figure 3. *A*, The RESON SeaBat 7125, and *B*, the RESON SeaBat 7125-SV2 multibeam echosounder as viewed mounted on the port side of the U.S. Geological Survey boat used for all but the last survey.

Information about the velocity of the river at various cross-sections in the study reach were obtained by means of an acoustic Doppler current profiler (ADCP), as was done in the study by Huizinga and others (2010) and during the 2011 summer flooding (Huizinga, 2012). A Teledyne RD Instruments Rio Grande ADCP operating at 600 kHz was used to obtain velocities at 1.64-ft (0.5-meter) increments, or “bins,” throughout the water column. The Rio Grande ADCP operates in depths from 2.3 to 245 ft, and determines the velocity of the water by measuring the Doppler shift of an acoustic signal reflected from various particles suspended in the water (Mueller and Wagner, 2009). By measuring the Doppler shift in four different beam directions, the velocity of the water in each bin can be determined in three dimensions.

Basic Description of Methods

The methods used to acquire and assure the collection of quality data were the same as those used in previous studies with the MBMS (Huizinga, 2010, 2011, 2012; Huizinga and others, 2010), and the reader is referred to those reports for the details of the methods used. A brief summary of—and differences from—these methods are highlighted below.

Surveying Methods

Generally, bathymetric data were obtained along longitudinal transect lines, as in the previous studies (Huizinga, 2010, 2011, 2012; Huizinga and others, 2010). In all of the surveys in this study, the flow conditions were such that the spur dikes were submerged, generally making it possible to survey from bank to bank. The transect lines were designed so that there was overlap of the survey swaths to ensure complete coverage of the channel bed and minimize sonic “shadows,” as described in previous studies. Substantial overlap was achieved for many of the surveyed swaths, except in shallow areas near the channel banks or over the crest of spur dikes. To minimize data acquisition times in the shallows, data gaps often were left between the swaths and data were interpolated in the gaps. The persistent presence of debris rafts near the construction trestle and cofferdam, combined with increased flow velocities in that area, made surveying difficult near these structures. The presence of a large construction crane and supply barges made surveying the left descending bank downstream from the construction trestle difficult or impossible during the surveys on October 27, 2010, and July 15, 2011.

Generally, the surveys were continuous under the bridges along the longitudinal transect lines; however, because of the high-flow conditions on the Missouri River during the surveys on June 30, 2010, and July 15, 2011, the minimal clearance under the upstream railroad bridge prevented continuation of the transects throughout the reach. On June 30, 2010, there was enough clearance under the railroad bridge to allow the boat to safely cross underneath in one place when the GPS and radio antennae were removed; therefore, that survey was completed in two parts, upstream and downstream from the railroad bridge, with enough overlap of the two parts to minimize interpolation of data in the area under the railroad bridge. On July 15, 2011, the water-surface elevation was almost 4 ft higher than in 2010; therefore, the survey was completed only for the area downstream from the railroad bridge, as the clearance was so small that surveying upstream from the railroad bridge was considered dangerous.

After completion of the bathymetric survey with the MBMS, the velocity data were obtained with the ADCP. During the first four surveys, velocity data were collected in a manner similar to that done in the habitat study near the new Interstate 70 bridge in St. Louis, Missouri (Huizinga and others, 2010), wherein data were collected on unplanned lateral traverses of the channel at approximately right angles to the average flow direction, with a slight upstream or downstream trend depending on the survey (fig. 4*A*). In this way, velocity data were obtained in a zigzag pattern across the study area. For these first four surveys, the velocity data were spatially averaged for a given survey, and velocity data along lateral transects roughly perpendicular to flow were extracted (fig. 4*A*). In the last two surveys, velocity data were collected on as many as seven lateral transects across the channel within the study area (fig. 4*B*). The distance between the velocity transect lines was about 260 ft, with three transects upstream and four transects downstream from the Earhart Bridge. Each transect line was traversed two times, once in each direction across the river (fig. 4*B*). The reported velocity values for the last two surveys are the average from the two traverses. The survey on July 15, 2011, had only five lateral velocity transects, as data upstream from the railroad bridge were not collected.

Survey Quality-Assurance/Quality-Control Measures

For the MBMS, the principal quality-assurance measures were assessed in real time during the survey. The MBMS operator continuously assessed the quality of the collected data during the survey, making visual observations of across-track swaths (such as convex, concave, or skewed bed returns in flat, smooth bottoms), noting data quality flags and alarms from the MBES and the POS, and noting comparisons between adjacent overlapping swaths. In addition to the real-time quality-assurance assessments during the survey, beam angle checks and a suite of patch tests were executed to ensure quality data were acquired from the MBMS.

A quality-assurance plan has been established for discharge measurements using ADCPs from a moving boat that includes several instrument diagnostic checks and compass calibrations, as well as official procedures for streamflow measurement (Mueller and Wagner, 2009). Most of these standard operating procedures were followed when acquiring the velocity profile data for these surveys. However, velocity—not discharge—was the primary variable of interest in this study; therefore, the computed streamflow values were not used.

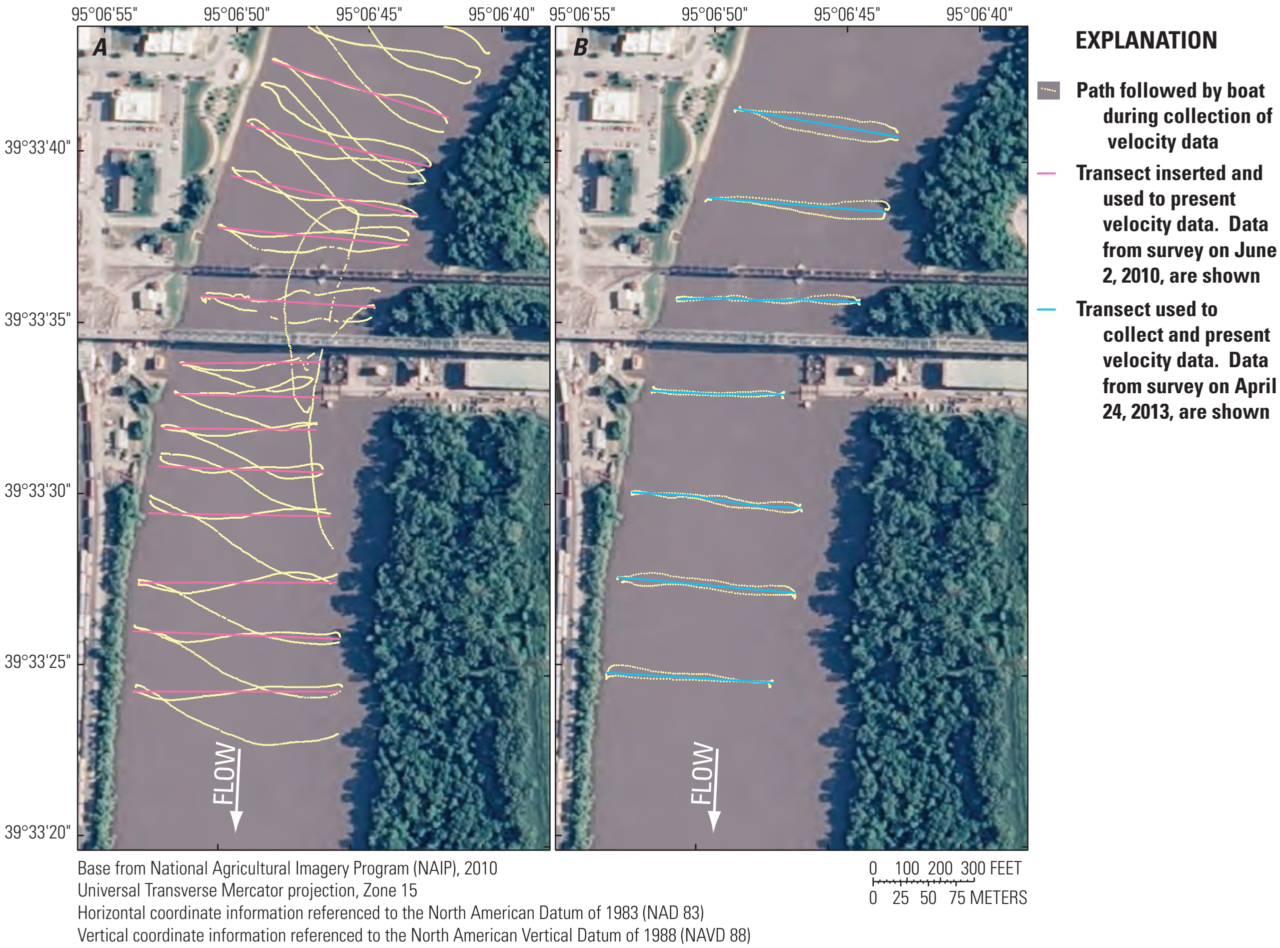


Figure 4. Examples of the method of velocity data collection and presentation for *A*, the first four surveys, and *B*, the last two surveys of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas.

Beam Angle Check

A beam angle check is used to determine the accuracy of the depth readings obtained by the outer beams [greater than 25 degrees from nadir (vertical)] of the MBES (U.S. Army Corps of Engineers, 2004a), which may change with time as a result of inaccurate sound velocities, physical configuration changes, and overall depth being surveyed. The HYPACK®/HYSWEEP® software has a program that develops a statistical assessment of the quality of the outer beams compared to a reference surface (HYPACK, Inc., 2011). The MBMS was being used in a variety of bathymetry studies with MoDOT throughout the course of study, and periodically a set of check lines were run across a reference surface created in various lakes in Missouri. The results of the periodic beam angle checks (table 2) were within the recommended standards utilized by the U.S. Army Corps of Engineers for hydrographic surveys for all angles (U.S. Army Corps of Engineers, 2004a), with the exception of the second check, which had maximum outliers that exceeded the standards for angles greater than 60 degrees from nadir (table 2).

Ideally, the average depth of the reference surface used in the beam angle check would be greater than or equal to the depth in the area being surveyed. Unfortunately, the depth of the Missouri River in the study area generally was impossible to estimate before each survey, because of the dynamic nature of the channel bed. The average depth of the reference surface was about 25 ft on Little Prairie Lake near Rolla, Missouri, about 35 ft on Blue Springs Lake, Missouri, and about 30 ft on Indian Hills Lake near Cuba, Missouri. This depth range was greater than or equal to the average depth observed in four of the six surveys (table 1). The two surveys for which the average depth was greater than the range of the reference surface depths (June 30, 2010, and July 15, 2011; table 1) were during flood conditions on the Missouri River. In these two surveys, areas with depths greater than the average depths generally had substantial overlap of the surveyed swath with adjacent swaths, as described under the “Surveying Methods” sections earlier in this report. Data from the outer beams in these areas were able to be either verified or removed to mitigate any detrimental effects caused by beam angle inaccuracies.

Table 2. Results of beam angle checks from two check lines over a reference surface at Little Prairie Lake near Rolla, Missouri, on July 6, 2009, at Blue Springs Lake, Missouri, at various dates in 2010 and 2011, and at Indian Hills Lake near Cuba, Missouri, on September 4, 2012.

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

Beam angle limit (degrees)	Maximum outlier, in feet					Mean difference, in feet					Standard deviation, in feet					95-percent confidence, in ft				
	July 6, 2009	Mar. 18, 2010	Oct. 26, 2010	Nov. 16, 2011	Sep. 4, 2012	July 6, 2009	Mar. 18, 2010	Oct. 26, 2010	Nov. 16, 2011	Sep. 4, 2012	July 6, 2009	Mar. 18, 2010	Oct. 26, 2010	Nov. 16, 2011	Sep. 4, 2012	July 6, 2009	Mar. 18, 2010	Oct. 26, 2010	Nov. 16, 2011	Sep. 4, 2012
20	0.52	0.85	0.62	0.17	0.82	0	0	0	0.01	0.13	0.10	0.10	0.07	0.03	0.16	0.16	0.20	0.16	0.06	0.30
25	0.33	0.85	0.62	0.14	0.82	0	0	0	0.02	0.13	0.07	0.10	0.07	0.03	0.16	0.16	0.16	0.16	0.07	0.30
30	0.43	0.85	0.62	0.15	0.82	-0.03	0	0	0.02	0.13	0.07	0.10	0.07	0.03	0.16	0.13	0.16	0.16	0.07	0.30
35	0.62	0.85	0.62	0.12	0.82	-0.03	0	0	0.02	0.10	0.07	0.10	0.07	0.03	0.16	0.13	0.16	0.16	0.07	0.30
40	0.89	0.85	0.62	0.12	0.82	-0.03	0	0	0.02	0.10	0.07	0.10	0.10	0.03	0.16	0.13	0.16	0.16	0.06	0.30
45	0.98	0.92	0.62	0.14	0.82	-0.03	0	0	0.01	0.10	0.07	0.10	0.10	0.03	0.16	0.13	0.16	0.16	0.06	0.30
50	0.46	0.92	0.62	0.15	0.82	-0.07	0	0	0.02	0.10	0.07	0.10	0.10	0.03	0.16	0.13	0.16	0.16	0.06	0.30
55	0.52	0.92	0.62	0.15	0.82	-0.03	0	0	0.02	0.10	0.10	0.10	0.10	0.03	0.13	0.16	0.16	0.16	0.06	0.30
60	0.52	1.02	0.66	0.16	0.82	-0.03	0	0	0.03	0.10	0.13	0.10	0.10	0.03	0.13	0.23	0.20	0.20	0.06	0.30
65	0.62	1.77	0.66	0.19	0.82	-0.07	-0.03	0	0.04	0.13	0.13	0.13	0.10	0.03	0.16	0.26	0.26	0.23	0.06	0.30
70	0.39	1.77	0.66	--	0.82	-0.13	-0.03	0	--	0.16	0.03	0.16	0.10	--	0.16	0.07	0.30	0.23	--	0.33
Performance standards[a]																				
	1.00	1.00	1.00	1.00	1.00	< 0.20	< 0.20	< 0.20	< 0.20	< 0.20	--	--	--	--	--	< 0.50	< 0.50	< 0.50	< 0.50	< 0.50
	Met	Met, < 60 degrees	Met	Met	Met	Met	Met	Met	Met	Met	--	--	--	--	--	Met	Met	Met	Met	Met

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

Patch Tests

Patch tests are a series of dynamic calibration tests that are used to check for subtle variations in the orientation and timing of the MBES with respect to the POS and real-world coordinates. The patch tests are used to determine timing offsets caused by latency between the MBES and the POS, and angular offsets to roll, pitch, and yaw caused by the alignment of the transducer head (fig. 5). These offsets are assumed to be constants for a given survey, barring an event that causes the mount to change, such as striking a submerged object. The offsets determined in the patch test are applied when processing the data collected during a given survey.

Patch tests were done before or during each of the surveys in the study, as in previous studies (Huizinga, 2010, 2011; table 3). Although offset values changed for each patch test (table 3), offset values were assumed to remain constant for a given survey, as noted in other studies, except after notable events that caused the mount to bend (see table 3 in Huizinga, 2010).

For this study, there was no measured timing offset (table 3; Δt=0, fig. 5), which is consistent with latency test results for this boat and similar equipment configuration used in other surveys (Huizinga, 2010, 2011, 2012; Huizinga and others, 2010; Richard Huizinga, unpub. data, 2013). All the other measured angular offsets (for pitch, roll, and yaw) varied through the course of the study, but were consistent with the measured angular offset values determined for the boat and sonar head during other coincident surveys (Huizinga, 2010, 2011, 2012; Huizinga and others, 2010; Richard Huizinga, unpub. data, 2013). Each change in the angular offset values can be traced to a documented event of changing the sonar configuration or vessel, or striking a submerged object.

Uncertainty Estimation

The Combined Uncertainty Bathymetric Estimator (CUBE) method (Calder and Mayer, 2003), as implemented in the HYPACK®/HYSWEEP® software (HYPACK, Inc., 2011),

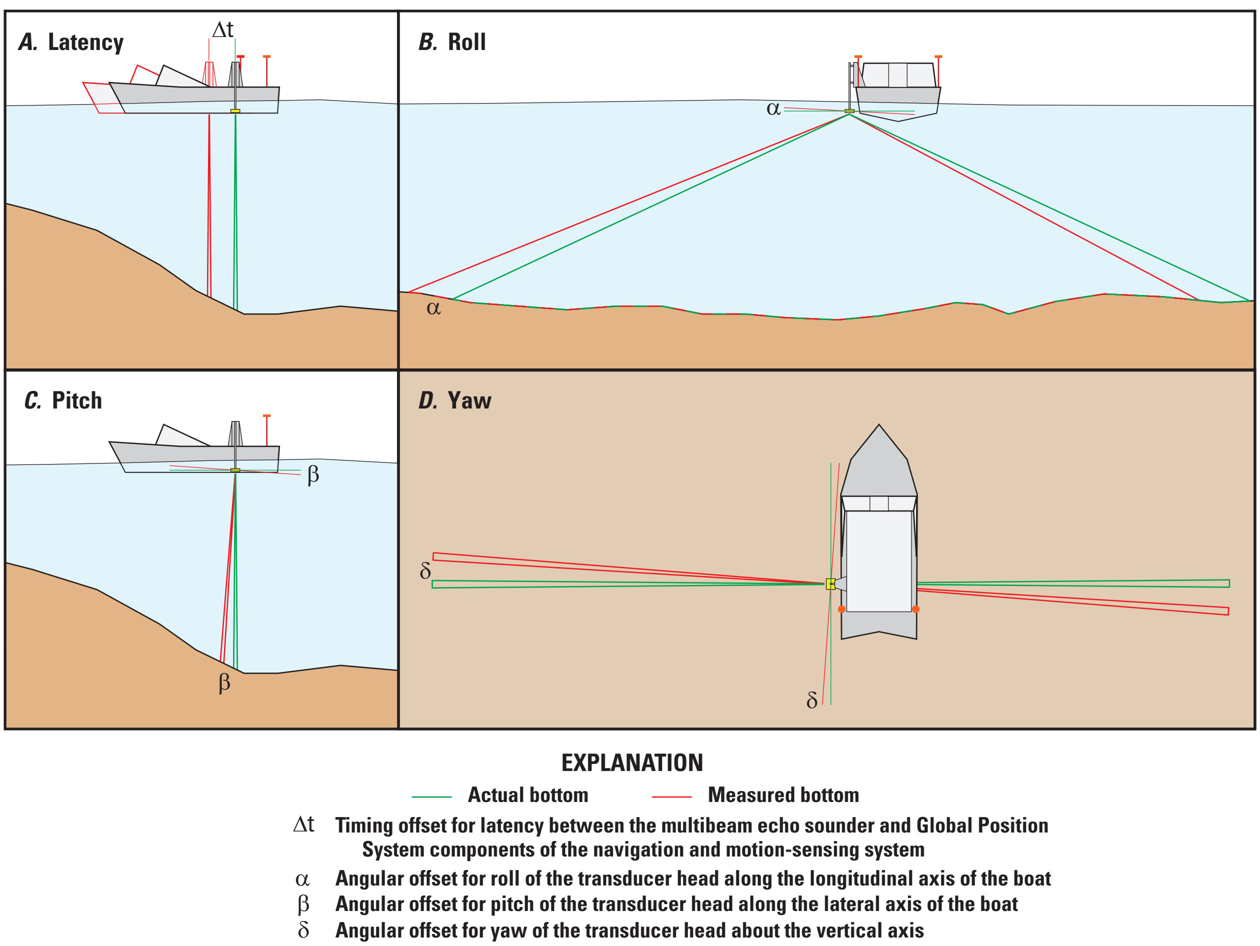


Figure 5. Effects of *A*, timing offset for latency, and angular offsets for *B*, roll, *C*, pitch, and *D*, yaw on data from a multibeam echosounder.

Table 3. Patch test results for surveys on the Missouri River at the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas.

[sec, seconds; deg, degrees]

Date of test	Timing offset (sec)	Angular offset for roll (deg)	Angular offset for pitch (deg)	Angular offset for yaw (deg)	Location (fig. 1)
06/30/09	0	0.55	-2.35	1.10	Missouri River at Atchison, Kansas.
06/02/10	0	0.15	-2.00	1.80	Missouri River at Atchison, Kansas.
06/29/10	0	0.38	-2.45	2.50	Blue Springs Lake, Missouri.
10/27/10	0	0.05	-1.80	2.70	Missouri River at Atchison, Kansas.
07/20/11	0	-2.50	3.20	2.70	Blue Springs Lake, Missouri.
04/16/13	0	-2.60	-2.50	0.70	Indian Hills Lake near Cuba, Missouri.

was used to estimate total propagated uncertainty (TPU) for the 1.64-ft gridded surface of each survey area. The CUBE method allows all random system component uncertainties and resolution effects to be combined and propagated through the data processing steps, which provides a robust estimate of the spatial distribution of possible uncertainty within the survey area (Czuba and others, 2011). Thus, the TPU of a point is a measure of the accuracy to be expected for such a point, when all relevant error sources are accounted for (Czuba and others, 2011). Statistics of TPU for each of the survey areas are shown in table 4, and the spatial distribution of TPU observed in the final survey data on April 24, 2013, which had generally the poorest statistics (highest values of mean and standard deviation, and lowest percentage of points within the various TPU ranges in table 4) is shown in figure 6 as an example.

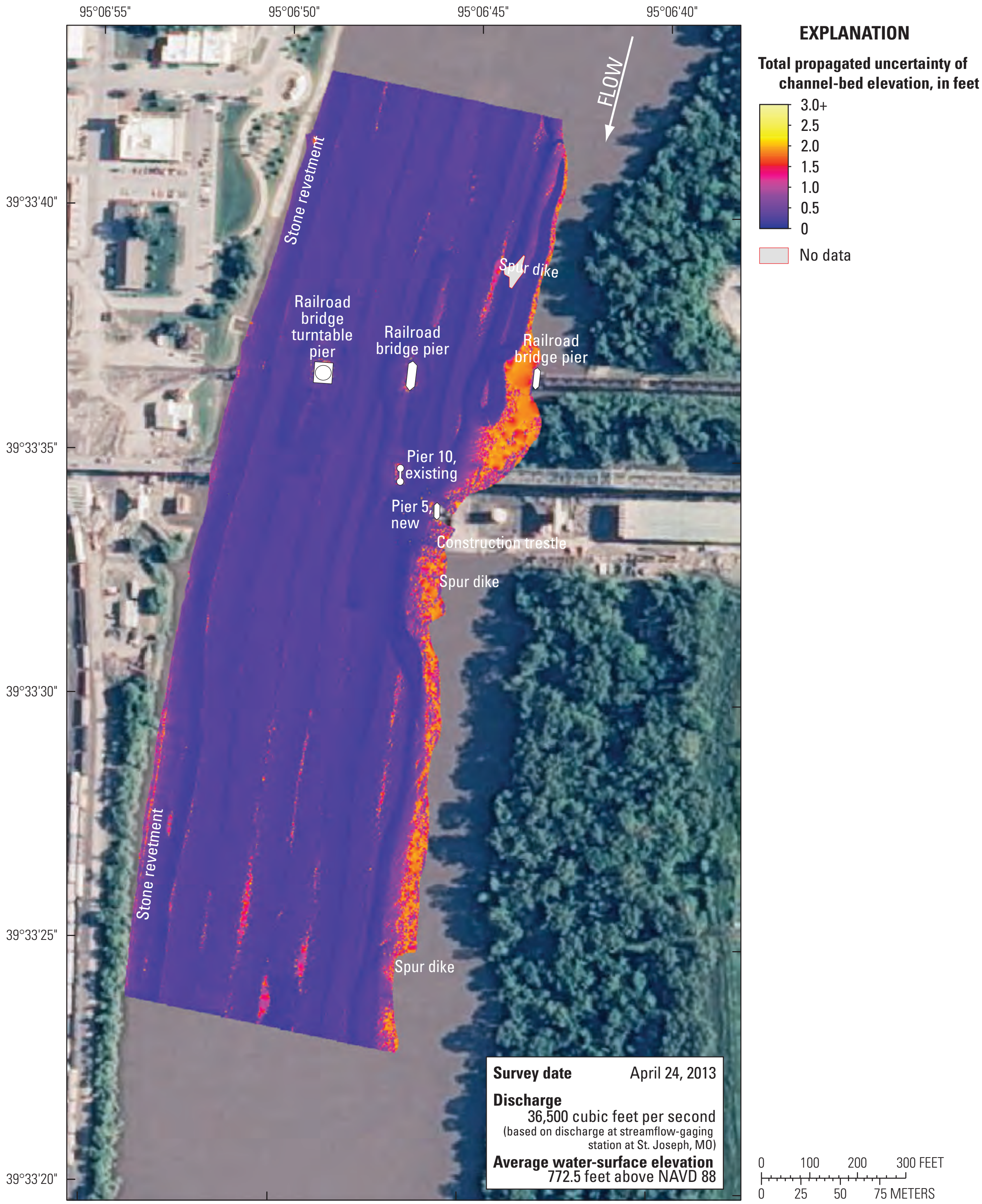
The largest TPU of the various survey dates was 4.63 ft (table 4); however, TPU values of this magnitude typically are observed near high-relief features, such as the front or side of the piers or large submerged object (fig. 6). Most of the TPU values (about 97.1 percent or more) were less than 2.00 ft (table 4), with larger values near moderate-relief features (banks, dune faces, rock riprap, spur dikes, and scour holes; fig. 6). Occasionally, these larger TPU values also are evident in the outermost beam parts of the multibeam swath in the overlap with an adjacent swath, typically in the channel thalweg, which is the line of maximum depth in the channel near the right descending bank, where substantial bed movement might be observed between survey passes (fig. 6). More than one-half (58 percent or more) of the channel bed had TPU values of 0.50 ft or less, and in one-half of the surveys more than 26 percent of the data had a total propagated uncertainty of less than 0.25 ft (table 4). Data at the top of the pier 10 caisson (the foundation of the pier) typically had TPU values of 0.20 ft or less.

The surveys on June 30, 2010; July 15, 2011; and April 24, 2013, had the highest statistics of TPU and the lowest percentage of points that were less than the various TPU ranges (table 4). During the survey on June 30, 2010, the water-surface elevation was high enough to restrict adequate clearance under the BNSF railroad bridge to only one location in the middle of the left approach span, which limited data collection near the railroad bridge. During the survey on July 15, 2011, the water-surface elevation was high enough to totally prevent clearance under the BNSF railroad bridge, preventing acquisition of data upstream from the railroad bridge. Near the railroad bridge and the highway bridge, smooth

Table 4. Total propagated uncertainty results for bathymetric data at a 1.64-foot (0.5-meter) grid spacing from surveys at the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas.

[TPU, total propagated uncertainty; ft, feet]

Survey date	Maximum value of TPU (ft)	Mean value of TPU (ft)	Median value of TPU (ft)	Standard deviation of TPU (ft)	Percent of bathymetry points with TPU value less than			
					2.00 ft	1.00 ft	0.50 ft	0.25 ft
06/30/09	3.71	0.32	0.30	0.16	99.8	99.4	96.9	27.0
06/02/10	3.97	0.29	0.26	0.15	99.9	99.6	98.1	36.1
06/30/10	4.53	0.42	0.39	0.22	99.7	98.8	73.0	12.0
10/27/10	3.90	0.34	0.30	0.19	99.8	99.3	85.5	26.0
07/15/11	4.63	0.52	0.49	0.25	99.5	96.9	58.6	3.5
04/24/13	3.61	0.57	0.46	0.45	97.1	92.6	65.7	1.3



Base from National Agricultural Imagery Program (NAIP), 2007
Universal Transverse Mercator projection, Zone 15
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 6. Total propagated uncertainty of bathymetric data from the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on April 24, 2013.

navigation of the boat was hampered by flow around piers during both surveys, and abrupt turns had to be made immediately downstream from the railroad bridge during the surveys; furthermore, GPS multipath errors likely were at a maximum with the steel superstructure of both bridges blocking or redirecting GPS signal. Values of TPU generally were greatest in the vicinity of the railroad and highway main channel piers during the surveys on June 30, 2010, and July 15, 2011 [see fig. 5 in Huizinga (2012)].

Although the survey on April 24, 2013, had the lowest maximum value of TPU, it had the highest value of TPU for the mean and standard deviation, and the lowest percentage of bathymetric points with TPU values less than the various categories (table 4). Part of the difference may be the different survey vessel used during this survey, the configuration of which may be more sensitive to factors that dictate TPU. Additionally, a substantial part of the left bank was acquired with the sonar head tilted, which introduces additional uncertainty and affects the overall statistics for the survey.

Results of Repeat Bathymetric and Velocimetric Surveys

The specific results for survey are discussed in the following sections in chronological order, followed by a discussion of general findings and observed trends. The range of bed elevations described as "the channel-bed elevations" for each survey were based on statistical analysis of the bathymetry data from each survey, and covers the percentile range from 5 to 95 percent of the data. Because each survey was limited to the active channel and generally excluded overbank areas, this percentile range generally covered the channel bed but excluded the banks and localized high or low spots, such as spur dikes or scour holes near piers. All elevation data were referenced to the North American Vertical Datum of 1988 (NAVD 88).

The discharge value reported for each survey was determined from the upstream USGS streamflow-gaging station (number 06818000) at St. Joseph, Missouri (index map of fig. 1). Discharge values from this streamgage have been checked for quality and consistency with respect to direct measurements and the long-term stage and discharge records at that streamgage. Figure 7 shows the daily discharge and median statistic values for the period January 1, 2009, to June 30, 2013, with the survey dates highlighted (U.S. Geological Survey, 2013). As stated earlier in the "Survey Quality Assurance/Quality Control Measures" section, although most of the established protocols (Mueller and Wagner, 2009) were followed when obtaining data for the velocity transects with the ADCP, velocity—not discharge—was the primary variable of interest.

The discharge ranged from 36,500 ft^3/s to 214,000 ft^3/s during the six surveys in this study (table 1), covering the range from low flow at the greater than 50-percent daily exceedance level (U.S. Geological Survey, 2003) to high flow at the 4-percent annual exceedance probability flood (25-year recurrence interval flood; U.S. Army Corps of Engineers, 2004b). In 2009 and 2012, the daily mean discharge generally was similar to the median daily statistic, whereas the daily

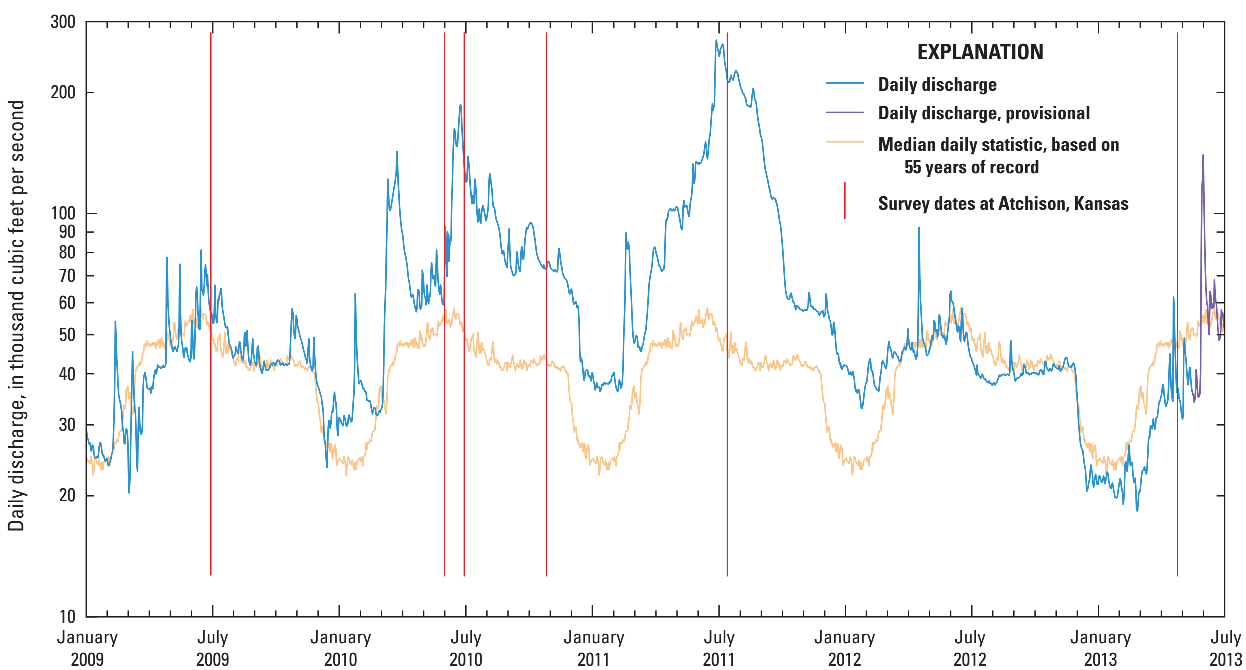


Figure 7. Daily value of discharge and median daily statistics at the streamflow-gaging station on the Missouri River at St. Joseph, Missouri, upstream from Atchison, Kansas, from January 1, 2009, to June 30, 2013, and the dates of the bathymetric and velocimetric surveys.

mean discharge consistently was larger than the median daily statistic for both 2010 and 2011. The daily mean discharge generally was lower than the median daily statistic until the end of May 2013.

Dune sizes are described in relative terms for each of the surveys at the site. These descriptions are qualitative only, as no direct measurements were made. In this report, small dunes and ripples are those that have a short wavelength and are small in height from crest to trough as compared with other bed features observed at the site during the various surveys, whereas large dunes are those that have a long wavelength and are substantial in height as compared with other bed features observed at the site during the various surveys.

When discussing the vertically averaged velocity values obtained during the surveys in the sections that follow, neighboring vectors with random variations in direction and magnitude were an indication of turbulence in the transect. On the other hand, neighboring vectors with gradual and systematic variations were an indication of uniform flow in the transect.

Pre-Construction Survey on June 30, 2009

Before construction began on the new U.S. Highway 59 Bridge (hereinafter referred to as the “new US 59 Bridge”), the site was surveyed on June 30, 2009, to establish a baseline condition of the bathymetry and velocities in the vicinity of the Earhart Bridge. The average water-surface elevation of the river in the survey area, determined by the RTK GPS tide solution, was 777.4 ft, and flow on the Missouri River was about 56,600 ft^3/s during the survey, according to the streamflow-gaging station at St. Joseph, Missouri (table 1). The channel-bed elevations for the first survey ranged from about 740 to 765 ft for most of the surveyed area (table 5), except near pier 10 (fig. 8). The channel bed throughout the survey area was covered with numerous medium and small dunes and ripples (fig. 8). Stone revetment was present on the right descending (west) bank throughout the reach (fig. 8).

In the vicinity of main channel pier 10, the scour hole had a minimum channel-bed elevation of approximately 721.9 ft (table 5), about 29 ft below the average channel bed to the right of the pier (figs. 8, 9). This scour hole was substantially affected by local scour caused by the railroad bridge pier upstream, which extended downstream to pier 10 (figs. 8, 9), causing the channel-bed elevation immediately upstream from pier 10 to be lower than it would have been without the upstream pier (figs. 8, 9). Typically, pier scour is measured from the channel-bed elevation immediately upstream from a pier (Richardson and Davis, 2001), so the lower channel bed immediately upstream from pier 10 caused by the upstream scour hole likely caused the scour hole for pier 10 to be deeper than it would have been without the upstream pier in place. Nevertheless, information from bridge plans indicates that pier 10 is founded on a caisson on bedrock, with about 21 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of pier 10 during this survey (fig. 10).

Table 5. Surveyed channel-bed elevations in the middle 90 percent of each survey, and at several key locations near the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas.

[ft, feet; --, not applicable; all elevations are in feet above the North American Vertical Datum of 1988]

Survey date	Approximate elevation of the indicated percentile of the bathymetric data		Approximate minimum elevation near nose of existing pier 10, Point A[1] (ft)	Change from previous survey (ft)	Change from baseline on 06/30/09 (ft)	Approximate minimum elevation near back corner of existing pier 10, nearest to coffer-dam, Point B (ft)	Change from previous survey (ft)	Change from baseline on 06/30/09 (ft)	Approximate elevation in thalweg on right bank, under existing bridge, Point C (ft)	Change from previous survey (ft)	Change from baseline on 06/30/09 (ft)
	5th percentile (ft)	95th percentile (ft)									
06/30/09	740	765	721.9	--	--	730.5	--	--	750.5	--	--
06/02/10	736	766	722.1	0.2	0.2	733.3	2.8	2.8	746.9	-3.6	-3.6
06/30/10	723	769	703.9	-18.2	-18.0	711.2	-22.1	-19.3	737.4	-9.5	-13.1
10/27/10	732	768	717.6	13.7	-4.2	728.7	17.4	-1.9	748.8	11.4	-1.7
07/15/11	729	769	704.8	-12.8	-17.0	713.2	-15.5	-17.4	738.0	-10.8	-12.5
04/24/13	749	764	738.9	34.0	17.0	742.7	29.6	12.2	749.6	11.6	-0.9

[1]Generally, also the minimum elevation of the survey, except on April 24, 2013.

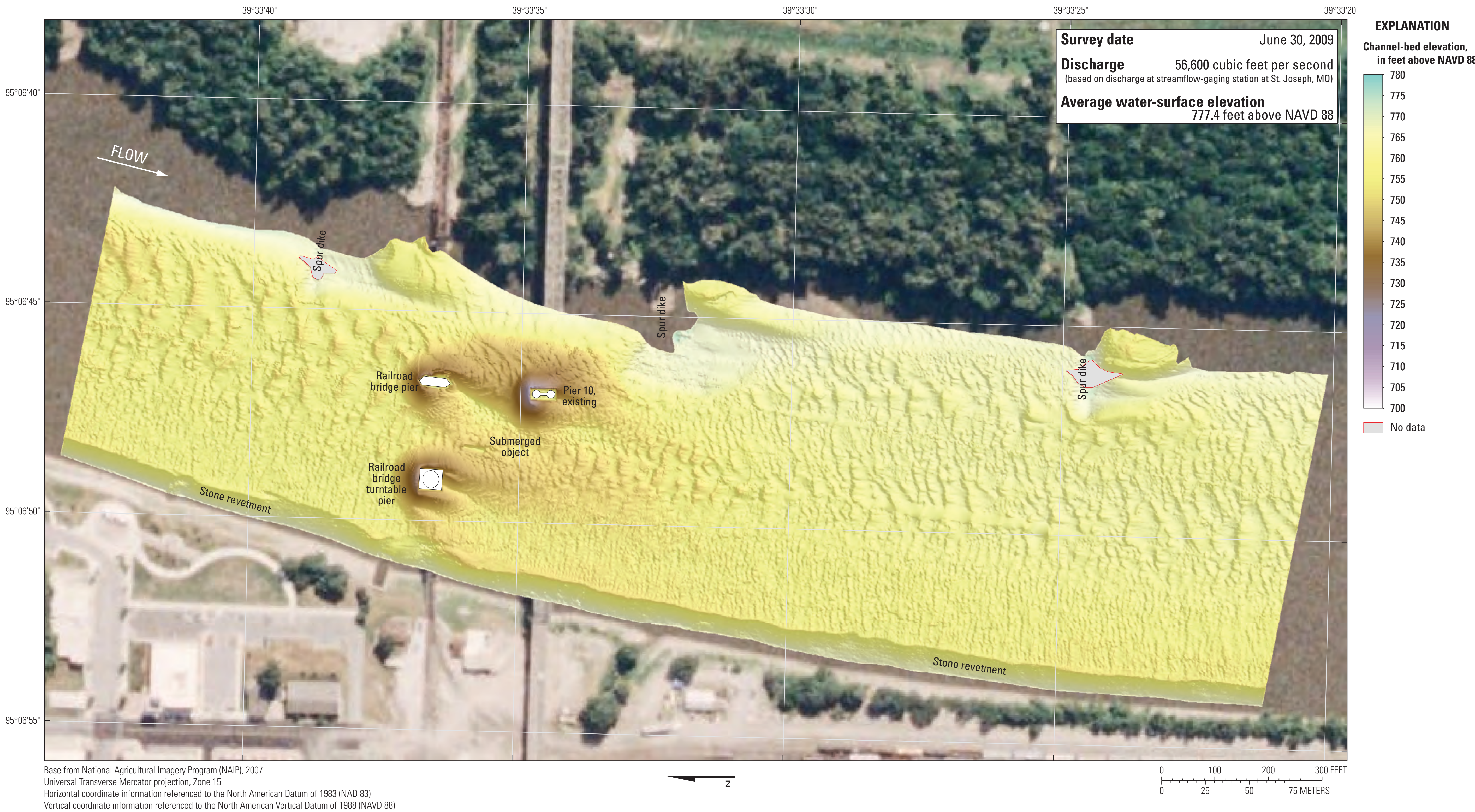


Figure 8. Bathymetric survey of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, before construction began on the new U.S. Highway 59 bridge.

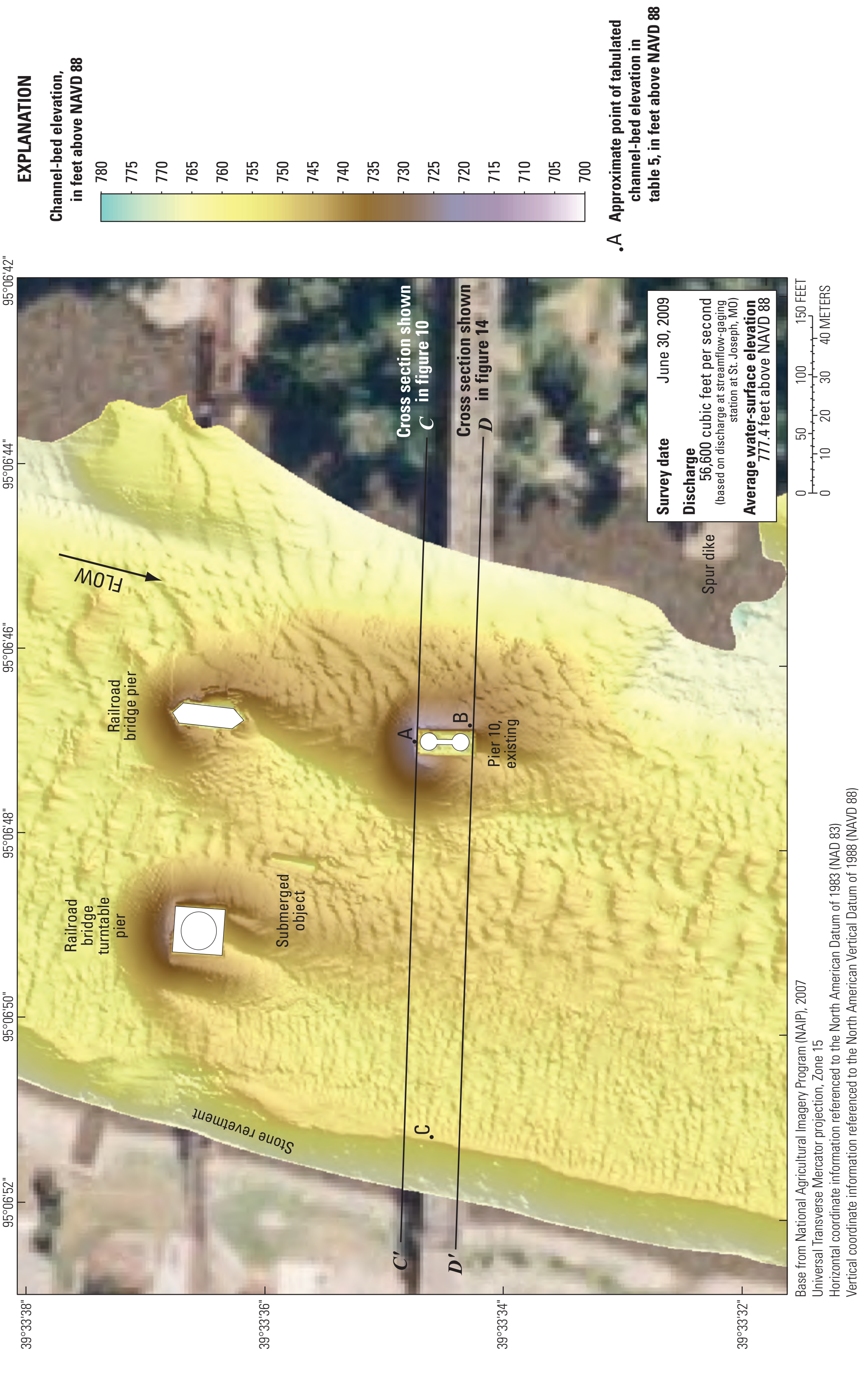


Figure 9. Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, before construction began on the new U.S. Highway 59 bridge.

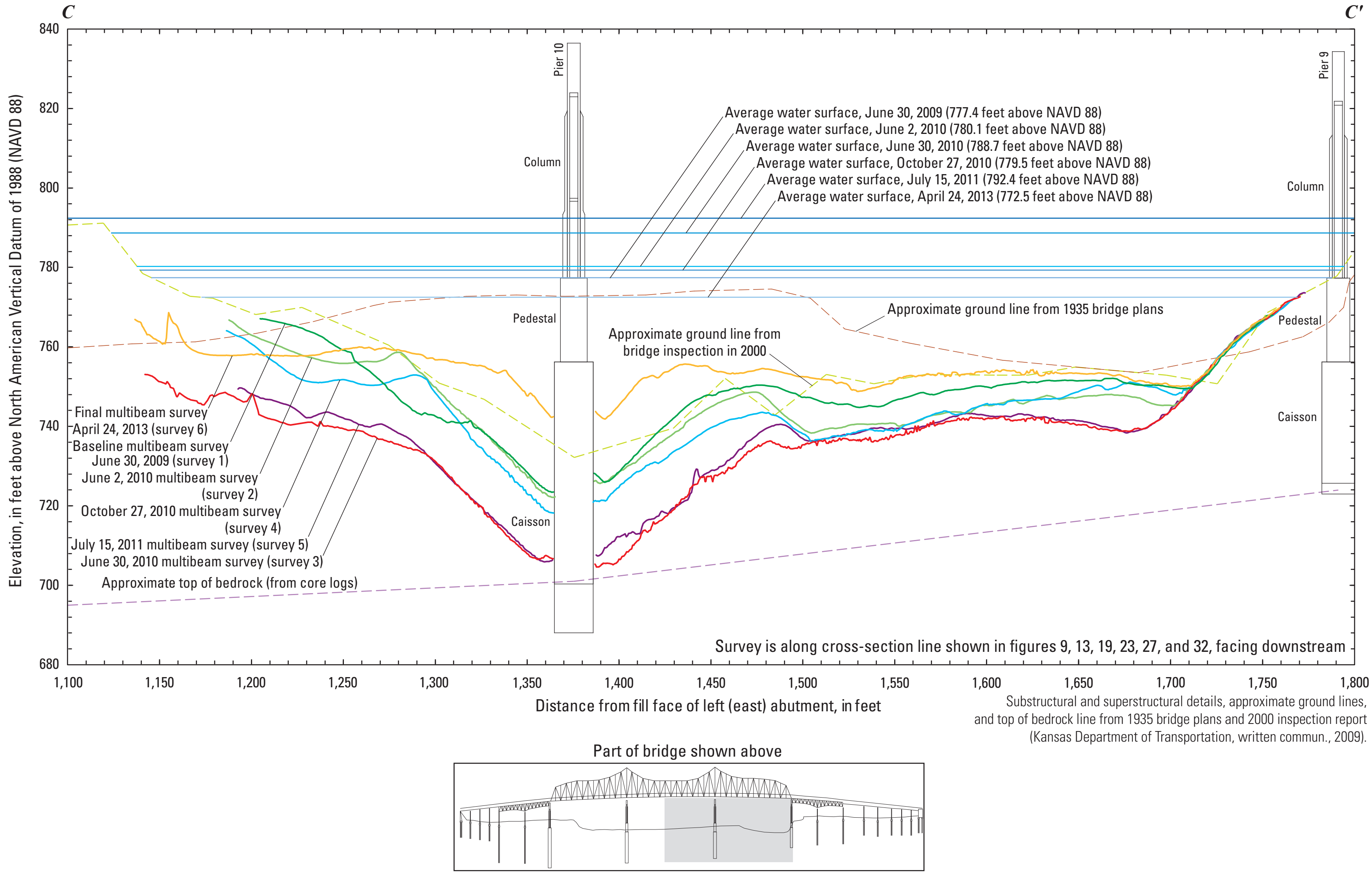


Figure 10. Key features, substructural and superstructural details, and surveyed channel bed along the upstream face of the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas, from periodic surveys.

A submerged object with straight features was observed on the channel bed between the bridges, downstream from and between the railroad bridge piers (figs. 8, 9). The object appeared to be approximately 40 ft long, and about 10 ft wide during the first survey. Given the regularity of its features, the object obviously is man-made, and likely is a sunken barge or other vessel.

The vertically averaged velocity vectors indicated mostly uniform flow throughout the reach, except downstream from the various piers of the railroad bridge and the Earhart Bridge where there was turbulence and spatial variability in velocity magnitude (fig. 11). Most of the turbulence and spatial variability abated in the downstream part of the reach. Average velocities ranged from 4 to 6 ft/s in the middle and right sides of the channel, and from 0 and 3 ft/s along the left bank near the spur dikes (fig. 11). The vectors indicate minor contraction of flow from immediately upstream from the railroad bridge to the Earhart Bridge, and minor expansion of flow along the transect at the spur dike downstream from the Earhart Bridge (fig. 11).

Survey on June 2, 2010

A trestle extending from the left bank and a cofferdam were built to facilitate construction of pier 5 of the new US 59 Bridge, and the cofferdam was completed in late May 2010. The site was surveyed a second time on June 2, 2010; the average water-surface elevation of the river in the survey area was 780.1 ft, and flow on the Missouri River was about 63,000 ft^3/s during the survey (table 1). These conditions were similar to those of the baseline survey on June 30, 2009. The channel-bed elevations for the second survey ranged from about 736 to 766 ft for most of the surveyed area, except near pier 10 (fig. 12; table 5); these values are similar to the baseline on June 30, 2009, but the lower end of the range is slightly less than the baseline. The channel downstream from the bridge again was covered with numerous medium and small dunes and ripples, although of a slightly longer wavelength than in June 2009 (fig. 12). The channel upstream from the bridge was filled with larger dunes of a substantially longer wavelength than in June 2009 (fig. 12).

In the vicinity of main channel pier 10, the scour hole had a minimum channel-bed elevation of approximately 722.1 ft (table 5), about 25 ft below the average channel bed to the right of the pier (figs. 12, 13). As with the baseline survey, this scour hole likely was substantially affected by local scour caused by the railroad bridge pier upstream (figs. 12, 13). Similar to the survey on June 30, 2009, there was about 21 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of pier 10 (fig. 10). The submerged object observed on the channel bed between the bridges during the first survey appears more substantially exposed in the second survey (figs. 12, 13) than in the first survey, with noticeable scour around the upstream end, indicating it is blocking more flow than in the first survey. In the second survey, the object appears to be about 100 ft long and about 25 ft wide, and the downstream end of the object appears damaged. The object appears to be a capsized tow barge that likely has settled into the bed material through scour action in successive floods through the years.

The cofferdam and construction trestle did not have a profound effect on the scour hole at the upstream face of existing pier 10, but there was some observed channel deepening closer to the left bank along the upstream bridge face and overall channel deepening in the channel to the right of the existing pier 10 (fig. 10). Along the downstream face of the existing bridge (fig. 14), a new scour hole appeared to be forming around the cofferdam, with a similar deepening of the channel to the right of the existing pier 10. Upstream from the bridges, the channel exhibited deposition, whereas at the bridges and downstream, most of the channel experienced scour (figs. 15, 16). An area of substantial scour was observed downstream from the spur dike upstream from the railroad bridge (figs. 15, 16), which likely was a result of flooding earlier in March 2010 (fig. 7). However, the left bank downstream from the construction trestle and cofferdam was substantially higher in the second survey compared to the baseline survey (figs. 15, 16). The average value of the difference between the June 2, 2010, and 2009 bathymetric surfaces is -1.8 ft (table 6), indicating minor to moderate scour overall between the surveyed dates. The appearance of substantial deposition or scour on the sides of the piers (areas of bright red or dark blue on the sides) in the difference map (fig. 15) results from minor horizontal positional variances between the surveys.

As in the baseline survey, the vertically averaged velocity vectors indicated mostly uniform flow throughout the reach, except downstream from the various piers of the railroad bridge and the Earhart Bridge where there was turbulence and spatial variability in velocity magnitude (fig. 17). Substantial turbulence also was observed downstream from the spur dike upstream from the railroad bridge (fig. 17). Most of the turbulence and spatial variability abated in the downstream part of the reach. Average velocities ranged from 6 to 10 ft/s in the middle and right sides of the channel, and from 0 and 4 ft/s along the left bank near the spur dikes (fig. 17). The vectors indicate a more substantial contraction of flow from immediately upstream from the railroad bridge to the Earhart Bridge, with an abrupt expansion and localized reversal of flow along the transect at the cofferdam downstream from the Earhart Bridge (fig. 17). Flow continued to expand throughout most of the downstream part of the reach. Velocities throughout the reach generally were faster in the second survey compared to the baseline, being 2 to 4 ft/s faster near the bridges, despite the similar flow conditions between the surveys.

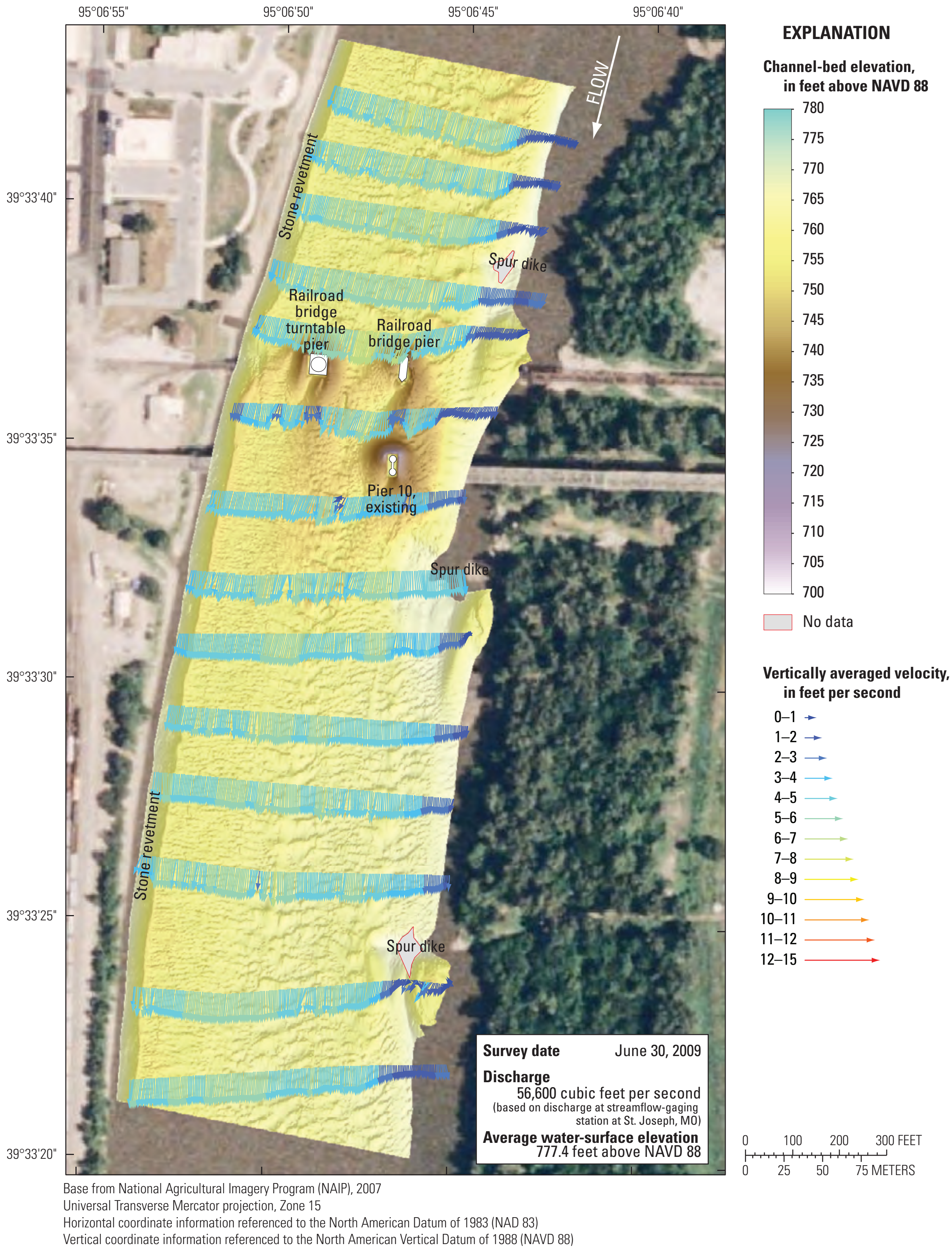


Figure 11. Bathymetry and vertically averaged velocities of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, before construction began on the new U.S. Highway 59 bridge.

Figure 12. Bathymetric survey of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 2, 2010, after the construction of the cofferdam for pier 5 of the new U.S. Highway 59 bridge.

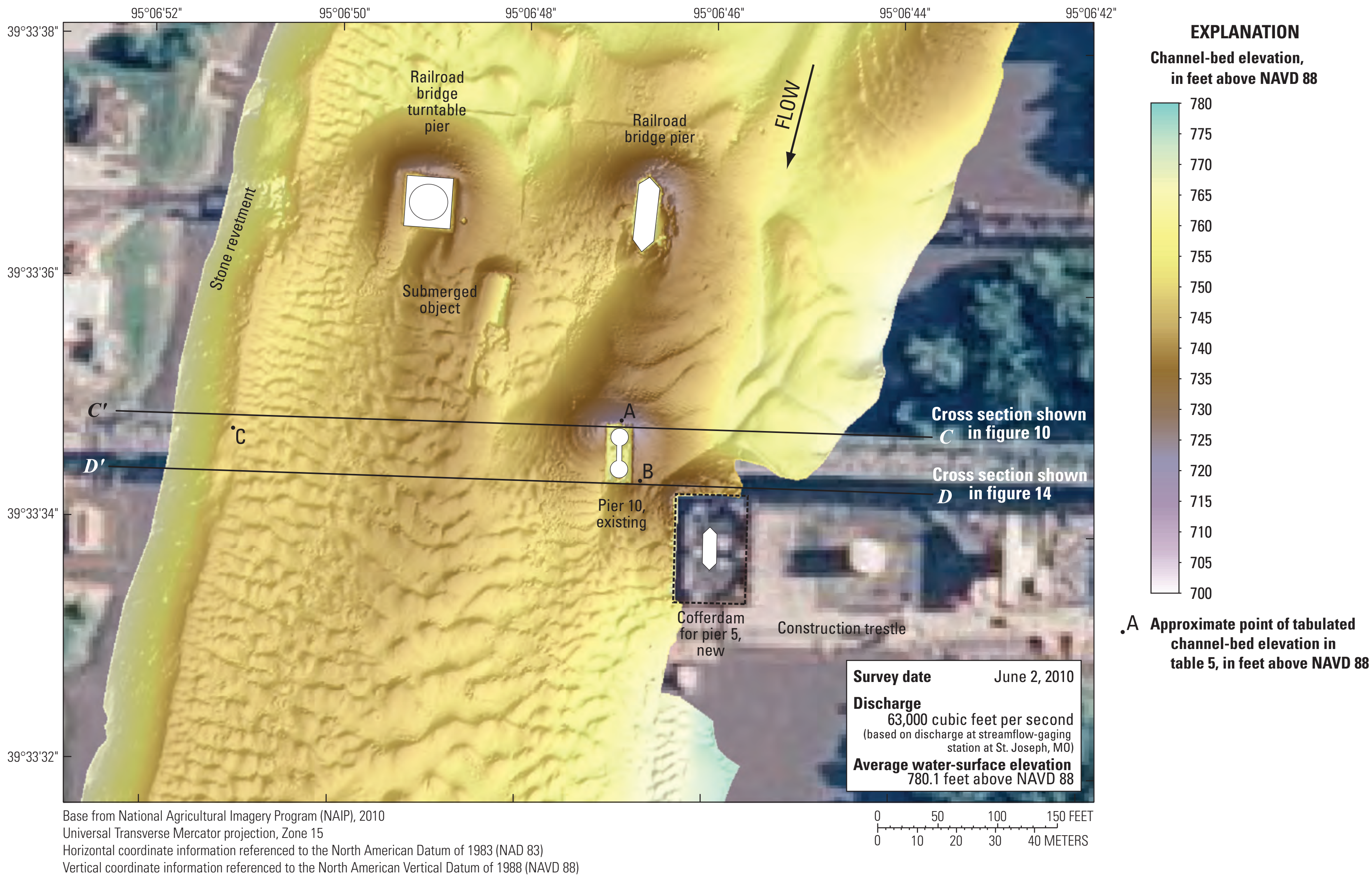


Figure 13. Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 2, 2010, after the construction of the cofferdam for pier 5 of the new U.S. Highway 59 bridge.

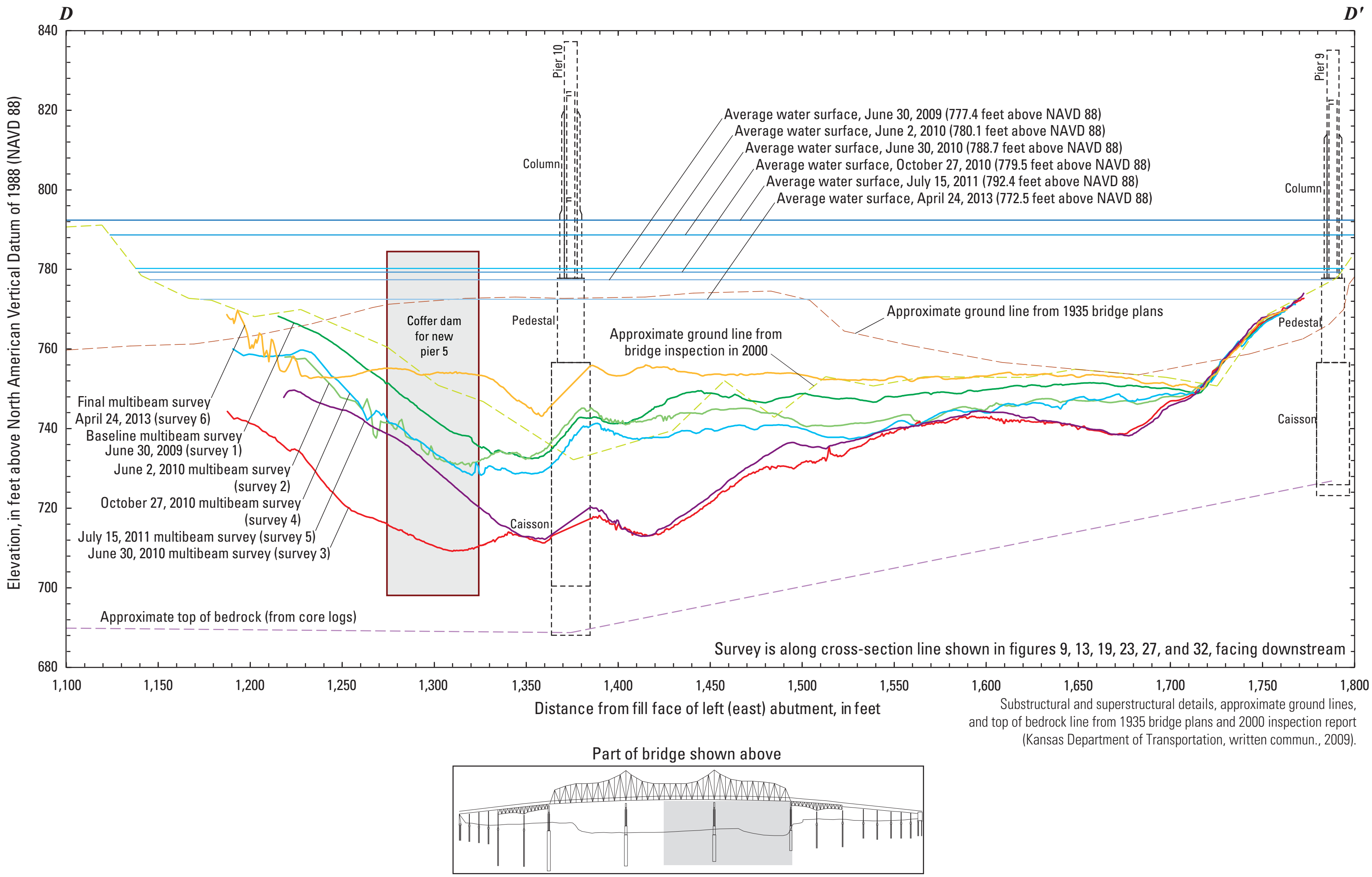


Figure 14. Key features, substructural and superstructural details, and surveyed channel bed along the downstream face of the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas, from periodic surveys.

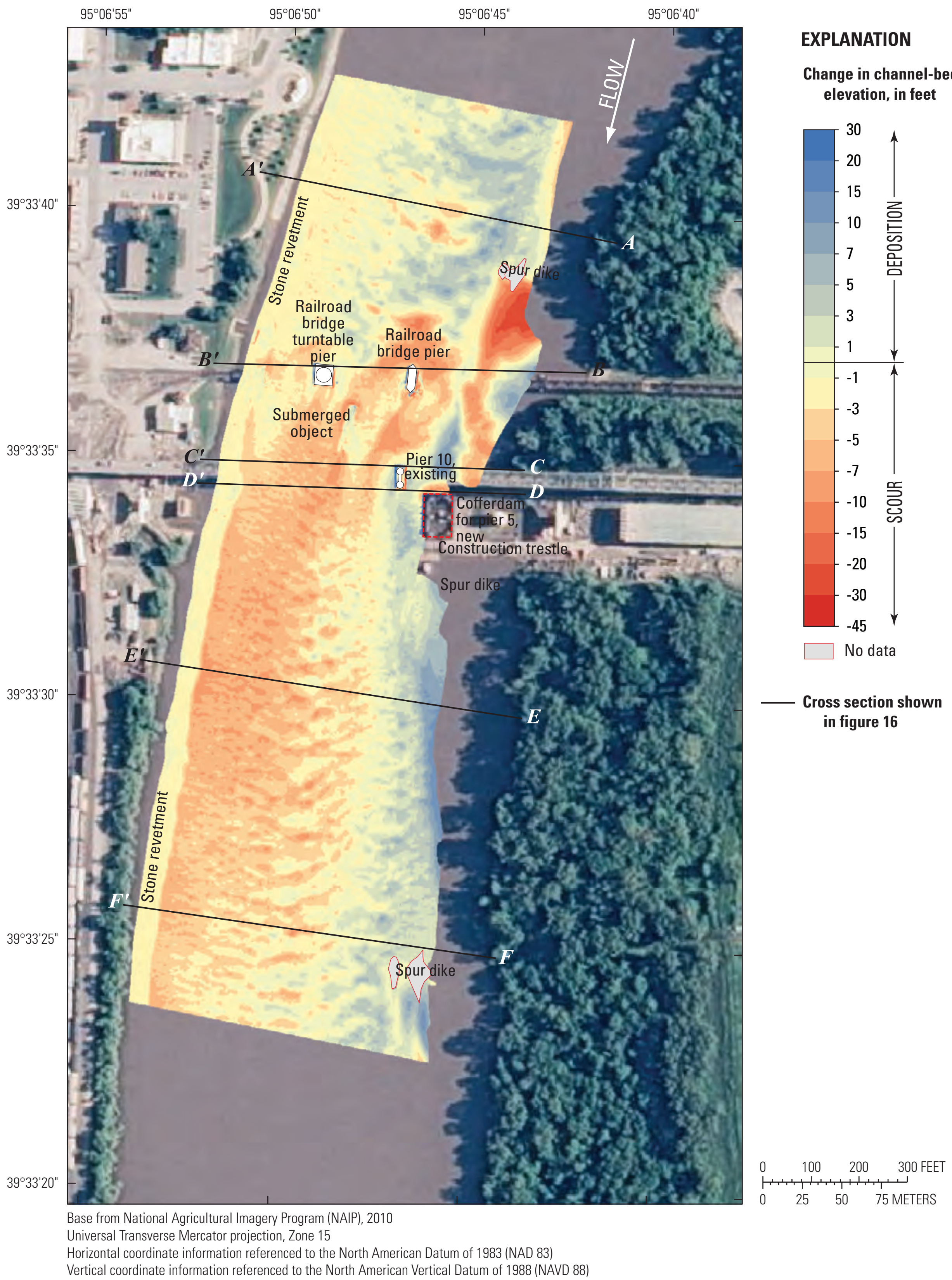


Figure 15. Difference between surfaces created from bathymetric surveys of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, and June 2, 2010, after the construction of the cofferdam for pier 5 of the new U.S. Highway 59 bridge.

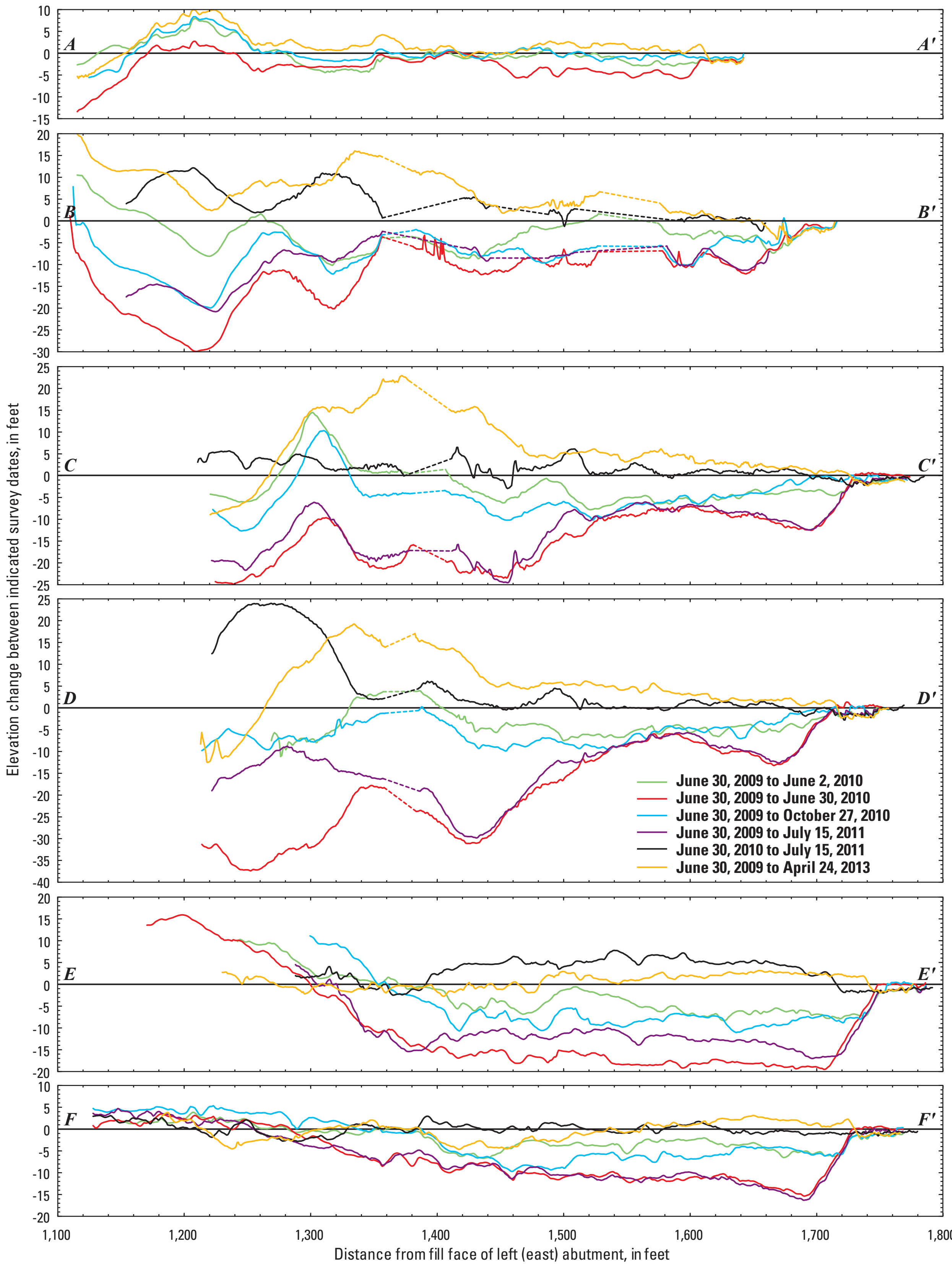
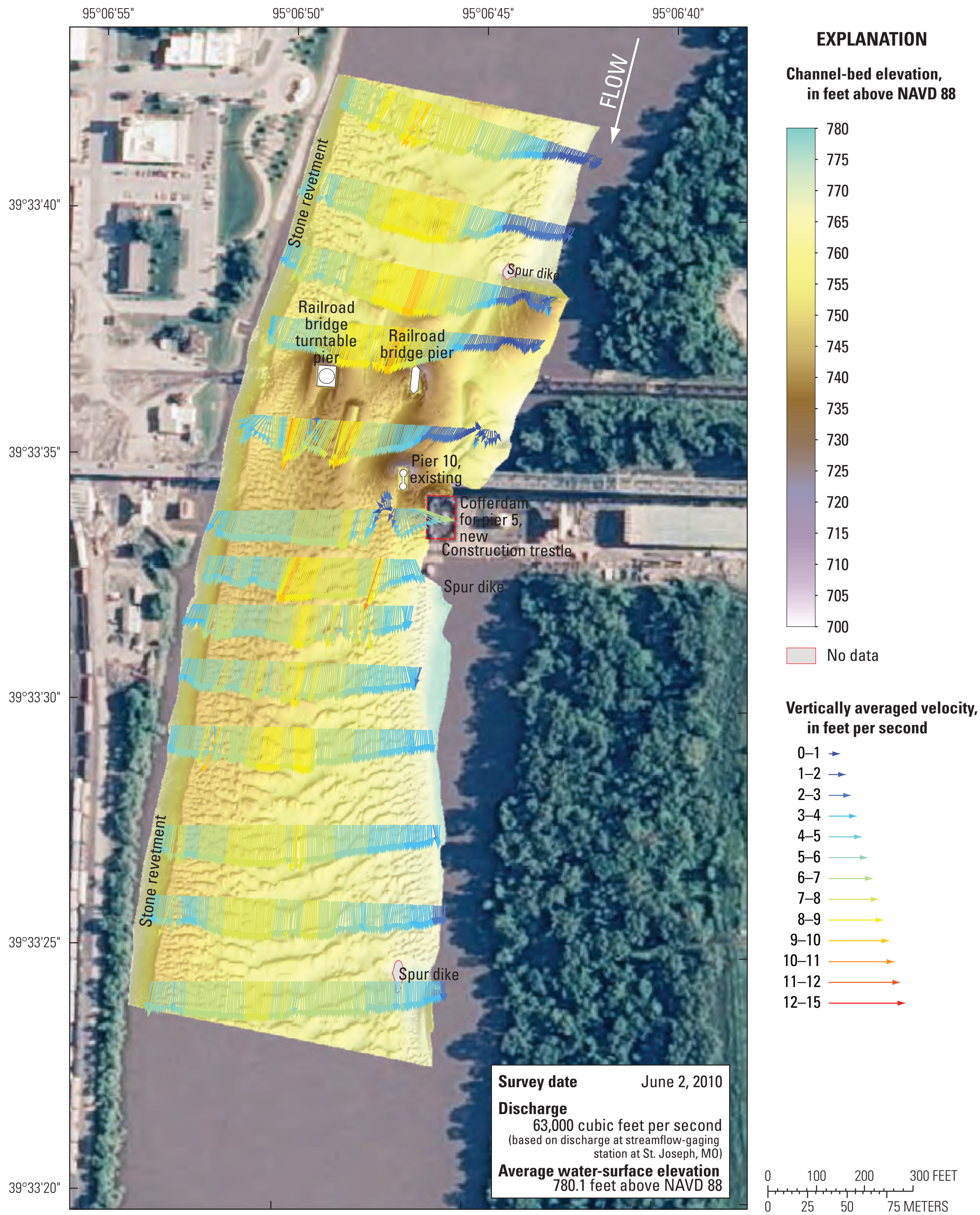


Figure 16. Elevation changes between indicated survey dates along various sections in downstream order near the Amelia Earhart Bridge on U.S. Highway 59 over the Missouri River at Atchison, Kansas.



Base from National Agricultural Imagery Program (NAIP), 2010
Universal Transverse Mercator projection, Zone 15
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 17. Bathymetry and vertically averaged velocities of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 2, 2010, after construction of the cofferdam for pier 5 of the new U.S. Highway 59 bridge.

Table 6. Mean value of difference between bathymetric surfaces from surveys on the Missouri River at the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas.

[--, not applicable]

Survey date	Mean value of difference between bathymetric surfaces on survey date and indicated resurvey date, in feet				
	06/02/10	06/30/10	10/27/10	07/15/11	04/24/13
06/30/09	-1.8	-7.0	-2.6	-8.8	1.7
06/02/10	--	-6.8	-1.3	-6.7	3.6
06/30/10	--	--	5.0	1.4	10.4
10/27/10	--	--	--	-5.2	5.0
07/15/11	--	--	--	--	11.1

Survey during Flooding, June 30, 2010

The Missouri River was above flood stage most of the month of June 2010, and a third survey on June 30, 2010, was to capture potential effects of the flooding. The average water-surface elevation of the river in the survey area was 788.7 ft, and flow on the Missouri River was about 134,000 ft^3/s during the survey (table 1). The channel-bed elevations for the third survey ranged from about 723 to 769 ft for most of the surveyed area, except near pier 10 (fig. 18; table 5). The channel downstream from the bridge again was covered with numerous medium and small dunes and ripples, as in the first two surveys, similar in size and shape to those in the June 2, 2010, survey (fig. 18). The channel upstream from the bridge was nearly devoid of ripples and dunes in the center of the channel, but small dunes and ripples were present near both banks (fig. 18). The elevations of the left bank downstream from the trestle and cofferdam were similar to the June 2, 2010.

In the vicinity of main channel pier 10, the scour hole had a minimum channel-bed elevation of approximately 703.9 ft (table 5), about 37 ft below the average channel bed to the right of the pier (figs. 18, 19). As in both earlier surveys, this scour hole was substantially affected by local scour caused by the railroad bridge pier upstream (figs. 18, 19). The minimum elevation at the nose of main channel pier 10 is approximately 18 ft deeper than the two previous surveys (table 5), with only about 3 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of pier 10 (fig. 10). In modern construction, bridge substructural elements usually are pinned or socketed to bedrock (American Association of State Highway Transportation Officials, 2012; Brown and others, 2010), but full exposure of usually buried substructural elements warrants special consideration and observation, particularly at an older bridge such as the Earhart Bridge. The scour hole caused by the cofferdam also is substantial (figs 18, 19). The submerged object on the channel bed between the bridges appears more substantially exposed in the third survey (figs. 18, 19) than in the previous two, appearing to be about 105 ft long and about 35 ft wide.

In the third survey, the combined effects of the cofferdam, the trestle, and the debris caught on each become more apparent. The scour holes near existing pier 10 and the cofferdam were substantial and interconnected (figs. 10, 14, 18, 19). The shape of the intertwined scour holes from the railroad bridge pier, existing pier 10, and the cofferdam appear swept to the right, towards the middle of the channel, as flow is deflected around the trestle and cofferdam (figs. 18, 19).

Channel deepening was observed throughout the channel during the third survey as compared to the first survey, except along the left bank downstream from the bridges (fig. 20), particularly along the upstream and downstream bridge faces of the Earhart Bridge (section *C-C*’ in figs. 10, 16 and section *D-D*’ in figs. 14, 16). Upstream from the bridges, the channel exhibited minor deposition, and the left bank downstream from the construction trestle and cofferdam was substantially higher in the third survey compared to the baseline survey (figs. 16, 20). The average value of the difference between the June 30, 2010, and 2009 bathymetric surfaces is -7.0 ft (table 6), indicating substantial scour overall between the surveyed dates. As in the previous survey, the appearance of substantial deposition or scour on the sides of the piers (areas of bright red or dark blue on the sides) in the difference map (fig. 20) results from minor horizontal positional variances between the surveys.

The vertically averaged velocity vectors indicated mostly uniform flow in the upstream part of the reach and most of the downstream part of the reach, with substantial turbulence and spatial variability in velocity magnitude near the bridges and cofferdam (fig. 21). Generally, average velocities ranged from 5 to 10 ft/s in the middle and right sides of the channel, and from 0 and 4 ft/s along the left bank near the spur dikes (fig. 21). The vectors indicate a substantial contraction of flow from immediately upstream from the railroad bridge to the Earhart Bridge, with an abrupt expansion and localized velocity spikes along the transect at the cofferdam downstream from the Earhart Bridge (fig. 21). As observed during the second survey, flow continued to expand throughout most of the downstream part of the reach. Velocities near the bridges were 5 to 10 ft/s faster in the third survey compared to the baseline; downstream from the railroad bridge turntable pier, the velocity reached a local maximum of more than 12 ft/s (fig. 21).

Survey on October 27, 2010

The fourth survey was on October 27, 2010, to capture the condition of the channel after the flooding in June 2010. The average water-surface elevation of the river in the survey area was 779.5 ft, and flow on the Missouri River was about 70,900 ft^3/s during the survey (table 1). Flow was about 25 percent greater than the baseline survey on June 30, 2009, and had been greater than the median statistic for most of 2010 (fig. 7). The channel-bed elevations for the fourth survey ranged from about 732 to 768 ft for most of the surveyed area, except near pier 10 (fig. 22; table 5). The size and shape of

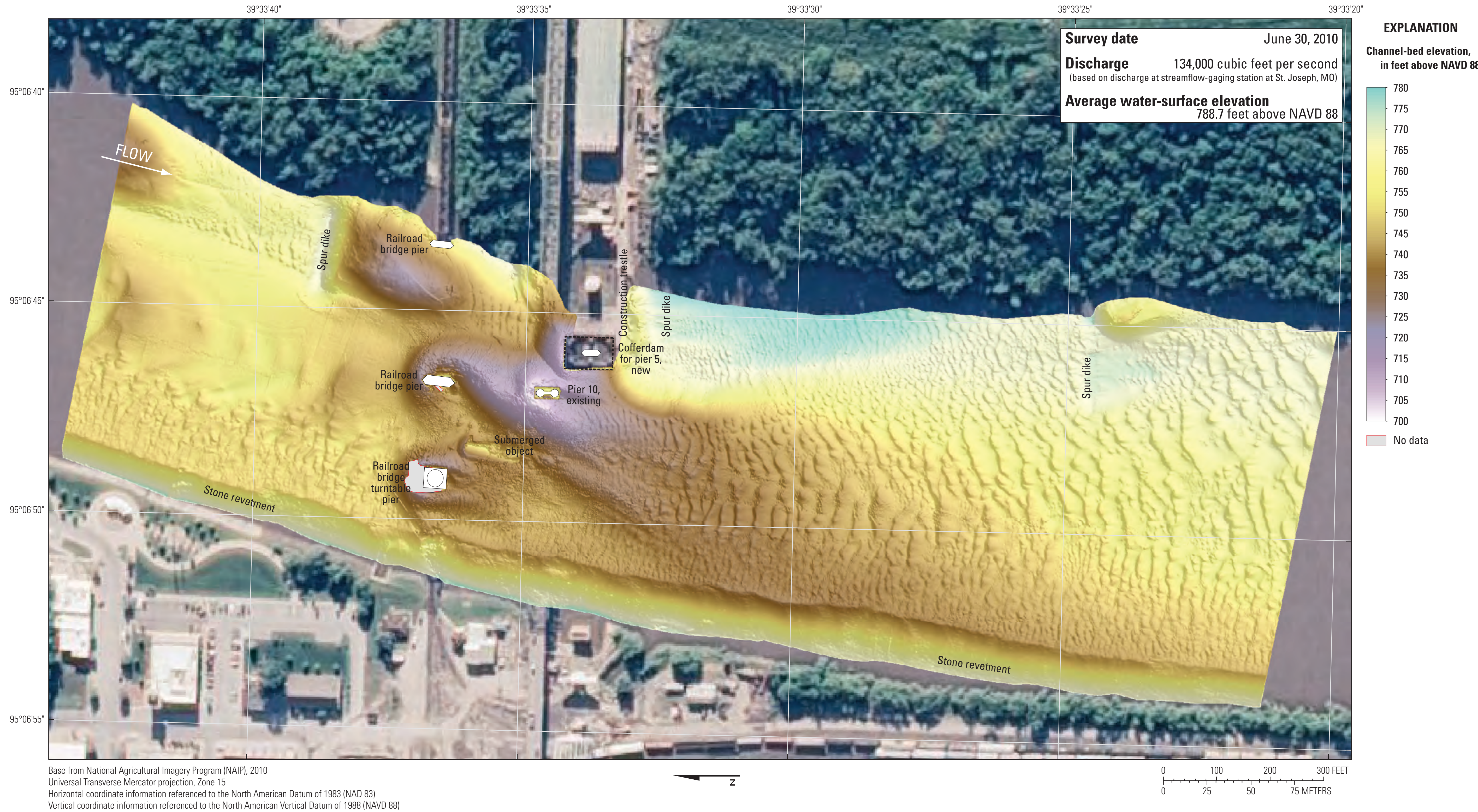


Figure 18. Bathymetric survey of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, during flooding on June 30, 2010.

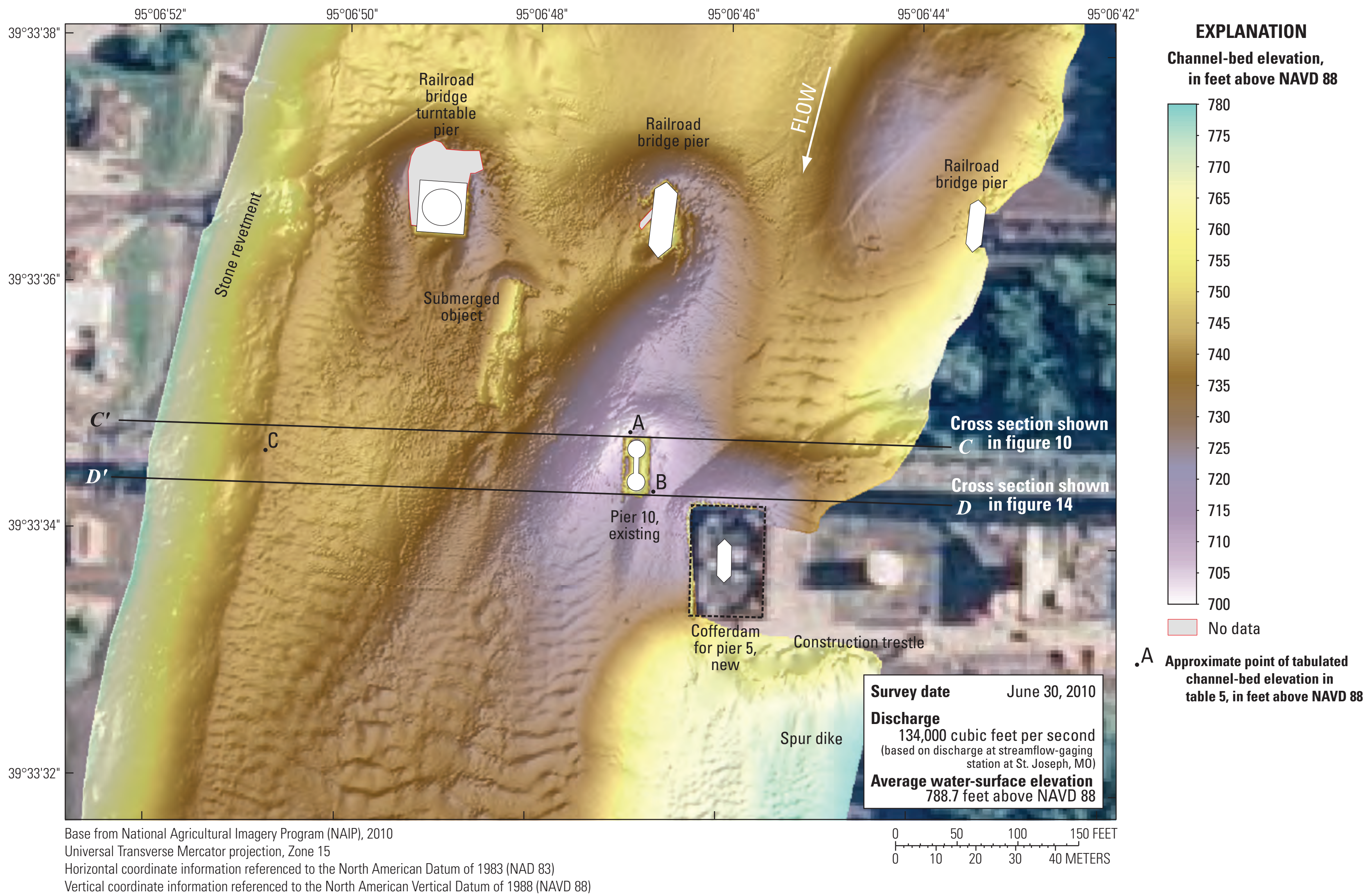
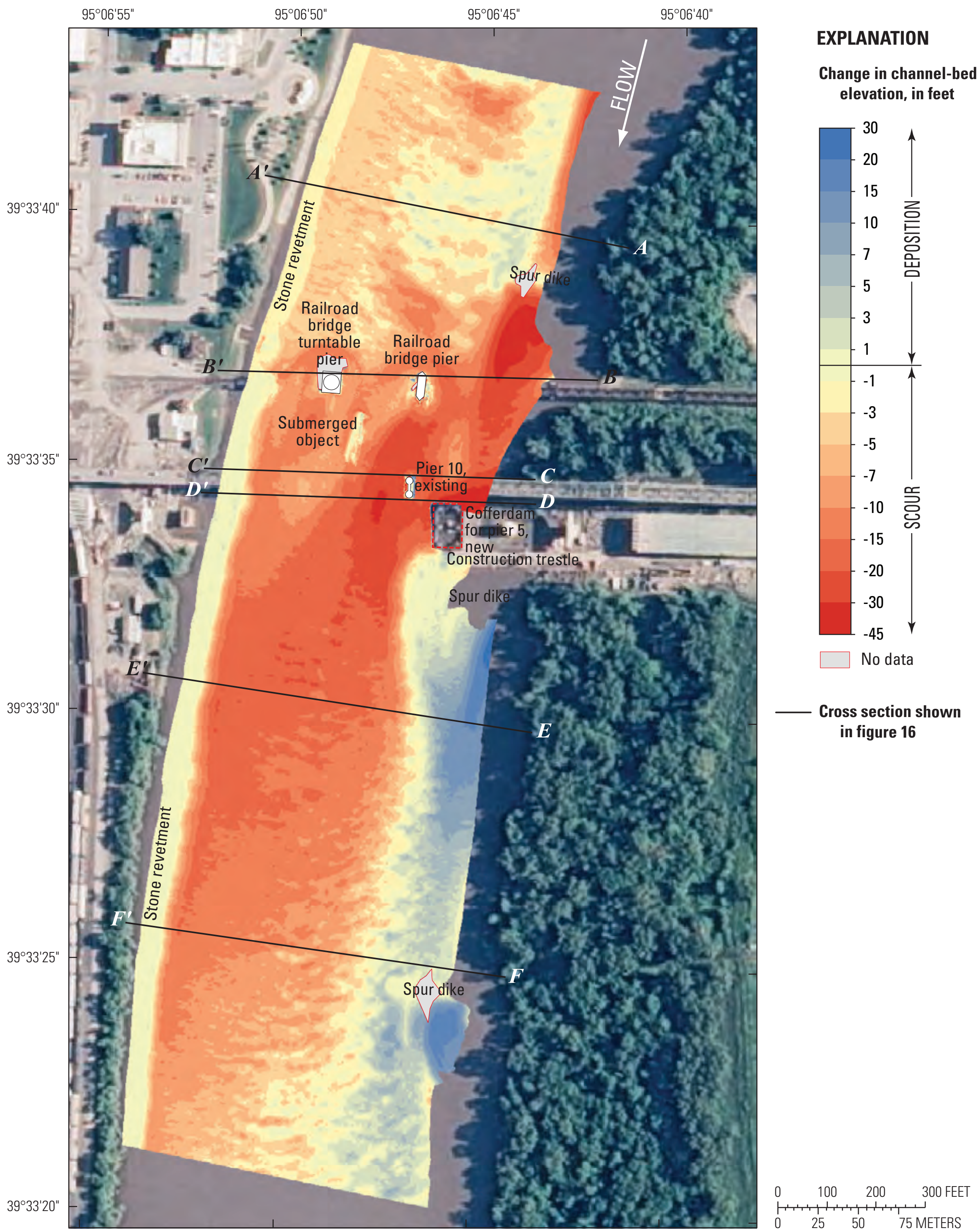


Figure 19. Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, during flooding on June 30, 2010.



Base from National Agricultural Imagery Program (NAIP), 2010
Universal Transverse Mercator projection, Zone 15
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 20. Difference between surfaces created from bathymetric surveys of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, and during flooding on June 30, 2010.

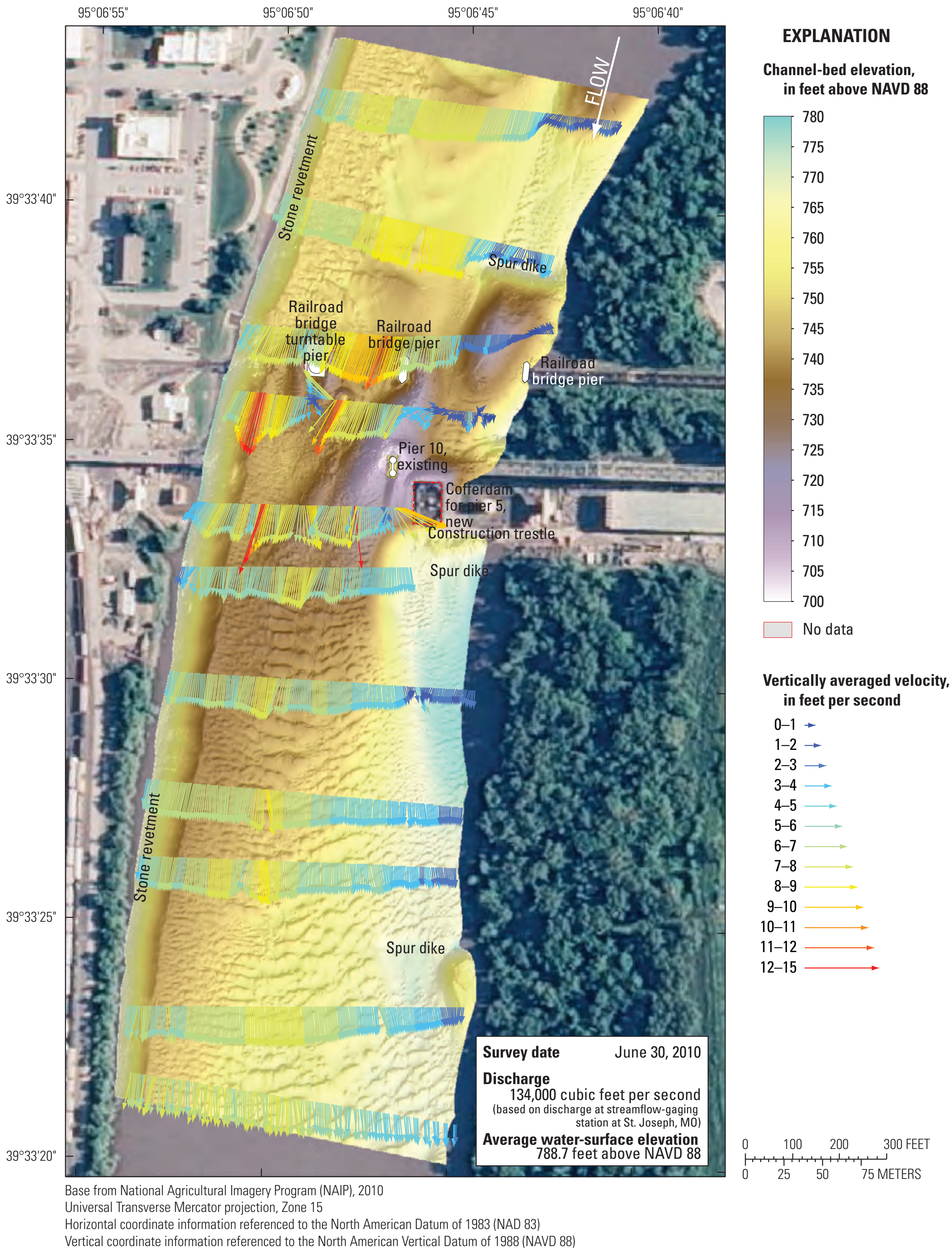


Figure 21. Bathymetry and vertically averaged velocities of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, during flooding on June 30, 2010.

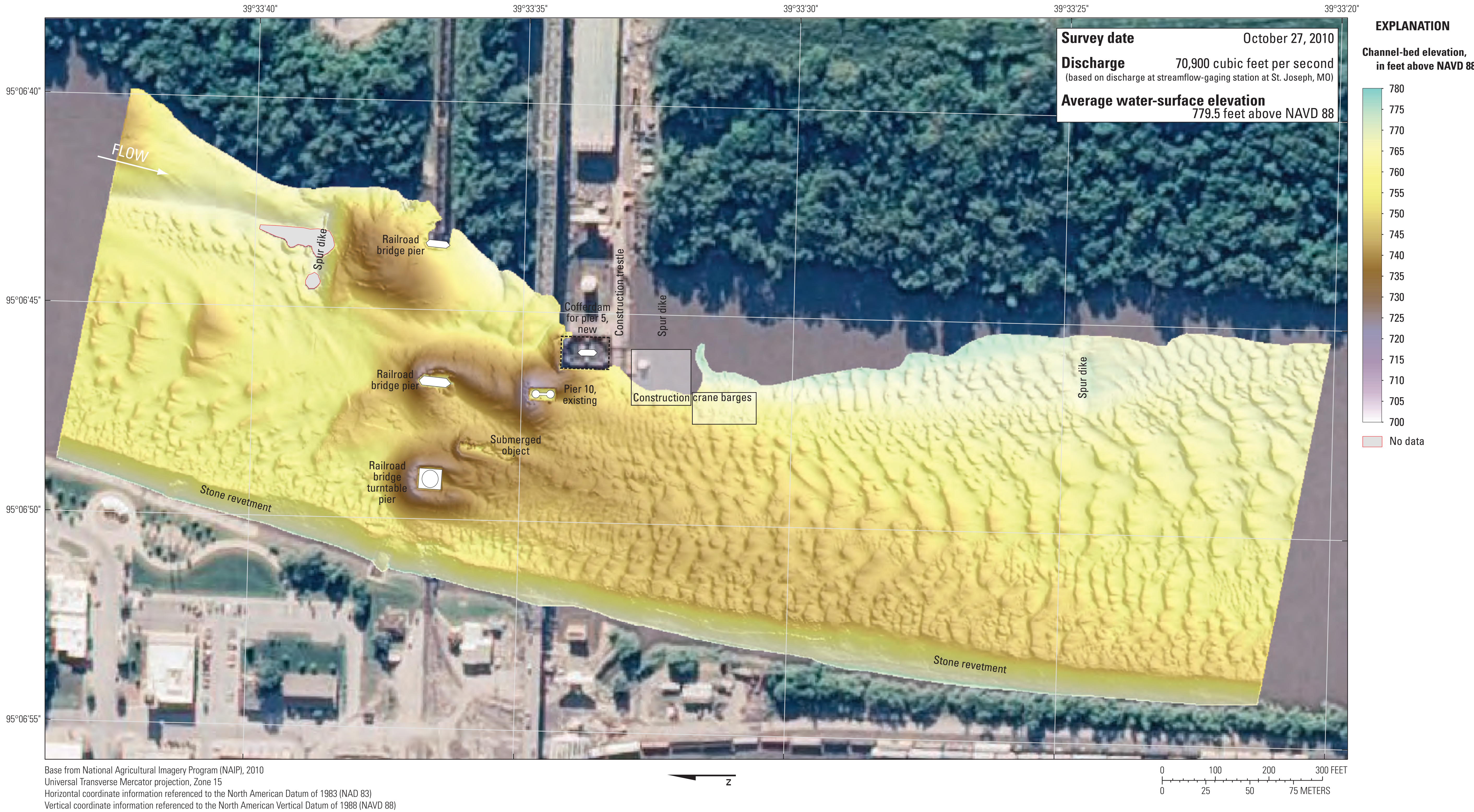


Figure 22. Bathymetric survey of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on October 27, 2010, after recession of summer flooding.

dunes and ripples in the channel were similar to those from the second survey on June 2, 2010 (figs. 12, 22). The elevations of the left bank downstream from the trestle and cofferdam appeared to be similar to previous two surveys, on the June 2 and 30, 2010. A construction crane and support barges were present downstream from the trestle and cofferdam, and the shallow area on the left bank was as extensive as was observed during the third survey on June 30, 2010, which prevented the acquisition of data in this area during the fourth survey.

In the vicinity of main channel pier 10, the scour hole had a minimum channel-bed elevation of approximately 717.6 ft (table 5), which is about 4 ft lower than the first and second surveys on June 30, 2009, and June 2, 2010, and about 14 ft higher than the third survey on June 30, 2010 (table 5). The bottom of the scour hole was about 25 ft below the average channel bed to the right of the pier (figs. 22, 23), with about 17 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of pier 10 (fig. 10). As in all previous surveys, this scour hole was substantially affected by local scour caused by the railroad bridge pier upstream (figs. 22, 23). The submerged object observed on the channel bed between the bridges during the first survey appears to remain more substantially exposed in the fourth survey (figs. 22, 23) similar to the second and third surveys.

In the fourth survey, the effects of the trestle and cofferdam remain apparent, as in the third survey. The scour holes near existing pier 10 and the cofferdam remain interconnected, but returned to nearly the same elevation as before the flood observed during the June 2, 2010, survey (figs. 10, 14). The shape of the intertwined scour holes from the railroad bridge pier, the existing pier 10, and the cofferdam remain swept to the right, as flow is deflected around the trestle and cofferdam (figs. 22, 23).

Scour deposition patterns from the fourth survey as compared to the baseline survey (fig. 24) were similar to those from the second survey (fig. 15); however, scour was more pronounced in the downstream part of the reach, and the deposition on the left bank appeared to be more substantial (fig. 24). The average value of the difference between the October 27, 2010, and 2009 bathymetric surfaces is -2.6 ft (table 6), indicating moderate scour overall between the surveyed dates, and slightly more than that observed for the second survey. The average value of the difference between the October 27 and June 30, 2010, bathymetric surfaces is +5.0 ft, indicating substantial deposition overall between the surveyed dates. Along the upstream and downstream bridge faces of the Earhart Bridge, the channel bed was similar to that observed during the survey on June, 2, 2010 (figs. 10, 14). As in the previous surveys, the appearance of substantial deposition or scour on the sides of the piers (areas of bright red or dark blue on the sides) in the difference map (fig. 24) results from minor horizontal positional variances between the surveys.

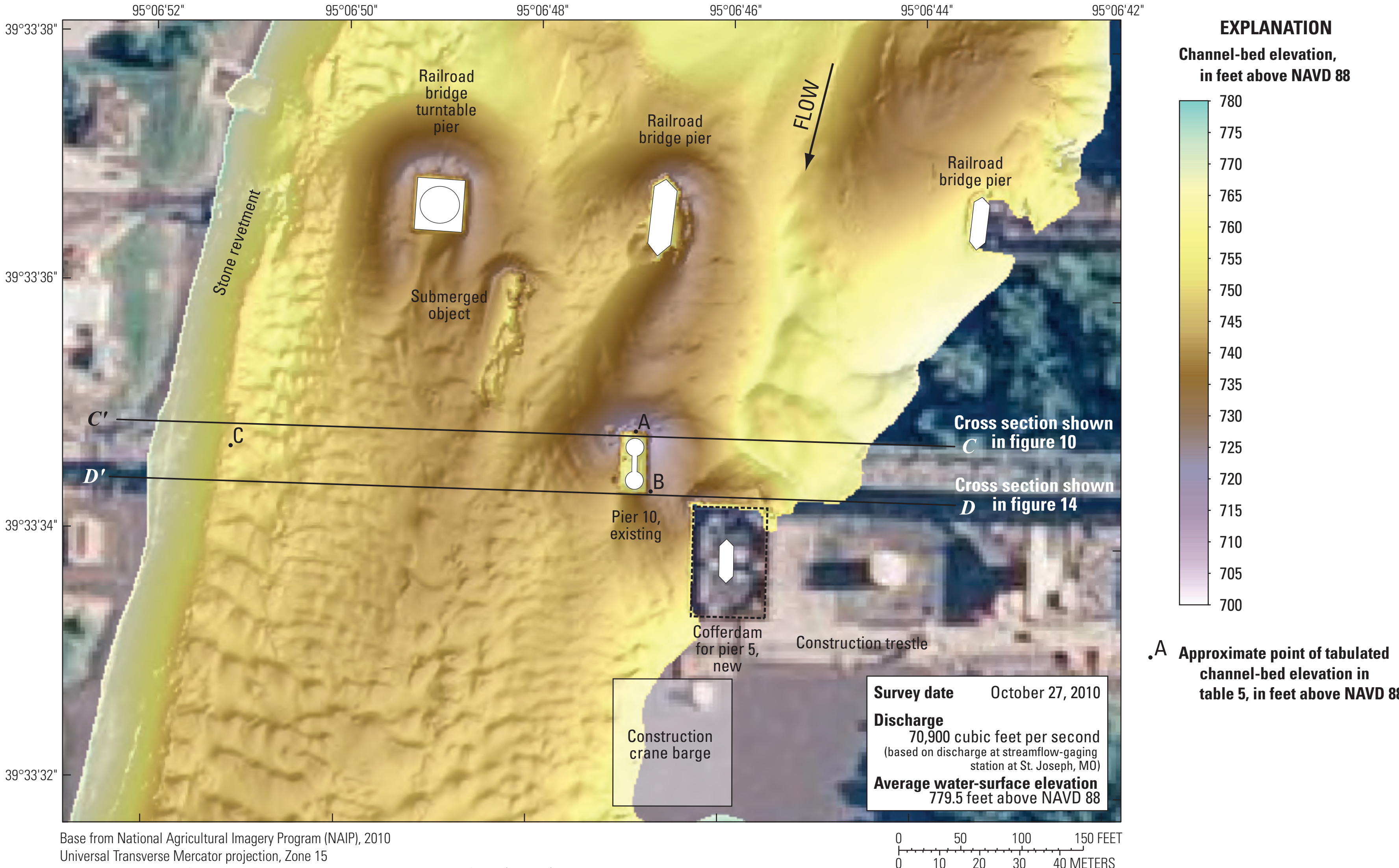
As with the first and second surveys, the vertically averaged velocity vectors indicated mostly uniform flow throughout the reach, except downstream from the various piers of the railroad bridge and the Earhart Bridge where turbulence and spatial variability in velocity magnitude were observed (fig. 25). Substantial turbulence and flow reversal also were observed downstream from the spur dike upstream from the railroad bridge (fig. 25). Most of the turbulence and spatial variability abated in the downstream part of the reach. Average velocities ranged from 5 to 9 ft/s in the middle and right sides of the channel, and from 0 and 3 ft/s along the left bank near the spur dikes (fig. 25). As with all surveys with the cofferdam in place, the vectors indicate a substantial contraction of flow from immediately upstream from the railroad bridge to the Earhart Bridge, and an abrupt expansion and localized reversal of flow along the transect at the cofferdam downstream from the Earhart Bridge (fig. 25). Additional flow contraction was evident near the construction crane barges downstream from the trestle, and flow expansion was evident throughout the downstream part of the reach (fig. 25). Velocities near the bridges were 1 to 3 ft/s faster in the fourth survey compared to the baseline, similar to those observed in the second survey (fig. 17).

Survey during 2011 Summer Flooding, July 15, 2011

The site was surveyed a fifth time on July 15, 2011, as part of a survey at each of the bridges across the Missouri River in and into Missouri during the extensive summer flooding of 2011 (Huizinga, 2012). The average water-surface elevation of the river in the survey area was 792.4 ft, and flow on the Missouri River was about 214,000 ft^3/s during the survey (table 1). The cofferdam around pier 5 of the new bridge had been removed in March 2011, although the construction trestle remained.

The survey area was limited by floating construction crane barges moored on the downstream left bank and the BNSF railroad bridge just upstream (fig. 26). The elevation of the railroad bridge did not have sufficient clearance to permit surveying under it, except where the width of the survey swath reached under the bridge as the boat passed laterally along the downstream face of the railroad bridge. The channel-bed elevations ranged from about 729 to 769 ft for most of the surveyed area, except near pier 10 (fig. 22; table 5). As in all previous surveys, the channel downstream from the bridge was covered with numerous medium and small dunes and ripples (fig. 26).

In the vicinity of main channel pier 10, the scour hole had a minimum channel-bed elevation of approximately 704.8 ft (table 5), about 34 ft below the average channel bed to either side of the pier (figs. 26, 27), with only about 4 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of pier 10 (fig. 10). As in all previous surveys, this scour hole was substantially affected by local scour caused by the railroad bridge pier upstream (figs. 26, 27). As noted in the survey during the flooding on June 30, 2010, bridge substructural elements usually are pinned or socketed to bedrock



Base from National Agricultural Imagery Program (NAIP), 2010
Universal Transverse Mercator projection, Zone 15
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 23. Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on October 27, 2010, after recession of summer flooding.

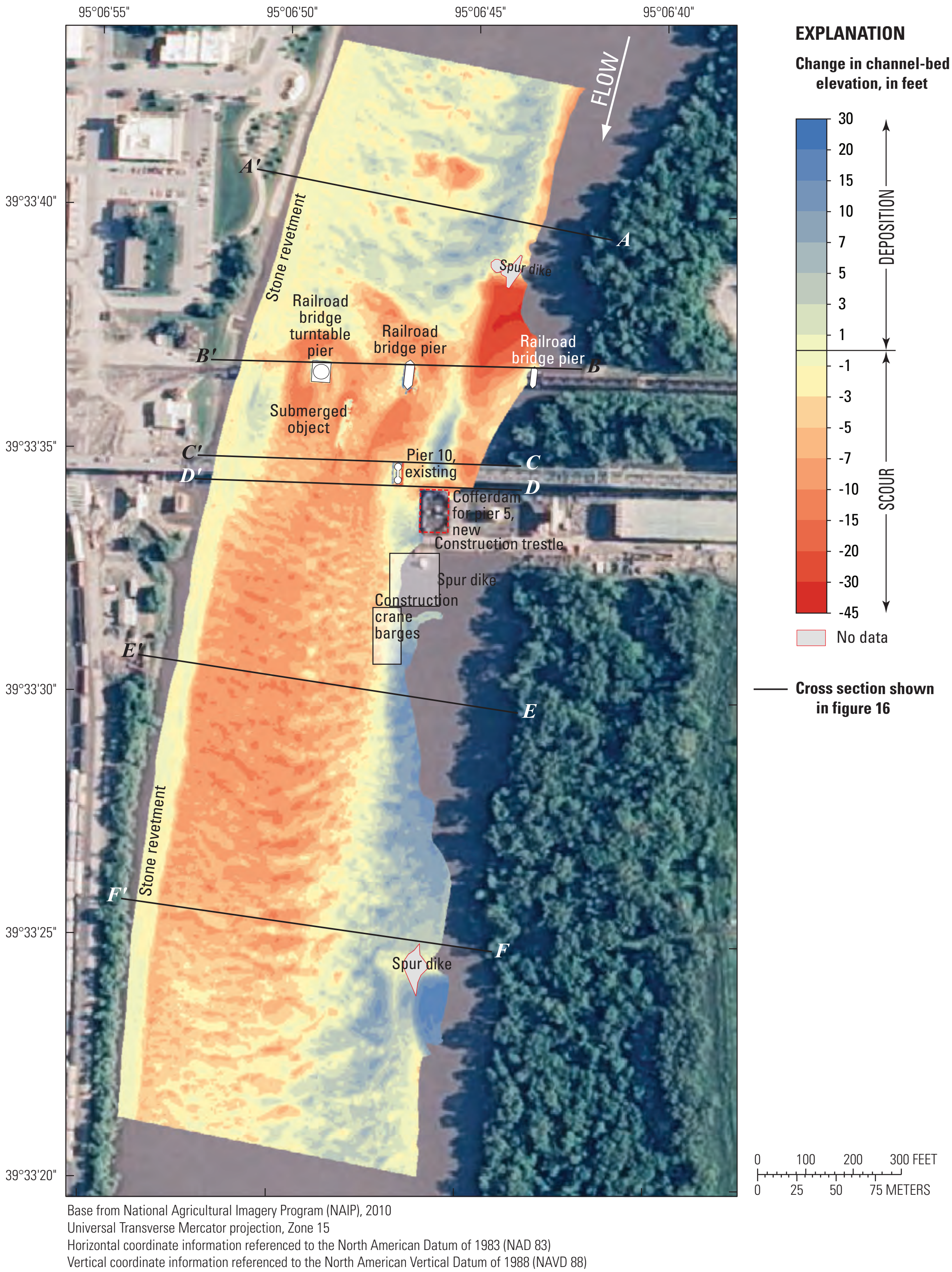
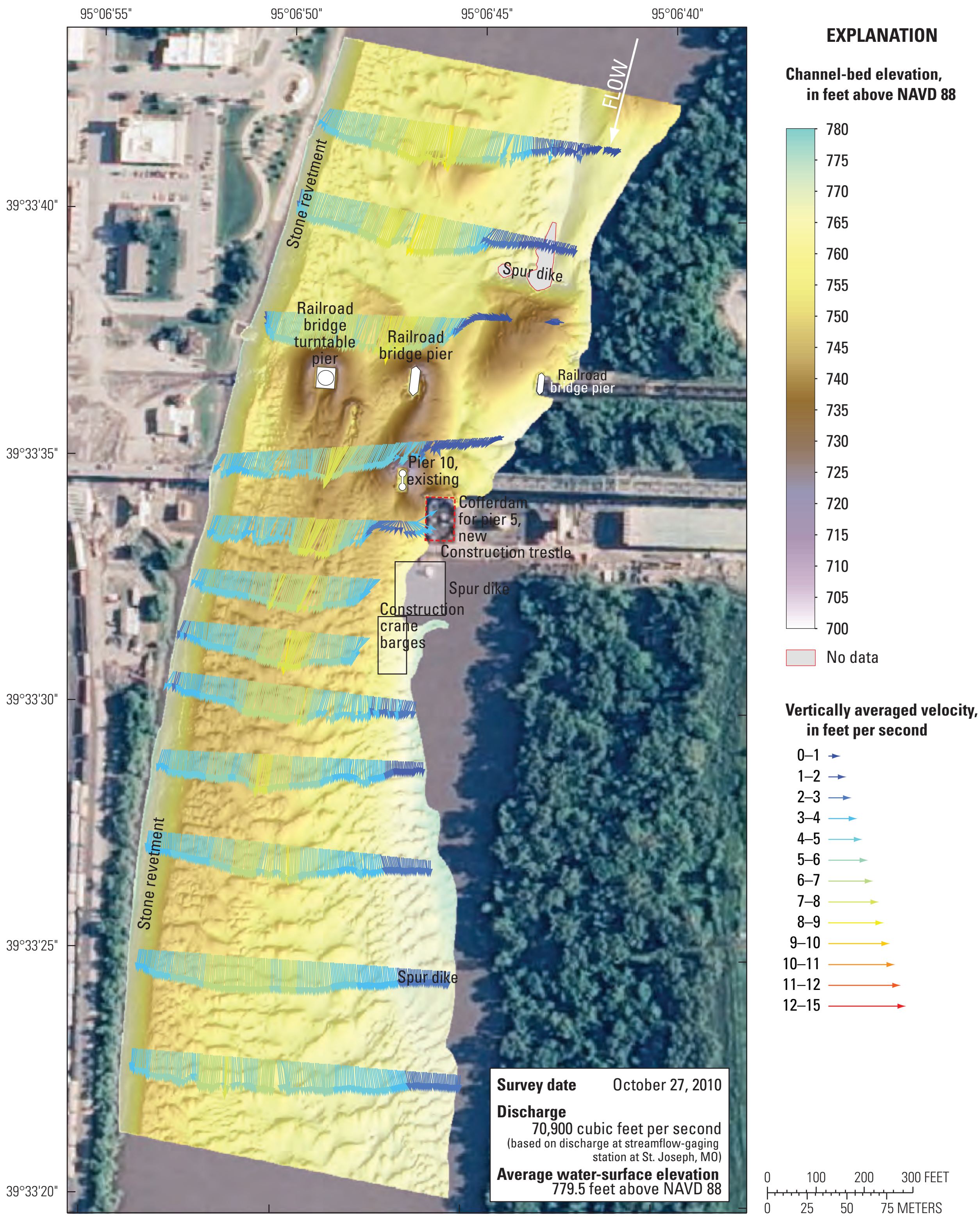


Figure 24. Difference between surfaces created from bathymetric surveys of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, and October 27, 2010, after recession of summer flooding.



Base from National Agricultural Imagery Program (NAIP), 2010
Universal Transverse Mercator projection, Zone 15
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 25. Bathymetry and vertically averaged velocities of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on October 27, 2010, after recession of summer flooding.

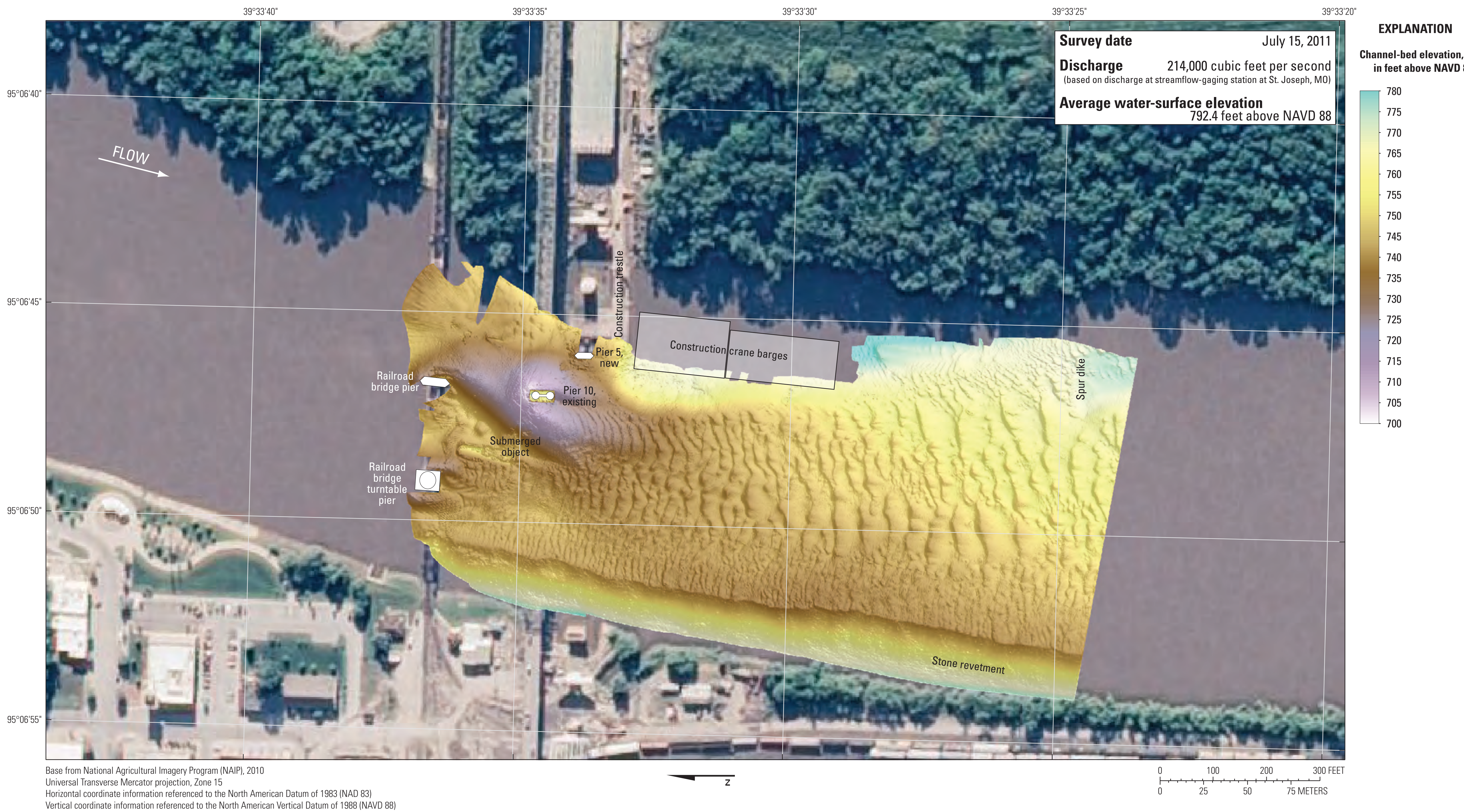


Figure 26. Bathymetric survey of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, during summer flooding on July 15, 2011, and after the removal of the cofferdam for pier 5 of the new U.S. Highway 59 bridge.

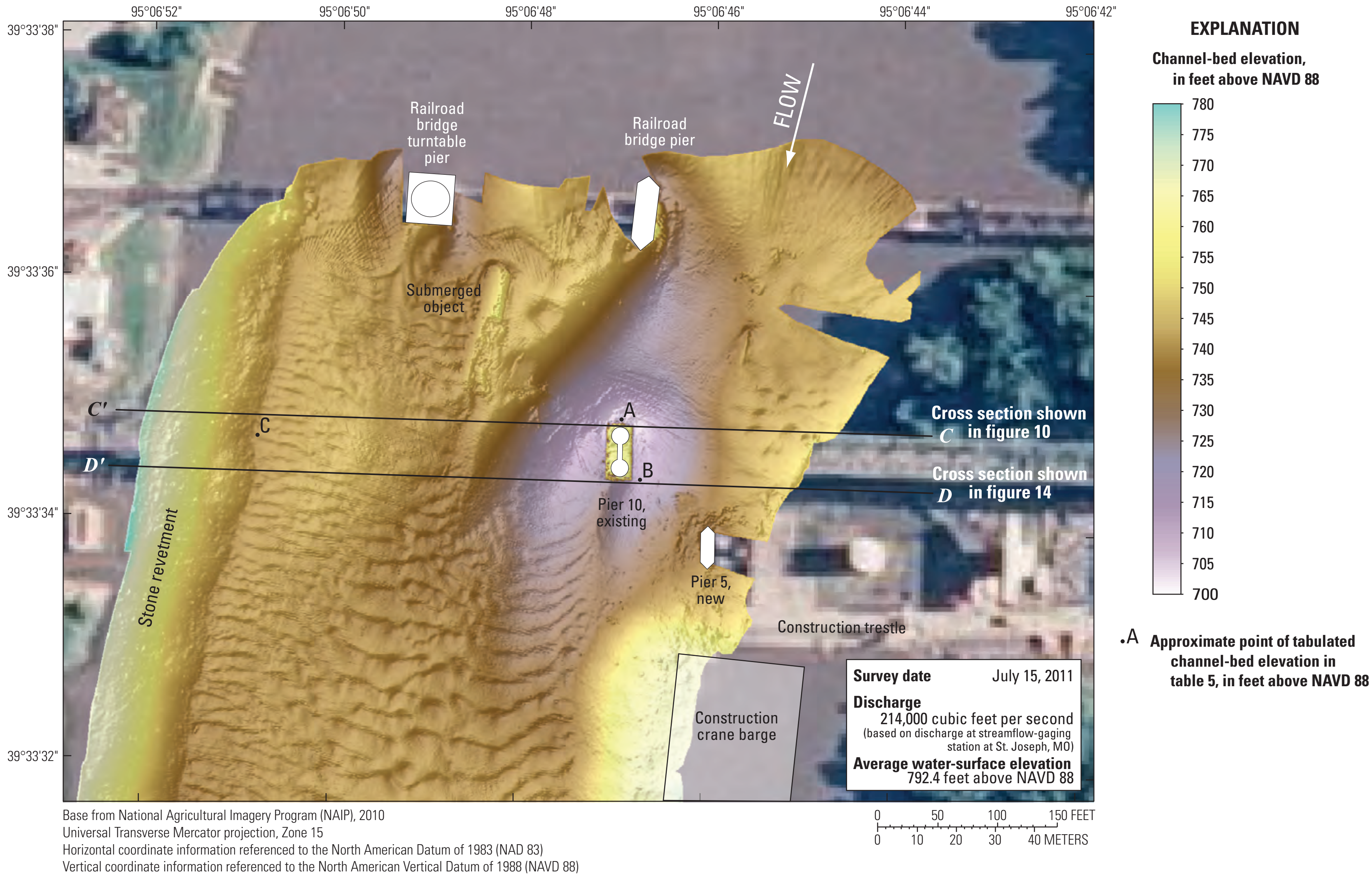


Figure 27. Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, during summer flooding on July 15, 2011, and after the removal of the cofferdam for pier 5 of the new U.S. Highway 59 bridge.

in modern construction (American Association of State Highway Transportation Officials, 2012; Brown and others, 2010), but full exposure of usually buried substructural elements warrants special consideration and observation, particularly at an older bridge such as the Earhart Bridge.

The difference between the fifth survey on July 15, 2011, and the baseline survey on June 30, 2009, before construction of the new US 59 Bridge began (fig. 28), indicates substantial scour of as much as 30 ft throughout the channel, with deposition of as much as 20 ft on the left bank. The average value of difference between the 2011 and 2009 bathymetric surfaces (using only the area that is common to both surveys) is -8.8 ft (table 6), indicating substantial scour overall, as might be expected given the water-surface elevation difference of 15 ft and flow difference of 157,400 ft^3/s (table 1). This difference is of greater magnitude than that observed between the third survey and the baseline of -7.0 ft (table 6); however, this is an artifact of the smaller survey area in the fifth survey being biased towards scour, based on the downstream part of the reach having experienced more scour than deposition in the previous surveys. The difference between the surveys during flooding on July 15, 2011, and June 30, 2010 (fig. 29), indicates a similar channel configuration between the two surveys, with deposition as much as 7 ft throughout the channel and minor local scour of as much as 5 ft. The average value of difference between the 2011 and 2010 bathymetric surfaces is +1.4 ft (table 6), indicating overall less scour in 2011 than in 2010. The area around pier 5 of the new US 59 Bridge had substantially less scour in the July 15, 2011 survey compared to the June 30, 2010 survey (fig. 29), likely as a result of the removal of the cofferdam. The removal of this constriction also may account for the overall deposition observed between 2010 and 2011, despite a water-surface elevation difference of nearly 4 ft and a flow difference of 80,000 ft^3/s (table 1). In both of the difference maps (figs. 28, 29), the appearance of substantial deposition or scour on the sides of the piers and cofferdam (areas of bright red or dark blue on the sides) results from minor horizontal positional variances between the surveys.

Along the upstream and downstream faces of the existing Earhart Bridge, the surveyed bed from 2011 was consistently 10 to 25 ft lower than the surveyed bed from 2009 before construction of the new US 59 Bridge began (figs. 10, 14, 16); however, the surveyed bed from 2011 varied from about 3 ft lower to about 7 ft higher than the surveyed bed from the June 30, 2010, survey near the 2010 flood peak (figs. 10, 14, 16) for much of the section, despite the fact that the 2011 flood had a higher flow rate and water-surface elevation than 2010 (table 1). As stated earlier in this section, this difference likely is the result of the removal of the cofferdam. Furthermore, the deposition of nearly 25 ft of material on the left side of the cross-section near pier 5 of the new bridge (section *D-D*', fig. 16) between June 30, 2010, and July 15, 2011, directly is a result of the removal of the cofferdam and the subsequent reduction in the size of the scour hole near the new pier (fig. 27).

The vertically averaged velocity vectors indicated that the removal of the cofferdam also removed part of the flow constriction observed near the bridges in previous surveys (fig. 30). Moderate turbulence was observed in the vicinity of the railroad and US 59 bridges. Downstream from the railroad bridge turntable pier, the velocity reached a local maximum of nearly 12 ft/s, but also dropped to about 5 ft/s about 20 ft to the right, downstream from the railroad bridge turntable pier (fig. 30). Most of the turbulence and local high velocity values abated in the downstream part of the reach, with average velocities between 6 and 9 ft/s in the channel and between 3 and 5 ft/s along the left bank. There also was moderate turbulence downstream from pier 10 of the existing bridge and pier 5 of the new bridge (fig. 30). As in previous surveys, flow expansion was observed in the downstream part of the reach (fig. 30). Velocities near the bridges were 2 to 3 ft/s faster in the fifth survey compared to the baseline, but were slower than in the third survey during flooding the previous summer (fig. 25).

Survey near end of construction, April 24, 2013

The site was surveyed a sixth and final time on April 24, 2013. The average water-surface elevation of the river in the survey area was 772.5 ft, and flow on the Missouri River was about 36,500 ft^3/s during the survey (table 1). The construction trestle was still present during this survey. The channel-bed elevations for the final survey ranged from about 749 to 764 ft for most of the surveyed area (table 5), except near the railroad piers and pier 10 of the Earhart Bridge (fig. 31). The size and shape of dunes and ripples in the channel were smaller, but similar to those from the baseline survey. The elevations of the left bank downstream from the trestle appeared to have lowered to an elevation similar to the baseline survey. A barge was present downstream from the trestle, as in the previous three surveys.

In the vicinity of main channel pier 10, the scour hole had a minimum channel-bed elevation of approximately 738.9 ft (table 5), which is about 17 ft higher than the first survey on June 30, 2009, and about 34 ft higher than the previous survey on July 15, 2011 (table 5). The bottom of the scour hole was about 18 ft below the average channel bed upstream and to the right of the pier (figs. 31, 32), with about 38 ft of bed material between the bottom of the scour hole and bedrock at the upstream face of pier 10 (fig. 10). Unlike all previous surveys, this scour hole was not substantially affected by local scour caused by the railroad bridge pier upstream (figs. 31, 32). The submerged object observed on the channel bed between the bridges during all the previous surveys was almost completely covered in bed material in the final survey, with only a small part evident in the bed dunes (figs. 31, 32).

The difference between the final survey on April 24, 2013, and the baseline survey on June 30, 2009, before construction of the new US 59 Bridge began (fig. 33), indicates substantial deposition throughout the channel, with

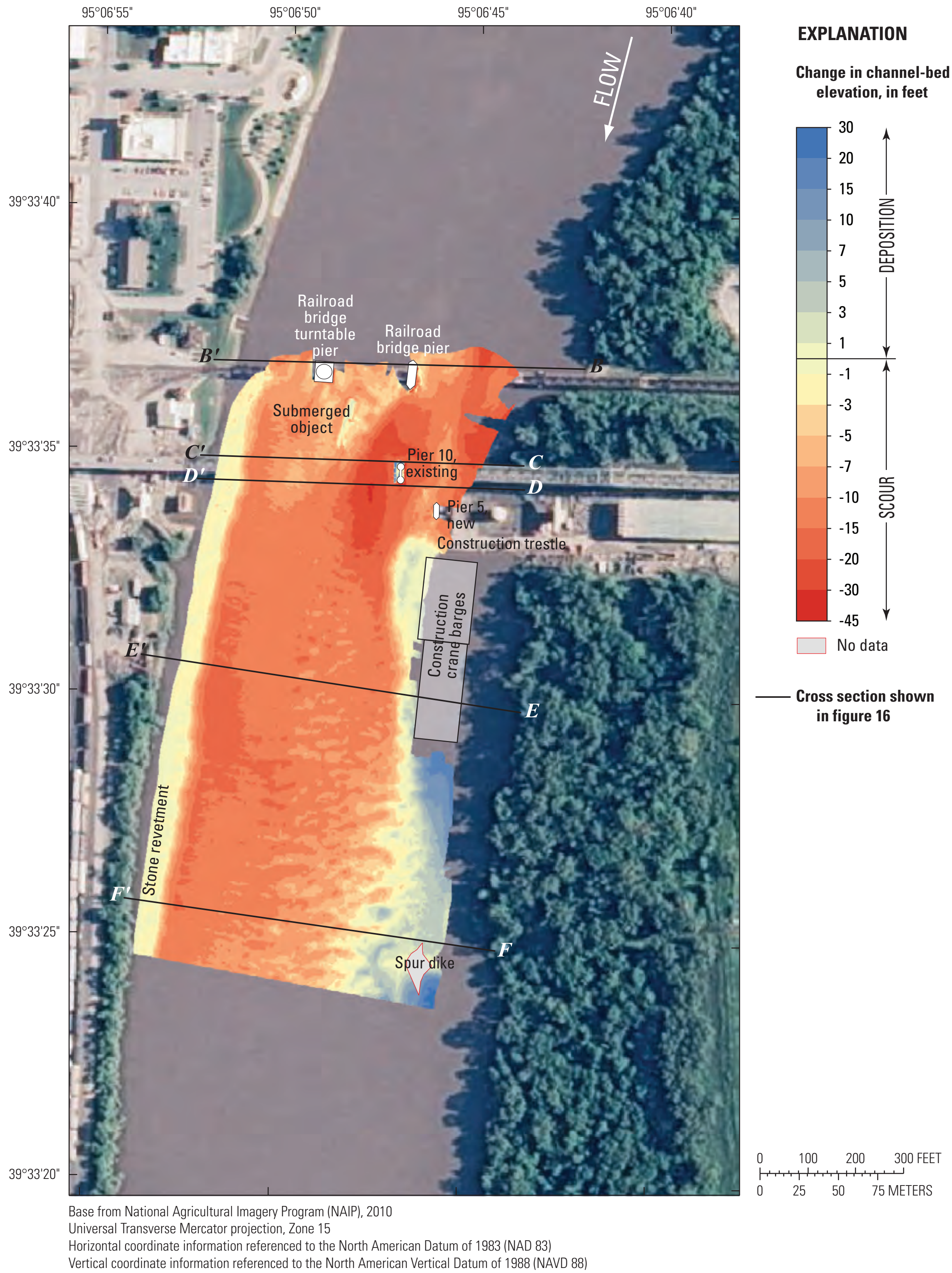


Figure 28. Difference between surfaces created from bathymetric surveys of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, and during summer flooding on July 15, 2011, after the removal of the cofferdam for pier 5 of the new U.S. Highway 59 bridge.

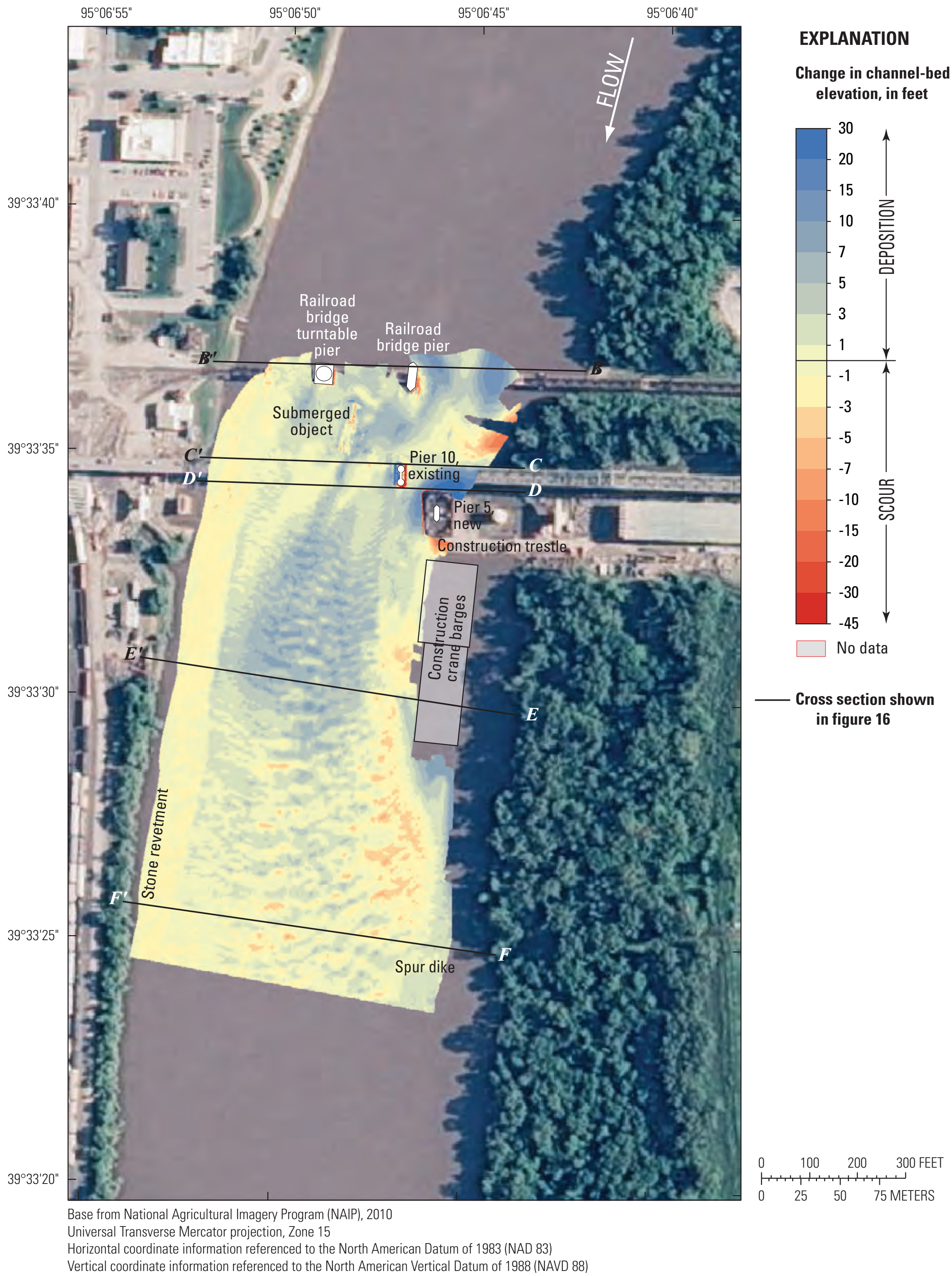
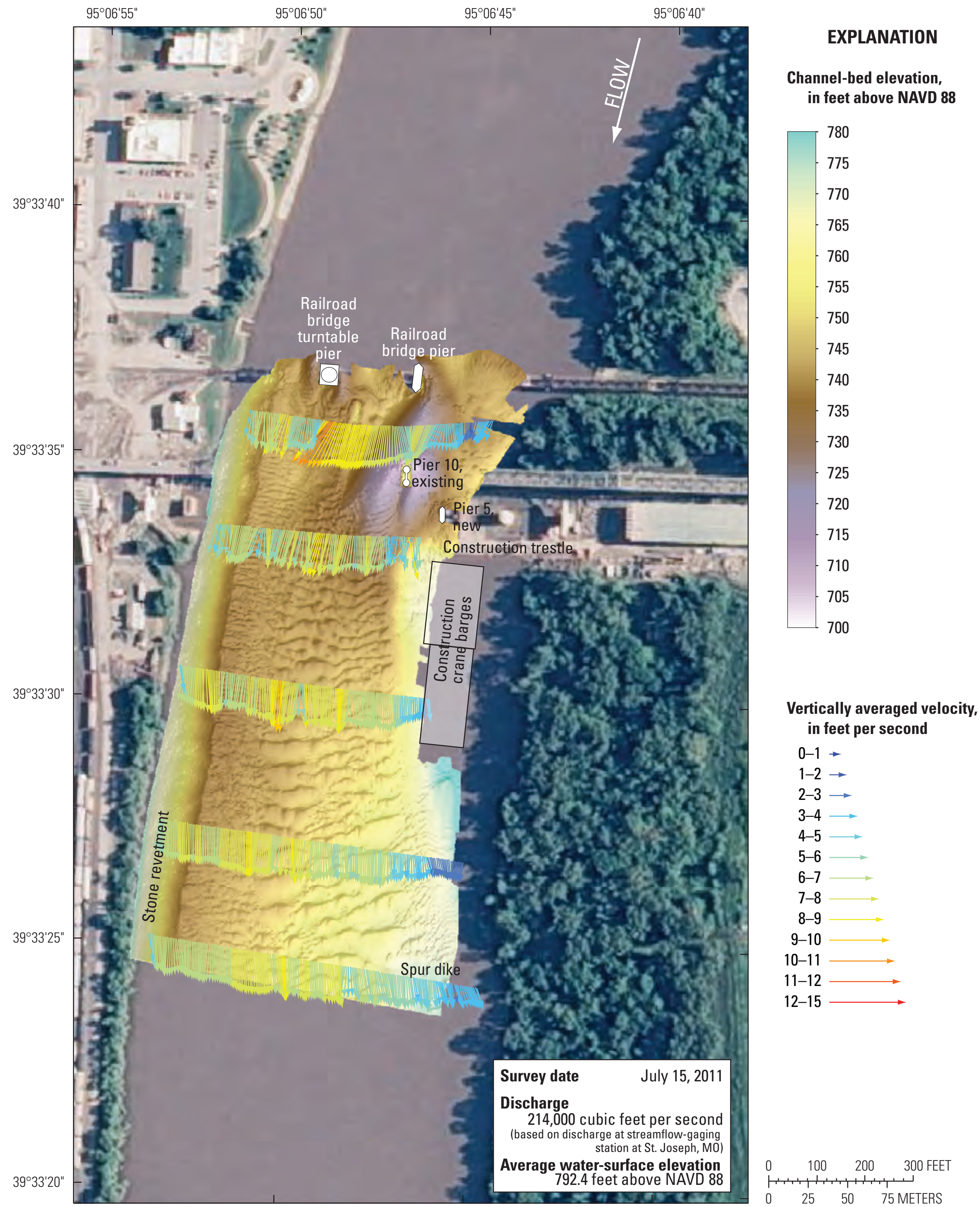
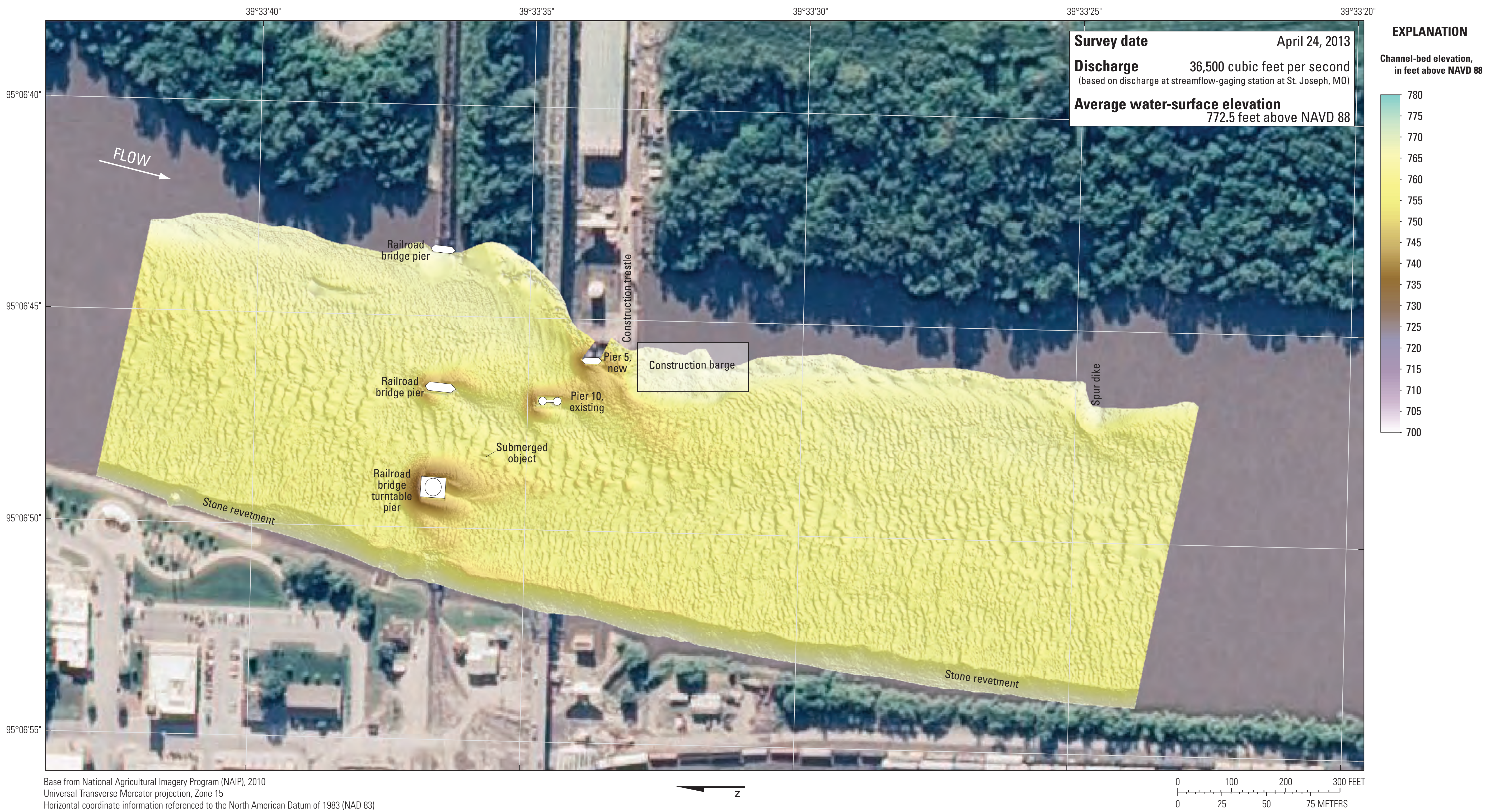


Figure 29. Difference between surfaces created from bathymetric surveys of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, during summer flooding on June 30, 2010, and July 15, 2011.



Base from National Agricultural Imagery Program (NAIP), 2010
Universal Transverse Mercator projection, Zone 15
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 30. Bathymetry and vertically averaged velocities of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, during summer flooding on July 15, 2011, and after the removal of the cofferdam for pier 5 of the new U.S. Highway 59 bridge.



Base from National Agricultural Imagery Program (NAIP), 2010
Universal Transverse Mercator projection, Zone 15
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 31. Bathymetric survey of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on April 24, 2013, near the end of construction of the new U.S. Highway 59 bridge.

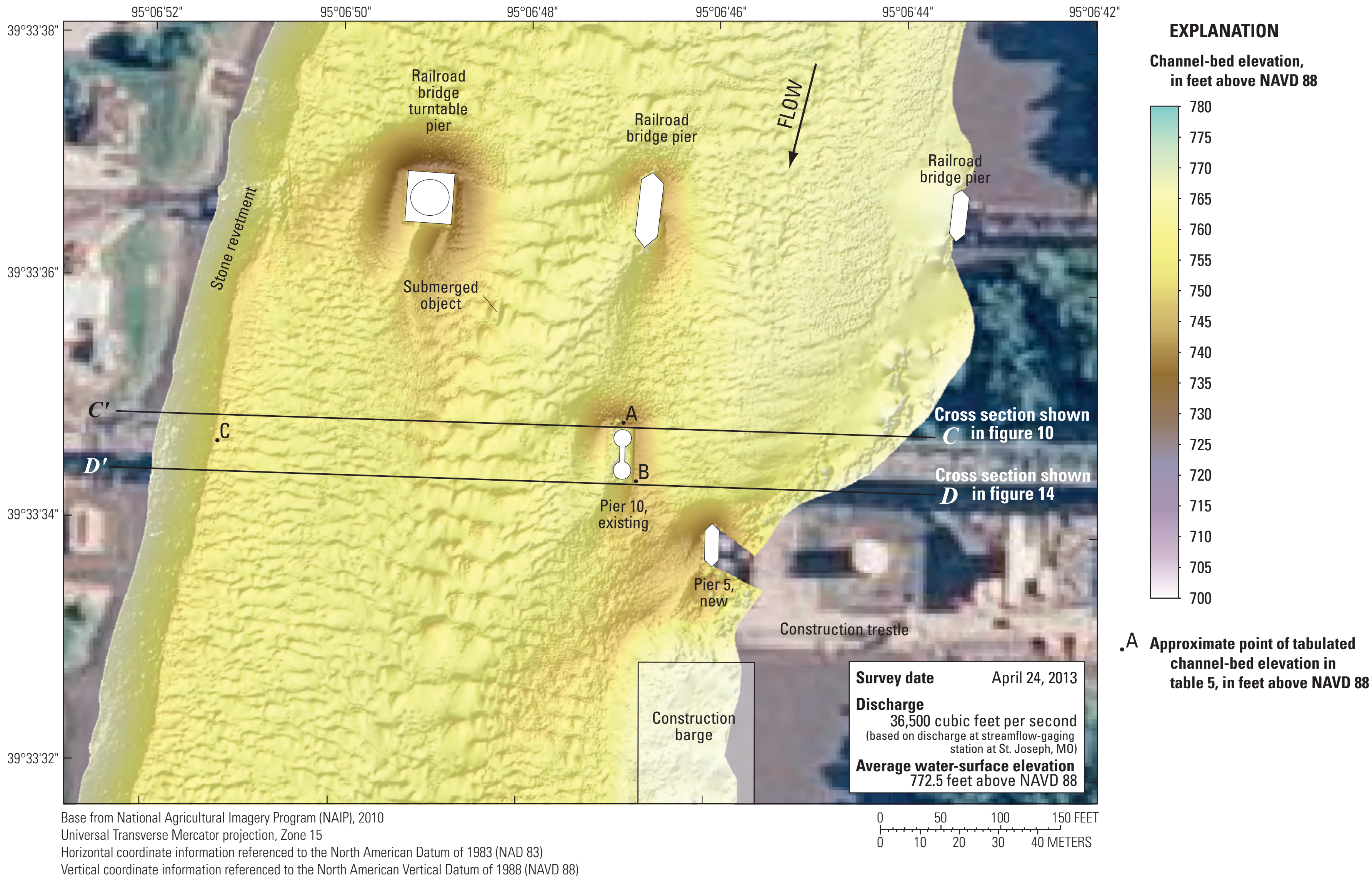


Figure 32. Bathymetric survey of the Missouri River channel near the piers of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on April 24, 2013, near the end of construction of the new U.S. Highway 59 bridge.

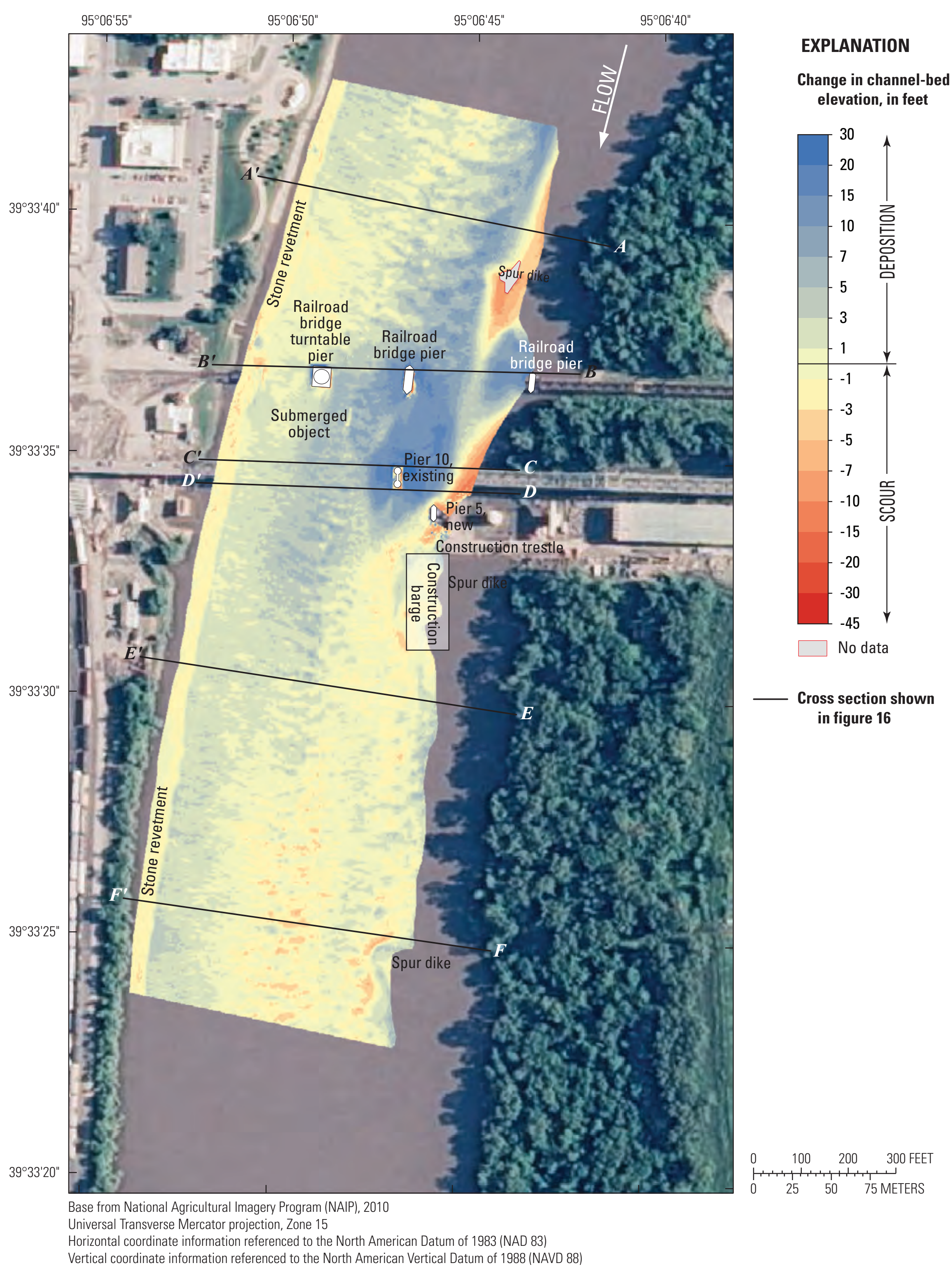


Figure 33. Difference between surfaces created from bathymetric surveys of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on June 30, 2009, and April 24, 2013, near the end of construction of the new U.S. Highway 59 bridge.

as much as 30 ft of deposition near pier 10 of the Earhart Bridge. Moderate scour of as much as 10 ft was observed near the spur dike upstream from the railroad bridge and along the left bank near pier 5 of the new bridge. The average value of the difference between the 2013 and 2009 bathymetric surfaces is 1.7 ft (table 6), indicating minor to moderate deposition overall between the surveyed dates. The lower flow rate and water-surface elevation of this final survey likely contribute to the overall deposition between 2009 and 2013 (table 1), combined with sediment deposition that may have resulted from the overall lower flows during 2012 into early 2013 (fig. 7). As in all previous surveys, the appearance of substantial deposition or scour on the sides of the piers (areas of bright red or dark blue on the sides) results from minor horizontal positional variances between the surveys.

In the final survey, the constricting effects of the trestle were diminished compared to most of the previous surveys, documenting results similar to those caused by the spur dike alone in the first survey. The scour hole near existing pier 10 and new pier 5 remain interconnected, but the scour holes near the railroad bridge pier and existing pier 10 were not interconnected. The shape of the scour holes from the railroad bridge, the existing pier 10, and the new pier 5 remain swept to the right, as flow is deflected around the trestle and barge (figs. 31, 32), but the depth and size of the scour holes is much smaller than in all previous surveys.

The vertically averaged velocity vectors indicated mild to moderate turbulence in the vicinity of the piers of the railroad bridge and the Earhart Bridge (fig. 34), but nearly all of the turbulence and local high velocity values abated in the downstream part of the reach. Average velocities ranged between 3 and 5 ft/s in the channel and between 1 and 2 ft/s along the left bank, which are about 1 ft/s less than the baseline survey. As in previous surveys, flow contraction was evident near the barge and spur dike downstream from the trestle, with flow expansion evident in the next two transects downstream (fig. 34).

General Findings and Implications

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

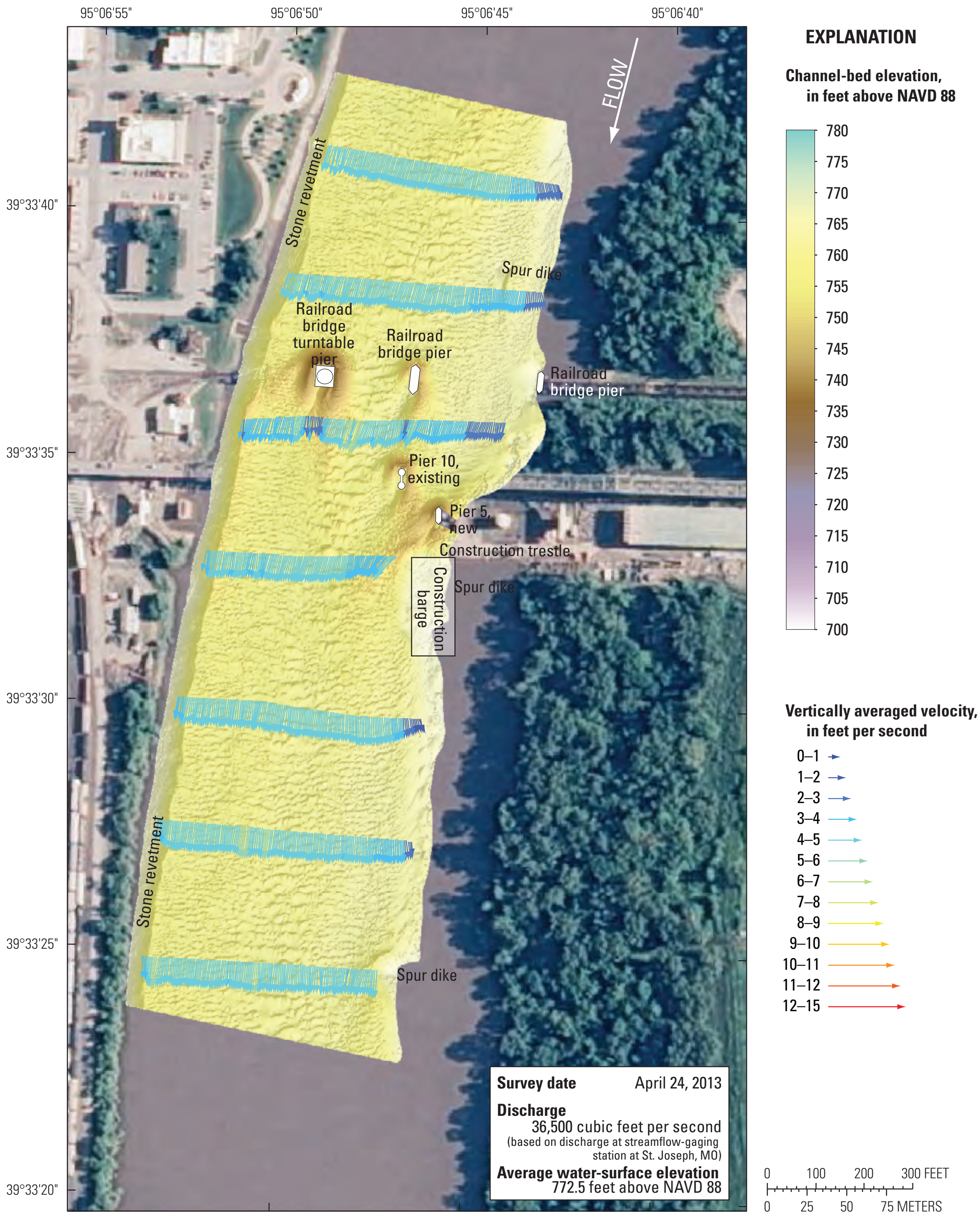
Effects of Moderate to High Flooding

As mentioned in the Introduction, scour processes continually are at work, and contraction and local scour generally are cyclic, resulting in a decrease and subsequent increase of the channel-bed elevation during the passage of a flood. Scour processes often are exacerbated during high-flow conditions. During the life of the study, two flood events were surveyed on June 30, 2010, and July 15, 2011. The similarities and differences of the scour resulting from these events, as well as the differences from the other surveys are discussed below.

Flood durations on the Missouri generally are measured in weeks and months because of the large upstream contributing drainage area. However, Huizinga (2012) noted the duration of the summer 2011 flood was made longer than usual—and the discharge at a given bridge was made nearly constant—by the releases from the upstream reservoir system, as compared with a rainfall-derived flood event on a nonregulated stream. Therefore, it might be reasonable to assume that the cyclic scour processes typically observed were circumvented somewhat to create a scour scenario that persisted at the site during most of the prolonged peak flow conditions observed in 2011. Data from a real-time scour monitor on the downstream main channel pier of the U.S. Highway 54 bridge over the Missouri River at Jefferson City, Missouri, well downstream from Atchison, Kansas, indicated the scour hole resulting from the summer 2011 flooding persisted into October through the recession limb of the hydrograph [fig. 35; see Huizinga (2012) for a description of the monitor]. Subsequent floods at Jefferson City, Missouri, in 2012 were of shorter but more-typical duration, and resulted in scour holes that filled in much more quickly than in 2011 (fig. 35). Repeat bathymetric surveys at the Missouri River bridge at Rulo, Nebraska, and other bridges upstream from Atchison, Kansas, by the USGS Nebraska Water Science Center during the summer 2011 flooding also indicated scour holes near the piers were persistent and did not refill with sediment during the duration of the flooding from July into August (Benjamin Dietsch and Brenda Densmore, U.S. Geological Survey, written commun., 2013). A reasonable assumption is that a similar, persistent scour scenario was developed at the Earhart bridge, and was observed during the July 15, 2011, survey.

The summer 2011 flood also was of greater magnitude than flow conditions during previous surveys, and it might be reasonable to assume the overall scour observed in a survey from the 2011 flood should be of a greater magnitude than that observed during the previous survey. However, comparison of the various bathymetric surfaces in this study indicates that velocity plays a substantial role as well. The velocities in the channel near the Earhart Bridge during the June 30, 2010, survey were greater than those during the July 15, 2011, survey (figs. 21, 30) because of the removal of the cofferdam, and widespread flooding of the floodplain in 2011 that did not happen in 2010 (Holmes and others, 2013).

The multiple surveys at the Earhart Bridge document these effects of moderate- to high-flow conditions on scour, compounded by the effect of adding and removing a constriction in the channel. The first, second, and last surveys at this site were during low- to moderate-flow conditions, whereas the fourth survey was during moderate to high-flow conditions and the third and fifth surveys were both during high-flow conditions [30- and 4-percent annual exceedance probability (3.3- and 25-year recurrence interval) floods, respectively; U.S. Army Corps of Engineers, 2004b] . During the third survey on June 30, 2010, the cofferdam for the construction of the



Base from National Agricultural Imagery Program (NAIP), 2010
Universal Transverse Mercator projection, Zone 15
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 34. Bathymetry and vertically averaged velocities of the Missouri River channel in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59 at Atchison, Kansas, on April 24, 2013, near the end of construction of the new U.S. Highway 59 bridge.

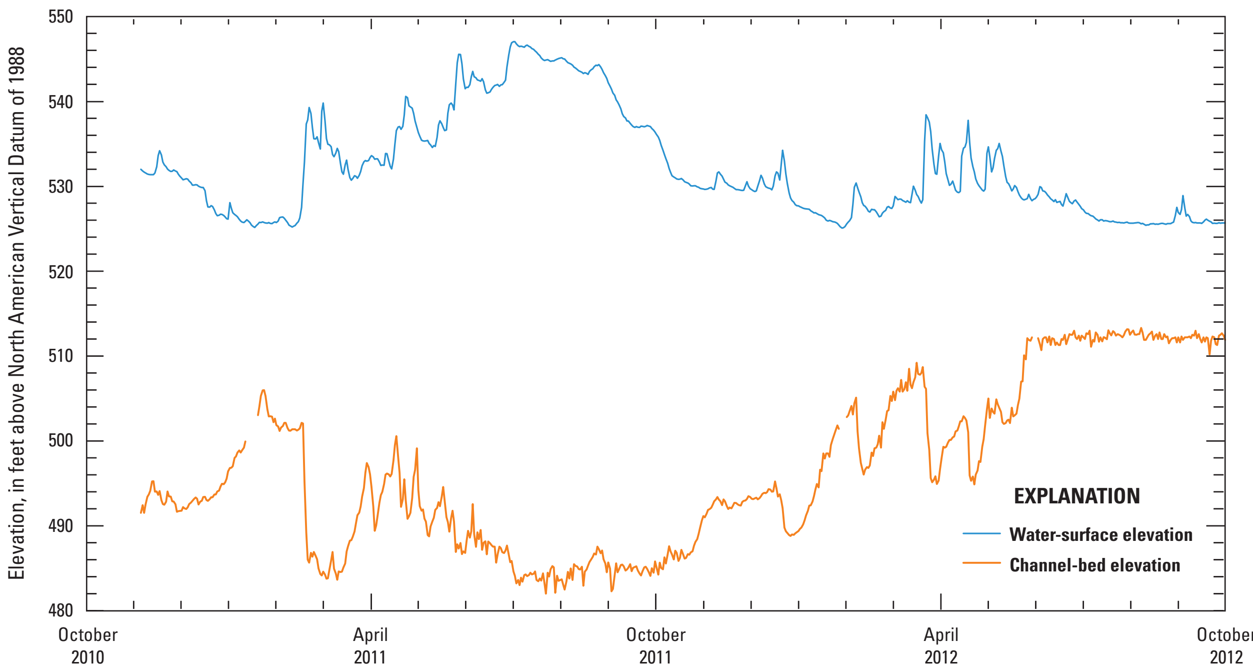


Figure 35. Water-surface and channel-bed elevations at the real-time scour monitor on the upstream nose of the downstream main channel pier of U.S. Highway 54 crossing the Missouri River at Jefferson City, Missouri, for the period November 1, 2010, to September 30, 2012.

new bridge pier on the left bank downstream from the existing bridge caused a substantial constriction of the channel. High-flow conditions, combined with the constriction, resulted in substantial scour of the overall channel, as well as increased local pier scour at the existing bridge pier (figs. 18–20; tables 5–6). Conversely, the fifth survey on July 15, 2011, had even higher flow conditions, but the removal of the constriction caused by the cofferdam resulted in less apparent scour throughout the channel compared with the June 30, 2010, flood (fig. 29; table 6). Although the construction trestle was still in place during the final survey on April 24, 2013, velocities throughout the study area were the lowest of all the surveys, and deposition was observed overall throughout the reach compared to the baseline—despite the presence of the trestle in the final survey (figs. 33, 34).

Additional Factors Affecting Size and Shape of Scour Holes

Pier 10 of the existing Earhart Bridge was surveyed in all six surveys, and the railroad bridge turntable pier and the pier upstream from pier 10 were surveyed in five of the six surveys; the cofferdam was surveyed in three of the six, and the new pier was surveyed in the final two surveys. The size and shape of the scour holes associated with each was different from one survey to the next. In the local pier scour equation in Richardson and Davis (2001), pier scour is a function of several factors, including the depth and velocity of approach flow, the width and nose shape of the pier, and the angle of approach flow. The depth and velocity of approach flow were discussed in general terms in the previous section entitled “Effects of Moderate to High Flooding,” but two other factors as observed in the study are discussed below.

The local pier scour equation in Richardson and Davis (2001) indicates that piers with wide or blunt noses result in larger, deeper scour holes than those with narrow, round, or sharp noses. This is apparent when comparing the scour hole caused by the cofferdam for pier 5 of the new bridge (figs. 19, 23) to the scour hole caused by the final, sharp-nosed pier 5 (figs. 27, 32) during low and high flow, respectively. Furthermore, the scour hole near the larger railroad turntable pier generally was larger than near the narrower railroad piers in all the surveys (figs. 9, 13, 19, 23, 27, 32).

All of the surveyed piers were skewed to approach flow, resulting in asymmetric scour holes. The scour hole typically was deeper and longer on the side of the pier with impinging flow, with some amount of deposition on the leeward side that usually formed a distinct ridge (figs. 9, 13, 19, 23, 27, 32). The angle of this ridge can be approximately measured with respect to the longitudinal axis of the pier that caused it to form. The angle of the ridge downstream from the railroad turntable pier was a constant 19 degrees in all of the surveys, whereas the angle of the ridge downstream from the railroad pier upstream from pier 10 of the Earhart Bridge varied from 25 to 44 degrees during the various surveys. The largest angle was observed in the survey during flooding on June 30, 2010 (fig. 23). Despite the addition and removal of the construction trestle and cofferdam, the angle of the ridge downstream from pier 10 of the Earhart Bridge was a nearly constant 15 degrees for all of the surveys (figs. 9, 13, 19, 23, 27) except the last, where it was about 27 degrees (fig. 32). Nevertheless, the velocity vectors indicate this constriction deflected flow to the right towards the center of the channel, which caused an unusual flow field with substantial turbulence in the vicinity of pier 10 (figs. 17, 21, 25). This constriction also resulted in an increase in velocity near existing pier 10, compounding the scour observed at that pier and enlarging the scour hole (figs. 10, 13, 19, 23), particularly during the flooding of June 30, 2010 (fig. 23).

Summary and Conclusions

Bathymetric and velocimetric data were collected six times in the vicinity of the Amelia Earhart Bridge on U.S. Highway 59, crossing the Missouri River at Atchison, Kansas, by the U.S. Geological Survey in cooperation with the Kansas Department of Transportation. A multibeam echosounder mapping system and an acoustic Doppler current profiler were used to obtain channel-bed elevations and cross-sectional velocities for an area approximately 2,300 feet long and extending from bank to bank across the active channel of the Missouri River during various flow conditions. Each bathymetric and velocimetric survey provided a “snapshot” of the channel conditions at the time of the survey, and the six surveys documented the changes to the channel-bed elevations and velocities during the course of construction of a new bridge downstream from the Earhart Bridge.

The estimated total propagated uncertainty for the gridded surface of each survey area was computed as an estimate of the accuracy to be expected for each point, when all relevant error sources are accounted for. An analysis of the surveys indicated that more than one-half of the bathymetric data have a total propagated uncertainty of less than 0.50 feet, and one-half the surveys have more than 26 percent of the data with a total propagated uncertainty of less than 0.25 feet. Of the remaining surveys, two were during flood conditions, with substantial turbulence and higher values of total propagated uncertainty near the bridges; a different survey vessel was used in the final survey, and it had more data collected with a tilted configuration, both of which appear to have adversely affected the total propagated uncertainty.

A baseline survey on June 30, 2009, revealed substantial scour holes existed at both the railroad bridge piers upstream from the Earhart Bridge as well as pier 10 of the Earhart Bridge. The scour hole at pier 10 of the Earhart Bridge appeared to be affected by local scour of the railroad bridge pier upstream. The vertically-averaged velocities indicated mostly uniform flow throughout the study reach, except near the various bridge piers, with a minor contraction of flow near the Earhart and railroad bridges.

The second survey was on June 2, 2010, after construction of a trestle and cofferdam built to facilitate construction of pier 5 of the new U.S. Highway 59 bridge. The flow conditions were similar to the baseline survey, and the scour holes near the Earhart and railroad bridge piers were similar in size and shape to the baseline survey. The contraction of flow near the bridges was more substantial than the baseline, with velocities that were 2 to 4 feet per second faster than the baseline, and a new scour hole appeared to be forming around the cofferdam. The channel-bed elevations to the right of pier 10 of the Earhart Bridge were 3 to 7 feet lower than the baseline in the second survey, and the average value of the difference between the bathymetric surfaces from the baseline and second surveys was -1.8 feet, indicating minor to moderate scour overall between the survey dates.

The third survey was during flooding on June 30, 2010, with a measured discharge of more than twice the baseline value. The contraction of flow near the bridges caused by the construction trestle and cofferdam resulted in velocities that were 5 to 10 feet per second faster than the baseline, and the scour holes near pier 10 of the Earhart Bridge and the cofferdam were substantial and interconnected. At the upstream face of pier 10 of the Earhart Bridge, the scour hole was 18 feet deeper than in the first two surveys. The shape of the intertwined scour holes from the railroad bridge pier, existing pier 10, and the cofferdam appeared swept toward the middle of the channel, as flow was deflected around the trestle and cofferdam. The channel-bed elevations throughout the channel generally were substantially lower than the baseline, and the average value of the difference between the bathymetric surfaces from the baseline and third surveys was -7.0 feet, indicating substantial scour overall between the survey dates.

The fourth survey on October 27, 2010, was intended to capture the condition of the channel after the flooding in June 2010; the construction trestle and cofferdam were both present, and flow conditions were similar to the baseline and second surveys. Velocities near the bridges were 1 to 3 feet per second faster in the fourth survey compared to the baseline, similar to those observed in the second survey. The shape of the intertwined scour holes from the railroad bridge pier, existing pier 10, and the cofferdam again appeared swept toward the middle of the channel, as flow was deflected around the trestle and cofferdam; however, at the upstream face of pier 10, the scour hole was only 4 feet deeper than in the first two surveys, and about 14 feet shallower than in the third survey. The channel-bed elevations throughout the channel generally were higher than the previous survey, but remained lower than the baseline, with the average value of the difference between the bathymetric surfaces from the baseline and fourth surveys being -2.6 feet.

The fifth survey was during flooding on July 15, 2011, and part of a larger study of all of the highway bridges crossing the Missouri River in and into Missouri during extensive summer flooding in 2011. Only the part of the channel downstream from the railroad bridge was surveyed, because there was insufficient clearance under the railroad bridge to allow the boat to pass underneath. The measured discharge of the fifth survey was almost four times that of the baseline survey, and 1.6 times that of the third survey the previous summer. Velocities near the bridges were 2 to 3 feet per second faster in the fifth survey compared to the baseline, but were slower than in the third survey during flooding the previous summer. As in the third survey, the channel-bed elevations throughout the channel generally were substantially lower than the baseline; however, the channel-bed elevations near the bridges generally were higher than those observed in the third survey, and the average value of the difference between the bathymetric surfaces from the third and fifth surveys was 1.4 feet, indicating overall deposition between those survey dates. Substantial deposition was observed near existing pier 10, likely caused by the removal of the cofferdam. The removal of this constriction also may account for the overall deposition observed between 2010 and 2011, despite the substantial increase in discharge between the two surveys.

The final survey was on April 14, 2013, near the end of the construction of the new US 59 Bridge. The measured discharge was about two-thirds that of the baseline survey, and the lower discharge resulted in substantially smaller scour holes near the various piers and lower velocities throughout the channel. The average value of the difference between the bathymetric surfaces from the final and baseline surveys was 1.7 feet, indicating minor to moderate deposition between the surveys. The construction trestle was still in place in the final survey, but its effect on the flow was minimal compared to earlier surveys. The scour holes near the railroad bridge pier and existing pier 10 were not interconnected in the final survey, and the bottom of the scour hole at the upstream end of existing pier 10 was 17 feet higher than the baseline survey, and 34 feet higher than in the previous survey on July 15, 2011.

The multiple surveys at the Amelia Earhart Bridge document the effects of moderate- to high-flow conditions on scour, compounded by the effect of adding and removing a constriction in the channel. The high-flow conditions of the third survey, combined with the constriction caused by the cofferdam and trestle, resulted in substantial scour of the overall channel as well as increased local pier scour at the existing bridge pier. Conversely, the even higher flow conditions during the fifth survey resulted in deposition throughout the downstream channel compared to the third survey, likely because of the removal of the constricting effect of the cofferdam. During the final survey, velocities throughout the study area were the lowest of all the surveys, resulting in overall deposition throughout the reach compared to the baseline—despite the presence of the trestle in the final survey.

Several additional factors affecting scour at piers were observed at the various piers during the surveys. The wide, blunt nose of the cofferdam for new pier 5 caused substantially more scour than the final, sharp-nosed pier during high- and low-flow conditions. Furthermore, the scour hole near the larger railroad turntable pier generally was larger than near the narrower railroad piers in all the surveys. All of the surveyed piers were skewed to approach flow, resulting in asymmetric scour holes that were deeper and longer on the side of the pier with impinging flow and having some amount of deposition on the leeward side. The angle of approach for the railroad turntable pier was essentially constant throughout the surveys, whereas the angle was variable for the railroad bridge pier upstream from pier 10 of the Earhart Bridge. Despite the addition and removal of the construction trestle and cofferdam, the angle of approach flow for pier 10 of the Earhart Bridge appeared to remain nearly constant for all of the surveys. Nevertheless, the velocity vectors indicate the constriction caused by the cofferdam and construction trestle deflected flow to the right towards the center of the channel, which caused an unusual flow field with substantial turbulence in the vicinity of pier 10 that compounded the scour observed at that pier and enlarged the scour hole, particularly during the flooding of June 30, 2010.

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Back cover. Upper: The Amelia Earhart Bridge on U.S. Highway 59 (foreground) and the Burlington Northern Santa Fe railroad bridge (background) over the Missouri River at Atchison, Kansas, on June 30, 2009, before construction of the new U.S. Highway 59 bridge, as viewed from downstream.

Middle: The cofferdam for pier 5 of the new U.S. Highway 59 bridge being installed just downstream from the existing pier 10 of the Amelia Earhart Bridge over the Missouri River at Atchison, Kansas, on June 2, 2010, as viewed from the right bank immediately upstream from the Amelia Earhart Bridge.

Lower: The nearly completed U.S. Highway 59 Bridge (foreground) over the Missouri River at Atchison, Kansas, on April 24, 2013, as viewed from downstream. The Amelia Earhart Bridge and the Burlington Northern Santa Fe railroad bridge are visible in the background.

(All photos by Richard J. Huizinga, U.S. Geological Survey)