USGS
science for a changing world

Prepared in cooperation with Environment and Natural Resources Trust Fund, U.S. Army Corps of Engineers, Lower Minnesota River Watershed District, Minnesota Pollution Control Agency, and Minnesota Department of Natural Resources

Using Acoustic Doppler Velocity Meters to Estimate Suspended Sediment along the Lower Minnesota and Mississippi Rivers

Scientific Investigations Report 2018–5165

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

Cover: J. William Lund (U.S. Geological Survey) installing an acoustic Doppler velocity meter at the Minnesota River near Jordan, Minn., from a Minnesota Department of Transportation Snooper. Brett Savage and Joshua Ayers (U.S. Geological Survey) are looking on from a boat.

Using Acoustic Doppler Velocity Meters to Estimate Suspended Sediment along the Lower Minnesota and Mississippi Rivers

By Joel T. Groten, Jeffrey R. Ziegeweid, J. William Lund, Christopher A. Ellison, Samuel B. Costa, Erin N. Coenen, and Erich W. Kessler

Prepared in cooperation with Environment and Natural Resources Trust Fund, U.S. Army Corps of Engineers, Lower Minnesota River Watershed District, Minnesota Pollution Control Agency, and Minnesota Department of Natural Resources

Scientific Investigations Report 2018–5165

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

U.S. Department of the Interior
DAVID BERNHARDT, Acting Secretary

U.S. Geological Survey
James F. Reilly II, Director

U.S. Geological Survey, Reston, Virginia: 2019

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 https://www.usgs.gov or call 1–888–ASK–USGS.

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

Suggested citation:
Groten, J.T., Ziegeweid, J.R., Lund, J.W., Ellison, C.A., Costa, S.B., Coenen, E.N., and Kessler, E.W., 2019, Using acoustic Doppler velocity meters to estimate suspended sediment along the lower Minnesota and Mississippi Rivers: U.S. Geological Survey Scientific Investigations Report 2018–5165, 30 p., https://doi.org/10.3133/sir20185165.

ISSN 2328-0328 (online)

Acknowledgments

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

Gerald Storey, Joshua Ayers, Brent Mason, Trent Sherman, Camille Buckley, and Bradley Claggett of the U.S. Geological Survey are acknowledged for assistance with equipment installation, maintenance, data management, and (or) report preparation. Molly Wood and Faith Fitzpatrick of the U.S. Geological Survey are acknowledged for their technical reviews of the report.

Contents

Figures

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)
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	
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)
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)	1.057	quart (qt)

Supplemental Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/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
MPCA	Minnesota Pollution Control Agency
p-value	probability value
R^2	coefficient of determination
SAC	sediment attenuation coefficient
SCB	sediment-corrected backscatter
SSC	suspended-sediment concentration
SSL	suspended-sediment load
TSS	total suspended solids
USGS	U.S. Geological Survey
WY	water year

Using Acoustic Doppler Velocity Meters to Estimate Suspended Sediment along the Lower Minnesota and Mississippi Rivers

By Joel T. Groten,[1] Jeffrey R. Ziegeweid,[1] J. William Lund,[1] Christopher A. Ellison,[1] Samuel B. Costa,[2] Erin N. Coenen,[1] and Erich W. Kessler[1]

Abstract

Lake Pepin is the largest naturally formed lake on the Mississippi River and has complex management needs to satisfy economic, environmental, and cultural demands. Lake Pepin is filling in with sediment at a rapid rate compared to conditions before settlement by European immigrants and intense agricultural cultivation. Accordingly, the Minnesota Pollution Control Agency has developed aggressive plans to prioritize sediment sources, understand transport mechanisms, and implement large-scale strategies to reduce sedimentation in Lake Pepin.

The Minnesota River is the primary sediment source to Lake Pepin, and reductions in sediment loading from the Minnesota River are needed to reduce sedimentation in Lake Pepin. Current loading estimates were calculated from grab sampling and total suspended solids laboratory methods that greatly underestimate the actual concentrations in the rivers when compared to U.S. Geological Survey width and depth integrated sampling and laboratory methods for determining suspended-sediment concentration (SSC). Therefore, the U.S. Geological Survey, with funding from the Environment and Natural Resources Trust Fund and in cooperation with the U.S. Army Corps of Engineers, Lower Minnesota River Watershed District, Minnesota Pollution Control Agency, and Minnesota Department of Natural Resources, collected SSCs and acoustic backscatter data from acoustic Doppler velocity meters over a 2-year period at nine sites. The purpose of the study was to improve understanding of sediment-transport processes and increase accuracy of estimating SSCs and suspended-sediment loads for the lower Minnesota River and the Mississippi River compared to traditional measures.

The study results indicated that acoustic backscatter worked well in estimating SSCs at sites not regulated by locks, dams, and lakes. The results also confirmed previous studies that determined most of the suspended-sediment loading into the Mississippi River is from the Minnesota River and the largest sediment sink is Lake Pepin. Suspended-sediment loading from site to site and year to year was often variable when compared to streamflow, which has been traditionally used to estimate SSC. As a result, this study demonstrates the value in having high temporal and spatial resolution of continuous sediment monitoring from acoustic devices to help manage the sources of sediment into Lake Pepin.

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, 2009a). Excessive sediment in rivers degrades water quality, is deleterious to aquatic habitat, leads to increased navigation channel dredging, reduces recreational opportunities, and can transport harmful contaminants (U.S. Army Corps of Engineers, 2006; Minnesota Pollution Control Agency, 2009a). The U.S. Army Corps of Engineers, St. Paul District, maintains commercial navigation channels in the upper Mississippi River and lower parts of the Minnesota and St. Croix Rivers (U.S. Army Corps of Engineers, 2001, 2007, 2011).

The Minnesota and St. Croix Rivers are the two largest tributaries to the Mississippi River upstream from Lake Pepin, each contributing about 25 percent of the total flow into Lake Pepin (Stark and others, 1996; Engstrom and others, 2009; fig. 1). The lower St. Croix River contributes little sediment to the Mississippi River (Blumentritt and others, 2009; U.S. Army Corps of Engineers, 2011). In contrast, sediment loads in the Minnesota River have been a concern among Minnesota State agencies. About 85–90 percent of the sediment being deposited into Lake Pepin originates from the Minnesota River Basin (Engstrom and others, 2009; Minnesota Pollution Control Agency, 2015).

[1] U.S. Geological Survey.

[2] Institute for Technological Research.

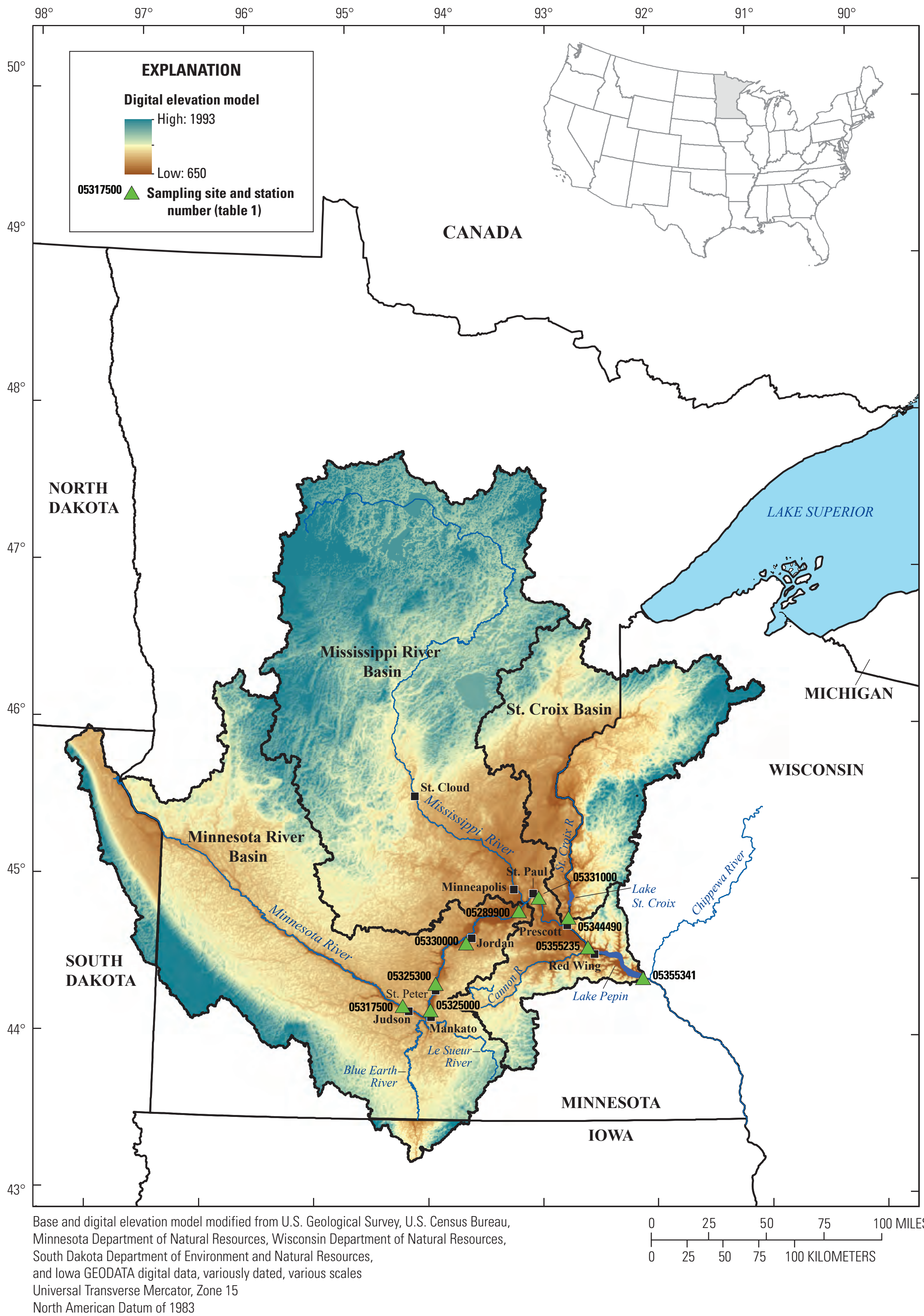

Figure 1. Location of the study area and sampling sites in the Mississippi River Basin.

Lake Pepin is an important recreational and commercial resource that is about 50 miles (mi) downstream from the Minneapolis-St. Paul (hereafter referred to as “Twin Cities”) metropolitan area of Minnesota. A sediment coring study demonstrated that sediment loading to Lake Pepin has increased by an order of magnitude since 1830, and the highest sediment accumulation rates were between 1940 and 1970 (Engstrom and others, 2009). Generally poor water quality in Lake Pepin reflects the combined effects of urban and agricultural developments in the basin (Engstrom and others, 2009). The Minnesota Pollution Control Agency (MPCA) is addressing sediment-related impairments in Lake Pepin by developing total maximum daily loads for total suspended solids (TSS) in the Minnesota and the Mississippi Rivers. To help meet water-quality targets of the total maximum daily loads, the MPCA adopted a Sediment-Reduction Strategy that includes 90- and 50-percent reductions in sediment loads by 2040 for the Minnesota River and the Mississippi River between the Twin Cities and Lake Pepin, respectively (Minnesota Pollution Control Agency, 2015).

The MPCA began collecting suspended-sediment grab samples for analysis of TSS in the early 1970s based on recommendations by the U.S. Environmental Protection Agency. From 2007 through 2011, the U.S. Geological Survey (USGS) and the MPCA completed a cooperative, statewide study that built upon a previous USGS study (Gray and others, 2000) to compare sediment loads calculated using the grab sampling and TSS laboratory methods to sediment loads calculated using standard USGS sampling methods that integrate the width, depth, and velocity of the river cross section (Edwards and Glysson, 1999) and the suspended-sediment concentration (SSC) laboratory method. The study results indicated that grab sampling and TSS laboratory methods underrepresented sediment concentrations by about 50 percent (Ellison and others, 2014). A subsequent report demonstrated that the grab sampling and TSS laboratory methods accurately estimated concentrations of fine sediments but underestimated sand concentrations compared to the standard USGS sampling and SSC laboratory methods (Groten and Johnson, 2018). Underrepresentation of sediment concentrations results in inaccurate sediment load computations and subsequent misinterpretations of data that inform management decisions.

Physically collected suspended-sediment samples provide the most accurate measurements of suspended-sediment loads (SSLs) and erosion in a basin, but physical samples do not provide accurate, real-time estimates of SSLs. Historically, SSLs have been estimated by a rating curve approach that relates SSC to streamflow (Crawford, 1991; Horowitz, 2003), and continuous streamflow records can be used to estimate SSLs for unsampled periods using this approach. However, uncertainties in SSLs based on streamflow are high because of the effects of hysteresis (Walling, 1997), which means that the relation between streamflow and SSC changes between the rising and falling limb of the streamflow hydrograph (Knighton, 1998). Sediment transport and streamflow also do not correlate well in regulated or supply-limited systems; therefore, accurate and cost-effective methods for providing real-time sediment information could help the U.S. Army Corps of Engineers better maintain the commercial navigation channel. In addition, real-time sediment information can help State agencies monitor progress toward sediment reduction goals and effectiveness of implemented best management practices and other restoration activities.

From water years (WYs) 2015 through 2017, the USGS, with funding from the Environment and Natural Resources Trust Fund and in cooperation with the U.S. Army Corps of Engineers, Lower Minnesota River Watershed District, MPCA, and Minnesota Department of Natural Resources, installed and operated side-looking acoustic Doppler velocity meters (ADVMs) at nine streamgages in the Minnesota, Mississippi, and St. Croix Rivers upstream from Lake Pepin. The ADVMs emit sound pulses into the water and measure the strength of the returned pulses (called acoustic backscatter) after reflecting off sediment and other particulate matter in the water. The measured acoustic backscatter data were used as a surrogate for SSCs according to methods in Landers and others (2016). The measured acoustic backscatter data were corrected for various losses to compute the sediment-corrected backscatter (SCB) and sediment attenuation coefficient (SAC) and then were correlated to SSCs measured from water samples collected using approved USGS depth-integrated, isokinetic techniques. Statistical relations among SCB, SAC, streamflow, and SSC were combined with streamflow data to estimate SSLs at streamgages included in this study.

Purpose and Scope

The purpose of this report is to summarize and interpret collected SSC and acoustic backscatter data to improve understanding of the timing and loading of suspended-sediment transport for the lower Minnesota River, the St. Croix River, and the Mississippi River between the Twin Cities and Lake Pepin. Specifically, the report describes (1) the relations among acoustic backscatter, streamflow, and SSCs in the lower Minnesota River and the Mississippi River (WYs 2012 through 2017); (2) annual and seasonal SSLs (WYs 2015 through 2017); and (3) suspended-sediment budgets for selected reaches on the lower Minnesota River and Mississippi River (WYs 2016 through 2017).

Description of the Study Area

The study area includes parts of the Minnesota River, Mississippi River, and St. Croix River Basins (fig. 1). The outlet of Lake Pepin represents the downstream end of the study area and drains 47,400 square miles (mi^2). Lake Pepin is a natural flood plain lake on the Mississippi River that was formed by a tributary fan caused by the confluence with the Chippewa River during the end of the last glaciation (Blumentritt and others, 2009).

Land use in the Mississippi River Headwaters Basin transitions from forest in the northern areas to agricultural areas in the central part and finally to the Twin Cities at the southern end of the basin marked by the confluence with the St. Croix River (fig. 1). The poor water quality in the part of the study area from the confluence of the Mississippi and St. Croix Rivers to the outlet of Lake Pepin (fig. 1) reflects the combined effects of agricultural and urban development upstream (Engstrom and others, 2009).

The Minnesota River Basin drains 16,900 mi^2 (fig. 1). The Minnesota River flows from the origin along the Minnesota-South Dakota border (fig. 1) across south-central Minnesota for 335 mi to the Mississippi River near the city of St. Paul, Minnesota. The Minnesota River valley was formed by incision from Glacial River Warren (not shown), and tributaries to the Minnesota River flow through highly erodible knickpoints made up of fine-grained till (Minnesota Pollution Control Agency, 2011).

Land use in the Minnesota River Basin is about 85–90 percent agriculture (Engstrom and others, 2009; Minnesota Pollution Control Agency, 2015), and modifications in the watershed have altered the manner in which water moves from the landscape to the river channel. Previous work by Schottler and others (2014) in the Minnesota River Basin demonstrated that artificial drainage was the primary factor for an increase in streamflow since 1940 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 in the past three decades; furthermore, the increase in streamflow from artificial drainage in the Minnesota River has increased channel erosion and widened channels (Schottler and others, 2014). Finally, Lenhart and others (2013) determined that the Minnesota River has widened by 52 percent and shortened by 7 percent between Mankato and St. Paul, Minn., since 1938.

The St. Croix Basin (fig. 1) drains 7,700 mi^2 in Minnesota and Wisconsin (Lenz and others, 2001). Before European settlement, the St. Croix Basin was dominated by forests, peatlands, and prairie grasslands (Niemela and Feist, 2000; Payne and others, 2002). Currently, the St. Croix Basin is dominated by forest, pastures, and croplands, with most of the urban lands concentrated in the areas around the lowest 25 mi of the St. Croix River (Heiskary and Vavricka, 1993; Larson and others, 2002). The final 25 mi of the river forms Lake St. Croix, a natural flood plain lake formed by a tributary fan at the confluence of the Mississippi River during the end of the last glaciation (Robertson and Lenz, 2002; Blumentritt and others, 2009). Sediment deposition in Lake St. Croix further reduces sediment loads from the St. Croix River into the Mississippi River.

Sampling Sites

A total of 5 sites on the Minnesota River, 3 sites on the Mississippi River, and 1 site on the St. Croix River were sampled for SSCs during this study (fig. 1; table 1). The Minnesota River at Judson, Minn. (USGS station 05317500; hereafter referred to as “Judson”), site is positioned highest in the basin (fig. 1). The Minnesota River at Mankato, Minn. (USGS station 05325000; hereafter referred to as “Mankato”), site is downstream from the Judson site and just downstream from where the Blue Earth River flows into the Minnesota River. The Le Sueur River is a tributary to the Blue Earth River (fig. 1). Downstream from the Mankato site are the Minnesota River at County Highway 22 in St. Peter, Minn. (USGS station 05325300; hereafter referred to as “St. Peter”); Minnesota River near Jordan, Minn. (USGS station 05330000; hereafter referred to as “Jordan”); and Minnesota River at Fort Snelling State Park, Minn. (USGS station 05330920; hereafter referred to as “Ft. Snelling”), sites (fig. 1). Ft. Snelling is just above the confluence with the Mississippi River, which is below Lock and Dam Number 1 (fig. 2). The Mississippi River at St. Paul, Minn. (USGS station 05331000; hereafter referred to as “St. Paul”), site is just downstream from the confluence of the Minnesota and Mississippi Rivers (fig. 1). The St. Croix River at Prescott, Wisconsin (USGS station 05344490; hereafter referred to as “Prescott”), site is just above the confluence with the Mississippi River (fig. 1). The Mississippi River above Red Wing below Diamond Island, Minn. (USGS station 05355235; hereafter referred to as “Red Wing”), site is below Lock and Dam Number 3 and downstream from the Cannon River’s confluence with the Mississippi River (fig. 1). The last site at Mississippi River (Lake Pepin) above Reads Landing, Minn. (USGS station 05355341; hereafter referred to as “Pepin”), is at the outlet of Lake Pepin and above the confluence of the Chippewa and Mississippi Rivers (fig. 1).

The nine sampling locations represent a wide range of stream gradients that affect relative differences in sediment-transport capacity throughout the study area (fig. 2; MnTOPO, 2018). Steeper gradients cause water to flow faster, increasing sediment-transport capacity, and can also cause erosion, which can change river geomorphology. Gradual gradients can lead to slower moving water, which can decrease the sediment transport of the river and lead to sediment deposition. Of the nine sites, Judson had the steepest gradient. The gradient decreased downstream along the Minnesota River at the Mankato, St. Peter, and Jordan sites. The Ft. Snelling site had the most gradual gradient of all Minnesota River sites in the study area because its location in the valley bottomlands is near the confluence of the Minnesota and Mississippi Rivers. Gradients at Mississippi River sites at St. Paul and above Red Wing are affected by locks and dams. Finally, the St. Croix and Pepin sites are affected by backwater in Lake St. Croix and Lake Pepin, respectively.

Precipitation

Precipitation is a primary factor affecting sediment transport because of direct effects on streamflow. Precipitation varied from WYs 2015 through 2017 in the study area (Minnesota Department of Natural Resources, 2018a). During

Table 1. Study area sediment monitoring sites in the Mississippi River Basin.

[USGS, U.S. Geological Survey; Minn., Minnesota; MNDNR, Minnesota Department of Natural Resources; MPCA, Minnesota Pollution Control Agency; St., Saint; Ft., Fort; Wisc., Wisconsin; the boldfaced text under station names are station name abbreviations used in the text of this report (see "Sampling Sites" section)]

Station name	USGS station number	Responsible for streamgage operation	Latitude (north)	Longitude (west)	Drainage area (square miles)
Minnesota River at **Judson**, Minn.	05317500	MNDNR/MPCA	44.20000	−94.19333	11,300
Minnesota River at **Mankato**, Minn.	05325000	USGS	44.16889	−94.00306	14,900
Minnesota River at County Highway 22 in **St. Peter**, Minn.	05325300	MNDNR/MPCA	44.30750	−93.95008	15,100
Minnesota River near **Jordan**, Minn.	05330000	USGS	44.69306	−93.64167	16,200
Minnesota River at **Ft. Snelling** State Park, Minn.	05330920	USGS	44.89611	−93.18861	16,900
Mississippi River at **St. Paul**, Minn.	05331000	USGS	44.94440	−93.08806	36,800
St. Croix River at **Prescott**, Wisc.	05344490	USGS	44.74917	−92.80444	7,700
Mississippi River above **Red Wing** below Diamond Island, Minn.	05355235	USGS	44.60417	−92.57917	45,200
Mississippi River (Lake **Pepin**) above Reads Landing, Minn.	05355341	USGS	44.41028	−92.09722	47,400

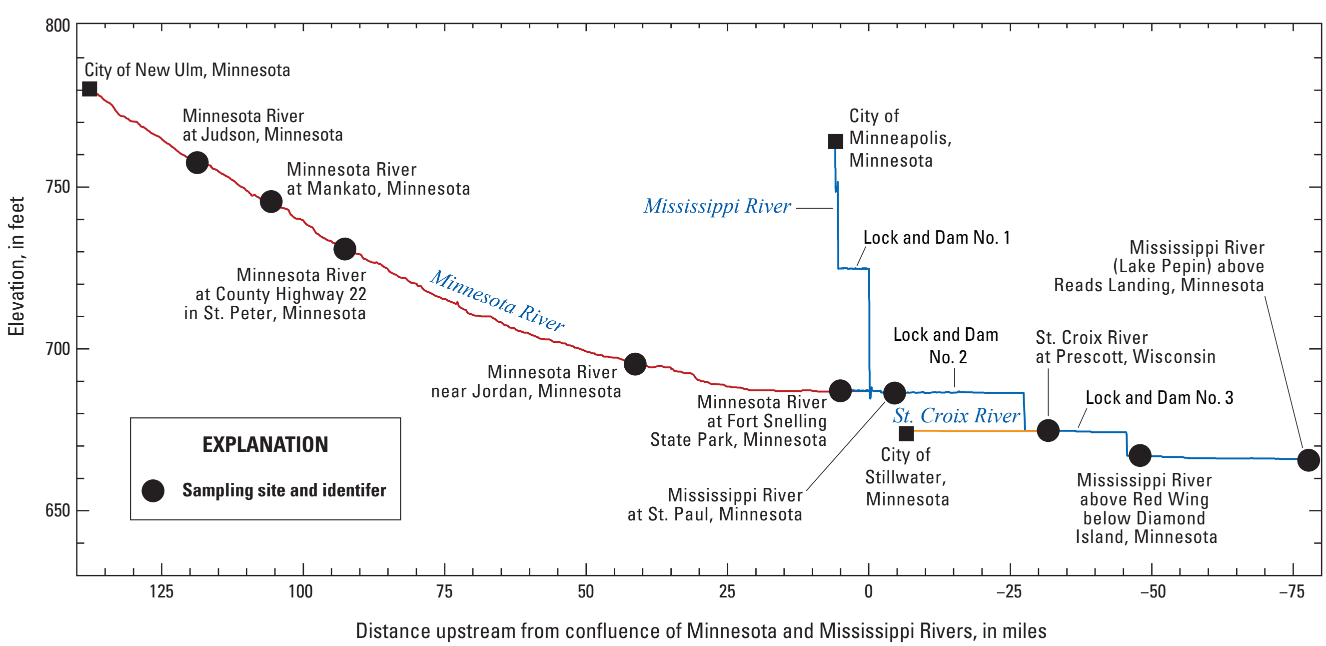

Figure 2. Stream gradients (MnTOPO, 2018) along the Mississippi River (from Minneapolis to the outlet of Lake Pepin) and two tributaries (Minnesota River and St. Croix River).

WY 2015, precipitation was less than the historical mean in the upper part of the Minnesota River Basin and similar to historical means in the rest of the study area, with isolated pockets of above average precipitation near the Le Sueur River Basin (not shown; Minnesota River subbasin) and the confluence of the Mississippi and St. Croix Rivers (Minnesota Department of Natural Resources, 2018a). Precipitation during WY 2016 was higher than historical mean precipitation throughout Minnesota, and parts of the Blue Earth (not shown) and Le Sueur River Basins (not shown) received 16–24 inches of precipitation above the historical mean. In the WY 2017, precipitation was similar to the historical mean for much of the study area; however, the upper Minnesota River Basin received more precipitation than the historical mean, whereas the Blue Earth and Le Sueur River Basins received average amounts of precipitation.

Streamflow

Historical mean streamflows measured at long-term streamgages on the Minnesota (the Jordan site; 1935–2017), Mississippi (the St. Paul site; 1901–2017), and St. Croix (St. Croix River at St. Croix Falls, Wisc., USGS station 05340500; 1911–2017) Rivers were used to make general assessments of streamflow during the study period (U.S. Geological Survey, 2018a). Observed streamflow patterns were similar in the Minnesota and Mississippi Rivers, with annual mean streamflows being slightly less than the historical mean in the WY 2015 and substantially higher than the historical mean in WYs 2016 and 2017. In contrast, the annual mean streamflows in the St. Croix River were higher than the historical mean for all study years, but the magnitudes of differences from the historical mean were lower compared to observed differences in the Minnesota and Mississippi Rivers.

Methods of Data Collection and Analysis

Field crews attempted to collect samples over the full range of observed streamflows during the open-water season at each site (fig. 3). A total of eight sites (table 1) were sampled for SSCs during WYs 2016 through 2017, and Ft. Snelling was sampled for SSCs during WYs 2012 through 2017 (table 1). Corresponding acoustic backscatter data were collected during SSC sample collection at all sites. Sites were at established USGS or Minnesota Department of Natural Resources and MPCA cooperative streamgages (table 1), and samples were collected 8 to 13 times per year over a range of streamflows during the open-water season (March through November; fig. 3) when the rivers were not covered by ice. Water samples were analyzed for SSC and percentage of fines (defined as particle sizes [clay and silt] less than 0.0625 millimeter [mm]).

Sampling Methods

Water samples were collected using isokinetic samplers and depth-integrating techniques at equal-width intervals or equal-discharge intervals (Edwards and Glysson, 1999; Davis, 2005). For collection of water samples, the stream width was divided into 10 equal widths for equal-width interval samples or 5 equal-discharge increments for equal-discharge interval samples. Each isokinetic, depth-integrated sample was collected at the centroid of each increment according to procedures in Edwards and Glysson (1999). Depending on the river depth and velocity, samples from each centroid were collected from the stream transect with a D–74 or D–96 sampler lined with either a 1-pint glass bottle, a 1-quart glass bottle, or a 3-liter bag. Each sample collected from all the centroids of the stream transect were composited into one sample and sent to the laboratory for analysis.

Acoustic Backscatter Data

During this study, an ADVM was deployed at each of the nine sampling sites (table 1; fig. 1). The ADVMs at Ft. Snelling, St. Paul, and Prescott already were installed to compute streamflow using the index velocity method (Levesque and Oberg, 2012) because these sites are affected by backwater. Because these three ADVMs were installed to assist in streamflow computations, the ADVMs were configured differently from methods recommended for using acoustic backscatter data as a surrogate for SSCs (Landers and others, 2016). For example, these ADVMs were programmed to collect 5 cells of acoustic backscatter data, instead of the 10 cells recommended by Landers and others (2016). The other six sites (Judson, Mankato, St. Peter, Jordan, Red Wing, and Pepin; table 1) were configured according to recommendations made by Landers and others (2016) and were programmed with 10 cells.

The ADVMs were configured to collect and average backscatter measurements over 12 minutes out of each 15-minute measurement interval. Data were downloaded from ADVMs about every 8 weeks during the duration of the study. Acoustic backscatter data were processed and corrected for signal losses using the Surrogate Analysis and Index Developer software tool (Domanski and others, 2015; available at https://water.usgs.gov/osw/SALT/SAID/downloads.html). Acoustic backscatter data were adjusted through three separate corrections: (1) attenuation of the acoustic signal because of beam spreading, (2) acoustic absorption by water, and (3) attenuation of the acoustic signal by suspended sediment. The two acoustic surrogate metrics produced by these corrections were SCB, in decibels, and SAC, in decibels per meter; SCB, SAC, and streamflow were tested as explanatory variables for SSC in the development of linear regression models. Data generated during this study are available as a USGS data release (Groten, 2018).

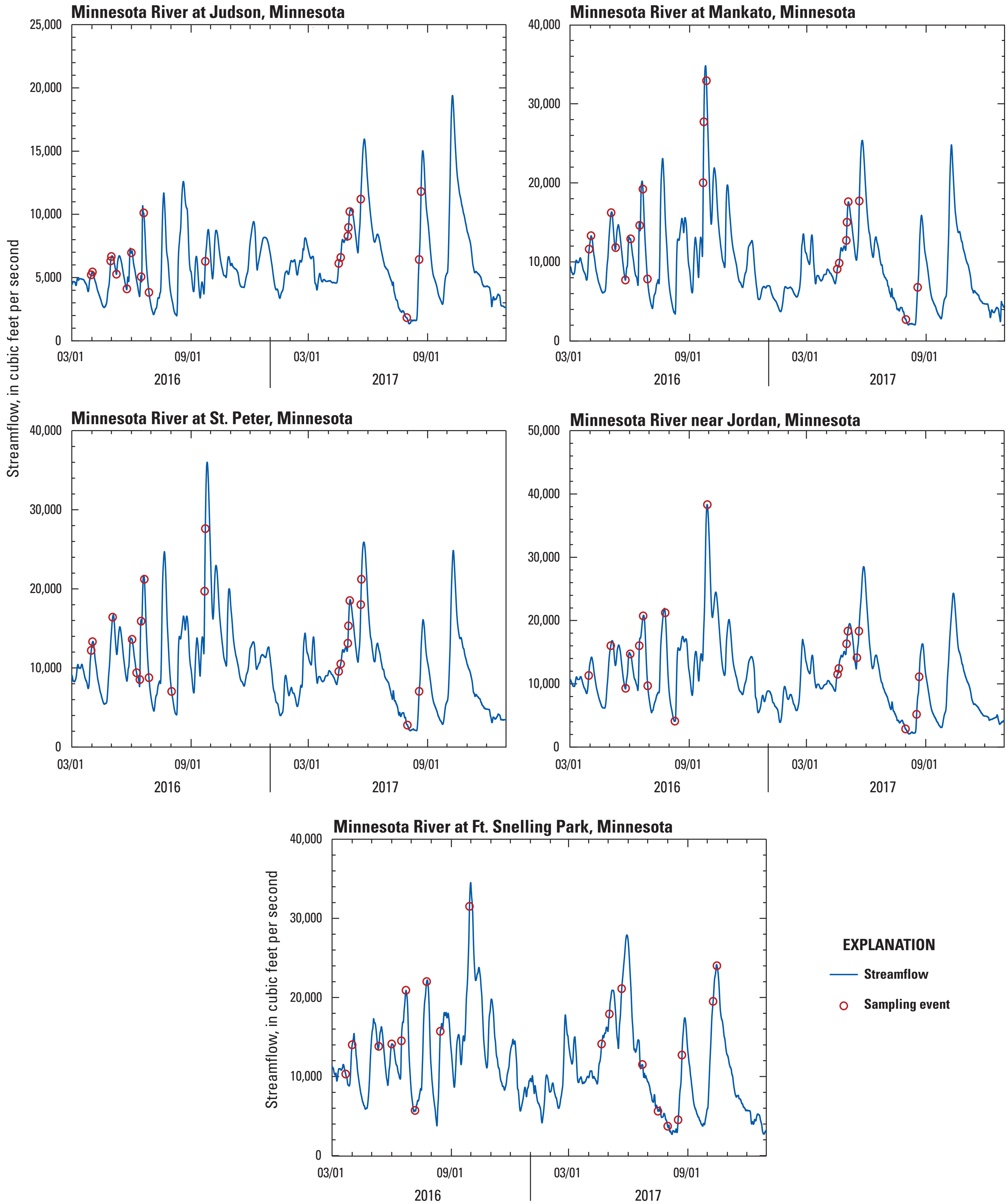

Figure 3. Hydrographs and collection dates of suspended-sediment samples at nine sites (table 1) in the Mississippi River Basin, water years 2016 through 2017.

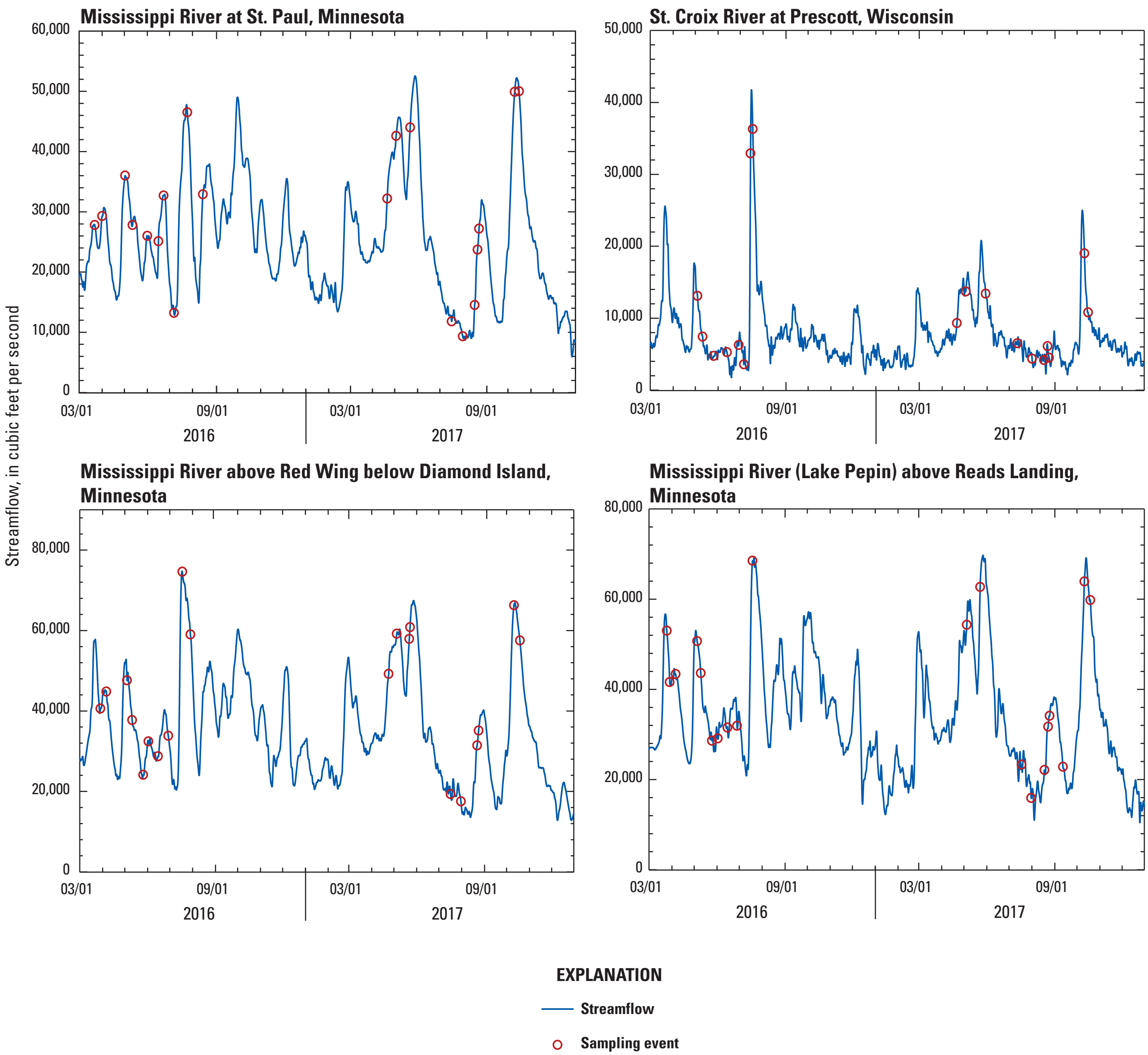

Figure 3. Hydrographs and collection dates of suspended-sediment samples at nine sites (table 1) in the Mississippi River Basin, water years 2016 through 2017.—Continued

Streamflow Data

Suspended-sediment sampling sites for this study were collocated at established streamgages (table 1; fig. 1). Instantaneous and daily mean streamflow data obtained from USGS and Minnesota Department of Natural Resources/MPCA streamgages are available at the USGS National Water Information System web page (https://doi.org/10.5066/F7P55KJN; U.S. Geological Survey, 2018) and https://www.dnr.state.mn.us/waters/csg/index.html (Minnesota Department of Natural Resources, 2018), respectively.

Laboratory Analysis

Water samples were analyzed for SSC following method D3977–97 (Guy, 1969; American Society for Testing and Materials, 2000) by the USGS Sediment Laboratory in Iowa City, Iowa. Percentage of fines (particle sizes less than 0.0625 mm) also were determined for SSC samples at the same laboratory by wet sieving (Guy, 1969). Particles that measure greater than or equal to 0.0625–2.0 mm are sands. Results from laboratory analyses are available at the USGS National Water Information System web page (U.S. Geological Survey, 2018).

Statistical Analysis for Suspended Sediment

Data analyses included the computation of summary statistics, the development of linear regression models, and the computation of daily and annual SSL estimates. Data analyses also included the identification of outliers (Groten, 2018) in the datasets, which represent random errors. Outliers were identified by a low percentage of fines (particle sizes less than 0.0625 mm), which indicated a high sand content in the sample. Sample outliers can exist during data collection when the streambed is inadvertently sampled because the sampler disturbed and entrained deposited bed sediment or when the sampler nozzle accidentally contacted a sand dune. Identified outliers were removed before data analysis.

Development of Linear Regression Models

The suitability of acoustic surrogate relations was tested at each site by completing ordinary least squares regression analyses (Helsel and Hirsch, 2002) using acoustic surrogate metrics (SCB and SAC) and streamflow as explanatory variables and SSC as the response variable. Different combinations of simple and multiple linear regressions on untransformed and transformed data were tested. A level of significance (α) of 0.05 was used for all statistical analyses presented in this study. For sites that used acoustic surrogate metrics in the linear regression models, gaps in continuous acoustic data caused by equipment malfunctions were filled using SSC values estimated using streamflow as an explanatory variable in linear regression models to estimate SSC. Gaps in continuous acoustic backscatter data (less than 18 percent of the time) are identified and described in detail in a corresponding USGS data release (Groten, 2018).

For all nine sites in the study area, Surrogate Analysis and Index Developer was used to develop regression models and evaluate the accuracy of developed models for estimating SSCs. Diagnostic plots, residual errors, and probability values (p-values) were examined to ensure models met the assumptions of ordinary least squares regression analyses (Helsel and Hirsch, 2002). Streamflow and SSC were log transformed (base-10 logarithms), and bias-correction factors were applied (Duan, 1983) after SSC data were retransformed into the original units. The final linear regression models were used to generate a time series of estimated SSC values and prediction intervals (Helsel and Hirsch, 2002). The following model form was used to predict SSC:

$$SSC = 10^{b_0 + b_1 x_1 + \ldots + b_k x_k} \times BCF \quad (1)$$

where

- SSC is suspended-sediment concentration, in milligrams per liter;
- b_0 is the intercept;
- b_1 is the slope for the first explanatory variable;
- x_1 is the first explanatory variable;
- b_k is the slope for the kth explanatory variable;
- x_k is the kth explanatory variable (when multiple linear regression is used); and
- BCF is the bias-correction factor (Duan, 1983).

Daily and Annual Suspended-Sediment Load Estimates

Daily mean SSC values and 90-percent prediction intervals were calculated from the time series (15-minute interval) of SSCs estimated from linear regression models, and daily SSLs were estimated using the following equation (Porterfield, 1972):

$$SSL = Q \times SSC \times c_f \quad (2)$$

where

- SSL is the daily mean suspended-sediment load, in tons per day;
- Q is the daily mean streamflow, in cubic feet per second;
- SSC is the daily mean suspended-sediment concentration, in milligrams per liter; and
- c_f is a coefficient (0.0027) that converts the units of streamflow and SSC into tons per day and assumes a specific gravity of 2.65 for sediment.

When regression equations were deemed not accurate enough to use as predictive surrogate models (coefficient of determination [R^2] less than [<] 0.5), the mean SSC of the collected samples was used with the daily mean streamflow to compute daily mean SSL. A 90-percent confidence interval of each mean SSC was computed (Helsel and Hirsch, 2002). The daily mean SSL estimates were summed for the WY to obtain the annual SSL estimates.

Streamflow, Suspended-Sediment Concentrations, and Surrogate Relations

Summary statistics of streamflow, SSCs, and acoustic metrics (SCB and SAC) for the nine sites in the study area (table 2; fig. 1) demonstrate considerable variability in sediment transport that is likely affected by many factors such as sediment sources, sediment supply, rate of erosion, magnitude, intensity and duration of storm events, and antecedent conditions. The increase in median SSC for the Minnesota River between Judson and Mankato (table 2) likely is a result of sediment from the Blue Earth River entering the Minnesota River just upstream from Mankato (fig. 1). The Le Sueur River (fig. 1) flows into the Blue Earth River near the town of Rapidan, Minn. (not shown), upstream from where the Blue Earth River joins the Minnesota River. The Le Sueur and Blue Earth Rivers previously have been determined to transport elevated SSCs (Minnesota Pollution Control Agency, 2009b; Ellison and others, 2014; Groten and others, 2016; Groten and Johnson, 2018).

Median suspended-sand concentrations generally decreased downstream, similar to how the stream gradients decreased downstream (table 2; figs. 2 and 4). Median suspended-sand concentrations increased in the Minnesota River from Judson to Mankato (table 2; fig. 4), whereas suspended-sand concentrations were similar for the Minnesota River between Mankato and St. Peter (table 2; fig. 4). In contrast, suspended-sand concentrations decreased in the Minnesota River between Mankato and Ft. Snelling (table 2; fig. 4), and suspended-sand concentrations were substantially lower at Prescott and substantially decreased from St. Paul to Red Wing and to Pepin (table 2; fig. 4). This observed decrease in suspended-sand concentrations corresponds to a transition from higher gradient stream sites to lower gradient stream sites (fig. 2), indicating that higher gradients may provide the velocities required to keep sand particles in suspension. When the stream gradient decreases, the suspended sands likely settle out and deposit in the river channel and (or) flood plain. Also, suspended-fines concentrations followed similar patterns as suspended-sands concentrations.

The Mississippi River upstream from the confluence with the Minnesota River generally is low in SSC. Downstream from the confluences of the Minnesota and Mississippi Rivers and the St. Croix and Mississippi Rivers, streamflows increase because of the contribution of streamflow from these two tributaries (table 2). The combination of low SSCs and high streamflow volumes helps to dilute high concentrations of suspended sediment entering the Mississippi River from the Minnesota River. Median SSC drops from Ft. Snelling (221 milligrams per liter [mg/L]; table 2) to St. Paul (119 mg/L; table 2), which is just downstream from the confluence of the Minnesota and Mississippi Rivers (fig. 1). The median SSC at Prescott was low (2.00 mg/L; table 2), and the median SSC of Red Wing is less than one-half (46.0 mg/L; table 2) of the observed median SSC at St. Paul (119 mg/L; table 2). Finally, the stream gradient decreases furthest downstream in Lake Pepin, and the median SSC at Pepin decreased to 5.00 mg/L (table 2).

Surrogate Relations for Suspended-Sediment Concentrations

Statistically significant linear relations (p-value <0.05) and high coefficients of determination (R^2 greater than 0.75) demonstrated that SAC and SCB could be useful for improving estimates of SSCs at five of the nine study sites: the Minnesota River at (1) Mankato, (2) St. Peter, (3) Jordan, and (4) Ft. Snelling and the Mississippi River at (5) St. Paul (table 3; fig. 5). A significant linear relation could not be developed for Judson because of data quality issues caused by the ADVM going out of water during low flow periods and by low signal return for the vertical elevation beam during high flow periods (Xue Fan, Sontek, written commun., 2018). For Judson, the linear relation between streamflow and SSC (R^2=0.79) was statistically significant (p<0.01) and was used in estimating annual SSL (table 4; Groten, 2018). Because more samples were collected during the rising limb rather than the falling limb of the streamflow hydrograph, there is likely to be hysteresis in SSCs with respect to rising- and falling-limb flow conditions; therefore, this study likely did not capture the full range of variability in SSCs at different streamflows. Thus, the streamflow regression statistics (table 3) likely overestimate R^2, underestimate standard error, and produce higher biased estimated SSCs for falling-limb conditions. For sites that included acoustic surrogate metrics to estimate SSC in the linear regression model, the models with acoustic metrics consistently explained more variability (had higher R^2 values) than streamflow-based models (fig. 5; Groten, 2018).

A pattern was evident when comparing surrogate models developed for two sites. Linear regression model forms were similar for Mankato and St. Peter and different compared to the other sites. Similar elevation gradients (fig. 3) and close proximity (13 mi) without an intervening major tributary likely contributed to the similarities in these regression models.

Significant linear relations could not be developed to predict SSC from acoustic data or streamflow for Prescott, Red Wing, or Pepin (fig. 5). Mean SSC values from physically collected samples (table 3) at each site were used to estimate SSLs at these sites. Samples collected in 2016 at Red Wing

Table 2. Summary statistics for streamflow, suspended sediments, and acoustic surrogate model metrics.

[*n*, number of samples; Minn., Minnesota; ft³/s, cubic foot per second; mg/L, milligram per liter; St., Saint; Ft., Fort; Wisc., Wisconsin]

Constituent	Minimum	Mean	Median	Maximum	Total *n*
Minnesota River at Judson, Minn.					
Streamflow, instantaneous (ft³/s)	654	5,170	4,810	15,900	731
Suspended-sediment concentration (mg/L)	62.0	252	234	558	21.0
Suspended sands (mg/L)	3.72	49.6	46.6	92.1	21.0
Suspended fines (mg/L)	58.3	202	178	513	21.0
Minnesota River at Mankato, Minn.					
Streamflow, instantaneous (ft³/s)	1,020	8,820	8,050	34,700	731
Suspended-sediment concentration (mg/L)	66.0	407	330	1,190	20.0
Suspended sands (mg/L)	4.62	85.9	84.7	288	20.0
Suspended fines (mg/L)	61.4	321	241	1,120	20.0
Sediment attenuation coefficient (in decibels per meter)	0.170	0.558	0.474	7.35	38,600
Minnesota River at County Highway 22 in St. Peter, Minn.					
Streamflow, instantaneous (ft³/s)	1,160	9,440	8,870	36,000	731
Suspended-sediment concentration (mg/L)	83.0	398	332	1,620	22.0
Suspended sands (mg/L)	7.47	89.9	80.5	292	22.0
Suspended fines (mg/L)	75.5	308	231	1,330	22.0
Sediment attenuation coefficient (in decibels per meter)	0.189	0.806	0.764	4.59	30,200
Minnesota River near Jordan, Minn.					
Streamflow, instantaneous (ft³/s)	1,320	10,200	9,470	38,300	731
Suspended-sediment concentration (mg/L)	67.0	370	312	1,390	21.0
Suspended sands (mg/L)	5.36	54.9	56.8	99.0	21.0
Suspended fines (mg/L)	61.6	315	244	1,290	21.0
Sediment-corrected backscatter (in decibels)	22.7	80.1	80.6	94.8	56,600
Minnesota River at Ft. Snelling State Park, Minn.					
Streamflow, instantaneous (ft³/s)	1,120	8,340	7,400	34,500	1,100
Suspended-sediment concentration (mg/L)	18.0	257	221	1,010	54.0
Suspended sands (mg/L)	0.360	29.7	17.6	171	54.0
Suspended fines (mg/L)	17.6	227	189	909	54.0
Sediment-corrected backscatter (in decibels)	32.4	72.3	74.4	92.4	99,500
Mississippi River at St. Paul, Minn.					
Streamflow, instantaneous (ft³/s)	5,670	22,800	22,000	52,500	731
Suspended-sediment concentration (mg/L)	13.0	139	119	333	19.0
Suspended sands (mg/L)	0.520	14.0	13.6	38.3	19.0
Suspended fines (mg/L)	12.5	125	107	316	19.0
Sediment-corrected backscatter (in decibels)	46.0	73.0	75.7	93.6	65,200
St. Croix River at Prescott, Wisc.					
Streamflow, instantaneous (ft³/s)	1,750	7,580	6,290	41,500	731
Suspended-sediment concentration (mg/L)	1.00	3.00	2.00	7.00	19.0
Suspended sands (mg/L)	0	0.225	0.140	0.810	19.0
Suspended fines (mg/L)	0.790	2.56	1.90	6.72	19.0

Table 2. Summary statistics for streamflow, suspended sediments, and acoustic surrogate model metrics.—Continued

[*n*, number of samples; Minn., Minnesota; ft³/s, cubic foot per second; mg/L, milligram per liter; St., Saint; Ft., Fort; Wisc., Wisconsin]

Constituent	Minimum	Mean	Median	Maximum	Total *n*
Mississippi River above Red Wing below Diamond Island, Minn.					
Streamflow, instantaneous (ft³/s)	12,800	33,300	31,500	74,600	731
Suspended-sediment concentration (mg/L)	20.0	49.6	46.0	89.0	20.0
Suspended sands (mg/L)	0.230	2.42	2.20	7.70	20.0
Suspended fines (mg/L)	19.0	47.1	44.4	87.2	20.0
Mississippi River (Lake Pepin) above Reads Landing, Minn.					
Streamflow, instantaneous (ft³/s)	11,100	32,500	30,500	69,700	731
Suspended-sediment concentration (mg/L)	3.00	5.30	5.00	10.0	20.0
Suspended sands (mg/L)	0	0.300	0.250	0.870	20.0
Suspended fines (mg/L)	2.13	5.00	4.63	9.50	20.0

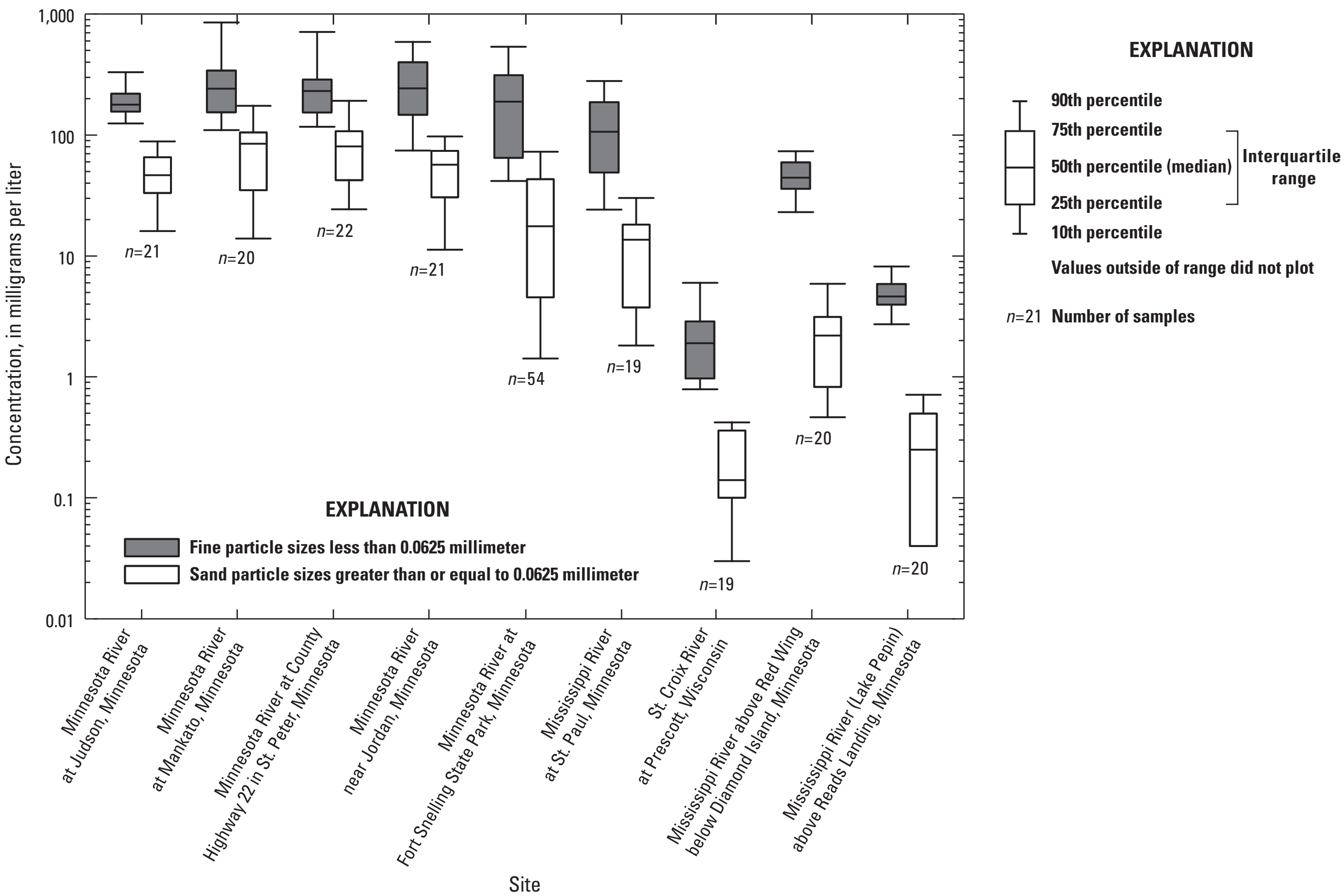

Figure 4. Measured suspended-sand and suspended-fines concentrations at nine sites in the Mississippi River Basin.

Table 3. Summary of linear regression models for selected sites in the Mississippi River Basin.

[*n*, number of samples; R^2, coefficient of determination; *p*-value, probability value of explanatory variable(s); Minn., Minnesota; --. no data; SSC, suspended-sediment concentration laboratory analysis method; SAC, sediment attenuation coefficient; *Q*, streamflow; <, less than; St., Saint; SCB, sediment corrected backscatter; Ft., Fort]

Station name	*n*	Linear regression model	Standard error	R^2	Average model standard percentage error	*p*-value
Acoustic model or acoustic and streamflow model						
Minnesota River at Judson, Minn.	--	--	--	--	--	--
Minnesota River at Mankato, Minn.	18	[a]$SSC=10^{-1.1+0.215\times SAC+0.825\times Q}\times 1.01$[b]	0.0777	0.94	18	<0.01
Minnesota River at County Highway 22 in St. Peter, Minn.	20	[a]$SSC=10^{0.135+0.405\times SAC+0.467\times Q}\times 1.02$[b]	0.0833	0.916	19.3	<0.01
Minnesota River near Jordan, Minn.	19	$SSC=10^{-4.76+0.0869\times SCB}\times 1.04$[b]	0.13	0.829	30.5	<0.01
Minnesota River at Ft. Snelling State Park, Minn.	49	$SSC=10^{-5.27+0.0976\times SCB}\times 1.07$[b]	0.165	0.84	38.8	<0.01
Mississippi River at St. Paul, Minn.	17	$SSC=10^{-8.94+0.14\times SCB}\times 1.07$[b]	0.166	0.803	39.2	<0.01
Streamflow model						
Minnesota River at Judson, Minn.	20	$SSC=10^{-0.598+0.774\times Q}\times 1.01$[b]	0.077	0.794	17.8	<0.01
Minnesota River at Mankato, Minn.	19	$\mathrm{SSC}=10^{-2.23+1.14\times Q}\times 1.06$[b]	0.148	0.781	34.8	<0.01
Minnesota River at County Highway 22 in Saint Peter, Minn.	21	$\mathrm{SSC}=10^{-1.37+0.931\times Q}\times 1.08$[b]	0.167	0.659	39.5	<0.01
Minnesota River near Jordan, Minn.	19	$\mathrm{SSC}=10^{-0.78+0.805\times Q}\times 1.18$[b]	0.248	0.379	60.3	<0.01
Minnesota River at Fort Snelling State Park, Minn.	49	$\mathrm{SSC}=10^{-2.46+1.18\times Q}\times 1.18$[b]	0.267	0.577	65.6	<0.01
Mississippi River at St. Paul, Minn.	17	$\mathrm{SSC}=10^{-3.58+1.28\times Q}\times 1.18$[b]	0.262	0.513	64	<0.01

[a]Multiple linear regression model.

[b]Bias correction factor or "smearing" estimator is used to correct retransformation bias of regression estimates (Duan, 1983).

seemed to indicate that a strong linear relation could be developed between acoustic data and SSC; however, a large rain event deposited a substantial amount of sediment around the streamgage and buried the ADVM, and the ADVM was repositioned higher in the water column on November 17, 2016. A significant linear relation could not be developed using samples collected in 2017 after the ADVM was repositioned. The mean SSC for this site based on physically collected samples was 49.6 mg/L (table 2).

Linear regression models for Prescott and Pepin were not significant and could not be used to accurately estimate SSCs. Because acoustic backscatter and streamflow data were not correlated to SSC, mean SSC and daily mean streamflows are reasonable to estimate SSLs at these sites. Increased water residence times and lower flow velocities upstream caused by natural reservoirs in Lake St. Croix and Lake Pepin, respectively, likely resulted in low suspended sediment in the water column and corresponding low acoustic return signals, which limited the ability to develop surrogate relations. Mean SSCs based on physically collected samples were 3.00 and 5.30 mg/L for the outlets of Lake St. Croix and Lake Pepin, respectively (table 2).

During model development, several samples collected after a storm event on August 17, 2017 (fig. 6), were outliers in regression models (Groten, 2018). The storm was in the upper parts of the Minnesota River Basin and did not affect sediment-rich tributaries (Blue Earth and Le Sueur Rivers) in the lower part of the basin; therefore, the localized nature of this storm may have caused sediment-transport patterns to differ in the study area.

Linear regression models were used to produce time series estimates of SSCs (fig. 7) at a 15-minute interval for six sites. Caution should be taken with interpretations of estimates of SSCs that extend beyond the site-specific calibration dataset (table 2). The estimated SSCs at Judson only used streamflow as an explanatory variable, so Judson's estimates of SSCs followed the 15-minute time series of streamflow pattern more closely. However, regression models for the other five sites (Mankato, St. Peter, Jordan, Snelling, and St. Paul) included SCB or SAC as one of the explanatory variables, and the resulting estimated SSCs did not follow the streamflow pattern.

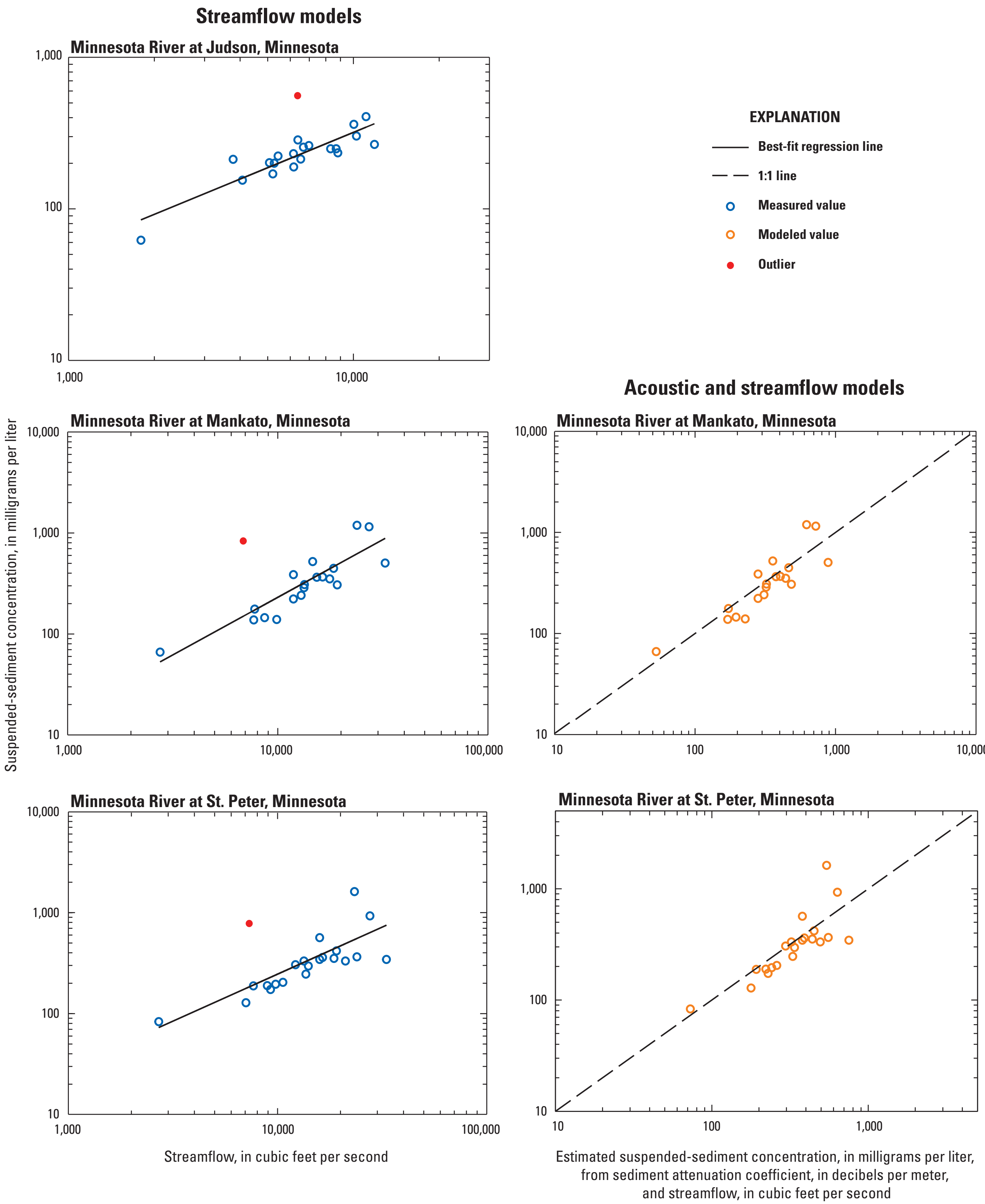

Figure 5. Relations among suspended-sediment concentrations, acoustic surrogate metrics, and streamflow at nine sites in the Mississippi River Basin.

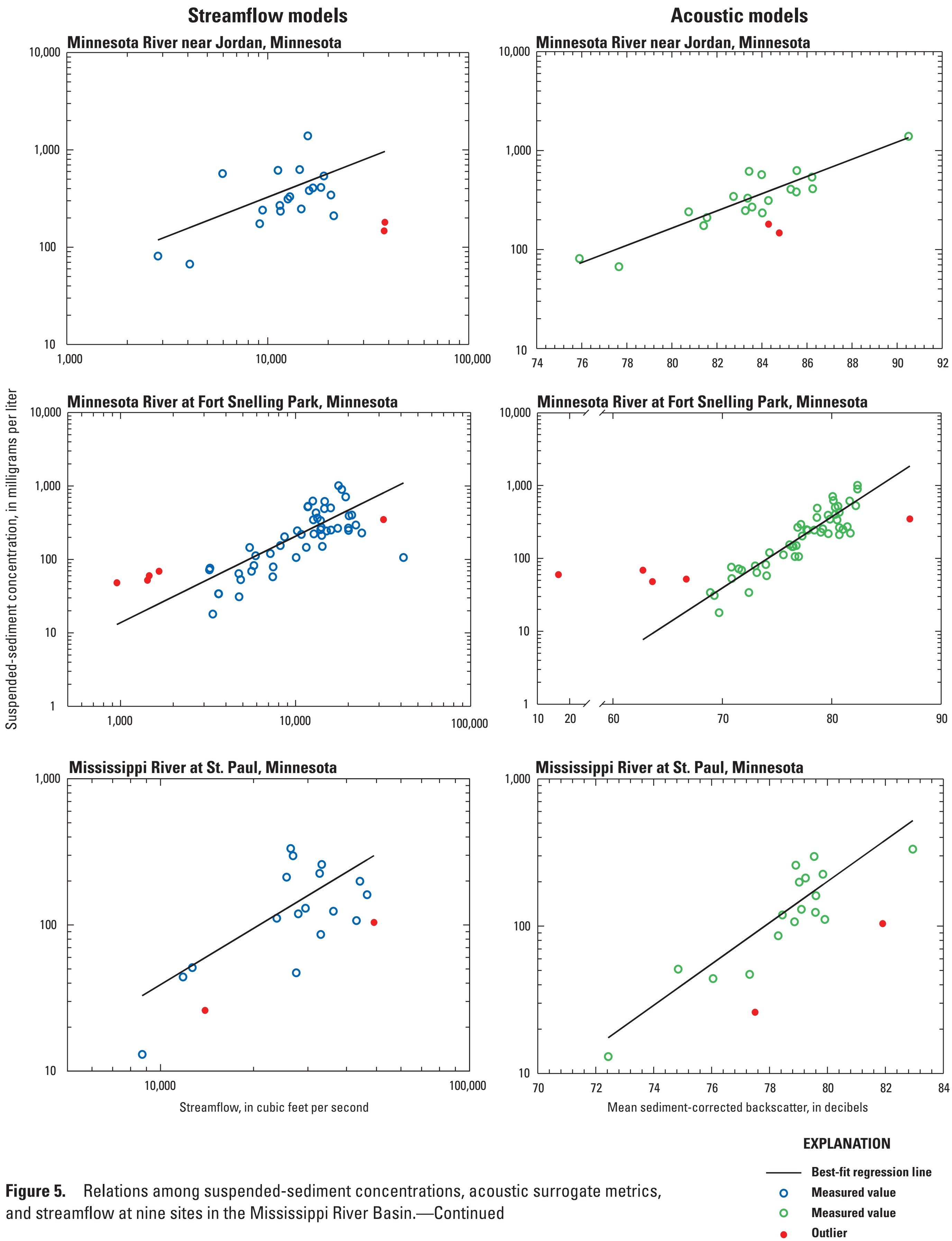

Figure 5. Relations among suspended-sediment concentrations, acoustic surrogate metrics, and streamflow at nine sites in the Mississippi River Basin.—Continued

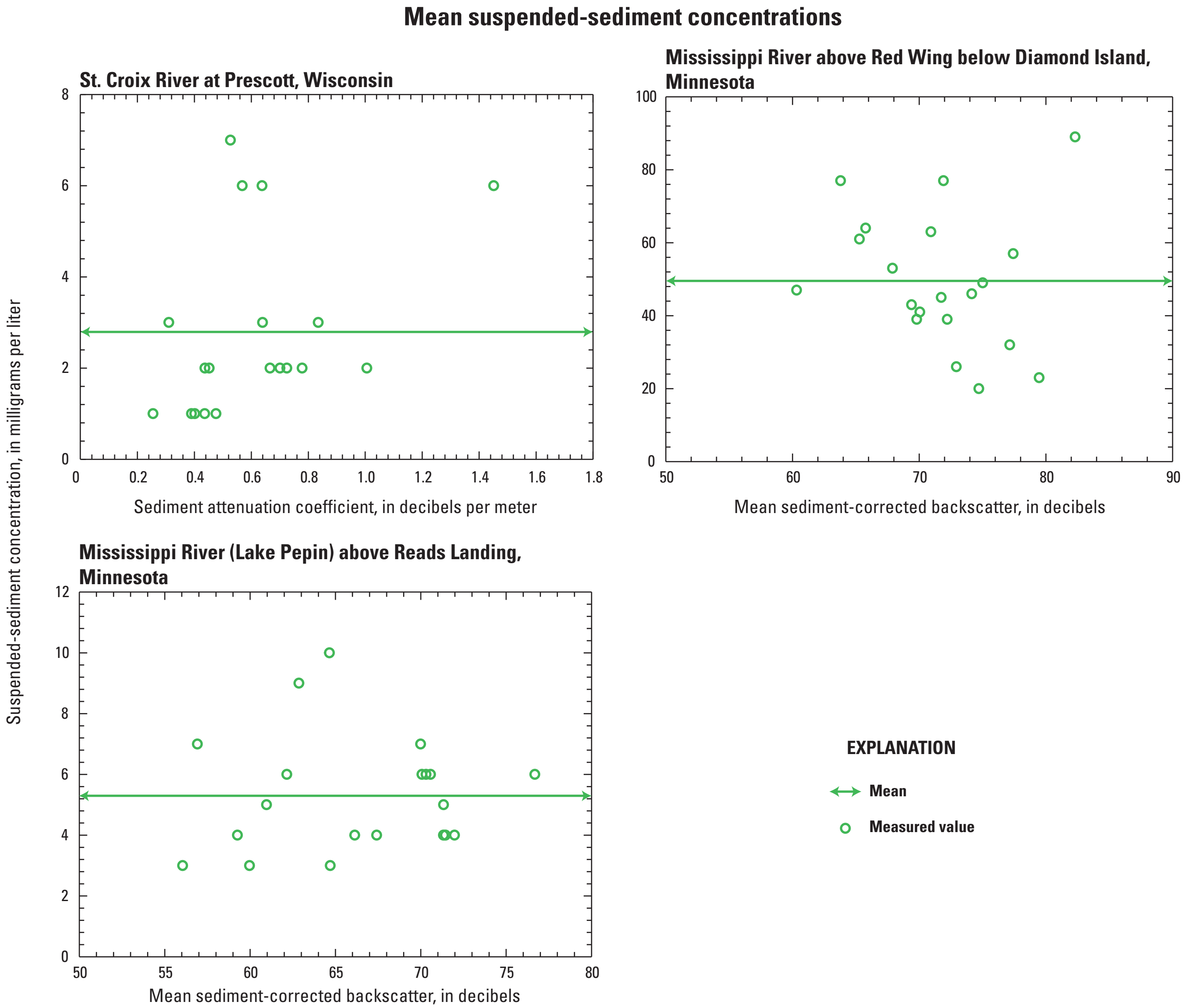

Figure 5. Relations among suspended-sediment concentrations, acoustic surrogate metrics, and streamflow at nine sites in the Mississippi River Basin.—Continued

Table 4. Estimated annual suspended-sediment loads for the lower Minnesota, St. Croix, and Mississippi Rivers.

[Minn., Minnesota; St., Saint; Ft., Fort; Wisc., Wisconsin]

Water year	Lower 90-percent prediction or confidence interval for suspended-sediment load, in tons per day	Suspended-sediment load, in tons per day	Upper 90-percent prediction or confidence interval for suspended-sediment load, in tons per day
Minnesota River at Judson, Minn.			
2016	577,718[a]	799,361[b]	1,106,289[a]
2017	1,133,249[a]	1,565,415[b]	2,162,627[a]
Minnesota River at Mankato, Minn.			
2016	1,491,665[a]	2,211,463[b]	3,328,612[a]
2017	1,626,969[a]	2,268,078[b]	3,162,194[a]
Minnesota River at County Highway 22 in St. Peter, Minn.			
2016	1,482,868[a]	2,281,159[b]	3,588,246[a]
2017	1,894,383[a]	2,745,851[b]	4,004,410[a]
Minnesota River near Jordan, Minn.			
2016	1,421,022[a]	2,604,897[b]	4,949,749[a]
2017	1,472,402[a]	2,541,865[b]	4,389,835[a]
Minnesota River at Ft. Snelling State Park, Minn.			
2015	295,917[a]	566,605[b]	1,086,033[a]
2016	1,389,583[a]	2,676,231[b]	5,165,522[a]
2017	1,545,841[a]	2,969,812[b]	5,711,388[a]
Mississippi River at St. Paul, Minn.			
2016	1,027,759[a]	2,083,186[b]	4,234,288[a]
2017	1,277,846[a]	2,783,848[b]	6,230,043[a]
St. Croix River at Prescott, Wisc.			
2016	16,781[c]	24,742[d]	29,230[c]
2017	13,649[c]	20,124[d]	23,775[c]
Mississippi River above Red Wing below Diamond Island, Minn.			
2016	1,388,773[c]	1,602,771[d]	1,816,769[c]
2017	1,435,699[c]	1,656,927[d]	1,878,156[c]
Mississippi River (Lake Pepin) above Reads Landing, Minn.			
2016	146,481[c]	168,371[d]	190,262[c]
2017	149,003[c]	171,271[d]	193,538[c]

[a]Upper or lower 90-percent prediction interval for suspended-sediment load by regression.

[b]Suspended-sediment load by regression.

[c]Upper or lower 90-percent confidence interval for suspended-sediment load by mean.

[d]Suspended-sediment load by mean.

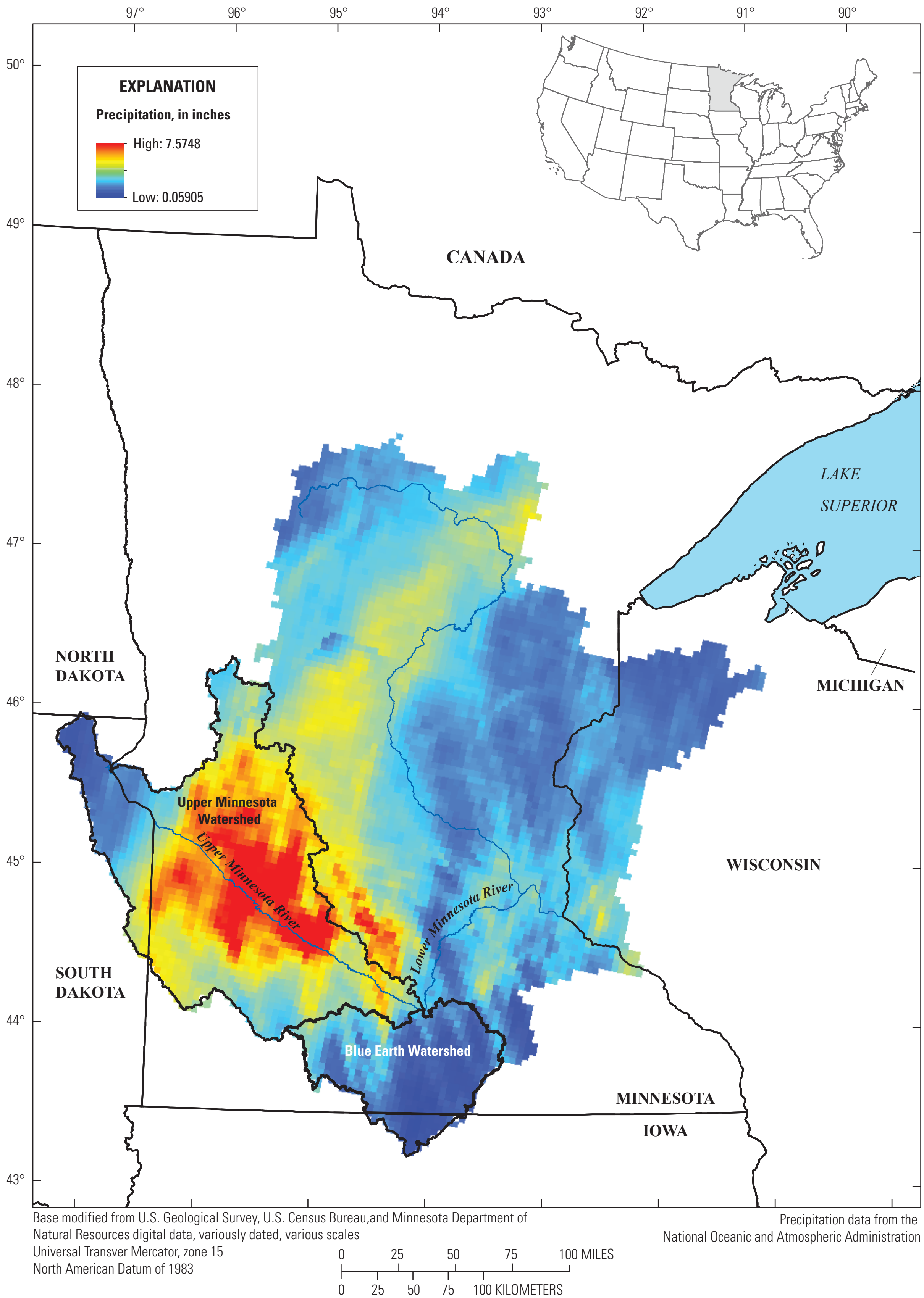

Figure 6. Precipitation totals in the Mississippi River Basin and upper Minnesota River and Blue Earth River subbasins on August 17, 2017.

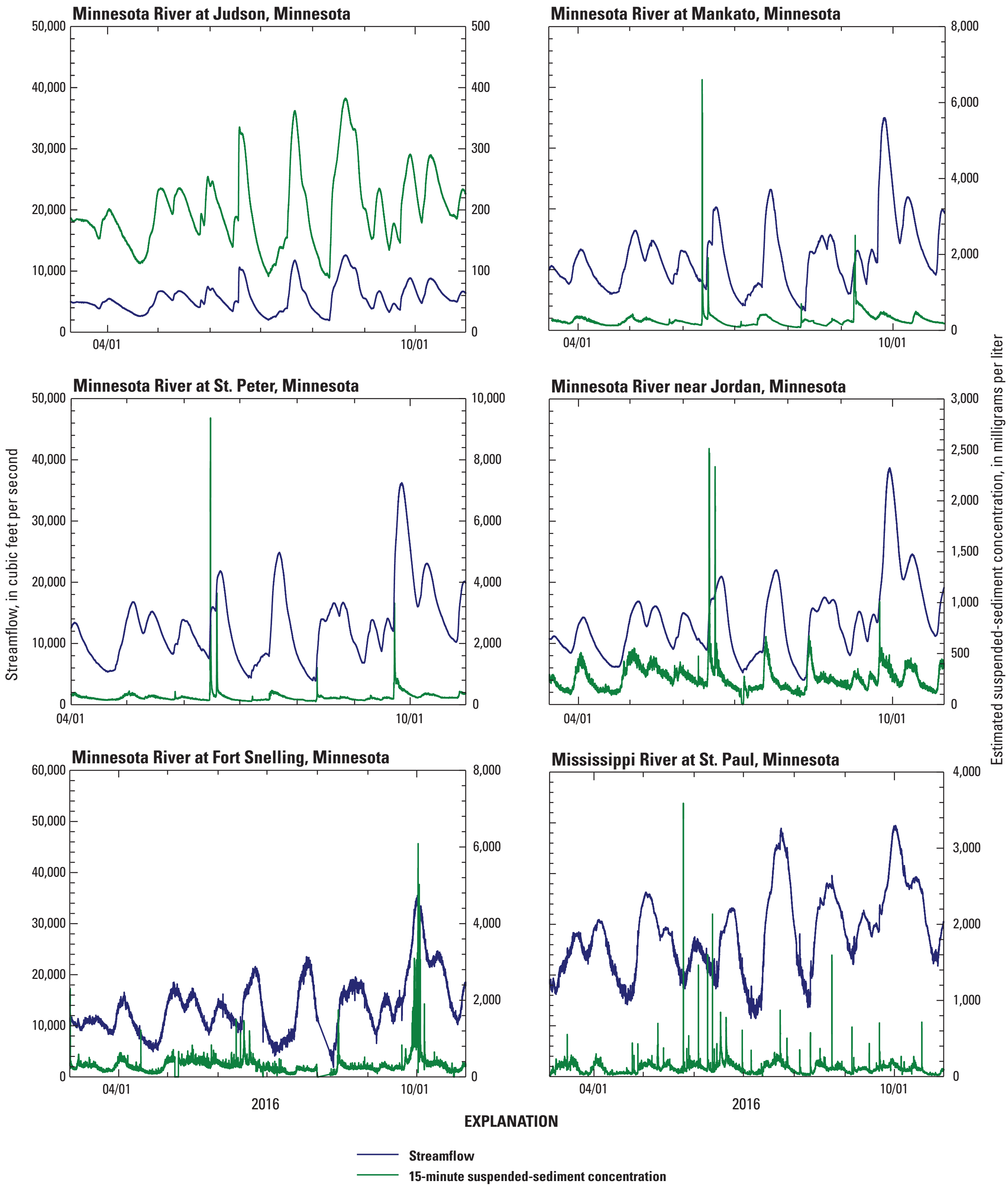

Figure 7. Streamflow and estimated 15-minute suspended-sediment concentrations during the open-water season (March through October) at six sites in the Mississippi River Basin.

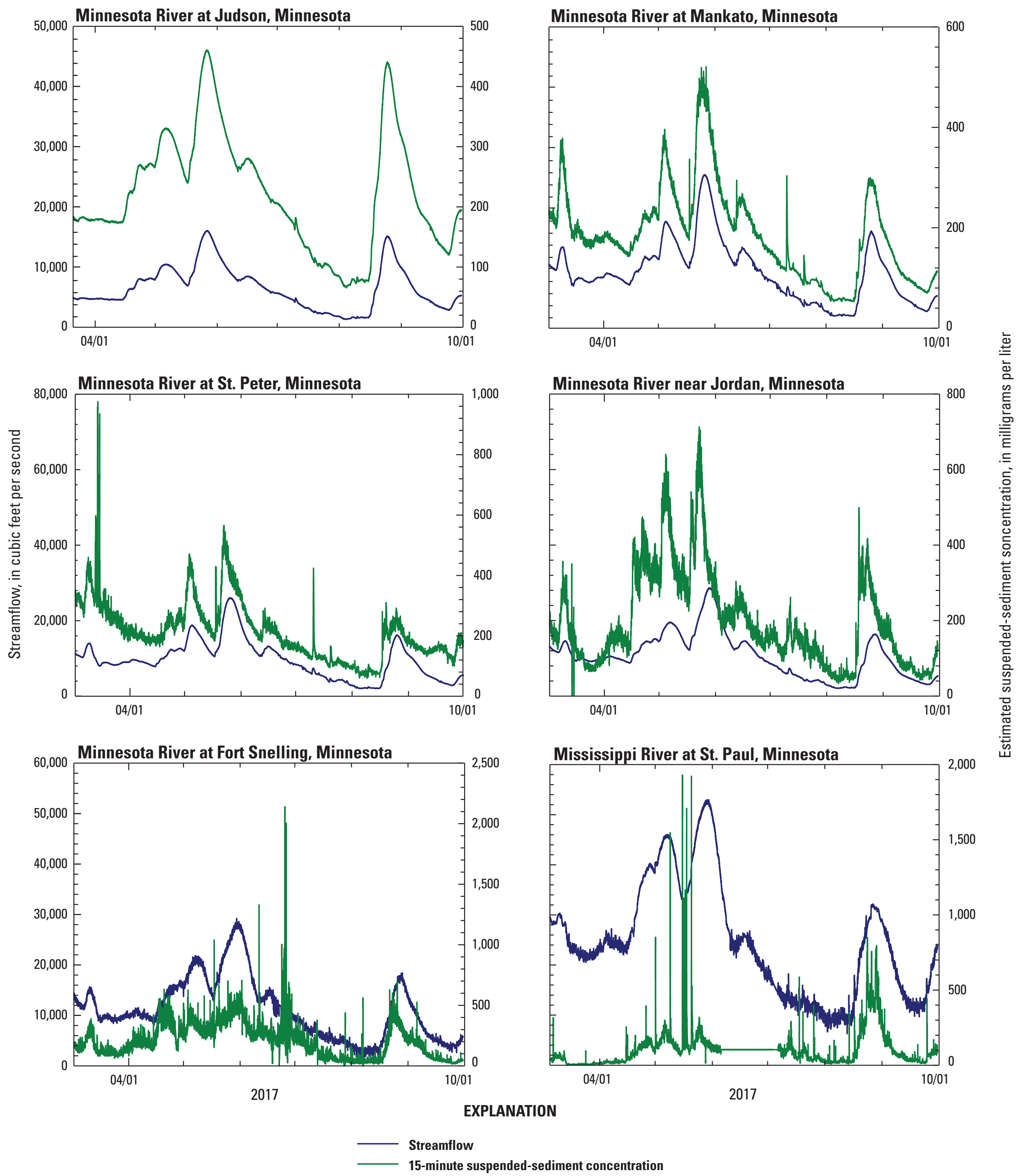

Figure 7. Streamflow and estimated 15-minute suspended-sediment concentrations during the open-water season (March through October) at six sites in the Mississippi River Basin.—Continued

The inconsistency of SSC-streamflow relations can be illustrated using examples from the WY 2016. At Mankato, St. Peter, and Jordan, the highest estimated SSC was in mid-June 2016 even though a greater streamflow peak was at the end of September 2016; furthermore, both estimated SSC peaks were before the corresponding streamflow peaks at all 3 sites for these 2 events in 2016. However, the estimated SSCs seemed to follow the streamflow pattern more closely in 2017 than in 2016 at Mankato and St. Peter; whereas, Jordan's estimated SSCs diverged from the streamflow pattern by peaking before streamflow more than the other two sites in 2017. The estimated SSC at Ft. Snelling and St. Paul more closely matched the streamflow pattern except for occasional spikes that likely resulted from tow boats and barge traffic causing resuspension of bottom sediment.

Suspended-Sediment Loads

Time series of daily estimated SSLs and streamflow are shown in figure 8. Estimated daily SSLs were highest from March to November. Generally, there was more SSL in the spring because of higher precipitation amounts; however, daily SSL peaked in fall of 2016 at many sites (fig. 8) because of a substantial rainfall event in late September.

Comparing annual estimated SSLs (fig. 9) helped to determine differences among sites to determine potential sediment sources and sinks (fig. 10). The 15-minute estimates of SSC and daily SSL estimates highlighted the variable nature of suspended sediment (figs. 7 and 8) because of the resolution of the data; however, annual SSLs gave a coarser resolution of annual suspended-sediment budgets. The annual SSLs (fig. 9) indicate the variability between the 2 measured years. Annual SSLs are greater in 2017 than in 2016 at all sites except Jordan and Prescott.

Possible sediment sources (brown triangles) and sinks (blue triangles) are illustrated in figure 10 by the longitudinal changes in annual SSLs among sites along the Minnesota and Mississippi Rivers. The height of the triangle represents the amount of suspended sediment gained or lost between sampling sites. There were substantial differences in SSLs between sites when a major tributary joined the river between them; for example, the SSL was larger at Mankato than Judson likely because of the elevated SSL from the Blue Earth River. Also, the decrease in SSL from Ft. Snelling to St. Paul likely is a result of the upper Mississippi River, which is less sediment laden than the Minnesota River, diluting the SSL at St. Paul. The second most substantial decrease in SSL was a 23- (WY 2016) and 40- (WY 2017) percent decrease from St. Paul to Red Wing. The most substantial decrease in SSL was a 90-percent decrease from Red Wing to Lake Pepin. These sediment sinks from St. Paul to the outlet of Lake Pepin likely are linked to storage in the pools upstream from Locks and Dams Numbers 2 and 3 and Lake Pepin, respectively.

Comparing the sediment yield (annual load divided by basin area) provides insight on the relative measure of erosion rates, sediment contributions from tributaries, and amount of storage between sites (fig. 11). Longitudinal patterns in sediment yields among the nine sites were similar to the annual SSLs (fig. 8). The lower Minnesota River outlet yielded 70 and 50 times more sediment than the outlets of Lake St. Croix and Lake Pepin, respectively (fig. 11). Also, the highest sediment yield was at St. Peter in 2017 (182 tons per year per square mile [(tons/yr)/mi^2]). In contrast, the lowest sediment yield was at Prescott in 2017 (2.6 (tons/yr)/mi^2). In WYs 2016 and 2017, the St. Croix River contributed little SSL to the Mississippi River, whereas the Minnesota River contributed a substantial part of the total SSL to the Mississippi River.

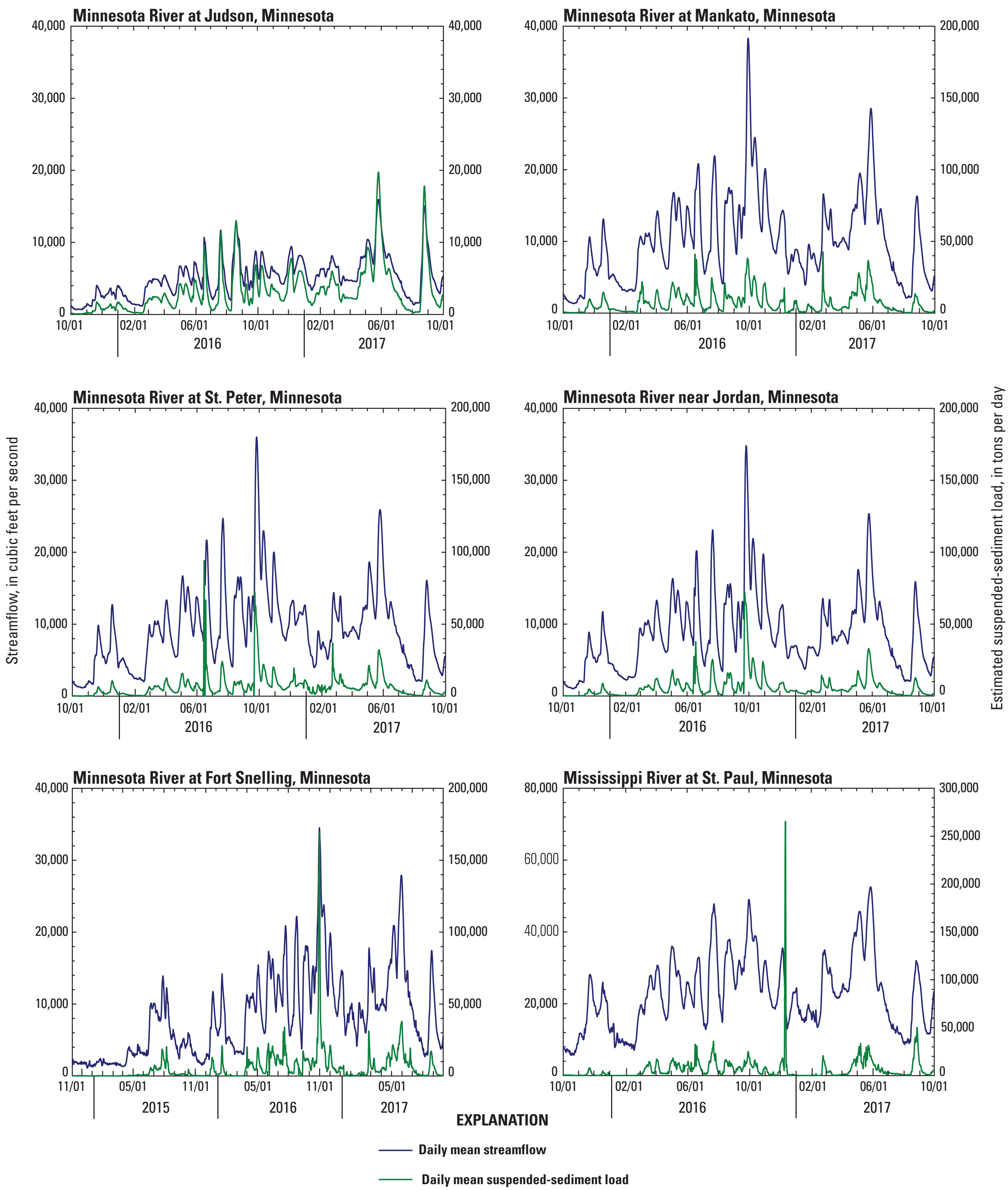

Figure 8. Daily mean streamflow and daily estimated suspended-sediment loads at nine sites in the Mississippi River Basin.

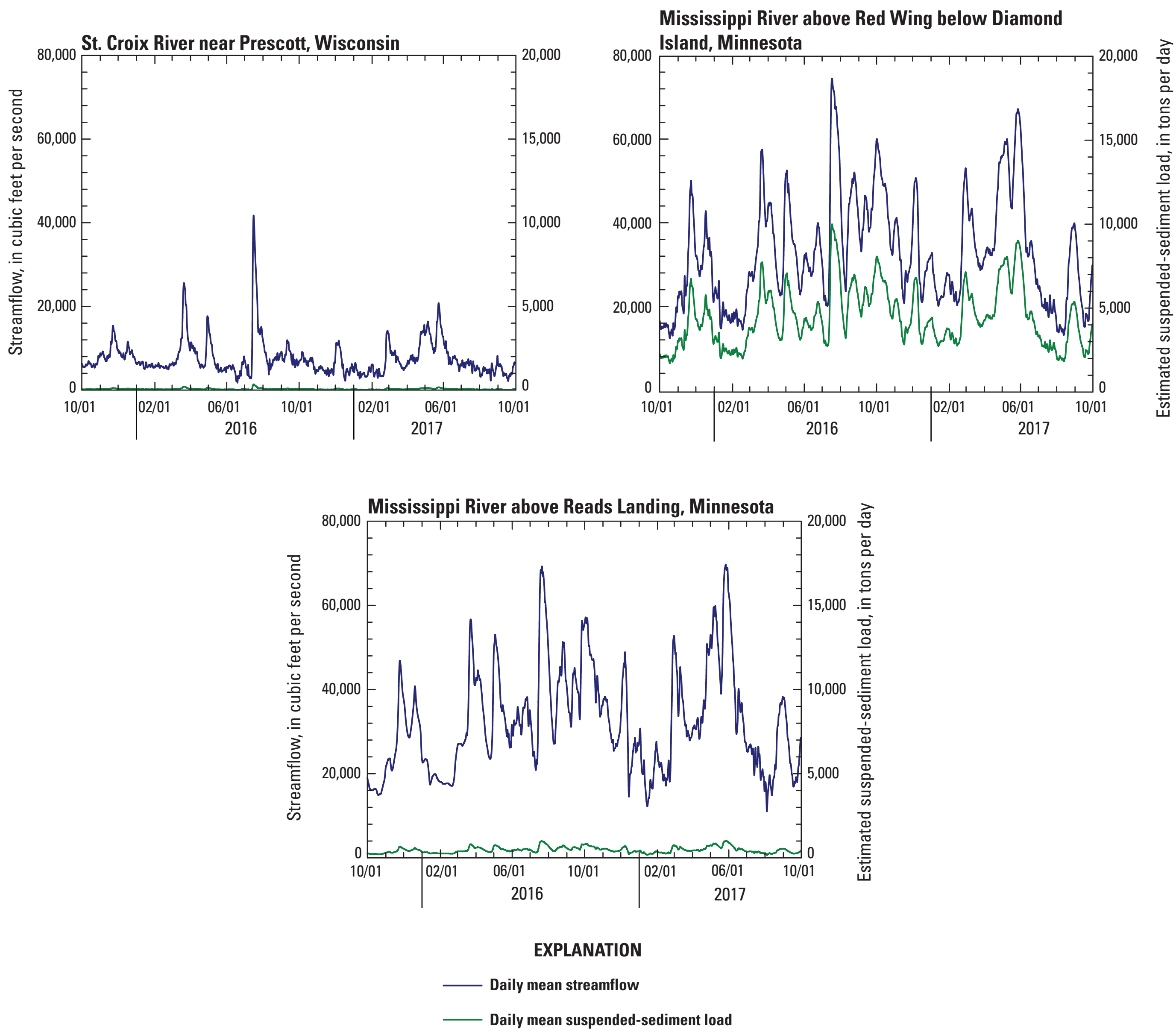

Figure 8. Daily mean streamflow and daily estimated suspended-sediment loads at nine sites in the Mississippi River Basin.—Continued

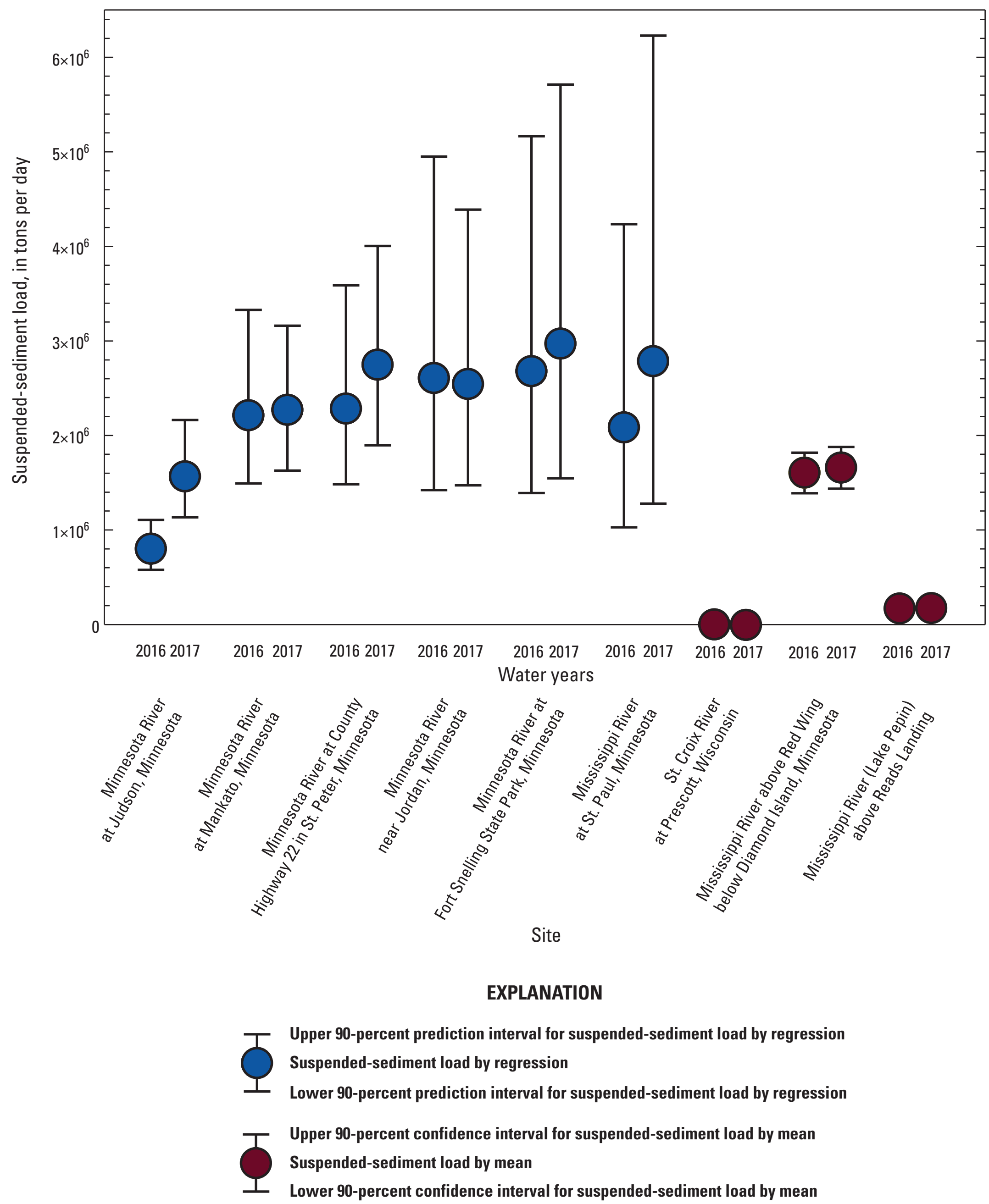

Figure 9. Estimated annual suspended-sediment loads at nine sites in the Mississippi River Basin, water years 2016 through 2017.

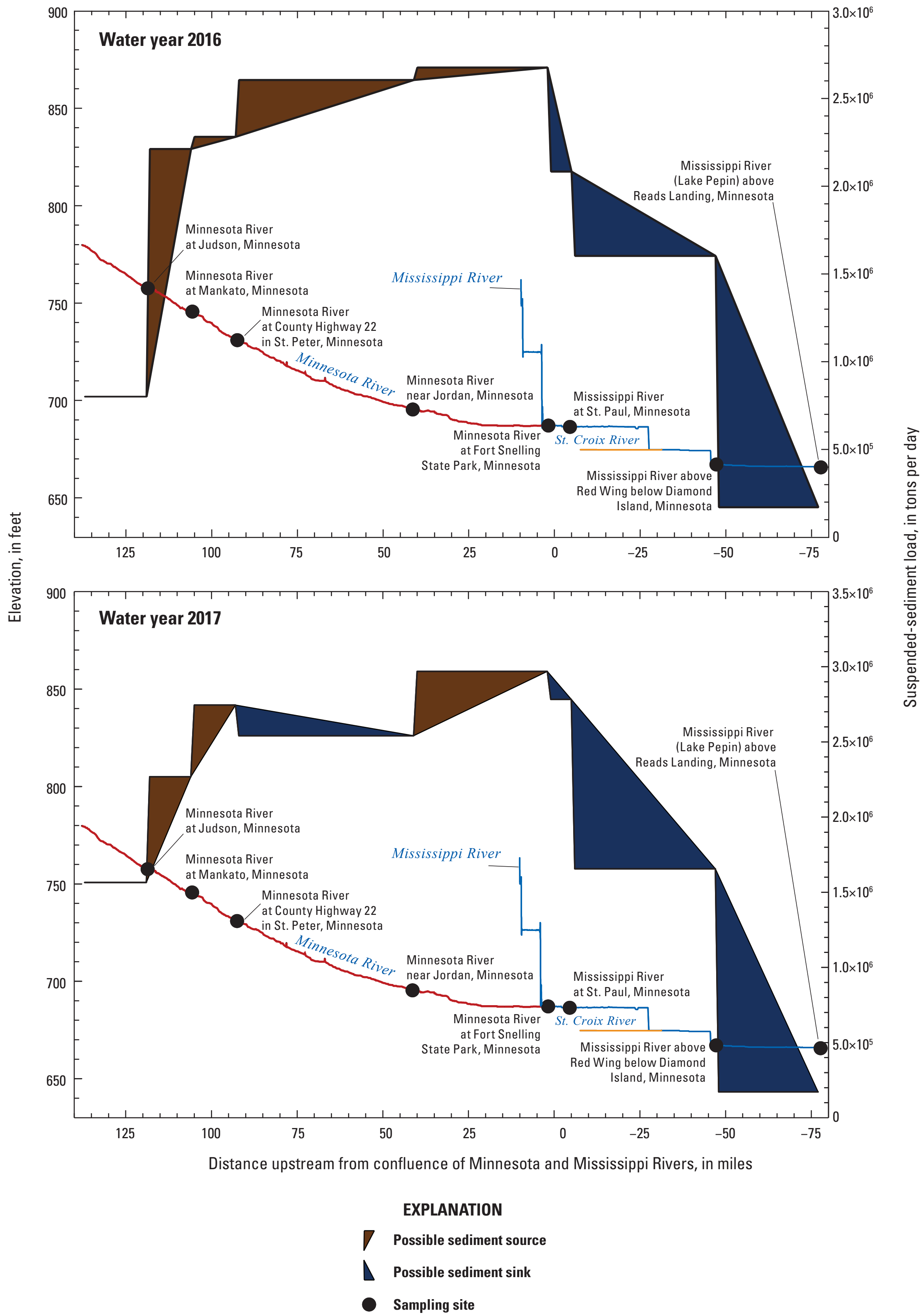

Figure 10. Possible sediment sources and sinks with stream gradients along the Minnesota and Mississippi Rivers at eight sites, water years 2016 and 2017.

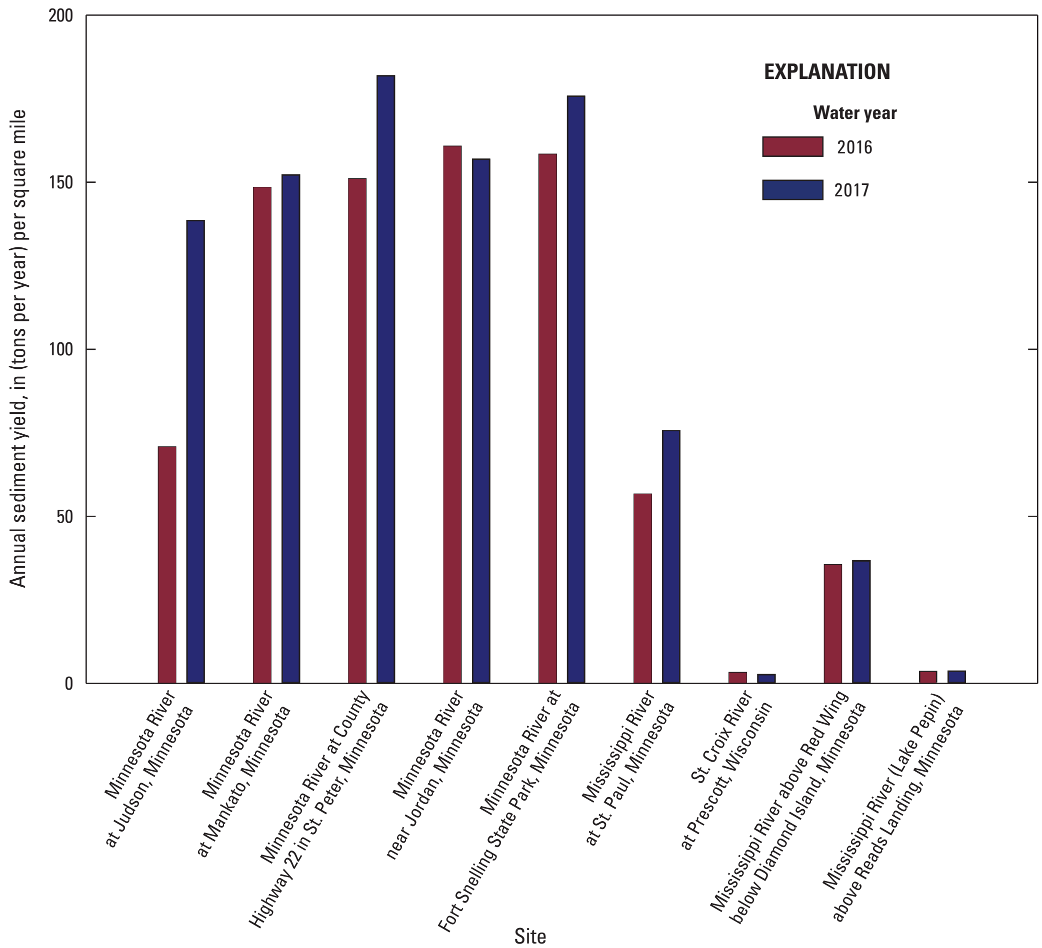

Figure 11. Annual sediment yield at nine sites in the Mississippi River Basin, water years 2016 and 2017.

Summary and Conclusions

Sediment-laden rivers in Minnesota cost river users millions of dollars each year (U.S. Army Corps of Engineers, 2006; Minnesota Pollution Control Agency, 2009a). Excessive sediment in rivers degrades water quality, is deleterious to aquatic habitat, leads to increased navigation channel dredging, reduces recreational opportunities, and can transport harmful contaminants. Sediment loads in the Minnesota River have been a concern among Minnesota State agencies. Most of the sediment loading in the Mississippi River between the Minneapolis-St. Paul (also referred to as “Twin Cities”) metropolitan area and Lake Pepin originates in the Minnesota River; furthermore, most of the sediment being deposited into Lake Pepin originates from the Minnesota River Basin. Lake Pepin is an important recreational and commercial resource, and concerns over its fill rate have led Minnesota State agencies to adopt a Sediment-Reduction Strategy.

From 2015 through 2017, the U.S. Geological Survey (USGS), with funding from the Environment and Natural Resources Trust Fund and in cooperation with the U.S. Army Corps of Engineers, Lower Minnesota River Watershed District, Minnesota Pollution Control Agency, and Minnesota Department of Natural Resources, installed and operated side-looking acoustic Doppler velocity meters (ADVMs). These ADVMs were used to estimate continuous, real-time suspended-sediment concentrations (SSCs) at five streamgages in the Minnesota and Mississippi Rivers upstream from Lake Pepin. Acoustic backscatter data from ADVMs were correlated to physically collected suspended-sediment samples. This information is intended to help State agencies monitor progress toward sediment-reduction goals and effectiveness of implemented best management practices and other restoration activities.

This report documents findings based on suspended-sediment data collected at 5 sites on the lower Minnesota River (Minnesota River at Judson, Minnesota [USGS station 05317500; hereafter referred to as “Judson”]; Minnesota River at Mankato, Minn. [USGS station 05325000; hereafter referred to as “Mankato”]; Minnesota River at County Highway 22 in St. Peter, Minn. [USGS station 05325300; hereafter referred to as “St. Peter”]; Minnesota River near Jordan, Minn. [USGS station 05330000; hereafter referred to as “Jordan”]; and Minnesota River at Fort Snelling State Park, Minn. [USGS station 05330920; hereafter referred to as “Ft. Snelling”]), 1 site on the St. Croix River (St. Croix River at Prescott, Wisconsin [USGS station 05344490; hereafter referred to as

"Prescott"]), and 3 sites on the Mississippi River (Mississippi River at St. Paul, Minn. [USGS station 05331000; hereafter referred to as "St. Paul"]; Mississippi River above Red Wing below Diamond Island, Minn. [USGS station 05355235; hereafter referred to as "Red Wing"]; and Mississippi River [Lake Pepin] above Reads Landing, Minn. [USGS station 05355341; hereafter referred to as "Pepin"]) to improve the understanding of fluvial suspended-sediment concentrations and suspended-sediment loads (SSLs). Samples were collected for suspended sediment at Ft. Snelling during water years 2012 through 2017, and samples were collected at the rest of the eight sites during water years 2016 through 2017.

Suspended-sand concentrations among study sites related to stream gradients and indicated that higher gradients may provide the velocities needed to keep larger sand particles in suspension. Generally, suspended-sand and -fines concentrations decreased moving downstream in the Minnesota and Mississippi Rivers. The observed decreases corresponded to decreases in stream gradients and to proximity of pools and lakes.

The Mississippi River upstream from the confluence with the Minnesota River and the St. Croix River upstream from the Mississippi River generally are low in SSCs. In addition, the confluences of the Minnesota and Mississippi Rivers and the St. Croix and Mississippi Rivers substantially increase streamflow downstream. The combination of low SSCs and high streamflows from the upper Mississippi and St. Croix Rivers helped dilute the high SSCs entering the Mississippi River from the Minnesota River and Mississippi River upstream from the St. Croix River, respectively. Decreases in stream gradients corresponded to decreases in SSCs in the Mississippi River from St. Paul to Red Wing and from Red Wing to the outlet of Lake Pepin. Decreases in stream gradients and SSCs likely relate to the presence of locks, dams, and lakes between sampling sites.

Results from statistically significant linear relations indicated that acoustic backscatter data were useful for improving estimates of SSCs for five of the nine study sites: the Minnesota River at (1) Mankato, (2) St. Peter, (3) Jordan, and (4) Ft. Snelling and the Mississippi River at (5) St. Paul. A significant linear relation could not be developed for Judson because of data quality issues caused by the ADVM; however, the linear relation between streamflow and SSC was significant and useful in estimating annual SSLs. For sites that used acoustic backscatter data as an explanatory variable in the linear regression model, the linear relations consistently explained more variability than streamflow alone. Significant linear relations could not be developed to estimate SSC from acoustic backscatter data or streamflow for Prescott, Red Wing, or Pepin, presumably because of consistently low SSCs regardless of acoustic backscatter or streamflow magnitudes.

Relations between streamflows and physically collected sediment samples traditionally have been used to estimated suspended-sediment loads; however, continuous estimated SSC data illustrated that changes in SSCs often did not track with changes in streamflows at study sites. Furthermore, time series comparisons illustrated how duration, time, and extent of SSCs can change from site to site and from year to year. Daily SSLs were highest at all sites from March through November, and results indicated a peak sediment loading event at many of the sites in the fall of 2016. Finally, estimated SSCs peaked before observed streamflow peaks at many sites.

Comparing annual SSLs helped to determine possible sediment sources and sinks. Substantial differences were observed between sites that have tributaries entering the river between them; for example, Mankato had higher SSLs than Judson because of the Blue Earth River flowing into the Minnesota River upstream from the Mankato site. Also, the decrease in SSLs from Ft. Snelling to St. Paul was due to the clearer upper Mississippi River water mixing with and diluting the higher SSL at St. Paul and backwater from the Mississippi River. The second largest decrease in SSL was from St. Paul to Red Wing, and then the largest difference from Red Wing to Lake Pepin illustrates the largest sediment sink with a 90-percent decrease. These sinks along the Mississippi River are likely linked to storage in pools along the lock and dam system and Lake Pepin. The sediment yield patterns among the nine sites were similar to the annual SSLs. The outlet of the Minnesota River contributed more SSL than the outlets of Lake St. Croix and Lake Pepin.

This study provides data from which to characterize suspended sediment across the lower Minnesota River, St. Croix River, and Mississippi River Basins. The analyses discussed 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, restoration, and best management practices that may affect sediment dynamics in the lower Minnesota River, St. Croix River, and Mississippi River Basins.

References Cited

American Society for Testing and Materials, 2000, Standard test methods for determining sediment concentration in water samples: West Conshohocken, Pa., American Society for Testing and Materials International, D3977–97, v. 11.02, Water (II), p. 395–400.

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 & Technology, v. 45, no. 20, p. 8804–8810. [Also available at https://doi.org/10.1021/es2019109.]

Blumentritt, D.J., Wright, H.E., Jr., and Stefanova, V., 2009, Formation and early history of Lakes Pepin and St. Croix of the upper Mississippi River: Journal of Paleolimnology, v. 41, no. 4, p. 545–562. [Also available at https://doi.org/10.1007/s10933-008-9291-6.]

Community Collaborative Rain, Hail and Snow Network, 2018, Minnesota Daily Precipitation Reports: Community Collaborative Rain, Hail and Snow Network web page, accessed June 14, 2018, at https://www.cocorahs.org/View-Data/StateDailyPrecipReports.aspx?state=MN.

Crawford, C.G., 1991, Estimation of suspended-sediment rating curves and mean suspended-sediment loads: Journal of Hydrology, v. 129, no. 1–4, p. 331–348. [Also available at https://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 https://doi.org/10.3133/ofr20051087.]

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., accessed February 26, 2018 at https://doi.org/10.3133/ofr20151177.

Duan, N., 1983, Smearing estimate—A nonparametric retransformation method: Journal of the American Statistical Association, v. 78, no. 383, p. 605–610. [Also available at https://doi.org/10.2307/2288126.]

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 https://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 https://pubs.er.usgs.gov/publication/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, no. 4, p. 563–588. [Also available at https://doi.org/10.1007/s10933-008-9292-5.]

Gray, J.R., Glysson, G.D., Turcios, L.M., and Schwarz, G.E., 2000, Comparability of suspended-sediment concentration and total suspended solids data: U.S. Geological Survey Water-Resources Investigations Report 00–4191, 14 p. [Also available at https://doi.org/10.3133/wri004191.]

Groten, J.T., 2018, Suspended-sediment concentrations, acoustic data, and linear regression models for the Lower Minnesota River, Mississippi River, and Lake Pepin, 2015–2017: U.S. Geological Survey data release, https://doi.org/10.5066/F7542MXV.

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., accessed February 26, 2018 at https://doi.org/10.3133/sir20165174.

Groten, J.T., and Johnson, G.D., 2018, Comparability of river suspended-sediment sampling and laboratory analysis methods: U.S. Geological Survey Scientific Investigations Report 2018–5023, 23 p., accessed July 13, 2018, at https://pubs.er.usgs.gov/publication/sir20185023.

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. [Also available at https://pubs.usgs.gov/twri/twri5c1/.]

Heiskary, S., and Vavricka, M., 1993, Mississippi River phosphorus study, section 3, description of the study area—Lake Pepin water quality, 1976–1991: St. Paul, Minn., Minnesota Pollution Control Agency, Water Quality Division, 103 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.

Horowitz, A.J., 2003, An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations: Hydrological Processes, v. 17, no. 17, p. 3387–3409. [Also available at https://doi.org/10.1002/hyp.1299.]

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

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 https://doi.org/10.3133/tm3c5.

Larson, C.E., Johnson, D.K., Flood, R.J., Meyer, M.L., O’Dea, T.J., and Schellhaus, S.M., 2002, Lake Pepin phosphorus study, 1994–1998—Effects of phosphorus loads on water quality of the upper Mississippi River, Lock and Dam No. 1 through Lake Pepin: St. Paul, Minn., Metropolitan Council Environmental Services, 84 p.

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. [Also available at https://doi.org/10.13031/2013.42686.]

Lenz, B.N., Robertson, D.M., Fallon, J.D., and Ferrin, R., 2001, Nutrient and suspended-sediment concentrations and loads and benthic-invertebrate data for tributaries to the St. Croix River, Wisconsin and Minnesota, 1997–99: U.S. Geological Survey Water-Resources Investigations Report 2001–4162, 57 p. [Also available at https://doi.org/10.3133/wri014162.]

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 https://pubs.usgs.gov/tm/3a23/.]

Minnesota Department of Natural Resources, 2018a, Water year precipitation maps: Minnesota Department of Natural Resources digital data, accessed July 16, 2018, at https://www.dnr.state.mn.us/climate/historical/water_year_maps.html.

Minnesota Department of Natural Resources, 2018b, Cooperative stream gaging: Minnesota Department of Natural Resources digital data, accessed May 25, 2018, at https://www.dnr.state.mn.us/waters/csg/index.html.

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

Minnesota Pollution Control Agency, 2009b, Identifying sediment sources in the Minnesota River Basin: Minnesota Pollution Control Agency wq–b3–43, 18 p., accessed July 25, 2018, at https://www.pca.state.mn.us/sites/default/files/wq-b3-43.pdf.

Minnesota Pollution Control Agency, 2011, An integrated sediment budget for the Le Sueur River Basin: Minnesota Pollution Control Agency wq–iw7–29o, 128 p., accessed May 12, 2016, at https://www.pca.state.mn.us/sites/default/files/wq-iw7-29o.pdf.

Minnesota Pollution Control Agency, 2015, Sediment reduction strategy for the Minnesota River Basin and South Metro Mississippi River: Minnesota Pollution Control Agency wq–iw4–02, 67 p., accessed May 12, 2016, at https://www.pca.state.mn.us/sites/default/files/wq-iw4-02.pdf.

MnTOPO, 2018, Line elevation: Department of Natural Resources digital data, accessed April 3, 2018, at http://arcgis.dnr.state.mn.us/maps/mntopo/.

Niemela, S., and Feist, M., 2000, Index of biotic integrity (IBI) guidance for coolwater rivers and streams of the St. Croix River basin in Minnesota: St. Paul, Minn., Minnesota Pollution Control Agency, Biological Monitoring Program, 47 p.

Payne, G.A., Lee, K.E., Montz, G.R., Talmage, P.J., Hirsch, J.K., and Larson, J.D., 2002, Water quality and aquatic-community characteristics of selected reaches of the St. Croix River, Minnesota and Wisconsin, 2000: U.S. Geological Survey Water-Resources Investigations Report 2002–4147, 43 p. [Also available at https://doi.org/10.3133/wri024147.]

Robertson, D.M., and Lenz, B.N., 2002, Response of the St. Croix River pools, Wisconsin and Minnesota, to various phosphorus-loading scenarios: U.S. Geological Survey Water-Resources Investigations Report 2002–4181, 36 p. [Also available at https://doi.org/10.3133/wri024181.]

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, no. 4, p. 1951–1961. [Also available at https://doi.org/10.1002/hyp.9738.]

Stark, J.R., Andrews, W.J., Fallon, J.D., Fong, A.L., Goldstein, R.M., Hanson, P.E., Kroening, S.E., and Lee, K.E., 1996, Water-quality assessment of part of the upper Mississippi River basin, Minnesota and Wisconsin, environmental setting and study design: U.S. Geological Survey Water-Resources Investigations Report 96–4098, 62 p., accessed July 13, 2018, at https://doi.org/10.3133/wri964098.

U.S. Army Corps of Engineers, 2001, Channel Maintenance Management Plan, Upper Mississippi River Navigation System, St. Paul District: U.S. Army Corps of Engineers, St. Paul District, 28 p., 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, 143 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/environmental assessment, 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. Army Corps of Engineers, 2011, Upper Mississippi River Land Use Allocation Plan: U.S. Army Corps of Engineers, St. Paul District, 86 p., accessed July 13, 2018, at http://www.mvp.usace.army.mil/Portals/57/docs/Recreation/UpperMissLandUse/UMRL_Allocation_Plan.pdf.

U.S. Geological Survey, 2018, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed July 16, 2018, at https://doi.org/10.5066/F7P55KJN.

Walling, D.E., 1977, Limitations of the rating curve technique for estimating suspended sediment loads, with particular reference to British rivers: IAHS Publication, 122 p. [Also available at http://hydrologie.org/redbooks/a122/iahs_122_0034.pdf.]

For more information about this publication, contact:
Director, USGS Upper Midwest Water Science Center
2280 Woodale Drive
Mounds View, MN 55112
763–783–3100

For additional information, visit: https://mn.water.usgs.gov

Publishing support provided by the
Rolla Publishing Service Center

Groten and others—**Acoustic Doppler Velocity Meters to Estimate Suspended Sediment along the Lower Minnesota and Mississippi Rivers**—SIR 2018–5165

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20185165