USGS
science for a changing world

Prepared in cooperation with the U.S. Army Corps of Engineers, Minnesota Pollution Control Agency, and Lower Minnesota River Watershed District

Suspended-Sediment Concentrations, Bedload, Particle Sizes, Surrogate Measurements, and Annual Sediment Loads for Selected Sites in the Lower Minnesota River Basin, Water Years 2011 through 2016

Scientific Investigations Report 2016–5174

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

Cover photograph. A suspended-sediment sampler (D–74) prior to sampling (top left, photograph by Samuel Costa, U.S. Geological Survey). A bedload sampler (BL–84) prior to sampling (top right, photograph by Samuel Costa, U.S. Geological Survey). The confluence of Minnesota (left) and Mississippi (right) Rivers near Fort Snelling State Park, Minnesota (center, photograph courtsey of Brian Peterson, Star Tribune). A 1.5-megahertz acoustic Doppler velocity meter prior to deployment (bottom right, photograph by Joel Groten, U.S. Geological Survey). A collected bedload sample of varying particle sizes (bottom left, photograph by Samuel Costa, U.S. Geological Survey).

Suspended-Sediment Concentrations, Bedload, Particle Sizes, Surrogate Measurements, and Annual Sediment Loads for Selected Sites in the Lower Minnesota River Basin, Water Years 2011 through 2016

By Joel T. Groten, Christopher A. Ellison, and Jon S. Hendrickson

Prepared in cooperation with the U.S. Army Corps of Engineers, Minnesota Pollution Control Agency, and Lower Minnesota River Watershed District

Scientific Investigations Report 2016–5174

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

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

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

U.S. Geological Survey, Reston, Virginia: 2016

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://store.usgs.gov/.

Suggested citation:
Groten, J.T., Ellison, C.A., and Hendrickson, J.S., 2016, Suspended-sediment concentrations, bedload, particle sizes, surrogate measurements, and annual sediment loads for selected sites in the lower Minnesota River Basin, water years 2011 through 2016: U.S. Geological Survey Scientific Investigations Report 2016–5174, 29 p., https://doi.org/10.3133/sir20165174.

ISSN 2328-0328 (online)

Contents

Figures

Tables

Appendix Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton, short (2,000 lb)	0.9072	metric ton (t)
	Transport	
ton, short (2,000 lb), per day	0.9072	metric ton per day (t/d)
ton per year per square mile (tons/yr)/mi^2	0.3503	metric ton per year per square kilometer

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
	Volume	
liter (L)	2.113	pint (pt)
liter (L)	0.2642	gallon (gal)

Datum

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88).

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

Supplemental Information

Concentrations of chemical constituents in water are given in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Water year (WY) is the 12-month period, October 1 through September 30, and is designated by the calendar year in which it ends.

Abbreviations

ADVM	acoustic Doppler velocity meter
CY	calendar year
D100	largest particle size
D50	median particle size
EDI	equal-discharge interval
EWI	equal width interval
GCLAS	Graphical Constituent Loading Analysis System
LOADEST	LOAD ESTimator (program)
NSE	Nash-Sutcliffe efficiency values
NWIS	National Water Information System
p-value	probability value
R^2	coefficient of determination
SAID	surrogate analysis and index developer
SCB	sediment-corrected backscatter
SLR	simple linear regression
SSC	suspended-sediment concentration
TSS	total suspended solids
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WY	water year

Acknowledgments

This report presents a compilation of information supplied by many agencies and individuals. The authors would like to thank the U.S. Army Corps of Engineers, Minnesota Pollution Control Agency, Lower Minnesota River Watershed District, and Minnesota Department of Natural Resources for their assistance with this study.

Brett Savage, Gerald Storey, Molly McCool, Kristen Kieta, Michael Roberts, J. William Lund, and Daniel Daly of the U.S. Geological Survey are acknowledged for assistance with data collection. Samuel Barsanelli Costa of the Institute for Technological Research, Sao Paulo, Brazil, is acknowledged for assistance with data analysis. Jeffrey Ziegeweid and Molly Wood of the U.S. Geological Survey are acknowledged for their technical reviews of the report.

Suspended-Sediment Concentrations, Bedload, Particle Sizes, Surrogate Measurements, and Annual Sediment Loads for Selected Sites in the Lower Minnesota River Basin, Water Years 2011 through 2016

By Joel T. Groten,[1] Christopher A. Ellison,[1] and Jon S. Hendrickson[2]

Abstract

Accurate measurements of fluvial sediment are important for assessing stream ecological health, calculating flood levels, computing sediment budgets, and managing and protecting water resources. Sediment-enriched rivers in Minnesota are a concern among Federal, State, and local governments because turbidity and sediment-laden waters are the leading impairments and affect more than 6,000 miles of rivers in Minnesota. The suspended sediment in the lower Minnesota River is deleterious, contributing about 75 to 90 percent of the suspended sediment being deposited into Lake Pepin. The Saint Paul District of the U.S. Army Corps of Engineers and the Lower Minnesota River Watershed District collaborate to maintain a navigation channel on the lower 14.7 miles of the Minnesota River through scheduled dredging operations. The Minnesota Pollution Control Agency has adopted a sediment-reduction strategy to reduce sediment in the Minnesota River by 90 percent by 2040.

The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, the Minnesota Pollution Control Agency, and the Lower Minnesota River Watershed District, collected suspended-sediment, bedload, and particle-size samples at five sites in the lower Minnesota River Basin during water years 2011 through 2014 and surrogate measurements of acoustic backscatter at one of these sites on the lower Minnesota River during water years 2012 through 2016 to quantify sediment loads and improve understanding of sediment-transport relations. Annual sediment loads were computed for calendar years 2011 through 2014.

Data collected from water years 2011 through 2014 indicated that two tributaries, Le Sueur River and High Island Creek, had the highest sediment yield and concentrations of suspended sediment. These tributaries also had greater stream gradients than the sites on the Minnesota River. Suspended fines were greater than suspended sand at all sites in the study area. The range of median particle sizes matched the range for stream gradients from greatest to smallest. Bedload ranged from 3 to 20 percent of the total load at the Le Sueur River, Minnesota River at Mankato, and High Island Creek and was less than 1 percent of the total load at the Minnesota River near Jordan and at Fort Snelling State Park. The reach of the Minnesota River between Mankato and Jordan is a major source of sediment, with the sediment yield at Jordan being two and a half times greater than at Mankato. Between Jordan and Fort Snelling, the sediment yield decreases substantially, which indicates that the Minnesota River in this reach is a sink for sediment. Surrogate measurements (acoustic backscatter) collected with suspended-sediment concentration data from water years 2012 through 2016 from the Minnesota River at Fort Snelling State Park indicated strong relations between the acoustic backscatter and suspended-sediment concentrations. These results point to the dynamic nature of sediment aggradation, degradation, and transport in the Minnesota River Basin. The analyses described in this report will improve the understanding of sediment-transport relations and sediment budgets in the Minnesota River Basin.

Introduction

Sediment-laden rivers in Minnesota cost river users millions of dollars each year (U.S. Army Corps of Engineers, 2006; Minnesota Pollution Control Agency, 2009). Excessive sediment in rivers degrades water quality, is deleterious to aquatic habitat, may lead to increased navigation channel dredging, reduces recreational opportunities, and can transport harmful contaminants (U.S. Army Corps of Engineers, 2006; Minnesota Pollution Control Agency, 2009). The U.S. Army Corps of Engineers (USACE), Saint Paul District, is responsible for maintaining the navigation channels of the upper Mississippi River and several of its tributaries (including the lower 14.7 miles (mi) of the Minnesota River) from Minneapolis,

[1]U.S. Geological Survey.

[2]U.S. Army Corps of Engineers.

Minnesota, to Guttenberg, Iowa (U.S. Army Corps of Engineers, 2001, 2007). The Minnesota River is one of the largest tributaries to the Mississippi River in this region and is a primary source of sand that has to be dredged in the navigation channel upstream from Lake Pepin (fig. 1). The local sponsor for the Minnesota River navigation channel is the Lower Minnesota River Watershed District and is responsible for managing dredge material. The Lower Minnesota River Watershed District either stores or sells the dredge material (Jon Hendrickson, U.S. Army Corps of Engineers, oral commun., various dates).

Suspended sediments in the Minnesota River have been analyzed for total suspended solids (TSS) by the Minnesota Pollution Control Agency since the early 1970s. The Minnesota River Basin contributes about 75 to 90 percent of fine sediments being deposited into Lake Pepin (Minnesota Pollution Control Agency, 2015; Engstrom and others, 2009). Lake Pepin is a natural riverine lake on the Mississippi River that was formed by the prograding Chippewa River delta at its downstream end (Minnesota Department of Natural Resources, 2016b; fig. 1). It also has been estimated that 24 to 30 percent of the TSS load entering the Minnesota River originates from the Le Sueur River; however, the Le Sueur River Basin constitutes only 7 percent of the basin area of the Minnesota River Basin (Minnesota Pollution Control Agency and others, 2007).

The Minnesota Pollution Control Agency is addressing degraded water quality associated with large sediment loads by developing total maximum daily loads for the Minnesota River and the Mississippi River from the confluence with the Minnesota River to Lake Pepin. To meet the water-quality targets of the total maximum daily loads, a sediment-reduction strategy has been adopted to reduce sediment loads in the Minnesota River by 90 percent by 2040 (Minnesota Pollution Control Agency, 2015). A possible confounding factor for the sediment-reduction strategy is that a previous study determined that the TSS concentrations were 50 percent smaller than suspended-sediment concentrations (SSCs) in Minnesota's rivers (Ellison and others, 2014).

Isokinetic samplers are designed to sample the entire water column with the exception of the lowest 4 inches (in.) of the water column near the streambed, commonly referred to as the unsampled zone (Edwards and Glysson, 1999). The unsampled zone is where bedload particles are transported by rolling, sliding, or bouncing along the streambed. Historically, bedload has been rarely sampled due to the difficulty and

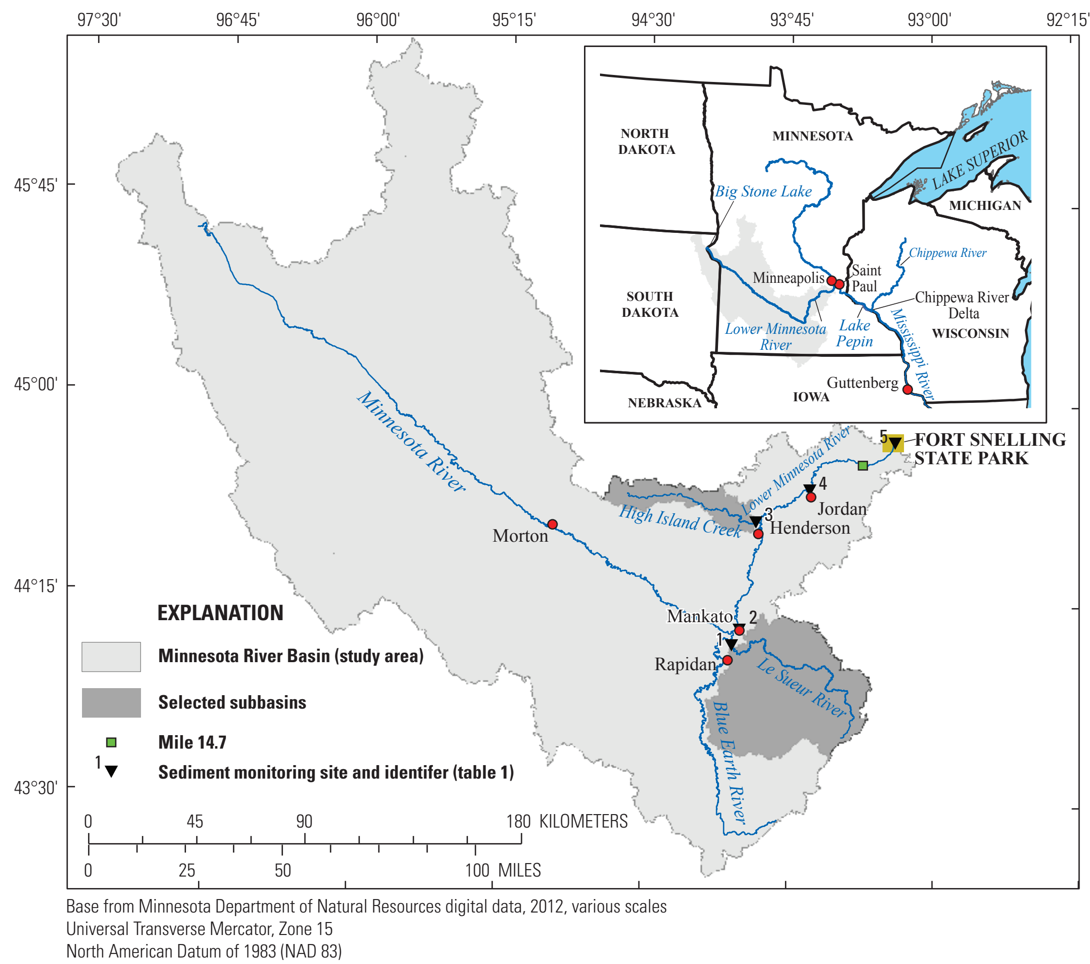

Figure 1. Location of Minnesota River Basin study area.

uncertainty associated with collecting and obtaining representative samples. In Minnesota, information is sparse regarding bedload and its contribution to total-sediment loads.

Physical collection of suspended-sediment and bedload samples remains the most accurate and reliable method for determining sediment loads; however, physical samples do not provide real-time estimates of loads because of the frequency at which data are collected. In addition, the effects of hysteresis lead to uncertainty when using streamflow to predict sediment concentrations. Hysteresis occurs when changes in a physical property are different than changes in the streamflow. For example, clockwise hysteresis can occur when streamflows of the same value have a higher SSC on the ascending portion of the hydrograph when compared to the descending portion of the hydrograph (Knighton, 1998), whereas counterclockwise hysteresis occurs when SSC peaks after the streamflow peak (Knighton, 1998). The variation in SSC is controlled by the rate of supply, which is determined by season, sediment availability, drainage basin size, and the source location within the basin (Knighton, 1998).

The U.S. Geological Survey (USGS) has traditionally used streamflow as a surrogate to estimate SSC and sediment loads (Porterfield, 1972; Glysson, 1987; Nolan and others, 2005). The surrogate relation, typically referred to as a sediment-transport curve, is derived by using regression analysis to develop the relation between streamflow and SSC. Ellison and others (2014) indicated that 7 out of 14 rivers sampled in Minnesota had poor or no relations between SSC and streamflow.

The uncertainties associated with streamflow and SSC relations have led to the adoption of new surrogate techniques to predict SSC. Acoustic backscatter measured by acoustic Doppler velocity meters (ADVMs) has been used with success to estimate SSC (Topping and others, 2004, 2006; Wood and Teasdale, 2013). The ADVMs emit an acoustic pulse that reflects off particles (assumed to be sediment), and the strength of the returned pulse is measured as backscatter (SonTek/Yellow Springs Instruments, 2007). Theoretically, backscatter is greater when there are more suspended particles in the water and should be a more direct measure of SSC than streamflow.

The U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, the Minnesota Pollution Control Agency, and the Lower Minnesota River Watershed District, collected suspended-sediment, bedload, and particle-size samples at five sites (fig. 1) during water years (WYs) 2011 through 2014 in the lower Minnesota River Basin. Surrogate measurements of acoustic backscatter at one of these sites on the lower Minnesota River during WYs 2012 through 2016 were used to compute sediment loads and improve understanding of sediment-transport relations. Annual sediment loads were computed for calendar years (CYs) 2011 through 2014. A WY is the 12-month period from October 1 through September 30, and is designated by the CY in which it ends.

This study provides data from which to characterize suspended sediment and bedload across the lower Minnesota River Basin. These data provide a baseline that can be used in understanding future changes in climate, land use, stream restoration, and best-management practices that may affect sediment dynamics in the lower Minnesota River Basin.

Purpose and Scope

The purpose of this report is to summarize and interpret collected sediment data (suspended-sediment concentrations, bedload, and particle sizes) during WYs 2011 through 2014 and computed annual sediment loads during CYs 2011 through 2014 at five selected sites: three sites on the lower Minnesota River and two sites on tributaries to the Minnesota River downstream from the city of Morton (fig. 1). In addition, analyses of surrogate measurements of acoustic backscatter collected from an ADVM at one of the sites for WYs 2012 through 2016 are described to quantify sediment loads and improve understanding of sediment-transport relations. Specifically, the report describes: (1) the relation between streamflow and SSC and between streamflow and bedload at five sites (WYs 2011 through 2014); (2) the relation between the acoustic backscatter signal and SSC at one site (WYs 2012 through 2016); (2) particle-size characteristics for SSC and bedload (WYs 2011 through 2014); and (3) annual loads from suspended-sediment concentrations, sand concentrations, bedload, and total-sediment loads (CYs 2011 through 2014).

Description of the Study Area

The Minnesota River Basin encompasses 16,770 square miles (mi^2). The river flows from its origin near the border between Minnesota and South Dakota across south-central Minnesota for 335 mi to the Mississippi River near the city of Saint Paul, Minn. Land use in the basin is dominated by agriculture (Musser and others, 2009). Wetlands, known as prairie potholes, were once prominent in the basin, but most have been drained for agricultural use (Lenhart and others, 2011). The geologic history that occurred in and near the Minnesota River Basin explains the presence of contemporary erosional features. The Des Moines Lobe of the Wisconsin ice sheet, which covered the basin approximately 12,000 years ago (Minnesota Pollution Control Agency, 2012), transported large amounts of poorly sorted sediment from the north and west to the current (2016) Minnesota River Basin. Much of the basin was covered by a thick flat-lying layer of unconsolidated material consisting of equal amounts of clay, silt, and sand. Lake Agassiz (not shown) began forming 11,700 years ago, and Lake Agassiz drained and formed glacial River Warren (not shown) 9,000 years ago (Minnesota Department of Natural Resources, 2016a). Glacial River Warren incised a large valley that created a drop in base level and is now partially occupied by the

Minnesota River. The incision resulted in a highly erodible knickpoint, a break in the stream gradient of a river profile caused by erosion, which has migrated up the tributaries flowing into the Minnesota River. The break in stream gradient from the tributaries flowing into the Minnesota River made the tributary knickpoints highly erodible because the river was incising through fine-grained till (Minnesota Pollution Control Agency, 2011). For example, the current Le Sueur River knickpoint has traveled approximately 22 to 25 mi upstream since the incision to the present-day (Gran and others, 2009).

Previous work by Schottler and others (2014) in Minnesota has shown that artificial drainage was the primary factor for an increase in streamflow and that climate and crop conversion explained less than one-half of the observed increase in streamflow. Belmont and others (2011) indicated that most of the sediment loading in the Minnesota River Basin has shifted from agricultural erosion to bluff and streambank erosion. The increase in streamflow in the Minnesota River has eroded wider channels (Schottler and others, 2014). Lenhart and others (2013) showed that the Minnesota River has widened by 52 percent and shortened in length by 7 percent between Mankato and Saint Paul, Minn., since 1938.

Sampling Sites

Five sites within the Minnesota River Basin were sampled during this study (fig. 1; table 1) and were numbered in order from upstream to downstream. The three sites located on the main stem of the Minnesota River were the Minnesota River at Mankato, Minn. (USGS station 05325000; hereafter referred to as “site 2”), Minnesota River near Jordan, Minn. (USGS station 05330000; hereafter referred to as “site 4”), and Minnesota River at Fort Snelling State Park, Minn. (USGS station 05330920; hereafter referred to as “site 5”). The two sites located on tributaries of the Minnesota River were the Le Sueur River near Rapidan, Minn. (USGS station 05320500; hereafter referred to as “site 1”) and High Island Creek near Henderson, Minn. (USGS station 05327000; hereafter referred to as “site 3.”) The Le Sueur River flows into the Blue Earth River, which in turn flows into the Minnesota River approximately 1.8 mi upstream from site 2. The Blue Earth River is substantially more sediment-laden when compared to the Minnesota River; therefore, the river may not be well mixed during high-flow events at site 2 because of the short distance between the confluence of the two rivers and site 2. The confluence of High Island Creek and the Minnesota River is approximately 21 mi upstream from site 4. Site 4 is assumed to be well mixed because of the longer distance from the confluence of High Island Creek and the Minnesota River to site 4.

The dynamic geologic history of the Minnesota River Basin led to variable stream gradients in the Minnesota River and its tributaries. The Minnesota River stream gradient gradually declines 274 feet (ft) over 335 mi from the headwaters at Big Stone Lake (fig. 1) on the Minnesota and South Dakota border to the confluence of the Mississippi River in Saint Paul, Minn., with a mean drop in elevation of 0.8 foot per mile (ft/mi) (Minnesota River Basin Data Center, 2016; fig. 2). The stream gradient in the upper part of the basin from the Minnesota River at Morton, Minn., to site 2 was 1 ft/mi (MnTOPO, 2016; fig. 2), and the stream gradient from site 2 to site 4 was 0.8 ft/mi (MnTOPO, 2016). In the lower basin, the stream gradient from site 4 to site 5 was only 0.2 ft/mi (MnTOPO, 2016). In contrast, tributary sites had greater stream gradients than sites on the Minnesota River. Site 3 had the largest stream gradients among the five sites; the stream gradient was 6 ft/mi from site 3 to the confluence with the Minnesota River (MnTOPO, 2016). The stream gradient was 5.5 ft/mi from site 1 to the confluence of the Blue Earth and Minnesota River (MnTOPO, 2016).

Precipitation

Precipitation is a primary factor affecting sediment transport in the Minnesota River Basin because of its effect on streamflow. Precipitation varied from 2011 through 2014 in the lower Minnesota River Basin. During 2011, precipitation was less than the historical mean in the southern part of the basin and greater than the historical mean in the northern part of the basin (Minnesota Department of Natural Resources, 2016c). In 2012 and 2013, precipitation was less than the

Table 1. Sediment sampling at five sites in the lower Minnesota River Basin, water years 2011 through 2014.

[USGS, U.S. Geological Survey; NGVD29, National Geodetic Vertical Datum of 1929; Minn., Minnesota; °, degrees; ', minutes; ", seconds]

Site name	Site identifier (fig. 1)	USGS station number	Latitude (North)	Longitude (West)	Gage vertical datum (feet) (NGVD29)	Drainage area (square mile)
Le Sueur River near Rapidan, Minn.	Site 1	05320500	44° 06' 35"	94° 02' 30"	775.8	1,110
Minnesota River at Mankato, Minn.	Site 2	05325000	44° 10' 08"	94° 00' 11"	747.9	14,900
High Island Creek near Henderson, Minn.	Site 3	05327000	44° 34' 19"	93° 55' 18"	728.6	238
Minnesota River near Jordan, Minn.	Site 4	05330000	44° 41' 35"	93° 38' 30"	690.0	16,200
Minnesota River at Fort Snelling State Park, Minn.	Site 5	05330920	44° 52' 13"	93° 11' 32"	680.0	16,900

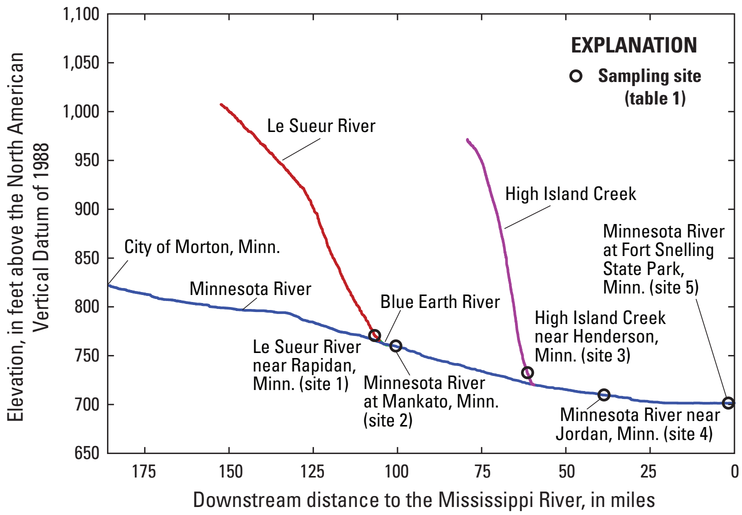

Figure 2. Stream gradients along the Minnesota River (from Morton to Fort Snelling State Park, Minnesota) and three tributaries (Le Sueur River, Blue Earth River, and High Island Creek).

historical mean (Minnesota Department of Natural Resources, 2016c). June 2014 was the wettest month of the modern record in Minnesota, with the Minnesota River Basin receiving 8 to 14 in. of precipitation (Minnesota Department of Natural Resources, 2016c). In 2014, precipitation was greater than the historical mean for most of the basin (Minnesota Department of Natural Resources, 2016c).

Streamflow

Annual mean streamflow also varied from WYs 2011 through 2014 in the lower Minnesota River. Annual mean streamflow in the lower Minnesota River was greater than the historical mean (WYs 2004 through 2014) in WY 2011 but lower than the historical mean in WYs 2012, 2013, and 2014 (U.S. Geological Survey, 2016). Because June 2014 was the wettest month on record in Minnesota, streamflow in the Minnesota River was in the 90th percentile to maximum percentile for the month of June (U.S. Geological Survey, 2016). The 90th-percentile duration streamflow value for a given day indicates a high-streamflow condition such that streamflows that are less than or equal to the value for the given day occur 90 percent of the time.

Methods of Data Collection and Analysis

This section describes methods used for collection of SSC, bedload, and particle-size samples, measurement of streamflow, collection of surrogate measurements of acoustic backscatter data, and analyses of all collected data. A total of five sites (table 1) were sampled for SSC, bedload, and particle sizes during WYs 2011 through 2014, with most samples collected during WYs 2012 through 2014. Acoustic backscatter data were collected at site 5 during WYs 2012 through 2016 along with additional samples for analyses of SSC in WYs 2015 and 2016. Sites were located at established USGS streamgages (table 1), and samples were collected 5 to 10 times per year over a range of streamflows during the open-water season (March through November).

Water samples were analyzed for SSC and particle-size fractions less than 0.0625 millimeters (mm; categorized as fines). Particles greater than or equal to 0.0625 mm are categorized as sands. Bedload samples were collected at sites 3 and 5 during WYs 2011 through 2014 and at sites 1, 2, and 4 during WYs 2012 through 2014. Streamflow data were obtained from existing USGS streamgages (table 1). An ADVM at site 5 provided data for relating the acoustic backscatter signal to physical samples of SSC.

Suspended-Sediment Concentrations and Fine Particle Sizes

Depth-integrated suspended-sediment samples were collected at equal width intervals (EWIs) at all five sites during WYs 2011 through 2014 (and at site 5 during WYs 2015 and 2016); however, in WY 2011, samples from site 2 were collected at equal-discharge intervals (EDIs) to assess SSC variability across the stream transect. Samples were collected across stream transects using isokinetic samplers and procedures described by Edwards and Glysson (1999). For collection of suspended-sediment samples, the stream width was divided into 10 equal widths for EWI samples or 5 equal-discharge increments for EDI samples, and each depth-integrated sample was collected at the centroid of each increment. Samples from each centroid were primarily kept in 1-pint glass bottles, with each sample contained within a single bottle. Under certain conditions, 1-quart glass bottles or 1- or 3-liter (L) plastic bags were used to collect the samples following procedures by Edwards and Glysson (1999). Samples were transported to the USGS sediment laboratory in Iowa City, Iowa, to be analyzed for SSC and the fine (less than 0.0625 mm) particle-size fraction according to Guy (1969).

Most SSC samples were collected using a D–74 rigid bottle sampler suspended from a bridge during nonwadeable flows or a DH–48 hand-held sampler during wadeable flows. When river depths exceeded 15 ft, a collapsible-bag sampler was used to collect the sample (Davis, 2005).

For site 2, in addition to cross-section samples using EWI and EDI methods, a B-reel and D–74 rigid bottle sampler mounted inside an enclosure were used to collect point samples. The bridge-mounted sampler was on the upstream side of the bridge, above the centroid of the river, and was lowered to the bottom of the channel to collect a single vertical sample. An observer, under contract by the USGS, collected two to three samples per week from the bridge-mounted sampler during the open-water period (generally from April to November). Samples also were collected by USGS field staff using the bridge-mounted sampler before and after EWI and EDI samples were collected from the downstream side of the bridge.

Bedload and Sand Particle Sizes

Bedload samples were collected concurrently with suspended-sediment samples during WYs 2011 through 2014 at all five sites. A BL–84, pressure-differential bag sampler (Davis, 2005) was used to collect bedload samples during nonwadeable flows or a BLH–84 hand-held sampler during wadeable flows. The mesh pore sizes of the bags used to collect bedload samples varied from 0.112 to 0.5 mm depending on site conditions. The single EWI method of collecting bedload samples (Edwards and Glysson, 1999) was used at all sites. Collection of bedload samples was accomplished by starting at one streambank and collecting one sample at 20 evenly spaced increments across the stream cross-section. Bag samples were transferred into 3-L plastic rigid containers and composited for analysis. Bedload samples were analyzed for total mass (grams) and nine sand particle-size distributions ranging from 0.0625 to 16 mm (Guy, 1969). Also, the largest particle from each sample was measured during the analyses. The three axes of the largest particle were measured, multiplied together, and the cube root of the product was reported as the largest bedload particle (D100; table 1–1 in appendix 1).

$$\text{D100} = \sqrt[3]{X \times Y \times Z} \tag{1}$$

where

X is width, in millimeters;

Y is height, in millimeters; and

Z is depth, in millimeters.

Analyses of bedload samples were completed at the University of Minnesota Civil Engineering Department by USGS Minnesota Water Science Center staff.

Streamflow Data

The USGS uses the relation between streamgage height (stage) and instantaneous streamflow measurements to generate continuous streamflow records (rating curve method; Rantz and others, 1982). Instantaneous and daily mean streamflow data were obtained from USGS streamgages to develop the relation between streamflow and SSC and to compute annual sediment loads. Site 5 is within 1 river mile of the confluence of the Minnesota River and the Mississippi River, and the site is affected by backwater, so the stage-discharge method cannot be used to generate streamflow records. Instead, an alternative method called the index velocity method (Levesque and Oberg, 2012) was used to compute streamflow at site 5. The index velocity method computes streamflow by developing two ratings: the index velocity rating and the stage-area rating (Levesque and Oberg, 2012). The outputs from both ratings, mean velocity and cross-sectional area, are multiplied together to compute streamflow (Levesque and Oberg, 2012). The five sites in this study are continuous-record streamgages, and streamflow data are available at the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2016).

Acoustic Surrogate Data

Site 5 was equipped with a 1.5-megahertz SonTek™/YSI Argonaut-SL ADVM beginning in September 2008. In 2010, the ADVM was destroyed during a flood event and was replaced with a new ADVM in 2012. The ADVM was installed to enable the computation of streamflow because of backwater effects; therefore, the programming of the ADVM is slightly different than methods recommended for using ADVM backscatter data as a surrogate for SSCs (Landers and others, 2016). For example, the ADVM was programmed to collect backscatter using 5 cells, instead of 10, as recommended by Lander and others (2016), and the ADVM was not equipped with a voltage conditioner, which is important for improving the quality of the backscatter signal. The ADVM measures backscatter (in units of decibels) in a horizontal sampling zone that consists of five equally sized discrete cells. The ADVM reports backscatter measurements collected and averaged over 12 minutes out of a 15-minute measurement interval. The backscatter data from the ADVM was used as a surrogate to develop the relation with physically measured SSC samples. The SSC predicted from mean sediment-corrected backscatter (SCB) will hereafter be referred to as "acoustic surrogate SSC."

Data Analysis

Data analyses included the computation of summary statistics, the Kendall's tau statistic (Kendall, 1938, 1975), nonlinear regression analysis, Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970), acoustic surrogate model development, and the computation of annual sediment load estimates. Total-sediment loads were calculated using suspended-sediment loads and bedload. Two methods for estimating annual loads at site 2 were compared, and two techniques for estimating annual loads at site 5 also were compared. Outliers represent random errors and may result from mistakes that were made during data collection or natural anomalies that are inconsistent with the rest of the dataset. Identified outliers were removed before data analysis.

Kendall's Tau Statistic

The significance and strength of the relations between SSC and streamflow and between bedload and streamflow were evaluated using the rank correlation analyses (Kendall, 1938, 1975) at each site because SSC and bedload data did not follow a normal distribution and were not linearly related. Rank correlation measures the strength of nonlinear relations based on ranks of the data (Helsel and Hirsch, 2002); calculated probability values (*p*-values) of less than 0.05 indicate a statistically significant monotonic relation. Rank correlation analysis produces the Kendall's tau statistic, which ranges from -1 to 1. Similar to Pearson's correlation coefficient, a positive tau indicates that SSC or bedload is increasing as streamflow increases, a negative tau indicates that SSC or bedload is decreasing as streamflow increases, and a tau not substantially different than zero indicates no relation between streamflow and SSC or between streamflow and bedload.

Development of the Nonlinear Models

A weighted nonlinear least squares regression approach was applied using the R statistical environment (R Development Core Team, 2011). Weighted least squares were used to generate estimates of model parameters that account for observed heteroscedastic variance of the residuals (residuals increased as streamflow increased) (Chaterjee and others, 2000). Weights were estimated using ordinary nonlinear least squares. The R statistical environment was used to compute the relational slopes (B_2) between response (SSC and bedload) and explanatory (streamflow) variables. Weights were calculated using the following equation:

$$W_i = 1 / Q_i^{B_2} \tag{2}$$

where

W_i is the weight applied to each measured value;
Q_i is streamflow, in cubic feet per second; and
B_2 is the estimated slope between response and explanatory variables.

Weights are used to assign each sample its proportionate amount of influence over the parameter estimates (Chaterjee and others, 2000). Using weighted least squares, samples with less error (smaller residuals) are assigned more weight than samples with greater error (larger residuals). Using ordinary nonlinear least squares regression for this dataset would treat all data equally, giving samples with greater error more influence than they should have and giving samples with less error less influence. If there was a distinct pattern in the residuals, then a weighted nonlinear least squares regression approach was not carried out and a nonlinear least squares regression approach was used.

Nash-Sutcliffe Efficiency

Nash-Sutcliffe Efficiency (NSE; Nash and Sutcliffe, 1970) values were used to evaluate the effectiveness of the nonlinear models to approximate measured SSCs and bedload values. NSE values can range from negative infinity to 1. An NSE value of 1 indicates the model matches the observed values exactly. An NSE value of 0 indicates that the model is predicting values that are no better than the mean of the measured values. A negative NSE value indicates that the mean of the observed values is better than the model.

Development of the Acoustic Surrogate Model

The surrogate analysis and index developer (SAID) software tool (Domanski and others, 2015) was used to develop a simple linear model using acoustic backscatter data and measured SSCs at site 5 during WYs 2012 through 2016. The explanatory variable used to predict SSC was mean SCB. Raw measured backscatter, reported as signal-to-noise ratio by the ADVM, was processed by SAID through three separate corrections to the acoustic signal that included (1) attenuation of the acoustic signal due to beam spreading, (2) acoustic absorption by water, and (3) attenuation of the acoustic signal by sediment (Landers and others, 2016). The SAID tool matched the physically collected SSC samples during WYs 2012 through 2016 with the mean SCB at the time closest to when an SSC sample was collected. The time difference was selected at 30 minutes. The resulting matched dataset (table 2) was used to develop a simple linear regression equation. Model results were evaluated using the SAID tool, which provides diagnostic plots, residual errors, and *p*-values to ensure the model meets the assumptions of the ordinary least squares (Helsel and Hirsch, 2002). The SSC was log transformed with SAID and a bias correction factor was applied. The final acoustic surrogate model was used to generate a time series of estimated SSC values for CYs 2012 through 2014 at site 5.

Annual Load Estimates

Annual load estimates were computed using three different methods. These three methods are described below.

Acoustic Surrogate Data

The regression model using mean SCB to estimate SSC at site 5 (described in the "Relations Between Suspended-Sediment Concentrations and Surrogate Measurements" section) was used to compute annual suspended-sediment loads at site 5. Mean daily values were calculated from the predicted acoustic surrogate SSCs and used to estimate daily suspended-sediment loads with the following equation (Porterfield, 1972):

$$Q_s = Q_w \times C_s \times K \tag{3}$$

where

Q_s is the sediment load, in tons per day;
Q_w is the daily mean streamflow, in cubic feet per second;
C_s is the acoustic surrogate SSC, in milligrams per liter; and
K is a coefficient (0.0027) that converts the units

Table 2. Suspended-sediment concentrations and mean sediment-corrected backscatter values used for simple linear regression model development at the Minnesota River at Fort Snelling State Park, Minnesota (U.S. Geological Survey station 05330920).

[mm/dd/yy, month/day/year; SSC, suspended-sediment concentration; mg/L, milligram per liter; SCB, sediment-corrected backscatter; --, unavailable for model development]

Date (mm/dd/yyy)	SSC (mg/L)	Mean SCB (decibels)
3/15/2012	34	68.7
4/24/2012	34	72.3
5/9/2012	1010	82.5
5/10/2012	897	82.9
5/11/2012	709	80.1
5/15/2012	255	79.4
5/16/2012	346	80.0
5/17/2012	245	78.5
8/14/2012	48	63.8
4/24/2013	365	78.3
5/9/2013	146	76.6
5/17/2013	154	76.1
7/10/2013	248	77.5
7/15/2013	244	78.0
8/9/2013	72	71.2
10/22/2013	69	62.2
11/5/2013	52	66.7
4/10/2014	203	76.7
4/14/2014	120	73.8
4/15/2014	79	72.9
4/22/2014	53	70.6
4/30/2014	520	80.5
5/1/2014	491	78.3
5/7/2014	150	76.5
5/29/2014	58	74.0
7/2/2014	177	72.6
7/3/2014	106	77.2
6/29/2015	430	80.4
7/8/2015	530	82.2
7/30/2015	83	--
9/9/2015	64	--
9/10/2015	112	74.9
10/1/2015	83	70.9
10/20/2015	67	--
3/22/2016	107	77.0
4/1/2016	269	81.6
5/2/2016	256	--
5/12/2016	219	80.9
6/1/2016	341	80.2
6/16/2016	616	81.9
6/23/2016	360	--
7/7/2016	145	76.5
7/25/2016	294	76.9
8/15/2016	503	--

of streamflow and SSC into tons per day and assumes a specific gravity of 2.65 for sediment.

The daily loads were summed for each year to obtain the annual suspended-sediment load for site 5.

R-LOADEST

The R-LOADEST package (Runkel and others, 2004; Cohn and others, 1989; R Development Core Team, 2011) was used to compute annual sediment loads for SSC, suspended-sand concentration, and bedload along with 95-percent prediction intervals for the five sampling sites. The R-LOADEST package (available at https://github.com/USGS-R/rloadest), an implementation in R of the LOAD ESTimator (LOADEST) program (Runkel and others, 2004), uses the rating-curve method (Cohn and others, 1989; Cohn and others, 1992; Crawford, 1991) by performing regression analyses between constituent loads and explanatory variables (typically streamflow, time, and a seasonal component).

The final models were selected through statistical evaluation, such as the coefficient of determination (R^2), *p*-values, and residual plots. Model selection was based on the largest R^2, statistical significance (*p*-value less than 0.05), and residuals that did not show heteroscedasticity.

Graphical Constituent Loading Analysis System

Another established method for computing annual sediment loads, Graphical Constituent Loading Analysis System (GCLAS) (Koltun and others, 2006), was used to compute the annual load and daily mean SSCs at site 2. The annual SSC and suspended-sediment discharge data are available online for site 2 at http://waterdata.usgs.gov/mn/nwis/sw/ (U.S. Geological Survey, 2016). Loads are computed in GCLAS as a function of an equal-interval streamflow time series and an equal- or unequal-interval time series of SSC. The GCLAS program also was used to assess if there was a difference between the single vertical samples, which were collected from the bridge-mounted sampler, and SSC samples collected using EWI and EDI methods (Koltun and others, 2006).

Streamflow, Suspended-Sediment Concentrations, Bedload, Particle Sizes, and Surrogate Measurements

Suspended-sediment and bedload samples were collected for a variety of streamflow conditions. Temporal and spatial distributions of the samples collected along the streamflow hydrograph are illustrated in figure 3. Flow-duration curves (fig. 4) show the percentage of time that streamflow was equaled or exceeded along with the SSC sampling events associated with the given streamflow.

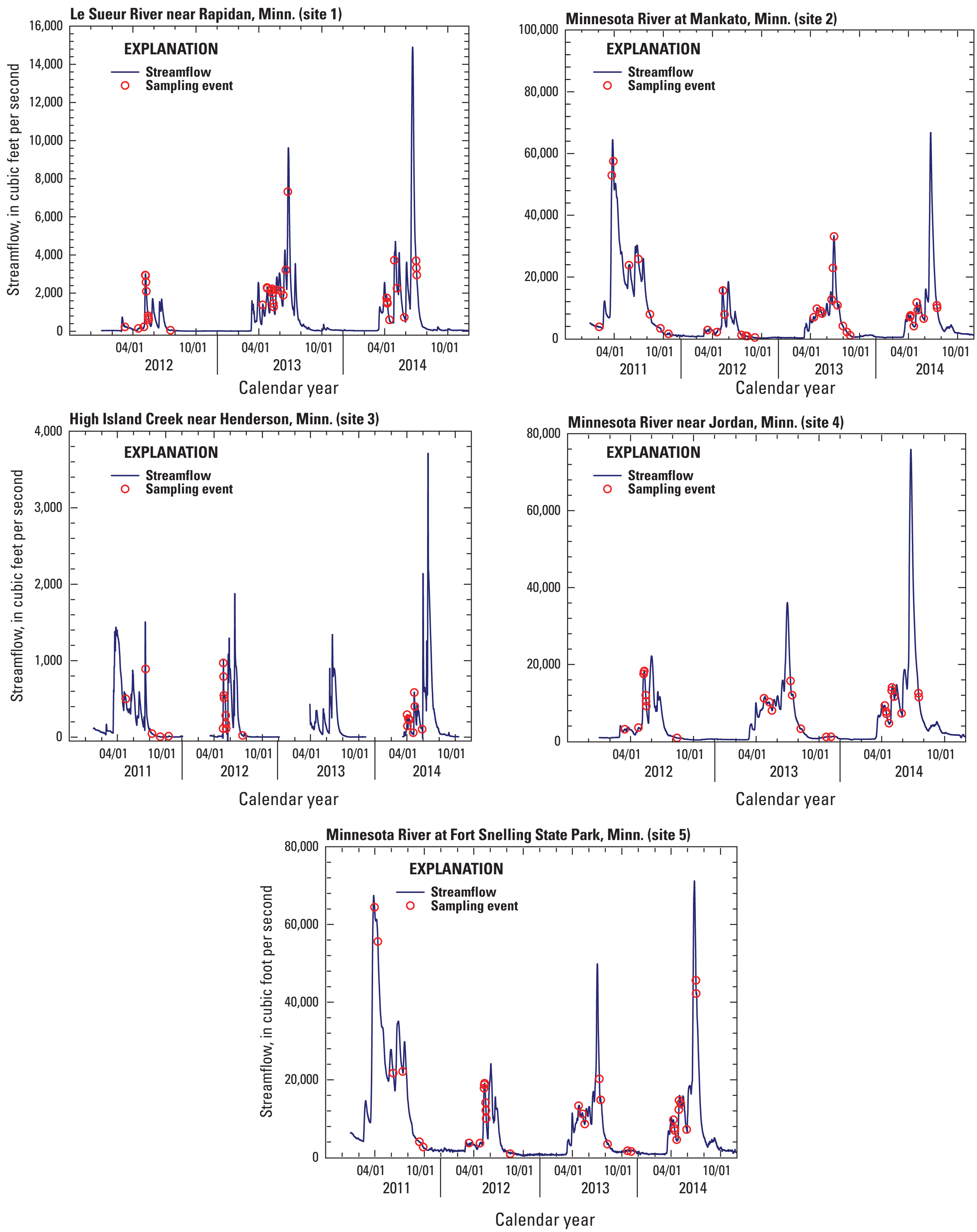

Figure 3. Hydrograph and collection dates of suspended-sediment samples at five sites (table 1) in the lower Minnesota River Basin, water years 2011 through 2014.

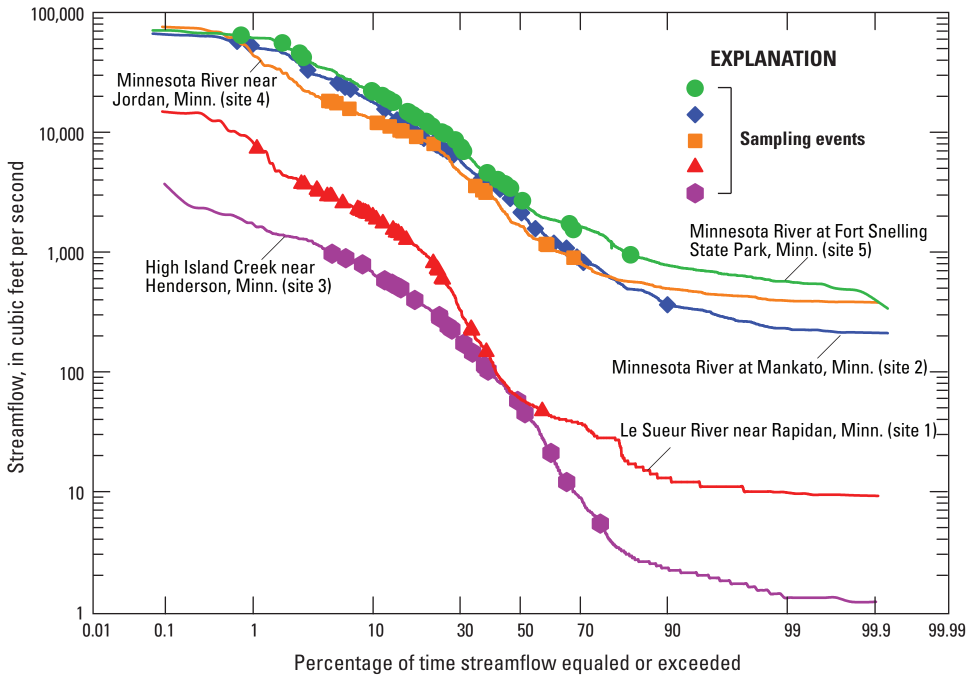

Figure 4. Flow-duration curves and associated suspended-sediment concentration samples at five sites (table 1) in the lower Minnesota River Basin, water years 2011 through 2014.

Streamflow, SSC, bedload, suspended particle-size fractions, and bedload particle-size class distributions are presented in table 1–1 in appendix 1; data also are available at http://waterdata.usgs.gov/mn/nwis/ (U.S. Geological Survey, 2016). In this study, a total of 3 outliers out of 204 SSC samples were identified and removed because of unusually high percentages of sand for the respective streamflow (table 1–2 in appendix 1). High percentages of sand in SSC samples likely occur because the sampler was not reversed quickly enough, which causes the sampler to disturb the streambed and contaminate the sample. The other explanation for the high percentages of sand in SSC samples is that the nozzle dug into a sand dune (table 1–2 in appendix 1). Summary statistics for streamflow, SSC, suspended sands, bedload transport, and the bedload D100 particle size for the five sites are in table 3.

Suspended-Sediment Concentrations

Site 3 on High Island Creek had the largest stream gradient (fig. 2) and the highest mean SSC (1,077 milligrams per liter [mg/L]) followed by sites 1, 4, 5, and 2, with mean SSCs of 432, 274, 222, and 194 mg/L, respectively (table 3). Site 3 also had the single highest SSC of 5,830 mg/L at a streamflow of 193 cubic feet per second (ft^3/s) during a spring rainfall event in May 2012.

The Blue Earth River flows into the Minnesota River a short distance (approximately 1.8 mi) upstream from site 2. Because of this short distance, the cross-sectional variability was assessed to determine if the river was well mixed at site 2. Sampling entailed five discrete depth-integrated samples during three sampling events (May 26, June 30, and August 12) in 2011. The EDI method (Edwards and Glysson, 1999) was used to determine the location of the vertical sampling increments, and each sample at each of the five vertical increments was analyzed separately for SSC and particle-size fractions greater than 0.0625 mm. The results of the cross-sectional variability assessment are shown in figure 5. The SSC and sand followed similar patterns for all three sampling events. Generally, the second and fourth verticals had the highest concentrations of SSC, and the first and second verticals were highest for sand-sized particles. Standard deviations were determined for each day from the five discrete samples and velocities. The standard deviations were 15, 10, and 12 mg/L for SSC and 13, 11, and 8 mg/L for sand-sized particles on May 26, June 30, and August 12, respectively. The velocity standard deviations were 0.5, 0.7, and 0.4 feet per second on May 26, June 30, and August 12, respectively. The standard deviations of SSC and sand-sized particles indicate that the river at site 2 is not perfectly mixed. The initial rank correlation analysis included the mean SSC concentration from the five discrete EDI verticals during the three sampling events; however, it was determined through the Kendall's tau analysis that the mean SSC from the discrete EDI verticals was not equal to the mean SSC from the EWI composite sample. Only SSCs collected using EWIs were used to calculate Kendall's tau statistic for site 2.

Bedload

Bedload samples were collected concurrently with SSC samples. Site 2 had the highest mean bedload of 341 tons per day followed by sites 1, 3, 5, and 4 (table 3). Differences in bedload transport rates among sites can be attributed in part to stream proximity to geologic features, streamflow magnitude, and streamflow velocities. The Minnesota River is actively down-cutting through thick layers of glacial till, and the stream gradient at site 2 is larger than the gradients at sites 4 and 5 downstream. The Le Sueur River and High Island Creek cut through easily erodible valley walls of the lower Minnesota River Basin.

Table 3. Summary statistics for streamflow, suspended-sediment concentrations, suspended-sands concentrations, suspended-fines concentrations, bedload, and largest bedload particle size at five sites in the lower Minnesota River Basin, water years 2011 through 2014.

[*n*, number of samples; StdDev, standard deviation; Minn., Minnesota; ft³/s, cubic foot per second; mg/L, milligram per liter; D100, largest bedload particle; mm, millimeter]

Constituent	Minimum	Mean	Median	Maximum	Total *n*	StdDev
Le Sueur River near Rapidan, Minn. (site 1)						
Streamflow, instantaneous (ft^3/s)	43	2,094	1,985	9,650	80	1,704
Suspended-sediment concentration (mg/L)	34	432	378	1,840	47	381
Suspended sands (mg/L)	1	158	147	552	47	123
Bedload transport (tons per day)	0.03	250	207	661	33	159
Bedload D100 particle size (mm)	6	27	23	65	33	13
Minnesota River at Mankato, Minn. (site 2)						
Streamflow, instantaneous (ft^3/s)	366	9,570	7,819	57,195	86	9,891
Suspended-sediment concentration (mg/L)	9	194	149	927	52	180
Suspended sands (mg/L)	3	47	31	196	48	48
Bedload transport (tons per day)	0.4	341	222	1,145	34	326
Bedload D100 particle size (mm)	2	14	14	34	34	7
High Island Creek near Henderson, Minn. (site 3)						
Streamflow, instantaneous (ft^3/s)	5	368	243	1,177	56	331
Suspended-sediment concentration (mg/L)	39	1,077	590	5,830	28	1,338
Suspended sands (mg/L)	2	262	167	760	28	218
Bedload transport (tons per day)	1	69	61	214	26	60
Bedload D100 particle size (mm)	0.1	17	17	34	28	9
Minnesota River near Jordan, Minn. (site 4)						
Streamflow, instantaneous (ft^3/s)	900	10,072	10,300	18,300	41	4,987
Suspended-sediment concentration (mg/L)	33	274	230	794	26	193
Suspended sands (mg/L)	7	34	29	88	26	23
Bedload transport (tons per day)	0.1	3	2	13	15	4
Bedload D100 particle size (mm)	3	6	6	10	9	3
Minnesota River at Fort Snelling State Park, Minn. (site 5)						
Streamflow, instantaneous (ft^3/s)	937	17,177	12,467	64,400	53	16,584
Suspended-sediment concentration (mg/L)	26	222	136	1,010	33	247
Suspended sands (mg/L)	2	29	8	149	33	41
Bedload transport (tons per day)	0.3	25	16	105	20	26
Bedload D100 particle size (mm)	3	9	7	20	11	5

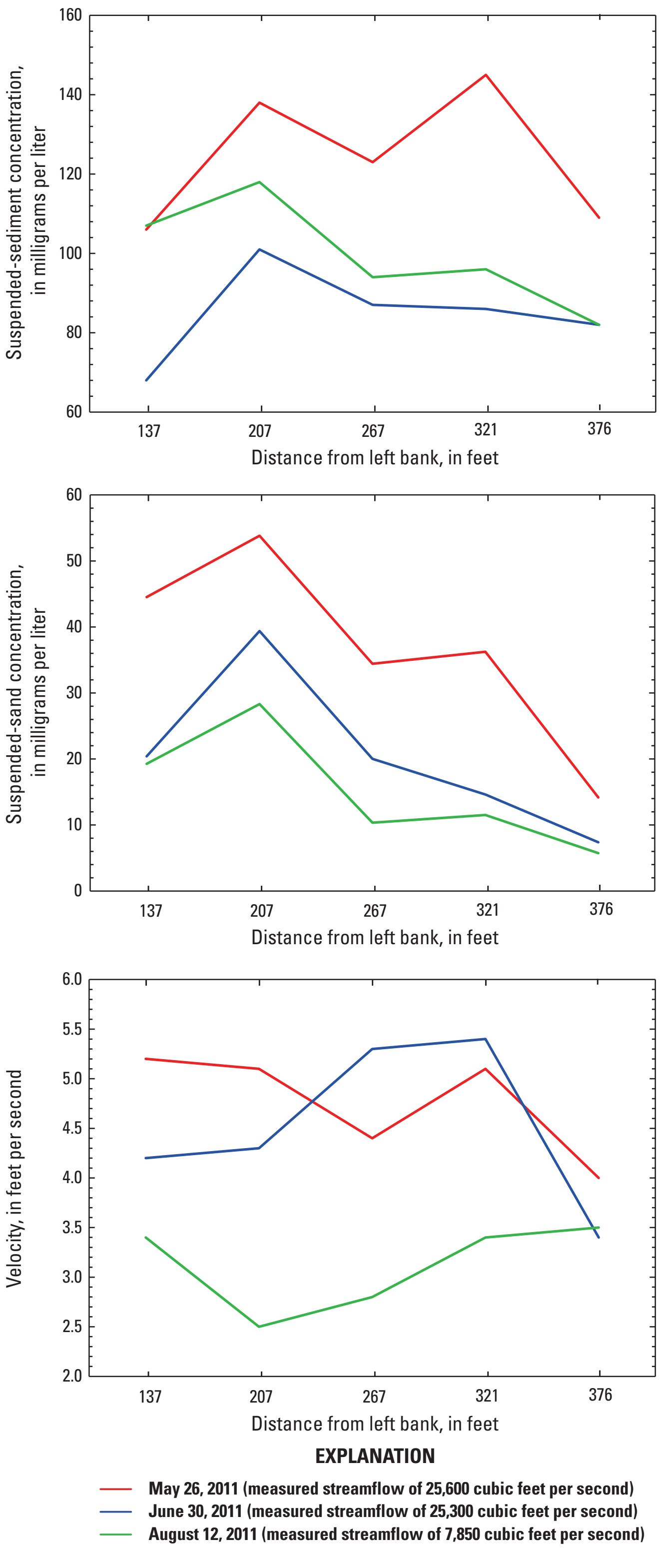

Figure 5. Five discrete samples of suspended-sediment concentrations, suspended-sand concentrations, and velocity from three sampling events on May 26, 2011; June 30, 2011; and August 12, 2011 at the Minnesota River at Mankato, Minnesota (site 2; U.S. Geological Survey station 05325000).

Particle Sizes

The percentage of fine-sized suspended sediment (less than 0.0625 mm) was greater than the percentage of suspended sand (greater than 0.0625 mm) at all sites (table 1–1 in appendix 1). Site 1 had the largest mean percentage of sand-sized particles in suspension at 37 percent. It was expected that percentages of sand-sized particles would decline as the stream gradient lessened, and this was observed in samples collected at sites 2, 4, and 5 (fig. 6), from upstream to downstream along the Minnesota River. The sites with the highest sand concentrations in suspension coincide with sampling sites that have the highest stream gradients in descending order (sites 3, 1, 2, 4, and 5; fig. 2).

Particle-size distributions provide insight on stream-channel bed-material response to geologic setting and stream energies and improve understanding of differences among the five sites. The five sites had varying distributions, with site 1 having the highest percentage of larger sized particles followed by sites 2, 3, 4, and 5 (fig. 7). The median particle size or D50 at sites 1, 2, 3, 4, and 5 were 1, 0.75, 0.64, 0.45, and 0.34 mm, respectively (fig. 7). Particle sizes indicate the composition of the material in the basin that could be made available for transport along the bottom of the rivers. Larger sized particles were located in the upper basin (sites 1 and 2) and were observed less frequently lower in the basin (sites 3, 4, and 5). Larger particle sizes are likely being deposited as they move downstream in the Minnesota River after site 2 and prior to reaching sites 4 and 5.

Relations Among Suspended-Sediment Concentrations and Bedload with Streamflow

Rank correlation analyses were used at each site to measure the strength of relations between streamflow and SSC and between streamflow and bedload. Kendall's tau statistics for relating SSC and bedload to streamflow are presented in table 4. Relations between streamflow and SSC and between streamflow and bedload are shown in figures 8 and 9, respectively. Sites 1, 2, 3, and 4 had significant relations (p-values less than 0.05) between SSC and streamflow and between bedload and streamflow throughout the entire range of samples collected over the study period. The weighted nonlinear least squares regression approach was carried out on sites 1 through 4 (table 5) but not for site 5 because the residuals followed a distinct pattern that violated the assumptions of the model. The approach used for the site 5 models, SSC and bedload, was the nonlinear least squares regression approach (table 5).

For site 5, the scatter plots of the relation between SSC and streamflow and the relation between bedload and streamflow indicated the presence of two distinctly different relations, with the delineation points on the streamflow hydrograph at approximately 19,000 ft^3/s (fig. 8) for SSC

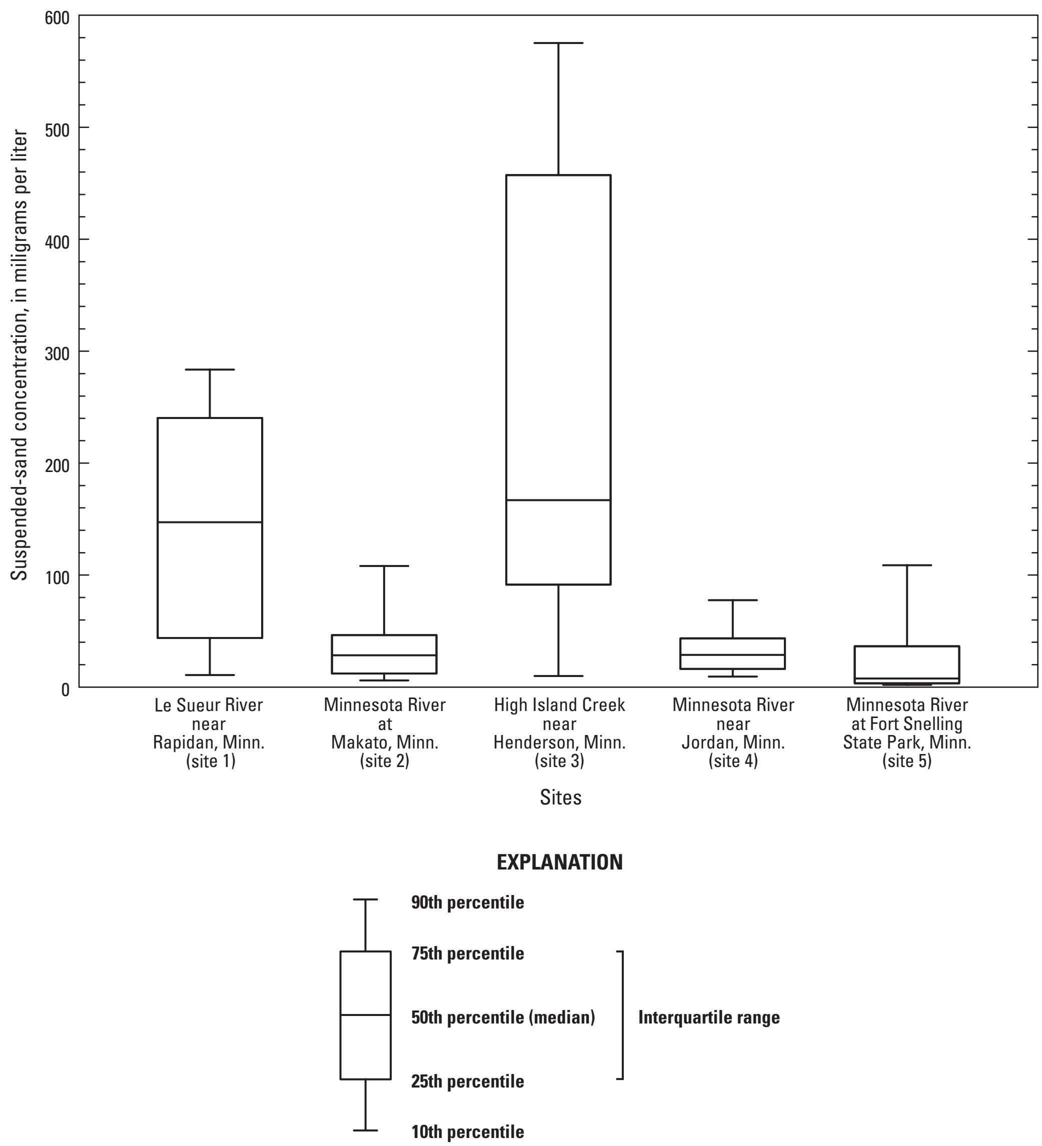

Figure 6. Suspended-sand concentrations at five sites in the lower Minnesota River Basin, water years 2011 through 2014.

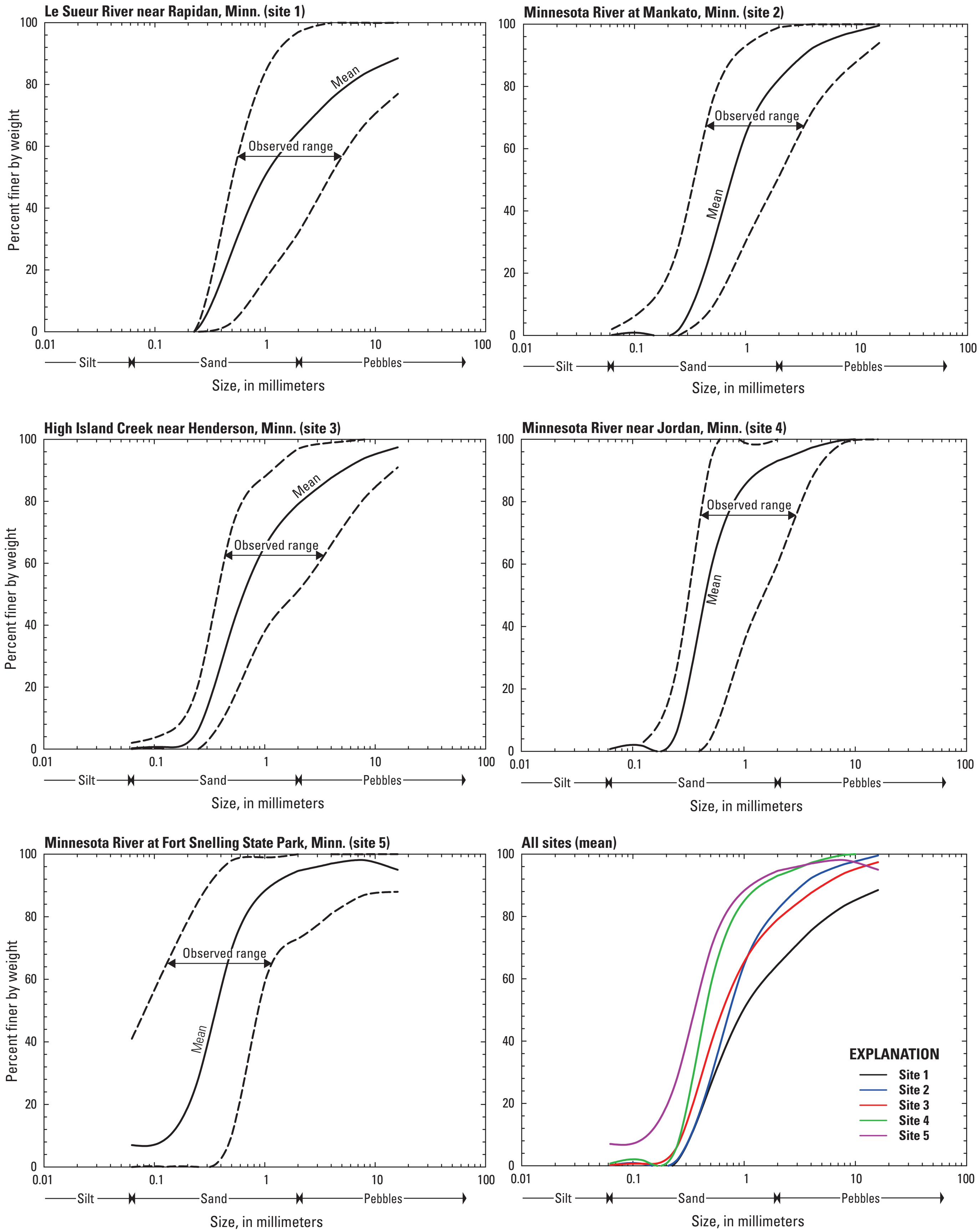

Figure 7. Cumulative-frequency distribution of mean and range of particle sizes in bedload samples at five sites (table 1) in the lower Minnesota River Basin, water years 2011 through 2014.

Table 4. Kendall's tau statistics for relating total suspended-sediment concentrations and bedload to streamflow at five sites in the lower Minnesota River Basin, water years 2011 through 2014.

[*n*, number of samples; Minn., Minnesota; mg/L, milligram per liter; <, less than; ft³/s, cubic foot per second]

Constituent	Tau	*p*-value	Total *n*
Le Sueur River near Rapidan, Minn. (site 1)			
Total suspended-sediment concentration (mg/L)	0.76	<0.01	47
Bedload transport (tons per day)	0.48	<0.01	33
Minnesota River at Mankato, Minn. (site 2)			
Total suspended-sediment concentration (mg/L)	0.57	<0.01	48
Bedload transport (tons per day)	0.67	<0.01	34
High Island Creek near Henderson, Minn. (site 3)			
Total suspended-sediment concentration (mg/L)	0.63	<0.01	28
Bedload transport (tons per day)	0.40	<0.01	26
Minnesota River near Jordan, Minn. (site 4)			
Total suspended-sediment concentration (mg/L)	0.62	<0.01	26
Bedload transport (tons per day)	0.57	<0.01	15
Minnesota River at Fort Snelling State Park, Minn. (site 5)			
Total suspended-sediment concentration (mg/L)	0.37	<0.01	34
Bedload transport (tons per day)	0.40	0.01	20
Minnesota River at Fort Snelling State Park, Minn. (site 5) less than 19,000 ft³/s			
Total suspended-sediment concentration (mg/L)	0.68	<0.01	27
Minnesota River at Fort Snelling State Park, Minn. (site 5) greater than 19,000 ft³/s			
Total suspended-sediment concentration (mg/L)	-0.43	0.24	7
Minnesota River at Fort Snelling State Park, Minn. (site 5) less than 22,200 ft³/s			
Bedload transport (tons per day)	0.41	0.06	13
Minnesota River at Fort Snelling State Park, Minn. (site 5) greater than 22,200 ft³/s			
Bedload transport (tons per day)	-0.52	0.14	7

and 22,200 ft³/s for bedload (fig. 9). Because there were two different relations between SSC and streamflow and between bedload and streamflow, the Kendall's tau correlation analyses were separated into two categories for SSC and bedload samples (table 4). SSC and streamflow correlations were stronger at streamflows less than approximately 19,000 ft³/s. Closer inspection of the data indicated that all of the samples collected at streamflows greater than 19,000 ft³/s were collected during the falling limb of the hydrograph; thus, all of the samples likely have negative bias because of the effects of hysteresis (fig. 8). This negative bias would explain, in part, the observed negative relation between SSC and streamflow for samples collected at streamflows that exceeded 19,000 ft³/s. Backwater effects from the Mississippi River during higher streamflows and the Minnesota River spilling over its banks into the flood plain are two potential sources of variability in the relations between SSC and streamflow and between bedload and streamflow that may contribute to the negative relation between SSC and higher streamflows at site 5.

The largest Kendall's tau statistic between SSC and streamflow was at site 1 followed by sites 5 (streamflow under approximately 19,000 ft³/s), 3, 4, and 2 (table 4). Even though site 2 has a larger stream gradient than sites 4 and 5, the relation between SSC and streamflow at site 2 was not as strong as the relation at downstream sites 4 and 5. It is hypothesized that the weaker relation between SSC and streamflow at site 2 is because of increased variability in the samples. This increased variability is caused by poor mixing during high flows because of the proximity of the site to the confluence of the Blue Earth and Minnesota Rivers.

Surrogate Measurements

Surrogate measurements of acoustic backscatter at site 5 were used to quantify sediment loads and improve understanding of sediment-transport relations. The final acoustic surrogate model was used to generate a time series of estimated SSC values for comparison to streamflow.

Table 5. Nonlinear regression coefficients, confidence intervals, residual standard errors, Nash-Sutcliffe efficiencies, and Kendall's tau statistics at five sites in the lower Minnesota River Basin, water years 2011 through 2014.

[USGS, U.S. Geological Survey; A, regression coefficient; %, percent; B, regression coefficient; RSE, residual standard error, NS, Nash-Sutcliffe; Tau, Kendall's tau statistic; Minn., Minnesota; *SSC*, suspended-sediment concentration in milligrams per liter; *Q*, streamflow in cubic feet per second; WLS, weighted nonlinear least squares; NLS, nonlinear least squares; E, approximately 2.71828 and often called Euler's number; *qb*, bedload discharge in tons per day]

Station name	Short name	USGS station number	Model	Regression approach	Regression coefficient						RSE	NS	Tau
					A	Confidence interval 2.5%	Confidence interval 97.5%	B	Confidence interval 2.5%	Confidence interval 97.5%			
SSC													
Le Sueur River near Rapidan, Minn.	Site 1	05320500		WLS	0.77	0.19	2.74	0.83	0.67	1.00	11.31	0.60	0.76
Minnesota River at Mankato, Minn.	Site 2	05325000		WLS	1.51	0.33	7.73	0.55	0.37	0.73	12.80	0.37	0.57
High Island Creek near Henderson, Minn.	Site 3	05327000	$SSC = A \times Q^B$	WLS	55.59	-107.72	218.90	0.52	0.04	1.00	348.90	0.18	0.63
Minnesota River near Jordan, Minn.	Site 4	05330000		WLS	0.02	-0.03	0.06	1.07	0.77	1.36	0.30	0.64	0.62
Minnesota River at Fort Snelling State Park, Minn.	Site 5	05330920		NLS	2.52E-08	-1.53E-07	2.04E-07	2.46	1.73	3.19	121.80	0.80	0.68
Bedload													
Le Sueur River near Rapidan, Minn.	Site 1	05320500		WLS	2.75	0.57	12.65	0.60	0.40	0.83	16.81	0.44	0.48
Minnesota River at Mankato, Minn.	Site 2	05325000		WLS	0.04	0.01	0.29	1.01	0.79	1.25	3.36	0.67	0.67
High Island Creek near Henderson, Minn.	Site 3	05327000	$qb = A \times Q^B$	WLS	3.51	-3.21	10.23	0.51	0.20	0.83	12.82	0.28	0.40
Minnesota River near Jordan, Minn.	Site 4	05330000		WLS	1.83E-05	-2.41E-04	2.78E-04	1.30	-0.21	2.80	0.00	0.25	0.57
Minnesota River at Fort Snelling State Park, Minn.	Site 5	05330920		NLS	8.01E-11	-1.27E-09	1.43E-09	2.75	1.05	4.45	17.07	0.67	0.55

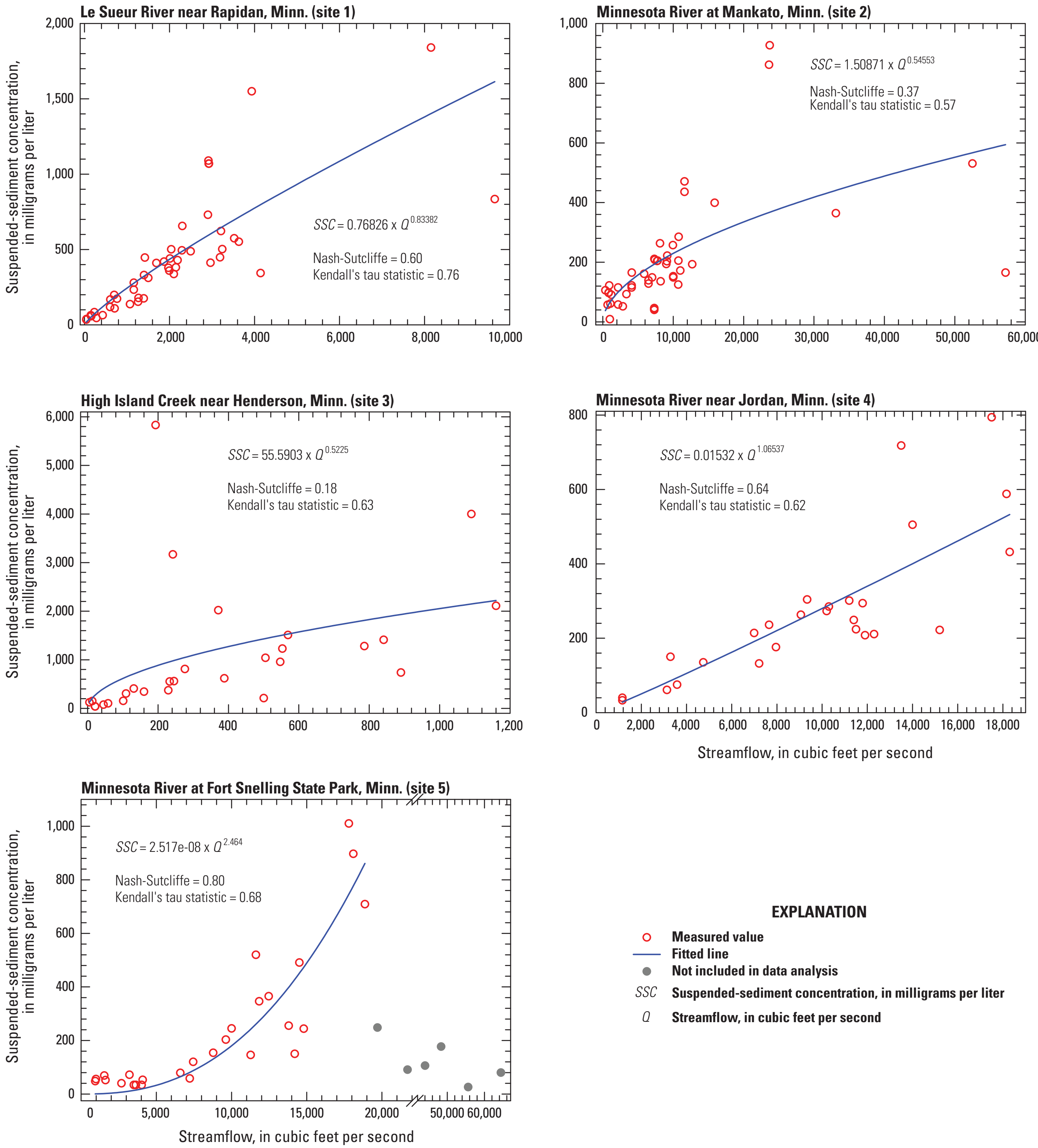

Figure 8. Relation between suspended-sediment concentrations and streamflow at five sites in the lower Minnesota River Basin, water years 2011 through 2014.

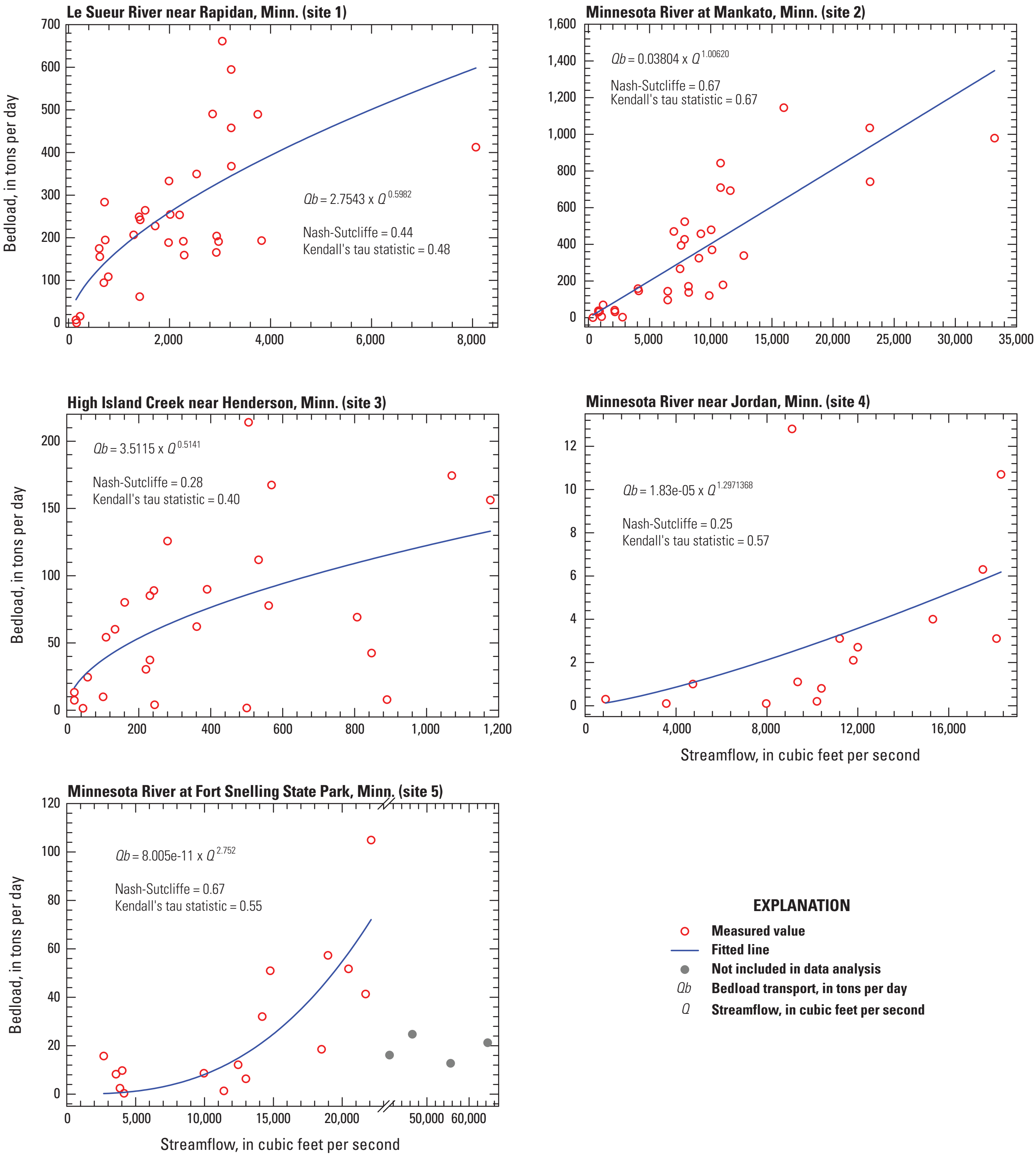

Figure 9. Relation between bedload and streamflow at five sites in the lower Minnesota River Basin, water years 2011 through 2014.

Relations Between Suspended-Sediment Concentrations and Surrogate Measurements

At site 5, 44 SSC samples were collected while the ADVM was installed (from WY 2012 through WY 2016); however, 6 of the 44 SSC samples were unavailable for model development because the acoustic records were missing or unusable. Of the 38 SSC samples available for model development, 4 were not used because 1 was deemed to be an outlier based on diagnostic statistics (Helsel and Hirsch, 2002) and the other 3 SSC samples did not have a relation with mean SCB (fig. 10). The one sample that was deemed an outlier either had elevated sand in the sample or an erroneous acoustic measurement (fig. 10). The other three SSC samples that were not used in the dataset were collected at low concentrations and the reflected acoustic signal may have been so close to the ADVM's noise level that the instrument could not differentiate the return from the ADVM's noise level. It was determined that SSC and mean SCB did not have a relation at mean SCB values less than 68.5 decibels. As described in the "Development of the Acoustic Surrogate Model" section, the final dataset of mean SCB matched to the time closest to when an SSC sample was collected (table 2) was used to generate a simple linear regression equation (SLR). The final SLR equation had a *p*-value less than 0.01 and a R^2 of 0.825 (fig. 10). The SLR equation had a strong and significant relation between SSC and mean SCB. The SLR was the final acoustic surrogate model used to generate a time series of estimated SSC values based on the continuous acoustic backscatter record from the ADVM.

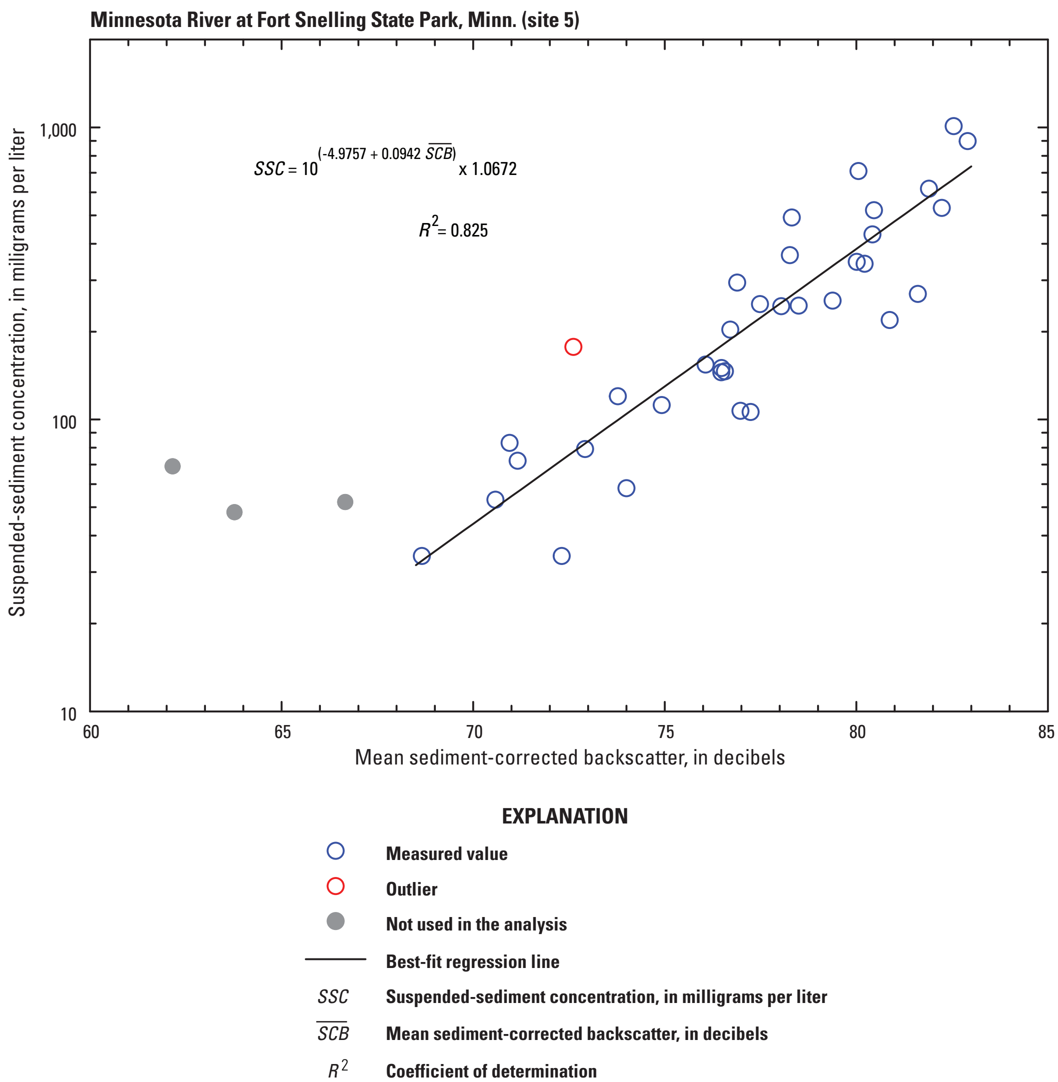

Figure 10. Relation between suspended-sediment concentrations and sediment-corrected backscatter at the Minnesota River at Fort Snelling State Park, Minnesota, water years 2012 through 2016 (U.S. Geological Survey station 05330920).

Missing Data

There were four missing periods in the continuous backscatter record from the ADVM during WYs 2012 through 2016 at site 5 because the low angle of the sun was not fully charging the battery through the solar panel in the winter months. One missing period was in WY 2012 (January 1 to February 5, 2012), one missing period was in WY 2013 (on December 16, 2012), one missing period was in WY 2014 (December 21 to December 25, 2013), and one missing period was in WY 2015 (October 9 to December 31, 2014). Missing SSC values during these data gaps were estimated so annual loads could be computed. Missing SSC values were estimated by two methods. The first method estimated values by using the fillMissing (available at https://github.com/USGS-R/smwrBase/blob/master/R/fillMissing.R) values function in the R statistical environment (R Development Core Team, 2011). This function uses a smoothing algorithm to predict the slope from known values before and after the missing period and interpolates missing values to account for any changes in the slope (R Development Core Team, 2011). Using the fillMissing values function, SSC values were estimated from missing periods on December 16, 2012, and from December 21 to December 25, 2013.

The fillMissing values function could not be used to estimate missing values from January 1 to February 5, 2012, and from October 9 to December 31, 2014, because no data were available prior to CY 2012 or after CY 2014 for interpolation. For these periods of missing data, it was assumed sediment transport was low because a previous study by Tornes (1986) indicated that sediment transport during the winter months in Minnesota accounted for less than 4 percent of the annual sediment loads. This assumption was supported by the SCB data collected during the winter months because it was notably lower compared to the other months. The missing SSC values for these time periods were estimated by using data from 2 years with available data collected during the study at site 5 (2013 and 2014 for January 1 to February 5, and 2012 and 2013 for October 9 to December 31) that had SSC values at similar streamflows to the same periods in 2012 or 2014, respectively. The mean of the two SSC values for each day during the periods with available data was used to fill the missing SSC values.

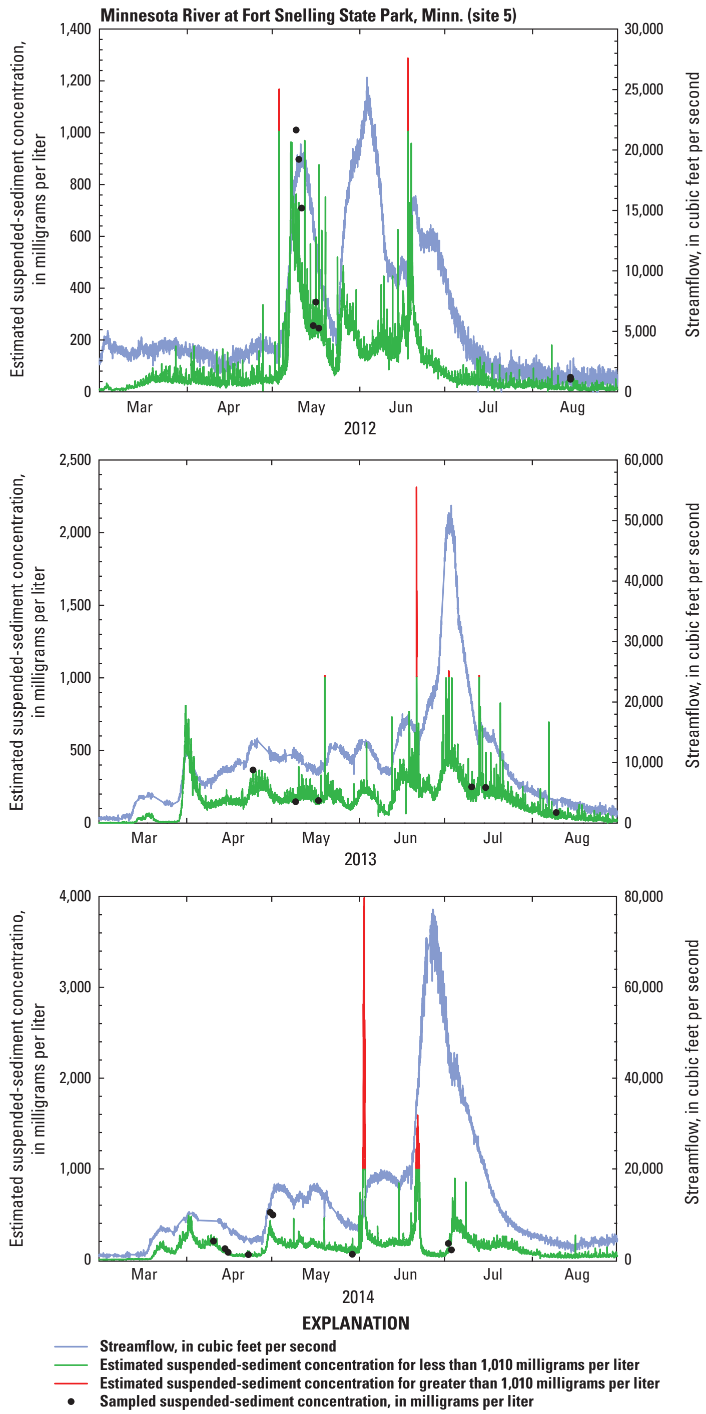

Figure 11. Streamflow and estimated suspended-sediment concentrations from sediment-corrected backscatter for three time periods in water years 2012, 2013, and 2014 at the Minnesota River at Fort Snelling State Park, Minnesota (U.S. Geological Survey station 05330920).

Comparison of Acoustic Surrogate Suspended-Sediment Concentrations and Streamflow on Short Time Scales

The comparisons of streamflow and estimated acoustic surrogate SSCs are shown on figure 11 for site 5. The three periods shown are from March 1 to August 31 in WYs 2012, 2013, and 2014. The acoustic surrogate SSCs shown in red are above the highest calibration value and should be interpreted with caution.

In WY 2012, acoustic surrogate SSC peaked prior to three streamflow events (streamflow peaks occurred on May 11, June 3, and June 19). The largest acoustic surrogate SSC peak for 2012 was 1,290 mg/L on June 17, and the corresponding streamflow peak of 16,000 ft^3/s occurred on June 19. The May 26 acoustic surrogate SSC peak was the smallest (500 mg/L) prior to the three largest streamflow peaks in WY 2012, and the June 3 streamflow peak was the largest (26,000 ft^3/s) compared to the other two streamflow peaks in WY 2012. The timing and magnitude of the peaks varied in WY 2012, with the longest duration between the acoustic surrogate SSC peak and the streamflow peak occurring on May 26 and June 3, respectively. The shortest duration between the acoustic surrogate SSC peak and the streamflow peak occurred on June 17 and June 19, respectively.

In WY 2013, the acoustic surrogate SSC (800 mg/L) peak occurred 10 hours prior to the streamflow peak on March 31, 2013. After streamflow peaked, the river receded for 7 days to approximately 6,000 ft^3/s and then began to ascend on April 8 to a streamflow greater than 6,000 ft^3/s until the end of July. There was an acoustic surrogate SSC peak (June 21) that was much greater than the one on March 31. This short-duration peak was likely caused by an obstruction or disturbance near the acoustic device and not a streamflow event.

In WY 2014, historical rainfall totals in June caused a streamflow event greater than in 2012 and 2013. The acoustic surrogate SSC peaked (1,600 mg/L) on the ascending limb of the hydrograph (37,000 ft^3/s) 5 days before the streamflow peak of 76,000 ft^3/s on June 26, 2014. The highest predicted acoustic surrogate SSC occurred during a much smaller storm event in which streamflow peaked at 18,000 ft^3/s on June 7 and surrogate SSC peaked (4,000 mg/L) on June 6 at a streamflow of 11,600 ft^3/s.

For WYs 2012 through 2014, the streamflow peaks on July 2, 2013, and June 26, 2014, are the two streamflow events that extended the farthest into the flood plain. When the streamflow was ascending in 2013 and 2014, acoustic surrogate SSC peaked and began a rapid recession as streamflow continued to ascend. In WY 2013, the sediment peaked at a lower SSC but at a higher streamflow than in WY 2014. These rapid recessions during elevated streamflows apparently led to sediment deposition in the flood plain and sediment storage in the channel. The stored sediment can be remobilized during subsequent high-energy streamflow events.

The three periods shown in figure 11 emphasize the variability of SSC compared to streamflow. Rarely do observed patterns of acoustic surrogate SSC match observed patterns in streamflow, which is commonly used to estimate SSC. The acoustic surrogate SSC also indicated that the timing and magnitude of sediment transport varied greatly over a variety of streamflow events.

Annual Sediment Loads

The annual suspended-sediment loads from R-LOADEST are shown on figure 12 and the information on the R-LOADEST regression models is included in table 6. The GCLAS loads for site 2 and acoustic surrogate SSC loads for site 5 are presented in tables 7 and 8, respectively.

Results from the annual load estimates indicate an increase in sediment loading between sites 2 and 4 (fig. 12). The sediment loading at site 4 was two and a half times greater than the sediment loading at site 5, which indicates that this reach of the lower Minnesota River is a sink for sediment. Apparently, the sediment loads at site 4 are exceeding the sediment transport of the river and are being stored in the channel between site 4 and site 5. Annual load estimates from R-LOADEST at sites 4 and 5 indicate there is more SSC load at site 4 (fig. 12) even though there is overall greater streamflow at site 5 during the year. A decreasing stream gradient from site 4 to the confluence with the Mississippi River, backwater effects from the Mississippi River further decreasing the stream gradient, and streamflow that exceeds bankfull and enters the floodplain all contribute to deposition and storage of sediment.

Comparison of Load Calculations

Estimated annual loads for site 2 based on GCLAS are within the range of the 95-percent prediction intervals for annual loads estimated from R-LOADEST and are not statistically different (table 7) in CYs 2012 through 2014. In CY 2011, the estimated annual load for site 2 based on GCLAS was below the lower 95-percent prediction interval for the annual load estimated from R-LOADEST and was statistically different (table 7). However, loads estimated using GCLAS are based on more samples for the 4 years and are assumed to be better estimates of annual loads than loads estimated using R-LOADEST.

Annual SSC loads estimated using the ADVM SCB at site 5 are within the range of the 95-percent prediction intervals of the annual loads from R-LOADEST for CYs 2012 through 2014 (table 8). The R-LOADEST dataset did not have SSC samples available for ascending streamflows greater than 19,000 ft^3/s from CYs 2012 through 2014. The annual SSC loads estimated using the ADVM SCB were calibrated from data collected from WYs 2012 through 2016.

The annual bedload contribution to the total annual loads was minimal at sites 4 and 5 and ranged from 0.02 to 0.8 percent, respectively. At remaining sites (1, 2, and 3), contributions of bedload to the total annual loads ranged from 3 to 20 percent. Site 1 contributed the greatest portion of bedload to the total annual loads (fig. 12).

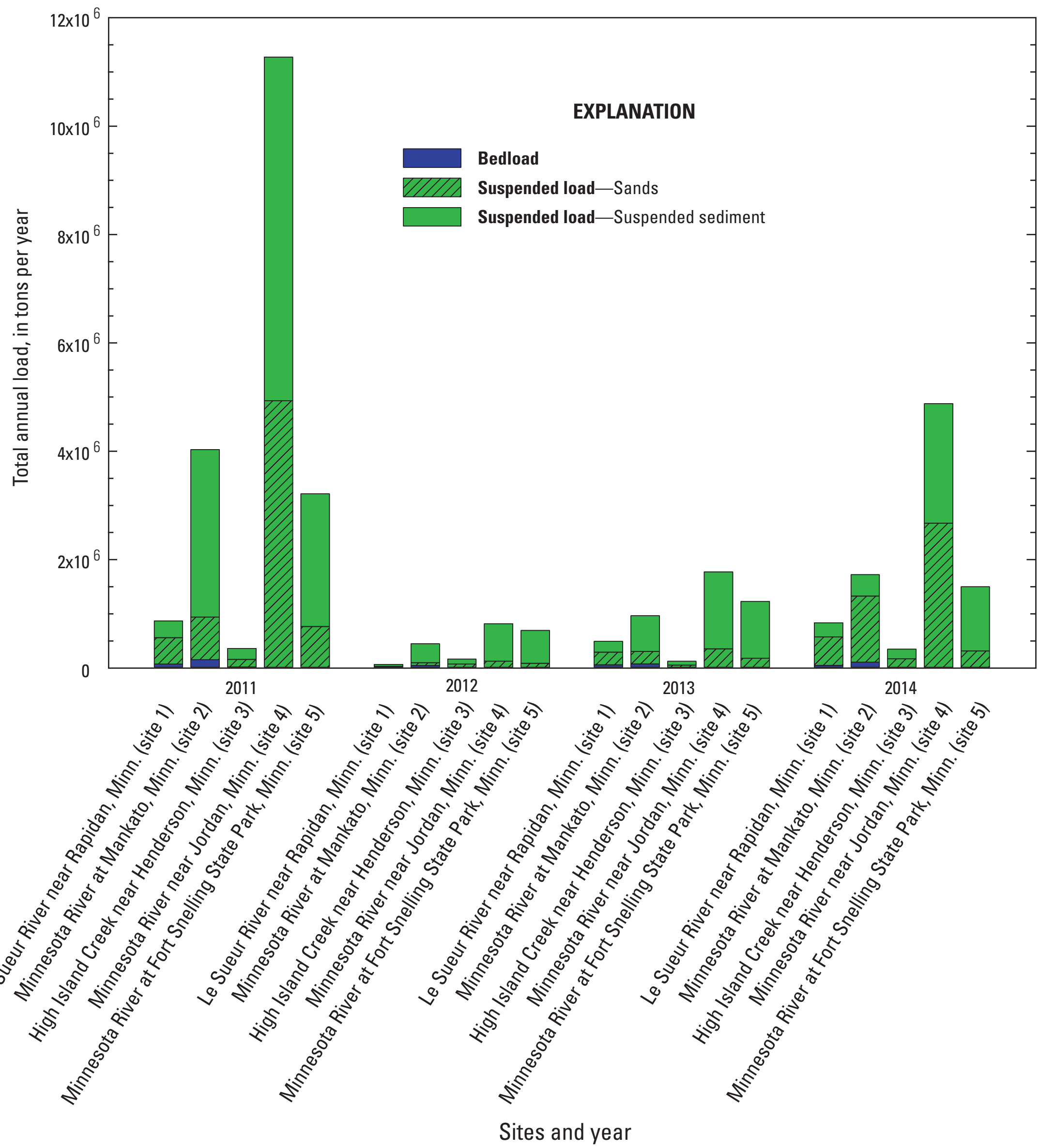

Figure 12. R-LOADEST loads at five sites in the lower Minnesota River Basin, calendar years 2011 through 2014.

Table 6. R-LOADEST regression coefficients for the final models used to compute loads at five sites in the lower Minnesota River Basin, calendar years 2011 through 2014.

[USGS, U.S. Geological Survey; ln, natural log; Q, streamflow; DECTIME, decimal time; sin, sine; cos, cosine; R^2, coefficient of determination; *p*-value, calculated probability; Minn., Minnesota; --, cells are not computed; <, less than]

Station name	Short name	USGS station number	Model number	Regression coefficient							R^2	*p*-value
				Intercept	lnQ	lnQ²	DECTIME	DECTIME²	sin (DECTIME)	cos (DECTIME)		
Suspended load—suspended-sediment models												
Le Sueur River near Rapidan, Minn.	Site 1	05320500	1	5.9780	1.7970	--	--	--	--	--	0.9645	<0.0001
Minnesota River at Mankato, Minn.	Site 2	05325000	1	7.4040	1.4320	--	--	--	--	--	0.8880	<0.0001
High Island Creek near Henderson, Minn.	Site 3	05327000	1	4.3270	1.6180	--	--	--	--	--	0.8735	<0.0001
Minnesota River near Jordan, Minn.	Site 4	05330000	1	7.4590	1.9560	--	--	--	--	--	0.9533	<0.0001
Minnesota River at Fort Snelling State Park, Minn.	Site 5	05330920	2	8.2883	1.4312	-0.3157	--	--	--	--	0.7757	<0.0001
Suspended loads—sands models												
Le Sueur River near Rapidan, Minn.	Site 1	05320500	1	4.5960	2.1380	--	--	--	--	--	0.9032	<0.0001
Minnesota River at Mankato, Minn.	Site 2	05325000	5	5.3923	1.6747	0.2023	0.4196	--	--	--	0.9273	<0.0001
High Island Creek near Henderson, Minn.	Site 3	05327000	1	2.9500	1.8450	--	--	--	--	--	0.9054	<0.0001
Minnesota River near Jordan, Minn.	Site 4	05330000	2	5.1898	1.7674	0.4006	--	--	--	--	0.9404	<0.0001
Minnesota River at Fort Snelling State Park, Minn.	Site 5	05330920	1	5.4630	1.6980	--	--	--	--	--	0.6563	<0.0001
Bedload models												
Le Sueur River near Rapidan, Minn.	Site 1	05320500	2	4.8716	1.5068	-0.5536	--	--	--	--	0.6238	<0.0001
Minnesota River at Mankato, Minn.	Site 2	05325000	4	2.5518	0.9378	--	--	--	1.1956	-2.5955	0.8021	<0.0001
High Island Creek near Henderson, Minn.	Site 3	05327000	2	3.1849	1.1599	-0.3682	--	--	--	--	0.6725	<0.0001
Minnesota River near Jordan, Minn.	Site 4	05330000	2	-1.2905	1.1973	[1]0.7622	--	--	--	--	0.4932	0.0061
Minnesota River at Fort Snelling State Park, Minn.	Site 5	05330920	9	1.7379	0.9569	0.7283	-0.7102	-0.8939	-0.8431	-2.4220	0.8481	<0.0001

[1]*p*-value is 0.0558 and no other model produced coefficients significant at 0.05.

Table 7. Graphical Constituent Loading Analysis System and R-LOADEST load comparison at the Minnesota River at Mankato, Minnesota, calendar years 2011 through 2014 (U.S. Geological Survey station 05325000).

[GCLAS; Graphical Constituent Loading Analysis System; tons/year, tons per year; Minn., Minnesota; USGS, U.S. Geological Survey]

Water year	GCLAS annual load (tons/year)	R-LOADEST annual load (tons/year)	Lower 95-percent prediction interval (tons/year)	Upper 95-percent prediction interval (tons/year)	Standard error (tons/year)
Minnesota River at Mankato, Minn.—total suspended-sediment load					
2011	1,761,855	3,876,115	2,665,589	5,451,692	665,793
2012	500,050	399,517	299,978	521,594	44,710
2013	943,160	885,647	655,249	1,171,075	111,099
2014	1,856,755	1,615,024	1,096,732	2,295,314	256,463

Table 8. R-LOADEST and acoustic surrogate load comparison at the Minnesota River at Fort Snelling State Park, Minnesota, calendar years 2012 through 2014 (U.S. Geological Survey station 05330920).

[tons/year, tons per year; Minn., Minnesota; USGS, U.S. Geological Survey]

Water year	R-LOADEST annual load (tons/year)	Acoustic surrogate annual load (tons/year)	R-LOADEST lower 95-percent prediction interval (tons/year)	Acoustic surrogate lower 90-percent confidence interval (tons/year)	R-LOADEST upper 95-percent prediction interval (tons/year)	Acoustic surrogate upper 90-percent confidence interval (tons/year)
Minnesota River at Fort Snelling State Park, Minn.—total suspended-sediment load						
2012	687,399	545,973	451,542	281,758	1,003,873	1,058,241
2013	1,223,603	1,233,515	821,975	742,309	1,754,577	2,053,696
2014	1,500,264	1,639,165	984,110	984,984	2,193,489	2,735,019

Sediment Yield by Site

Mean annual sediment yields are shown in figure 13, which were determined by dividing the total annual load in figure 12 by the drainage area of each site in table 1 and computing the mean for the 4 calendar years. Comparing mean annual sediment yields across drainage areas provides insight on the relative measure of erosion rates. Among the five sites, the two tributaries to the Minnesota River had the highest mean annual sediment yields. Site 3 had the highest mean annual sediment yield of 1,054 tons per year per square mile ([tons/yr]/mi²), and the mean annual sediment yield at site 1 was 508 (tons/yr)/mi². Mean annual sediment yield at sites 4, 2, and 5 on the Minnesota River were 289, 120, and 98 (tons/yr)/mi², respectively.

The sediment yield at site 4 is more than twice the yield at site 2. The reach from site 2 to site 4 is a primary source of large sediment inputs to the Minnesota River. The decrease in sediment yield between sites 4 and 5 is consistent with previously mentioned evidence of sediment deposition in the section of the Minnesota River and provides evidence that aggradation is continuing downstream from site 4. These results point to the dynamic nature of sediment aggradation, degradation, and transport in the Minnesota River Basin.

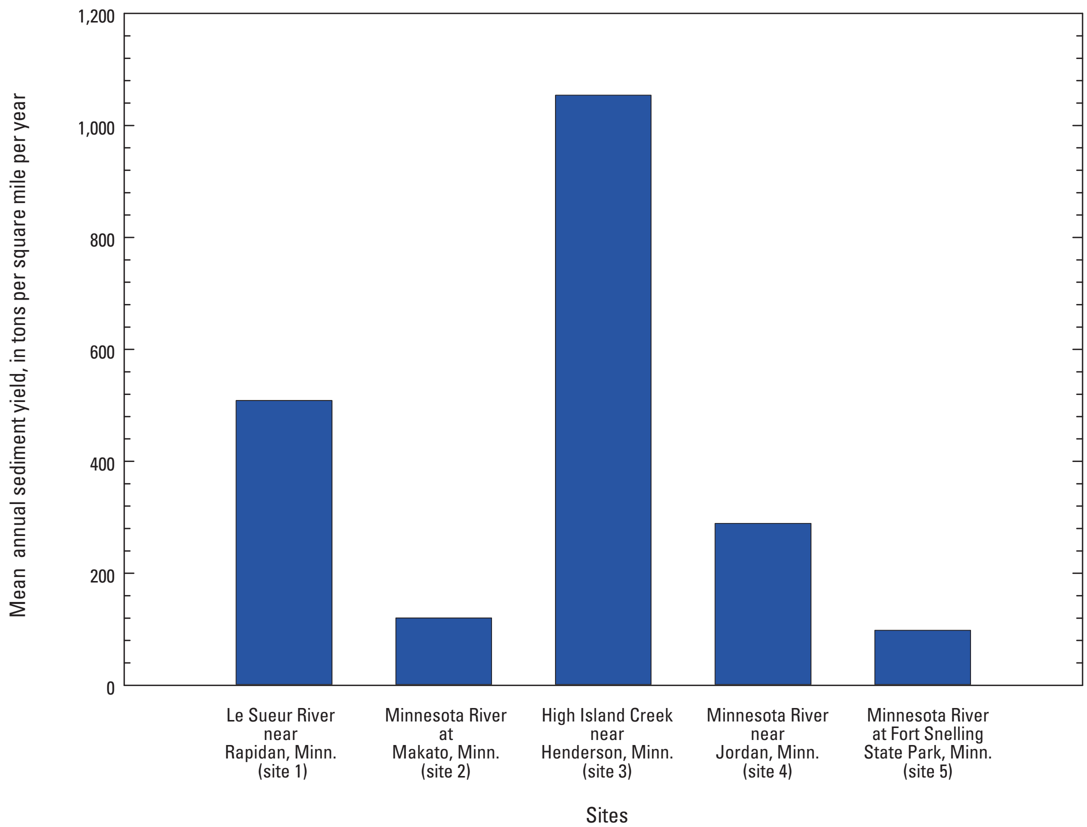

Figure 12. Mean annual sediment yield at five sites in the lower Minnesota River Basin, calendar years 2011 through 2014.

Summary and Conclusions

Excessive sediment in rivers degrades water quality and aquatic habitat, increases navigation channel dredging, reduces recreational opportunities, and can transport harmful contaminants. The Minnesota River contributes a significant sediment load to the Mississippi River, and about 75 to 90 percent of the suspended sediment being deposited into Lake Pepin is from the Minnesota River. A substantial amount of sand dredged by the U.S. Army Corps of Engineers in the Mississippi River upstream from Lake Pepin originates from the Minnesota River.

This report documents findings based on sediment data collected by the U.S. Geological Survey (USGS) in cooperation with the U.S. Army Corps of Engineers, Minnesota Pollution Control Agency, and the Lower Minnesota River Watershed District. Sediment data were collected on the lower Minnesota River at Mankato, near Jordan, and at Fort Snelling and selected tributaries (Le Sueur River near Rapidan and High Island Creek near Henderson) to improve the understanding of fluvial sediment transport. Samples were collected for suspended sediment, bedload, and particle sizes at the five sites in the lower Minnesota River Basin during water years 2011 through 2014, and surrogate measurements of acoustic backscatter were collected at one of these sites on the lower Minnesota River during water years 2012 through 2016. Annual sediment loads were computed for calendar years 2011 through 2014.

Suspended-sediment samples collected from five sites during water years 2011 through 2014 indicated that High Island Creek near Henderson had the highest mean suspended-sediment concentration (SSC), and the Minnesota River at Mankato had the lowest mean SSC. Suspended fines (sediment smaller than 0.0625 millimeters) had higher concentrations than suspended sand at all sites. The Le Sueur River had the greatest mean percentage of sand-sized particles in suspension.

Bedload samples collected from the five sites during water years 2011 through 2014 indicated Minnesota River at Mankato had the highest mean bedload. Particle-size distributions are helpful in classifying the type of sediment in the bedload samples. Of the five sites, the median particle size in the bedload samples was 1, 0.75, 0.64, 0.45, and 0.34 millimeters at the Le Sueur River near Rapidan (USGS station 05320500), Minnesota River at Mankato (USGS station 05325000), High Island Creek near Henderson (USGS station 05327000), Minnesota River near Jordan (USGS station 05330000), and Minnesota River at Fort Snelling State Park (USGS station 05330920), respectively (hereafter sites 1, 2, 3, 4, and 5, respectively).

The variations in SSC, bedload, and particles sizes are related to the change in stream gradient between the five sites. The greatest measured SSC and percentage of sand size particles were in the tributaries, which had the greatest stream gradients of the five sites. The decrease in particle sizes and stream gradient moving down the Minnesota River followed the same pattern.

The Kendall's tau statistic was used to determine what sites had significant relations between SSC and streamflow and between bedload and streamflow. Sites 1, 2, 3, and 4 had significant monotonic relations between SSC and bedload to streamflow. Site 5 had a significant positive relation at streamflows less than approximately 19,000 cubic feet per second.

The SSCs estimated using acoustic backscatter at site 5 rarely matched observed patterns in streamflow, which is commonly used to estimate SSC. The acoustic surrogate SSC also indicated that the timing and magnitude of sediment transport varied greatly over a variety of streamflow events.

The sediment yield at site 4 was more than twice the yield at site 2, indicating that the reach upstream from site 4 is a primary source of sediment to the Minnesota River. The decrease in sediment yield between sites 4 and 5 is consistent with evidence of sediment deposition in that reach of the Minnesota River and provides evidence that storage of sediment is continuing downstream from site 4.

This study provides data from which to characterize suspended sediment and bedload across the lower Minnesota River Basin. The analyses performed in this report will improve the understanding of sediment-transport relations and sediment budgets. These data provide a baseline that can be used in understanding future changes in climate, land use, stream restoration, and best-management practices that may affect sediment dynamics in the lower Minnesota River Basin.

References Cited

Belmont, P., Gran, K.B., Schottler, S.P., Wilcock, P.R., Day, S.S., Jennings, C., Lauer, J.W., Viparelli, E., Willenbring, J.K., Engstrom, D.R., and Parker, G., 2011, Large shift in source of fine sediment in the upper Mississippi River: Environmental Science and Technology, v. 45, no. 20, p. 8804–8810. [Also available at http://dx.doi.org/10.1021/es2019109.]

Chaterjee, S., Hadi, A.S., and Price, B., 2000, Regression analysis by example (3d ed.): New York, John Wiley and Sons, Inc., 359 p.

Cohn, T.A., Caulder, D.L., Gilroy, E.J., Zynjuk, L.D., and Summers, R.M., 1992, The validity of a simple statistical model for estimating fluvial constituent loads—An empirical study involving nutrient loads entering Chesapeake Bay: Water Resources Research, v. 28, no. 9, p. 2353–2363. [Also available at http://dx.doi.org/10.1029/92WR01008.]

Cohn, T.A., Delong, L.L., Gilroy, E.J., Hirsch, R.M., and Wells, D.K., 1989, Estimating constituent loads: Water Resources Research, v. 25, no. 5, p. 937–942. [Also available at http://dx.doi.org/10.1029/WR025i005p00937.]

Crawford, C.G., 1991, Estimation of suspended-sediment rating curves and mean suspended-sediment loads: Journal of Hydrology, v. 129, p. 331–348. [Also available at http://dx.doi.org/10.1016/0022-1694(91)90057-O.]

Davis, B.E., 2005, A guide to the proper selection and use of federally approved sediment and water-quality samplers: U.S. Geological Survey Open-File Report 2005–1087, 20 p. [Also available at http://pubs.usgs.gov/of/2005/1087/.]

Domanski, M.M., Straub, T.D., and Landers, M.N., 2015, Surrogate Analysis and Index Developer (SAID) tool (version 1.0, September 2015): U.S. Geological Survey Open-File Report 2015–1177, 38 p., http://dx.doi.org/10.3133/ofr20151177.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 89 p. [Also available at http://pubs.usgs.gov/twri/twri3-c2/.]

Ellison, C.A., Savage, B.E., and Johnson, G.D., 2014, Suspended-sediment concentrations, loads, total suspended solids, turbidity, and particle-size fractions for selected rivers in Minnesota, 2007 through 2011: U.S. Geological Survey Scientific Investigations Report 2013–5205, 43 p., accessed April 28, 2016, at http://dx.doi.org/10.3133/sir20135205.

Engstrom, D.R., Almendinger, J.E., and Wolin, J.A., 2009, Historical changes in sediment and phosphorus loading to the upper Mississippi River—Mass-balance reconstructions from the sediments of Lake Pepin: Journal of Paleolimnology, v. 41, p. 563–588. [Also available at http://dx.doi.org/10.1007/s10933-008-9292-5.]

Glysson, G.D., 1987, Sediment-transport curves: U.S. Geological Survey Open-File Report 87–218, 47 p. [Also available at http://pubs.er.usgs.gov/publication/ofr87218.]

Gran, K.B., Belmont, P., Day, S.S., Jennings, C., Johnson, A., Perg, L., and Wilcock, P.R., 2009, Geomorphic evolution of the Le Sueur River, Minnesota, USA, and implications for current sediment loading, *in* James, L.A., Rathburn, S.L., and Whittecar, G.R., eds., 112 Management and restoration of fluvial systems with broad historical changes and human impacts: Geological Society of America Special Paper 451, p. 119–130.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, 58 p.

Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A3, 510 p.

Kendall, M.G., 1938, A new measure of rank correlation: Biometrika, v. 30, p. 81–93.

Kendall, M.G., 1975, Rank correlation methods (4th ed.): London, Oxford University Press, Inc., 202 p.

Knighton, David, 1998, Fluvial forms and processes, a new perspective (1st ed.): New York, Oxford University Press Inc., 383 p.

Koltun, G.F., Eberle, Michael, Gray, J.R., and Glysson, G.D., 2006, User's manual for the Graphical Constituent Loading Analysis System (GCLAS): U.S. Geological Survey Techniques and Methods, book 4, chap. C1, 51 p., accessed April 28, 2016, at http://pubs.usgs.gov/tm/2006/tm4C1/pdf/tm4C1.pdf.

Landers, M.N., Straub, T.D., Wood, M.S., and Domanski, M.M., 2016, Sediment acoustic index method for computing continuous suspended-sediment concentrations: U.S. Geological Survey Techniques and Methods, book 3, chap. C5, 63 p., accessed August 9, 2016 at http://dx.doi.org/10.3133/tm3c5.

Lenhart, C.F., Titov, M.L., Ulrich, J.S., Nieber, J.L., and Suppes, B.J., 2013, The role of hydrologic alteration and riparian vegetation dynamics in channel evolution along the lower Minnesota River: Transactions of the ASABE, v. 56, no. 2, p. 549–561.

Lenhart C.F., Verry E.S., Brooks K.N., Magner J.A., 2011, Adjustment of prairie pothole streams to land-use, drainage, and climate changes and consequences for turbidity impairment: River Research and Applications, v. 28, p. 1609–1619. [Also available at http://dx.doi.org/10.1002/rra.1549.]

Levesque, V.A., and Oberg, K.A., 2012, Computing discharge using the index velocity method: U.S. Geological Survey Techniques and Methods, book 3, chap. A23, 148 p. [Also available at http://pubs.usgs.gov/tm/3a23/.]

Minnesota Department of Natural Resources, 2016a, Geomorphology: Geology: accessed April 3, 2016, at http://www.dnr.state.mn.us/whaf/about/5-component/geology.html.

Minnesota Department of Natural Resources, 2016b, Lake Pepin: accessed June 23, 2016, at http://www.dnr.state.mn.us/areas/fisheries/lakecity/pepin.html.

Minnesota Department of Natural Resources, 2016c, Water year precipitation maps: accessed May 12, 2016, at http://www.dnr.state.mn.us/climate/historical/water_year_maps.html.

Minnesota Pollution Control Agency, 2009, Total maximum daily load (TMDL) projects: accessed May 12, 2016 at http://www.pca.state.mn.us/water/tmdl/index.html.

Minnesota Pollution Control Agency, 2011, An integrated sediment budget for the Le Sueur River Basin: accessed May 12, 2016, at https://www.pca.state.mn.us/sites/default/files/wq-iw7-29o.pdf.

Minnesota Pollution Control Agency, 2012, Minnesota River turbidity total maximum daily load: accessed January 12, 2016 at https://www.pca.state.mn.us/sites/default/files/wq-iw7-32b.pdf.

Minnesota Pollution Control Agency, 2015, Sediment reduction strategy for the Minnesota River Basin and South Metro Mississippi River: accessed May 12, 2016 at http://www.pca.state.mn.us/index.php/view-document.html?gid=20703.

Minnesota Pollution Control Agency, Minnesota Department of Agriculture, Minnesota State University, Mankato Water Resources Center, and Metropolitan Council Environmental Services, 2007, State of the Minnesota River—Summary of surface water quality monitoring, 2000–2005: St. Paul, Minn., 20 p.

Minnesota River Basin Data Center, 2016, Minnesota River profile: accessed April 4, 2016, at http://mrbdc.mnsu.edu/minnesota-river-profile.

MnTOPO, 2016, Line elevation: accessed April 3, 2016, at http://arcgis.dnr.state.mn.us/maps/mntopo/.

Musser, K., S. Kudelka, R. Moore and others on behalf of the Water Resources Center, Minnesota State University – Mankato, 2009, Minnesota River Basin Trends. [Also available at http://mrbdc.mnsu.edu/minnesota-riverbasin-trends-report.]

Nash, J.E., and Sutcliffe, J.V., 1970, River flow forecasting through conceptual models part 1—A discussion of principles: Journal of Hydrology, v. 10, no. 3282–3290. [Also available at http://dx.doi.org/10.1016/0022-1694(70)90255-6.]

Nolan, K.M., Gray, J.R., and Glysson, G.D., 2005, Introduction to suspended-sediment sampling: U.S. Geological Survey Scientific Investigations Report 2005–5077, CD-ROM. [Also available at http://pubs.usgs.gov/sir/2005/5077/.]

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C3, 65 p. [Also available at http://pubs.usgs.gov/twri/twri3-c3/.]

R Development Core Team, 2011, R installation and administration, Version 2.14.1, 2011-12-22: 73 p. [Also available at http://streaming.stat.iastate.edu/CRAN/doc/manuals/R-admin.pdf.]

R Development Core Team, 2011, R installation and administration, Version 2.14.1, 2011-12-22: 73 p. [Also available at http://streaming.stat.iastate.edu/CRAN/doc/manuals/R-admin.pdf.]

Rantz, S.E., and others, 1982, Measurement and computation of streamflow—Volume 1, Measurement of stage and discharge, and volume 2, Computation of discharge: U.S. Geological Survey Water-Supply Paper 2175, 631 p. [Also available at http://pubs.usgs.gov/wsp/wsp2175/.]

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load Estimator (LOADEST)—A FORTRAN program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques and Methods, book 4, chap. A5, 69 p. [Also available at https://pubs.er.usgs.gov/publication/tm4A5.]

Schottler, S.P., Ulrich, J., Belmont, P., Moore, R., Lauer, J.W., Engstrom, D.R., and Almendinger, J.E., 2014, Twentieth century agricultural drainage creates more erosive rivers: Hydrologic Processes, v. 28, p. 1951–1961. [Also available at http://onlinelibrary.wiley.com/doi/10.1002/hyp.9738/full]

SonTek/Yellow Springs Instruments, 2007, Argonaut-SL system manual firmware version 11.8: San Diego, Calif., SonTek/YSI Inc., 314 p.

Topping, D., Melis, T., Rubin, D., and Wright, S.A., 2004, High-resolution monitoring of suspended-sediment concentration and grain size in the Colorado River using laser-diffraction instruments and a three-frequency acoustic system, *in* Liu, Cheng, ed., Proceedings of the 9th International Symposium on River Sedimentation, October 18–21, 2004, Yichang, China: Beijing, China, Tsinghua University Press, p. 2507–2514.

Topping, D., Wright, S.A., Melis, T.S., and Rubin, D.M., 2006, High-resolution monitoring of suspended-sediment concentration and grain size in the Colorado River using laser-diffraction instruments and a three-frequency acoustic system—Proceedings of the 8th Federal Interagency Sedimentation Conference, April 2–6, 2006, Reno, Nevada: CD-ROM, ISBN 0-9779007-1-1, p. 539–546.

Tornes, L.H., 1986, Suspended sediment in Minnesota streams: U.S. Geological Survey Water-Resources Investigations Report 85–4312, 33 p. [Also available at http://pubs.er.usgs.gov/publication/wri854312.]

U.S. Army Corps of Engineers, 2001, Channel Maintenance Management Plan, Upper Mississippi River Navigation System, St. Paul District: accessed May 25, 2016, at http://www.mvp.usace.army.mil/Portals/57/docs/Navigation/CMMP/GenInfo.pdf.

U.S. Army Corps of Engineers, 2006, Sedimentation in the upper Mississippi River basin: U.S. Army Corps of Engineers, St. Louis District, 142 p., accessed May 25, 2016, at http://mvs-wc.mvs.usace.army.mil/arec/Documents/Geomorphology/Sedimentation_Upper_Mississippi_River_Basin_2.pdf.

U.S. Army Corps of Engineers, 2007, Dredged material management plan Minnesota River: U.S. Army Corps of Engineers, St. Paul District, 285 p., accessed May 25, 2016, at http://www.mvp.usace.army.mil/Portals/57/docs/Navigation/River%20Resource%20Forum/MN_River_DMMP_2007_Final.pdf.

U.S. Geological Survey, 2016, National Water Information System (NWISWeb)—USGS surface-water data for Minnesota: U.S. Geological Survey database, accessed May 25, 2016, at http://waterdata.usgs.gov/mn/nwis/sw/. [Also available at http://dx.doi.org/10.5066/F7P55KJN.]

Wood, M.S., and Teasdale, G.N., 2013, Use of surrogate technologies to estimate suspended sediment in the Clearwater River, Idaho, and Snake River, Washington, 2008–10: U.S. Geological Survey Scientific Investigations Report 2013−5052, 30 p., accessed March 9, 2016, at http://pubs.usgs.gov/sir/2013/5052/.

Appendix 1

A summary of sampling sites at which suspended-sediment samples and bedload samples were collected during water years 2011 through 2014 are provided in table 1–1. There were 201 suspended-sediment concentrations (SSCs) and 130 bedload values used in data analyses. Table 1–1 is presented as a Microsoft Excel® spreadsheet and is available for download at https://doi.org/10.3133/sir20165174.

Table 1–1. Summary of suspended-sediment concentrations and bedload data used for analyses for five sites in the Lower Minnesota River Basin study area, water years 2011 through 2014.

SSC outliers collected during 2012 and 2014 are provided in table 1–2. Outliers were not included in data analysis. Table 1–2 is presented as a Microsoft Excel® spreadsheet and is available for download at https://doi.org/10.3133/sir20165174.

Table 1–2. Suspended-sediment concentration outliers collected at three sites in the Lower Minnesota River Basin study area, water years 2011 through 2014.

Publishing support provided by:
Rolla Publishing Service Center
For more information concerning this publication, contact:
Director, USGS Minnesota Water Science Center
2280 Woodale Drive
Mounds View, Minnesota 55112
(763) 783–3100
Or visit the Minnesota Water Science Center Web site at:
http://mn.water.usgs.gov/

USGS

Groten and others—**Suspended Sediment, Bedload, Particle Sizes, Surrogate Measurements, and Sediment Loads for Five Sites in the Lower Minnesota River Basin**—SIR 2016–5174

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20165174