Prepared in cooperation with the U.S. Army Corps of Engineers, Kansas City District

A Velocimetric Survey of the Lower Missouri River from River Mile 492.38 to 290.20, July–October 2011 and July 2012

Scientific Investigations Report 2013–5197

Cover photographs. Background: Missouri River, downstream from the boat ramp at River Front Park in Kansas City, Missouri, with a nearby channel structure exposed in the foreground (photograph by Richard D. Norman, U.S. Geological Survey, 2012). Left: Workskiff boat. Right: Acoustic Doppler Current Profile/Geographic Positioning System sampling equipment attached to the port side of the workskiff boat. Photographs by Daniel Armstrong, U.S. Geological Survey, 2012.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
Area		
square foot (ft ²)	929.0	square centimeter (cm ²)
square foot (ft ²)	0.09290	square meter (m ²)
square inch (in ²)	6.452	square centimeter (cm ²)
Volume		
cubic foot (ft ³)	0.02832	cubic meter (m ³)
Flow rate		
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)

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Abstract

Velocimetric surveys were made by the U.S. Geological Survey in 2011 and 2012 to provide data for the U.S. Army Corps of Engineers' ongoing study of bed degradation in the Lower Missouri River. Using Acoustic Doppler Current Profile technology, velocity data were collected at 87 river miles along the Lower Missouri River from Rulo, Nebraska to Waverly, Missouri, from July to October 2011 and in July 2012, for a total of 118 velocimetric surveys. Multiple-repeat velocimetric surveys were done eight times at three river miles from July to October 2011. Synoptic velocimetric surveys spanning 2–4 days were done twice at ten river miles, once in July 2011 and once in October 2011. Additional synoptic velocimetric surveys were done at proximal river miles in October 2011 and July 2012. Main-channel, near-bed, near-bank, and whole-river velocities were extracted from the Acoustic Doppler Current Profile data using AdMap and compiled as an average of reciprocal pairs for each survey. In addition, the mean velocity computed by the Winriver II software for each survey was integrated with the extracted data.

Multiple-repeat velocimetric surveys in the vicinity of Kansas City and Waverly, Missouri, in 2011 indicated that main-channel, near-bed, near-bank, and whole-river velocities generally declined with respect to declining daily mean discharges at the St. Joseph and Waverly, Missouri streamgaging stations. Statistical analysis of the four extracted velocity types indicated that multiple-repeat velocimetric surveys were strongly correlated with daily mean discharges at nearby streamgaging stations (coefficient of determination greater than 0.75). Main-channel velocity exceeded whole-river velocity by an average of 25 percent at river mile 357.70, 22 percent at river mile 357.09, and 6.8 percent at river mile 290.20 for all velocimetric surveys at each location, respectively. Main-channel, near-bed, near-bank, and whole-river velocities declined about 48 percent from July to October 2011 at the Kansas City sites and about 38 percent at the Waverly site. Winriver II mean velocity from multiple-repeat velocimetric surveys indicated that the relation between all velocities was inconsistent from July to October 2011. Percent changes in

channel width from July to October 2011 were typically less than concurrent changes in channel area and instantaneous discharge. The combined synoptic and multiple-repeat survey data for July 2011 did not indicate a clear longitudinal trend of velocity as instantaneous discharge increased downstream. Main-channel velocity exceeded whole-river velocity by an average of 22 percent during July 2011 and in some cases by more than 40 percent (river miles 452.50 and 308.80). Evaluation of 10 pairs of synoptic and synoptic-repeat velocimetric surveys with multiple-repeat velocimetric surveys from July to October 2011 indicated that all velocity types and channel width decreased by about one-third. Channel area and instantaneous discharge decreased by more than 50 percent from July to October 2011 and the percent by which main-channel velocity exceeded whole-river velocity decreased slightly from 22 percent in July to 19 percent. Comparing high (July 2011) to low (October 2011) discharge, where the channel width and area expanded by a factor of nearly 3.0 or more at high discharge (river miles 492.38 to 452.50), main-channel, near-bed, near-bank, and whole-river velocities increased by factors in the range of 1.1 to 1.7 and Winriver II mean velocity decreased. At the Kansas City river miles, all velocity types and channel areas nearly doubled at high discharge and channel widths remained similar to those at low discharge. Multiple-repeat and synoptic velocimetric surveys evaluated in October 2011 indicated that main-channel, near-bed, near-bank, and whole-river velocities generally increased downstream from river miles 424.20 to 404.70 and then decreased, until river mile 290.20, where they increased slightly.

Of the July 2012 synoptic velocimetric surveys, velocities near St. Joseph, Missouri, indicated no longitudinal trends in the main-channel, near-bed, near-bank, and whole-river velocities. The Kansas City and Waverly synoptic velocimetric surveys indicated a general decrease in these velocities proceeding downstream. For all 2012 surveys, near-bed velocity was closest in magnitude to Winriver II mean velocity and near-bed and whole-river velocities decreased with increasing channel area. For the entire study, variations in near-bank velocity may have been due to the influence of channel structures and their diversion of higher velocities away from the channel edges.

Introduction

Six main-stem dams were constructed on the Missouri River between 1940 and 1964, the most downstream of which (Gavins Point Dam near Yankton, South Dakota) was completed in 1955 (U.S. Army Corps of Engineers, 2009). With the construction of these dams, sediment was subsequently trapped by the upstream reservoirs and average annual river bed elevations have declined near Kansas City by approximately 12 feet since 1940 (U.S. Army Corps of Engineers, 2011). In 2009, the U.S. Army Corps of Engineers (USACE) in partnership with local stakeholders began a study of Missouri River bed degradation centered on the Kansas City reach of the Missouri River. A major component of the ongoing USACE study is the development and calibration of a hydraulic model that simulates flow and bedload transport on the Missouri River. To provide data for the calibration of this model and to better understand how velocity behaves over the course of a flood, velocimetric surveys (where appropriate referred to as survey in this report) of the Lower Missouri River (LMR) were done in 2011 by the U.S. Geological Survey (USGS) in cooperation with the USACE. Velocity was characterized by zones of a cross-section profile specified by the USACE and evaluated for longitudinal trends. Additional velocimetric surveys of the LMR were done in 2012 to provide reference data at navigational flows. The study reach is the Missouri River from river mile (rm) 492.38, southeast of Rulo, Nebraska, just north of the Nebraska/Kansas State line to rm 290.20 near Waverly, Missouri. (fig. 1).

Background

The Missouri River spans a distance of more than 2,300 miles from Montana to Missouri. The LMR is the reach of the Missouri River between the Gavins Point Dam and its confluence with the Mississippi River and accounts for nearly one-half of the total drainage area. The river from Sioux City, Iowa, to St. Louis, Missouri, has been channelized for navigation and the substrate in this reach is predominantly sand (Galat and others, 2005). Beginning as early as the 19th century and into the present day (2013), engineering modifications designed to maintain navigation depths, minimize lateral erosion, and confine flood flows to the river channel have transformed a multichannel system into a single uniform channel that, combined with upstream flow impoundment, has resulted in sediment starvation and channel incision in the LMR (Pinter and Heine, 2005). These modifications, collectively referred to by the USACE as the Bank Stabilization Navigation Project (BSNP) include dikes, revetments, and cutoffs that have reduced the channel area, increased river velocity, and removed or altered terrestrial and aquatic habitat causing a reduction of wildlife and fish populations (U.S. Army Corps of Engineers, 2009). Flood control features such as levees, floodwalls and upstream reservoirs are

not included in the BSNP (John Shelley, U.S. Army Corps of Engineers, written commun., 2013).

Purpose and Scope

The purpose of this report is to present and describe velocimetric data measured in four zones in each of 118 cross-section surveys: the main-channel, near-bed, near-bank, and whole-river zones. In addition, the mean velocity as computed by the Winriver II software (which includes an estimation for unmeasured zones) was included as a fifth velocity parameter. Velocity is characterized over the course of the 2011 flood and its longitudinal behavior is evaluated in 2011 and 2012.

Velocimetric surveys were done over a range of discharges at 37 river miles (rm 492.38 to 290.20) from July to October 2011 and at 50 additional river miles (rm 442.52 to 297.65) in June 2012. Monthly and daily mean discharges from streamgaging stations at St. Joseph (station number 06818000), Kansas City (station number 06893000) and Waverly (station number 06895500), Missouri were used as a reference over the course of the study period. The channel width, channel area, and instantaneous discharges computed during each of the surveys were included to expand the evaluation of spatial and temporal changes.

This report includes maps of all survey and streamgaging station locations in the study reach as well as graphs of velocity data with discharge over time and by river mile. Supplemental regression curves were generated to evaluate the relation of velocity to discharge (coefficient of determination, R^2) for multiple-repeat surveys in 2011. For 2012, graphs of near-bed and whole-river velocities were plotted for specific comparison with instantaneous discharge, Winriver II mean velocity, and channel area.

Previous Studies

Velocity and bathymetry mapping studies using echo sounder, Acoustic Doppler Current Profile (ADCP), and related technologies have been done in the continental United States and in regions as remote as West Central Africa (Jackson and others, 2009). Using bed velocity measurements derived from concurrent ADCP and Geographic Positioning System (GPS) data, it has been determined that bedloads in the thalweg are transported at all discharges and increase “linearly with increasing discharge” in the LMR (Elliot and others, 2009). Bathymetric and velocimetric surveys were done by Huizinga (2012) in the vicinity of Missouri River highway bridges and submerged bridge piers in July and August 2011. These data indicated the presence of flood-induced scour holes at most sites and that scour conditions during the 2011 flood were generally similar to previous surveys (Huizinga, 2010).

Base from U.S. Geological Survey digital data, 2005, 1:100,000
 Universal Transverse Mercator projection
 Zone 15

Figure 1. Location of study reach and 2011 and 2012 Missouri River velocimetric surveys.

Methods

ADCP surveys of the Missouri River were done by the USGS during record flooding in the late spring and summer months of 2011 (National Oceanic and Atmospheric Administration, 2012). In 2012, the USGS made additional surveys at selected river miles in the same reach during navigation flows. Velocimetric data were collected at 87 pre-designated river miles along the LMR for a total of 118 individual surveys (fig. 1). Data were collected and quality assured according to standard USGS methods (Mueller and Wagner, 2009). The velocity types extracted from each survey included main-channel, near-bed, near-bank, and whole-river velocities. The

mean velocity, channel width, channel area, and instantaneous discharge computed by the Teledyne RD Instruments (TRDI; Poway, California) Winriver II software used to operate the ADCP also were used as a part of the dataset. In addition, monthly and daily mean discharges computed at nearby streamgaging stations were included for reference.

Sampling Methods

ADCP data were collected using a TRDI 600 kHz Workhorse Rio Grande ADCP paired with a Trimble (Dayton, Ohio) DSM 232 Differential Global Positioning System (DGPS) receiver. TRDI's Winriver II software package was used for

simultaneous operation of the ADCP and DGPS. The DGPS used the Wide Area Augmentation System (WAAS) to provide corrected positional data. The ADCP was attached to a fixed mount on the side of an aluminum motor boat and the DGPS antenna was fixed to the side of the boat just above the ADCP. In all cases Winriver II was used to configure the ADCP to the existing river channel conditions, which resulted in a minimum bin (depth cell) size of 1.64 ft. In general, standard USGS protocols were followed for instrument preparation, field procedures, and data management (Mueller and Wagner, 2009). However, some modifications to protocol were made to allow for efficient data collection in the time allotted (Jackson and others, 2009) because the determination of velocity at a pre-determined river mile was the primary focus of this study. A single velocimetric survey therefore consisted of two ADCP profiles, rather than the typical four to eight collected for a standard ADCP discharge measurement. In addition, Wagner and Mueller (2011) have indicated that an integrated GPS system can be used to avoid the negative bias of a moving streambed on river velocity and discharge measured with an ADCP. Therefore, because a DGPS/WAAS system was used for positioning, loop tests typically required for discharge measurements that may have provided additional information concerning the magnitude of moving beds (Mueller and Wagner, 2006) were not done as a part of the data collection effort.

Repeat velocimetric surveys at the same location were designed to determine temporal changes in velocimetric profiles in response to changes in river discharge, and synoptic velocimetric surveys were designed to evaluate longitudinal differences in velocimetric profiles over broad stretches of the river.

Velocimetric surveys were repeated at 2-week intervals between July and October 2011 at two locations in the vicinity of Kansas City, Missouri (rm's 357.70 and 357.09) and one location near Waverly, Missouri (rm 290.20) (fig. 2; table 1). These surveys are hereafter referred to in this report as multiple-repeat surveys. Multiple-repeat surveys provided velocity data in response to large changes in Missouri River discharge during this time (fig. 3). Kansas City, Missouri, data were in all cases collected within the same day and Waverly data were typically collected the following day. A single exception was the collection of data at Waverly on August 23 of 2011 followed by the collection of data at Kansas City on August 26 of 2011.

Each synoptic velocimetric survey was done over a short duration and during a period of minimal change in river discharge—typically over a span of a few days in upstream to downstream order and these surveys are referred to as synoptic surveys. The synoptic survey periods were July 19–20, 2011 (10 sites; fig. 2; table 1), October 18–21, 2011 (34 sites; fig. 4), and July 17–20, 2012 (50 sites; figs. 5–7; table 1). The 10 synoptic sites surveyed in July 2011 also were surveyed in October 2011 (fig. 4), and these surveys are referred to as synoptic-repeat surveys.

Quality Assurance

Each velocimetric survey consisted of reciprocal transects (ADCP profiles across and back) at pre-determined locations along the river. The average percent difference in extracted velocities between reciprocal transects measured during this study was 2.4 percent. The average percent difference (of standard deviation from the mean) in Winriver II mean velocity between reciprocal transects was 4.7 percent. Velocity data collected during each survey was carefully inspected at the time of collection and concurrent GPS data were logged by the Winriver II software to ensure no distortion or bias of velocity and position by a moving bed. In cases where the measuring party deemed the number of missing ensembles to be unacceptable or problems with GPS data were caused by proximity with bridge structures, additional transects were recorded to ensure a result of two usable transects.

Data Analysis

Velocimetric survey data were analyzed for temporal and longitudinal (upstream to downstream) variation and relation to stream discharge. Velocimetric survey data includes velocities extracted from Winriver II ADCP profile output and the mean velocity (water speed) computed by the Winriver II software. The extracted velocities are presented in four pre-defined zones (main channel, near bed, near bank, whole river) of a river cross-section as shown in figure 8 and were computed for each measured zone as the average of values determined from reciprocal transects in a cross-section. The data extracted from the Winriver II ADCP output include only those areas measured by the ADCP and the Winriver II mean velocity computation is the mean of all measured values with an estimate of velocity in the unmeasured zones of the ADCP profile.

Main-channel velocity is defined as the depth-averaged mean of all ensembles (discrete columns of bins) recorded in the zone of the river from the toe of revetment (where the outer edge of the main channel meets the bank on the deepest side of the channel) to where the channel begins to shallow towards the inner edge. Near-bed velocity is the mean of the last valid bin from all ensembles recorded across the channel. Near-bank velocity is the depth-averaged mean of all ensembles in a 100-ft swath centered on the toe of the revetment. Whole-river velocity is the depth-averaged mean of all ensembles recorded across the channel. The Winriver II mean velocity is mean water speed with an adjustment by the Winriver II software to estimate velocity in unmeasured zones (fig. 8).

Graphical ADCP profiles (fig. 9) of Winriver II measured velocity were visually examined for variation in the distribution of velocity across the channel and for evidence of the influence of channel structures to aid in the characterization of channel features. Additionally, satellite imagery of survey locations (fig 10) was examined to note orientations of respective surveys and confirm the presence of channel structures.

Figure 2. Location of Missouri River multiple-repeat velocimetric surveys between July and October 2011 and synoptic surveys in July 2011.

Table 1. Velocimetric data surveys for the period July through October 2011 and July 2012.

[ft/s; foot per second; ft², square foot; ft³/s, cubic foot per second; bold where sampled as synoptic-repeat survey, July 2011 synoptic survey statistics include multiple-repeat survey data from July 11–28, 2011; October 2011 synoptic and synoptic-repeat survey statistics include multiple-repeat survey data from October 20–21, 2011, for October 2011; --, no data]

River mile and identifier (figs. 2, 4–7)	Date	Velocity (ft/s)				Velocimetric comparison and survey data						Velocity percent difference	
		Depth-averaged mean			Mean	Main-channel percent difference from whole-river velocity	Channel width (feet)	Channel area (ft²)	Discharge, instantaneous (ft³/s)	Winriver II near-bed	Winriver II whole-river		
		Main- channel	Near-bed	Near-bank	Whole- river								
July–October 2011 multiple-repeat survey statistics													
357.70	7/11/2011	8.81	6.81	7.04	7.47	6.87	18	985	34,600	238,000	0.8	-8.8	
	7/27/2011	8.30	6.13	7.40	7.04	6.06	18	981	33,300	202,000	-1.2	-16	
	8/11/2011	7.33	5.31	6.24	5.99	6.03	22	985	31,100	187,000	12	0.6	
	8/26/2011	7.22	5.00	5.64	5.58	5.88	29	1,010	32,200	189,000	15	5.1	
	9/7/2011	7.45	5.51	5.87	5.97	5.80	25	990	24,000	139,000	5.0	-2.9	
	9/19/2011	6.70	4.50	4.98	5.19	5.21	29	980	24,400	127,000	14	0.4	
	10/4/2011	6.71	4.68	4.47	5.13	5.06	31	959	18,300	92,900	7.6	-1.5	
	10/20/2011	4.75	3.39	3.71	3.74	3.79	27	935	16,500	62,400	11	1.4	
	Minimum	4.75	3.39	3.71	3.74	3.79	18	935	16,500	62,400	0.8	0.4	
	Maximum	8.81	6.81	7.40	7.47	6.87	31	1,010	34,600	238,000	15	-8.8	
	Average	7.16	5.17	5.67	5.76	5.59	25	978	26,800	154,663	7.9	-2.7	
	7/11/2011	9.24	7.33	8.10	7.99	7.66	16	906	31,100	238,000	4.3	-4.3	
	7/27/2011	8.59	6.55	8.11	7.34	7.08	17	908	30,700	217,000	7.5	-3.6	
	8/11/2011	7.80	5.27	7.37	6.21	6.35	26	879	29,600	188,800	17	2.2	
	8/26/2011	9.06	7.29	7.63	7.74	7.44	17	896	25,300	188,000	2.1	-4.0	
	9/7/2011	7.25	4.80	6.64	5.48	5.85	32	892	24,900	145,000	18	6.4	
	9/19/2011	7.11	5.04	5.84	5.69	5.58	25	906	22,300	124,000	9.6	-2.0	
10/4/2011	6.04	4.40	4.88	4.83	4.94	25	880	18,700	92,300	11	2.3		
10/20/2011	4.50	3.49	4.18	3.92	4.04	15	822	15,100	60,800	14	2.9		
Minimum	4.50	3.49	4.18	3.92	4.04	15	822	15,100	60,800	2.1	-2.0		
Maximum	9.24	7.33	8.11	7.99	7.66	32	908	31,100	238,000	18	6.4		
Average	7.45	5.52	6.59	6.15	6.12	22	886	24,713	156,738	10	-0.02		
7/12/2011	8.03	7.10	6.77	7.80	7.22	3.0	1,320	32,700	236,000	1.6	-8.0		
7/28/2011	7.03	6.26	5.64	6.91	6.46	1.7	1,160	32,600	211,000	3.0	-7.0		
8/12/2011	7.54	6.68	6.02	7.24	6.85	4.3	1,170	28,300	194,000	2.5	-5.6		

Table 1. Velocimetric data surveys for the period July through October 2011 and July 2012.—Continued

[ft/s; foot per second; ft², square foot; ft³/s, cubic foot per second; bold where sampled as synoptic-repeat survey; July 2011 synoptic survey statistics include multiple-repeat survey data from July 11–28, 2011; October 2011 synoptic and synoptic-repeat survey statistics include multiple-repeat survey data from October 20–21, 2011, for October 2011; --, no data]

River mile and identifier (figs. 2, 4-7)	Date	Velocity (ft/s)				Velocimetric comparison and survey data							Velocity percent difference	
		Depth-averaged mean			Mean	Main-channel				Channel width (feet)	Channel area (ft²)	Discharge, instantaneous (ft³/s)		
		Main- channel	Near-bed	Near-bank		Whole- river	Winriver II¹	percent difference from whole-river velocity						
July–October 2011 multiple-repeat survey statistics—Continued														
290.20	8/23/2011	6.97	6.14	5.41	6.78	6.40	2.7	1,300	33,700	216,000	4.0	-6.0		
	9/8/2011	6.17	5.13	5.16	5.81	5.59	6.2	1,170	25,800	144,000	8.2	-3.9		
	9/20/2011	6.65	5.96	5.54	6.35	5.97	4.7	1,170	20,300	121,000	0.2	-6.3		
	10/5/2011	4.95	3.63	4.01	4.03	4.49	23	1,130	20,600	92,500	19	10		
	10/21/2011	4.81	4.08	3.96	4.43	4.22	8.7	1,130	15,200	63,900	3.3	-4.9		
	Minimum	4.81	3.63	3.96	4.03	4.22	1.7	1,130	15,200	63,900	0.2	-3.9		
	Maximum	8.03	7.10	6.77	7.80	7.22	23	1,320	33,700	236,000	19	10		
	Average	6.52	5.62	5.31	6.17	5.90	6.8	1,194	26,150	159,800	5.3	-3.9		
July 2011 synoptic survey statistics														
492.38	7/19/2011	6.14	4.34	5.52	4.98	3.35	23	2,560	49,000	165,000	-29	-49		
471.71	7/19/2011	6.74	5.07	6.50	5.61	4.44	20	2,970	47,600	211,000	-14	-26		
452.50	7/19/2011	8.21	5.43	6.47	5.83	3.18	41	2,400	60,900	193,000	-71	-83		
432.68	7/19/2011	8.62	6.78	6.13	7.41	6.20	16	1,720	35,200	218,000	-9.3	-20		
412.55	7/19/2011	6.37	4.86	6.01	5.26	--	21	--	--	--	--	--		
394.50	7/20/2011	8.37	5.45	7.71	6.32	4.16	33	1,670	45,600	189,000	-31	-52		
373.65	7/20/2011	8.42	5.64	7.09	6.35	6.36	33	1,170	32,200	205,000	11	0.2		
348.87	7/20/2011	7.54	5.37	6.26	6.28	6.15	20	1,020	35,000	215,000	13	-2.1		
326.30	7/20/2011	6.83	4.34	4.15	5.24	5.11	30	1,310	41,000	210,000	15	-2.5		
308.80	7/20/2011	8.34	5.36	5.52	5.88	4.96	42	1,360	45,300	225,000	-8.1	-19		
	Minimum	6.14	4.34	4.15	4.98	3.18	1.7	906	30,700	165,000	0.8	0.2		
	Maximum	9.24	7.33	8.11	7.99	7.66	42	2,970	60,900	238,000	-71	-83		
	Average	7.85	5.80	6.53	6.48	5.68	22	1,496	39,120	211,533	-7.2	-20		
October 2011 synoptic and synoptic-repeat survey statistics														
492.38	10/18/2011	5.31	4.06	4.16	4.47	4.30	19	818	13,600	58,300	5.5	-3.9		
488.60	10/18/2011	5.19	4.00	5.49	4.42	4.13	17	735	14,100	58,400	3.2	-6.9		

Table 1. Velocimetric data surveys for the period July through October 2011 and July 2012.—Continued

[ft/s; foot per second; ft², square foot; ft³/s, cubic foot per second; bold where sampled as synoptic-repeat survey, July 2011 synoptic survey statistics include multiple-repeat survey data from July 11–28, 2011; October 2011 synoptic and synoptic-repeat survey statistics include multiple-repeat survey data from October 20–21, 2011, for October 2011; --, no data]

River mile and identifier (figs. 2, 4-7)	Date	Velocity (ft/s)				Velocimetric comparison and survey data						Velocity percent difference	
		Depth-averaged mean				Main-channel percent difference from whole-river velocity	Channel width (feet)	Channel area (ft²)	Discharge, instantaneous (ft³/s)	Winriver II near-bed	Winriver II whole-river		
		Main- channel	Near-bed	Near-bank	Whole- river							Mean	
October 2011 synoptic and synoptic-repeat survey statistics—Continued													
476.20	10/18/2011	4.96	3.76	5.15	4.12	4.24	20	875	14,000	59,400	11	2.7	
471.71	10/18/2011	4.11	3.38	4.30	3.75	3.66	9.6	969	16,600	60,700	7.5	-2.4	
464.70	10/18/2011	5.10	3.67	2.24	4.01	3.80	27	946	15,900	60,100	3.4	-5.4	
452.50	10/18/2011	4.71	3.79	4.18	4.21	4.13	12	825	14,700	60,500	8.1	-1.8	
446.60	10/18/2011	4.15	3.25	3.96	3.64	3.82	14	776	15,800	60,600	15	4.8	
432.68	10/19/2011	4.73	3.73	4.33	4.18	4.03	13	822	15,100	61,000	7.5	-3.8	
424.20	10/19/2011	4.56	3.62	3.27	3.87	3.84	18	1,000	15,500	59,300	5.8	-0.7	
416.70	10/19/2011	5.26	4.02	5.09	4.39	4.36	20	793	13,900	60,500	7.7	-0.8	
412.55	10/19/2011	5.37	4.09	4.99	4.51	4.63	19	811	13,500	62,500	12	2.6	
404.70	10/19/2011	7.18	5.38	4.21	5.62	4.41	28	912	13,800	59,300	-22	-27	
402.50	10/19/2011	7.05	4.91	5.65	5.26	5.33	34	774	11,300	60,100	7.9	1.2	
394.50	10/19/2011	5.19	3.83	4.83	4.29	3.56	21	845	18,400	62,300	-7.6	-21	
391.00	10/19/2011	5.32	4.24	4.85	4.76	4.60	12	606	13,100	60,200	7.9	-3.4	
387.90	10/19/2011	5.75	4.37	5.80	4.79	4.76	20	826	12,700	60,600	8.1	-0.6	
376.50	10/20/2011	5.17	3.89	4.63	4.30	4.33	20	806	13,900	60,400	10	0.7	
373.65	10/20/2011	5.09	3.81	5.07	4.25	4.37	20	873	13,700	59,900	13	2.8	
371.28	10/20/2011	5.32	3.43	3.54	3.91	4.21	36	878	14,200	59,600	19	7.2	
370.72	10/20/2011	4.59	3.42	4.27	3.78	3.85	21	816	15,300	58,800	11	1.9	
366.60	10/20/2011	4.39	3.70	4.59	4.09	4.05	7.5	1,010	15,300	62,000	8.6	-0.9	
365.40	10/20/2011	4.48	3.66	3.98	4.09	4.07	9.7	895	15,100	61,600	10	-0.4	
365.30	10/20/2011	4.38	3.55	4.13	3.88	3.98	13	919	15,400	61,500	11	2.5	
363.50	10/20/2011	4.50	3.72	4.37	4.03	4.04	12	884	15,200	61,600	7.9	0.1	
363.40	10/20/2011	4.63	3.25	4.27	3.41	2.71	36	924	22,900	62,000	-20	-26	
359.10	10/20/2011	4.35	3.14	4.20	3.35	3.51	30	1,020	17,500	61,600	10	4.7	
358.60	10/20/2011	4.49	3.62	3.19	4.04	4.06	11	855	15,000	61,000	11	0.5	

Table 1. Velocimetric data surveys for the period July through October 2011 and July 2012.—Continued

[ft/s; foot per second; ft², square foot; ft³/s, cubic foot per second; bold where sampled as synoptic-repeat survey; July 2011 synoptic survey statistics include multiple-repeat survey data from July 11–28, 2011; October 2011 synoptic and synoptic-repeat survey statistics include multiple-repeat survey data from October 20–21, 2011, for October 2011; --, no data]

River mile and identifier (figs. 2, 4–7)	Date	Velocity (ft/s)			Velocimetric comparison and survey data							Velocity percent difference	
		Depth-averaged mean			Main- channel	Main-channel			Discharge, instantaneous (ft³/s)				
		Main- channel	Near-bed	Near-bank		Whole- river	Winriver II¹	percent difference from whole-river velocity		Channel width (feet)	Channel area (ft²)	Winriver II near-bed	Winriver II whole-river
October 2011 synoptic and synoptic-repeat survey statistics—Continued													
350.80	10/20/2011	4.84	3.58	5.02	3.92	4.00	23	1,110	15,800	63,100	10	2.0	
348.87	10/20/2011	4.57	3.52	3.93	3.84	3.98	19	957	15,800	62,800	11	3.5	
340.30	10/20/2011	5.06	3.90	3.56	4.28	3.77	18	1,110	16,700	63,000	-3.5	-14	
331.50	10/21/2011	4.53	3.17	4.31	3.44	3.59	32	1,270	17,200	61,800	12	4.1	
326.30	10/21/2011	4.40	3.30	3.01	3.56	3.50	23	974	17,900	62,700	5.8	-1.7	
308.80	10/21/2011	4.26	2.81	3.92	3.10	2.50	37	1,030	24,700	61,900	-12	-24	
298.90	10/21/2011	4.08	3.08	0.58	3.30	2.90	24	1,170	21,300	61,800	-6.4	-14	
	Minimum	4.08	2.81	0.58	3.10	2.50	7.5	606	11,300	58,300	3.2	0.1	
	Maximum	7.18	5.38	5.80	5.62	5.33	37	1,270	24,700	63,900	-22	-27	
	Average	4.90	3.72	4.19	4.08	3.97	20	911	15,722	61,027	5.9	-3.2	
October 2011 combined synoptic-repeat and multiple-repeat survey statistics													
	Minimum	4.11	2.81	3.01	3.10	2.50	8.7	811	13,500	58,300	3.3	1.4	
	Maximum	5.37	4.09	5.07	4.51	4.63	37	1,130	24,700	63,900	14	-24	
	Average	4.75	3.64	4.20	4.02	3.90	19	909	16,215	61,515	6.0	-3.8	
July 2012 synoptic survey statistics													
Segment 1—near St. Joseph, Missouri													
442.52	7/17/2012	4.02	2.71	2.53	2.81	2.26	43	990	17,100	38,600	-20	-25	
441.90	7/17/2012	4.09	3.58	--	3.91	3.57	4.7	903	10,500	37,500	-0.4	-9.4	
441.38	7/17/2012	4.51	3.43	3.71	3.79	3.50	19	863	11,200	39,100	2.1	-8.3	
440.87	7/17/2012	4.23	3.49	4.23	3.70	3.39	14	829	11,300	38,400	-3.0	-9.1	
440.44	7/17/2012	4.28	3.45	3.64	3.91	3.61	9.6	826	11,000	39,700	4.5	-8.2	
439.97	7/17/2012	4.07	3.26	2.33	3.54	3.41	15	828	11,100	37,700	4.5	-3.9	
439.45	7/17/2012	4.41	3.88	4.20	4.32	4.13	2.1	714	10,300	42,400	6.0	-4.7	
439.07	7/17/2012	4.30	3.39	3.97	3.72	3.59	15	880	11,000	39,500	5.6	-3.7	
438.88	7/17/2012	4.16	3.31	--	3.67	3.68	14	716	10,500	38,800	10	0.3	

Table 1. Velocimetric data surveys for the period July through October 2011 and July 2012.—Continued

[ft/s; foot per second; ft², square foot; ft³/s, cubic foot per second; bold where sampled as synoptic-repeat survey; July 2011 synoptic survey statistics include multiple-repeat survey data from July 11–28, 2011; October 2011 synoptic and synoptic-repeat survey statistics include multiple-repeat survey data from October 20–21, 2011, for October 2011; --, no data]

River mile and identifier (figs. 2, 4–7)	Date	Velocity (ft/s)				Velocimetric comparison and survey data						Velocity percent difference			
		Depth-averaged mean				Mean									
		Main- channel	Near-bed	Near-bank	Whole- river	Winriver II'	Main-channel percent difference from whole-river velocity	Channel width (feet)	Channel area (ft²)	Discharge, instantaneous (ft³/s)	Winriver II near-bed	Winriver II whole-river			
438.55	7/17/2012	4.22	3.78	4.01	4.18	3.90	0.8	682	10,200	39,700	3.2	-7.3			
437.70	7/17/2012	3.58	2.94	4.08	3.18	3.21	13	767	11,900	38,100	8.3	0.8			
Segment 1—near St. Joseph, Missouri—Continued															
381.37	7/18/2012	4.23	3.63	3.78	3.93	3.76	7.7	794	10,800	40,600	3.5	-4.5			
380.28	7/18/2012	4.39	3.80	3.50	4.05	3.93	8.4	770	10,100	39,700	3.2	-3.0			
379.53	7/18/2012	4.57	4.08	4.64	4.34	3.98	5.4	839	10,200	40,500	-2.4	-9.0			
378.26	7/18/2012	4.60	4.06	--	4.34	4.12	5.9	692	9,630	39,700	1.5	-5.4			
377.43	7/18/2012	4.76	4.11	--	4.42	4.06	7.8	941	10,200	41,500	-1.2	-8.8			
376.10	7/18/2012	4.16	3.53	4.01	3.82	3.61	8.8	788	10,600	38,100	2.3	-5.9			
375.32	7/18/2012	4.33	3.43	--	3.80	3.66	14	687	10,400	37,900	6.3	-3.9			
374.74	7/18/2012	4.77	3.68	4.50	4.04	3.80	18	784	10,400	39,500	3.2	-6.3			
374.12	7/18/2012	4.67	3.51	4.13	3.87	3.77	21	676	10,300	39,000	7.0	-2.6			
373.74	7/18/2012	4.37	3.80	--	4.15	3.78	5.3	822	10,600	40,000	-0.4	-9.7			
372.99	7/18/2012	4.38	3.59	3.92	3.83	3.72	14	816	10,800	40,200	3.5	-3.0			
372.51	7/18/2012	4.60	3.64	3.69	3.91	3.87	18	753	10,300	39,900	5.9	-1.0			
371.73	7/18/2012	4.39	3.83	4.10	4.11	4.12	6.7	625	10,200	41,900	7.0	0.2			
371.28	7/18/2012	4.22	3.46	2.54	3.79	3.57	11	871	11,000	39,400	3.1	-6.2			
370.72	7/18/2012	3.87	3.22	3.45	3.49	3.33	11	834	11,500	38,200	3.2	-4.8			
370.01	7/18/2012	4.25	3.35	3.61	3.64	3.71	17	658	10,000	37,300	9.8	1.9			
369.63	7/18/2012	3.83	3.48	--	3.80	3.53	0.8	784	11,000	38,700	1.5	-7.5			
369.11	7/18/2012	4.22	3.53	4.16	3.82	3.67	10	716	10,400	38,300	3.9	-4.2			
368.60	7/18/2012	3.76	3.18	2.53	3.41	3.01	10	824	12,500	37,400	-5.7	-13			
368.17	7/18/2012	4.04	2.88	3.38	3.08	3.29	31	797	11,400	37,400	12	6.3			
Segment 3—near Kansas City, Missouri (below the Kansas River)															
362.84	7/18/2012	3.76	2.93	2.66	3.11	2.84	21	1,240	15,400	43,800	-3.1	-9.6			
362.24	7/18/2012	4.68	3.88	3.90	4.17	3.94	12	867	10,800	42,700	1.6	-5.9			

Table 1. Velocimetric data surveys for the period July through October 2011 and July 2012.—Continued

[ft/s; foot per second; ft², square foot; ft³/s, cubic foot per second; bold where sampled as synoptic-repeat survey; July 2011 synoptic survey statistics include multiple-repeat survey data from July 11–28, 2011; October 2011 synoptic and synoptic-repeat survey statistics include multiple-repeat survey data from October 20–21, 2011, for October 2011; --, no data]

River mile and identifier (figs. 2, 4–7)	Date	Velocity (ft/s)				Velocimetric comparison and survey data							Velocity percent difference	
		Depth-averaged mean			Mean	Main-channel				Discharge, instantaneous (ft³/s)	Winriver II near-bed	Winriver II whole-river		
		Main- channel	Near-bed	Near-bank	Whole- river	Winriver II'	Main-channel percent difference from whole-river velocity	Channel width (feet)	Channel area (ft²)					
Segment 3—near Kansas City, Missouri (below the Kansas River)—Continued														
361.83	7/18/2012	4.11	3.41	3.67	3.63	3.53	13	915	11,600	40,900	3.3	-2.9		
360.92	7/19/2012	4.09	3.54	--	3.76	3.59	8.7	894	11,300	40,600	1.4	-4.7		
360.31	7/19/2012	3.98	3.26	2.54	3.54	3.37	12	837	12,200	41,200	3.1	-4.9		
359.34	7/19/2012	4.27	3.70	--	3.95	3.61	8.3	757	11,400	41,300	-2.4	-9.4		
358.28	7/19/2012	3.88	3.24	--	3.56	3.35	9.1	893	12,400	41,200	3.4	-6.2		
357.28	7/19/2012	4.11	3.08	--	3.35	3.34	23	811	12,500	41,700	7.8	-0.3		
356.43	7/19/2012	3.74	2.98	1.72	3.17	3.16	18	927	13,400	42,500	5.7	-0.4		
353.45	7/19/2012	3.94	3.24	3.50	3.48	3.37	13	906	12,300	41,600	3.8	-3.3		
351.14	7/19/2012	3.78	3.31	3.35	3.52	3.41	7.4	864	12,000	41,000	2.9	-3.3		
348.25	7/19/2012	3.97	3.49	3.57	3.81	3.54	4.2	906	11,900	42,000	1.4	-7.5		
Segment 4—near Waverly, Missouri														
306.17	7/20/2012	4.40	3.69	3.40	3.91	3.47	12	1,250	13,100	45,500	-6.2	-13		
304.99	7/20/2012	4.72	3.94	4.69	4.22	3.79	12	1,100	11,100	42,200	-3.8	-11		
303.87	7/20/2012	4.44	3.53	3.93	3.74	3.37	19	1,160	13,500	45,500	-4.9	-11		
302.82	7/20/2012	3.90	3.20	--	3.44	3.31	13	964	12,400	41,200	3.4	-3.9		
301.25	7/20/2012	3.88	3.52	3.49	3.84	3.60	1.1	739	11,500	41,300	2.3	-6.6		
299.13	7/20/2012	3.86	2.82	3.71	2.98	2.76	29	1,160	15,400	42,300	-2.3	-8.1		
297.65	7/20/2012	3.78	3.08	--	3.26	3.06	16	1,200	12,800	39,200	-0.7	-6.5		
	Minimum	3.58	2.71	1.72	2.81	2.26	0.8	625	9,630	37,300	-0.4	0.2		
	Maximum	4.77	4.11	4.69	4.42	4.13	43	1,250	17,100	45,500	-20	-25		
	Average	4.19	3.46	3.59	3.74	3.54	13	857	11,509	40,248	2.1	-5.7		
Averaged values for individual segments (2012)														
442.52– 437.70	7/17/2012	4.17	3.38	3.63	3.70	3.48	--	818	11,464	39,045	--	--		
381.37– 368.17	7/18/2012	4.32	3.59	3.73	3.88	3.71	--	774	10,617	39,260	--	--		

Table 1. Velocimetric data surveys for the period July through October 2011 and July 2012.—Continued

[ft/s; foot per second; ft², square foot; ft³/s, cubic foot per second; bold where sampled as synoptic-repeat survey, July 2011 synoptic survey statistics include multiple-repeat survey data from July 11–28, 2011; October 2011 synoptic and synoptic-repeat survey statistics include multiple-repeat survey data from October 20–21, 2011, for October 2011; --, no data]

River mile and identifier (figs. 2, 4-7)	Date	Velocity (ft/s)				Velocimetric comparison and survey data					Velocity percent difference	
		Depth-averaged mean			Mean	Main-channel percent difference from whole-river velocity	Channel width (feet)	Channel area (ft²)	Discharge, instantaneous (ft³/s)	Winriver II near-bed	Winriver II whole-river	
		Main- channel	Near-bed	Near-bank	Whole- river							
Averaged values for individual segments (2012)—Continued												
362.84– 348.25	7/18–19/ 2012	4.03	3.34	3.11	3.59	3.42	--	901	12,267	41,708	--	--
306.17– 297.65	7/20/2012	4.14	3.40	3.84	3.63	3.34	--	1,082	12,829	42,457	--	--

¹Includes estimation for areas of unmeasured velocity.

Winriver II output (fig. 9) was further processed using AdMap software (David Mueller, U.S. Geological Survey, written commun., August 2011) to extract the main-channel, near-bed, near-bank, and whole-river velocities based upon the selection criteria and available data. Defining the main channel and/or revetment for a given transect was, in some cases, ambiguous or not possible because of a lack of edge data. If a shallowing away from the inner edge of the main channel was not clearly observable, the relative velocities of a given transect profile were closely inspected to determine the boundary between slower and moderate to higher velocities. This boundary was then used with any identifiable changes in channel bottom from steep to shallow to define the inner edge of the main channel. Where the channel shape and/or depth did not allow for a 100-ft swath on the toe of a clearly observable revetment, the distance from the toe to the outer edge of the channel was used as one-half of the swath. An equal distance was then measured back from the toe toward the inner edge of channel and the mean of these depth-averaged velocities was used to compute near-bank velocity. In cases where a revetment was not observed, near-bank velocity was not computed and the main-channel velocity was computed as the mean of depth averaged velocities from the inner edge to furthest measured outer edge of the channel. All computations with the AdMap program ignored areas of missing data (see unmeasured zones, fig. 8), where an ADCP is unable to measure in the upper and lower parts of a water column because of boat draft, blanking distance, and beam (side lobe) interference at the bottom of the column (Mueller and Wagner, 2009). Beam interference typically affects the lower 6 percent of the water column measured with a 20° beam system (as used in this study) and the computation of this distance from the streambed is derived using the angle of the transducers and the total distance from the ADCP transducer to the streambed. The near-bed velocity zone is therefore defined as the last readable and valid bin (1.64 ft) of the water column just above the lowest unmeasured zone (fig. 8). Because the Winriver II mean velocity computation estimates velocities in unmeasured areas (including those areas between missing ensembles) and the proportion of estimated area is directly affected by changes in channel conditions, Winriver II velocities may in some cases deviate substantially from the whole-river velocities computed with AdMap.

Monthly and daily mean discharges from the St. Joseph, Kansas City, and Waverly, Missouri, streamgaging stations (fig. 1) were retrieved from approved and published data archived in the USGS National Water Information System (NWIS) database and are available from the USGS at <http://waterdata.usgs.gov/nwis/sw>.

Figure 3. Monthly mean discharge for the Missouri River at St. Joseph and Waverly, Missouri, for 2011 through 2012, velocimetric survey sampling periods, and instantaneous Missouri River discharge measured during velocimetric surveys at multiple locations.

Figure 4. Location of Missouri River synoptic and synoptic-repeat velocimetric surveys in October 2011 with multiple-repeat velocimetric survey locations between July and October 2011.

Figure 5. Location of Missouri River synoptic velocimetric surveys in July 2012 in the vicinity of St. Joseph, Missouri.

Figure 6. Location of Missouri River synoptic velocimetric surveys in July 2012 with multiple-repeat velocimetric surveys between July and October 2011 in the vicinity of Kansas City, Missouri, and Kansas City, Kansas.

Figure 7. Location of Missouri River synoptic velocimetric surveys in July 2012 with multiple-repeat velocimetric survey locations between July and October 2011 in the vicinity of Waverly, Missouri.

Figure 8. Generalized diagram depicting the four measured (main-channel, near-bank, whole-river,) and un-measured (Winriver II) cross-sectional zones for which velocities were determined.

Figure 9. Graphical example of Winriver II ADCP profile output on the Missouri River at river mile 357.70 in *A*, July 2011 and *B*, October 2011 and *C*, from river mile 464.70 in October 2011.

Figure 10. Aerial imagery depicting channel structures under flow conditions that existed in the Missouri River near river mile 394.50 in *A*, July 2012 showing channel structures (yellow lines) exposed and in *B*, June 2011 when structures were submerged and resultant turbulence (white areas) created by flood conditions.

Velocimetric Survey of the Lower Missouri River from River Mile 492.38 to 290.20

Velocimetric surveys were made along the LMR from July to October 2011 and in July 2012 (fig. 1) with a total of 118 surveys at 87 sites (table 1). Multiple-repeat surveys were made at three sites from July to October (fig. 2) and were used to characterize velocity changes over the course of the 2011 flood (fig. 3). Synoptic surveys were made in July and October 2011 (figs. 2, 4) and again in July 2012 (figs. 5–7). The synoptic surveys were used to compare velocities from segment to segment and to observe velocities at typical navigation discharge (approximately 35,000 to 49,200 cubic feet per second). The monthly mean discharges computed at the St. Joseph and Waverly, Missouri River streamgaging stations, along with instantaneous discharges computed at the individual survey sites (fig. 3; table 1) also are presented.

Multiple-Repeat Surveys

Multiple-repeat surveys were done at two sites (rm 357.70 and 357.09) downstream from the Kansas City, Missouri, streamgaging station (rm 366.10) and at one site (rm 290.20) downstream from the Waverly, Missouri, streamgaging station (rm 293.50) from the peak of flood discharge in July 2011 to the end of the recession in October 2011 (fig. 3; table 1). Plots of the four velocity types (excluding unmeasured zones) with daily mean discharges computed at the St. Joseph (rm 448.20) and Waverly, Missouri, streamgaging stations indicated a general decline over time with respect to declining discharge (fig. 11). All velocities increased at rm 357.09 on August 26, which appeared to be the direct result of increased discharge during the same time period (fig. 11). To characterize the velocity distribution of each survey, the percent difference of main-channel velocity from the whole-river velocity was computed (table 1). Main-channel velocity exceeded whole-river velocity by an average of 25 and 22 percent for surveys at rm's 357.70 and 357.09, respectively. Surveys at rm 290.20 indicated that velocity distribution at this location was comparatively more uniform as main-channel velocity exceeded whole-river velocity by an average of only 6.8 percent.

To make the multiple-repeat survey data more comparable with the synoptic and synoptic-repeat surveys between July and October (rm 492.38 to 308.80) the multiple-repeat survey data was presented for each river mile in table 2 as the average of two surveys in July and only the very last surveys were included for October. On average, velocity from all measured zones declined by about 48 percent between July and October 2011 at the Kansas City sites and by about 38 percent at the Waverly site (table 2). Velocities from all measured zones were strongly correlated (R^2 greater than 0.75) with daily mean discharges (fig. 12). River mile 357.09 had the strongest of these correlations with an R^2 greater than or equal to 0.98 for

near-bank velocity. With the exception of main-channel velocity, rm 290.20 had the weakest correlations of velocity with discharge with an R^2 less than 0.78 for near-bed velocity. Near-bed velocities were computed from a single bin in each ensemble across a section and the smaller size of this subset could be a source of weakness in the correlation.

Examining individual velocity types by river mile over time (including Winriver II mean velocity with estimates for unmeasured zones, fig. 13; table 1), velocities from each of the three multiple-repeat survey sites generally behaved in an inconsistent manner. A relative increase in all velocity types did occur on August 26 at rm 357.09 (in response to an increase in Missouri River discharge around the same time, fig. 11) but was not observed at the upstream rm 357.70 or at rm 290.20 on August 23 (fig. 13). From July to August 2011, rm 357.09 maintained the highest magnitudes for main-channel velocity with a relative spike to 9.06 ft/s on August 26. From September to October, the remaining main-channel velocity values tended to be lowest for rm 290.20, with the exception of October 21 where it exceeded values at the other two river miles by a small margin. Near-bed velocity from July to October 2011 was variable with a relative spike to 7.29 ft/s on August 26 at rm 357.09 and a small spike to 5.96 ft/s on September 20 at rm 290.20. Of the last October multiple-repeat surveys, rm 290.20 had the highest value for near-bed velocity on October 21. River mile 357.09 consistently demonstrated the highest values for near-bank velocity from July to October 2011. Values at rm 357.70 were comparatively higher than those at rm 290.20 until September 19, where values began to alternate with from site to site. The pattern of whole-river velocity from July to October 2011 was quite similar to near-bed velocity with a relative spike to 7.74 ft/s on August 26 at rm 357.09. The final whole-river velocity value (4.43 ft/s) on October 21 at rm 290.20 was the highest among the three sites. The Winriver II mean velocity values were lowest at rm 357.70 until after August 26 where values began to alternate from site to site. A relative spike to 7.44 ft/s (similar to the other velocity types) was reported on August 26 at rm 357.09 and the final value for Winriver II mean velocity (4.22 ft/s) was highest for rm 290.20 on October 21.

Percent changes in channel width from July to October 2011 at the multiple-repeat survey sites were considerably less than corresponding changes in channel area and instantaneous discharge (table 2). Channel width decreased by an average of about 7 percent at the Kansas City sites and about 9 percent at the Waverly site. At all three sites, channel area decreased by an average of about 52 percent and instantaneous discharge decreased by about 72 percent. In profile view the velocity distribution at the Waverly site was generally more uniform than at the Kansas City sites. Higher velocities at the Kansas City sites were generally focused in the deeper part of the channel with the exception of one instance: the first profile surveyed at rm 357.09 where higher velocities were somewhat centered in the channel. In most cases, areas of high and low velocity maintained the same distribution at all three sites from July to October. At Waverly however, higher velocities migrated over time from the left to the right side of the channel.

Figure 11. Velocimetric survey data in the four measured zones of the Missouri River between July and October 2011 at multiple-repeat surveys with daily mean discharge at Kansas City, and Waverly, Missouri.

Table 2. Velocity, channel dimensions, and discharge measured at Missouri River synoptic and synoptic-repeat velocimetric surveys with multiple-repeat velocimetric surveys between July (high discharge) and October (low discharge) 2011.

[ft/s, foot per second; Q, discharge; ft², square foot; ft³/s, cubic foot per second; --, no data; bold where sampled as multiple-repeat survey, multiple-repeat survey data from July 11–28, 2011, (averaged) for July 2011; and October 20–21, 2011, for October 2011]

River mile	Main-channel velocity (ft/s)				High Q to low Q ratio	Near-bed velocity (ft/s)				High Q to low Q ratio	Near-bank velocity (ft/s)				High Q to low Q ratio
	July		October			Decline, in percent	July		October		Decline, in percent	July		October	
492.38	6.14	5.31	13	1.2		4.34	4.06	6	1.1		5.52	4.16	25	1.3	
471.71	6.74	4.11	39	1.6		5.07	3.38	33	1.5		6.50	4.30	34	1.5	
452.50	8.21	4.71	43	1.7		5.43	3.79	30	1.4		6.47	4.18	35	1.5	
432.68	8.62	4.73	45	1.8		6.78	3.73	45	1.8		6.13	4.33	29	1.4	
412.55	6.37	5.37	16	1.2		4.86	4.09	16	1.2		6.01	4.99	17	1.2	
394.50	8.37	5.19	38	1.6		5.45	3.83	30	1.4		7.71	4.83	37	1.6	
373.65	8.42	5.09	40	1.7		5.64	3.81	33	1.5		7.09	5.07	29	1.4	
357.70	8.56	4.75	44	1.8		6.47	3.39	48	1.9		7.22	3.71	49	1.9	
357.09	8.91	4.50	50	2.0		6.94	3.49	50	2.0		8.11	4.18	48	1.9	
348.87	7.54	4.57	39	1.7		5.37	3.52	34	1.5		6.26	3.93	37	1.6	
326.30	6.83	4.40	36	1.6		4.34	3.30	24	1.3		4.15	3.01	27	1.4	
308.80	8.34	4.26	49	2.0		5.36	2.81	48	1.9		5.52	3.92	29	1.4	
290.20	7.53	4.81	36	1.6		6.68	4.08	39	1.6		6.21	3.96	36	1.6	

Table 2. Velocity, channel dimensions, and discharge measured at Missouri River synoptic and synoptic-repeat velocimetric surveys with multiple-repeat velocimetric surveys between July (high discharge) and October (low discharge) 2011.—Continued

[ft/s, foot per second; Q, discharge; ft², square foot; ft³/s, cubic foot per second; --, no data; bold where sampled as multiple-repeat survey, multiple-repeat survey data from July 11–28, 2011, (averaged) for July 2011; and October 20–21, 2011, for October 2011]

River mile	Whole-river velocity (ft/s)			High Q to low Q ratio	Velocity from Winriver II'			High Q to low Q ratio
	(ft/s)		Decline, in percent		(ft/s)		Change, in percent	
	July	October			July	October		
492.38	4.98	4.47	10	3.35	4.30	28	0.8	
471.71	5.61	3.75	33	4.44	3.66	-18	1.2	
452.50	5.83	4.21	28	3.18	4.13	30	0.8	
432.68	7.41	4.18	44	6.20	4.03	-35	1.5	
412.55	5.26	4.51	14	--	4.63	--	--	
394.50	6.32	4.29	32	4.16	3.56	-14	1.2	
373.65	6.35	4.25	33	6.36	4.37	-31	1.5	
357.70	7.25	3.74	48	6.47	3.79	-41	1.7	
357.09	7.66	3.92	49	7.37	4.04	-45	1.8	
348.87	6.28	3.84	39	6.15	3.98	-35	1.5	
326.30	5.24	3.56	32	5.11	3.50	-32	1.5	
308.80	5.88	3.10	47	4.96	2.50	-50	2.0	
290.20	7.35	4.43	40	6.84	4.22	-38	1.6	

Table 2. Velocity, channel dimensions, and discharge measured at Missouri River synoptic and synoptic-repeat velocimetric surveys with multiple-repeat velocimetric surveys between July (high discharge) and October (low discharge) 2011.—Continued

[ft/s, foot per second; Q, discharge; ft², square foot; ft³/s, cubic foot per second; --, no data; bold where sampled as multiple-repeat survey, multiple-repeat survey data from July 11–28, 2011, (averaged) for July 2011; and October 20–21, 2011, for October 2011]

River mile	Channel width (feet)			High Q to low Q ratio	Channel area (ft²)			High Q to low Q ratio	Instantaneous discharge (ft³/s)			High Q to low Q ratio
	July	October	Decline, in percent		July	October	Decline, in percent		July	October	Decline, in percent	
492.38	2,560	818	68	3.1	49,000	13,600	72	3.6	165,000	58,300	65	2.8
471.71	2,970	969	67	3.1	47,600	16,600	65	2.9	211,000	60,700	71	3.5
452.50	2,400	825	66	2.9	60,900	14,700	76	4.1	193,000	60,500	69	3.2
432.68	1,720	822	52	2.1	35,200	15,100	57	2.3	218,000	61,000	72	3.6
412.55	--	811	--	--	--	13,500	--	--	--	62,500	--	--
394.50	1,670	845	49	2.0	45,600	18,400	60	2.5	189,000	62,300	67	3.0
373.65	1,170	873	25	1.3	32,200	13,700	57	2.4	205,000	59,900	71	3.4
357.70	983	935	4.9	1.1	33,950	16,500	51	2.1	220,000	62,400	72	3.5
357.09	907	822	9.4	1.1	30,900	15,100	51	2.0	227,500	60,800	73	3.7
348.87	1,020	957	6.2	1.1	35,000	15,800	55	2.2	215,000	62,800	71	3.4
326.30	1,310	974	26	1.3	41,000	17,900	56	2.3	210,000	62,700	70	3.3
308.80	1,360	1,030	24	1.3	45,300	24,700	45	1.8	225,000	61,900	72	3.6
290.20	1,240	1,130	8.9	1.1	32,650	15,200	53	2.1	223,500	63,900	71	3.5

¹Includes estimation for areas of unmeasured velocity.

Figure 12. Relation of velocimetric survey data in the four measured zones at multiple-repeat surveys with daily mean discharge at Kansas City, and Waverly, Missouri, for July through October 2011.

Synoptic Surveys

Synoptic surveys were done over a short period of time to help characterize longitudinal changes in velocities with similar rates of discharge. Three sets of synoptic surveys were done in July 2011, October 2011, and July 2012.

2011 Synoptic Surveys

Synoptic surveys were done at 10 sites for the period of July 19–20, 2011, and at 34 sites from October 18–21, 2011. The 34 sites surveyed in October include synoptic-repeat surveys of the initial 10 synoptic sites surveyed in July (figs. 2, 4; tables 1, 2). Multiple-repeat survey data collected during the intervals of July 11–28 and October 20–21 were grouped with synoptic survey data (tables 2) to provide a more complete evaluation of changes from July to October and were included

Figure 13. Velocimetric survey data in the four measured zones of the Missouri River with Winriver II mean velocity between July and October 2011 at multiple-repeat surveys arranged by velocity type.

in the computation of the July and October 2011 synoptic survey statistics (table 1).

Synoptic and multiple-repeat survey profiles from July 2011 are plotted by river mile with instantaneous discharge in figure 14. A clear longitudinal trend of velocity in the measured zones is not apparent although instantaneous discharge measured during the July surveys increased downstream. River mile 357.09 on average exhibited the highest values for velocity in the measured zones in July and main-channel velocities exceeded 8 ft/s at rm's 452.50, 432.68, 394.50, 373.65, 357.70, and 308.80. Aerial imagery at rm 394.50 from June 2011 (fig. 10) shows substantial turbulence under flood conditions and this may have been the case for other sites at the time. On average, main-channel velocity exceeded whole-river velocity by 22 percent during July and at rm's 452.50 and 308.80 the difference reached above 40 percent (table 1). These two sections may therefore be considered as having the

least uniform velocity distribution of all the July surveys. The near bank velocities were highest in July at rm 357.09 and then dropped abruptly at rm 326.30 where higher velocities were centered in the channel (fig. 14).

From July to October 2011, evaluation of combined data from 10 pairs of synoptic and synoptic-repeat survey sites with multiple-repeat surveys sites determined that all velocity types (including Winriver II mean velocity), as well as channel width decreased by an average of 30 to 40 percent or about one-third (table 2). Channel area and instantaneous discharge decreased by an average of 58 and 70 percent, respectively. The average percent by which main-channel velocity exceeded whole-river velocity at these sites decreased slightly from 22 percent in July to 19 percent in October (table 1). At rm 452.50 this percent difference dropped markedly from 41 percent in July to 12 percent in October (table 1) and may imply that velocity distribution at this section became increasingly

Figure 14. Missouri River velocimetric survey data in the four measured zones from multiple-repeat and synoptic surveys in July 2011 and October 2011 with approximate locations of July 2012 synoptic surveys.

uniform over the course of the flood. On the whole, survey channel sections were a mixture of bends and crossings and velocity distribution patterns varied with respect to orientation from July to October. In some cases, patterns of velocity distribution across sections may have been strongly influenced by channel structures at all times.

Comparing the ratios at high (July 2011) to low (October 2011) discharge of velocity, channel width, and channel area, relative changes in velocity may be indicators of the varying influence of channel width, channel area and in some cases channel structures (table 2). At rm's 492.38, 471.71 and 452.50 (Rulo, Nebraska, to St. Joseph, Missouri) channel width and area both expanded at high discharge by factors of nearly 3.0 or more and the near-bed, near-bank, and whole-river velocities increased by factors of 1.5 or less. Main-channel velocities at rm's 471.71 and 452.50 increased at high discharge by slightly larger factors of 1.6 and 1.7 (respectively) and the Winriver II mean velocities (that account for channel area) at rm's 492.38 and 452.50, in fact, decreased (factors of 0.8). Channel width and area changed by factors of 1.3 or less from rm 373.65 to 290.20 at high discharge and the respective changes in velocity at rm's 357.70, 357.09 (below the Kansas River, near Kansas City) and 308.80 may have indicated a stronger influence of channel structures at these sections. At these three sections channel width increased minimally at high discharge (factors of 1.3 or less), channel area effectively doubled and all velocity types increased by factors of 1.8 or more. The differences between velocities at high and low discharge were greatest at these three sections indicating that the channel (and possibly structures) at these locations effectively constrains flow over a wide range of discharge. At rm's 432.68, 394.50, 373.65 (three sections above the Kansas River), 348.87, 326.30 (two sections below the Kansas River), and 290.2 (near Waverly, Missouri) the channel area increased by factors of 2.0 to 2.5 times at high discharge and velocities increased by factors less than 2.0. At these locations, the Winriver II mean velocity was in all cases greater at high discharge. The influence of channel structures may have been lesser at these locations because the relative changes in velocity at high discharge at these sections were slightly less than those at rm's 357.70, 357.09 and 308.80. Due to an incomplete dataset at rm 412.55, it was not possible to evaluate relative changes in channel characteristics and Winriver II mean velocity; however, this section reported lower relative differences (factors of 1.2) for the remaining velocity types, similar to those seen at rm 492.38 (factors of 1.2 or less).

For the velocimetric profiles evaluated solely in October 2011 (fig. 14), a clear downstream trend in velocity in measured zones was not evident until the survey at rm 424.20 where these velocities appeared to increase approaching rm 404.70. Proceeding downstream from rm 404.70, the net trend in velocities from measured zones was downward with slight increases at rm 290.20. The maximum and minimum instantaneous discharges remained within 5 percent of the mean (table 1) from rm 492.38 to rm 290.20. River mile 404.70 exhibited the highest values for main-channel, near-bed and whole river

velocities whereas rm 387.90 had the highest near-bank velocity. Main-channel velocity exceeded 7 ft/s at rm's 404.70 and 402.50. On average, main-channel velocity exceeded whole-river velocity by 36 percent at rm's 371.28 and 363.40 and by 37 percent at rm 308.80. These sections may have had the most variable velocity distribution for the October part of the study. Near-bank velocity varied from section to section with comparatively low values at rm's 464.70 (2.24 ft/s) and 298.90 (0.58 ft/s). Channel structures near these sections may have diverted higher velocities away from the edges resulting in the lower near-bank velocities.

2012 Synoptic Surveys

In July 2012, additional synoptic surveys were done at 50 sites in stream segments near St. Joseph (segment 1), near Kansas City above (segment 2) and below (segment 3) the Kansas River, and near Waverly, Missouri (segment 4) (figs. 5–7; table 1). These surveys were typically no more than 3 miles apart within a given stream segment and in some cases were separated by only a few tenths of a mile (figs. 5–7). Velocimetric profile data from measured zones are plotted by river mile for each survey in figure 15. Instantaneous discharge, near-bed velocity, whole-river velocity, Winriver II velocity, and channel area are plotted by river mile in figure 16. The St. Joseph stream segment length was approximately 5 miles and no longitudinal trend was observed in velocities. However, at stream segments 2 and 3 near Kansas City (total surveyed distance, 28 miles) and segment 4 near Waverly (segment length, 8.5 miles), velocities generally decreased proceeding downstream. The highest main-channel velocity (4.77 ft/s) was reported at rm 374.74 and the highest near-bank velocity (4.69 ft/s) at rm 304.99. Near-bed (4.11 ft/s) and whole-river (4.42 ft/s) velocities were highest at rm 377.43. Main-channel velocity exceeded whole-river velocity on average by 13 percent and at rm 442.52 the difference was as much as 43 percent (table 1). Velocity distribution in this section was therefore possibly the most variable of the 2012 synoptic surveys. Near-bank velocity was typically the most variable of all velocity types (fig. 15; table 1), and may have been influenced by channel structures near the survey sections. At rm 356.43, near-bank velocity fell to 1.72 ft/s, where flow at the outer edge of the river bend may have been impeded by a channel structure. The variability of near-bank velocity data also may have been caused by the inability in some cases to measure near the revetment of a profile section. Comparing near-bed, whole-river, and Winriver II velocity in all segments, it was apparent that near-bed velocity was closest in relation to Winriver II mean velocity (fig. 16; table 1). The source of this relation may have been the Winriver II software's inclusion of unmeasured zones in its mean velocity computation and the near-bed velocity being computed from values that physically bordered these unmeasured zones (fig. 8).

Near-bed and whole-river velocities decreased somewhat with respect to increasing channel area (fig. 16, table 1). Surveys at rm's 442.52, 368.17, 362.84, and 299.13 had the

Figure 15. Missouri River velocimetric survey data in the four measured zones from synoptic surveys during July 2012.

Figure 16. Missouri River instantaneous discharge with velocimetric survey data in two measured zones (near-bed, whole-river), Winriver II velocity and channel area from synoptic surveys during July 2012.

lowest relative near-bed and whole-river velocities (near or below 3 ft/s) and channel areas ranging from 11,400 to 17,100 ft². Conversely, surveys at rm's 439.45, 377.43, 362.24, and 304.99 each had the highest near-bed and whole-river velocities (closer to 4 ft/s) in their respective segments and channel areas less than or equal to 11,200 ft². Where channel area exceeded 15,000 ft² (rm's 442.52, 362.84 and 299.13), Winriver II mean velocity fell below 3 ft/s. The Winriver II mean velocity may have maintained an inverse relation with channel width and area because the software is able to account for the entire area of the channel (fig. 8). Main-channel and near-bank velocity were not related to channel area and their magnitudes were more likely related to velocity distribution across a given section.

Comparing averages between the respective segments (table 1), all velocity types (including the Winriver II mean velocity) generally either decreased or increased slightly as channel width and area increased. From St. Joseph to Kansas City (segment 1–2) instantaneous discharge increased by about one-half a percent, channel width and area decreased, and all velocity types increased. At Kansas City, discharge increased by about 6 percent crossing the Kansas River (segment 2–3), channel area increased (the greatest amount among all four segments), and all velocity types decreased. From Kansas City to Waverly (segment 3–4), instantaneous discharge increased by less than 2 percent and, whereas most velocity types reported a small increase, the Winriver II mean velocity slightly decreased. The low near-bank velocity at rm 356.43 (1.72 ft/s, table 1) reduced the average for segment 3 and was likely influenced by channel structures. It is also relevant to note that the average near-bank velocities at each segment may have been different had it been possible to compute values for every survey location. Comparing the averages for the St. Joseph and Waverly (segments 1 and 4), the increase in instantaneous discharge was about 9 percent, and relative increases in channel width and area corresponded to minimal changes in velocity. Near-bed and near-bank velocities increased only slightly and main-channel, whole-river, and the Winriver II mean velocities conversely decreased.

Summary and Conclusions

A velocimetric study was done in the Lower Missouri River in cooperation with the U.S. Army Corps of Engineers to evaluate the behavior of velocity over the course of a flood by characterizing velocity in zones of a cross-sectional profile and evaluating data for longitudinal trends. Sediment has been trapped in reservoirs upstream from main-stem dams constructed on the Missouri River and average annual river-bed elevations have fallen measurably near Kansas City since 1940. Additional velocity data were needed to continue the U.S. Army Corps of Engineers' study of Missouri River bed degradation and assist development of a hydraulic model that simulates flow and bedload transport.

In this study, a total of 118 velocimetric Acoustic Doppler Current Profile surveys were collected at 87 pre-designated river miles along the Lower Missouri River. Multiple-repeat surveys made at the same three sites from July to October were used to determine temporal changes in velocimetric profiles in response to changes in river discharge over the course of the 2011 flood. Synoptic surveys in July 2011 (10 sites) and October 2011 (34 sites, including synoptic-repeats of the 10 synoptic surveys in July 2011), and again in July 2012 (50 sites) were used to compare velocities from segment to segment over broad stretches of the river and observe velocities at navigation discharge.

Velocity data were distinguished in four zones (main channel, near bed, near bank, whole river) of a river cross-section and were extracted from Winriver II ADCP profile output data and computed for each measured zone as the average of values determined from reciprocal transects. Where possible, the analysis was extended to include zones of unmeasured velocity estimated by Winriver II mean velocity computation. Monthly and daily mean discharges from the St. Joseph, Kansas City, and Waverly, Missouri, streamgaging stations were retrieved from the U.S. Geological Survey National Water Information System database and provided as a reference.

For the multiple-repeat surveys in the vicinity of Kansas City and Waverly, Missouri, comparison of the main-channel, near-bed, near-bank, and whole-river velocities with daily mean discharges computed at the St. Joseph and Waverly, Missouri, streamgaging stations indicated a general decline in velocity with respect to declining discharge. Evaluation of the percent difference of main-channel velocity from whole-river velocity at multiple-repeat surveys indicated that velocity distribution at the Waverly location was more uniform than the Kansas City sites. In addition, velocities from all measured zones of the river channel at all three locations were strongly correlated with daily mean discharges at St. Joseph, and Waverly, Missouri River streamgaging stations. When the Winriver II mean velocity data (with estimates for unmeasured zones) were included in the analysis for these sites, the relation between all velocities was determined to be inconsistent from July to October 2011. Percent changes in channel width from July to October 2011 at each of the multiple-repeat sites were less than corresponding changes in channel area and instantaneous discharge.

Synoptic and multiple-repeat survey profiles from July 2011 compared with instantaneous discharge did not indicate a clear longitudinal trend of velocity in the measured zones as discharge increased downstream. Aerial imagery in June of 2011 showed substantial turbulence during flood conditions. On average, main-channel velocity exceeded whole-river velocity by 22 percent during July 2011 and in some cases this difference was nearly 40 percent (rm's 452.50 and 308.80). Evaluation of 10 pairs of synoptic and synoptic-repeat surveys with multiple-repeat surveys from July to October 2011 determined that all velocity types (including Winriver II mean velocity) and channel width decreased by about one-third, channel area and instantaneous discharge decreased

by an average of more than 50 percent and the percent by which main-channel velocity exceeded whole-river velocity decreased slightly from 22 percent in July to 19 percent in October. The ratios of velocity, channel width, and channel area at high to low discharge indicated that if both channel width and area expanded by a factor of nearly 3.0 or more (rm's 492.38 to 452.50), velocity in measured zones increased by factors in the range of 1.1 to 1.7 and Winriver II mean velocity decreased at rm's 492.38 and 452.50 (factor of 0.8). The channel widths at the Kansas City sites were similar from high to low discharge and channel areas and all velocities were about double at high discharge. The differences of velocities at high and low discharge at these locations indicated that the channel (and possibly structures) effectively constrains flow over a wide range of discharge. For all velocimetric profiles evaluated in October 2011, a clear downstream trend in velocity in measured zones was only evident beginning at river mile 424.20, where velocity increased toward rm 404.70 and then generally decreased downstream, until rm 290.20, where velocity increased slightly.

Additional synoptic surveys were done in July 2012 in four segments near St. Joseph, Kansas City (above and below the Kansas River), and Waverly, Missouri. The St. Joseph stream segment reported no longitudinal trend for velocity in measured zones and the Kansas City and Waverly segments reported a general decrease in these velocities proceeding downstream. The highest main-channel velocity (4.77 ft/s) was reported at rm 374.74 and the highest near-bank velocity (4.69 ft/s) at rm 304.99. Near-bed (4.11 ft/s) and whole-river (4.42 ft/s) velocities were highest at rm 377.43. Main-channel velocity exceeded whole-river velocity on average by 13 percent and at rm 442.52 the difference was as much as 43 percent. Comparing near-bed, whole-river, and Winriver II velocity in all segments, near-bed velocity was closest in relation to Winriver II mean velocity. The Winriver II software's estimation of velocity in unmeasured zones for the mean velocity computation and the near-bed velocity being computed from values that physically border these unmeasured zones may have been the source of this relation. Throughout the entire study, near-bank velocity was typically the most variable of all velocity types and this may have been caused by the persistent influence of channel structures and their diversion of higher velocities away from the channel edges. For the 2012 portion of the study, the inability in some cases to measure near the revetment of a profile section may have contributed to this variability. Near-bed and whole-river velocities decreased somewhat with increasing channel area. Surveys at rm's 442.52, 368.17, 362.84, and 299.13 had the lowest relative near-bed and whole-river velocities (near or below 3 ft/s) and channel areas ranging from 11,400 to 17,100 ft². Where channel area exceeded 15,000 ft² (rm's 442.52, 362.84 and 299.13), Winriver II mean velocity fell below 3 ft/s. The Winriver II mean velocity may have maintained an inverse relation with channel width and area because the software is able to account for the entire area of the channel. Comparing segment to segment, from St. Joseph to Kansas City discharge increased,

channel width and area decreased, and all velocity types increased. At Kansas City, discharge increased crossing the Kansas River, channel area increased, and all velocity types decreased. From Kansas City to Waverly, discharge increased and although most velocity types reported a small increase, the Winriver II mean velocity conversely decreased. Comparing the averages for the St. Joseph and Waverly segments, the increase in instantaneous discharge was about 9 percent, and relative increases in channel width and area corresponded to minimal changes in velocity. Near-bed and near-bank velocities increased only slightly and main-channel, whole-river, and the Winriver II mean velocities conversely decreased.

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