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Scientific Investigations Report 2015–5127

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

Cover photograph. Sampling the Missouri River near Omaha, Nebraska, on July 8, 2011. Note flooding in the background. Photograph by David Rus, U.S. Geological Survey.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)

Datum

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

Supplemental Information

Concentrations of suspended sediment in water are given in milligrams per liter (mg/L).

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By David L. Rus, Joel M. Galloway, and Jason S. Alexander

Abstract

Extreme flooding in the Missouri River in 2011, followed by a year of more typical streamflows in 2012, allowed the sediment-transport regime to be compared between the unprecedented conditions of 2011 and the year immediately following the flooding. As part of a cooperative effort between the U.S. Geological Survey and the U.S. Army Corps of Engineers, this report follows up U.S. Geological Survey Scientific Investigations Report 2013–5006 by comparing sediment transport between years and among sampling sites spanning the Garrison Segment in North Dakota, the Gavins Point Segment downstream from Lewis and Clark Lake, and a part of the Channelized Segment along the Nebraska-Iowa border. Suspended sediment, bed material, bedload, and streamflow data from June 2011 through November 2012 were designated as "measured" total loads, wash loads, and bed-material loads; and, alternatively, were applied to the Modified-Einstein Procedure to compute sediment loads that were designated as "estimated" total loads.

Beyond the expected result that sediment loads were much lower during typical streamflows than those measured during the flooding, the measured data indicated some localized sediment-transport processes for further examination. Extreme and prolonged flooding can temporarily deplete sediment supplies locally, and evidence indicating such depletion was present at some sites. Unexpectedly high bed-material loads in the Gavins Point Segment may reflect episodic bar erosion just upstream from the sampling site. The relative contribution of bedload was typically 10 percent or less of the total load during the flooding. Following the flooding, this relative amount increased at some sites but not others, the reasons for which are possibly related to differences in stream velocity. Ultimately, the bedload decreased as it entered the Channelized Segment because of increased velocity and the turbulent mixing ability of the river as compared to the Gavins Point Segment. This turbulent mixing may also convert bed-material load into wash load, thereby rendering those sediments unavailable for creating sandbars and other bedforms. Though some of the sampling data support this premise, it was not consistently manifested by differences between the sediment load of the two segments during typical-streamflow conditions.

The Modified-Einstein Procedure tended to predict greater total-sediment loads when compared to measured values. These differences may be the result of sediment deficits in the Missouri River that lead to an overprediction by the Modified-Einstein Procedure, the unsampled zone above the streambed that leads to an underprediction by the suspended sampler, or general uncertainty in the sampling approach. The differences between total-sediment load obtained through measurements and that estimated from applied theoretical procedures such as the Modified-Einstein Procedure pose a challenge for reliably characterizing total-sediment transport. Though it is not clear which of the two techniques is more accurate, the general tendency of the two to be within an order of magnitude of one another may be adequate for many sediment studies.

Introduction

In 2011, a combination of above-normal snowpack in headwater regions of Montana and Wyoming, near record snowfall and saturated soil conditions in North and South Dakota, and record rainfall in May across the upper Missouri River Basin contributed to record annual runoff into the Missouri River Mainstem Reservoir System (Grigg and others, 2012; Vining and others, 2013). These unprecedented inflows led to releases of record high-magnitude discharges from the main-stem reservoirs operated by the U.S. Army Corps of Engineers (USACE) into the Missouri River (Holmes and others, 2013). These record discharges eroded, transported, and deposited massive amounts of sediment, which, at some locations, dramatically altered the channel and flood plain geomorphology (Alexander and others, 2013; Juracek, 2014; Schenk and others, 2014). Measured Missouri River discharges in 2012 contrasted markedly with its 2011 peaks, with most sites characterized by below-average peak discharges.

Although the large discharges in 2011 provided an opportunity to examine characteristics of total-sediment transport in the Missouri River at high-magnitude discharges and over a long duration (Galloway and others, 2013), discharges in 2012 provided an opportunity to compare total-sediment-transport characteristics during more typical discharge conditions and to re-examine methods of sediment-transport estimation.

To characterize total-sediment transport on the Missouri River during 2011 and 2012, the U.S. Geological Survey (USGS), in cooperation with the USACE, collected sediment samples at selected locations extending from Washburn, North Dakota, to Nebraska City, Nebraska (fig. 1).

Purpose and Scope

This report supplements USGS Scientific Investigations Report 2013–5006, which described a previous study of sediment transport at selected sites along the Missouri River during the high-streamflow conditions of 2011 (Galloway and others, 2013). The focus herein is sediment transport during the more typical-streamflow conditions of 2012, in contrast to those of 2011. Four of the original six study sites on the Missouri River sampled in 2011 (at Washburn, N. Dak.; at Bismarck, N. Dak.; near Maskell, Nebr.; at Sioux City, Iowa; at Omaha, Nebr.; and at Nebraska City, Nebr.) were resampled in 2012 for suspended sediment, bedload, and bed material (fig. 1). These results were used to provide further information on the characteristics of Missouri River sediment, including suspended-sediment concentration (SSC) and grain-size distribution, bedload mass and grain-size distribution, suspended and bedload transport rates, and temporal and spatial variability therein. Though much more suspended-sediment data are available for some sites as a result of historical and ongoing monitoring, this report focuses on datasets that allow the total-sediment transport to be characterized on a given date through the inclusion of suspended-sediment, bedload, and bed-material data.

Description of Study Area

Six locations (sites) were sampled to characterize total-sediment transport in the Missouri River in 2011. The Washburn and Bismarck sites were located between Lake Sakakawea and Lake Oahe (henceforth referred to as the “Garrison Segment”); the Maskell site was located downstream from Lewis and Clark Lake in a free-flowing, nonchannelized length of the river (referred to as the “Gavins Point Segment”); and the Sioux City, Omaha, and Nebraska City sites were located within part of the channelized section of the river (referred to as the “Channelized Segment”) (table 1, fig. 1). The Washburn and Bismarck sites (Garrison Segment), the Maskell site (Gavins Point Segment), and the Sioux City site (Channelized Segment) were resampled in 2012 for total-sediment transport. Streamflow data from two additional tributary sites (table 1) were used in estimating streamflow at the Maskell site (a stage-only streamgage).

In the remainder of this section of the report, a basic description of the hydrologic and sediment budget characteristics of the sampling sites is provided. More comprehensive information is in Galloway and others (2013). Some of the segment characteristics are described in terms of the USACE system of river miles, which reference the mileage upstream from the confluence with the Mississippi River along the Missouri River channel centerline as it existed in 1960 (Dan Pridal, U.S. Army Corps of Engineers, written commun., 2012).

Hydrologic Characteristics

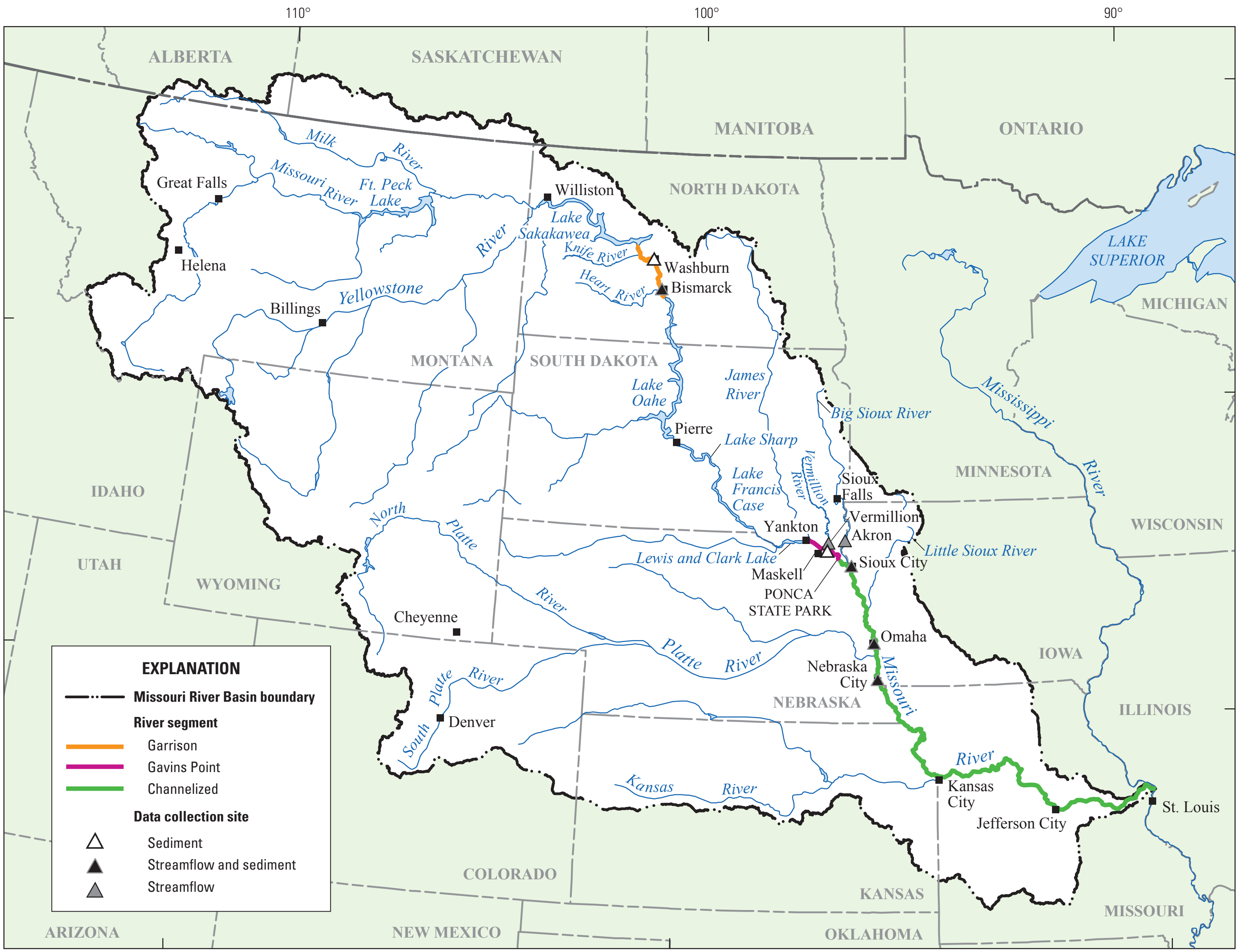
Streamflow at all six sites is affected by upstream reservoirs (Fort Peck Lake, Lake Sakakawea, Lake Oahe, Lake Sharpe, Lake Francis Case, and Lewis and Clark Lake) that dampen hydrologic extremes in the Missouri River (National Research Council, 2002). Continuous-streamflow records are available for four of the six sites from the USGS, two of which are summarized in table 2 (U.S. Geological Survey, 2015). At both sites, streamflow conditions during 2011 were the highest since the 1966 completion of the reservoir system. Although the reservoirs attenuated the peak streamflows in 2011 by as much as 100,000 cubic feet per second (ft^3/s) (U.S. Army Corps of Engineers, 2012), they nonetheless released streamflows at or above flood levels and lengthened the duration of those high streamflows. In 2011, the daily mean streamflows at the Bismarck site were greater than 68,900 ft^3/s—the existing peak-of-record after dam completion but prior to 2011—for

Table 1. Streamflow and sediment data-collection sites for the Missouri River and selected tributary streams.

[NA, not applicable]

Site name (fig. 1)	Main-stem segment	U.S. Geological Survey station number	Full station name	Data collected during 2011–12
Washburn	Garrison	06341000	Missouri River at Washburn, North Dakota	Sediment.
Bismarck	Garrison	06342500	Missouri River at Bismarck, North Dakota	Streamflow, sediment.
Maskell	Gavins Point	06478526	Missouri River near Maskell, Nebraska	Sediment.
Akron	NA	06485500	Big Sioux River at Akron, Iowa	Streamflow.
Vermillion	NA	06479010	Vermillion River near Vermillion, South Dakota	Streamflow.
Sioux City	Channelized	06486000	Missouri River at Sioux City, Iowa	Streamflow, sediment.
Omaha	Channelized	06610000	Missouri River at Omaha, Nebraska	Streamflow, sediment.[1]
Nebraska City	Channelized	06807000	Missouri River at Nebraska City, Nebraska	Streamflow, sediment.[1]

[1]Bedload samples collected in 2011 only.



Base from U.S. Geological Survey digital data, 2013, 1:10,000,000
Albers Equal-Area Conic projection
Standard parallels 29°30′N and 45°30′N, central meridian 96°00′W
North American Datum of 1983

0 50 100 200 MILES
0 50 100 200 KILOMETERS

Figure 1. Missouri River Basin with locations of sediment-data collection sites.

Table 2. Summary of streamflow characteristics for two Missouri River sites.

[All streamflows are reported in cubic feet per second]

Summary period, in water years	Bismarck, North Dakota, site		Sioux City, Iowa, site	
	Mean annual streamflow	Peak streamflow	Mean annual streamflow	Peak streamflow
1966–2010	22,800	68,900	30,700	104,000
2011	53,200	155,000	79,100	192,000
2012	25,000	30,400	34,400	45,100

98 consecutive days. Similarly, at the Sioux City site, daily mean streamflows in 2011 were greater than 104,000 ft^3/s for 90 consecutive days. In contrast, streamflow conditions in 2012 more closely approximated the long-term average from 1966 to 2010.

Sediment Budget Characteristics

The sediment budgets of altered rivers such as the Missouri River are important in characterizing their geomorphic condition and potential for future change (Jacobson and others, 2009). Sediment budgets account for the erosion, transport, and deposition of sediments within a river as well as the dynamic interactions between those processes and streamflow. If a river has less capacity to transport sediment than the sediment quantity that is being supplied (a common scenario where a river enters a reservoir), the river is said to have a sediment surplus, and those sediments will eventually deposit into the streambed and increase the amount of sediment in storage. Conversely, if a river has a greater capacity to transport sediment than the sediment quantity that is being supplied (a common scenario downstream from dams; Williams and Wolman, 1984), then the river has a sediment deficit and consequent erosional processes will remobilize the sediments out of storage (in the streambed or stream banks) to meet that excess transport capacity.

In historical context, the completion of upstream reservoirs has reduced the downstream sediment supply at all six sites (National Research Council, 2002; Jacobson and others, 2009; National Research Council, 2011). In addition, the systematic bank stabilization and channelization downstream from Ponca State Park, river mile (RM) 753 (fig. 1), has reduced the supply of bank-eroded sediment to downstream sites (Sioux City, Omaha, and Nebraska City sites). With the exception of the Nebraska City site, the channelization and dams have resulted in channel incision, with the greatest amounts of incision measured at sites nearest to dam outlets (Williams and Wolman, 1984; Chen and others, 1999; Jacobson and others, 2009). Upstream from the Nebraska City site, sediment contributions from the Platte River may largely have offset incision from that confluence downstream. Channel incision and bank-erosion rates in the Garrison Segment (the Washburn and Bismarck sites) were much greater during the initial 20 years following completion of Lake Sakakawea (fig. 1) as compared to more recent periods (Pokrefke and others, 1998), indicating that the segment may be recovering its dynamic equilibrium (Biedenharn and others, 2001; Skalak and others, 2013). A similar trend of diminishing incision and erosion was not as apparent at the Maskell site (Pokrefke and others, 1998) subsequent to the completion of Lewis and Clark Lake, indicating that erosional processes may be ongoing at this site.

More recently, the extreme and prolonged flooding of 2011 affected the sediment budget in the Missouri River. The high streamflows added a considerable amount of energy for mobilizing sediment stored in the channel while the reservoirs simultaneously trapped sediment and limited the sediment supply available to downstream segments. Potentially, such a situation might cause a sediment-supply deficit in the part of the river system downstream from the impoundments, dependent on the magnitude of sediment discharges from tributaries. The flood of 2011 was unique in that most of the streamflow originated in the part of the basin regulated by the reservoir system. Unlike prior floods, the tributaries downstream from the reservoirs were not contributing substantial amounts of sediment to the main stem to offset that deficit, which may explain the relatively low suspended-sediment concentrations in 2011 (Alexander and others, 2013). It also implies that much of the flood-mobilized sediment had to originate from within the local main-stem river segment through streambed, streambank, and, where applicable, flood-plain erosion, thereby depleting the local sediment in storage.

Horowitz (2003) pointed out that it took about 3 years for the local sediment in storage to recover following the 1993 floods on the Mississippi River. Typical of many fluvial systems, erosion of sediments in one location generally led to the deposition of those sediments elsewhere. At several levee breaks, sediments were transported out of the stream channel and onto the flood plain, where they subsequently were deposited as crevasse splay deposits (Alexander and others, 2013). At other locations, sandbars were formed (such as one observed just upstream from the Maskell site) and numerous side-channel chutes were cut off from the main channel of the river as a result of sand deposition. Similar to the Mississippi River following the 1993 floods (Horowitz, 2003), it is likely that the channel of the Missouri River will recover some of its balance of local sediment storage through erosional processes that may continue for several years after 2011, and may include the erosion of morphometric features that were created by the 2011 flood.

Methods

The following sections describe methods used for the assessment of sediment transport during 2011 and 2012. Generally, sediment transport was estimated using data for streamflow, SSC, bedload, and bed-material samples analyzed for grain-size distribution. These data were collected by the USGS at six study sites on the main stem of the Missouri River (table 1; fig. 1).

This report uses terminology for sediment transport that categorizes sediment load either according to a measurement principle or a transport mechanism (Church, 2006). Terms used to describe sediment characteristics by the measurement principle include suspended-sediment load, bedload, and bed material (table 3). Terms used to describe sediment characteristics by the transport mechanism include wash load, bed-material load, and total-sediment load (table 3).

Measurements and sample collection were generally consistent in methodology from site to site and from high to typical streamflow with a few exceptions. Most measurements were made from bridges rather than from boats. The collection of bedload samples from a boat during the high-streamflow conditions was deemed both dangerous and prone to sampling error caused by boat movement. The suspended-sediment samples and streamflow measurements at the Sioux City, Omaha, and Nebraska City sites were collected from a boat as part of another data-collection program done simultaneously with this study.

Suspended-sediment and bedload sampling took place on the same day, with one exception (the Nebraska City site samples of June 27 and 28, 2011). With the exception of the Omaha site, all field measurements and samples for each study site were collected within the same reach of the Missouri River. For these purposes, a river reach can be considered a length of river approximately 10 channel widths long. At the Omaha site, measurements of SSC were made from a boat near U.S. Interstate 480 (I–480) at RM 616. Because of safety concerns associated with heavy traffic on the I–480 Bridge, measurements of bedload and bed material were made about 10.4 miles upstream at the U.S. Interstate 680 (I–680) Bridge at RM 626.4, which was closed to traffic during the 2011 sampling period. Unfortunately, hydraulic conditions were quite different at the two measurement locations in 2011. At the I–680 Bridge, the river flooded most of the valley bottom and attained a width of more than 4 miles during the peak of the flood, but measurements of bedload were limited to the main channel under the bridge, which contained most, but not all, of the streamflow. In comparison, all of the streamflow near the I–480 Bridge was confined to the main channel by levees and was approximately 0.2 miles wide. Although most of the streamflow at the I–680 Bridge was located within the 0.2-mile-wide channel under the bridge, there were likely higher stream velocities and thus greater sediment-transport capacity at the I–480 Bridge. Consequently, some sediment grains that were transported as bedload at the I–680 Bridge may have become suspended load once reaching the area near the I–480 Bridge. Therefore, total-sediment transport estimates for the Omaha site may be positively biased as a result of the double-accounting of these grains.

Table 3. Terms used to describe sediment-transport characteristics.

[Descriptions used in this table were derived from Church, 2006 and Edwards and Glysson, 1999]

Term	Description
	Measurement principle
Suspended-sediment load	Component of sediment load consisting of inorganic grains that move in a downstream direction by suspension within the water column; operationally, it is the component of sediment transport within the vertical interval from the water surface down to a depth associated with the unsampled zone of the water sampler.
Bedload	Component of sediment load consisting of inorganic grains that move in a downstream direction by rolling, saltating, or bouncing along the riverbed or, operationally, the component of sediment in transport within the vertical interval from the surface of the riverbed up to the height of the top of the bedload sampler nozzle.
Bed material	Sediment grains on the surface of the bed of the river and below the surface down to the maximum sampling depth of the sampling device (varies with sampler type and design).
	Transport mechanism
Wash load	Component of sediment load that remains continuously in suspension under given hydraulic conditions. Wash load consists of grain sizes finer than those represented in the bed, and therefore constrained to being measured in the suspended-sediment sample.
Bed-material load	Component of sediment load (whether measured as bedload or in suspension) able to be moved under given hydraulic conditions but unable to remain in suspension continuously. Bed-material load consists of grain sizes represented in the streambed.
Total-sediment load	Computed as either (1) sum of the wash load and the bed-material load or (2) the sum of the bedload and suspended-sediment load.

Sediment-Data Collection and Laboratory Analyses

Suspended-sediment, bedload, and bed-material samples were collected at various time intervals from all six Missouri River sites in 2011 and from the Washburn, Bismarck, Maskell, and Sioux City sites in 2012 (fig. 1). Because of practicality considerations, samples were collected from the main channel of the river only and did not include the sediment load associated with flood-plain overbank streamflow; however, flood-plain overbank streamflow only coincided with sampling at the Omaha and Nebraska City sites and only during the highest-streamflow conditions at those sites. Though field techniques did not vary with streamflow condition, the samples were categorized as being high-streamflow samples or typical-streamflow samples based on the measured streamflow at the time of sampling. Most of the samples collected in 2011 were associated with high streamflow, and all of the samples collected in 2012 were associated with typical-streamflow conditions.

Suspended-sediment samples were collected to estimate the suspended load transported past the six sites. Samples were collected isokinetically (water enters the sampler nozzle at the same velocity as the stream current) using depth-integrated samplers (Davis, 2005) at multiple locations along a transect (or cross-section) to represent the vertical and horizontal variability of suspended sediment in the stream channel.

Different types of suspended samplers and sampling methods were used at different sites because some of the samples were collected as part of a previously established data-collection program. Suspended samples from the three most upstream sites—Washburn, Bismarck, and Maskell—were collected using a US-D-96 bag sampler (Davis, 2005). These suspended samples were collected at 10 stations across the channel, spaced at equal intervals using the equal-width increment (EWI) sampling method (Edwards and Glysson, 1999). Samples collected using the EWI method were composited in a plastic churn splitter for subsequent processing into aliquots using plastic bottles.

Suspended samples from the three most downstream sites—Sioux City, Omaha, and Nebraska City—were collected using one of two samplers. Samples collected before July 20, 2011, used a US P–61 sampler (Davis, 2005), which normally is used for collecting a sample at a discrete point but can be used in depth-integrated sampling if the nozzle is left in the open position throughout the sample (Edwards and Glysson, 1999). Samples collected after July 20, 2011, used a US-D-96 bag sampler (Davis, 2005). The suspended samples from the three downstream sites were collected at three stations along the transect, specified using the equal-discharge increment (EDI) method (Edwards and Glysson, 1999). For samples collected using the EDI method, samples associated with the individual stations (verticals) were submitted separately for laboratory analysis, at which time they were composited.

In many cases at all of the sites, the sampler was not lowered all the way to the streambed to avoid the potential for compromising the sample by inclusion of bed material. Therefore, the suspended-sediment sample did not include the water column interval from 0.5 to 2 feet (ft) above the streambed.

Replicate samples were obtained for SSC determinations by collecting a second representative volume of water from the churn splitter concurrently with the regular sample. Nine such replicate samples were collected: four for the Washburn site, three for the Bismarck site, and two for the Maskell site. The relative standard deviation (Mueller and others, 2015) of the pairs of replicate SSC samples varied between 2 and 41 percent and averaged 14 percent. Some of the variability is the result of the high concentration of sand-sized grains in suspension in the samples. For example, the replicate pair with the largest variability included a sample in which 97 percent of the sediments were sand-sized or coarser. Though better reproducibility would have been desirable, the results were considered acceptable given the flood conditions.

Bedload samples were collected to estimate the sediment transport near the streambed at the six sites. Bedload samples were obtained using a Helley-Smith Model 8035 sampler (at the Washburn and Bismarck sites) or a BL–84 sampler (at the Maskell, Sioux City, Omaha, and Nebraska City sites) (Davis, 2005) suspended on a cable from a crane. Both samplers are designed for orientation in the direction of streamflow when deployed on the streambed. Bedload samples were collected at 20 equally spaced verticals across the stream transect. At the Washburn and Bismarck sites, sediment masses from each vertical were composited before further processing. At the Maskell, Sioux City, Omaha, and Nebraska City sites, the 20 equally spaced verticals were sampled twice, using 2 sequential passes across the bridge for every sample. The bedload was derived by compositing the sediments from all verticals before being weighed. The composited sediments were then subsampled for sieve analysis.

Due to time and resource limitations, replicate bedload samples were not able to be collected; however, for a subset of 29 bedload samples (associated with the 2011 Maskell, Sioux City, Omaha, and Nebraska City samples), sediments from each vertical were air dried and weighed separately at the USGS Nebraska Water Science Center prior to being composited. Relative standard deviations between passes averaged 19 percent but were as high as 50 percent in one sample. Because these weights were not obtained using standard procedures, the true variability between passes is not confidently known. In addition, the standard procedure of compositing two sequential passes is intended to reduce the effect of this variability on the final bedload values used in the analyses.

The hydraulic conditions of the Missouri River in 2011 likely exceeded the operational range of the Helley-Smith and BL–84 bedload samplers. Criteria for the proper collection of bedload at any given vertical include (1) that the sampler comes to rest on the streambed with no forward velocity, (2) that the sampler remains stationary during collection, and (3) that, in lifting the sampler off the streambed, it does not maintain contact with the streambed (such as might happen on the leeward—or downstream facing—side of a dune). Violation of these conditions may lead to the dredging of bed material that was not concurrently part of the bedload. The hydraulic conditions of the Missouri River in 2011 challenged these criteria with depths exceeding 50 ft (at sites in the lower segment) and stream velocities frequently exceeding 10 feet per second (ft/s). Before collecting the first sample, the collection procedures were refined to gain as much confidence as possible that the criteria were being met. This included the addition of as much as 75 pounds of weight to the sampler (using sounding weights affixed above the sampler), the lowering of the sampler as quickly as the equipment would allow (typically at a downward rate of 4 to 5 ft/s), the maintenance of slack cable during the sampling period (to the extent possible given the hydraulic conditions), and the retrieval of the sampler as quickly as the equipment would allow (typically at an upward rate of 3 to 5 ft/s). Without any means of visually observing the behavior of the sampler on the bed of the river, this technique was assumed to be effectively attaining the criteria. In addition, the temporal variation in bedload at a given vertical will increase as the sampling time on the streambed becomes small relative to the cycle period of the dune being measured (Edwards and Glysson, 1999). Because of the limited sampler volume, the samplers were left on the streambed for 20 to 40 seconds at individual stations during 2011 sampling; in 2012, the samplers were left on the streambed for 60 to 120 seconds.

Bed-material samples were collected using a US BM–54 sampler (Davis, 2005). The bed-material samples were collected at five equally spaced stations (hereinafter referred to as “verticals”) along the stream transect and composited for analysis. Four planned bed-material samples (two each from the Omaha and Nebraska City sites) were not collected as a result of sampler malfunctions.

All suspended-sediment samples were analyzed for concentration and grain-size distribution at the USGS Sediment Laboratory at Iowa City, Iowa, using methods described in Guy (1969). Bedload samples were weighed and bed-material and bedload samples were analyzed for grain-size distribution at the same laboratory using the methods described in Guy (1969). Results from the laboratory analyses were stored in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2015).

Streamflow Data Collection

Streamflow data were important for understanding the hydraulic conditions of the river and the resulting capacity to transport sediment. Streamflow measurements were made concurrently with most of the sediment samples collected at the six sites. Streamflow was measured using an acoustic Doppler current profiler (ADCP) with the methods and procedures described in Mueller and Wagner (2009). For analyzing sediment transport, the streamflow measurements at the Nebraska City site that included flooded-overbank areas were adjusted such that the adjusted streamflow corresponded only to the area where sediment-transport measurements were being made. For example, on June 27, 2011, streamflow in the main channel at the Nebraska City site was estimated at 193,000 ft^3/s, or 91 percent of the total streamflow of 211,000 ft^3/s (U.S. Geological Survey, 2015).

In addition to the discrete measurements, continuous-streamflow data were available at the Bismarck, Sioux City, Omaha, and Nebraska City sites (table 1, fig. 1). Streamflow data from the Bismarck site were used as estimated streamflow for the computation of sediment loads at the Washburn site. Daily mean streamflow for the Maskell site was estimated by subtracting the daily mean streamflow for the Big Sioux River (Big Sioux River at Akron, Iowa, USGS station number 06485500, fig. 1, table 1) and the Vermillion River (Vermillion River near Vermillion, S. Dak., USGS station number 06479010, fig. 1, table 1) from the daily mean streamflow at the Sioux City site—located 43 river miles downstream from Maskell—for the same date (U.S. Geological Survey, 2015).

Total-Sediment Load

One of the most difficult problems in open-channel hydraulics is the determination of the rate of movement of material along the streambed (bedload; table 3) (Einstein, 1950; Gray and others, 2010); however, an estimate of total-sediment load could be underestimated if bedload is neglected. Total-sediment load was estimated at each site using two methods: the sum of sampled rates of transport of suspended sediment and bedload, and a computational estimate derived from the Modified-Einstein procedure of Colby and Hembree (1955).

Measured Sediment Load

The measured total-sediment load was computed as the sum of the measured suspended-sediment load and bedload. Suspended-sediment loads (sediment discharge) were estimated for the six sites using daily mean streamflow data and measured SSC data (Porterfield, 1972) collected at each site:

$$Q_s = Q_w C_s K_s \tag{1}$$

where

- Q_s is the suspended-sediment load (sediment discharge), in tons (English short tons) per day;
- Q_w is the daily mean streamflow (water discharge), in cubic feet per second;
- C_s is the SSC, in milligrams per liter; and
- K_s is a coefficient (0.0027) to convert the units of measurement of streamflow and SSC into tons per day and assumes a specific gravity of sediment of 2.65.

The bedload component was calculated from the measured data using the following equation (Edwards and Glysson, 1999):

$$Q_b = K_b(W_T/t_T)M_T \quad (2)$$

where

- Q_b is the bedload, in tons per day;
- K_b is a units conversion factor (10.8 for a 3-inch wide nozzle);
- W_T is the total width of the stream from which samples were collected, in feet, and is equal to the increment width times the total number of verticals sampled;
- t_T is the total time the sampler was on the streambed, in seconds, computed by multiplying the individual sample time by the total number of verticals sampled; and
- M_T is the total mass of sample collected from all verticals sampled in the transect, in ounces.

Estimated Sediment Load

The second method to estimate sediment transport used a theoretical model to quantify bedload. Einstein (1950) first presented the technique for calculating the transport of sediment with grain sizes also present in appreciable quantities in the streambed or the bed-material load. This method used a probabilistic relation of SSC with stream velocity over a given vertical profile and for a finite longitudinal distance along a given river reach. Colby and Hembree (1955) and Colby and Hubbell (1967) developed a modified version of Einstein's procedure (Modified-Einstein Procedure [MEP]) that used sediment and hydraulic data from a single transect to calculate the total bed-material load for a specific stream reach. The MEP is considered an improvement on the original Einstein method because it is simpler in computation and it uses characteristics more readily available from typical measurements of sediment conditions at a site. The MEP model was implemented for this study by using the executable program Bureau of Reclamation Automated Modified-Einstein Procedure (BORAMEP) (Holmquist-Johnson and others, 2009). Input data needed for the MEP model include streamflow, average channel velocity, wetted channel width, average channel depth, water-surface slope, water temperature, SSC, the grain-size distributions of the suspended sediment and bed material, and the proportion of the suspended sediment also represented in the bed. A water-surface slope of 0.00017 ft of vertical change for every foot traveled downstream was assumed from the slope of the streambed given in Carlston (1969). Though this assumption may not have been explicitly met, sensitivity analysis indicated that slope did not affect results even when varied over three orders of magnitude relative to the assumed streambed slope.

Although MEP estimates are commonly referred to as "total-sediment discharge" procedures (Einstein, 1950; Colby and Hembree, 1955), it is important to note that the predictive capacity of the MEP is limited to estimates of the bed-material load or the transport of grain sizes represented in the streambed. The transport of wash load (table 3) is derived from erosional processes external to the hydraulics of the local river reach such as rainfall-derived runoff, tributary inputs, and bank erosion. Therefore, it is a supply-dependent component of sediment transport, and must be incorporated separately. However, the measurements of suspended-sediment load include the wash load and the suspended part of the bed-material load.

For this report, the wash load was classified as that part of the suspended-sediment load consisting of grain sizes finer than those represented in the bed. More specifically, the fifth-percentile diameter of the bed-material grain-size distribution was used as the threshold for determining the percentage of the suspended-sediment load that was considered wash load. The remaining suspended-sediment load (consisting of grain sizes coarser than the threshold diameter) was considered bed-material load that was in suspension. Because the MEP method utilizes the suspended bed-material load to predict the total bed-material load, the wash load was removed from the suspended-sediment load before input to the BORAMEP program. The wash load was then added to the BORAMEP-derived estimate of bed-material load to produce the MEP-estimated total-sediment load (Colby and Hembree, 1955).

Characteristics of Sediment Transport at Selected Sites Along the Missouri River, 2011–2012

In much of the Missouri River, the 2011 streamflows were unprecedented since the advent of the main-stem dams era, and much has been written about the flood's effect on sediment transport (Alexander and others, 2013; Galloway and others, 2013; Juracek, 2014; Schenk and others, 2014). This section of the report focuses on Missouri River sediment transport during the more typical-streamflow conditions of 2012 and contrasts it with that during the high streamflows of 2011 previously reported by Galloway and others (2013). Sediment-transport characteristics are described below in terms of the transport mechanisms (wash load and bed-material load) and measurement principle (suspended-sediment load, bedload, and bed-material characteristics), either of which can be used to quantify total-sediment load (table 3).

Generally speaking, the great magnitude of the streamflows of 2011 obscured subtle differences in sediment-transport characteristics among the sites. These differences became more apparent during typical-streamflow conditions during 2012. Those differences among sites also are examined in this section of the report.

Sediment-Load Sampling Results

A total of 46 samples associated with high-streamflow conditions and 40 samples associated with typical-streamflow conditions were analyzed from six sites between June 2011 and November 2012. The field data included streamflow, suspended-sediment concentration and grain size, bedload and grain size, and bed-material grain size characteristics of the river (tables 1–1, 1–2, and 1–3). These data were used to compute the total-sediment load and to discriminate between wash load and bed-material load (table 4, fig. 2, fig. 3).

At all sites, sediment loads were considerably lower during typical conditions as compared to the high-streamflow conditions of 2011 (table 4). Given the extreme decrease in streamflow, this is not noteworthy; however, there are more subtle aspects to these decreases that warrant further examination.

Sediment Depletion

Because the high streamflow of 2011 was coupled with the sediment trapping effect from the reservoirs, the resulting conditions were unnatural with respect to sediment transport. Local sediments stored in the channel were probably mobilized and transported downstream. The extended duration of the flood made it more likely that these locally stored sediments may have become depleted, and consequently may take several years to be replenished (Horowitz, 2003). Decreased streambed elevations that persisted into 2013 at the Sioux City and Omaha sites (Juracek, 2014) provide some evidence of sediment depletion in the Channelized Segment. In the Garrison Segment, a 157-percent increase in the mean bed-material load from Washburn to Bismarck (table 4) in the absence of any major tributary inputs during the typical streamflows following the flooding indicates that erosional processes within the channel, such as bank and bar erosion and streambed incision, are contributing sediments to downstream reaches. This also may indicate that the Garrison Segment has shifted out of dynamic equilibrium following the 2011 flood.

Bar Formation and Erosion in the Gavins Point Segment

Sediment load data at the Maskell site within the Gavins Point Segment were difficult to interpret during the high streamflows as well as the more typical streamflows that followed. It was expected that sediment transport in the Gavins Point Segment would differ from that in the Channelized Segment because of the differences in the hydraulic conditions (as characterized by velocity and depth, table 4) both during and after the flood; however, much of the suspended-sediment data collected in 2011 resulted in sediment loads that seemed unreasonably large when compared to the next site downstream. In addition to being considerably coarser (table 1–1), these questionable suspended-sediment loads at the Maskell site were consistently greater than those at the Sioux City site by hundreds of thousands of tons. As a result, it was presumed that these suspended-sediment samples were compromised by incorrect sampler contact with the streambed and were subsequently omitted from the analyses (Galloway and others, 2013; loads “not calculated” in table 4). In addition, suspended samples at the Maskell site in 2012 were collected more carefully. The sampling protocol was adjusted at this site to direct that the suspended-sediment sampler was only lowered to within 3 ft of the bottom (as determined by prior bedload sampling) and that a sample be discarded and recollected for any verticals at which the sampling crew suspected contact of the sampler with the streambed. Despite these efforts, three of seven 2012 samples from the Maskell site still exhibited much greater sediment loads when compared to the other Maskell samples and all of the Sioux City samples (table 4, fig. 3). Although it is possible that the samples were again compromised by inclusion of streambed sediments, it seems much less likely than in 2011.

To retain these sediment-load results in the dataset for subsequent analyses, a reasonable explanation for these seemingly episodic increases was needed. One potential explanation that is supported by anecdotal and bathymetric evidence is the erosion of a large sandbar directly upstream from the Maskell site. Coincidentally, bathymetric data were collected repeatedly just upstream from the sampling location (fig. 10 in Schenk and others, 2014). These bathymetric data indicate the formation of a sandbar near the left bank between December 2010 and November 2011, coinciding with the high streamflows of 2011. Subsequent bathymetric data from March 2012 show a narrowing of that sandbar, indicating erosion had taken place along the edges of the bar. It is reasonable to assume that this erosion was episodic and that much of this eroded material probably redeposited at points in the channel downstream from the sandbar; however, given the proximity of the sampling location to an eroding sandbar, collected samples may have captured some of this eroded material before it redeposited, thereby contributing to the unexpectedly high sediment loads at the site.

Contribution of Bedload to Total Load

In many fluvial sediment studies, bedload is not included in the monitoring design because of the practical limitations associated with collecting a bedload sample and the uncertainty that accompanies bedload data. Instead, sediment characteristics are derived from the results of suspended-sediment sampling, and the contribution of bedload is often neglected by necessity. In this study, bedload data were available, although the corresponding uncertainty was large. Nonetheless, these data provide insight into the part of sediment load that would otherwise be missed during the extremely high streamflows of 2011 as well as more typical streamflows that followed through 2012. During the flooding, sediment loads for none of the sites were dominated by bedload, with only the Maskell site having bedloads that were typically greater than 10 percent of the total-sediment load (table 4).

Table 4. Measured sediment loads for six Missouri River sites on dates of sample collection, 2011–12.

[Load data for for all samples in 2011 from Galloway and others, 2013. ft³/s, cubic feet per second; ft, feet; ft/s, feet per second; ton/d, tons per day; % of total, percent of total-sediment load; --, not calculated]

Date	Streamflow conditions				Measurement principle				Total-sediment load (ton/d)	Transport mechanism			
	Type	Daily mean streamflow (ft³/s)	Mean depth (ft)	Mean velocity (ft/s)	Suspended-sediment load		Bedload			Wash load		Bed-material load	
					ton/d	% of total	ton/d	% of total		ton/d	% of total	ton/d	% of total
Missouri River at Washburn, North Dakota (Washburn site)													
06/16/2011	High	147,000	25.4	5.1	182,000	100	344	0	182,000	70,000	38	112,000	62
06/23/2011	High	151,000	26.8	4.9	157,000	99	625	0	158,000	53,800	34	104,000	66
06/30/2011	High	145,000	27.1	4.8	97,500	100	206	0	97,700	45,600	47	52,100	53
07/06/2011	High	143,000	28.8	4.2	115,000	100	164	0	115,000	46,500	40	68,700	60
07/14/2011	High	131,000	26.9	4.4	78,200	99	479	1	78,700	31,900	41	46,800	59
07/27/2011	High	114,000	24.9	4.5	115,000	97	2,790	2	118,000	43,200	37	74,600	63
08/04/2011	High	108,000	23.0	4.2	48,700	94	2,890	6	51,600	16,100	31	35,500	69
08/17/2011	High	88,400	22.5	3.5	26,700	91	2,790	9	29,500	9,600	33	19,900	67
09/08/2011	High	53,600	17.5	2.8	9,550	89	1,100	10	10,700	3,060	29	7,590	71
09/15/2011	High	49,100	15.9	2.8	7,160	97	192	3	7,350	3,440	47	3,910	53
09/22/2011	Typical	30,800	13.9	2.1	2,500	93	199	7	2,700	1,480	55	1,220	45
09/29/2011	Typical	24,300	12.7	1.8	1,770	76	554	24	2,320	1,530	66	794	34
05/18/2012	Typical	25,200	8.8	2.5	1,630	84	316	16	1,950	976	50	970	50
06/19/2012	Typical	25,000	9.2	2.4	1,080	81	246	18	1,330	809	61	517	39
07/10/2012	Typical	21,700	8.2	2.3	2,290	82	503	18	2,790	2,240	80	553	20
08/07/2012	Typical	23,100	8.7	2.3	873	64	490	36	1,360	710	52	653	48
09/05/2012	Typical	23,400	8.6	2.4	1,010	94	70	6	1,080	721	67	359	33
09/25/2012	Typical	19,000	7.5	2.0	616	63	366	37	982	564	57	418	43
10/16/2012	Typical	19,800	8.0	2.0	909	50	905	50	1,810	658	36	1,160	64
10/30/2012	Typical	23,200	8.0	2.2	689	33	1,430	67	2,120	482	23	1,640	77
11/06/2012	Typical	23,100	8.0	2.3	1,870	82	423	18	2,290	956	42	1,340	59
	High mean	**113,000**	**23.9**	**4.1**	**83,700**	**97**	**1,160**	**3**	**84,900**	**32,300**	**38**	**52,500**	**62**
	Typical mean	**23,500**	**9.2**	**2.2**	**1,390**	**73**	**500**	**27**	**1,880**	**1,010**	**54**	**875**	**47**

Table 4. Measured sediment loads for six Missouri River sites on dates of sample collection, 2011–12.—Continued

[Load data for all samples in 2011 from Galloway and others, 2013. ft³/s, cubic feet per second; ft, feet; ft/s, feet per second; ton/d, tons per day; % of total, percent of total-sediment load; --, not calculated]

Date	Streamflow conditions: Type	Streamflow conditions: Daily mean streamflow (ft³/s)	Streamflow conditions: Mean depth (ft)	Streamflow conditions: Mean velocity (ft/s)	Measurement principle: Suspended-sediment load: ton/d	Measurement principle: Suspended-sediment load: % of total	Measurement principle: Bedload: ton/d	Measurement principle: Bedload: % of total	Total-sediment load (ton/d)	Transport mechanism: Wash load: ton/d	Transport mechanism: Wash load: % of total	Transport mechanism: Bed-material load: ton/d	Transport mechanism: Bed-material load: % of total
Missouri River at Bismarck, North Dakota (Bismarck site)													
06/09/2011	High	138,000	17.7	5.0	278,000	100	1,500	1	279,000	139,000	50	140,000	50
06/15/2011	High	142,000	18.3	5.0	276,000	100	1,270	0	277,000	83,100	30	194,000	70
06/22/2011	High	151,000	20.9	4.6	196,000	99	2,160	1	198,000	93,900	47	104,000	53
07/01/2011	High	146,000	21.6	4.3	165,000	99	2,470	1	167,000	81,500	49	86,000	51
07/05/2011	High	145,000	21.6	4.3	110,000	99	1,340	1	111,000	74,500	67	36,800	33
07/13/2011	High	139,000	21.2	4.2	127,000	98	2,540	2	130,000	65,300	50	64,200	49
07/26/2011	High	120,000	20.4	3.7	82,600	91	8,530	9	91,100	24,300	27	66,800	73
08/04/2011	High	110,000	20.2	3.5	113,000	93	8,890	7	122,000	27,800	23	94,100	77
08/16/2011	High	92,100	19.9	4.2	93,200	96	3,510	4	96,700	18,800	19	77,900	81
09/08/2011	High	56,700	15.6	2.8	21,900	96	871	4	22,800	10,700	47	12,100	53
09/15/2011	High	51,000	14.5	2.8	15,000	96	594	4	15,600	7,680	49	7,910	51
09/22/2011	Typical	34,500	12.0	2.5	5,960	95	343	5	6,300	3,970	63	2,330	37
09/29/2011	Typical	28,200	11.6	2.3	3,050	96	142	4	3,190	2,370	74	822	26
05/17/2012	Typical	27,000	12.6	3.3	8,310	99	75	1	8,390	2,670	32	5,720	68
06/19/2012	Typical	27,400	13.3	3.1	6,290	100	20	0	6,310	2,110	33	4,200	67
07/10/2012	Typical	23,700	12.4	2.9	2,620	94	172	6	2,790	1,380	49	1,410	51
08/07/2012	Typical	25,300	12.2	2.8	4,030	94	261	6	4,290	1,700	40	2,590	60
09/05/2012	Typical	23,900	11.3	2.8	4,650	99	46	1	4,700	2,370	50	2,330	50
09/25/2012	Typical	19,800	10.2	2.4	1,760	85	303	15	2,060	1,320	64	740	36
10/16/2012	Typical	20,700	10.5	2.4	1,900	88	249	12	2,150	1,450	67	700	33
10/30/2012	Typical	21,300	10.4	2.5	2,420	94	148	6	2,570	1,080	42	1,490	58
11/06/2012	Typical	23,500	10.6	2.7	4,060	99	43	1	4,100	1,700	41	2,400	59
	High mean	**117,000**	**19.3**	**4.0**	**134,000**	**97**	**3,060**	**3**	**137,000**	**57,000**	**42**	**80,300**	**58**
	Typical mean	**25,000**	**11.6**	**2.7**	**4,100**	**95**	**164**	**5**	**4,260**	**2,010**	**51**	**2,250**	**49**

Table 4. Measured sediment loads for six Missouri River sites on dates of sample collection, 2011–12.—Continued

[Load data for all samples in 2011 from Galloway and others, 2013. ft³/s, cubic feet per second; ft, feet; ft/s, feet per second; ton/d, tons per day; % of total, percent of total-sediment load; --, not calculated]

Date	Streamflow conditions				Measurement principle				Total-sediment load (ton/d)	Transport mechanism			
	Type	Daily mean streamflow (ft³/s)	Mean depth (ft)	Mean velocity (ft/s)	Suspended-sediment load		Bedload			Wash load		Bed-material load	
					ton/d	% of total	ton/d	% of total		ton/d	% of total	ton/d	% of total
Missouri River near Maskell, Nebraska (Maskell site)													
06/23/2011	High	156,000	16.9	3.8	--	--	13,300	--	--	--	--	--	--
06/30/2011	High	168,000	16.5	4.8	118,000	89	15,000	11	133,000	58,000	44	75,000	56
07/21/2011	High	179,000	16.1	3.6	--	--	29,000	--	--	--	--	--	--
08/04/2011	High	161,000	19.7	4.3	168,000	84	32,900	16	201,000	50,300	25	151,000	75
08/18/2011	High	154,000	18.1	4.3	--	--	27,500	--	--	--	--	--	--
09/01/2011	High	99,000	18.0	3.8	--	--	16,800	--	--	--	--	--	--
09/15/2011	High	93,500	11.2	4.1	--	--	27,400	--	--	--	--	--	--
11/02/2011	Typical	43,800	8.2	2.8	--	--	6,260	--	--	--	--	--	--
05/31/2012	Typical	30,900	7.0	2.4	90,900	96	3,370	4	94,300	5,520	6	88,800	94
06/20/2012	Typical	32,100	7.3	2.9	76,400	97	2,570	3	79,000	7,710	10	71,300	90
07/09/2012	Typical	33,200	6.9	2.4	6,630	70	2,820	30	9,450	3,590	38	5,860	62
08/09/2012	Typical	37,200	10.0	2.0	6,730	68	3,180	32	9,910	2,800	28	7,110	72
09/06/2012	Typical	37,700	9.4	2.0	64,900	96	2,350	3	67,300	15,900	24	51,400	76
10/11/2012	Typical	37,000	8.1	2.3	16,600	81	4,000	19	20,600	7,430	36	13,200	64
11/15/2012	Typical	35,700	7.3	2.4	11,100	78	3,070	22	14,200	3,160	22	11,000	77
	High mean	**165,000**	**18.1**	**4.6**	**143,000**	**86**	**24,000**	**14**	**167,000**	**54,200**	**34**	**113,000**	**66**
	Typical mean	**34,800**	**8.0**	**2.3**	**39,000**	**84**	**3,050**	**16**	**42,100**	**6,590**	**23**	**35,500**	**77**
Missouri River at Sioux City, Iowa (Sioux City site)													
07/01/2011	High	179,000	35.1	6.6	217,000	97	6,070	3	223,000	59,400	27	164,000	74
08/05/2011	High	164,000	30.8	6.0	163,000	95	9,450	5	172,000	58,800	34	114,000	66
08/19/2011	High	160,000	32.8	5.2	163,000	95	9,140	5	172,000	58,800	34	113,000	66
09/02/2011	High	101,000	36.8	5.1	54,800	91	5,100	9	59,900	25,300	42	34,600	58
09/16/2011	High	94,300	25.9	6.2	59,600	92	5,210	8	64,800	26,200	40	38,600	60
11/01/2011	Typical	42,500	14.8	5.3	46,200	91	4,420	9	50,600	17,900	35	32,700	65
06/01/2012	Typical	44,500	18.7	4.4	26,600	92	2,410	8	29,000	24,300	84	4,710	16
06/19/2012	Typical	34,200	14.2	3.7	12,700	89	1,500	11	14,200	11,900	84	2,300	16
07/10/2012	Typical	33,800	16.0	3.2	13,800	94	946	6	14,700	7,430	51	7,320	50
08/10/2012	Typical	37,800	17.4	3.3	17,500	91	1,760	9	19,300	9,110	47	10,200	53

Table 4. Measured sediment loads for six Missouri River sites on dates of sample collection, 2011–12.—Continued

[Load data for all samples in 2011 from Galloway and others, 2013. ft^3/s, cubic feet per second; ft, feet; ft/s, feet per second; ton/d, tons per day; % of total, percent of total-sediment load; --, not calculated]

Date	Streamflow conditions				Measurement principle				Total-sediment load (ton/d)	Transport mechanism			
	Type	Daily mean streamflow (ft^3/s)	Mean depth (ft)	Mean velocity (ft/s)	Suspended-sediment load		Bedload			Wash load		Bed-material load	
					ton/d	% of total	ton/d	% of total		ton/d	% of total	ton/d	% of total
Missouri River at Sioux City, Iowa (Sioux City site)—Continued													
09/07/2012	Typical	37,700	17.2	3.3	14,100	89	1,820	11	15,900	7,390	46	8,530	54
10/12/2012	Typical	37,300	20.1	2.8	26,000	98	549	2	26,500	11,000	42	15,500	58
11/16/2012	Typical	36,000	18.5	3.0	28,700	97	902	3	29,600	17,300	58	12,300	42
	High mean	**140,000**	**32.3**	**5.8**	**131,000**	**94**	**6,990**	**6**	**138,000**	**45,700**	**36**	**92,800**	**65**
	Typical mean	**38,000**	**17.1**	**3.6**	**23,200**	**93**	**1,790**	**7**	**25,000**	**13,300**	**56**	**11,700**	**44**
Missouri River at Omaha, Nebraska (Omaha site)													
07/08/2011	High	190,000	29.9	8.2	399,000	99	3,870	1	403,000	95,800	24	307,000	76
07/18/2011	High	191,000	31.3	8.0	184,000	98	2,620	1	187,000	134,000	72	52,600	28
08/01/2011	High	186,000	29.3	7.4	119,000	97	3,990	3	123,000	85,700	70	37,300	30
08/15/2011	High	168,000	30.7	7.1	224,000	98	3,930	2	228,000	76,000	33	152,000	67
08/29/2011	High	132,000	33.8	5.0	73,800	91	7,020	9	80,800	45,800	57	35,000	43
09/12/2011	High	102,000	31.3	4.2	41,300	90	4,710	10	46,000	27,700	60	18,300	40
10/31/2011	Typical	47,300	16.9	3.8	20,600	88	2,880	12	23,500	14,400	61	9,080	39
	High mean	**162,000**	**31.1**	**6.7**	**174,000**	**96**	**4,360**	**4**	**178,000**	**77,500**	**53**	**100,000**	**47**
Missouri River at Nebraska City, Nebraska (Nebraska City site)													
06/21/2011	High	195,000	33.6	7.3	225,000	96	9,940	4	235,000	201,000	86	33,900	14
06/27/2011	High	193,000	36.9	7.0	257,000	94	16,100	6	273,000	235,000	86	38,100	14
07/19/2011	High	141,000	36.5	5.3	78,800	87	12,200	13	91,000	78,000	86	13,000	14
08/02/2011	High	144,000	36.0	4.1	110,000	92	9,980	8	120,000	73,500	61	46,500	39
08/16/2011	High	136,000	29.7	4.7	91,100	93	6,960	7	98,100	49,100	50	49,000	50
08/30/2011	High	110,000	39.8	3.7	61,200	90	6,870	10	68,100	40,900	60	27,200	40
09/13/2011	High	93,300	30.3	4.1	55,900	94	3,360	6	59,300	34,600	58	24,700	42
11/03/2011	Typical	54,200	17.0	4.2	50,300	95	2,380	5	52,700	26,300	50	26,400	50
	High mean	**145,000**	**34.7**	**5.2**	**126,000**	**92**	**9,340**	**8**	**135,000**	**102,000**	**70**	**33,200**	**30**

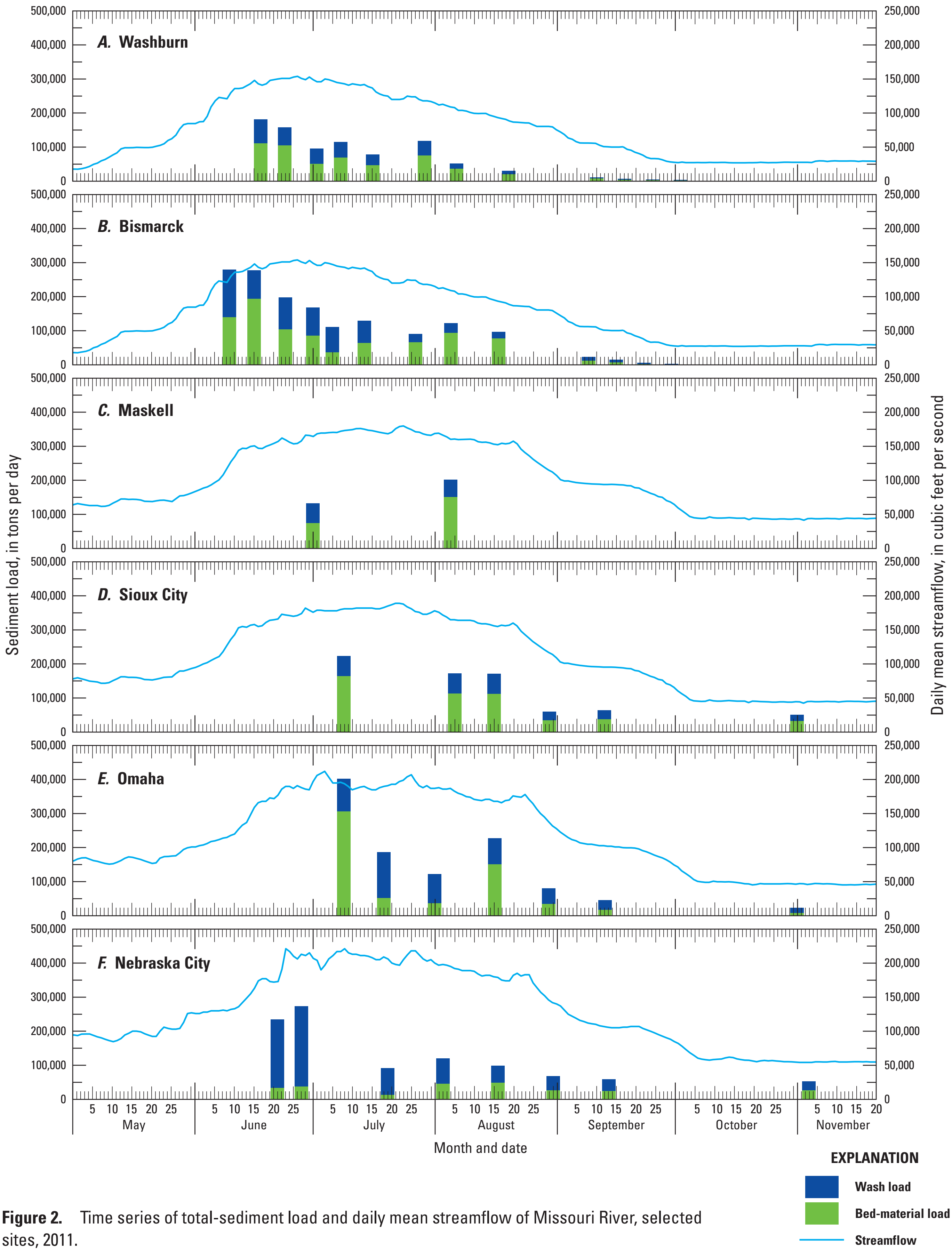


Figure 2. Time series of total-sediment load and daily mean streamflow of Missouri River, selected sites, 2011.

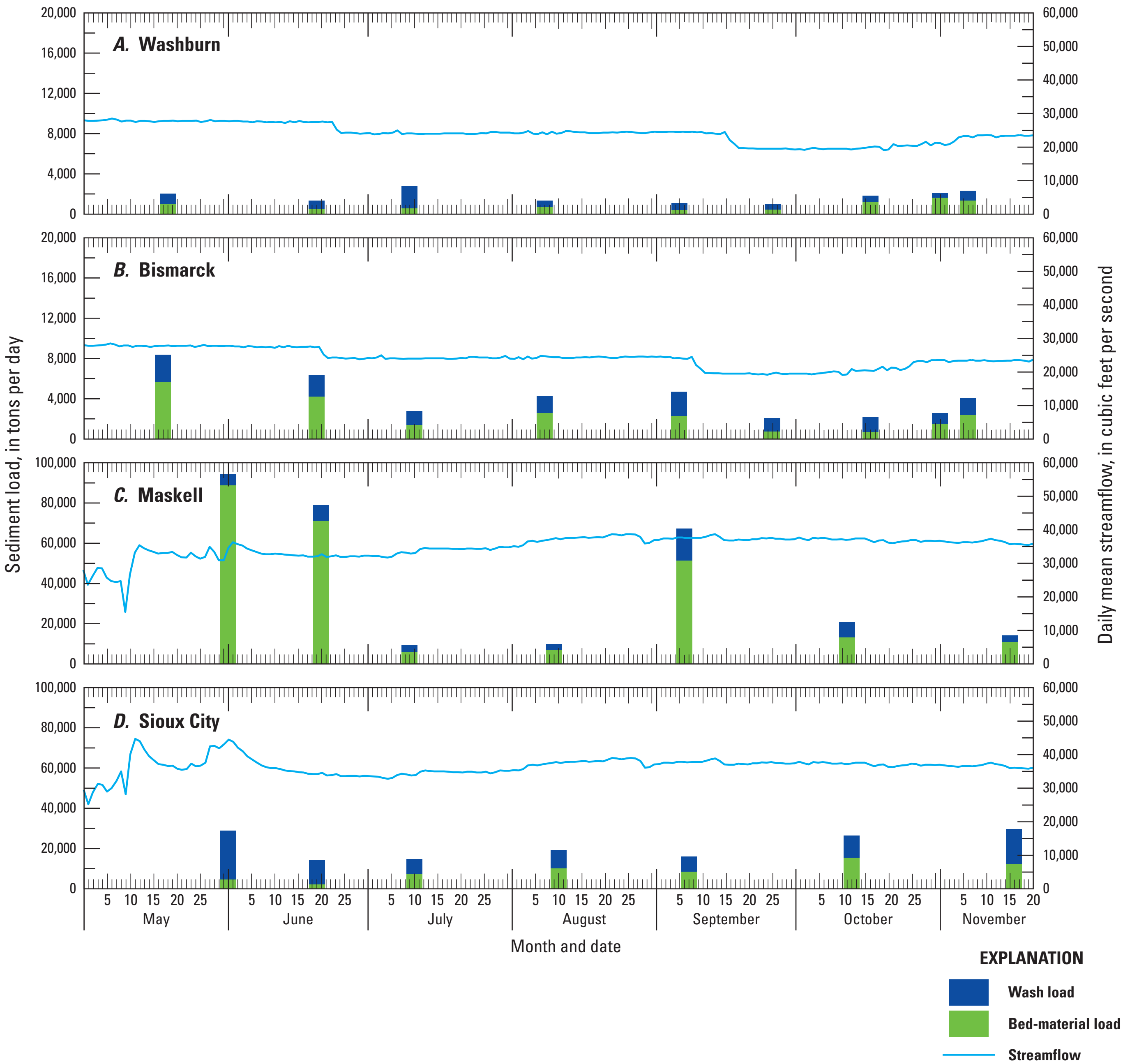


Figure 3. Time series of total-sediment load and daily mean streamflow of Missouri River, selected sites, 2012.

Interestingly, when streamflows returned to more typical conditions in the Garrison Segment, bedload became more important at the Washburn site—increasing from a high-streamflow mean of 3 percent to a typical-streamflow mean of 27 percent of the total load. However, bedload at the Bismarck site remained at approximately 5 percent of the total load (table 4). Some of this difference between sites may be explained by higher velocities at the Bismarck site during typical conditions (table 4) that are likely able to suspend some of the materials that otherwise traveled as bedload past the Washburn site.

Even though the amount of bedload at the Maskell site in the Gavins Point Segment did not vary greatly during typical-streamflow conditions, the proportion of bedload relative to total load was quite variable. As before, the presumed erosion of a recently formed sandbar likely added large amounts of locally resuspended material, which may not have remained suspended beyond the local scale but was within the sampling zone of the Maskell site, thereby affecting the bedload proportion. For three 2012 samples that were much higher in total-sediment load, bedload made up only 3 to 4 percent of the total load (table 4); however, for the other 4 samples from 2012 not believed to be affected by sandbar erosion, bedload made up 26 percent of the total load, on average.

At the Sioux City site in the Channelized Segment, bedload was generally lower in magnitude as compared to the Gavins Point Segment, regardless of streamflow conditions. The average bedload percentage was 7 percent of total-sediment load overall.

Changes in Transport Mechanisms Between the Gavins Point and Channelized Segments

The contrast in relative bedload contribution between the Maskell site in the Gavins Point Segment and the Sioux City site in the Channelized Segment likely reflects changing hydraulic conditions in the Channelized Segment. During typical-streamflow conditions, the hydraulic area of cross-sections in the Channelized Segment is constricted by 20 to 30 percent compared to counterparts in the Gavins Point Segment, thereby producing velocity increases of 30 to 50 percent. These velocity increases led to greater sediment-transport capacity within the stream channel through turbulent mixing. The greater turbulence more effectively resuspends bed sediments within the water column. As bedload sediments encounter this turbulence as they enter the Channelized Segment, some of these sediments enter suspension, though they still remain part of the bed-material load (table 3). This may in part explain the smaller bedloads observed at the Sioux City site as compared to the Maskell site (table 4).

This additional turbulent mixing may also convert bed-material load into wash load. This conversion becomes important in the context of habitat restoration because sediments in the wash load are effectively unavailable for creating sandbars and other bedforms; however, this pattern was not consistently manifested by differences between the sediment loads of the Maskell and Sioux City sites during typical-streamflow conditions. Wash loads at Sioux City were, on average, 6,000 tons per day (ton/d) higher than at Maskell (table 4, fig. 3). Some of this increase is related to contributions from the Big Sioux River. Though the average decrease in bed-material load between Maskell and Sioux City was 23,800 ton/d during typical streamflows, this trend likely was affected by the localized sandbar erosion at the Maskell site that may have contributed large amounts of bed-material load to a subset of samples (fig. 3). When that subset of samples is omitted, bed-material load increased from the Maskell site to the Sioux City site by 2,000 ton/d, on average. As a result, the actual amount of bed-material load that gets converted to wash load as it enters the Channelized Segment is not well understood.

Sediment Load Estimates

Because of the difficulty in obtaining a high-quality bedload sample, the MEP, specifically the BORAMEP model (Holmquist-Johnson and others, 2009), was used as an alternative approach for estimating bed-material loads. This model relies on some overlap between the suspended-sediment grain-size distribution (table 1–1) and the bed-material grain-size distribution (table 1–3). A 5-percent overlap was used by default with 1-percent overlap used for some samples dominated by wash load; however, several samples had less than 1 percent overlap in grain size, and thus loads could not be estimated for those samples. Using the samples collected in 2011, Galloway and others (2013) determined that the MEP tended to overpredict total-sediment load by 19 percent on average, and bedload by 133 percent, when compared to measured values (table 5). In addition to practical limitations with the bedload sampler, Galloway and others (2013) suggested that results were affected both by supply limitations and the potential existence of streamflow in the upper-flow regime—where the streambed is characterized by plane-bed or anti-dune configurations (van Rijn, 1984). The transition into plane-bed or anti-dune transport would have greatly reduced the amount of bedload captured by the bedload samplers, thereby resulting in measurements less than the MEP estimates.

Sediment loads estimated by the MEP from typical-streamflow samples for this report also were greater than measured values (table 5, fig. 4). On average, the MEP-estimated total-sediment load was 21 percent greater than measured during the typical-streamflow conditions. As with the 2011 flooding, much of the difference is associated with the characterization of bedload (fig. 4*B*). Although the bedload differences varied considerably in magnitude, MEP-estimated bedloads were greater than measured in 23 of 28 samples during typical-streamflow conditions with an average difference of 99 percent. Limitations of the MEP technique in streams with coarse streambeds relative to the grains in suspension became apparent at the Washburn site subsequent to the 2011 flooding. Little overlap in grain-size distributions

Table 5. Sediment loads estimated by the Modified-Einstein Procedure for six Missouri River sites, 2011–12.

[Load data for all samples in 2011 from Galloway and others, 2013. MEP, Modified-Einstein Procedure; --, not enough overlap in grain sizes to compute]

Date	Streamflow conditions	MEP estimated load, in tons per day			Percent difference between measured and MEP estimated load[1]		
		Bed-material load	Bedload	Total-sediment load	Bed-material load	Bedload	Total-sediment load
Missouri River at Washburn, North Dakota (Washburn site)							
06/16/2011	High	170,000	58,000	240,000	-41	-198	-27
06/23/2011	High	143,000	40,000	197,000	-32	-194	-22
06/30/2011	High	80,900	28,500	126,000	-43	-197	-25
07/06/2011	High	83,800	15,000	130,000	-20	-196	-12
07/14/2011	High	61,400	15,100	93,300	-27	-188	-17
07/27/2011	High	86,600	15,000	130,000	-15	-137	-10
08/04/2011	High	44,400	11,800	60,500	-22	-121	-16
08/17/2011	High	26,400	9,300	36,000	-28	-108	-20
09/08/2011	High	14,400	7,950	17,500	-62	-151	-48
09/15/2011	High	7,690	3,940	11,100	-65	-181	-41
09/22/2011	Typical	2,720	1,700	4,200	-76	-158	-43
09/29/2011	Typical	503	260	2,030	45	72	13
05/18/2012	Typical	--	--	--	--	--	--
06/19/2012	Typical	1,000	730	1,810	-64	-99	-31
07/10/2012	Typical	--	--	--	--	--	--
08/07/2012	Typical	--	--	--	--	--	--
09/05/2012	Typical	--	--	--	--	--	--
09/25/2012	Typical	--	--	--	--	--	--
10/16/2012	Typical	707	461	1,370	49	65	28
10/30/2012	Typical	--	--	--	--	--	--
11/06/2012	Typical	--	--	--	--	--	--
	High mean	**71,900**	**20,500**	**104,000**	**-36**	**-170**	**-24**
	Typical mean	**1,230**	**788**	**2,350**	**-12**	**-30**	**-8**
Missouri River at Bismarck, North Dakota (Bismarck site)							
06/09/2011	High	202,000	63,000	341,000	-36	-191	-20
06/15/2011	High	257,000	64,000	340,000	-28	-192	-20
06/22/2011	High	142,000	40,000	236,000	-31	-180	-18
07/01/2011	High	127,000	43,000	208,000	-38	-178	-22
07/05/2011	High	48,800	13,000	123,000	-28	-163	-10
07/13/2011	High	87,100	25,000	152,000	-30	-163	-16
07/26/2011	High	83,900	25,400	108,000	-23	-99	-17
08/04/2011	High	99,400	14,000	127,000	-5	-45	-4
08/16/2011	High	99,400	24,800	118,000	-24	-150	-20
09/08/2011	High	16,800	5,600	27,500	-33	-146	-19
09/15/2011	High	11,900	4,600	19,600	-40	-154	-23
09/22/2011	Typical	--	--	--	--	--	--
09/29/2011	Typical	2,360	1,680	4,730	-97	-169	-39
05/17/2012	Typical	10,500	4,890	13,200	-59	-194	-45
06/19/2012	Typical	7,850	3,670	9,960	-61	-198	-45
07/10/2012	Typical	3,440	2,200	4,820	-84	-171	-53

Table 5. Sediment loads estimated by the Modified-Einstein Procedure for six Missouri River sites, 2011–12.—Continued

[Load data for all samples in 2011 from Galloway and others, 2013. MEP, Modified-Einstein Procedure; --, not enough overlap in grain sizes to compute]

Date	Streamflow conditions	MEP estimated load, in tons per day			Percent difference between measured and MEP estimated load[1]		
		Bed-material load	Bedload	Total-sediment load	Bed-material load	Bedload	Total-sediment load
Missouri River at Bismarck, North Dakota (Bismarck site)—Continued							
08/07/2012	Typical	4,880	2,550	6,580	-61	-163	-42
09/05/2012	Typical	4,950	2,670	7,320	-72	-193	-44
09/25/2012	Typical	1,910	1,470	3,230	-88	-132	-44
10/16/2012	Typical	--	--	--	--	--	--
10/30/2012	Typical	3,090	1,750	4,170	-70	-169	-47
11/06/2012	Typical	5,050	2,690	6,750	-71	-194	-49
	High mean	**107,000**	**29,300**	**164,000**	**-29**	**-150**	**-17**
	Typical mean	**4,890**	**2,620**	**6,750**	**-74**	**-180**	**-45**
Missouri River near Maskell, Nebraska (Maskell site)							
06/23/2011	High	--	--	--	--	--	--
06/30/2011	High	103,000	43,000	161,000	-31	-97	-19
07/21/2011	High	--	--	--	--	--	--
08/04/2011	High	194,000	76,000	244,000	-25	-79	-19
08/18/2011	High	--	--	--	--	--	--
09/01/2011	High	--	--	--	--	--	--
09/15/2011	High	--	--	--	--	--	--
11/02/2011	Typical	--	--	--	--	--	--
05/31/2012	Typical	113,000	28,100	119,000	-24	-157	-23
06/20/2012	Typical	100,000	31,600	108,000	-34	-170	-31
07/09/2012	Typical	5,740	2,700	9,330	2	4	1
08/09/2012	Typical	5,620	1,690	8,420	23	61	16
09/06/2012	Typical	51,200	2,200	67,100	0	7	0
10/11/2012	Typical	13,700	4,500	21,100	-4	-12	-2
11/15/2012	Typical	11,300	3,400	14,500	-3	-10	-2
	High mean	**149,000**	**59,500**	**203,000**	**-28**	**-88**	**-19**
	Typical mean	**42,900**	**10,600**	**49,600**	**-6**	**-40**	**-6**
Missouri River at Sioux City, Iowa (Sioux City site)							
07/01/2011	High	171,000	13,000	230,000	-4	-73	-3
08/05/2011	High	171,000	67,000	230,000	-40	-151	-29
08/19/2011	High	139,000	35,000	198,000	-21	-117	-14
09/02/2011	High	51,600	22,100	76,900	-39	-125	-25

Table 5. Sediment loads estimated by the Modified-Einstein Procedure for six Missouri River sites, 2011–12.—Continued

[Load data for all samples in 2011 from Galloway and others, 2013. MEP, Modified-Einstein Procedure; --, not enough overlap in grain sizes to compute]

Date	Streamflow conditions	MEP estimated load, in tons per day			Percent difference between measured and MEP estimated load[1]		
		Bed-material load	Bedload	Total-sediment load	Bed-material load	Bedload	Total-sediment load
Missouri River at Sioux City, Iowa (Sioux City site)—Continued							
11/01/2011	Typical	49,200	20,900	67,100	-40	-130	-28
06/01/2012	Typical	--	--	--	--	--	--
06/19/2012	Typical	--	--	--	--	--	--
07/10/2012	Typical	10,200	3,800	17,600	-33	-120	-18
08/10/2012	Typical	[2]10,800	[2]2,400	[2]19,900	[2]-6	[2]-31	-3
09/07/2012	Typical	[2]9,630	[2]2,900	[2]17,000	[2]-12	[2]-46	-7
10/12/2012	Typical	18,000	3,000	29,000	-15	-138	-9
11/16/2012	Typical	14,300	2,900	31,600	-15	-105	-7
	High mean	**117,000**	**31,500**	**163,000**	**-27**	**-120**	**-18**
	Typical mean	**18,700**	**5,980**	**30,400**	**-20**	**-95**	**-12**
Missouri River at Omaha, Nebraska (Omaha site)							
07/08/2011	High	435,000	132,000	531,000	-35	-189	-27
07/18/2011	High	94,900	45,000	229,000	-57	-178	-20
08/01/2011	High	65,000	32,000	151,000	-54	-156	-20
08/15/2011	High	297,000	149,000	373,000	-65	-190	-48
08/29/2011	High	50,500	22,500	96,300	-36	-105	-18
09/12/2011	High	22,900	9,300	50,600	-22	-66	-10
10/31/2011	Typical	12,400	6,200	26,800	-31	-73	-13
	High mean	**161,000**	**65,000**	**238,000**	**-45**	**-150**	**-24**
Missouri River at Nebraska City, Nebraska (Nebraska City site)							
06/21/2011	High	--	--	--	--	--	--
06/27/2011	High	49,700	28,000	285,000	-26	-54	-4
07/19/2011	High	--	--	--	--	--	--
08/02/2011	High	55,600	19,000	129,000	-18	-62	-7
08/16/2011	High	92,200	49,900	141,000	-61	-151	-36
08/30/2011	High	29,600	9,300	70,500	-8	-30	-3
09/13/2011	High	34,900	13,600	69,500	-34	-121	-16
11/03/2011	Typical	37,000	13,000	63,300	-33	-138	-18
	High mean	**52,400**	**24,000**	**139,000**	**-29**	**-84**	**-13**

[1]Calculation of percent difference is: 100 times (x1 - x2) / (0.5 times (x1 + x2)), where x1 equals measured load component, x2 equals MEP estimated load component.

[2]Grain-size distribution data from the July 2012 suspended sample were used for MEP computations in lieu of missing grain-size data during this sample.

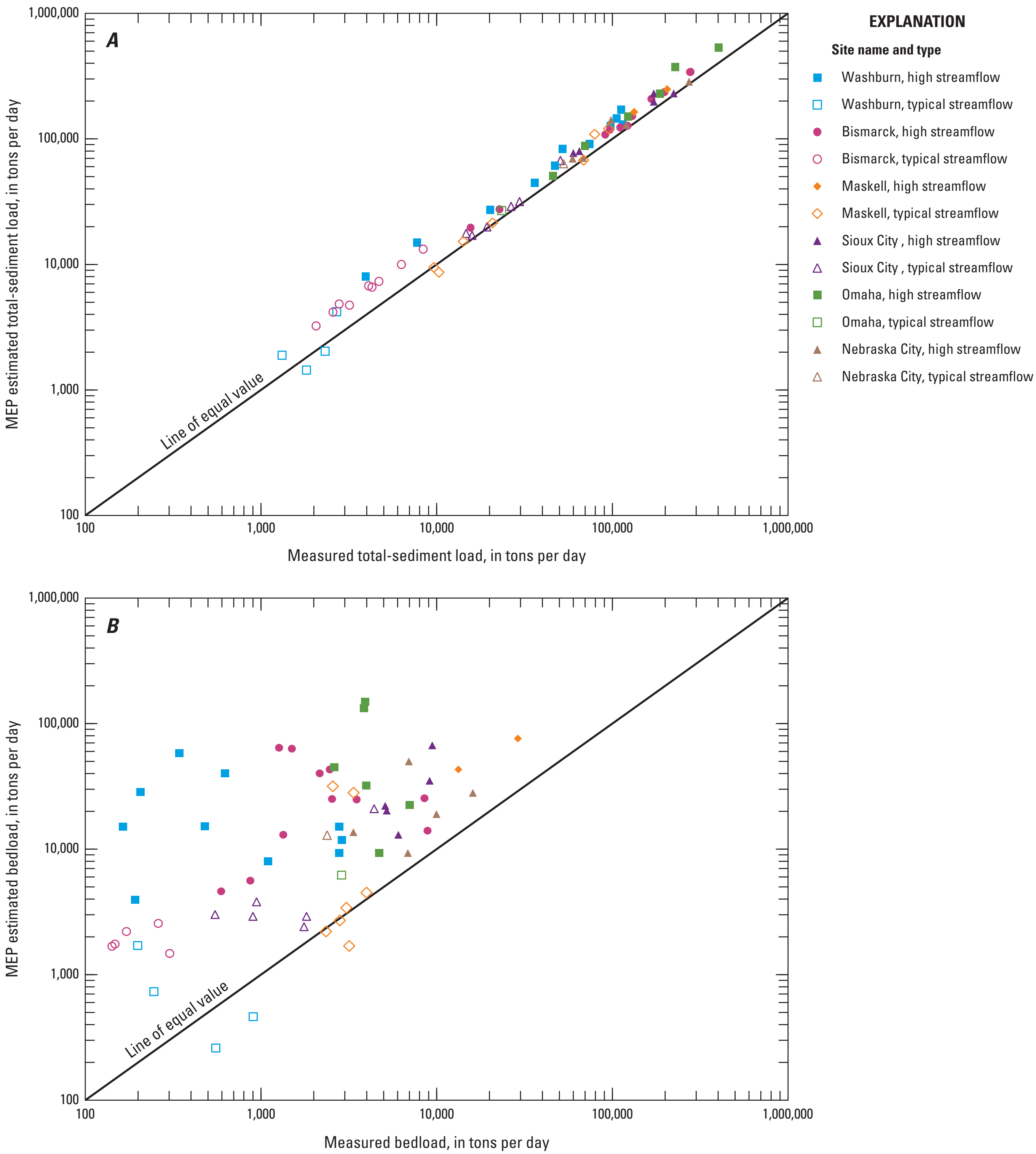


Figure 4. Relations of sediment loads estimated by the Modified-Einstein Procedure (MEP) to measured loads for *A*, total-sediment load; and *B*, bedload, for selected Missouri River sites, 2011–12.

of suspended-sediment load and bed material was measured in samples collected during the typical-streamflow conditions at the Washburn site; hence, MEP estimates could only be computed for 4 of 11 samples. Unfortunately, grain-size distributions were not available for two samples collected at the Sioux City site in August and September 2012. To compute MEP estimates for these samples, the suspended grain-size distributions of the July 2012 sample were applied to the SSC values for those two samples instead. It is readily acknowledged that this substitution introduced a large amount of uncertainty into MEP estimates from those two samples.

The differences between MEP-derived sediment loads and measured sediment loads pose a dilemma in understanding Missouri River sediment transport. The measured data may be missing some of the bed-material load that is transported through the unsampled zone near the streambed, thereby leading to an underprediction of the true sediment load. Conversely, the MEP relies on assumptions of ample sediment supplies that may not be valid in the Missouri River, which would lead to an overprediction of sediment load. The reliance on this assumption combined with the uncertainty associated with sampling complicates the determination of the correct sediment load; however, both techniques tended to produce total-load and bed-material-load values that agreed within the same order of magnitude, and for many applications this level of uncertainty is adequate. Furthermore, the development of newer techniques for estimating bedload using field measurements, such as the use of time-sequenced bathymetric data (Nittrouer and others, 2008; McElroy and Mohrig, 2009; Abraham and others, 2011) may be useful for reducing the uncertainties associated with quantifying sediment-load components.

Summary

During 2011, the Missouri River experienced flooding caused by a combination of above-normal snowpack in headwater regions of Montana and Wyoming, near record snowfall and wet soil conditions in North and South Dakota, and record rainfall in May across the upper Missouri River Basin. Several reports have already examined the characteristics of sediment transport associated with the 2011 flooding on the Missouri River. The emphasis of this report is to compare sediment transport in 2011 to that of sediment transport in 2012, a year characterized by more typical streamflows. As part of a cooperative effort between the U.S. Geological Survey and the U.S. Army Corps of Engineers, sediment samples were collected at six sites on the Missouri River: two between Lake Sakakawea and Lake Oahe in North Dakota from what was designated as the Garrison Segment ; one in the free-flowing, nonchannelized length of the river downstream from Lewis and Clark Lake along the Nebraska-South Dakota border in what was designated as the Gavins Point Segment; and three in the channelized length of the river along the Nebraska-Iowa border, which is part of the designated Channelized Segment. Sampling took place from June 2011 to November 2012 at various time intervals among the six sites. Suspended-sediment, bed-material, and bedload samples were collected in tandem with streamflow measurements during each sampling event. Sediment samples were analyzed for concentration, weight, and grain-size distribution. Using streamflow rates and these sediment data, the measured sediment loads were computed. Additionally, the Modified-Einstein Procedure (MEP) was used to estimate sediment loads for those same samples.

Relative to the high-streamflow event in 2011, samples collected in 2012 during typical streamflows were associated with much lower streamflows. As expected for this decrease, the sediment loads measured in 2012 during typical streamflows also were much lower than those measured during the 2011 flooding. It also was anticipated that sediment supplies may have been depleted during the extreme and prolonged flooding and might take several years to recover. Some evidence of sediment depletion existed at some sites, and may suggest a shift out of dynamic equilibrium following the 2011 flood.

Bedload measurements are not typically included in a sediment monitoring program, and their inclusion in this study provided some insight to the relative contribution of bedload in the Missouri River. During the flooding, sediment loads for none of the sites were dominated by bedload, with only the Maskell site having bedloads that were typically greater than 10 percent of the total load. Following the flooding, bedload increased to an average 27 percent of the total load at one site in the Garrison Segment but not for the next site downstream, possibly as the result of increased velocity at the downstream site. In the Gavins Point Segment, the relative amount of bedload varied greatly in response to the presumed sandbar erosion there, but made up an average 26 percent of the total load when this erosion was not suspected to be active. Bedload decreased to an average 7 percent of the total load during typical streamflows as it entered the Channelized Segment. Stream velocities increased by 30 to 50 percent in the Channelized Segment, thereby increasing the turbulent mixing potential of the river that likely suspended some of the bedload. This turbulent mixing also may convert bed-material load into wash load, thereby rendering those sediments unavailable for creating sandbars and other bedforms. Though some of the sampling data support this premise, it was not consistently manifested by differences between the sediment loads of the Maskell and Sioux City sites during typical-streamflow conditions.

Because of the difficulty in obtaining a high-quality bedload sample, the MEP was used as an alternative approach for estimating sediment loads. The MEP tended to predict greater total-sediment loads than the measured values, averaging 19 percent greater during high streamflows and 21 percent during typical streamflows. These differences may be the result of a sediment deficit in the Missouri River that leads to an overprediction by the MEP, the unsampled zone above the streambed that leads to an underprediction by the suspended sampler, or general uncertainty associated with the sampling approach.

The differences between MEP-derived sediment loads and measured sediment loads pose a dilemma in understanding Missouri River sediment transport. Though it is not clear which of the two techniques is better or more accurate, the two values for sediment load tend to be within an order of magnitude of one another, and this may be adequate for many sediment applications. Furthermore, newer techniques for estimating bedload have been developed and may be useful for reducing uncertainties in quantifying sediment transport in the future.

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Appendix Tables

Table 1–1. Suspended-sediment concentrations and grain sizes for six Missouri River sites, 2011–12.

[mg/L, milligram per liter; mm, millimeter; D65, grain-size diameter at which 65 percent of the mass is finer; <, less than; --, not available]

Date	Stream-flow conditions	Suspended-sediment concentration (mg/L)	Suspended-sediment fall diameter (grain size) (percent in size range, by weight)						D65 (mm)
			Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	
Missouri River at Washburn, North Dakota (Washburn site)									
06/16/2011	High	458	31	4	27	38	0	0	0.27
06/23/2011	High	384	21	16	55	8	0	0	0.19
06/23/2011	High[1]	277	29	--	--	--	--	--	--
06/30/2011	High	249	21	25	33	21	0	0	0.20
07/06/2011	High	297	16	21	59	4	0	0	0.18
07/14/2011	High	221	17	19	62	2	0	0	0.18
07/27/2011	High	374	9	26	46	10	9	0	0.21
07/27/2011	High[1]	437	7	--	--	--	--	--	--
08/04/2011	High	167	13	13	68	3	3	0	0.20
08/17/2011	High	112	19	14	57	10	0	0	0.20
08/17/2011	High[1]	96	20	--	--	--	--	--	--
09/08/2011	High	66	24	16	52	8	0	0	0.19
09/15/2011	High	54	33	15	45	7	0	0	0.17
09/22/2011	Typical	30	53	19	28	0	0	0	0.10
09/29/2011	Typical	27	75	11	8	6	0	0	<0.062
05/18/2012	Typical	24	40	12	48	0	0	0	0.16
06/19/2012	Typical	16	55	7	31	7	0	0	0.14
07/10/2012	Typical	39	59	39	2	0	0	0	0.07
08/07/2012	Typical	14	58	20	22	0	0	0	0.08
09/05/2012	Typical	16	63	8	5	24	0	0	0.08
09/25/2012	Typical	12	88	2	10	0	0	0	<0.062
10/16/2012	Typical	17	67	1	28	4	0	0	<0.062
10/16/2012	Typical[1]	16	46	--	--	--	--	--	--
10/30/2012	Typical	11	59	5	36	0	0	0	0.13
11/06/2012	Typical	30	31	16	53	0	0	0	0.17
Missouri River at Bismarck, North Dakota (Bismarck site)									
06/09/2011	High	745	38	10	35	17	0	0	0.19
06/15/2011	High	721	18	9	43	28	2	0	0.24
06/22/2011	High	480	22	20	39	19	0	0	0.20
06/22/2011	High[1]	429	28	--	--	--	--	--	--
07/01/2011	High	418	14	24	39	23	0	0	0.21
07/05/2011	High	280	20	22	52	4	2	0	0.18
07/13/2011	High	338	15	19	49	14	3	0	0.20
07/26/2011	High	255	10	5	65	20	0	0	0.22
08/04/2011	High	380	7	7	48	20	18	0	0.29
08/16/2011	High	375	9	7	37	15	32	0	0.45
08/16/2011	High[1]	341	10	--	--	--	--	--	--
09/08/2011	High	143	24	23	49	4	0	0	0.17
09/15/2011	High	109	25	24	47	4	0	0	0.17

Table 1–1. Suspended-sediment concentrations and grain sizes for six Missouri River sites, 2011–12.—Continued

[mg/L, milligram per liter; mm, millimeter; D65, grain-size diameter at which 65 percent of the mass is finer; <, less than; --, not available]

Date	Stream-flow conditions	Suspended-sediment concentration (mg/L)	Suspended-sediment fall diameter (grain size) (percent in size range, by weight)						D65 (mm)
			Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	
Missouri River at Bismarck, North Dakota (Bismarck site)—Continued									
09/22/2011	Typical	64	48	18	34	0	0	0	0.12
09/29/2011	Typical	40	61	16	11	12	0	0	0.08
05/17/2012	Typical	114	16	13	66	5	0	0	0.19
06/19/2012	Typical	85	22	10	63	5	0	0	0.19
07/10/2012	Typical	41	38	13	42	7	0	0	0.17
08/07/2012	Typical	59	33	7	59	1	0	0	0.18
09/05/2012	Typical	72	33	15	48	4	0	0	0.17
09/25/2012	Typical	33	60	14	13	13	0	0	0.08
10/16/2012	Typical	34	53	22	25	0	0	0	0.10
10/16/2012	Typical[1]	35	52	--	--	--	--	--	--
10/30/2012	Typical	42	29	14	46	11	0	0	0.18
11/06/2012	Typical	64	24	15	51	10	0	0	0.19
Missouri River near Maskell, Nebraska (Maskell site)									
06/23/2011	High	[2]830	[2]11	[2]4	[2]30	[2]55	[2]0	[2]0	[2]0.34
06/30/2011	High	261	29	14	48	9	0	0	0.18
07/21/2011	High	[2]760	[2]9	[2]3	[2]32	[2]48	[2]8	[2]0	[2]0.36
08/04/2011	High	386	17	6	42	33	2	0	0.25
08/18/2011	High	[2]895	[2]7	[2]3	[2]28	[2]58	[2]4	[2]0	[2]0.37
09/01/2011	High	[2]822	[2]7	[2]3	[2]19	[2]69	[2]2	[2]0	[2]0.38
09/15/2011	High	[2]3,250	[2]2	[2]0	[2]26	[2]53	[2]17	[2]2	[2]0.42
11/02/2011	Typical	[2]2,270	[2]2	[2]0	[2]9	[2]73	[2]16	[2]0	[2]0.43
05/31/2012	Typical	1,090	3	1	15	73	5	3	0.41
05/31/2012	Typical[1]	599	4	2	18	67	9	0	0.40
06/20/2012	Typical	881	7	1	14	67	9	1	0.41
07/09/2012	Typical	74	33	8	49	10	0	0	0.19
07/09/2012	Typical[1]	60	29	4	51	16	0	0	0.20
08/09/2012	Typical	67	31	7	36	26	0	0	0.22
09/06/2012	Typical	638	6	1	35	56	2	0	0.35
10/11/2012	Typical	166	20	4	26	42	8	0	0.34
11/15/2012	Typical	115	24	6	59	11	0	0	0.20
Missouri River at Sioux City, Iowa (Sioux City site)									
07/01/2011	High	449	22	3	28	22	5	11	0.39
08/05/2011	High	367	23	7	42	26	2	0	0.23
08/19/2011	High	378	23	8	39	27	3	0	0.23
09/02/2011	High	201	34	8	32	23	3	0	0.21
09/16/2011	High	234	27	12	38	20	3	0	0.21
11/01/2011	Typical	403	14	9	44	33	0	0	0.24
06/01/2012	Typical	221	63	10	18	9	0	0	0.07
06/19/2012	Typical	138	49	11	33	7	0	0	0.14

Table 1–1. Suspended-sediment concentrations and grain sizes for six Missouri River sites, 2011–12.—Continued

[mg/L, milligram per liter; mm, millimeter; D65, grain-size diameter at which 65 percent of the mass is finer; <, less than; --, not available]

Date	Stream-flow conditions	Suspended-sediment concentration (mg/L)	Suspended-sediment fall diameter (grain size) (percent in size range, by weight)						D65 (mm)
			Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	
Missouri River at Sioux City, Iowa (Sioux City site)—Continued									
07/10/2012	Typical	151	36	12	40	12	0	0	0.18
08/10/2012	Typical	171	--	--	--	--	--	--	--
09/07/2012	Typical	139	--	--	--	--	--	--	--
10/12/2012	Typical	258	16	9	49	26	0	0	0.23
11/16/2012	Typical	295	15	13	58	14	0	0	0.20
Missouri River at Omaha, Nebraska (Omaha site)									
07/08/2011	High	778	19	3	32	42	3	1	0.32
07/18/2011	High	356	40	5	27	23	5	0	0.22
08/01/2011	High	237	44	4	24	26	2	0	0.21
08/15/2011	High	493	18	1	21	57	3	0	0.36
08/29/2011	High	207	44	5	21	27	3	0	0.22
09/12/2011	High	150	54	9	18	19	0	0	0.14
10/31/2011	Typical	161	43	13	25	19	0	0	0.17
Missouri River at Nebraska City, Nebraska (Nebraska City site)									
06/21/2011	High	427	79	5	4	12	0	0	<0.062
06/27/2011	High	494	75	2	14	7	2	0	<0.062
07/19/2011	High	207	82	4	13	1	0	0	<0.062
08/02/2011	High	283	54	5	14	19	8	0	0.18
08/16/2011	High	248	41	7	25	23	4	0	0.21
08/30/2011	High	206	53	6	30	11	0	0	0.15
09/13/2011	High	222	53	8	23	12	4	0	0.15
11/03/2011	Typical	344	42	4	30	20	4	0	0.20

[1]Analytical results associated with a replicate sample.

[2]Value is considered erroneous because the result of the sample is presumed to have been compromised by bed-material particles.

Table 1–2. Grain sizes and mass of bedload samples for six Missouri River sites, 2011–12.

[mm, millimeter; ton/d, tons per day]

Date	Streamflow conditions	Bedload-sediment fall diameter (grain size) (percent in size range, by weight)										Measured bedload (ton/d)
		Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	2 to 4 mm	4 to 8 mm	8 to 16 mm	16 to 32 mm	
Missouri River at Washburn, North Dakota (Washburn site)												
06/16/2011	High	0	4	51	34	4	1	1	1	4	0	344
06/23/2011	High	0	3	41	45	3	0	1	1	3	3	625
06/30/2011	High	1	4	54	34	2	0	1	3	1	0	206
07/06/2011	High	0	2	55	35	4	1	0	0	3	0	164
07/14/2011	High	0	5	72	19	2	2	0	0	0	0	479
07/27/2011	High	0	0	24	72	2	1	0	1	0	0	2,790
08/04/2011	High	0	0	11	68	8	2	1	2	4	4	2,890
08/17/2011	High	0	0	13	79	4	2	1	1	0	0	2,790
09/08/2011	High	0	0	7	73	4	3	4	5	4	0	1,100
09/15/2011	High	0	0	1	56	24	4	5	9	1	0	192
09/22/2011	Typical	0	0	4	81	13	2	0	0	0	0	199
09/29/2011	Typical	0	0	3	70	21	2	3	1	0	0	554
05/18/2012	Typical	0	0	8	87	4	1	0	0	0	0	316
06/19/2012	Typical	0	0	12	80	6	1	1	0	0	0	246
07/10/2012	Typical	0	1	17	69	8	3	1	1	0	0	503
08/07/2012	Typical	0	0	27	69	3	1	0	0	0	0	490
09/05/2012	Typical	0	3	25	70	1	1	0	0	0	0	70
09/25/2012	Typical	0	0	12	79	6	2	1	0	0	0	366
10/16/2012	Typical	0	0	29	66	3	1	1	0	0	0	905
10/30/2012	Typical	0	0	21	69	7	2	0	1	0	0	1,430
11/06/2012	Typical	0	0	8	83	7	1	1	0	0	0	423
Missouri River at Bismarck, North Dakota (Bismarck site)												
06/09/2011	High	0	3	46	45	4	1	0	1	0	0	1,500
06/15/2011	High	0	2	43	51	3	0	1	0	0	0	1,270
06/22/2011	High	0	1	21	57	14	4	1	2	0	0	2,160
07/01/2011	High	0	1	21	39	33	3	1	1	1	0	2,470
07/05/2011	High	0	2	19	40	30	4	0	2	0	3	1,340
07/13/2011	High	0	1	20	36	34	6	2	1	0	0	2,540
07/26/2011	High	0	0	13	47	27	7	2	2	2	0	8,530
08/04/2011	High	0	1	17	49	19	5	2	1	0	6	8,890
08/16/2011	High	0	0	7	48	26	8	5	4	2	0	3,510
09/08/2011	High	0	0	3	44	29	8	5	4	7	0	871
09/15/2011	High	0	0	5	68	18	5	2	2	0	0	594
09/22/2011	Typical	0	0	4	58	26	7	4	1	0	0	343
09/29/2011	Typical	0	0	1	56	31	8	3	1	0	0	142
05/17/2012	Typical	0	1	53	40	4	2	0	0	0	0	75
06/19/2012	Typical	0	0	3	55	13	8	11	8	2	0	20
07/10/2012	Typical	1	0	10	72	8	5	3	1	0	0	172
08/07/2012	Typical	0	0	18	53	19	6	3	1	0	0	261

Table 1–2. Grain sizes and mass of bedload samples for six Missouri River sites, 2011–12.—Continued

[mm, millimeter; ton/d, tons per day]

Date	Streamflow conditions	Bedload-sediment fall diameter (grain size) (percent in size range, by weight)										Measured bedload (ton/d)
		Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	2 to 4 mm	4 to 8 mm	8 to 16 mm	16 to 32 mm	
Missouri River at Bismarck, North Dakota (Bismarck site)—Continued												
09/05/2012	Typical	0	0	12	49	18	10	6	5	0	0	46
09/25/2012	Typical	0	0	40	44	9	4	2	1	0	0	303
10/16/2012	Typical	0	0	18	66	10	4	2	0	0	0	249
10/30/2012	Typical	0	0	30	56	8	4	2	0	0	0	148
11/06/2012	Typical	0	0	5	81	8	4	2	0	0	0	43
Missouri River near Maskell, Nebraska (Maskell site)												
06/23/2011	High	0	0	10	68	18	3	1	0	0	0	13,300
06/30/2011	High	0	0	12	71	14	2	1	0	0	0	15,000
07/21/2011	High	0	0	8	65	23	2	1	1	0	0	29,000
08/04/2011	High	0	0	15	59	20	3	1	1	1	0	32,900
08/18/2011	High	0	0	13	63	18	4	1	1	0	0	27,500
09/01/2011	High	0	0	7	59	27	4	2	1	0	0	16,800
09/15/2011	High	0	0	9	50	31	4	0	6	0	0	27,400
11/02/2011	Typical	0	0	5	51	32	8	3	1	0	0	6,260
05/31/2012	Typical	0	0	5	51	32	8	3	1	0	0	3,370
06/20/2012	Typical	0	0	9	62	25	2	1	1	0	0	2,570
07/09/2012	Typical	0	0	16	54	25	4	1	0	0	0	2,820
08/09/2012	Typical	0	0	3	37	39	14	6	1	0	0	3,180
09/06/2012	Typical	0	0	5	46	34	10	4	1	0	0	2,350
10/11/2012	Typical	0	0	3	45	40	9	2	1	0	0	4,000
11/15/2012	Typical	0	0	10	61	25	3	1	0	0	0	3,070
Missouri River at Sioux City, Iowa (Sioux City site)												
07/01/2011	High	0	0	4	44	30	5	1	1	4	11	6,070
08/05/2011	High	0	0	10	43	18	8	5	4	7	5	9,450
08/19/2011	High	0	0	7	34	18	9	7	5	3	17	9,140
09/02/2011	High	0	0	14	47	16	6	3	3	1	10	5,100
09/16/2011	High	0	1	19	72	2	1	1	1	3	0	5,210
11/01/2011	Typical	0	1	16	77	5	1	0	0	0	0	4,420
06/01/2012	Typical	0	0	4	71	23	1	1	0	0	0	2,410
06/19/2012	Typical	0	0	7	58	28	4	2	0	1	0	1,500
07/10/2012	Typical	0	0	6	65	23	4	0	2	0	0	946
08/10/2012	Typical	0	0	3	65	21	2	0	0	9	0	1,760
09/07/2012	Typical	0	0	7	62	24	5	1	1	0	0	1,820
10/12/2012	Typical	0	0	9	62	23	4	1	1	0	0	549
11/16/2012	Typical	0	0	9	67	21	2	1	0	0	0	902

Table 1–2. Grain sizes and mass of bedload samples for six Missouri River sites, 2011–12.—Continued

[mm, millimeter; ton/d, tons per day]

Date	Streamflow conditions	Bedload-sediment fall diameter (grain size) (percent in size range, by weight)										Measured bedload (ton/d)
		Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	2 to 4 mm	4 to 8 mm	8 to 16 mm	16 to 32 mm	
Missouri River at Omaha, Nebraska (Omaha site)												
07/08/2011	High	0	0	3	65	27	4	1	0	0	0	3,870
07/18/2011	High	0	0	3	49	27	11	1	1	0	8	2,620
08/01/2011	High	0	0	5	62	27	5	0	1	0	0	3,990
08/15/2011	High	0	0	10	65	13	4	2	0	0	6	3,930
08/29/2011	High	0	0	8	57	23	5	2	1	4	0	7,020
09/12/2011	High	0	0	15	60	15	4	1	0	5	0	4,710
10/31/2011	Typical	0	0	11	72	9	3	3	1	1	0	2,880
Missouri River at Nebraska City, Nebraska (Nebraska City site)												
06/21/2011	High	0	0	2	26	25	20	19	6	2	0	9,940
06/27/2011	High	0	0	1	23	40	22	10	3	1	0	16,100
07/19/2011	High	0	0	3	27	37	18	7	3	5	0	12,200
08/02/2011	High	0	0	4	32	35	17	9	2	1	0	9,980
08/16/2011	High	0	0	5	22	32	19	12	7	3	0	6,960
08/30/2011	High	0	0	19	33	24	15	8	1	0	0	6,870
09/13/2011	High	0	0	12	48	21	12	4	2	1	0	3,360
11/03/2011	Typical	0	0	24	71	3	1	1	0	0	0	2,380

Table 1–3. Grain sizes of bed-material samples for six Missouri River sites, 2011–12.

[mm, millimeter; D65, grain-size diameter at which 65 percent of the mass is finer; --, not available]

Date	Streamflow conditions	Bed-material fall diameter (grain size) (percent in size range, by weight)												D65, in mm
		Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	2 to 4 mm	4 to 8 mm	8 to 16 mm	16 to 32 mm	32 to 63 mm	63 to 128 mm	
Missouri River at Washburn, North Dakota (Washburn site)														
06/16/2011	High	0	2	23	43	8	2	3	5	2	12	0	0	0.48
06/23/2011	High	0	6	48	38	7	1	0	0	0	0	0	0	0.32
06/30/2011	High	0	4	41	41	5	1	0	1	7	0	0	0	0.37
07/06/2011	High	0	3	33	7	5	1	2	1	14	34	0	0	15.43
07/14/2011	High	0	1	51	15	3	2	2	6	11	9	0	0	0.47
07/27/2011	High	0	2	54	27	3	2	1	4	4	3	0	0	0.33
08/04/2011	High	0	1	38	59	1	0	0	1	0	0	0	0	0.36
08/17/2011	High	0	3	39	52	4	0	0	1	1	0	0	0	0.36
09/08/2011	High	1	8	40	45	5	0	1	0	0	0	0	0	0.34
09/15/2011	High	0	5	70	24	1	0	0	0	0	0	0	0	0.23
09/22/2011	Typical	2	9	74	14	1	0	0	0	0	0	0	0	0.22
09/29/2011	Typical	0	2	44	25	4	1	2	5	7	10	0	0	0.44
05/18/2012	Typical	0	0	31	63	5	0	0	0	0	1	0	0	0.38
06/19/2012	Typical	0	0	12	80	6	1	1	0	0	0	0	0	0.42
07/10/2012	Typical	0	4	33	51	9	2	1	0	0	0	0	0	0.39
08/07/2012	Typical	0	0	33	61	5	1	0	0	0	0	0	0	0.38
09/05/2012	Typical	0	1	65	21	5	4	2	2	0	0	0	0	0.25
09/25/2012	Typical	0	0	31	62	6	0	1	0	0	0	0	0	0.39
10/16/2012	Typical	0	0	32	63	4	0	1	0	0	0	0	0	0.38
10/30/2012	Typical	0	0	30	63	5	1	1	0	0	0	0	0	0.39
11/06/2012	Typical	1	1	39	52	5	1	1	0	0	0	0	0	0.37
Missouri River at Bismarck, North Dakota (Bismarck site)														
06/09/2011	High	0	2	55	41	1	1	0	0	0	0	0	0	0.30
06/15/2011	High	0	2	42	54	2	0	0	0	0	0	0	0	0.35
06/22/2011	High	0	1	26	65	6	0	1	1	0	0	0	0	0.40
07/01/2011	High	0	0	17	56	25	2	0	0	0	0	0	0	0.46
07/05/2011	High	0	0	10	46	33	4	0	2	0	5	0	0	0.64
07/13/2011	High	0	0	14	42	34	7	2	1	0	0	0	0	0.63
07/26/2011	High	0	1	18	35	30	9	4	3	0	0	0	0	0.68
08/04/2011	High	0	1	18	39	26	6	1	2	0	7	0	0	0.63

Table 1–3. Grain sizes of bed-material samples for six Missouri River sites, 2011–12.—Continued

[mm, millimeter; D65, grain-size diameter at which 65 percent of the mass is finer; --, not available]

Date	Stream-flow conditions	Bed-material fall diameter (grain size) (percent in size range, by weight)												D65, in mm
		Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	2 to 4 mm	4 to 8 mm	8 to 16 mm	16 to 32 mm	32 to 63 mm	63 to 128 mm	
Missouri River at Bismarck, North Dakota (Bismarck site)—Continued														
09/08/2011	High	0	3	49	24	9	6	4	1	4	0	0	0	0.39
09/15/2011	High	0	3	43	25	15	6	4	4	0	0	0	0	0.44
09/22/2011	Typical	0	4	63	20	7	2	2	2	0	0	0	0	0.25
09/29/2011	Typical	0	2	50	29	13	4	2	0	0	0	0	0	0.36
05/17/2012	Typical	0	1	86	13	0	0	0	0	0	0	0	0	0.22
06/19/2012	Typical	0	3	78	9	2	0	1	2	5	0	0	0	0.22
07/10/2012	Typical	0	2	83	11	2	1	1	0	0	0	0	0	0.22
08/07/2012	Typical	0	2	81	16	1	0	0	0	0	0	0	0	0.22
09/05/2012	Typical	0	1	65	21	5	4	2	2	0	0	0	0	0.25
09/25/2012	Typical	0	2	53	15	7	4	3	4	12	0	0	0	0.42
10/16/2012	Typical	0	2	63	14	2	2	3	8	6	0	0	0	0.25
10/30/2012	Typical	0	2	73	11	1	2	2	5	4	0	0	0	0.23
11/06/2012	Typical	0	1	69	18	3	2	2	4	1	0	0	0	0.24
Missouri River near Maskell, Nebraska (Maskell site)														
06/23/2011	High	0	0	19	74	7	0	0	0	0	0	0	0	0.41
06/30/2011	High	0	1	32	58	8	1	0	0	0	0	0	0	0.39
07/21/2011	High	0	2	36	44	16	2	0	0	0	0	0	0	0.40
08/04/2011	High	0	1	24	45	22	6	2	0	0	0	0	0	0.47
08/18/2011	High	0	1	36	54	6	1	1	1	0	0	0	0	0.38
09/01/2011	High	0	0	17	50	22	4	1	1	5	0	0	0	0.49
09/15/2011	High	0	0	22	54	20	2	1	1	0	0	0	0	0.45
11/02/2011	Typical	0	0	12	64	21	2	0	0	1	0	0	0	0.46
05/31/2012	Typical	0	1	29	41	26	2	1	0	0	0	0	0	0.46
06/20/2012	Typical	0	2	20	48	23	4	1	0	2	0	0	0	0.47
07/09/2012	Typical	0	1	15	57	23	3	1	0	0	0	0	0	0.46
08/09/2012	Typical	0	3	20	45	19	8	3	2	0	0	0	0	0.48
09/06/2012	Typical	0	0	10	48	26	8	4	2	2	0	0	0	0.63
10/11/2012	Typical	0	1	5	49	37	5	2	1	0	0	0	0	0.64
11/15/2012	Typical	2	4	13	60	18	2	1	0	0	0	0	0	0.44

Table 1–3. Grain sizes of bed-material samples for six Missouri River sites, 2011–12.—Continued

[mm, millimeter; D65, grain-size diameter at which 65 percent of the mass is finer; --, not available]

Date	Stream-flow conditions	Bed-material fall diameter (grain size) (percent in size range, by weight)												D65, in mm
		Less than 0.062 mm	0.062 to 0.125 mm	0.125 to 0.250 mm	0.250 to 0.500 mm	0.500 to 1 mm	1 to 2 mm	2 to 4 mm	4 to 8 mm	8 to 16 mm	16 to 32 mm	32 to 63 mm	63 to 128 mm	
Missouri River at Sioux City, Iowa (Sioux City site)														
07/01/2011	High	1	0	47	36	16	0	0	0	0	0	0	0	0.37
08/05/2011	High	0	0	34	37	19	7	1	1	1	0	0	0	0.46
08/19/2011	High	0	1	31	35	6	5	6	9	5	2	0	0	0.49
09/02/2011	High	0	1	31	42	16	3	1	1	0	5	0	0	0.45
09/16/2011	High	0	1	31	64	2	1	1	0	0	0	0	0	0.38
11/01/2011	Typical	0	0	14	74	9	2	1	0	0	0	0	0	0.42
06/01/2012	Typical	0	0	3	34	13	1	0	1	1	0	0	47	79.60
06/19/2012	Typical	0	0	5	40	16	2	0	1	3	33	0	0	10.67
07/10/2012	Typical	0	1	27	61	10	1	0	0	0	0	0	0	0.40
08/10/2012	Typical	0	0	8	40	23	8	0	2	7	12	0	0	0.87
09/07/2012	Typical	0	0	10	71	16	2	0	1	0	0	0	0	0.44
10/12/2012	Typical	0	0	14	76	9	1	0	0	0	0	0	0	0.42
11/16/2012	Typical	0	0	9	70	17	4	0	0	0	0	0	0	0.45
Missouri River at Omaha, Nebraska (Omaha site)														
07/08/2011	High	1	3	16	56	18	3	1	2	0	0	0	0	0.45
07/18/2011	High	--	--	--	--	--	--	--	--	--	--	--	--	--
08/01/2011	High	0	0	5	56	30	7	2	0	0	0	0	0	0.57
08/15/2011	High	0	0	7	63	27	3	0	0	0	0	0	0	0.48
08/29/2011	High	--	--	--	--	--	--	--	--	--	--	--	--	--
09/12/2011	High	0	0	22	70	7	1	0	0	0	0	0	0	0.40
10/31/2011	Typical	0	0	9	58	15	5	4	2	7	0	0	0	0.49
Missouri River at Nebraska City, Nebraska (Nebraska City site)														
06/21/2011	High	--	--	--	--	--	--	--	--	--	--	--	--	--
06/27/2011	High	0	0	3	37	52	4	1	2	1	0	0	0	0.74
07/19/2011	High	0	0	4	24	33	20	13	6	0	0	0	0	1.20
08/02/2011	High	0	0	9	31	31	17	7	3	2	0	0	0	0.90
08/16/2011	High	0	1	17	30	33	12	5	2	0	0	0	0	0.76
08/30/2011	High	--	--	--	--	--	--	--	--	--	--	--	--	--
09/13/2011	High	0	3	51	26	13	4	2	1	0	0	0	0	0.36
11/03/2011	Typical	9	5	44	40	2	0	0	0	0	0	0	0	0.29

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For more information concerning this publication, contact:
Director, USGS Nebraska Water Science Center
5231 South 19th Street
Lincoln, NE 68512
(402) 328–4100

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