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Monitoring of Levees, Bridges, Pipelines, and Other Critical Infrastructure During the 2011 Flooding in the Mississippi River Basin

Chapter J of
2011 Floods of the Central United States

Professional Paper 1798–J

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

Front cover. U.S. Geological Survey scientists collecting capacitively coupled resistivity data on the levee surrounding the Omaha Public Power District Nebraska City power plant, June 13, 2011. Photograph by Jim Cannia, U.S. Geological Survey (USGS).

Back cover. Multibeam surveying boat on the Missouri River at Yankton, South Dakota, July 29, 2011, to collect hydrographic survey data of the riverbed around the Yankton Discovery bridge, U.S. Highway 81. Photograph by Benjamin Dietsch, USGS.

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SALLY JEWELL, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2014

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Volume	
cubic hectometer (hm^3)	810.7	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

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).

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Abstract

During the 2011 Mississippi River Basin flood, the U.S. Geological Survey evaluated aspects of critical river infrastructure at the request of and in support of local, State, and Federal Agencies. Geotechnical and hydrographic data collected by the U.S. Geological Survey at numerous locations were able to provide needed information about 2011 flood effects to those managing the critical infrastructure. These data were collected and processed in a short time frame to provide managers the ability to make a timely evaluation of the safety of the infrastructure and, when needed, to take action to secure and protect critical infrastructure. Critical infrastructure surveyed by the U.S. Geological Survey included levees, bridges, pipeline crossings, power plant intakes and outlets, and an electrical transmission tower.

Capacitively coupled resistivity data collected along the flood-protection levees surrounding the Omaha Public Power District Nebraska City power plant (Missouri River Levee Unit R573), mapped the near-subsurface electrical properties of the levee and the materials immediately below it. The near-subsurface maps provided a better understanding of the levee construction and the nature of the lithology beneath the levee. Comparison of the capacitively coupled resistivity surveys and soil borings indicated that low-resistivity value material composing the levee generally is associated with lean clay and silt to about 2 to 4 meters below the surface, overlying a more resistive layer associated with sand deposits. In general, the resistivity structure becomes more resistive to the south and the southern survey sections correlate well with the borehole data that indicate thinner clay and silt at the surface and thicker sand sequences at depth in these sections. With the resistivity data Omaha Public Power District could focus monitoring efforts on areas with higher resistivity values (coarser-grained deposits or more loosely compacted section), which typically are more prone to erosion or scour.

Data collected from multibeam echosounder hydrographic surveys at selected bridges aided State agencies in evaluating the structural integrity of the bridges during the flood, by assessing the amount of scour present around piers and abutments. Hydrographic surveys of the riverbed detected scour depths ranging from zero (no scour) to approximately 5.8 meters in some areas adjacent to North Dakota bridge piers, zero to approximately 6 meters near bridge piers in Nebraska, and zero to approximately 10.4 meters near bridge piers in Missouri. Substructural support elements of some bridge piers in North Dakota, Nebraska, and Missouri that usually are buried were exposed to moving water and sediment. At five Missouri bridge piers the depth of scour left less than 1.8 meters of bed material between the bottom of the scour hole and bedrock. State agencies used this information along with bridge design and construction information to determine if reported scour depths would have a substantial effect on the stability of the structure.

Multibeam echosounder hydrographic surveys of the riverbed near pipeline crossings did not detect exposed pipelines. However, analysis of the USGS survey data by pipeline companies aided in their evaluation of pipeline safety and led one company to further investigate the safety of their line and assisted another company in getting one offline pipeline back into operation. Multibeam echosounder hydrographic surveys of the banks, riverbed, and underwater infrastructure at Omaha Public Power District power plants documented the bed and scour conditions. These datasets were used by Omaha Public Power District to evaluate the effects that the flood had on operation, specifically to evaluate if scour during the peak of the flood or sediment deposition during the flood recession would affect the water intake structures. Hydrographic surveys at an Omaha Public Power District electrical transmission tower documented scour so that they could evaluate the structural integrity of the tower as well as have the information needed to make proper repairs after flood waters receded.

Introduction

During the 2011 Mississippi River Basin flood the U.S. Geological Survey (USGS) evaluated the effects of flood waters on aspects of critical river infrastructure at the request of and in support of numerous agencies including the North Dakota Department of Transportation, the North Dakota State Water Commission, the Nebraska Department of Roads, the Kansas Department of Transportation, the Missouri Department of Transportation, the Omaha Public Power District (OPPD), the U.S. Environmental Protection Agency (EPA), and the U.S. Coast Guard. These evaluations provided timely information needed by owners, operators, and regulators to assess the safety of continued operation of flood- or scour-threatened infrastructure or to weigh the need for scour countermeasures or abandonment of facilities.

Critical river infrastructure refers to the levees, bridges, roads, pipelines, powerline towers, and other structures that make modern life possible. It can be within, under, spanning, or along the banks of the river. Such infrastructure protects people and land from flood water, allows people and goods to be transported over or under the river, and provides water supplies for power production and municipal use. River infrastructure that had aspects surveyed by the USGS during the 2011 Mississippi River Basin flood included levees, bridges, pipeline crossings, power plant intakes and outlets, and an electrical transmission tower. This report concentrates on surveys of critical infrastructure completed along the Missouri River (figs. 1 and 2).

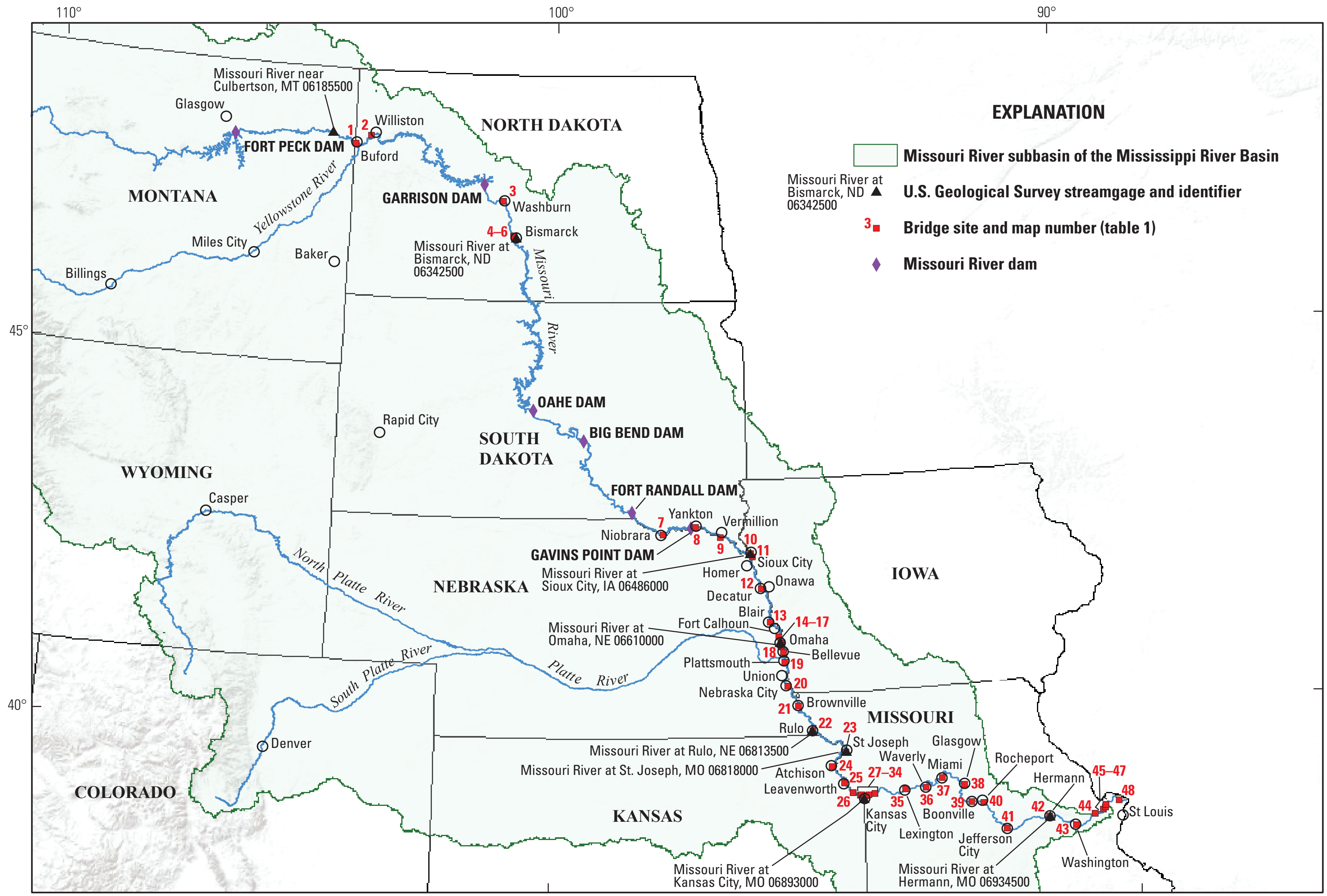
Background

A riverbed can be changed with the movement of sediment by flowing water. In such an environment, sediment can be eroded and deposited. The removal of riverbed sediment and bank material is known as scour and takes place as velocity and shear stress increase, typically with increasing flow (Leopold and others, 1964). Riverbed scour can have a detrimental effect on river infrastructure. Scour near river infrastructure is the result of short- and long-term geomorphic processes and the local effects caused by elements of the infrastructure in or adjacent to the waterway (Richardson and Davis, 2001; Huizinga and Rydlund, 2004). Scour depth, as discussed in this report, is the difference in elevation at the bottom of the scour hole to the approximate elevation of the riverbed upstream from the scour hole. Scour and fill around river infrastructure such as levees, bridge piers and abutments, water intakes and outlets, pipeline crossings, electrical transmission towers, and other river-management structures, potentially can destabilize, disrupt, damage, or destroy the infrastructure, resulting in threats to public safety and economic well-being.

River infrastructures, such as levees, must be maintained, monitored, and evaluated, because they are susceptible to deterioration, instability, and failure. Levees are susceptible to environmental factors that cause erosion and settlement when not in contact with river flows as well as during flooding. When levees are in contact with flood water, seepage, erosion, and overtopping become additional factors that can degrade the stability of the levees (State of California Department of Water Resources, 2012). Evaluation of levee integrity is important to reduce flood damages and prevent possible loss of life and property. Typical methods of assessing levee integrity include topographic assessments, hydrographic surveys, geomorphic mapping, and evaluation of levee materials and the underlying soils (State of California Department of Water Resources, 2008). To evaluate the integrity of the levee materials, core samples can be collected and for more detailed evaluations core samples can supplement geophysical methods such as airborne electromagnetic surveys (State of California Department of Water Resources, 2008) or capacitively coupled resistivity (Asch and others, 2008; Gillip and Payne, 2011). Capacitively coupled (CC) surveys have been used effectively by the USGS to map the near-surface electrical properties of the subsurface to a depth of approximately 8–12 meters (m; Ball and others, 2006; Lucius and others, 2008; Burton and others, 2009). This type of survey provides a nearly continuous resistivity dataset, which can be inverted to provide a distribution of resistivity with depth along a profile. These resistivity data can be interpreted to help understand the types of materials from which the levee is constructed. Evaluation of the levee materials and the underlying lithology aids in identifying areas of the levee construction and material types that are susceptible to seepage, erosion, settlement, or scour that could cause levee breaks or failures.

The effects of scour can be severe and dangerous; therefore, bridges and other critical infrastructure over, under, and in waterways are assessed routinely and monitored to detect scour conditions. Inspection during flooding is necessary to evaluate structural integrity and to document the true extent of scour, which often cannot be measured following the flood because of the subsequent refilling of scour holes by sediment deposition as floods wane. Sounding rods, sounding weights, physical inspection by divers, and echosounders have been used to measure scour holes near river infrastructure (Federal Highway Administration, 2011). High-water velocity, high turbulence, debris pile-up, large floating debris in the water, and other hazards make inspection of within-river infrastructure during flooding difficult, and many methods may not be capable of providing adequate information about the spatial extent of localized scour and may be dangerous, impractical, and of poor quality. Inspection with a multibeam echosounder (MBES) has many advantages during flood conditions and can be used to document details of the lateral and vertical extent of riverbed scour and to efficiently assess bridge stability (Federal Highway Administration, 2011). In addition, physical measurements of scour during flooding can lead to improved performance of scour-prediction techniques used by engineers to design river infrastructure and protect it during flood events.

Multibeam echosounders survey the underwater environment by sending a sound wave into the water. This sound



Base from World Terrain Base by Esri, 2012, 1:70,000
Universal Transverse Mercator projection, Zone 14
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)

0 100 200 300 400 KILOMETERS
0 100 200 MILES

Figure 1. The Missouri River Basin, U.S. Geological Survey streamgages, and bridge critical infrastructure survey sites.

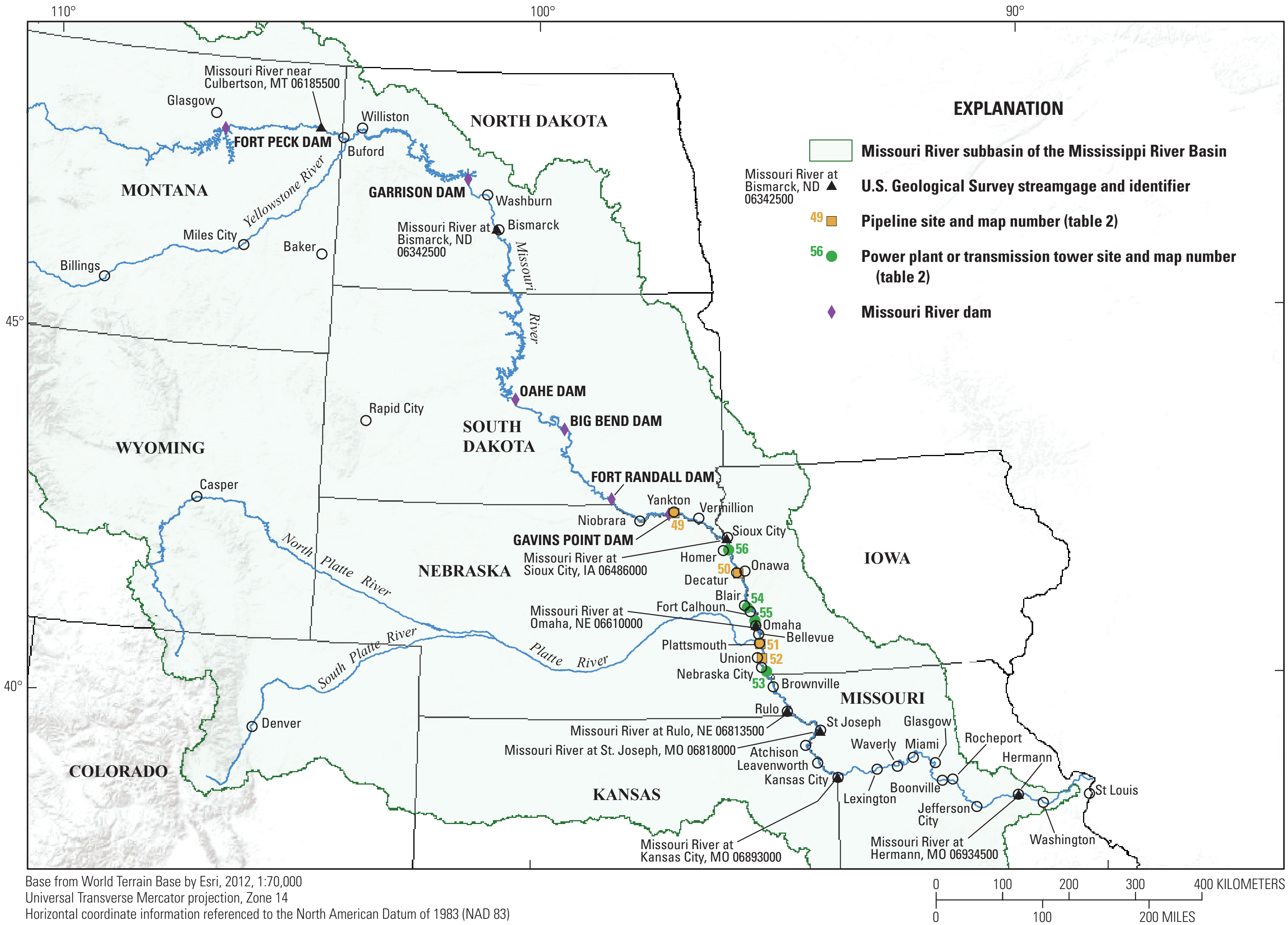


Figure 2. The Missouri River Basin, U.S. Geological Survey streamgages, and pipeline, power plant, and transmission tower critical infrastructure survey sites.

wave is reflected by objects under the water (the riverbed, river banks, bridge piers, items in the water column, and any other submerged structures) and the sound is returned back to the sonar. The MBES records the time of travel of the sonar signal to determine the distance to the object from the sonar unit by utilizing speed of sound for the specific water temperature and salinity (L-3 Communications SeaBeam Instruments, 2000). A MBES can record numerous depths per sounding (or ping) by forming the sound wave into multiple beams (fig. 3). The MBES used for the surveys described in this report collects 512 depth readings per ping. The sound wave spreads out to cover 128 degrees, which creates a swath width of approximately four times the water depth. These depth readings are converted into *x*, *y*, *z* coordinates utilizing Global Navigation Satellite Systems positioning data (horizontal and vertical) and boat motion data, which along with sounding angles can be used to calculate the true position and elevation of each depth reading.

Inspection of critical infrastructure during floods is time sensitive. There is only a short time frame in which to deploy survey crews, collect the data, and provide the data to those managing the infrastructure to ensure that they have time to evaluate the safety of the structure and take action to secure the structure if needed. If managers do not get these data in a timely fashion and are not aware of the effects flood waters have on the stability of critical infrastructure then the risk of failure increases. The importance of inspecting infrastructure during floods and the extreme danger that floods pose to river infrastructure can be partially assessed by evaluating the results of past disasters. Disasters caused by the damage or loss of river infrastructure during floods can be measured by the loss of life, the inconvenience and economic effects, the environmental contamination, and the cost to repair damages to the infrastructure.

Bridge collapses historically have cost numerous lives and millions of dollars in damage. The 2007 collapse of the I-35W bridge in Minneapolis, Minnesota (not shown) took 13 lives, injured 145 people, and cost $233.7 million dollars to replace (Minnesota Department of Transportation, 2007). The cost to replace the Burt County bridge near Decatur, Nebr. (fig. 1) is estimated to be $50–60 million (Hytrek, 2012) and the price tag on the recent replacement of the U.S. 159 bridge near Rulo, Nebr. (fig. 1) was around $32 million (Laukaitis, 2013). When bridges fail the results are devastating, with loss of life and huge cost to repair or replace the structure; however, even when bridges are closed for safety reasons there are economic consequences. All motorists have to spend extra time and fuel to detour to the next available bridge. With the Burt County bridge over the Missouri River closed in 2011 for 4 months because of flooding of the approaches to the bridge and scour around the Iowa abutment, motorists had a 7 mile trip from Decatur, Nebr. to Onawa, Iowa (fig. 1) turned into a 150 mile trip to cross the river (Hytrek, 2012).

Pipeline ruptures during the 2011 Mississippi River Basin flood alone can define the dangers that flooding causes to pipelines that run under riverbeds. A pipeline owned by Exxon Mobil Corporation on the Yellowstone River (fig. 1) ruptured during the 2011 flood and released 63,000 gallons of crude oil into the river (Rogers, 2012). The rupture cost the company an estimated $135 million (Rogers, 2012) on cleanup and repair, not including the $1.7 million in penalties (U.S. Department of Transportation, 2013) or the cost for numerous lawsuits. This spill contaminated dozens of miles of shoreline that required extensive cleanup. In addition, a NuStar Energy LP pipeline break released 4,200 gallons of anhydrous ammonia and an Enterprise Products Partners LP pipeline released 28,350 gallons of gasoline into the Missouri River (Brown, 2013). These types of spills not only cost millions of dollars to cleanup, but potentially can contaminate riverbank soils, drinking water supplies, and any other downstream water uses.

The 2011 Mississippi River Basin flood in the Missouri River subbasin began in early spring, caused by record snowfall and heavy spring rainfall (Vining and others, 2013). Because of the record snowfall and the heavy rainfall, the combined May-through-June runoff for the basin of 42,300 cubic hectometer (hm^3) was greater than the annual runoff in 102 of the 113 years of record (U.S. Army Corps of Engineers, 2011). This unexpected volume of water prompted the U.S. Army Corps of Engineers (USACE) to take emergency measures to lower main-stem reservoir levels to ensure dam safety. Flood conditions began in the upper Missouri River Basin in mid-May, and the Federal Emergency Management Agency (FEMA) officially expanded its emergency declaration to several North Dakota counties along the Missouri River on May 28, 2011 (Federal Emergency Management Agency, 2011). The official end to the 2011 Missouri River flood was declared by FEMA on October 17, 2011, when river levels from Montana to St. Louis, Missouri (fig. 1), dropped below flood stage.

The effects of heavy snow pack, wide-spread rain events, and ultimately unprecedented releases of water from the main-stem Missouri River dams are seen at numerous USGS Missouri River streamgages (Holmes and others, 2013). Streamflow at most of the streamgaging sites correlated to stream stages that exceeded National Weather Service designated flood stages (National Weather Service, 2014) (fig. 4). The extreme high flows and the extended duration of high flows on the Missouri River during the summer of 2011 created scour and other hydraulic forces that eroded riverbeds and riverbanks giving rise to concerns about the viability and safety of some river infrastructure.

The management of Mississippi River Basin water resources requires a continuing awareness of the current and forecasted streamflow and a well-founded understanding of the processes by which streamflow mobilizes and transports river sediment and associated chemical constituents. Obtaining that information requires an extensive field presence, advanced hydroacoustic and hydrographic instruments, field vehicles and boats suited to flood conditions, and highly trained hydrographers who can safely and effectively collect the data. These assets are used extensively by the USGS during normal conditions to supply data for river managers and support river

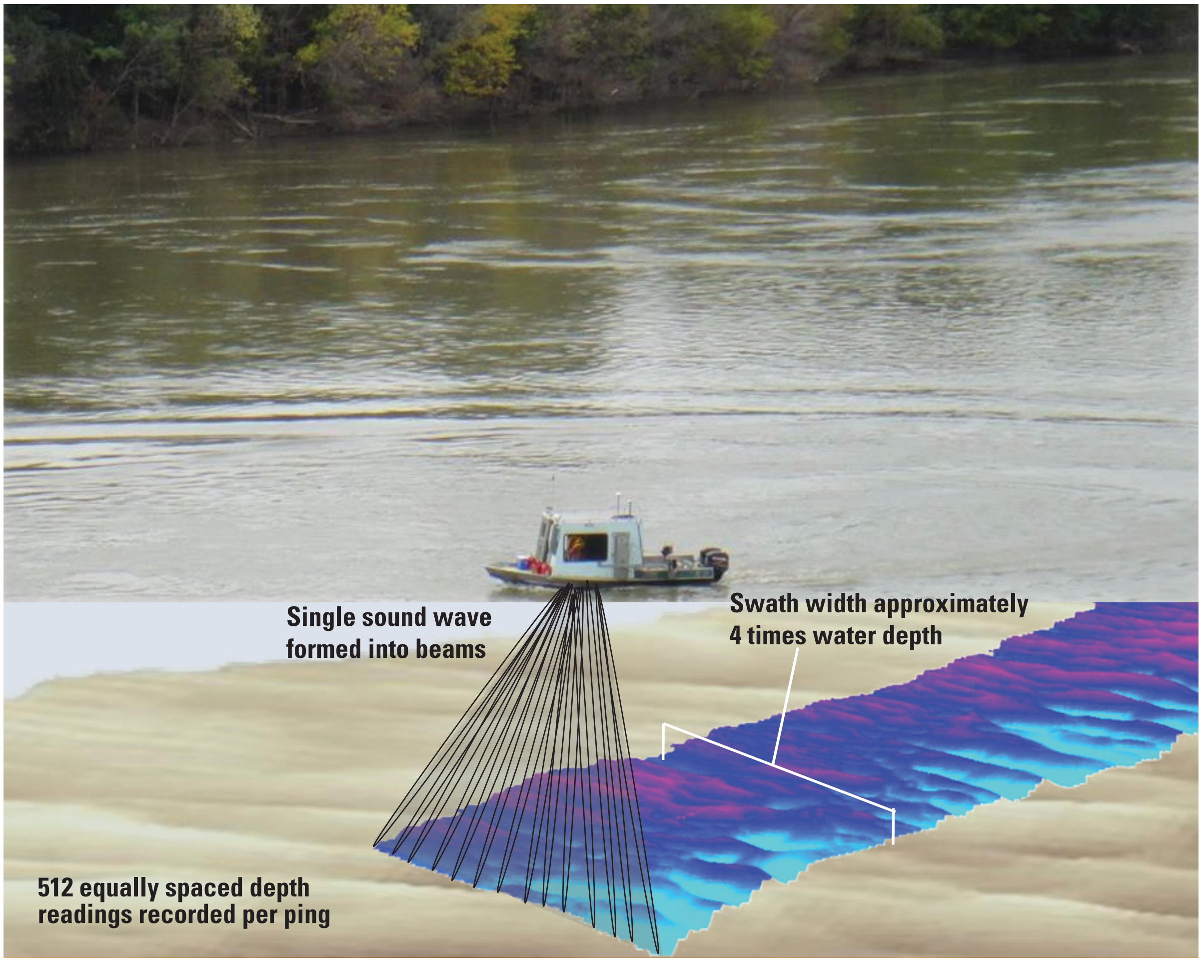


Figure 3. Diagram of a multibeam echosounder.

scientific investigations, but they also play a crucial role during floods. The effect that flood waters have on scour processes and river infrastructure factors into decisions about flow releases from flood control reservoirs, the deployment of scour countermeasures such as stone rip-rap, the closure or curtailment of some infrastructure activities, and even the evacuation of communities protected by levees.

The urgent need for such information caused the USGS to marshal its geomorphological monitoring assets to support the operation of a wide variety of river infrastructure on the Missouri River from western North Dakota, 2.4 kilometers (km) from the Montana State border, to St. Louis, Missouri (fig. 1). Seven kilometers of levee were surveyed in Nebraska along the Iowa/Nebraska section of the Missouri River. Missouri River bridges surveyed included six bridges in North Dakota, 3 in South Dakota/Nebraska, 11 in Iowa/Nebraska, 2 in Missouri/Nebraska, 9 in Missouri/Kansas, and 26 in Missouri. Two pipeline crossings were surveyed in the South Dakota/Nebraska section of the Missouri River, and 13 in the Iowa/Nebraska section. Power plant and electrical transmission tower surveys were all located in the Iowa/Nebraska section of the Missouri River. The size of each study area varied depending on the size and location of the infrastructure being surveyed.

Purpose and Scope

The purpose of this report is to summarize and present data collected during the 2011 Mississippi River Basin flood that aided in the evaluation of critical river infrastructure. This report summarizes geophysical data collected on 7 km of levees and hydrographic survey data of the Missouri River bed at 57 bridges, 15 pipeline crossings, 3 power plant intakes and outlets, and 1 electrical transmission tower. Data collected before and after the 2011 flood also are presented at selected locations to enable an analysis of trends and change in channel morphology. All of these datasets are presented, described, and analyzed in greater detail in separate reports including Burton and Cannia (2011), Densmore and others (2013), Dietsch and others (2014), and Huizinga (2012).

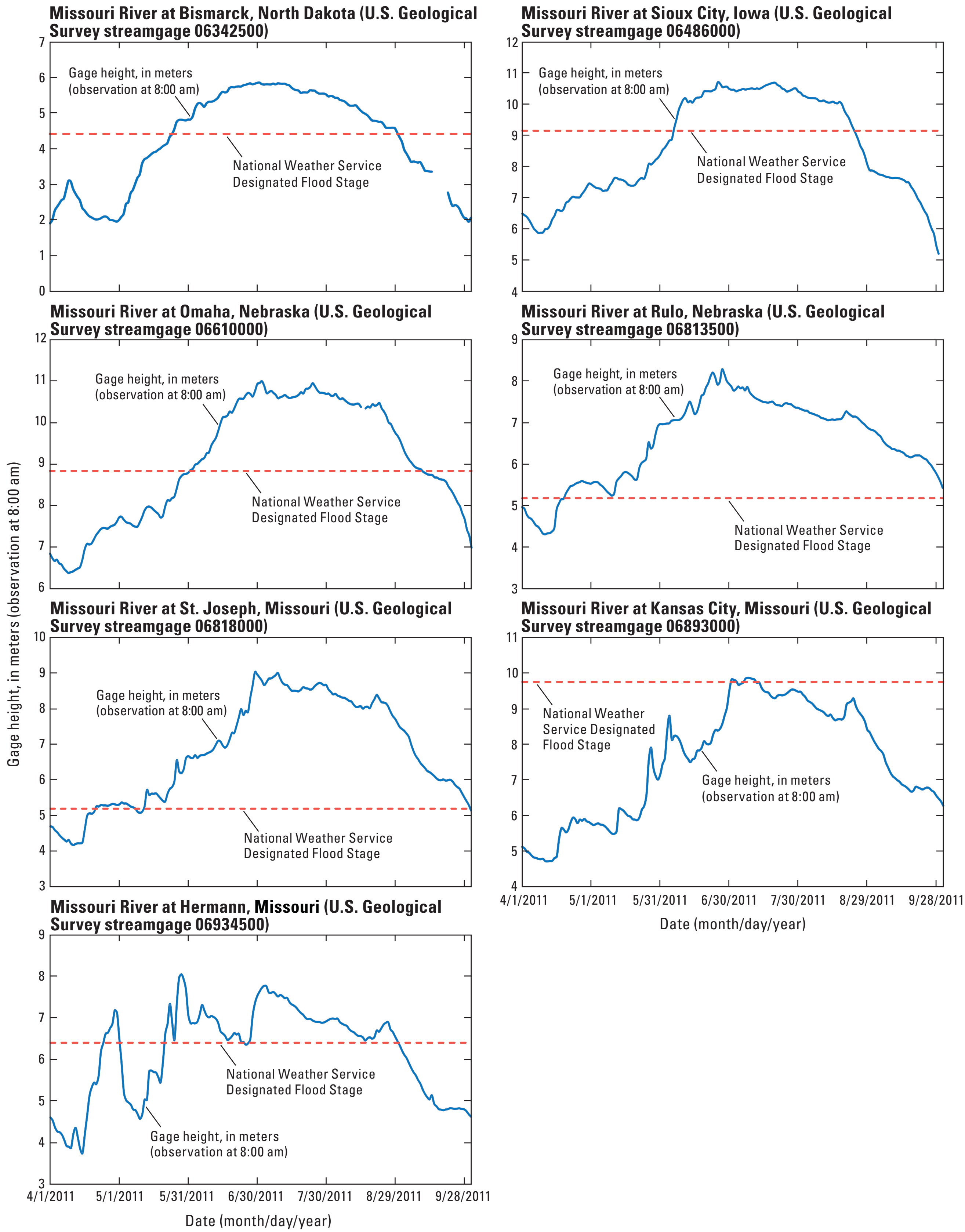


Figure 4. Gage height at select Missouri River streamgages, April to October, 2011.

Levees

During the 2011 Mississippi River Basin flood the USGS completed a capacitively coupled resistivity survey on June 13th on the Missouri River flood-protection levees surrounding the Omaha Public Power District (OPPD) Nebraska City power plant (Missouri River Levee Unit R573) (Burton and Cannia, 2011). The Nebraska City power plant lies approximately 9 km southeast of Nebraska City, Nebr. (figs. 2 and 5). Missouri River Levee Unit R573 was constructed in the floodplain of the Missouri River and has an approximate elevation of 275 m. The levee begins on the northwest corner of the power plant and circles around to the southwest corner. Data were collected along approximately 7 km of the center line of the levee. The objective of the survey was to map the near-subsurface electrical properties of the levee and the materials immediately below it, to gain a better understanding of the levee construction and the nature of the lithology beneath the levee. The resistivity survey was split into six sections that ranged from about 0.8 to 1.6 km long to aid in processing. Soil borings acquired in February and March 2012 along the survey area were analyzed and correlated with the resistivity data to create a lithologic interpretation. The resistivity section and soil-boring locations are shown in figure 5.

Capacitively Coupled Resistivity Method

Resistivity is the property of a material that opposes the flow of electric current. Measurements are made by sending a known current into the subsurface using two current electrodes and measuring the resulting voltage difference between two potential electrodes. Based on Ohm's Law, the resistance value is computed by taking the ratio of the measured voltage and the transmitted current. The apparent resistivity of the material, expressed in ohm-meters (ohm-m), is then determined by multiplying each resistance value by the corresponding geometric factor, which is based on the electrode geometry and spacing.

The main factors that affect the resistivity of a material are the amount of interconnected pore water present, the water quality [level of total dissolved solids (TDS)], and the amount of mineralogical clay present. In the unsaturated zone, if no mineralogical clay is present, a fine-grained material (for example, silt or fine sand) generally will retain more interconnected water through capillary forces than a coarse-grained material (for example, coarse sand or gravel). The fine-grained material will therefore have a lower resistivity compared to coarser-grained materials. In the saturated zone, water quality is an important factor because the concentration of ions in the water affects its ability to conduct electricity. Materials containing water with high TDS levels will have a lower resistivity compared to materials containing water with low TDS levels. The presence of even a small amount of mineralogical clay can dramatically decrease the overall bulk resistivity of a material because current is conducted through the pore fluids (electrolytically) as well as through cation exchange (electronically). For this survey, given that the sediments surrounding and underlying the levee, as well as the levee embankment materials themselves, are saturated because of flood water, and because of the relation between grain size and resistivity, the resistivity method can be a useful tool in differentiating lithologies to identify paleochannels or other coarser-grained deposits that could lead to preferential flow paths below the levee embankment during high-water events. Reynolds (1997), Sharma (1997), and Butler (2005) provide more detailed descriptions of the resistivity method and resistivity values for common geologic materials.

Data Acquisition, Processing, and Inversion

The CC resistivity data were acquired with the Geometrics OhmMapper TR5™ (Geometrics, Inc., San Jose, Calif., U.S.A.) towed behind an all-terrain vehicle (ATV) and integrated with a Trimble DSM 232™ (Trimble Navigation Ltd., Sunnyvale, Calif., U.S.A.) differential global positioning system (DGPS) unit with the OmniSTAR™ (OmniSTAR, 2005) High Precision (HP) subscription service (fig. 6). Further explanation of data acquisition methods used during this survey can be found in Burton and Cannia (2011). For further details on the CC resistivity method and acquisition system, refer to Timofeev and others (1994), Geometrics (2001), Ball and others (2006), Lucius and others (2008), and Burton and others (2009).

The raw binary data files were downloaded, correlated with GPS positions, projected, reviewed, edited, and binned (or averaged) to a 5-m bin size as described by Burton and Cannia (2011). The binned data were exported in a RES2DINV (Loke, 2011) data format. This format includes elevation data that were then imported into Advanced Geosciences, Inc. (AGI), EarthImager 2D™ (Advanced Geosciences, Inc., 2008) inversion program. All CC resistivity data were inverted using the smooth, finite-element inversion method in EarthImager 2D™ version 2.4.0 build 617. The smooth method, also known as Occam's inversion, finds the smoothest possible model whose response fits the data based on the assumption of a Gaussian distribution of data errors and uses the L2-norm parameter as an inversion criterion (Advanced Geosciences, Inc., 2008). The inverted resistivity sections were imported into Encom Profile Analyst™ (Pitney Bowes Software, North Sydney, Australia), along with the digitized soil borings, for analysis and interpretation.

Interpretation

To aid in the interpretation of the inverted CC resistivity data, information from a subset of 20 soil borings, completed by the USACE in February and March 2012, were imported into Encom Profile Analyst™ for comparison with the CC resistivity profiles. Although there were an additional 100 soil borings acquired between October 1946 and January 1950

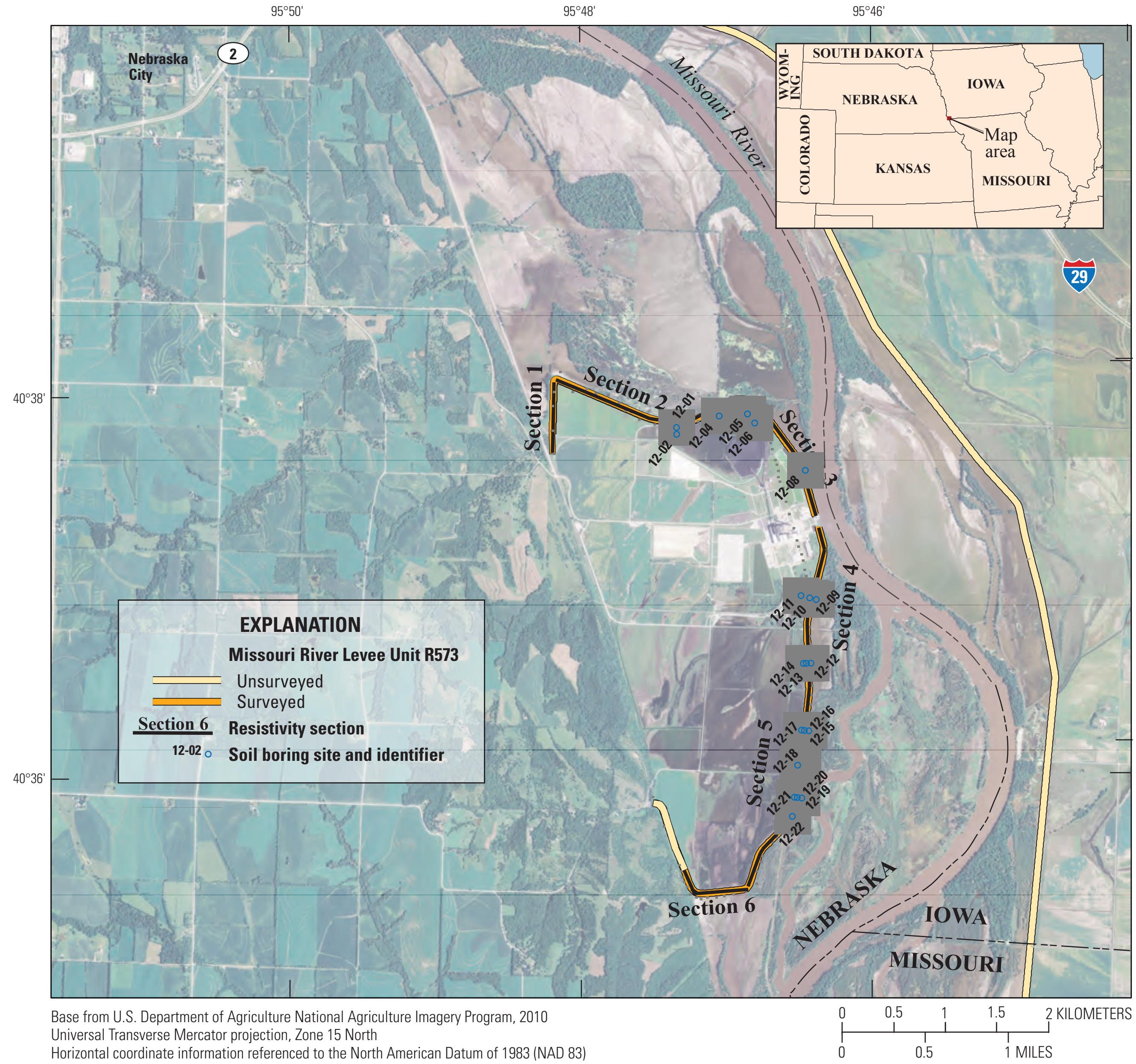


Figure 5. Location of levee study area, capacitively coupled resistivity survey sections, and soil borings along Missouri River Levee Unit R573.

(U.S. Army Corps of Engineers, 1983), most were generally shallow (about 2–4 m depth) and were acquired along the original levee location as it existed at that time. The levee has been realigned to its current (2011) location after those borings were completed, so the shallow ground had been reworked before the 2011 resistivity survey and the original borings may not be an accurate representation of the current (2011) subsurface conditions.

The CC resistivity sections indicate changes in resistivity with depth in the levees and the underlying material of the floodplain deposits to a depth of about 8 m (fig. 7). The resistivity values range from approximately 10 to 100 ohm-m along the length and depth of the measured sections. It is probable that changes in observed resistivity were the result of lithologic changes and not water saturation variations because most of the levee survey reach had standing water on either side making the levee's soil water content uniform, and the soil borings correlated well with resistivity values. These profiles can therefore be used to differentiate between finer-grained alluvial materials (silt and clay), which generally exhibit lower electrical resistivity values (cooler colors in fig. 7), and coarser-grained alluvial materials (sand and gravel), which exhibit higher resistivity values (warmer colors in fig. 7). Coarser-grained materials generally have a higher

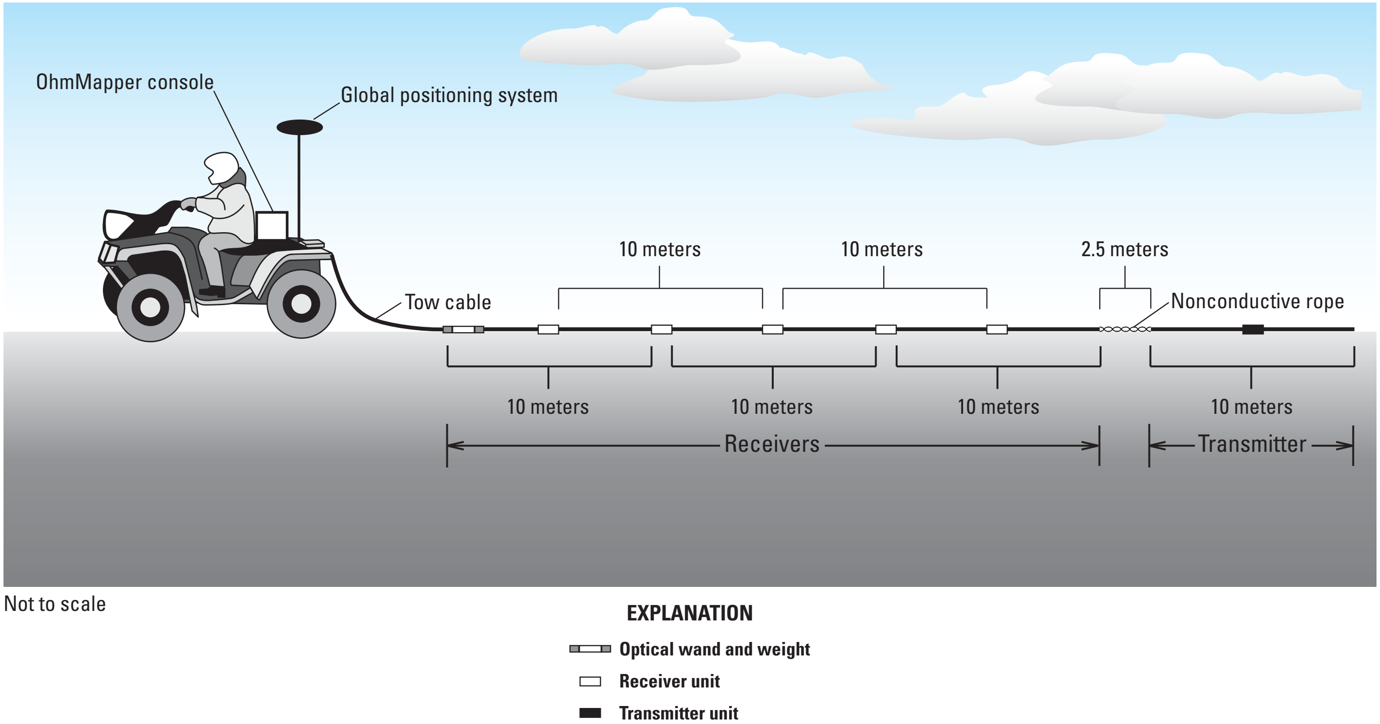


Figure 6. Schematic illustration showing the capacitively coupled resistivity acquisition system setup and geometry (modified from Ball and others, 2006).

capacity to transmit water than finer-grained materials (silt and clay), as would be expected in paleochannel deposits that typically exist in a river floodplain environment. It is these coarser-grained deposits that have the most potential for leakage through and under the levees.

It is important to note that there is a difference in resolution between the CC resistivity method and the soil borings. The soil borings provide higher resolution information for a particular location, and the CC resistivity data provide an average of the electrical property variations laterally and vertically. The CC resistivity data have been smoothed laterally into 5-m bins, and the vertical model layers displayed in figure 7 are approximately 1 to 1.5-m thick with thickness increasing with depth as the model resolution decreases.

There is generally a 2 to 4-m thick conductive surface layer that is assumed to be semicompacted impervious embankment material because the survey was done along the levee crest. The variations observed in this upper layer may be from variations in the borrow material obtained to construct the levees. The soil borings generally were acquired off of the crest, which accounts for the elevation differences between the tops of the soil borings and the resistivity sections. Based on the soil borings; the shallow, low-resistivity value material generally is associated with lean clay and silt down to a depth of about 2 to 4 m below the surface overlying a more resistive layer associated with sand deposits (fig. 7). In general, with section 1 exhibiting the lowest overall resistivity, the resistivity structure becomes more resistive to the south. Sections 5 and 6 are the most resistive and correlate well with the boreholes (section 5) that indicate thinner clay and silt at the surface and larger sand sequences at depth.

It is unknown at the time of the writing of this report whether OPPD or the U.S. Army Corps of Engineers have evaluated any sections of this levee in terms of structural integrity since this flood event. Because the CC resistivity method maps variations in the subsurface resistivity structure that can be due to various mechanisms (for example, changes in lithology or water content), these data cannot be used to determine ultimate integrity without additional investigations that could correlate potential weakened or susceptible zones with resistivity values. Areas with higher resistivity values either within or below the levee embankment material (coarser-grained deposits or more loosely compacted sections), however, typically are more prone to erosion or scour and can aid in prioritizing sites to investigate.

Mapping variations in the electrical property in the subsurface using a reconnaissance-style tool such as the CC resistivity method can be useful for delineating changes in either lithologic or saturation levels. There are other geophysical tools that measure subsurface electrical properties, including other electrical (ground and waterborne) and electromagnetic methods (ground, waterborne, and airborne; for example, Butler, 2009, Siemon and others, 2009, Robinson and others, 2008), but selecting the correct tool or suite of tools is important. The proper tool selection is based on desired levels of lateral and vertical resolution, desired depth of investigation, site conditions (for example, power lines or other infrastructure that may interfere with data quality, or whether the survey

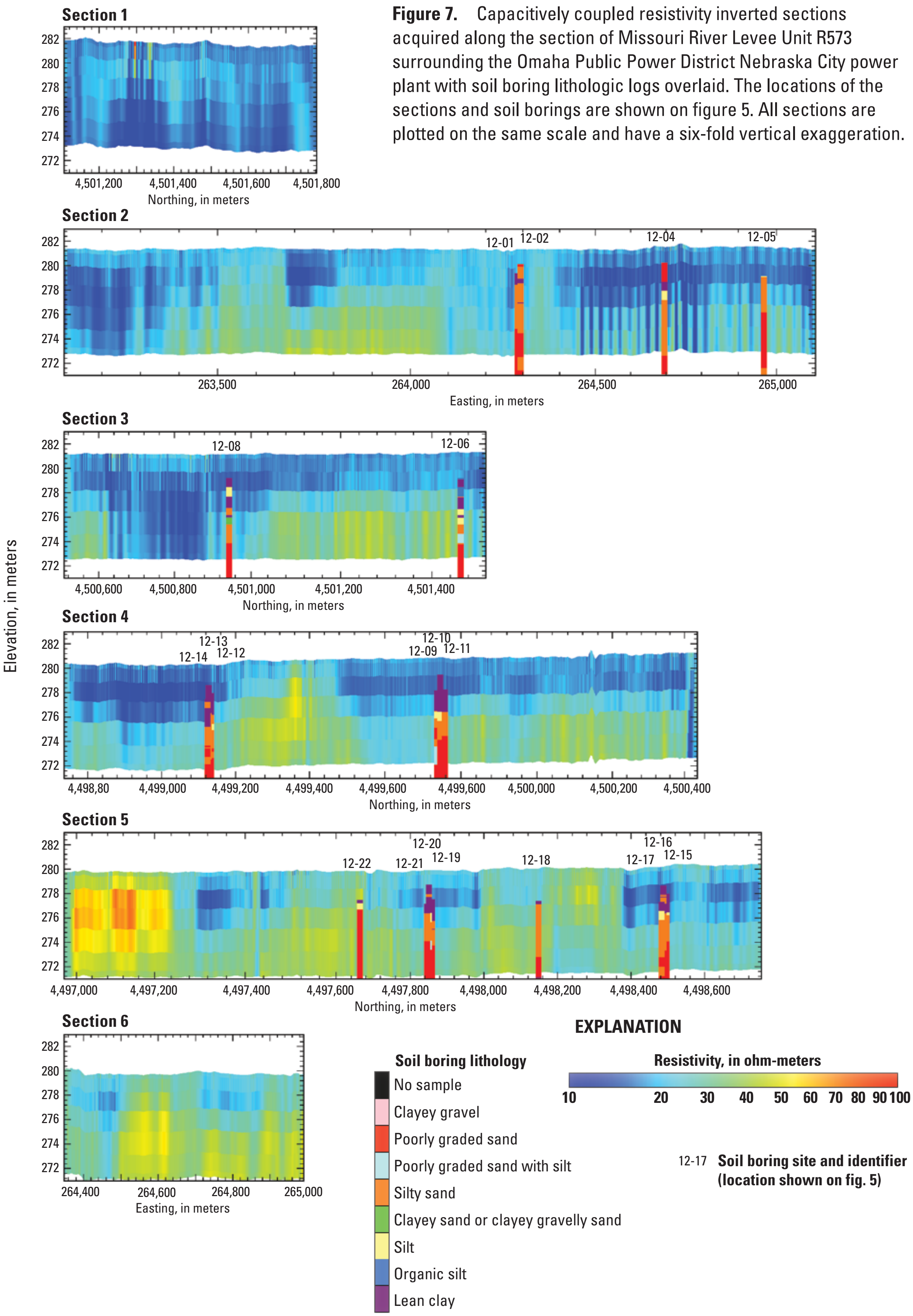


Figure 7. Capacitively coupled resistivity inverted sections acquired along the section of Missouri River Levee Unit R573 surrounding the Omaha Public Power District Nebraska City power plant with soil boring lithologic logs overlaid. The locations of the sections and soil borings are shown on figure 5. All sections are plotted on the same scale and have a six-fold vertical exaggeration.

site is flooded), and desired survey-area coverage. With all geophysical methods, the availability of borehole information is crucial to interpreting the modeled property variations.

Bridges

Hydrographic surveys completed in the vicinity of Missouri River bridges during the 2011 Mississippi River Basin flood include 6 in North Dakota, 3 in South Dakota/Nebraska, 11 in Iowa/Nebraska, 2 in Missouri/Nebraska, 9 in Missouri/Kansas, and 26 in Missouri. A total of 57 bridges were surveyed at 48 different locations (9 locations with dual bridges) (table 1). All riverbed surveys at bridge sites were completed using a multibeam echosounder (MBES) and extended approximately 200 to 500 m upstream and downstream from the bridge. Methods used for each bridge survey were similar and more details can be found in Densmore and others (2013), Dietsch and others (2014), and Huizinga (2012).

North Dakota Bridges

Ten bridge MBES surveys were completed at six bridge sites in North Dakota during the 2011 Mississippi River Basin flood in cooperation with the North Dakota Department of Transportation and the North Dakota State Water Commission (Densmore and others, 2013). Four bridge sites were surveyed twice, and two bridge sites were only surveyed once (table 1). Bridges surveyed twice include Washburn bridge, Grant Marsh bridge, West Bismarck Expressway bridge, and Memorial Highway bridge. Buford bridge and Williston bridge were only surveyed once because of their remote location and the results of the first surveys, which did not indicate any need for further investigation.

In general, the initial surveys at North Dakota bridge sites were collected during the rise of the hydrograph, when streamflows were above flood stage, and the second surveys were collected during the peak or the initial fall of the hydrograph. Elevations surveyed near North Dakota bridge piers documented scour depths from zero (no scour) to 5.8 m. Scour depth, as discussed in this report, is the difference in elevation at the bottom of the scour hole to the approximate elevation of the streambed upstream from the scour hole. The presence of a scour hole around a pier could mean that the pier is more vulnerable to failure; however to determine the extent of vulnerability, the elevation of the scour hole was compared to the construction details for that specific pier by the state agency managing the structure. Therefore, the managers could determine if the loss of support from the scoured sediment would have an effect on the stability of the pier, or if the construction of the pier was sufficient to withstand the increased forces being applied to it even with reduced support from the surrounding riverbed sediments. If scour was great enough for the pier to be considered vulnerable, the managers might continue monitoring the pier or might decide to take action and place protective material around the pier to add support and reduce the chance for additional scour. The results of these MBES surveys did not lead the North Dakota Department of Transportation to take action at any of the bridges surveyed; however, at the Grant Marsh bridge (table 1) protective material was being placed to stabilize an eroding bank around the bridge abutment. The survey of one pier at Grant Marsh bridge indicated protective material surrounding it; managers knew that protective material had been placed around the pier during a previous flood, but the current survey helped managers in evaluating the current condition and functionality of the material. The surveys also indicated that the footings of some piers at Washburn and Buford bridges (table 1) were partially exposed implying that the State Department of Transportation would need to further evaluate the bridge construction information to determine if this amount of scour would have a substantial effect on the bridge stability. Bridges may be constructed in such a manner that the exposure of the footing (and sometimes even the seal course) is minimal compared to the rest of the structure still buried, so exposure of these substructural elements may not substantially affect bridge stability. However, it is the responsibility of the state agency to use construction information in comparison to the survey data to make that determination.

Surveys of critical infrastructure provide additional information about the riverbed at the survey sites including the nature of bedforms, and overall channel-bed scour or deposition became apparent when multiple surveys were completed. Surveys at North Dakota bridges indicated that the riverbed surrounding the bridges had a variety of bedforms or dunes that varied greatly in size and location from bridge to bridge as well as from the initial survey to the second survey. Dunes varied in height from 0.5 to 2.7 m. The size and movement of dunes surrounding a bridge potentially could pose a danger to the bridge structure if the elevation of the dune trough was low enough to make a pier unstable as a dune sequence moved past the pier. Scour, which usually manifests as a horseshoe-shaped hole around the pier nose, is typically distinguishable from a dune trough. Regardless of whether scour is present or not, as the dune sequence moves through, the riverbed elevation surrounding the pier will increase and decrease with the dune movement and this must be considered by the state agencies when they evaluate the data. At bridge sites that were surveyed more than once there was a general correlation of increasing overall channel scour with increasing streamflow. However, most site results indicated a variation in spatial pattern with increased streamflow, with scour in some areas and deposition in others. The hydrographic datasets from the bridge surveys in North Dakota during the 2011 flood are published in Densmore and others (2013).

Table 1. Location and survey date of hydrographic surveys at Missouri River bridges during the 2011 flood, in downstream order.

[ND, North Dakota; Hwy, Highway; US, United States; NE, Nebraska; SD, South Dakota; I, Interstate; IA, Iowa; W, west; E, east; MO, Missouri; KS, Kansas; S, south; N, north]

Map number (fig. 1)	Bridge name	Route	City	Date surveyed (month/day/year)	Reference report
			North Dakota		
1	Buford bridge	ND Hwy 58	Buford, ND	6/8/2011	Densmore and others, 2013
2	Williston bridge	U.S. Hwy 85	Williston, ND	6/8/2011	Densmore and others, 2013
3	Washburn bridge	ND Hwy 200	Washburn, ND	6/9/2011 and 7/9/2011	Densmore and others, 2013
4	Grant Marsh bridge	I-94	Bismarck, ND	6/6/2011 and 7/5/2011	Densmore and others, 2013
5	West Bismarck Expressway bridge	ND Hwy 810	Bismarck, ND	6/6/2011 and 7/3/2011	Densmore and others, 2013
6	Memorial Highway bridge	Bussiness Loop I-94	Bismarck, ND	6/7/2011 and 7/3/2011	Densmore and others, 2013
			South Dakota/Nebraska		
7	Chief Standing Bear Memorial bridge	NE Hwy 14/SD Hwy 37	Niobrara, NE	7/25/2011 and 7/29/2011	Dietsch and others, 2014
8	Yankton Discovery bridge	US Hwy 81	Yankton, SD	7/20/2011, 7/29/2011, 9/6/2011, and 10/31/2011	Dietsch and others, 2014
9	Newcastle-Vermillion bridge	NE Hwy 15/SD Hwy 19	Vermilllion, SD	6/23/2011, 7/21/2011, 8/4/2011, and 9/1/2011	Dietsch and others, 2014
			Iowa/Nebraska		
10	Siouxland Veterans Memorial bridge	US Hwy 77	Sioux City, IA	7/24/2011, 8/5/2011, 9/2/2011, and 11/1/2011	Dietsch and others, 2014
11	Sergeant Floyd Memorial bridge	I-29, US Hwy 20, US Hwy 75	Sioux City, IA	7/24/2011, 8/5/2011, 9/2/2011, and 11/1/2011	Dietsch and others, 2014
12	Burt County bridge	NE Hwy 51/IA Hwy 175	Decatur, NE	7/12/2011, 7/28/2011, 8/31/2011, and 11/2/2011	Dietsch and others, 2014
13	Abraham Lincoln Memorial bridge	US Hwy 30	Blair, NE	7/25/2011, 7/28/2011, 9/6/2011, and 11/2/2011	Dietsch and others, 2014
14	Mormon Pioneer Memorial bridge	I-680	Omaha, NE	7/13/2011, 8/1/2011, 9/7/2011, and 11/3/2011	Dietsch and others, 2014
15	Grenville Dodge Memorial bridge	I-480	Omaha, NE	7/13/2011, 8/3/2011, 9/7/2011, and 11/3/2011	Dietsch and others, 2014
16	Interstate 80 bridge	I-80	Omaha, NE	7/13/2011, 8/3/2011, 9/7/2011, and 11/3/2011	Dietsch and others, 2014
17	South Omaha Veterans Memorial bridge	US Hwy 275, NE Hwy 92, IA Hwy 92	Omaha, NE	7/14/2011, 8/3/2011, 9/7/2011, and 11/3/2011	Dietsch and others, 2014
18	Bellevue bridge	NE Hwy 370/IA Hwy 370	Bellevue, NE	7/26/2011, 7/30/2011, 9/7/2011, and 11/9/2011	Dietsch and others, 2014
19	Plattsmouth Toll bridge	US Hwy 34	Plattsmouth, NE	7/18/2011, 7/27/2011, 9/8/2011, and 11/4/2011	Dietsch and others, 2014
20	Nebraska City bridge	US Hwy 2	Nebraska City, NE	7/19/2011, 8/2/2011, 9/13/2011, and 10/19/2011	Dietsch and others, 2014
			Missouri/Nebraska		
21	Brownville bridge	US Hwy 136	Brownville, NE	7/13/2011	Huizinga, 2012
22	Rulo bridge	US Hwy 159	Rulo, NE	7/26/2011, 7/30/2011, 9/14/2011, and 11/4/2011	Dietsch and others, 2014
			Missouri/Kansas		
23	St. Joseph bridge	US Hwy 36 W	St. Joseph, MO	7/14/2011	Huizinga, 2012
23	St. Joseph bridge	US Hwy 36 E	St. Joseph, MO	7/14/2011	Huizinga, 2012
24	Atchison bridge	US Hwy 59	Atchison, KS	7/15/2011	Huizinga, 2012
25	Leavenworth bridge	MO Hwy 92/KS Hwy 92	Leavenworth, KS	7/15/2011	Huizinga, 2012
26	Parkville bridge	I-435 S	Kansas City, MO	7/16/2011	Huizinga, 2012

Table 1. Location and survey date of hydrographic surveys at Missouri River bridges during the 2011 flood, in downstream order.—Continued

[ND, North Dakota; Hwy, Highway; US, United States; NE, Nebraska; SD, South Dakota; I, Interstate; IA, Iowa; W, west; E, east; MO, Missouri; KS, Kansas; S, south; N, north]

Map number (fig. 1)	Bridge name	Route	City	Date surveyed (month/day/year)	Reference report
			Missouri/Kansas—Continued		
26	Parkville bridge	I-435 N	Kansas City, MO	7/16/2011	Huizinga, 2012
27	Riverside bridge	I-635	Kansas City, MO	7/16/2011	Huizinga, 2012
28	Fairfax bridge	US Hwy 69 S	Kansas City, MO	7/16/2011	Huizinga, 2012
28	Fairfax Toll bridge	US Hwy 69 N	Kansas City, MO	7/16/2011	Huizinga, 2012
			Missouri		
29	Broadway Avenue bridge	US Hwy 169	Kansas City, MO	7/17/2011	Huizinga, 2012
30	Heart of America bridge	MO Hwy 9	Kansas City, MO	7/17/2011	Huizinga, 2012
31	kcICON bridge	I-35	Kansas City, MO	7/17/2011	Huizinga, 2012
32	Chouteau bridge	MO Hwy 269	Kansas City, MO	7/18/2011	Huizinga, 2012
33	Randolph bridge	I-435	Kansas City, MO	7/18/2011	Huizinga, 2012
34	Courtney bridge	MO Hwy 291 S	Kansas City, MO	7/19/2011	Huizinga, 2012
34	Courtney bridge	MO Hwy 291 N	Kansas City, MO	7/19/2011	Huizinga, 2012
35	Lexington bridge	MO Hwy 13	Lexington, MO	7/20/2011	Huizinga, 2012
36	Waverly bridge	US Hwy 24	Waverly, MO	7/21/2011	Huizinga, 2012
37	Miami bridge	MO Hwy 41	Miami, MO	7/21/2011	Huizinga, 2012
38	Glasgow bridge	MO Hwy 240	Glasgow, MO	7/22/2011	Huizinga, 2012
39	Boonville bridge	MO Hwy 5	Boonville, MO	7/25/2011	Huizinga, 2012
40	Rocheport bridge	I-70	Rocheport, MO	7/26/2011	Huizinga, 2012
41	Jefferson City bridge	US Hwy 54 S	Jefferson City, MO	7/27/2011	Huizinga, 2012
41	Jefferson City bridge	US Hwy 54 N	Jefferson City, MO	7/27/2011	Huizinga, 2012
42	Hermann bridge	MO Hwy 19	Hermann, MO	7/28/2011	Huizinga, 2012
43	Washington bridge	MO Hwy 47	Washington, MO	7/27/2011	Huizinga, 2012
44	Daniel Boone bridge	US Hwy 40 E	St. Louis, MO	7/29/2011	Huizinga, 2012
44	Daniel Boone bridge	US Hwy 40 W	St. Louis, MO	7/29/2011	Huizinga, 2012
45	Page Avenue bridge	MO Hwy 364 E	St. Louis, MO	8/1/2011	Huizinga, 2012
45	Page Avenue bridge	MO Hwy 364 W	St. Louis, MO	8/1/2011	Huizinga, 2012
46	Blanchette bridge	I-70 E	St. Louis, MO	8/2/2011	Huizinga, 2012
46	Blanchette bridge	I-70 W	St. Louis, MO	8/2/2011	Huizinga, 2012
47	Discovery bridge	MO Hwy 370 E	St. Louis, MO	8/2/2011	Huizinga, 2012
47	Discovery bridge	MO Hwy 370 W	St. Louis, MO	8/2/2011	Huizinga, 2012
48	Lewis & Clark bridge	US Hwy 67	St. Louis, MO	8/3/2011	Huizinga, 2012

Nebraska Bridges

Fifteen Missouri River bridges, 3 along the South Dakota/Nebraska border, 11 along the Iowa/Nebraska border, and 1 along the Missouri/Nebraska border, were surveyed in cooperation with the Nebraska Department of Roads during the 2011 Mississippi River Basin flood (table 1) (Dietsch and others, 2014). In addition to the highway and interstate bridges surveyed, three railroad bridges were surveyed because of their location within survey reaches. The Brownville bridge (table 1) is not included in this section; it is discussed in the Missouri bridges section because it was surveyed in cooperation with the Kansas and Missouri Departments of Transportation. Survey methods and detailed results for the survey of these 15 bridges are presented in Dietsch and others (2014). Fourteen of the 15 bridges were surveyed 4 different times throughout the flood event. In general, the first two surveys at each site were completed during the peak of the flood, and streamflows of more than 4,248 cubic meters per second (m^3/s) [150,000 cubic feet per second (ft^3/s)] were observed during this time. The third survey was completed as the flood receded, with streamflows between 2,548–3,144 m^3/s (90,000–111,000 ft^3/s). The final survey at each site was completed when streamflows were in the normal seasonal ranges, between 1,132-1,592 m^3/s (40,000–56,200 ft^3/s) (Dietsch and others, 2014).

Each bridge surveyed along the Nebraska border indicated a unique response to the flood event. Riverbed elevations near bridge piers indicated no scour or very limited scour at six bridges. Scour near bridge piers at the other nine bridge sites ranged from less than 1 m to a maximum of 6 m. The largest scour hole near a bridge pier was surveyed at the Nebraska City bridge (table 1) (6 m) and the usually buried substructural support elements of piers were exposed at several bridges. As described previously, the minimum elevation of the scour hole surrounding a pier is used by state agencies managing the structure and compared to the construction details of that pier to determine if the pier and overall bridge structure are safe. The largest scour near bridge infrastructure along the Nebraska border was surveyed in a relict or historic channel on the Iowa side of the Burt County bridge (Nebraska Highway 51) (table 1), where flood waters caused severe erosion around the abutment and threatened the safety of the bridge forcing closure of the bridge by the Iowa Department of Transportation (Hytrek, 2012). The Burt County bridge was closed on June 27 and remained closed throughout the flood event. This relict channel was surveyed during the first two surveys at the Burt County bridge on July 12 and 28 (fig. 8), and the greatest scour surveyed in this channel was 14.3 m. Of the 15 bridges surveyed in Nebraska, the Burt County bridge was the only bridge closed because of safety concerns from scour.

Additional information can be gained from the data collected while surveying the bridges along the Nebraska border, including information about bedforms, overall channel aggradation or degradation, and riverbed elevations near railroad bridges. Bedforms were prevalent on the riverbed at many of the bridge survey sites. Bedforms often changed with changing streamflow, and bedforms greater than 3 m from trough to peak were surveyed at several sites during the high flow conditions. Overall channel scour or deposition was described by Dietsch and others (2014) using histograms (fig. 9) of riverbed elevations from the active channel at each site for each survey. The active channel in this instance is defined as the riverbed in the main flow not including the river margins or the riverbed directly under the bridges, and was manually selected by the surveyor during analysis (Dietsch and others, 2014). These histograms help to visualize how the riverbed elevations changed from survey to survey, including change in the diversity through the channel as well as the overall average elevation of the channel. A comparison between the first surveys during high flows to the final surveys following the flood indicated no change in the mean active-channel elevation at 7 of the 15 bridges, approximately 1.5 to 2.0 m of deposition at 4 sites, substantial deposition greater than 4.5 m at three sites, and continued scour throughout all the surveys at 1 site. The South Omaha Veterans Memorial bridge (table 1) average active-channel elevation analysis documented approximately 1.5 m of scour between July 14 and November 3. This is especially interesting since more than 4.5 m of deposition was surveyed at the Bellevue bridge (table 1 and fig. 9), which is only 17 km downstream from the South Omaha Veterans Memorial bridge, so possibly the material scoured from the South Omaha Veterans Memorial bridge was deposited near the Bellevue bridge.

Overall the MBES surveys at Nebraska bridges indicated varying amounts of scour around bridge piers along the Nebraska border and throughout the flood event. As much as 6 m of scour was observed around some bridge piers and 14.3 m of scour was observed where water was flowing through a relict channel around a bridge abutment. Comparison of average active-channel elevations among the resurveys at each bridge indicated no change in the mean active-channel elevation to greater than 4.5 m of deposition. The surveys of the riverbed near bridge piers can provide needed information about scour, but also can provide much more detail about the riverbed in the vicinity of the infrastructure. Dietsch and others (2014) provides details on each bridge site surveyed.

Missouri Bridges

Thirty-six bridge structures were surveyed using an MBES at 27 crossing locations on the Missouri River on the Missouri/Nebraska border, Missouri/Kansas border, and in the State of Missouri in cooperation with the Kansas and Missouri Departments of Transportation during the 2011 flood (Huizinga, 2012). Bridges surveyed included 5 upstream from Kansas City, 12 in the greater Kansas City area, 10 between Kansas City and St. Louis, and 9 within the greater St. Louis area (table 1). Surveys were completed between July 13 and August 3, 2011 (table 1). In addition to the highway and

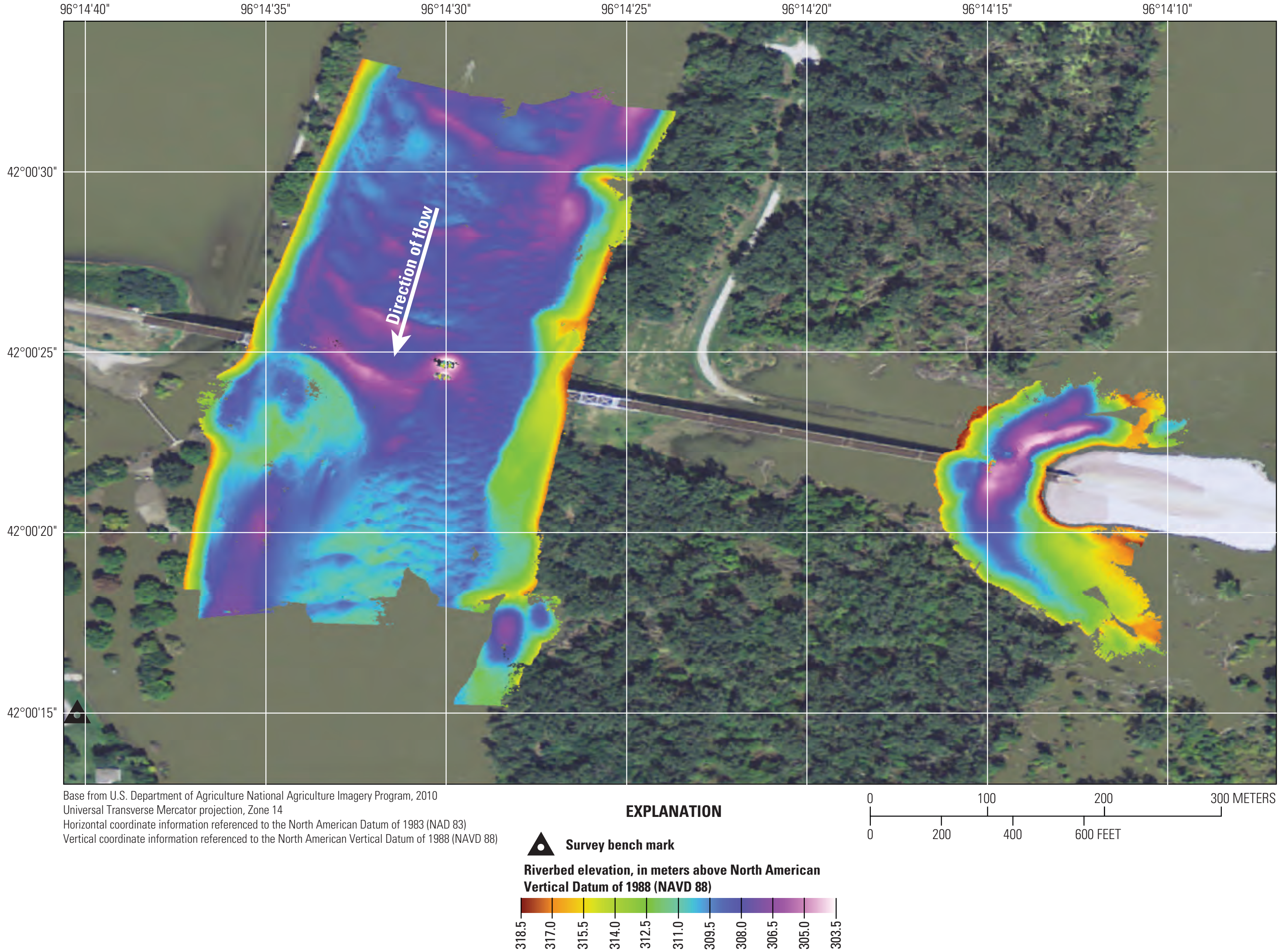


Figure 8. Riverbed elevations of the Missouri River in the vicinity of Burt County bridge in Decatur, Nebraska, on July 28, 2011 (modified from Dietsch and others, 2014).

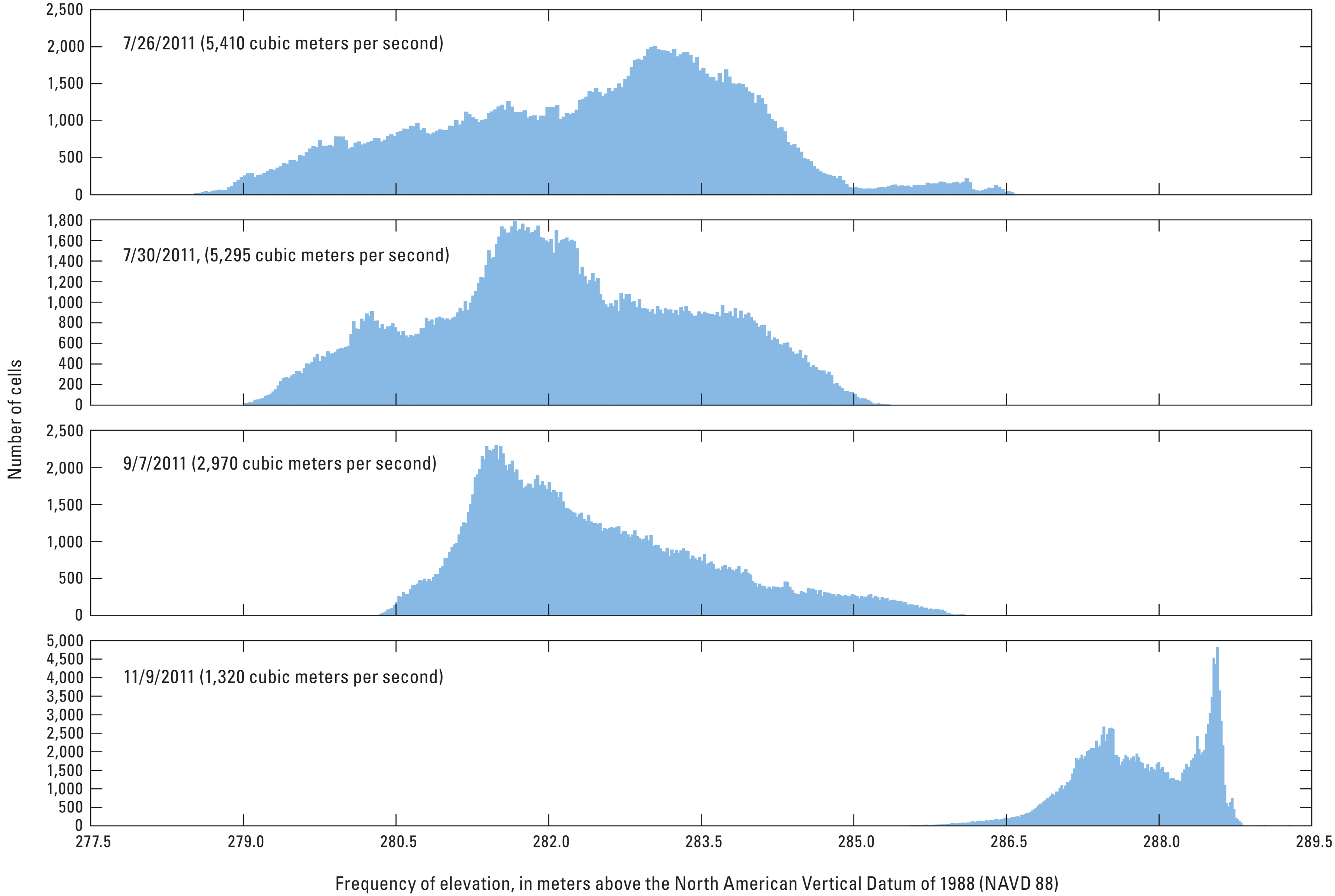


Figure 9. Frequency of elevation, in meters above the North American Vertical Datum of 1988, values for bathymetric grid cells (0.5 by 0.5 meters) collected on the Missouri River in the vicinity of Nebraska State Highway 370, in Bellevue, Nebraska (modified from Dietsch and others, 2014).

interstate bridges surveyed, six railroad bridges were surveyed because of their location within survey reaches.

The hydrographic surveys at Missouri bridges indicated the effects of bridge and channel structures on the riverbed, the diversity of bedforms present during the flood, two sunken barges, numerous remains of old bridge piers, several areas of bedrock outcropping, and some unidentified objects. Scour holes were present at most piers for which bathymetry could be obtained, except at piers on channel banks, those near or embedded in lateral or longitudinal spur dikes, and those on exposed bedrock outcrops (Huizinga, 2012). Occasionally the scour hole near the pier was difficult to discern from nearby bed features, and a few piers surveyed were surrounded by mounded scour-resistant material (Huizinga, 2012). Scour holes also were documented near railroad bridge piers as well as spur dikes. Riverbed elevations documented by Huizinga (2012) near bridge piers ranged from zero (no scour) to 10.4 m of scour. Bedform height, defined as the height of the dune peak relative to the trough, were described by Huizinga as small (less than 1.5 m), medium (1.5–3 m), large (3–4.5 m), and very large (greater than 4.5 m). Very large or large dunes, or both, were documented at 19 of the 27 survey locations.

Huizinga (2012) compared the 2011 flood hydrographic surveys at Missouri bridges against bridge-design elevations, as-built ground lines, previous bridge inspection ground lines, and previous MBES surveys where data were available. At several piers, substructural support elements could be discerned in the hydrographic surveys (fig. 10), and comparison to bridge-design elevations supported the visual analysis (fig. 11). Although substructural support elements were observed at several piers, at most sites the exposure likely can be considered minimal compared to the overall substructure that remained buried in bed material. However, exceptions were found at U.S. Highway 59 at Atchison, Kans.; State Highway 41 at Miami, Mo.; Missouri State Highway 240 at Glasgow, Mo.; Missouri State Highway 5 at Boonville, Mo.; and U.S. Highway 54 at Jefferson City, Mo. (table 1). At these locations the depth of scour holes near some piers left the bed material thickness between the bottom of the scour hole and bedrock at less than 1.8 m at the nose of the pier. Bridge plans for these bridges state that these piers are caissons founded on bedrock, and specific information about how the caissons are attached to bedrock is not available. It should be noted that with modern construction, bridge substructural elements usually are pinned or socketed to bedrock, but full exposure of usually buried substructural elements warrants special consideration and observation.

In 2010, MBES surveys were completed at most Kansas City area bridges (Riverside, Fairfax, Broadway Avenue, Heart of America, Chouteau, Randolph, and Courtney), all St. Louis area bridges, and at the Atchison, Kans., and Jefferson City, Mo., bridges (fig. 1 and table 1). Many of these previous surveys also were collected during high flow; however, water-surface elevations were much greater in 2011 than in 2010, with a difference of 1.1 m at Atchison, Kans.; 2.9–3.2 m in the Kansas City area; 1.4 m at Jefferson City, Mo.; and 2.8–3.6 m in the St. Louis area. Comparison of the 2011 surveys to the 2010 surveys in the greater Kansas City area indicate no consistent deepening of the channel or increase in the size of scour holes, despite a substantial increase in streamflow and water-surface elevation (Huizinga, 2012). Comparisons at four of the seven bridges in the greater Kansas City area indicate substantial deposition between the two surveys. This same scenario was seen at Atchison, Kans., where deposition was documented between the 2010 and the 2011 surveys. However, at Jefferson City, Mo., and at all bridges in the greater St. Louis area, scour was apparent between the 2010 and 2011 surveys. The mean difference between surveys ranged from relatively minimal scour (0.05 m) to substantial scour of the riverbed (1.5 m). A possible explanation for the deposition between the 2010 and the 2011 flood in the greater Kansas City area is that the surveys in 2011 took place as a plug or pulse of sediment was moving through the area. Huizinga (2012) also describes comparisons between the 2011 surveys and other surveys before 2010 at Atchison, Kans., and Jefferson City, Mo. A comparison of six repeat surveys at the Atchison, Kans., bridge, including the 2011 flood survey, can be found in Huizinga (2013).

In addition to MBES surveys, acoustic Doppler current profiler velocity surveys were collected along select transects at each Missouri bridge site. Typical velocities ranged from 1 to 3.7 meters per second (m/s) with some faster and slower localized velocities measured. In general, very large dunes (defined as greater than or equal to 4.5 m from trough to peak) and smooth riverbeds were surveyed in areas where velocities were from 2.7 to 3.7 m/s.

Huizinga (2012) also documents and compares scour holes near bridge piers as surveyed by a MBES in 2011 with real-time scour monitoring at the pier of the downstream bridge at Jefferson City, U.S. Highway 54 (table 1), using a single beam acoustic transducer (a similar study is documented in Rydlund, 2009). This comparison indicated that the MBES survey and the real time single beam surveys agreed well. The single-beam transducer was able to capture more than just one “snap shot” of the scour hole, and was able to document the formation and persistence of the scour hole throughout the 2011 flood event, followed by aggradation after the flood event (Huizinga, 2013).

Pipelines and Other Infrastructure

Hydrographic surveys of the riverbed near other critical infrastructure including pipelines, power plant intakes and outlets, and electrical transmission towers were completed during the 2011 Mississippi River Basin flood using a MBES.

Fifteen pipelines were surveyed in four different locations on the Missouri River along the Nebraska border in cooperation with the U.S. Environmental Protection Agency (EPA) and the U.S. Coast Guard. Pipeline monitoring and safety is handled by the Office of Pipeline Safety (OPS)—part of the

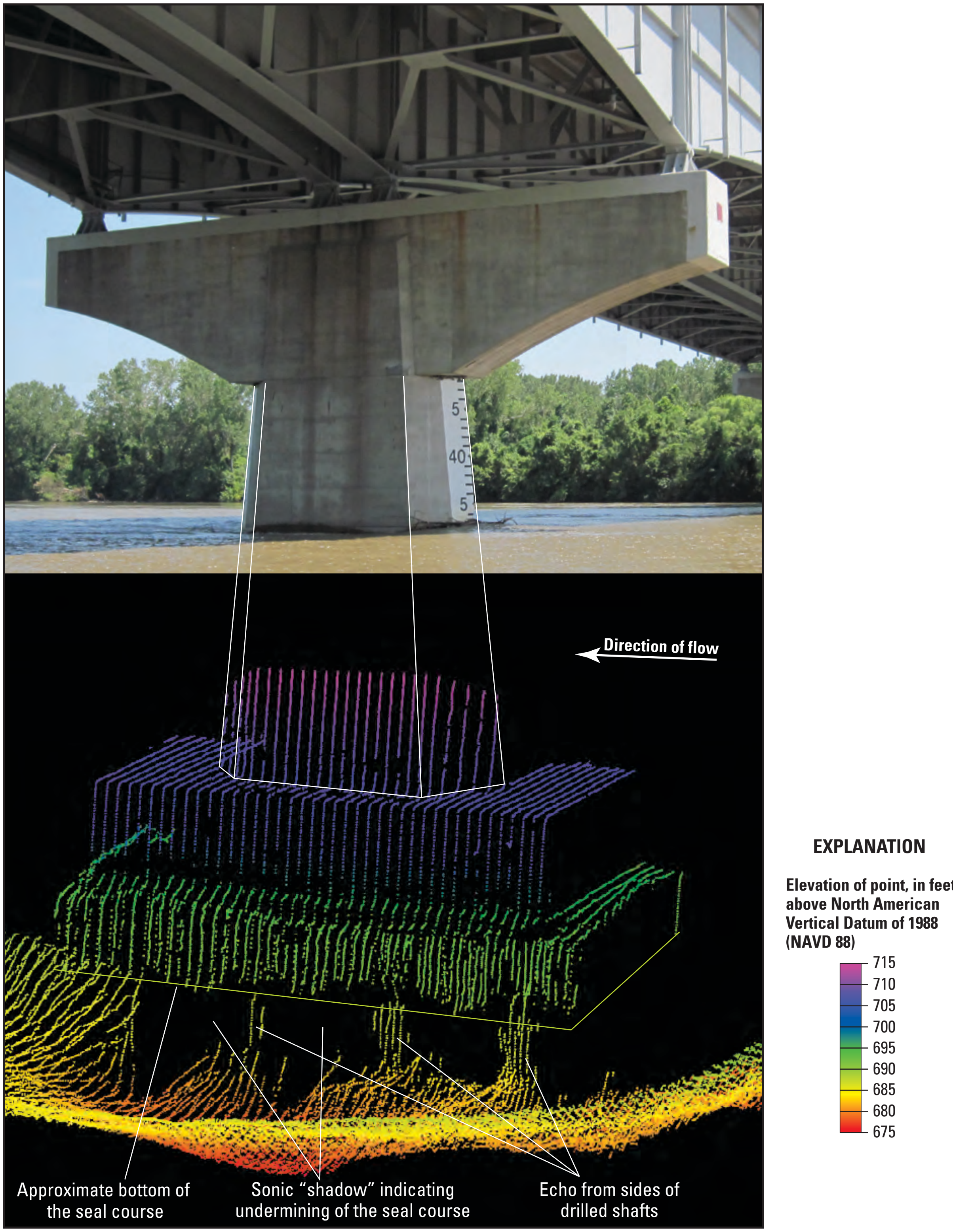


Figure 10. Point cloud visualization of the channel bed and left (north) side of main channel pier 7 of structure A0767 on Interstate 435 over the Missouri River in Kansas City, Missouri (from Huizinga, 2012).

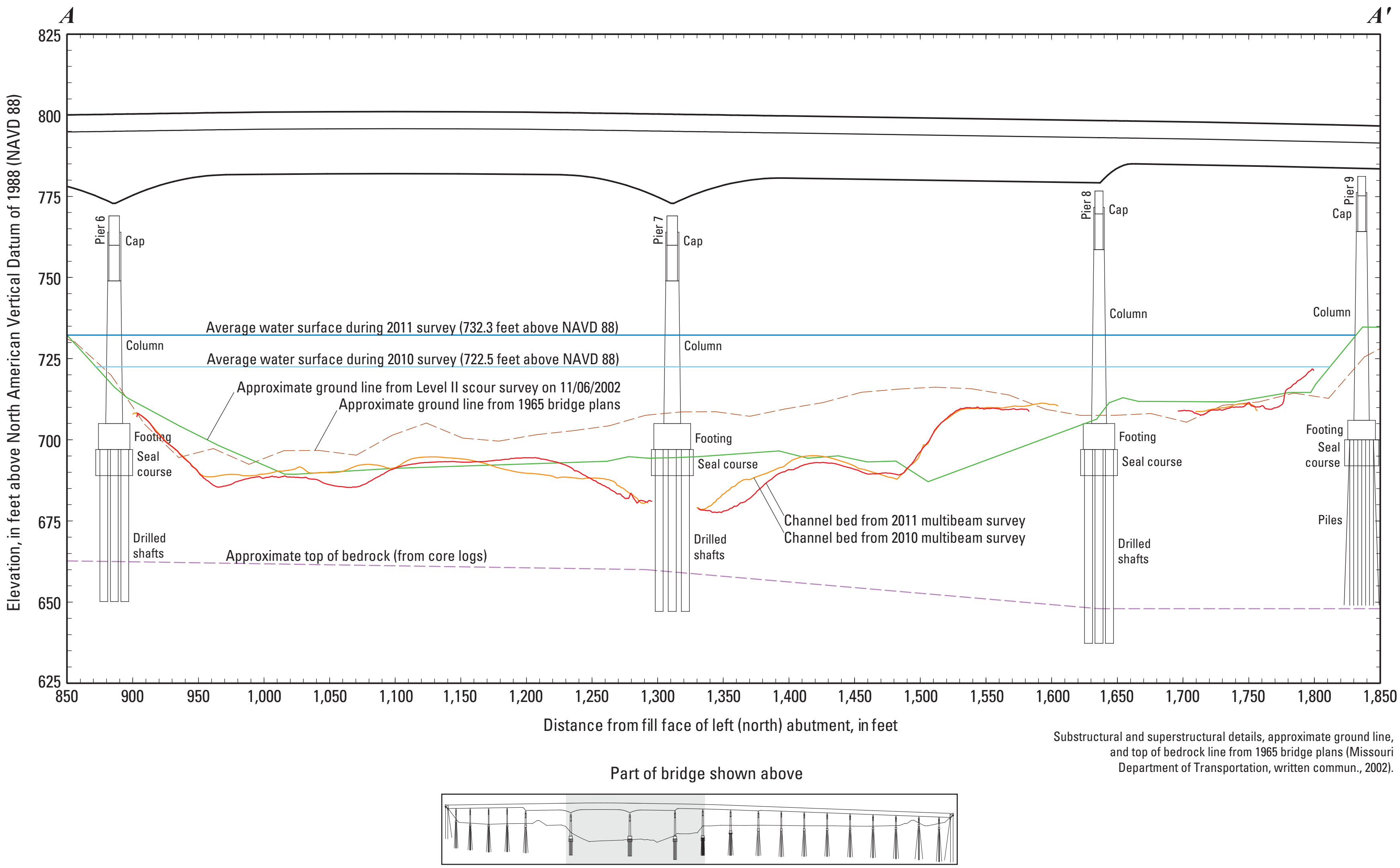


Figure 11. Key features, substructural and superstructural details, and surveyed channel bed of structure A0767 on Interstate 435 over the Missouri River in Kansas City, Missouri (from Huizinga, 2012).

U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration—and by the EPA. Pipelines that cross under and over rivers often are affected by flood waters, and if a pipeline ruptures and spills harmful materials into the water the EPA is typically the administrator that oversees the cleanup process and mitigation under the authority of the 1972 amendments to the Federal Water Pollution Control Act known as the Clean Water Act (CWA, 33 U.S.C. § 1321). During the 2011 Mississippi River Basin flood, the USGS in cooperation with the EPA completed MBES surveys of the riverbed in the vicinity of 15 pipelines at 4 different locations on the Missouri River. The data from the surveys were processed immediately following collection to determine the current elevation of the underlying riverbed. The EPA and the pipeline companies could then use the elevation data to determine if there was risk of the pipeline being exposed. Pipelines that are no longer covered and protected by riverbed sediments might not be able to withstand the pressure from the flood waters or might have debris catch on them increasing the chance of the pipeline rupturing. However, elevation information for these pipelines was either non-existent, roughly estimated, or not accessible to EPA and USGS. This made the riverbed surveys a less effective method in fully evaluating pipeline safety. Riverbed elevation could not be compared to pipeline elevation so the depth of the protective riverbed material was unknown. Most pipeline companies inspect their lines routinely to ensure safety and meet state and federal requirements (requirements vary depending on the type and location of the pipeline) (Pipeline and Hazardous Materials Safety Administration, 2014). The use of smart pipeline inspection gauges (PIGS) also referred to as in-line inspection tools, which have the ability to measure and internally record position from inertial measurement units (Pipesurvey International, 2011; Cooke, 2011), would aid in evaluating the safety of pipelines that cross under waterways by knowing the elevation of the pipeline which could be related to the elevation of the riverbed as determined through hydrographic surveys during a flood event.

Surveyed pipeline crossings were located at Yankton, S. Dak.; Decatur, Nebr.; Plattsmouth, Nebr.; and Union, Nebr. (fig. 2). Table 2 documents the location of pipelines surveyed, the owners of the pipelines surveyed, the dates the pipelines were surveyed, and the number of pipelines surveyed. The pipelines at Plattsmouth were located within the study area of the bridge surveys described above; therefore the riverbed in the vicinity of these pipelines was surveyed four different times.

Water is essential to the operation of power plants and interruptions to the flow of water into or out of them could disrupt power production. In response to concerns about the effects on the power plants, the riverbed, banks, and intake and outlet structures were surveyed at three power plants located on the Missouri River in Nebraska in cooperation with OPPD, including the Nebraska City coal-fired power plant, the Fort Calhoun nuclear power plant, and the North Omaha coal and natural gas power plant (table 2). OPPD requested that the USGS complete hydrographic surveys of the riverbed, banks, and inlets and outlets to document any possible scour, deposition, or damage caused by the flood that might affect the plants' operations.

In addition, OPPD requested that the USGS complete a hydrographic survey near an electrical transmission tower located about 30 m west of the Nebraska bank of the Missouri River, east of Homer, Nebr. (fig. 2), where the flooding river overtopped its banks and the swift current had scoured a hole and caused structural stability concerns for the tower. OPPD crews had manually monitored an expanding scour hole at this electrical transmission tower as flood waters rose, but as the hole expanded in width and depth, manual monitoring no longer provided OPPD with the information they needed. Therefore, the USGS completed three MBES hydrographic surveys of the area surrounding the tower (table 2).

Results of Hydrographic Surveys

No completely exposed pipelines were identified by the USGS. However, analysis of the USGS survey data by one pipeline company led them to further investigate the safety of a line, and aided another company in getting an offline pipeline back into operation. Results from the survey of the riverbed in the vicinity of the Yankton pipelines documented bed elevations ranging from 346.6 m to 353.3 m on July 20 (fig. 12). During the survey, a representative from the NuStar Energy LP Company observed the data collection and made real-time assessments of the pipeline safety. NuStar Energy LP had known elevations on the two pipelines in the Yankton area from a survey completed in May of 2011. The highest elevation of the pipelines under the riverbed is estimated to be 346.55 m from data provided to the USGS from the May 2011 survey (B. Myers, NuStar Energy LP Company, unpub. data, 2011). Riverbed elevations surveyed in the vicinity of pipelines at Decatur, Nebr., Plattsmouth, Nebr., and Union, Nebr. could not be compared to pipeline elevations since that information was not available to the USGS.

Survey results at the three OPPD power plants provided riverbed elevation data from the entire river channel upstream and downstream from the plants. This included information about the riverbed elevation (and change in elevation when more than one survey was completed) at the interface with the vertical wall of the inlet and outlet structures. Riverbed elevations at the interface with the vertical wall of the power plant structures were approximately 269 m during both surveys at the Nebraska City coal-fired power plant, approximately 296 m on July 25 and 295.2 m on September 15 at the Fort Calhoun nuclear power plant, and approximately 292 m at the North Omaha coal and natural gas power plant. Riverbed elevation near the inlet and outlet structures of the power plants are important to OPPD as deposition could block water intake or release and scour could leave the structures less stable, both of which could adversely affect plant operations. In addition, the flood waters could lodge debris in gates or

Table 2. Location and survey date of hydrographic surveys at pipelines, power plants, and transmission towers during the 2011 flood.

[SD, South Dakota; NE, Nebraska; LP, limited partnership; na, not applicable]

Map number (fig. 2)	Location	Owners	Date surveyed (month/day/year)	Number of pipelines surveyed
		Pipelines		
49	Yankton, SD	NuStar Energy LP	7/20/2011	2
50	Decatur, NE	Enterprise	7/12/2011	3
50	Decatur, NE	Magellan	7/15/2011	5
51	Plattsmouth, NE	Northern Natural Gas, National Refinery Association, ONEOK North Company	7/18/2011, 7/27/2011, 9/8/2011, and 11/4/2011	2, 1, 1 respective to owners
52	Union, NE	ONEOK North Company	7/27/2011	1
		Power plants		
53	Nebraska City coal-fired	Omaha Public Power District	7/19/2011 and 9/14/2011	na
54	Fort Calhoun nuclear	Omaha Public Power District	7/24/2011 and 9/15/2011	na
55	North Omaha coal and natural gas	Omaha Public Power District	10/14/2011	na
		Transmission towers		
56	Homer, NE	Omaha Public Power District	6/21/2011, 7/16/2011, and 8/31/2011	na

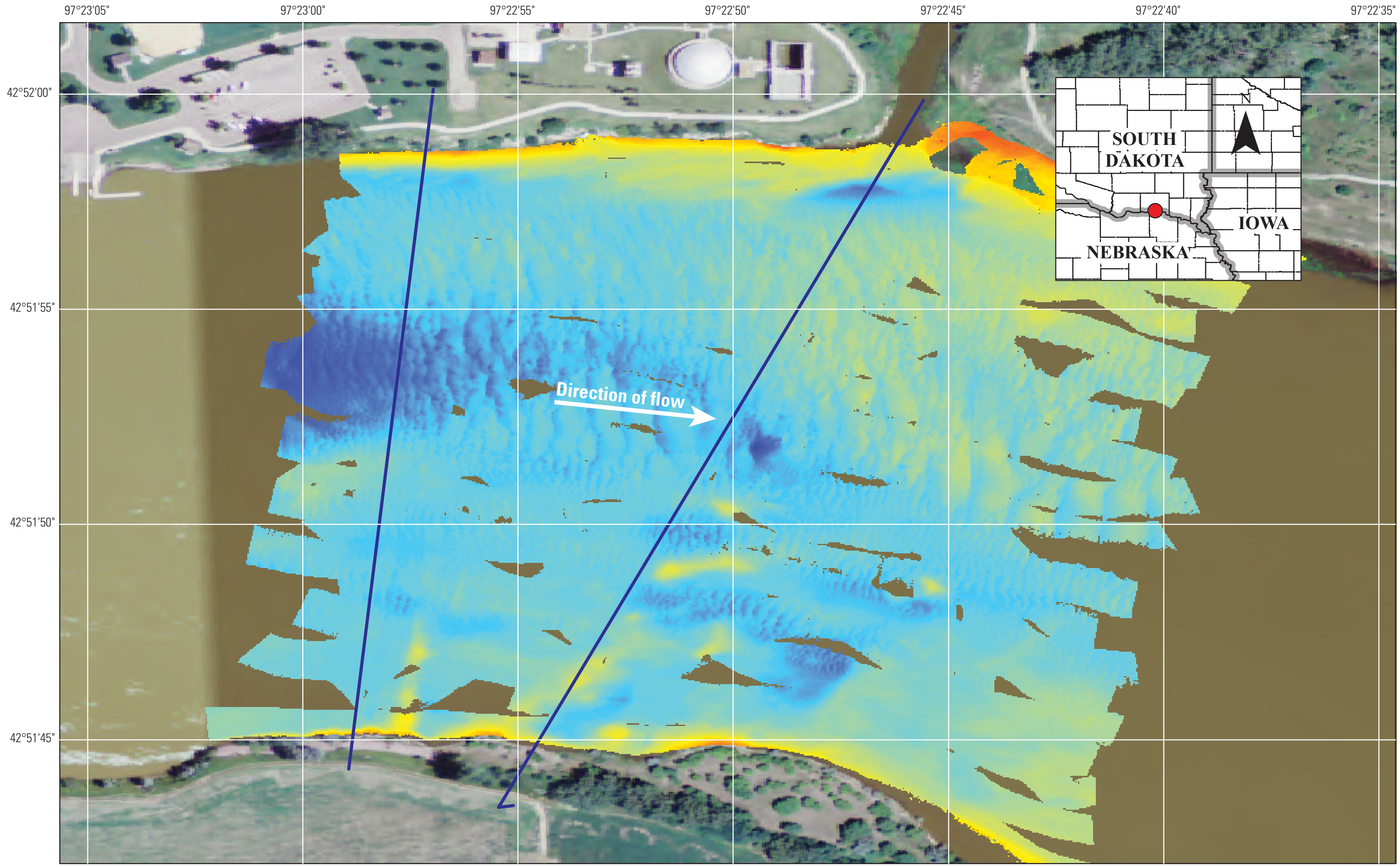
cause damage to other underwater structures. The vertical wall of the intake structures were captured in detail by the sonar in the North Omaha coal and natural gas power plant survey on October 14, 2011 (fig. 13) and similar details can be seen in the surveys of the other power plants.

Results from a hydrographic survey near the OPPD electrical transmission tower (table 2) indicated a scour hole was created around the support structures of the tower because of overbank flooding (fig. 14). The initial survey on June 21 identified a scour hole with a minimum elevation of 322 m near the northeast tower support and an estimated surrounding ground elevation of 324.6 m. The scour hole began near the northwest support and extended east approximately 18 m, with a north/south extent of approximately 19 m (fig. 14*A*). The survey on July 16 indicated the scour hole had not deepened, but had expanded to the east and the south (fig. 14*B*). The approximate size of the scour hole on July 16 was 22.5 m wide (east to west) and 22.7 m long (north to south) with an additional secondary scour hole extending from the main scour hole toward the edge of the river with a length of approximately 10 m. By the September 10 survey, most of the scour hole had filled in by 1 to 2 m, but the minimum elevation near the northeast support was still 322.6 m (fig. 14*C*). The scour hole had reduced in size to approximately 18 m east to west, but the survey did not capture the full north to south extent because of the change in current direction, shallower depths, and the downstream stand of trees. The data on the greatest extent and depth of the scour hole during the flood were used by OPPD to repair the tower structure once flood waters receded by removing the river sediments that had deposited around the tower and replacing those sediments with more supportive and stable materials.

Summary

During the 2011 Mississippi River Basin flood the U.S. Geological Survey evaluated critical river infrastructure at the request of and in support of local, State, and Federal Agencies. Critical infrastructure surveyed by the U.S. Geological Survey during the 2011 flood included levees, bridges, pipeline crossings, power plant intakes and outlets, and an electrical transmission tower. These data were collected and processed in a short time frame to provide managers the ability to make a timely evaluation of the safety of the infrastructure and, when needed, to take action to secure and protect critical infrastructure.

The 7 kilometers of capacitively coupled resistivity surveys on June 13, 2011, on the flood-protection levees surrounding the Omaha Public Power District Nebraska City power plant (Missouri River Levee Unit R573) mapped the near-subsurface electrical properties of the levee and the materials immediately below it. These data provided a better understanding of the levee construction and the nature of the lithology beneath the levee. Comparison of the capacitively coupled resistivity surveys and soil borings indicated that low-resistivity value material composing the levee generally is associated with lean clay and silt down to a depth of about 2 to 4 meters below the surface overlying a more resistive layer associated with sand deposits. In general, the resistivity structure



Base from U.S. Department of Agriculture National Agriculture Imagery Program, 2010
Universal Transverse Mercator projection, Zone 14
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)

EXPLANATION

Approximate location of pipeline

Riverbed elevation, in meters above North American Vertical Datum of 1988 (NAVD 88)

353.3 352.7 352.2 351.6 351.1 350.5 312.5 350.0 348.8 348.3 347.7 347.2 346.6

0 100 200 300 METERS
0 200 400 600 FEET

Figure 12. Riverbed elevations surveyed with a multibeam echosounder at pipeline crossings at Yankton, South Dakota, on July 20, 2011.

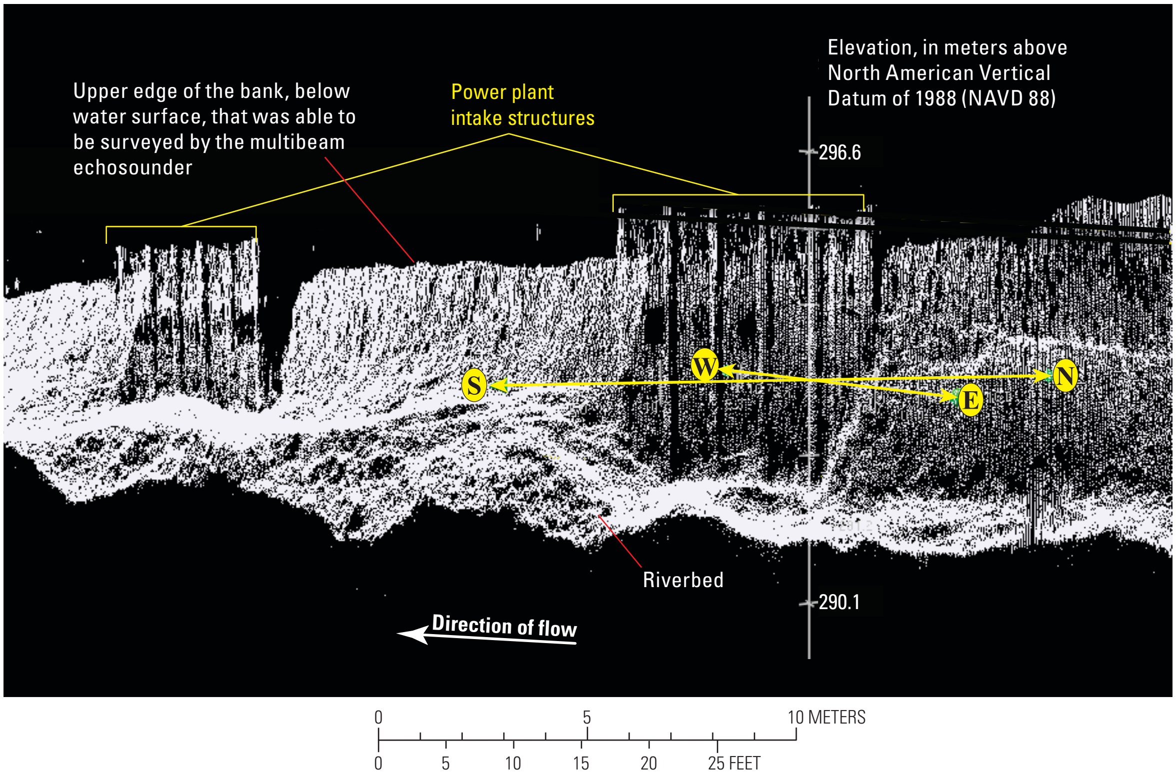


Figure 13. Point cloud showing the water structures of the North Omaha, Nebraska coal and natural gas power station from a multibeam echosounder survey on October 14, 2011.

becomes more resistive to the south, with the southernmost survey sections of levee described as the most resistive. These southern survey sections correlate well with the boreholes that indicate thinner clay and silt at the surface and thicker sand sequences at depth in these sections. The capacitively coupled resistivity reconnaissance-style tool proved to be able to map variations in the electrical property in the subsurface and was useful for delineating changes in either lithologic or saturation levels. The availability of borehole information was crucial for interpreting the modeled property variations. With the resistivity data Omaha Public Power District could focus monitoring efforts on areas with higher resistivity values (coarser-grained deposits or more loosely compacted section), which typically are more prone to erosion or scour.

Data collected from multibeam echosounder hydrographic surveys at selected bridges aided State agencies in evaluating the structural integrity of the bridges during the flood, by assessing the amount of scour present around piers and abutments. Riverbed elevations surveyed near North Dakota bridge piers indicated zero (no scour) to 5.8 meters of scour, and partially exposed footings of two piers were identified by the survey. Riverbed elevations around piers at bridges along the Nebraska border indicated zero to approximately 6 meters of scour and usually buried substructural support elements of some Nebraska bridge piers were exposed. In addition, 14.3 meters of scour was observed near the Iowa abutment of the Burt County bridge near Decatur, Nebraska, where water was flowing through a relict channel and threatened the safety of the bridge according to the Iowa Department of Transportation. Comparison of average active-channel elevations among the resurveys at each Nebraska bridge indicated no change in the mean active-channel elevation to greater than 4.5 meters of deposition. Riverbed elevations near bridge piers in Missouri indicated zero to 10.4 meters of scour. Substantial exposure of usually buried substructural support elements was observed at several piers of Missouri bridges, and at five piers the bed material thickness between the bottom of the scour hole and bedrock was less than 1.8 meters. State agencies used survey data along with bridge design and construction information to determine if these scour depths would have a substantial effect on the stability of the structure.

The 2011 surveys at many of the bridge sites in Missouri were compared to previous surveys, which were collected during high flow in 2010. Comparison of the 2011 surveys to the 2010 surveys in the greater Kansas City area indicate no consistent deepening of the channel or increase in the size of scour holes, despite a substantial increase in streamflow and water-surface elevation. Comparisons at four of the seven bridges in the greater Kansas City area indicate substantial deposition between the two surveys. Deposition also was documented at Atchison, Kans. A possible explanation for the deposition between the 2010 and the 2011 flood in the greater

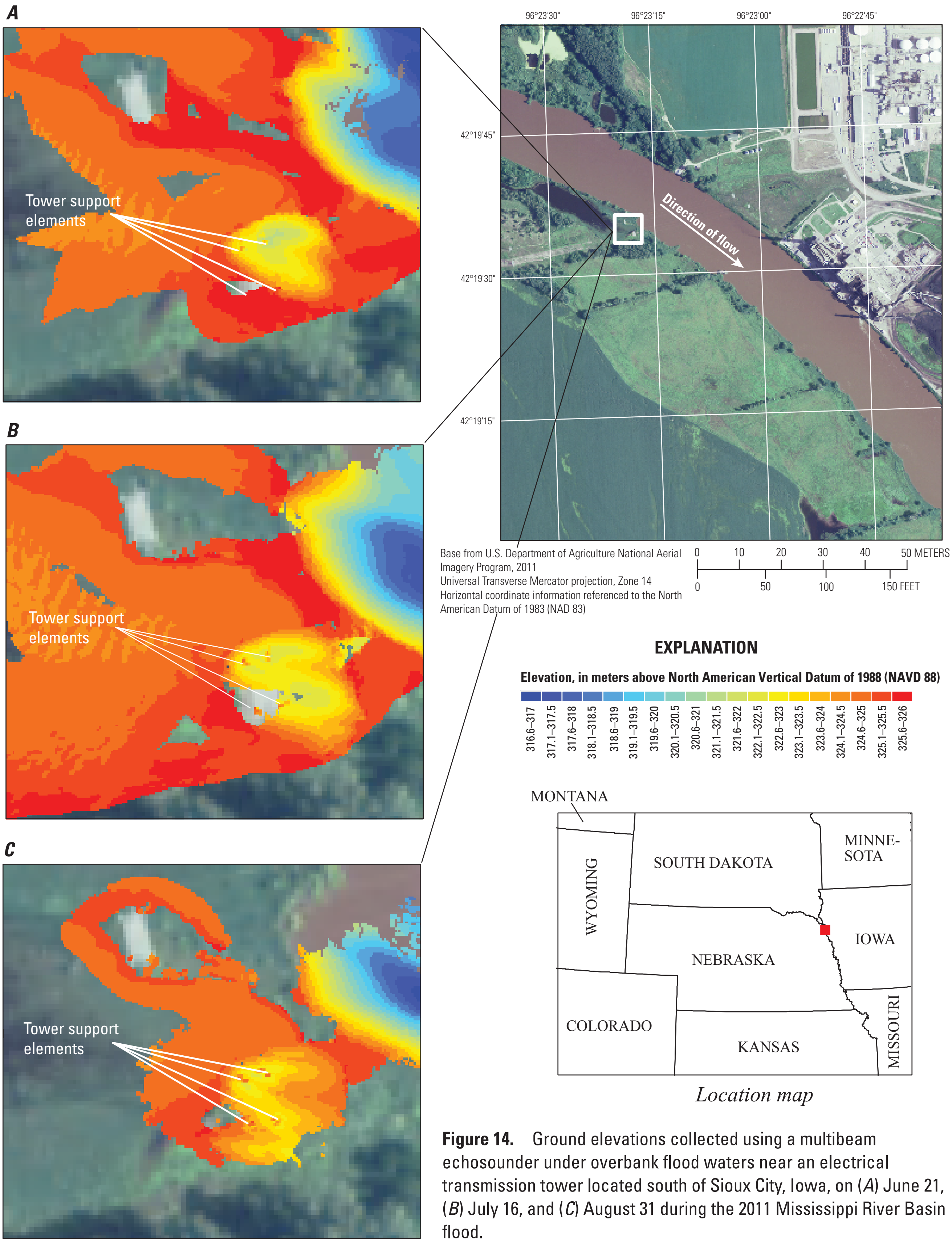


Figure 14. Ground elevations collected using a multibeam echosounder under overbank flood waters near an electrical transmission tower located south of Sioux City, Iowa, on (*A*) June 21, (*B*) July 16, and (*C*) August 31 during the 2011 Mississippi River Basin flood.

Kansas City area is that the surveys in 2011 took place as a plug or pulse of sediment was moving through the area. At Jefferson City, Mo., and at all bridges in the greater St. Louis area, scour was apparent between the 2010 and 2011 surveys.

Multibeam echosounder hydrographic surveys near pipeline crossings indicated no completely exposed pipelines. However, analysis of the U.S. Geological Survey data by one pipeline company led the company to further investigate the safety of one line, and aided another company in getting an offline pipeline back into operation. Multibeam echosounder hydrographic surveys at three Omaha Public Power District power plants documented the riverbed conditions as well as the details of the inlet and outlet structures during the flood event. These datasets were used by Omaha Public Power District to evaluate the effects the flood might have on safe operation of the power plants. Hydrographic surveys near an Omaha Public Power District electrical transmission tower also provided needed data on the effects the flood had on the banks of the Missouri River near the electrical transmission tower so that Omaha Public Power District could evaluate the safety of the tower as well as have the needed information to make proper repairs after flood waters receded. Results from the 2011 Mississippi River Basin flood surveys at power plants and electrical transmission towers indicated that multibeam echosounder hydrographic surveys were able to collect timely information that aided operators in evaluating the safe operation of these utilities.

Data collected by the U.S. Geological Survey at selected river infrastructure documented many of the effects of the 2011 Mississippi River Basin flood. These data made it possible for managers to better evaluate the safety of the critical infrastructure and to take action to secure or further evaluate it when needed.

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