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Suspended-Sediment Concentrations, Loads, Total Suspended Solids, Turbidity, and Particle-Size Fractions for Selected Rivers in Minnesota, 2007 through 2011

Scientific Investigations Report 2013–5205

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

Cover. View of the Knife River near State Route 61 at Knife River, Minnesota, June 20, 2012. Photograph by Brett Savage, U.S. Geological Survey.

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SALLY JEWELL, Secretary

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

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

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Suggested citation:
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., *http://dx.doi.org/10.3133/sir20135205*.

ISSN 2328-0328 (online)

Contents

Figures

Tables

Appendix Table

Conversion Factors

Inch/Pound to SI

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)
	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	megagram (Mg)
ton, long (2,240 lb)	1.016	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per year per square mile [(ton/yr)/mi^2]	0.3503	megagram per year per square kilometer [(Mg/yr)/km^2]
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year

SI to Inch/Pound (used for particle sizes and sampling methods)

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

Elevation, as used in this report, refers to distance above the vertical datum.

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

Water year is defined as the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends.

Abbreviations

AIC	Akaike's Information Criteria
BCF	bias-correction factor
HUC	Hydrologic Unit Code
log10	base-10 logarithm
MDNR	Minnesota Department of Natural Resources
MLR	multiple linear regression
MPCA	Minnesota Pollution Control Agency
NTRU	nephelometric turbidity ratio unit
R^2	coefficient of determination
SLR	simple linear regression
SSC	suspended-sediment concentration
TMDL	total maximum daily load
TSS	total suspended solids
USGS	U.S. Geological Survey
<	less than
®	registered trademark

Acknowledgments

This report presents a compilation of information supplied by many agencies and individuals. The authors would like to thank the Minnesota Pollution Control Agency, Wild Rice Watershed District, and the Rice Creek Watershed District for their assistance with this study. Jerry Bents, engineering consultant for the Wild Rice Watershed District from Houston Engineering, and Matt Kocian from the Rice Creek Watershed District provided historical documents and offered valuable insight.

Dave Lorenz, Kristen Kieta, Joel Groten, Domenic Murino, and Lance Ostiguy of the U.S. Geological Survey are acknowledged for assistance with office and field aspects of the study. Mark Brigham, Christiana Czuba, Guy Foster, and Janet Carter of the U.S. Geological Survey are acknowledged for their technical reviews of the report.

Suspended-Sediment Concentrations, Loads, Total Suspended Solids, Turbidity, and Particle-Size Fractions for Selected Rivers in Minnesota, 2007 through 2011

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Abstract

Sediment-laden rivers and streams pose substantial environmental and economic challenges. Excessive sediment transport in rivers causes problems for flood control, soil conservation, irrigation, aquatic health, and navigation, and transports harmful contaminants like organic chemicals and eutrophication-causing nutrients. In Minnesota, more than 5,800 miles of streams are identified as impaired by the Minnesota Pollution Control Agency (MPCA) due to elevated levels of suspended sediment.

The U.S. Geological Survey, in cooperation with the MPCA, established a sediment monitoring network in 2007 and began systematic sampling of suspended-sediment concentrations (SSC), total suspended solids (TSS), and turbidity in rivers across Minnesota to improve the understanding of fluvial sediment transport relations. Suspended-sediment samples collected from 14 sites from 2007 through 2011 indicated that the Zumbro River at Kellogg in the driftless region of southeast Minnesota had the highest mean SSC of 226 milligrams per liter (mg/L) followed by the Minnesota River at Mankato with a mean SSC of 193 mg/L. During the 2011 spring runoff, the single highest SSC of 1,250 mg/L was measured at the Zumbro River. The lowest mean SSC of 21 mg/L was measured at Rice Creek in the northern Minneapolis-St. Paul metropolitan area.

Total suspended solids (TSS) have been used as a measure of fluvial sediment by the MPCA since the early 1970s; however, TSS concentrations have been determined to underrepresent the amount of suspended sediment. Because of this, the MPCA was interested in quantifying the differences between SSC and TSS in different parts of the State. Comparisons between concurrently sampled SSC and TSS indicated significant differences at every site, with SSC on average two times larger than TSS concentrations. The largest percent difference between SSC and TSS was measured at the South Branch Buffalo River at Sabin, and the smallest difference was observed at the Des Moines River at Jackson.

Regression analysis indicated that 7 out of 14 sites had poor or no relation between SSC and streamflow. Only two sites, the Knife River and the Wild Rice River at Twin Valley, had strong correlations between SSC and streamflow, with coefficient of determination (R^2) values of 0.82 and 0.80, respectively. In contrast, turbidity had moderate to strong relations with SSC at 10 of 14 sites and was superior to streamflow for estimating SSC at all sites. These results indicate that turbidity may be beneficial as a surrogate for SSC in many of Minnesota's rivers.

Suspended-sediment loads and annual basin yields indicated that the Minnesota River had the largest average annual sediment load of 1.8 million tons per year and the largest mean annual sediment basin yield of 120 tons of sediment per year per square mile. Annual TSS loads were considerably lower than suspended-sediment loads. Overall, the largest suspended-sediment and TSS loads were transported during spring snowmelt runoff, although loads during the fall and summer seasons occasionally exceeded spring runoff at some sites.

This study provided data from which to characterize suspended sediment across Minnesota's diverse geographical settings. The data analysis improves understanding of sediment transport relations, provides information for improving sediment budgets, and documents baseline data to aid in understanding the effects of future land use/land cover on water quality. Additionally, the data provides insight from which to evaluate the effectiveness and efficiency of best-management practices at the watershed scale.

Introduction

Excessive sediment such as silt, sand, and gravel transported in rivers causes problems for flood control, soil conservation, irrigation, aquatic health, and navigation. Fluvial sediment becomes entrained in a stream by way of erosion from land surfaces, or from channel bed and bank erosion. Streams transport sediment by maintaining the finer particles in suspension with turbulent currents (suspended-sediment load) and by intermittent entrainment and movement of coarser particles along the streambed (bedload). Sediment enters stream channels in irregular pulses that are initiated and accelerated by flood events, snowmelt runoff, and freeze-thaw actions (Charlton, 2008). Fine-grained sediment can transport harmful contaminants such as organic chemicals, heavy metals, and eutrophication-causing nutrients (Baker, 1980). Sediment data are needed to better understand how sediment transport varies with changes in streamflow, to improve sediment budgets, and to provide information for river restoration prioritization and design.

The most recent U.S. Environmental Protection Agency compilation of States' water-quality reports under Section 305(b) of the Clean Water Act identifies sediment as one of the leading causes of impairment in the Nation's rivers and streams (U.S. Environmental Protection Agency, 2009, 2012). In Minnesota, more than 5,800 miles (mi) of streams are identified as impaired due to elevated levels of suspended sediments (Minnesota Pollution Control Agency, 2009a). The Minnesota Pollution Control Agency (MPCA) is responsible for monitoring and assessing water quality, listing impaired waters, and implementing total maximum daily load (TMDL) studies (Minnesota Pollution Control Agency, 2009a). Based on recent stressor identification processes, fluvial sediment likely will be one of the main stressors in nearly all impaired biota TMDLs (Minnesota Pollution Control Agency, 2009a).

Suspended-sediment sampling in Minnesota began as early as 1879 by the U.S. Engineer Department as part of a larger sampling project along the Mississippi and Missouri Rivers (Subcommittee on Sedimentation Inter-Agency Water Resources Council, 1940). From 1930 through 1933, daily samples on the upper Mississippi River and its tributaries were collected by the St. Paul U.S. Engineer District, and in 1937 and 1938, suspended-sediment samples were collected on the Minnesota, Zumbro, and Root Rivers by the U.S. Army Corps of Engineers (Lane, 1938). The U.S. Geological Survey (USGS) began collecting suspended-sediment samples in Minnesota in the early 1960s (Maderak, 1963; U.S. Geological Survey, 1966). The USGS sediment sampling consisted of a mixture of isokinetic depth- and width-integrated samples along with daily observer point samples. Following an active sampling period in the 1970s and 1980s, suspended-sediment sampling declined in Minnesota for more than two decades until 2007 when the USGS, in cooperation with the MPCA, established a sediment monitoring network of sites and began systematic sampling across the State.

The MPCA incorporated grab sampling and total suspended solids (TSS) laboratory analysis as its measure of fluvial sediment in the early 1970s. The TSS method was originally designed for analyses of point samples from wastewater treatment facilities (Gray and others, 2000). Total suspended solids were adopted by the MPCA for various reasons, some of which included the assumption that the TSS method would provide an adequate representation of suspended sediment, and that isokinetic sampling and laboratory analysis of whole sample suspended-sediment concentration (SSC) was too costly. Total suspended solids samples are collected at the center of the stream cross-section less than 3.3 feet (ft; 1 meter) below the water surface (Minnesota Pollution Control Agency, 2011), whereas SSC samples are collected using isokinetic samplers from width- and depth-integrated procedures as described by Edwards and Glyssen (1999). Isokinetic samplers are designed to obtain a representative sample of the water-sediment mixture by allowing water in the stream to enter the sampler at the same speed and direction as the streamflow (Edwards and Glyssen, 1999). The primary difference in laboratory procedures is that the TSS analytical method uses a pipette to extract a predetermined volume (subsample) from the original water sample to determine the amount of suspended material, whereas the SSC analytical method measures all of the sediment and the mass of the entire water-sediment mixture (American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1998). The use of a pipette to obtain subsamples subjects the analyses to substantial biases compared to the SSC method. Gray and others (2000) concluded that TSS samples were biased negatively when compared to SSC, particularly when sand-sized particles compose more than 20 percent of the sediment sample. Given that the use of TSS concentrations as a measure of sediment in water was determined to underrepresent the amount of suspended sediment, MPCA staff decided that it was important to examine the differences in different parts of the State. This study did not attempt to differentiate whether differences were due to sampling or laboratory analysis methods.

The MPCA, following guidance from the U.S. Environmental Protection Agency, adopted turbidity as a water-quality standard (Greg Johnson, Minnesota Pollution Control Agency, oral commun., March 1, 2013). The continued need to measure fluvial sediment and recent technological advances has led to the use of turbidity as a surrogate for suspended sediment, particularly in locations where streamflow alone is not a good estimator of SSC (Lewis, 1996; Rasmussen and others, 2009). Optical turbidity sensors measure the amount of emitted light that is reflected by suspended particles in the water column, and have been used successfully to predict SSC, assuming the relation between the turbidity signal and SSC can be calibrated from physical samples (Lewis, 1996; Christensen and others, 2000; Uhrich and Bragg, 2003; Rasmussen and others, 2009). Optical turbidity sensors can be placed permanently in-stream with minimum power requirements. The primary advantages of using turbidity to indirectly measure SSC are the continuous acquisition of data in real time and the low operating costs. Some disadvantages include the accumulation of residues on the lens of the sensor and the variable characteristics of sediment, such as size, shape, and color, that may affect the response of the optical sensor to the manner in which light is scattered (Hatcher and others, 2000). Rasmussen and others (2009) published guidelines and procedures for computing time-series SSC and loads from in-stream turbidity-sensor and streamflow data. For this study, a portable desktop turbidity meter was used to measure turbidity concurrently with SSC sampling to investigate what relation may exist between turbidity and SSC for streams in Minnesota.

This study provided data from which to characterize suspended sediment across Minnesota's diverse geographical settings. The data analysis improves understanding of sediment transport relations, provides information for improving sediment budgets and designing stream restoration, and documents baseline data to aid in understanding the effects of future land use/land cover on water quality. Additionally, the data provide insight from which to evaluate the effectiveness and efficiency of best-management practices at a large watershed scale. The purpose of this report is to document findings based on sediment data collected by the USGS, in cooperation with the MPCA, on selected rivers in Minnesota from 2007 through 2011. Specifically, the study examines suspended-sediment data to (1) describe SSC, TSS, turbidity, and particle-size fractions for selected rivers across Minnesota's major watersheds; (2) quantify the difference between SSC and TSS; (3) develop relations among streamflow, SSC, TSS, turbidity, and suspended-sediment loads; and (4) estimate annual and seasonal suspended-sediment loads and basin yields.

Description of the Study Area

The 10 watersheds selected for this study represent a cross-section of watershed characteristics present in Minnesota, which are described in detail in the following subsections. A map of the State showing the locations of the sites in this study relative to the major watersheds and major streams in Minnesota is shown in figure 1.

Minnesota's geologic history (Sims and Morey, 1972) of advancing and retreating glaciers affected most of the State and contributed to the development of the general soil types (fig. 2) and topographic relief (fig. 3). Most of the northeastern part of the State is forested, but has some open pasture and sparse cultivated crops (fig. 4). The far western and southern regions of Minnesota intensively are cultivated. Between these regions lies a transition area with a mixture of cultivated crops, pasture, and forests. Urban (developed) areas are scattered throughout the State, but the largest is the Minneapolis-St. Paul metropolitan area.

Knife River Watershed

The Knife River watershed encompasses an area of 86 square miles (mi^2) in the Western Lake Superior watershed. The river flows 24 mi in a southerly direction into Lake Superior 15 mi north of Duluth. Land use in the watershed is 70 percent forest, 15 percent grassland, and 9 percent wetland. Three soil types affect the amount of erosion in the watershed. The headwaters are composed of loamy soil over dense glacial till. Permeability in the loam is moderate and very slow in the dense till. The headwaters also have loamy outwash soils over sand or gravel, and can be a groundwater recharge area (South St. Louis County, Soil and Water Conservation District, 2010). The second soil type is transitional and has a discontinuous mantle of eolian sediment over friable till underlain by dense till. The eolian sediments are very fine and have high potential to erode if they are on steeper slopes. The third soil type in the lower one-quarter of the watershed is deposits of clay from the Superior Lobe Clay Plain (South St. Louis County Soil and Water Conservation District, 2010). The clays are not very permeable and have the potential to shrink and swell; also, mass-wasting is a problem with clay soils. Rivers such as the Knife River are referred to as "flashy" because they respond quickly to rain events, reaching peak streamflow in a short time period followed by a rapid return to base flow. This flashy nature, in combination with the soil types, causes high turbidity in the Knife River (South St. Louis County Soil and Water Conservation District, 2010).

South Branch Buffalo River Watershed

The South Branch Buffalo River watershed encompasses an area of 516 mi^2 in the Red River watershed in northwestern Minnesota. The South Branch Buffalo River flows for 71.8 mi northwest where it joins the main stem of the Buffalo River near Glyndon, Minnesota. Land use includes 67 percent cultivated crops; 9.3 percent grass/pasture/hay; 8.8 percent forest; 6.8 percent wetlands; 4.8 percent developed; and 3.6 percent open water (Natural Resources Conservation Service, 2011). Soils consist of glacial lake deposits of clay and silt from Glacial Lake Agassiz in the western part of the watershed, and glacial lakeshore deposits of delta sand and gravel, along with areas of beach sand ridges separated by silty wetland depressions (Natural Resources Conservation Service, 2011). The eastern part of the watershed has primarily glacial till deposits made up of clay, silt, sand, gravel, cobble, and boulders.

Wild Rice River Watershed

The Wild Rice River watershed encompasses an area of 1,629 mi^2 in the Red River watershed in northwestern Minnesota. The main stem is 160 mi long and flows east to west through three physiographic regions consisting of glacial moraine, lake shore deposits, and the lakebed of Glacial Lake Agassiz where it joins the Red River of the North near Hendrum, Minn. Land use in the watershed consists of 53 percent cultivated crops; 24 percent forest/shrub/scrub; 6.7 percent pasture; 8.5 percent wetland; 3.6 percent open water; and 3.7 percent developed (Minnesota Pollution Control Agency, 2009b). Soils in the lower part of the Wild Rice River watershed tend to be clays of low permeability, with poor internal drainage. The streambed substrates include a mixture of sand and silt.

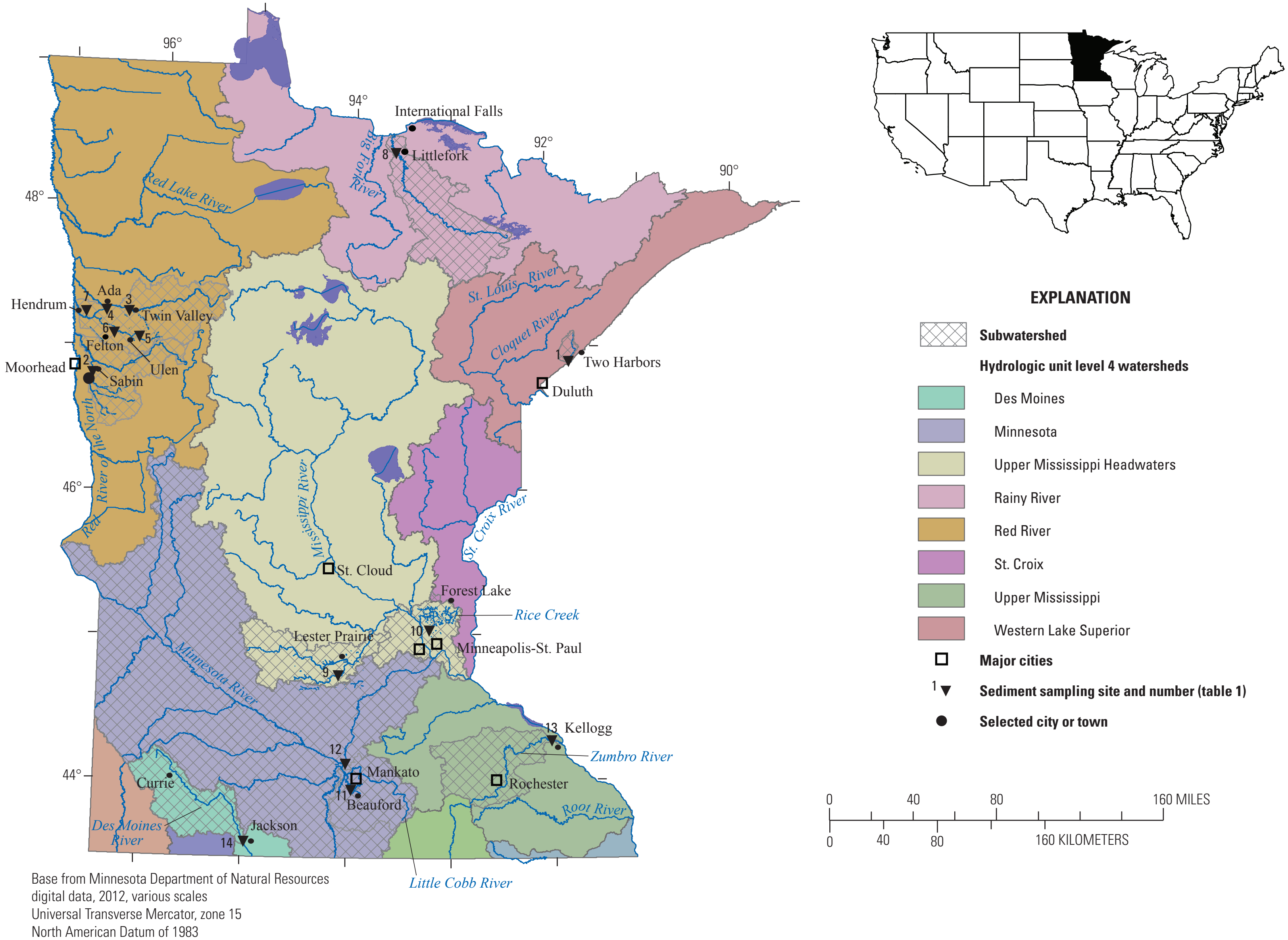
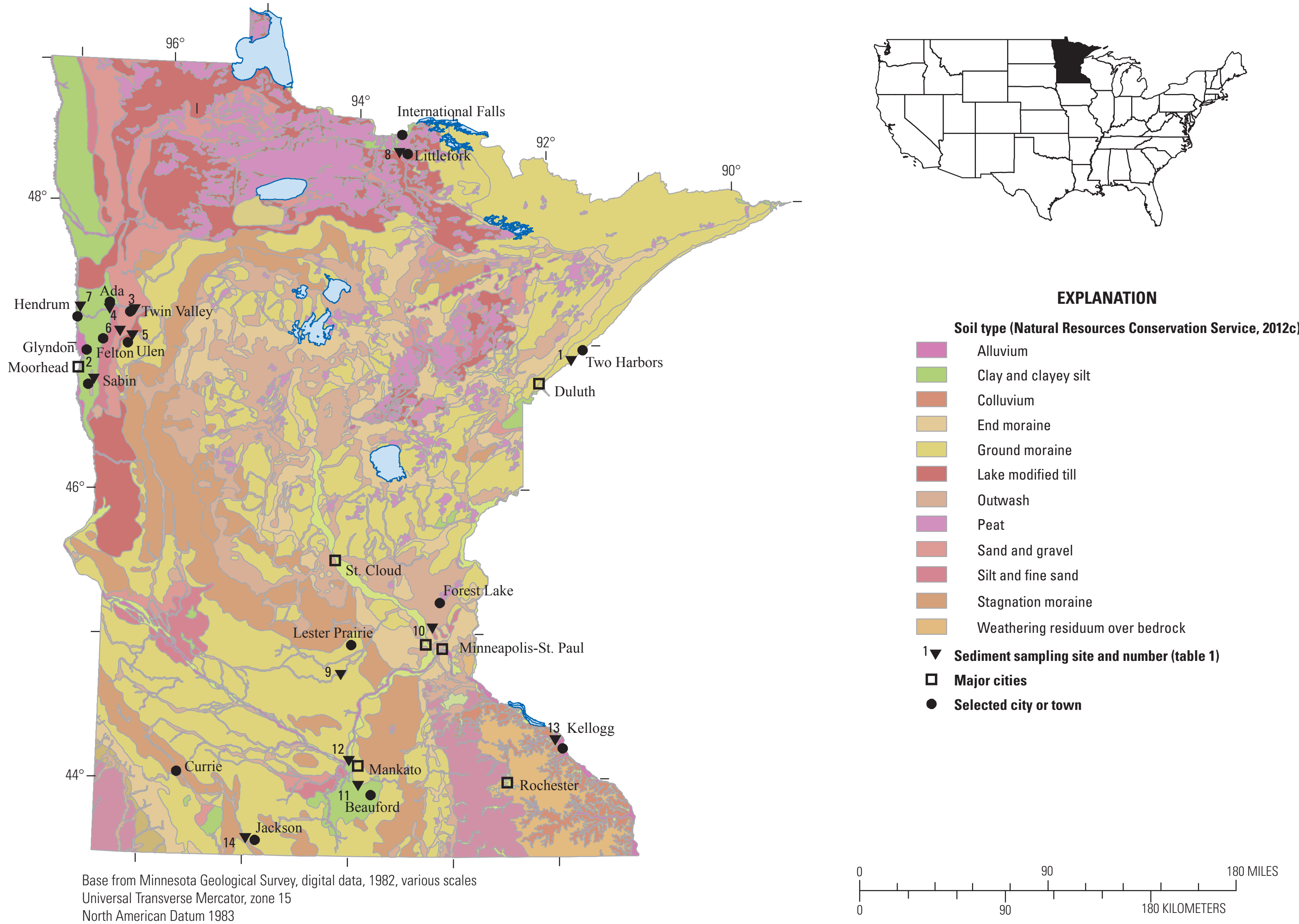
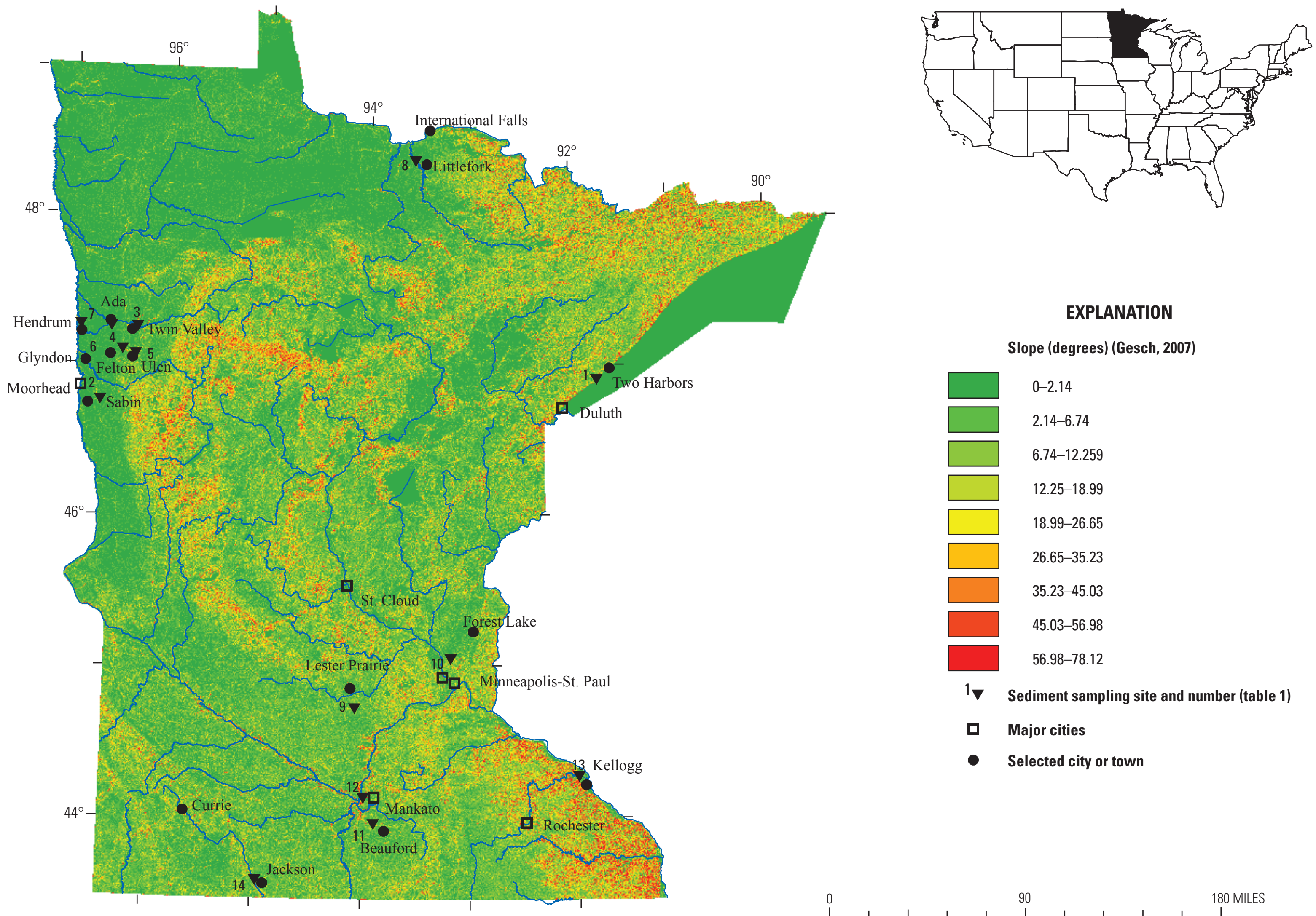


Figure 1. Major watersheds and locations of sediment sampling sites in Minnesota.



Base from Minnesota Geological Survey, digital data, 1982, various scales
Universal Transverse Mercator, zone 15
North American Datum 1983

Figure 2. Generalized soil types and locations of sediment sampling sites in Minnesota.



Base from Minnesota Department of Natural Resources digital data, 2012, various scales
Universal Trasnverse Mercator, zone 15

Figure 3. Landscape relief and locations of sediment sampling sites in Minnesota.

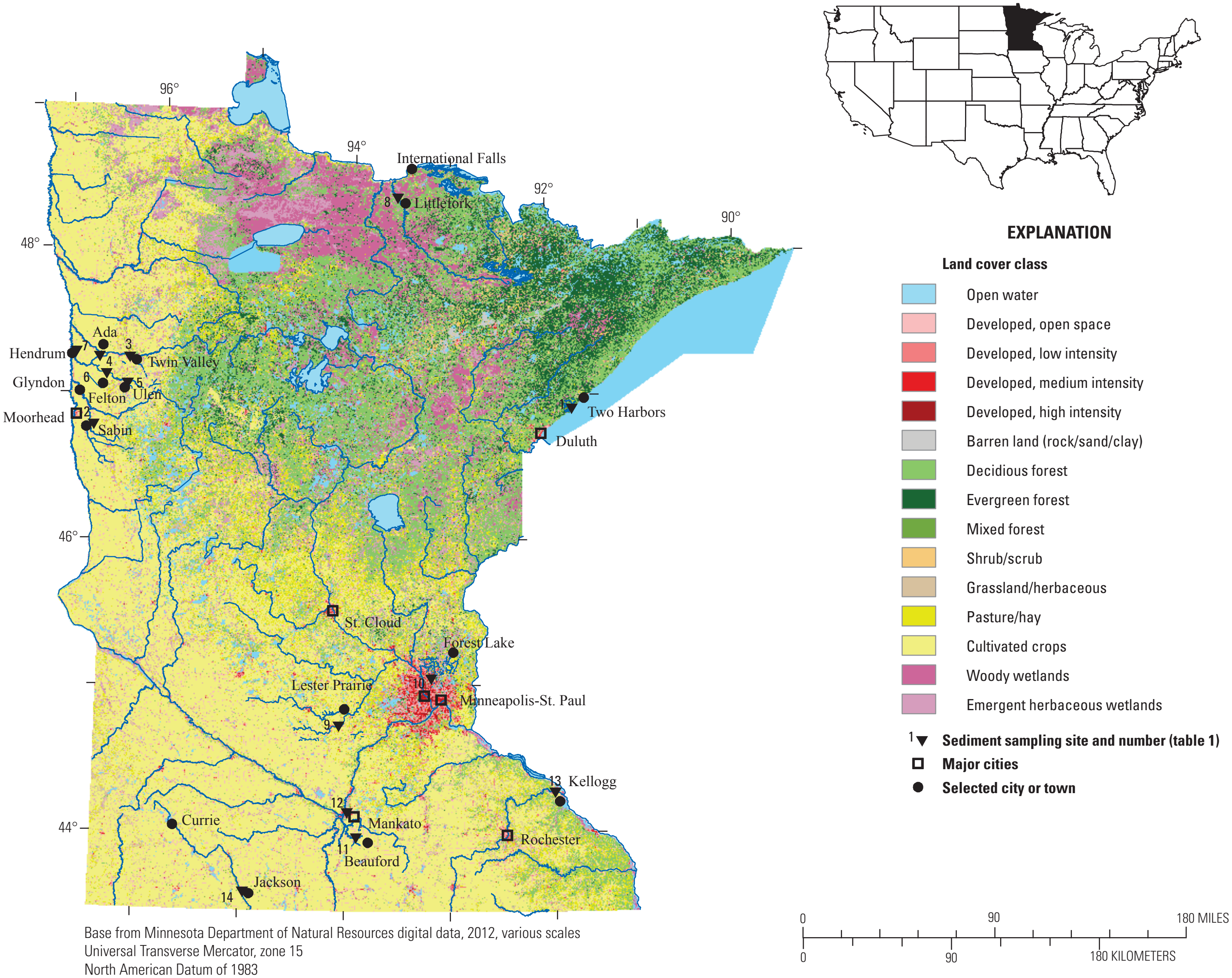


Figure 4. Generalized land cover and locations of sediment sampling sites in Minnesota.

Little Fork River Watershed

The Little Fork River watershed is in the Rainy River watershed in north-central Minnesota and encompasses an area of 1,843 mi^2. The river flows 160 mi in a northwest direction until it reaches its confluence with the Rainy River about 11 mi west of International Falls. Land use in the watershed is 62.6 percent forest/shrub; 33 percent wetland; 2 percent open water; 1.3 percent developed; 0.6 percent cropland; and 0.6 percent barren. Soils types range from peat over clay to glacial till and ledge rock in the upper watershed to mostly silty clay with sparse outcrops of ledge rock and glacial outwash in the lower part of the watershed (Minnesota Pollution Control Agency, 2001). The upper part of the watershed is dominated by forest cover, with alders and willows present in the lowlands, and black spruce and aspen on the uplands (Minnesota Pollution Control Agency, 2001).

Buffalo Creek Watershed

The Buffalo Creek watershed is approximately 30 mi west of the Minneapolis-St. Paul metropolitan area in the southern part of the Upper Mississippi Headwaters watershed and encompasses 422 mi^2. Buffalo Creek flows west to east for 84.3 mi near Lester Prairie, Minn. Land uses in the watershed include 88 percent cultivated crops; 4 percent grass/pasture/hay; 2.8 percent forest; 0.8 percent wetlands; 3 percent developed; and 1.4 percent open water (Buffalo Creek Watershed District, 2011). Soils in the region are believed to be some of the most fertile in the world (Buffalo Creek Watershed District, 2011) and consist of cohesive clays formed from glacial moraine deposits. Soils in the western part of the watershed range from clay loam and silty clay with generally poor infiltration rates to loam to clay loam with infiltration rates from good to poor. The central part of the watershed is composed of soils that range from loam to clay loam with infiltration rates from good to poor and silty clay loam and clay loam with poor infiltration rates. The eastern part of the watershed consists of loam, silty clay loam, and clay loam soils with good to poor infiltration rates (Buffalo Creek Watershed District, 2011).

Rice Creek Watershed

The Rice Creek watershed is in the northern part of the Minneapolis-St. Paul metropolitan area in the southern part of the Upper Mississippi Headwaters watershed and encompasses 114 mi^2. Rice Creek flows south from Forest Lake, Minn., and meanders southwest for 28 mi through a chain of lakes where it joins the Mississippi River. Land use ranges from heavily developed with a mix of industrial, commercial, retail, and multi-family and single-family residential land uses in the southwest part of the watershed to more rural, with agricultural and undeveloped land use in the north and east (Rice Creek Watershed District, 2010). The northwestern part of the watershed is composed of principally fine sand. The remainder of the watershed is a heterogeneous mixture of gray till and reddish-brown till consisting of sand, silt, clay, pebbles, cobbles, and sometimes boulders.

Little Cobb River Watershed

The Little Cobb River watershed is approximately 91 mi southwest of the Minneapolis-St. Paul metropolitan area and encompasses an area of 132 mi^2 in the Minnesota River watershed in south-central Minnesota. The Little Cobb River flows in a westerly direction for 36.9 mi near Beauford, Minn. Land use in the watershed is 86.6 percent cropland and 5.8 percent developed. Soils in the watershed predominantly are loamy glacial till soils with scattered lacustrine areas, potholes, outwash, and flood plains. Pleistocene glacial deposits cover almost the entire watershed and are an unconsolidated mixture of clay, silt, sand, and gravel (Natural Resources Conservation Service, 2012a).

Minnesota River Watershed

The Minnesota River watershed encompasses an area of 16,770 mi^2 and flows from its origin near the Minnesota and South Dakota border across the south-central part of the State for 335 mi where it joins the Mississippi River near the city of St. Paul. This large watershed is composed of 13 sub-watersheds (Minnesota Pollution Control Agency, 2012). Land use in the region is dominated by agriculture with only 6 percent in urban and developed land. The geologic history of the watershed lends insight to the presence of erosional features in the watershed. Around 12,000 years ago, the Minnesota River watershed was covered by a thick ice layer known as the Des Moines Lobe of the Wisconsin ice sheet (Minnesota Pollution Control Agency, 2012). The Des Moines Lobe transported large amounts of poorly sorted sediment from the north and west to the current day (2013) Minnesota River watershed. Much of the watershed was covered by a thick flat-lying layer of unconsolidated material in equal amounts of clay, silt, and sand. About 11,500 years ago, Glacial River Warren drained primordial Lake Agassiz, which was located northwest of the current day (2013) Minnesota River watershed. The River Warren carved a large valley that is now partially occupied by the Minnesota River. Steep bluffs formed at the margins of the Minnesota River valley are remnants of the River Warren incision.

Zumbro River Watershed

The Zumbro River watershed is located in the Upper Mississippi River watershed in southeastern Minnesota and encompasses an area of 1,428 mi^2. The Zumbro River flows north and east for 64.6 mi through six counties where it reaches the Mississippi River near Kellogg, Minn. Much of the drainage area is within a geologic region known as the driftless region, with topography composed of a unique landform known as "karst" (Natural Resources Conservation Service, 2012b). Karst features are characterized by numerous underground streams, sinkholes, and springs. Land use in the watershed is 56 percent cultivated crops; 24 percent grass, pasture, and hay; 9.7 percent forest; 8.5 percent developed; and 1.5 percent wetlands (Natural Resources Conservation Service, 2012b). The eastern part of the watershed consists of well-drained and moderately well-drained silty soils over bedrock residuum, whereas the western part consists of well-drained soils formed in thin silty material over loamy till, underlain by sedimentary bedrock (Natural Resources Conservation Service, 2012b).

West Fork Des Moines River Watershed

The West Fork Des Moines River watershed is in the Des Moines River watershed in southwestern Minnesota and encompasses an area of 1,333 mi^2. The river originates near Currie, Minn., and flows through seven counties in a southeasterly direction for 94 mi to the Minnesota/Iowa border and eventually enters the Mississippi River in Iowa. Land use in the watershed is 85.5 percent cultivated crop; 9.5 percent pasture; 3 percent wetlands and open water; 1.5 percent urban; and 0.5 percent forested (Minnesota Pollution Control Agency, 2008). The West Fork Des Moines River watershed is delineated into three regions of distinct soil types. The western part of the watershed consists of fine-textured moraine soils that generally are well drained and are located on moderately steep slopes. Water and wind erosion potentials can be moderate to severe for these soils. In the south-central part of the watershed, soils are fine textured, on low gradient surfaces, are poorly drained, and were developed in lacustrine deposits. These soils have a moderate potential for erosion. The eastern part of the watershed consists of Dryer Blue Earth Till, which are fine-textured soils developed from calcareous glacial till. These soils may be poorly or moderately well drained, and are located on flat to moderately steep slopes (Minnesota Pollution Control Agency, 2008). Water and wind erosion can be moderate to high.

Methods of Data Collection and Analysis

The following sections describe methods used for the collection and analysis of sediment samples and streamflow. Data for the study were collected from February 2007 through November 2011. Fourteen sites were sampled 5–14 times per year during the open-water season (table 1). Few samples (22) were collected during the winter months because historically, less than 4 percent of annual loads were transported during the winter months (Tornes, 1986). The small sediment contribution during the winter occurs because streamflow in Minnesota generally is contained under ice and receives little sediment input from the surrounding landscape. Eight of the sites are part of an ongoing collaborative study (statewide sediment network) between the USGS and MPCA (table 1; sites 1, 2, 8, 9, 11–14) and were sampled during the entire study period from 2007 through 2011. Five sites (sites 3–7) included in the report were part of a collaborative study between the USGS, MPCA, and the Wild Rice Watershed District and for which data were collected from 2007 through 2010. The final site (site 10) included in this report was sampled from 2010 through 2011 in cooperation with the Rice Creek Watershed District.

Water samples were collected at all sites for analysis of SSC and particle-size fractions less than 0.0625 millimeters (mm) (fines). For this study, particles in suspension greater than 0.0625 mm are categorized as sands. Samples for analysis of TSS concentrations were collected at 7 of the 8 sites as part of the statewide sediment network. A few TSS samples listed in table 1 and in table 1–1 in the appendix were collected from sites other than the statewide sediment network. These were collected inadvertently and are not included in the data analysis. Turbidity was measured in the field at 13 of the 14 sites included in this report; the exception was the Minnesota River at Mankato (site 12).

Streamflow data were obtained from existing USGS or MPCA/Minnesota Department of Natural Resources (MDNR) streamgages. Of the 14 sampling sites, 13 were colocated at the corresponding streamgage; the exception was the South Branch Wild Rice River near Ulen, Minn. (site 5).

Suspended-Sediment Data Collection

Suspended-sediment samples were collected using isokinetic samplers and equal-width and depth-integrating techniques following procedures by Edwards and Glysson (1999). Most samples were collected using a D–74 rigid bottle sampler suspended from a bridge during nonwadeable flows and a DH–48 hand-held sampler during wadeable flows. When river depths exceeded 15 ft, a D–96 collapsible-bag sampler was used to obtain the sample (Davis, 2005). For collection of suspended-sediment samples, the total stream width at each station was divided into 10 equal-width increments, and individual depth-integrated samples were collected at the centroid of each increment. Individual samples from each centroid were kept in 1-pint glass bottles with each vertical generally contained within a single bottle. Care was taken not to overfill the sample bottle. If a bottle inadvertently was overfilled, it was dumped and the vertical was resampled. Typically, ten 1-pint bottles were collected for each suspended-sediment sample, although on occasion, two or more verticals composed a single bottle following methods described by Edwards and Glyssen (1999). Following collection, samples were transported to the USGS sediment laboratory in Iowa City, Iowa, where they were composited into a single sample and analyzed for suspended-sediment concentration and fines particle-size fraction, according to Guy (1969).

Table 1. Sediment sampling sites in selected watersheds in Minnesota, 2007 through 2011.

[USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; NGVD 29, National Geodetic Vertical Datum of 1929; mi^2, square miles; Minn., Minnesota; C, continuous streamflow available; E, streamflow extended to site from nearby continuous-record streamgage; P, partial streamflow available, streamflow could not be extended during missing periods because nearby streamgage not available]

Site number (figs. 1–4)	USGS station number	Station name	Latitude (north) (NAD 83)	Longitude (west) (NAD 83)	Gage vertical datum (NGVD 29) (feet)	Drainage area (mi^2)	Sampling period	Type of streamflow record	Number of suspended-sediment samples	Number of total suspended solids samples[a]
1[b]	04015330	Knife River near Two Harbors, Minn.	46° 56’ 49”	91° 47’ 32”	614	84	05/2007–10/2011	C	27	22
2[b]	05061500	South Branch Buffalo River at Sabin, Minn.	46° 46’ 32”	96° 37’ 40”	902.4	454	06/2007–10/2011	C	40	27
3[c]	05062500	Wild Rice River at Twin Valley, Minn.	47° 16’ 00”	96° 14’ 40”	1,008.2	934	02/2007–05/2010	C	29	2
4[c,d]	05063000	Wild Rice River near Ada, Minn.	47° 15’ 50”	96° 30’ 00”	899	1,100	02/2007–07/2010	E	29	2
5[c]	05063340	South Branch Wild Rice River near Ulen, Minn.	47° 05’ 17”	96° 15’ 31”	1,112	141	03/2007–05/2010	E	25	2
6[c]	05063400	South Branch Wild Rice River near Felton, Minn.	47° 07’ 23”	96° 24’ 25”	930	180	03/2007–07/2010	C	28	0
7[c]	05064000	Wild Rice River at Hendrum, Minn.	47° 16’ 05”	96° 47’ 50”	836.8	1,560	03/2007–05/2010	C	27	1
8[b]	05131500	Little Fork River at Littlefork, Minn.	48° 23’ 45”	93° 32’ 57”	1,083.6	1,680	05/2007–10/2011	C	34	19
9[b,d]	05278930	Buffalo Creek near Glencoe, Minn.	44° 45’ 50”	94° 05’ 27”	971	373	05/2007–10/2011	P	44	28
10	05288580	Rice Creek below Old Highway 8 in Mounds View, Minn.	45° 05’ 36”	93° 11’ 42”	860.6	156	03/2010–10/2011	C	21	0
11[b]	05320270	Little Cobb River near Beauford, Minn.	43° 59’ 48”	93° 54’ 30”	975	130	01/2007–09/2011	C	68	24
12[b]	05325000	Minnesota River at Mankato, Minn.	44° 10’ 08”	94° 00’ 11”	747.9	14,900	07/2007–10/2011	C	32	0
13[b,d]	05374900	Zumbro River at Kellogg, Minn.	44° 18’ 43”	92° 00’ 14”	669.5	1,400	07/2007–10/2011	P	34	17
14[b]	05476000	Des Moines River at Jackson, Minn.	43° 37’ 06”	94° 59’ 05”	1,287.8	1,250	05/2007–10/2011	C	25	20

[a]Total suspended solids samples collected concurrently with suspended-sediment samples.

[b]Statewide sediment monitoring network site.

[c]Wild Rice River collaborative study site.

[d]Minnesota Pollution Control Agency/MinnesotaDepartment of Natural Resources streamgage.

Total Suspended Solids Data Collection

Grab samples for laboratory TSS analysis were collected in 1-liter (L) plastic containers near the centroid of the stream cross-section less than 1 meter (m) below the surface, following MPCA sampling protocols (Minnesota Pollution Control Agency, 2011). The TSS samples were refrigerated and delivered to the Minnesota Department of Health laboratory in St. Paul, Minn., within 7 days of the collection date. The TSS samples were analyzed by the Minnesota Department of Health laboratory following method 2540 D (American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1998) to determine the concentration of TSS in each sample (Jeff Brenner, Minnesota Department of Health laboratory, oral commun., December 30, 2011).

Turbidity Data Collection

Grab samples for field measurements of turbidity were collected from the centroid of the stream cross-section in a 1-L plastic container. A subsample of the contents was transferred into a glass vial, which was then placed into the instrument cell compartment of a portable Hach® model 2100P (Hach Company, Loveland, Colorado) turbidimeter to obtain the measurement. A potential consequence of using the portable desktop turbidimeter is the possibility for coarse particles to fall out of suspension before collecting the reading, adding an unquantifiable level of uncertainty to the readings. This bias, if present, could affect subsequent models that use turbidity as an explanatory variable. The error would be expected to increase with elevated SSC and greater percentages of sands in suspension. The field turbidimeter was calibrated using StablCal® Formazin Turbidity Standards (Hach Company, Loveland, Colorado) before the monitoring season and checked during each sampling site visit thereafter. The turbidity measurement, in nephelometric turbidity ratio units (NTRU), was recorded in the field notes.

Streamflow Data

Daily mean streamflow data were obtained from existing USGS or MDNR/MPCA streamgages to develop sediment transport relations and to calculate sediment loads. The USGS and MDNR/MPCA determine streamflow at streamgages by use of the rating-curve method (the relation between streamgage height and streamflow) for each station following Rantz and others (1982). Rating curves at streamgages are developed by relating gage height to streamflow for a range of streamflows. Of the sampling sites, 10 were USGS continuous-record streamgages, whereas three (sites 4, 9, and 13) were MDNR/MPCA streamgages. For the remaining site (South Branch Wild Rice River near Ulen; site 5), no streamgage was available onsite. Data for continuous-record streamgages are updated hourly, and preliminary data are available at *http://waterdata.usgs.gov/nwis/current* for USGS streamgages or at *http://www.dnr.state.mn.us/waters/csg/index.html* for MDNR/MPCA streamgages. The data are then finalized and published following the end of the water year (September 30) and calendar year for USGS (U.S. Geological Survey, 2013) and MDNR/MPCA (Minnesota Department of Natural Resources, 2013) streamgages, respectively. For two sites with missing data [Wild Rice River near Ada (site 4), and South Branch Wild Rice River near Ulen (site 5)], streamflow was estimated by extending streamflow from a nearby USGS streamgage using the MOVE-1 (Maintenance of Variance Extension, Type 1) statistical program (Hirsch, 1982). The correlation between the stations with missing data and the USGS continuous-record streamgage was then used to generate daily mean streamflows for the station during the time period for which sediment data were collected. Streamflow measurements made during periodic onsite measurements at the South Branch Wild Rice River near Ulen (site 5) from March 2007 through May 2010 were correlated to streamflow recorded at the continuous-record streamgage on the South Branch Wild Rice River near Felton (site 6) at the time of the measurement [coefficient of determination (R^2)=0.998]. The resultant relation was used to estimate daily mean streamflow at the South Branch Wild Rice River near Ulen. The same methodology was used to estimate daily mean streamflow for the Wild Rice River near Ada (site 4) by correlating periodic onsite measurements to streamflow recorded at the continuous-record streamgage on the Wild Rice River at Twin Valley (site 3) (R^2=0.981). For the other two MDNR/MPCA streamgages in the study, Buffalo Creek (site 9) and the Zumbro River at Kellogg (site 13), a partial streamflow record was available; however, a continuous-record streamgage was not available nearby for computing daily mean flows at the partial-record site using the MOVE-1 method. For these sites, instantaneous streamflow for the time the sediment samples were collected was estimated using periodic onsite measured streamflows and the streamgage height relation.

Data Analysis

Sediment concentration data and measures of daily mean streamflow were analyzed to obtain summary statistics, nonparametric match-pair tests, simple linear regression (SLR), and load estimation using S-Plus statistical analysis software (TIBCO® Software Inc., 2010). Summary statistics included the minimum, maximum, mean, median, total numbers of samples, and standard deviation. The Wilcoxon signed-rank test (Helsel and Hirsch, 2002) was used to determine if significant differences could be detected between matched pairs of SSC and TSS.

For model development, SLR was used to calculate SSC based on daily mean streamflow, TSS, and turbidity. For SLR models, *p*-values were used to evaluate the model's null hypothesis for statistical significance [*p*-values less than (<) 0.05 indicated statistical significance], whereas Pearson's R correlation (Helsel and Hirsch, 2002) and R^2 was used to assess the linear association between the response and explanatory variable and to assess how well the model was able to accurately predict outcomes of the response variable. Annual and seasonal loads for suspended sediment, TSS, suspended sands, and suspended fines were estimated using S-LOADEST, an interface-driven, S-PLUS version of LOADEST (load estimator), a FORTRAN (formula translation) program for estimating constituent loads in streams and rivers (Runkel and others, 2004).

For determining differences between matched pairs of SSC and TSS, the nonparametric Wilcoxon signed-rank test (Helsel and Hirsch, 2002) was used. The Wilcoxon signed-rank test compares the median value of the differences between SSC and TSS to zero. A required assumption is that positive and negative differences are symmetric around zero. If the assumption is true, the untransformed values were used for the test. If the differences were not symmetric around zero, the values were transformed to achieve symmetry before the test was done. If the median value of the differences was not close to zero and demonstrated a symmetric distribution around a nonzero median, then the two parameters were considered to be from different populations (Helsel and Hirsch, 2002). Percent difference (PD) was used to describe the magnitude of the difference between SSC and TSS concentrations for each site. The percent difference equation is applied when comparing two constituent values, where one of the values, in this case SSC, is considered to be the value that is more accurate, or "correct" value:

$$PD = 100\ [(x_1 - x_2) / x_1] \tag{1}$$

where

PD is the percent difference between x_1 and x_2;
x_1 is the median value of suspended-sediment concentration, in milligrams per liter; and
x_2 is the median value of total suspended solids, in milligrams per liter.

In contrast, relative percent difference (RPD) is used when comparing two constituent values when neither value is considered to be the "correct" value. The RPD equation is used to compare primary and replicate samples as measures of quality assurance to estimate variation in reproducibility in field-sampling techniques:

$$RPD = 100\ [(x_1 - x_2)/([x_1 + x_2]/2)] \tag{2}$$

where

RPD is the relative percent difference between x_1 and x_2;
x_1 is the value of suspended-sediment concentration in the primary sample, in milligrams per liter; and
x_2 is the value of suspended-sediment concentration in the sequential replicate sample, in milligrams per liter.

The SLR can be used to estimate unknown values of a response variable from a known quantity of an explanatory variable if a statistically significant correlation between the variables exists. This method minimizes the sum of squared vertical distances (residuals) between the observed values of the response variable and the calculated (fitted values) values from the linear approximation. For SLR to produce a useable model, assumptions are that the two variables are related linearly, that the variance of the residuals are constant (homoscedastic), and that the residuals are distributed normally (Helsel and Hirsch, 2002). These assumptions usually are violated by measured water data, so the data are transformed to logarithmic values to satisfy these assumptions. Transformation of data to a logarithmic scale often makes the residuals more symmetric, linear, and homoscedastic. Logarithmic base-10 (log10) transformation has been determined to be effective in normalizing residuals for many water-quality measures and streamflow (Helsel and Hirsch, 2002). There exists a consequence of transformation of the response variable, in this case SSC, which must be accounted for when computing SSC values. When the regression estimates are retransformed to the original units, bias is introduced (usually negative) in the computed SSC values (Miller, 1951; Koch and Smillie, 1986). The bias occurs because regression estimates are the mean of *y* given *x* in log units, and retransformation of these estimates is not equal to the mean of *y* given *x* in linear space. To correct for this retransformation bias, Duan (1983) introduced a nonparametric bias-correction factor (BCF) equation called the "smearing" estimator:

$$BCF = \left(\sum_{i=1}^{n} 10^{e_i}\right) / n \tag{3}$$

where

n is the number of samples, and
e_i is the difference between each measured and estimated concentration, in log units.

Regression-computed SSC values are corrected for bias by multiplying the retransformed SSC value by the BCF. For the SLR model, measures of correlation (Pearson R) and *p*-values are examined to evaluate the applicability of the model. The Pearson R correlation indicates the magnitude and direction of the correlation between two variables and is scaled to be in the range of -1.0 to 1.0. A value of 0 indicates no relation between two variables. Relations were considered to be significantly positive (with a value between 0 and 1.0 indicating that the response variable increased as the explanatory variable increased) or negative (with a value between 0 and -1.0 indicating that the response variable decreased as the explanatory variable increased) if the probability (two-sided *p*-value) of rejecting a correct hypothesis (in this case, no trend) was less than or equal to 0.05. The simple linear regression model predicts values of a response variable based on a single explanatory variable:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i, \quad i = 1, 2, \ldots n \tag{4}$$

where

y_i is the *i*th observation of the response variable,

x_i is the *i*th observation of the explanatory variable,
β_0 is the y-intercept,
β_1 is the slope,
ε_i is the random error or residual for the *i*th observation, and
n is the sample size.

For this study, the SLR model is based on log10-transformed data:

$$\log10(SSC_i) = \beta_0 + \beta_1 \log(x_i),\ i = 1, 2,.....n \quad (5)$$

where

SSC_i is the *i*th suspended-sediment concentration, in milligrams per liter;
β_0 is the y-intercept; and
β_1 is the slope;
x_i is the *i*th observation of the explanatory variable;
n is the sample size.

The log10-transformed SLR model (eq. 5) was retransformed and corrected for bias with a BCF:

$$SSC_i = 10^{\beta_0} x_i^{\beta_1} \times BCF,\ i = 1, 2,.....n \quad (6)$$

where

SSC_i is the *i*th suspended-sediment concentration, in milligrams per liter;
x_i is the *i*th observation of the explanatory variable;
β_0 is the intercept;
β_1 is the slope;
BCF is Duan's (Duan, 1983) bias-correction factor, as described in equation 3 above; and
n is the sample size.

Multiple linear regression (MLR) expands SLR from a model with a single explanatory variable to a model containing multiple explanatory variables. The goal of extending the model to include multiple explanatory variables is to explain as much of the variation as possible in the response variable (Helsel and Hirsch, 2002). Stepwise regression was used to develop the MLR models. Stepwise regression alternates between adding and removing variables in the model and testing each variable for significance. If a variable is added to the model and tests significant, and then later tests as insignificant after an additional variable is added, the variable will be eliminated from inclusion in the model (Helsel and Hirsch, 2002). In comparing models, Akaike's Information Criteria (AIC) (Helsel and Hirsch, 2002) was used to determine the best model. The AIC provides a measure of model error and includes a penalty for too many explanatory variables. The lower the AIC value, the better the model (that is improved goodness of fit and minimal model complexity) (Helsel and Hirsch, 2002).

For load computations, S-LOADEST was used for suspended-sediment, TSS, suspended-sands, and suspended-fines loads. S-LOADEST is based on a rating-curve method (Cohn and others, 1989, 1992; Crawford, 1991) that uses regression to estimate constituent loads in relation to several explanatory variables, which most often are streamflow, time, and a seasonal component. The regression is developed using daily loads calculated from the sample concentration and daily flow for that sample. An undesirable effect of using streamflow and time as explanatory variables in regression analysis is the presence of multicollinearity (Helsel and Hirsch, 2002). Closely related explanatory variables such as streamflow and time confound the interpretation of the model coefficients and tests of their significance. The S-LOADEST program incorporates a methodology to eliminate multicollinearity by centering the variables (for example, central value of flow and central value of time) and makes the streamflow and time variables orthogonal (independent) (Cohn and others, 1992). The equation for centering streamflow and time is in Cohn and others (1992). The regression model estimates sediment loads from streamflow, time, and a seasonal component:

$$\ln L = \beta_0 + \beta_1(\ln Q^*) + \beta_2(T^*) + \beta_3[\sin(2\pi T)] + \beta_4[\cos(2\pi T)] + \varepsilon \quad (7)$$

where

L is the suspended-sediment load, in tons per day;
β_0 is the regression intercept;
Q^* is Q/Q_c;
Q is streamflow, in cubic feet per second;
Q_c is the central value of flow;
T^* is $T-T_c$;
T is decimal time in years (for example, July 10, 2009, in decimal time is 2009.523);
T_c is the central value of time;
$\beta_1, \beta_2, \beta_3$, and β_4 are regression coefficients that remain constant over time; and
ε is unaccounted error associated with the regression model.

Suspended-Sediment Concentrations, Total Suspended Solids, Turbidity, and Particle-Size Fractions

Sediment samples were collected during a wide range of streamflow conditions (table 2; table 1–1 in appendix). The frequency, timing, and magnitudes of streamflow and the timing of suspended-sediment sampling during the study period are illustrated in figure 5 for selected sites. Samples encompassed a full range of flows at each site. A flow duration curve that shows the percentage of time that streamflow was equaled or exceeded along with corresponding values associated with SSC samples for the 10 sites colocated with continuous-record streamgages is shown in figure 6 and was created using S-Plus statistical analysis software (TIBCO® Software Inc., 2010).

Table 2. Range of streamflow sampled and suspended-sediment concentrations in samples collected from selected sites in Minnesota, 2007 through 2011.

[ft^3/s, cubic feet per second; mg/L, milligrams per liter; mm, millimeters; Minn., Minnesota]

Site number (figs. 1–4)	Station name	Range of streamflow sampled (ft^3/s)	1.5-year streamflow recurrence interval (ft^3/s)[a]	Median suspended-sediment concentration (mg/L)	Mean suspended-sediment concentration (mg/L)	Range of suspended-sediment concentrations (mg/L)	Median suspended-sediment fraction less than 0.0625 mm (percent)	Range of suspended-sediment concentrations less than 0.0625 mm (percent)
1	Knife River near Two Harbors, Minn.	3.7–1,940	1,980	16	60	2–414	84	31–99
2	South Branch Buffalo River at Sabin, Minn.	8.8–6,997	887	69	94	21–408	92	50–99
3	Wild Rice River at Twin Valley, Minn.	30–4,920	1,120	40	112	3–775	89	43–98
4	Wild Rice River near Ada, Minn.	20–2,731	1,310	39	184	6–1,140	76	33–96
5	South Branch Wild Rice River near Ulen, Minn.	0.5–1,400	365	25	37	3–118	82	18–98
6	South Branch Wild Rice River near Felton, Minn.	3–1,070	469	55	94	4–715	66	5–100
7	Wild Rice River at Hendrum, Minn.	31–8,497	2,260	65	99	15–474	95	76–99
8	Little Fork River at Littlefork, Minn.	38–9,710	7,110	23	37	9–181	90	25–100
9	Buffalo Creek near Glencoe, Minn.	0.6–3,500	1,030	44	63	5–298	86	16–98
10	Rice Creek below Old Highway 8 in Mounds View, Minn.	28–296	261	16	21	2–56	60	17–95
11	Little Cobb River near Beauford, Minn.	0.08–1,850	609	91	103	2–346	86	27–99
12	Minnesota River at Mankato, Minn.	324–77,470	12,330	151	193	27–671	76	15–98
13	Zumbro River at Kellogg, Minn.	420–5,380	7,280	107	226	17–1,250	71	2–96
14	Des Moines River at Jackson, Minn.	36–6,555	1,310	103	115	18–314	84	41–99

[a]From Lorenz and others (2009).

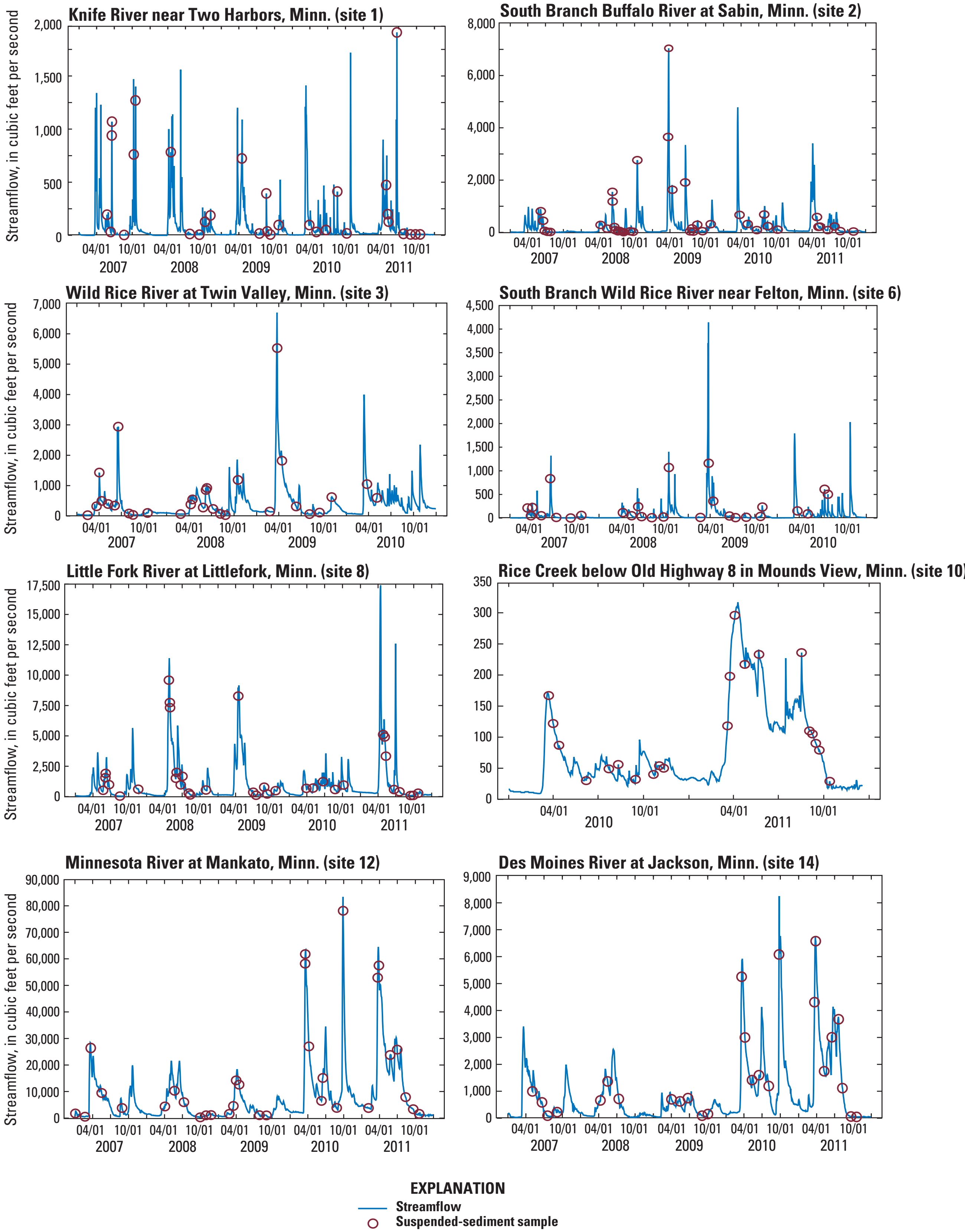


Figure 5. Hydrograph and dates of suspended-sediment sampling for selected sites in Minnesota, 2007 through 2011.

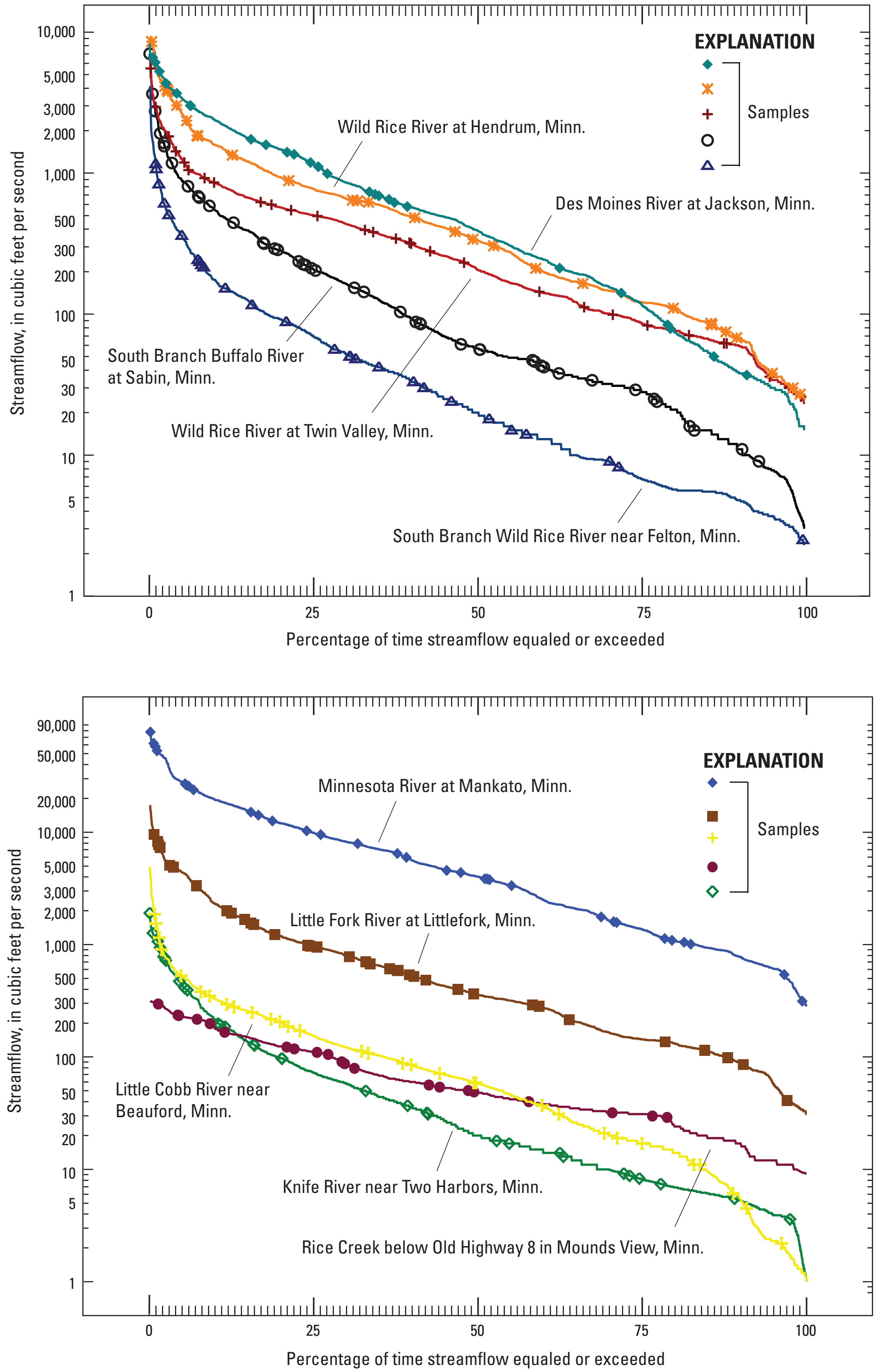


Figure 6. Flow duration curves and corresponding values associated with suspended-sediment concentration samples for selected sites in Minnesota, 2007 through 2011.

A summary of streamflow, SSC, TSS, turbidity, and suspended fines for the 14 sampled sites is presented in table 1–1 in the appendix. Summary statistics for SSC, TSS, turbidity, suspended sands, and suspended fines are presented for all 14 sites in table 3. The Zumbro River at Kellogg (site 13) demonstrated the highest mean SSC [226 milligrams per liter (mg/L)] for all sites. High SSC at the Zumbro River is attributed in part to the combined effects of climate, high topographic relief, and erodible soils. The Zumbro River watershed receives among the highest annual precipitation rates in the State, ranging from 29 to 33 inches each year (Minnesota Department of Natural Resources State Climatology Office, 2012). Steep terrain in the lower part of the watershed increases the erosion potential. The Minnesota River at Mankato (site 12) also demonstrated high mean SSC (193 mg/L). Although the Minnesota River Valley has low relief in the valley, the edges of the river valley are lined with steep bluffs and ravines (Minnesota Pollution Control Agency, 2009c). The Zumbro River at Kellogg produced the single highest SSC of 1,250 mg/L at a streamflow of 1,800 cubic feet per second (ft^3/s) during the 2011 spring snowmelt runoff. The Wild Rice River near Ada (site 4) had a mean SSC of 184 mg/L, similar in magnitude to the Minnesota River. Elevated SSC on the main stem of the Wild Rice River has been linked to cultivated agriculture (Brigham and others, 2001) and artificial channelization of the main stem from flood-control projects dating back to 1954 (Board of Soil and Water Resources, 2003). Excessive bank erosion, eroded surface soils, and channel degradation occurring upstream from the city of Ada excaberates sediment aggradation and flooding downstream from Ada. One of the lowest mean SSCs of 37 mg/L was measured at the South Branch Wild Rice River near Ulen (site 5).

The lowest mean SSC of 21 mg/L was measured at Rice Creek (site 10) in the northern Minneapolis-St. Paul metropolitan area. The lowest SSCs of 2 mg/L were measured at the Little Cobb River near Beauford (site 11) on December 28, 2010, at a streamflow of 70 ft^3/s; at Rice Creek on September 15, 2010, at a streamflow of 32 ft^3/s; and at the Knife River near Two Harbors (site 1) on September 10, 2008, at a streamflow of 5 ft^3/s.

TSS samples were collected concurrently with SSC at seven sites, and TSS concentrations followed similar spatial patterns as SSC (table 3). For example, the largest mean TSS concentration of 182 mg/L was measured at the Zumbro River, whereas the smallest mean TSS of 25 mg/L was measured at the Little Fork River at Littlefork (site 8).

Variability in turbidity measurements was relatively smaller than SSC variability and followed spatial patterns similar to those of SSC and TSS (table 3). The Zumbro River, Wild Rice River near Ada, and the Minnesota River had the largest mean turbidity values of 101, 89, and 61 NTRUs, respectively. Rice Creek had the smallest single turbidity value along with a very narrow range of values, ranging from 1 to 9 NTRU. The narrow range of values observed at Rice Creek is attributed to the combined effect of low SSC and high percentage of sand-sized particles. Laboratory trials indicate that turbidity sensors are less sensitive to sand-sized particles than to fine-sized particles (Conner and De Visser, 1992; Hatcher and others, 2000).

For particle sizes, suspended fines (sediment sizes less than 0.0625 mm) were measured in markedly higher percentages than suspended sands at all sites, with the exception of Rice Creek. The largest mean percentage of fines was at the Wild Rice River at Hendrum (site 7), where 92 percent of the material in suspension consisted of fines. Other large mean percentages of fines were at the South Branch Buffalo River at Sabin (site 2), Wild Rice River at Twin Valley (site 3), and the Little Fork River with 88, 83 and 84 percent, respectively (table 3). Suspended fines noticeably were lower at Rice Creek when compared to other sites. Although fine-sized particles composed most of the total suspended sediment, the percentage of suspended sands was appreciable for many samples at many sites. The largest mean percentage of sand particles in suspension was observed at Rice Creek, where an average of 45 percent of the material in suspension was sand-sized. Other substantial mean percentages of sands were measured at the Zumbro River, South Branch Wild Rice River near Felton (site 6), and the Minnesota River with 35, 33, and 28 percent, respectively.

Comparison between Suspended-Sediment Concentrations and Total Suspended Solids

The MPCA adopted TSS sampling and laboratory procedures as a measure of fluvial suspended sediment in the early 1970s. A study by Gray and others (2000) reported that TSS concentrations were biased negatively when compared to SSC. Given this negative bias, MPCA staff were interested in quantifying the differences between SSC and TSS in Minnesota streams. For this analysis, the Wilcoxon signed-rank test (Helsel and Hirsch, 2002) was used to test if concurrently sampled pairs of SSC and TSS were different within sites. Box plots show wide variation in SSC and TSS at all sites (fig. 7) and are consistent with the Wilcoxon signed-rank test results (table 4) that indicate median values of SSC were larger than median values of TSS at each of the seven sites where TSS samples were collected concurrently with SSC. Percent difference (PD) was used to quantify the magnitude of the difference between SSC and TSS concentrations. The overall PD between SSC and TSS median concentrations was 50 percent. The largest PD between median values of SSC and TSS occurred at the South Branch Buffalo River and the smallest difference occurred at the Des Moines River (table 4).

Table 3. Summary statistics for suspended-sediment concentrations, total suspended solids, turbidity, and particle sizes for selected sites in Minnesota, 2007 through 2011.

[mg/L, milligrams per liter; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; total N, total number of samples; std. dev., standard deviation; --, not measured]

Statistic	Suspended-sediment concentration (mg/L)	Suspended fines (percent)	Total suspended solids (mg/L)	Turbidity (NTRU)	Suspended sands (mg/L)	Suspended fines (mg/L)
Knife River near Two Harbors, Minn. (site 1)						
Minimum	2	31	1	1	1	2
Mean	60	80	29	34	14	46
Median	16	84	5	14	1	16
Maximum	414	99	240	210	108	335
Total N	31	31	21	31	31	31
Std. dev.	99.0	18.5	59.2	51.4	27.1	81.0
South Branch Buffalo River at Sabin, Minn. (site 2)						
Minimum	21	50	11	13	1	17
Mean	94	88	38	45	12	81
Median	69	92	24	27	5	57
Maximum	408	99	100	160	72	384
Total N	43	43	28	43	43	43
Std. dev.	75.0	11.6	28.9	37.4	16.0	70.5
Wild Rice River at Twin Valley, Minn. (site 3)						
Minimum	3	43	--	5	1	3
Mean	112	83	--	60	18	85
Median	40	89	--	25	5	22
Maximum	775	98	--	400	93	690
Total N	29	29	--	29	29	29
Std. dev.	171.3	15.8	--	92.7	27.0	154.6
Wild Rice River near Ada, Minn. (site 4)						
Minimum	6	33	--	4	1	5
Mean	185	75	--	89	47	122
Median	39	76	--	27	7	19
Maximum	1,140	96	--	680	332	980
Total N	29	29	--	29	29	29
Std. dev.	287.7	15.9	--	153.0	83.0	239.9
South Branch Wild Rice River near Ulen, Minn. (site 5)						
Minimum	3	18	--	3	1	3
Mean	37	74	--	16	12	23
Median	25	82	--	7	3	17
Maximum	118	98	--	77	85	71
Total N	25	25	--	25	25	25
Std. dev.	31.5	22.3	--	20.8	19.7	17.8

Table 3. Summary statistics for suspended-sediment concentrations, total suspended solids, turbidity, and particle sizes for selected sites in Minnesota, 2007 through 2011.—Continued

[mg/L, milligrams per liter; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; total N, total number of samples; std. dev., standard deviation; --, not measured]

Statistic	Suspended-sediment concentration (mg/L)	Suspended fines (percent)	Total suspended solids (mg/L)	Turbidity (NTRU)	Suspended sands (mg/L)	Suspended fines (mg/L)
South Branch Wild Rice River near Felton, Minn. (site 6)						
Minimum	4	5	--	1	0	2
Mean	94	67	--	52	30	54
Median	55	66	--	9	13	34
Maximum	715	100	--	500	307	408
Total N	27	27	--	27	27	27
Std. dev.	155.0	21.5	--	119.9	62.2	82.3
Wild Rice River at Hendrum, Minn. (site 7)						
Minimum	15	76	--	12	1	14
Mean	99	92	--	80	8	95
Median	65	95	--	52	7	62
Maximum	474	99	--	350	47	427
Total N	27	27	--	27	27	27
Std. dev.	93.3	6.1	--	85.2	9.5	87.8
Little Fork River at Littlefork, Minn. (site 8)						
Minimum	9	25	4	6	0	7
Mean	37	84	25	23	7	31
Median	23	90	12	16	2	17
Maximum	181	100	150	140	75	161
Total N	35	35	19	35	35	35
Std. dev.	36.7	18.6	34.0	27.1	14.1	31.9
Buffalo Creek near Glencoe, Minn. (site 9)						
Minimum	5	34	3	3	1	4
Mean	63	79	30	27	15	48
Median	44	86	20	19	8	30
Maximum	298	98	81	92	86	262
Total N	43	43	18	43	43	43
Std. dev.	65.2	17.3	23.0	25.9	20.2	53.2
Rice Creek below Old Highway 8 in Mounds View, Minn. (site 10)						
Minimum	2	17	--	1	1	1
Mean	21	55	--	4	10	11
Median	16	60	--	4	9	7
Maximum	56	95	--	9	46	42
Total N	21	21	--	21	21	21
Std. dev.	16.4	18.6	--	2.2	10.4	10.7

Table 3. Summary statistics for suspended-sediment concentrations, total suspended solids, turbidity, and particle sizes for selected sites in Minnesota, 2007 through 2011.—Continued

[mg/L, milligrams per liter; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; total N, total number of samples; std. dev., standard deviation; --, not measured]

Statistic	Suspended-sediment concentration (mg/L)	Suspended fines (percent)	Total suspended solids (mg/L)	Turbidity (NTRU)	Suspended sands (mg/L)	Suspended fines (mg/L)
Little Cobb River near Beauford, Minn. (site 11)						
Minimum	2	27	13	7	1	17
Mean	103	79	49	52	24	84
Median	92	86	39	28	13	62
Maximum	346	99	170	200	106	339
Total N	68	68	24	68	68	68
Std. dev.	67.4	19.6	37.1	53.4	27.9	65.9
Minnesota River at Mankato, Minn. (site 12)						
Minimum	27	15	--	5	1	19
Mean	193	72	--	61	58	99
Median	151	76	--	30	20	84
Maximum	671	98	--	170	236	335
Total N	33	33	--	33	33	33
Std. dev.	154.9	21.3	--	65.7	78.0	78.4
Zumbro River at Kellogg, Minn. (site 13)						
Minimum	17	2	7	2	3	10
Mean	226	65	182	101	81	145
Median	107	71	61	16	28	70
Maximum	1,250	96	1,100	990	646	938
Total N	34	34	17	34	34	34
Std. dev.	305.9	23.5	299.8	229.4	136.3	228.3
Des Moines River at Jackson, Minn. (site 14)						
Minimum	18	41	39	18	1	14
Mean	116	78	95	60	29	87
Median	103	84	74	51	16	82
Maximum	314	99	350	210	185	285
Total N	26	26	20	26	26	26
Std. dev.	81.0	20.6	69.3	46.2	41.1	61.8

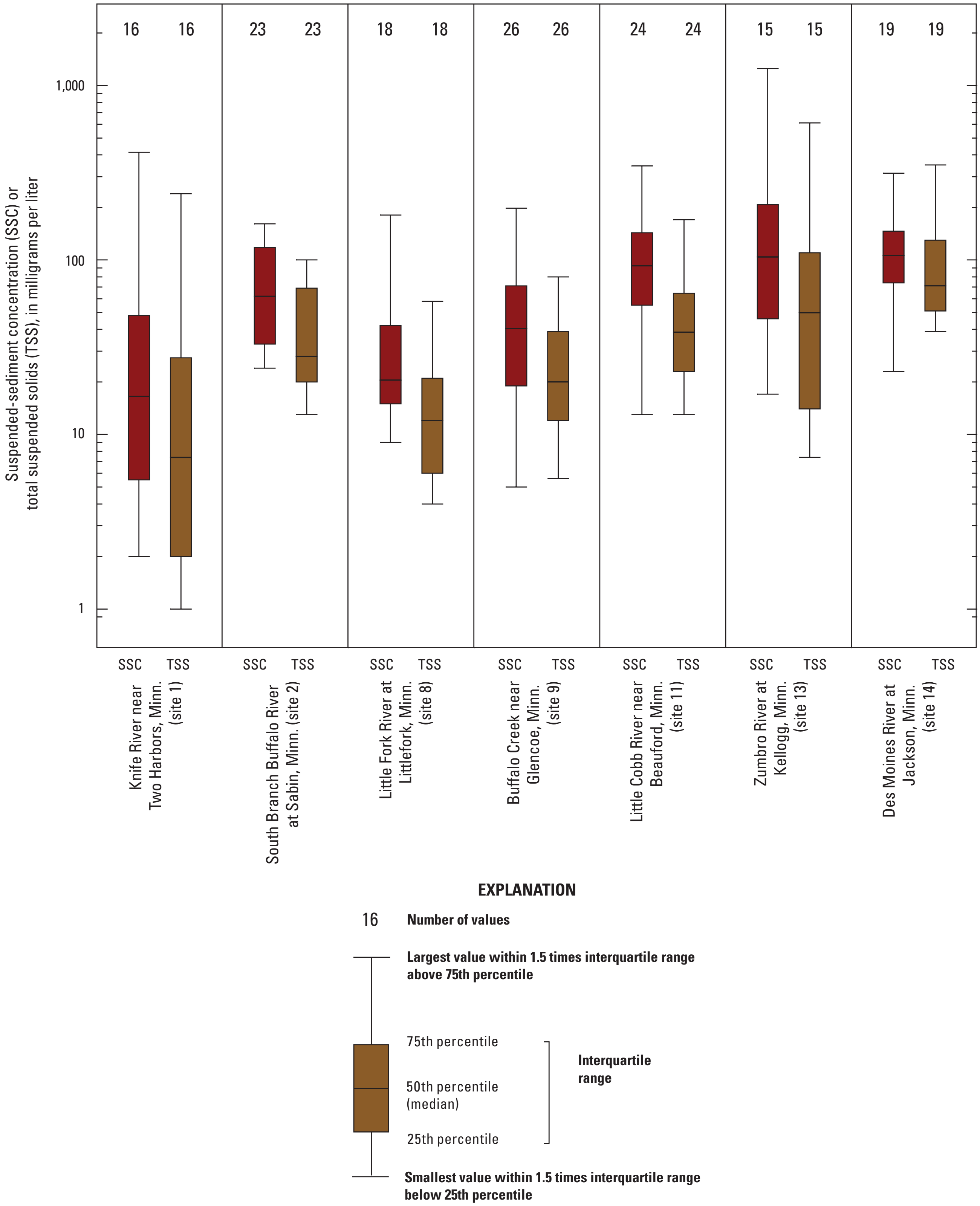


Figure 7. Suspended-sediment concentrations and total suspended solids for selected sites in Minnesota, 2007 through 2011.

Table 4. Summary of Wilcoxon signed-rank tests used to evaluate differences between suspended-sediment concentrations and total suspended solids for selected monitoring sites in Minnesota, 2007 through 2011.

[Z-score is a measure of standard deviation (values greater than 1.96 or less than -1.96 indicate population medians are different). The *p*-value is a measure of the likelihood that the null hypothesis is correct. In this case, the *p*-value indicates whether the two population medians are equal. A *p*-value of 0.05 typically is used as the threshold value to indicate there is a 5-percent probability that the medians are equal. SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; Z, Z-score; PD, percent difference; Minn., Minnesota; <, less than]

Site number (figs. 1–4)	Station name	Number of paired samples	SSC median (mg/L)	TSS median (mg/L)	Z	PD[a] (percent)	*p*-value
1	Knife River near Two Harbors, Minn.	19	16	7	3.75	56	<0.01
2	South Branch Buffalo River at Sabin, Minn.	25	63	24	4.29	62	<0.01
8	Little Fork River at Littlefork, Minn.	18	28	12	3.70	57	<0.01
9	Buffalo Creek near Glencoe, Minn.	28	50	20	3.91	60	<0.01
11	Little Cobb River near Beauford, Minn.	24	70	39	3.99	44	<0.01
13	Zumbro River at Kellogg, Minn.	17	104	61	3.45	41	<0.01
14	Des Moines River at Jackson, Minn.	19	106	71	2.39	33	0.02

[a]Calculation of percent difference is $[(x_1-x_2)/x_1] \times 100$, where x_1 = SSC median concentration and x_2 = TSS median concentration.

Relations among Streamflow, Suspended-Sediment Concentrations, Total Suspended Solids, and Turbidity

Variation in streamflow provides important information for the timing and changes in sediment concentrations and has widely been used to develop SSC prediction models. Turbidity, SSC, and TSS inherently are related given that each principally is a measure of suspended sediment in streams. The association of SSC and TSS to streamflow typically is used in the calculation of suspended-sediment and TSS loads. Historically, the USGS computed daily suspended-sediment loads based on the relation between SSC and streamflow in conjunction with an interpolative process using near-daily sediment sampling (Porterfield, 1972). Suspended-sediment loads also are calculated using a regression approach based on the relation between SSC or TSS with streamflow and other variables using models such as LOADEST (Runkel and others, 2004). The advancement of in-stream turbidity sensors and the development of the turbidity-SSC surrogate procedures (Rasmussen and others, 2009) offer an opportunity to improve the evaluation of suspended-sediment transport in streams and the estimation of suspended-sediment loads. In general, higher streamflows transport larger amounts of sediment. In Minnesota, the magnitude and timing of streamflow typically is highest in the spring because of melting of the winter snowpack. Streamflow usually diminishes following spring runoff and alternately rises and lowers with varying magnitudes in response to storm events through the rest of the year. Streamflow tends to drop gradually during the summer with low flow reached in late August or September. Larger rivers such as the Minnesota River, the Little Fork River, and the Red River of the North generally rise and maintain their flows longer during precipitation events when compared to smaller streams, such as the Knife River.

Relations between Suspended-Sediment Concentrations and Streamflow

Streamflow has been used predominantly as the primary explanatory variable for SSC even though streamflow is not always directly related to SSC and the relation between the two is known to vary extensively (Guy, 1970; Tornes, 1986; Tornes and others, 1997; Blanchard and others, 2011). According to Knighton (1998), this variation occurs largely because the dominant control on SSC is the rate of supply, which is affected by myriad factors such as sediment availability, season, watershed size, and source location within the watershed. Considerable variation in SSC also may be the result of a hysteresis effect with streamflow. Clockwise hysteresis (higher sediment concentration on the rising limb of the hydrograph) is common in small watersheds because sediment sources are closer to the stream channel. Counterclockwise hysteresis may occur in large watersheds where upstream sources continue to supply the bulk of the load after the streamflow peak occurs (Knighton, 1998). Seasonal differences contribute to the variation in SSC because sediment transport typically is greater in the spring during snowmelt runoff. The availability of sediment at their sources also affects how SSC varies with streamflow at a particular location. Because of these and other factors, the variation and range of SSCs during any runoff event may differ from the concentrations during other periods, even though streamflow may be identical or similar (Porterfield, 1972).

The relation between SSC and streamflow for each site is illustrated in figure 8. Best-fit regression lines represent the relation between SSC and streamflow, and can be used to evaluate how SSC responds to changes in streamflow within and among sites. The gradient of the lines provides an indication of how quickly SSC changes with changes in streamflow. The strength

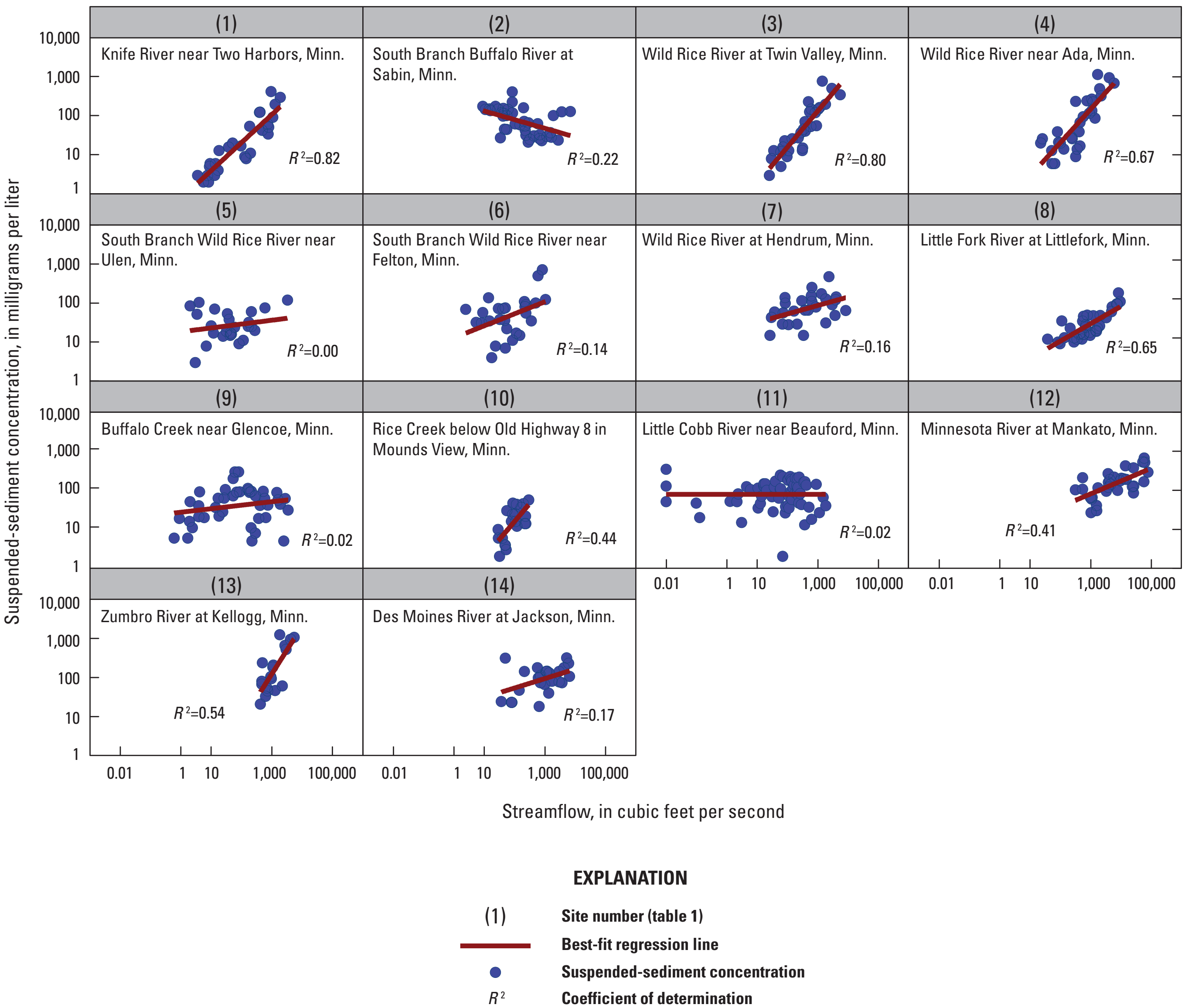


Figure 8. Relation between suspended-sediment concentrations and streamflow for selected sites in Minnesota, 2007 through 2011.

of the relation also can be seen in how closely the observed data fall along the regression line. Lines with steep positive gradients from left to right indicate SSC increases quickly as streamflow increases. In this study, the sites with the steepest gradients were the Knife River, Wild Rice River near Twin Valley, Wild Rice River near Ada, Little Fork River, Rice Creek, Minnesota River, and Zumbro River. Moderate gradients were observed at the South Branch Wild Rice River near Felton and the Des Moines River. Low or level gradients indicate that SSC changes little as streamflow increases. This was observed at the South Branch Wild Rice River near Ulen, Buffalo Creek, and the Little Cobb River. The negative relation, indicated by a negative gradient, for the South Branch Buffalo River, is unusual. Negative gradients indicate that the amount of suspended sediment in streams may be diluted during increased streamflow due to limited supply. Studies in the Red River watershed indicate that SSC and streamflow may be correlated poorly. Blanchard and others (2011) and Galloway and Nustad (2012) collected SSC and streamflow data at sites in the Red River watershed near Fargo, North Dakota, during the 2010 and 2011 spring high-flow events and during the summer of 2011. Their evaluations of the relation between SSC and streamflow indicated that only two of the six sites sampled during the 2010 spring runoff event had significant relations.

Results of the SLR analysis between SSC and streamflow presented in table 5 provide a quantitative description of the plots shown in figure 8. Wide ranges in R^2 values, relative percent errors, and standard error values for the SLR models were determined from data analyses for the study. The relation between SSC and streamflow was significant statistically (p-value < 0.05) at 11 of the 14 sites (table 5). The strongest correlations between SSC and streamflow were determined for the Knife River (R^2=0.82) and the Wild Rice River at Twin Valley (R^2=0.80). The Wild Rice River near Ada, Little Fork River, and Zumbro River had moderate R^2 values of 0.67, 0.65, and 0.54, respectively. Rice Creek and the Minnesota River had modest R^2 values of 0.44 and 0.41, respectively. The remainder of the sites (7 out of 14 sites) had poor relations between SSC and streamflow. The three sites that did not have a significant relation were the South Branch Wild Rice River near Ulen, Buffalo Creek, and Little Cobb River.

Relations between Suspended-Sediment Concentrations and Total Suspended Solids

The relation between SSC and TSS for the seven sites where SSC and TSS were collected concurrently is illustrated in figure 9, and the SLR models are presented in table 6. Although the relation between SSC and TSS is variable among sites, figure 9 indicates that the overall fit of the data is fairly good. Most data points plot above the 1:1 line in figure 9, indicating that SSC consistently is larger than TSS concentrations for all sites. This is quantified with the SLR slope coefficients in the regression models listed in table 6, which are greater than 1 for each site.

Table 5. Summary of simple linear regression models to evaluate suspended-sediment concentrations using streamflow as the explanatory variable for selected sites in Minnesota, 2007 through 2011.

[mg/L, milligrams per liter; R^2, coefficient of determination; RPE, relative percent error between sample and model results; BCF, Duan's bias correction factor; Minn., Minnesota; *SSC*, suspended-sediment concentration; *Q*, daily mean streamflow; <, less than]

Site number (figs. 1–4)	Station name	Number of samples used for regression	Regression model (mg/L)	R^2	RPE (percent)	Standard error residual (mg/L)	p-value	BCF
1	Knife River near Two Harbors, Minn.	27	$SSC = 0.9276 \times Q^{0.7175}$	0.82	-14.4	12.7	<0.01	1.227
2	South Branch Buffalo River at Sabin, Minn.	40	$SSC = 280.7 \times Q^{-0.2213}$	0.22	280.7	10.7	<0.01	1.270
3	Wild Rice River at Twin Valley, Minn.	29	$SSC = 0.2691 \times Q^{0.9241}$	0.80	0.4	25.8	<0.01	1.212
4	Wild Rice River near Ada, Minn.	29	$SSC = 0.5526 \times Q^{0.8579}$	0.67	-4.7	34.0	<0.01	1.417
5	South Branch Wild Rice River near Ulen, Minn.[a]	25	$SSC = 26.1 \times Q^{0.0987}$	0.00	2.1	6.2	0.34	1.423
6	South Branch Wild Rice River near Felton, Minn.	27	$SSC = 20.93 \times Q^{0.3085}$	0.14	-10.3	26.1	0.03	1.643
7	Wild Rice River at Hendrum, Minn.	27	$SSC = 24.84 \times Q^{0.2163}$	0.16	-0.6	17.0	0.02	1.284
8	Little Fork River at Littlefork, Minn.	32	$SSC = 1.360 \times Q^{0.4563}$	0.65	-3.9	3.8	<0.01	1.119
9	Buffalo Creek near Glencoe, Minn.[a]	42	$SSC = 43.2 \times Q^{0.0897}$	0.02	-0.4	10.2	0.19	1.581
10	Rice Creek below Old Highway 8 in Mounds View, Minn.	21	$SSC = 0.2842 \times Q^{0.9223}$	0.44	6.1	3.1	<0.01	1.263
11	Little Cobb River near Beauford, Minn.[a]	68	$SSC = 102 \times Q^{0.0003}$	0.02	0.0	8.2	0.99	1.310
12	Minnesota River at Mankato, Minn.	32	$SSC = 9.738 \times Q^{0.3286}$	0.41	0.1	20.0	<0.01	1.173
13	Zumbro River at Kellogg, Minn.	18	$SSC = 0.0348 \times Q^{1.2314}$	0.54	-29.8	61.5	<0.01	1.399
14	Des Moines River at Jackson, Minn.	25	$SSC = 23.07 \times Q^{0.2419}$	0.17	6.4	15.6	0.02	1.313

[a]Streamflow (*Q*) is not a statistically significant parameter in explaining the variation in *SSC*.

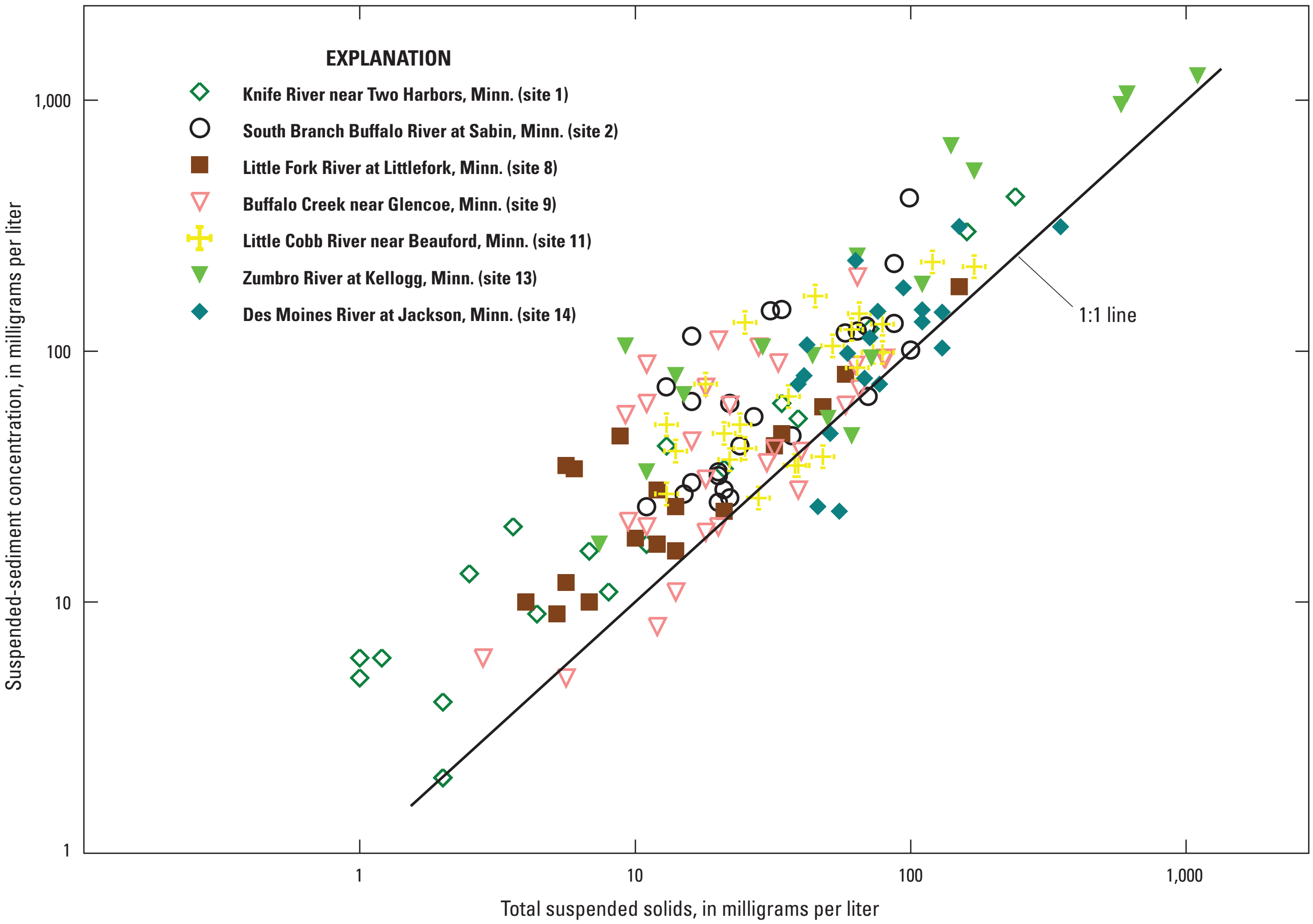


Figure 9. Relation between suspended-sediment concentration and total suspended solids for selected sites in Minnesota, 2007 through 2011.

Table 6. Summary of simple linear regression models to evaluate suspended-sediment concentrations using total suspended solids as the explanatory variable for selected sites in Minnesota, 2007 through 2011.

[mg/L, milligrams per liter; R^2, coefficient of determination; RPE, relative percent error between sample and model results; BCF, Duan's bias correction factor; Minn., Minnestoa; *SSC*, suspended-sediment concentration; *TSS*, total suspended solids; <, less than]

Site number (figs. 1–4)	Station name	Number of samples used for regression	Regression model (mg/L)	R^2	Average RPE (percent)	Standard error residual (mg/L)	*p*-value	BCF
1	Knife River near Two Harbors, Minn.	19	$SSC = 3.541 \times TSS^{0.8485}$	0.88	-1.8	3.7	<0.01	1.127
2	South Branch Buffalo River at Sabin, Minn.	25	$SSC = 4.765 \times TSS^{0.8083}$	0.51	-0.1	12.1	<0.01	1.157
8	Little Fork River at Littlefork, Minn.	18	$SSC = 5.117 \times TSS^{0.6708}$	0.67	0.6	3.3	<0.01	1.111
9	Buffalo Creek near Glencoe, Minn.	28	$SSC = 4.777 \times TSS^{0.7652}$	0.44	7.2	6.9	<0.01	1.257
11	Little Cobb River near Beauford, Minn.	24	$SSC = 6.301 \times TSS^{0.6885}$	0.51	0.2	7.0	<0.01	1.101
13	Zumbro River at Kellogg, Minn.	17	$SSC = 7.747 \times TSS^{0.7621}$	0.78	4.4	33.7	<0.01	1.172
14	Des Moines River at Jackson, Minn.	19	$SSC = 2.693 \times TSS^{0.8639}$	0.41	3.3	2.9	<0.01	1.130

The coefficients of determination (R^2) for the relation between SSC and TSS in the SLR models are listed in table 6. The R^2 values for the regression models are noticeably larger for the SSC-TSS models than for the SSC-streamflow models. The biggest increase in R^2 between the SSC-streamflow models and SSC-TSS models was for Buffalo Creek and the Little Cobb River, where values increased from 0.02 to 0.44 and 0.02 to 0.51, respectively. At the Zumbro River and Des Moines River, R^2 values increased from 0.54 to 0.78 and from 0.17 to 0.41, respectively. The R^2 value for the South Branch Buffalo River increased from 0.22 to 0.51. The Knife River and the Little Fork River had modest increases in R^2 (6 and 2 percent, respectively) between the SSC-streamflow models and the SSC-TSS models.

Relations between Suspended-Sediment Concentrations and Turbidity

The overall relation between SSC and turbidity is shown in figure 10, and regression models for the SSC-turbidity relation are presented in table 7. The R^2 values for the SSC-streamflow models and SSC-turbidity models indicated that turbidity was correlated more strongly to SSC than was streamflow at all sampling sites (tables 5 and 7). Among the largest increases in R^2 was at the Wild Rice River at Hendrum, which increased from 0.16 to 0.86 between the SSC-streamflow model and SSC-turbidity model. Two sites, the Knife River and the Wild Rice River at Twin Valley, had modest increases in R^2 values from 0.82 to 0.87 and from 0.80 to 0.82, respectively. The Wild Rice River near Ada, the Little Fork River, and the Zumbro River, had notable increases in R^2 values from 0.67 to 0.85, 0.65 to 0.82, and 0.54 to 0.63, respectively. Five sites with poor or no relation between SSC and streamflow had significant correlations and large increases in R^2 when using turbidity as the explanatory variable. For example, R^2 values for the Wild Rice River near Ulen and the Little Cobb River increased from 0.00 to 0.57 and from 0.02 to 0.70, respectively. For the South Branch Buffalo River, South Branch Wild Rice River near Felton, and Buffalo Creek, R^2 values increased from 0.22 to 0.54, from 0.14 to 0.50, and from 0.02 to 0.25, respectively. The smallest change was for Rice Creek, where only a 1-percent increase in R^2 was determined. These results indicate that turbidity was superior to streamflow in estimating SSC, and that turbidity may be beneficial as a surrogate for SSC in many of Minnesota's rivers.

Relations between Suspended-Sediment Concentrations and Streamflow and Turbidity

Stepwise regression procedures were used to evaluate whether the SLR of SSC with streamflow could be improved by including turbidity in a MLR to improve the results of the model (table 8). In only 2 of the 14 models, streamflow alone produced the best model. In five models, turbidity alone produced the best model, and in seven models, turbidity combined with streamflow produced the best model.

Unique circumstances met at the South Branch Wild Rice River near Ulen and Felton affected development of the optimum model. During the study, dune migration was observed at both sites, which altered the channel bed by forming a convex mound in the stream cross-section. The consequence of the dune mound in the channel was episodic high SSC values during periods of low streamflow. This occurred on occasion when stream velocity accelerated over the dune and generated turbulence that remobilized the sand particles. Removing the outlier SSC values, which were judged to be non-representative of natural conditions at low streamflow, substantially improved the model.

Estimated Suspended-Sediment Loads and Basin Yields

Suspended-sediment, TSS, suspended-sand, and suspended-fine sediment loads were estimated using the S-LOADEST program. The S-LOADEST program incorporates time-series data for streamflow, a dataset of constituent concentrations, and a time component to estimate annual and seasonal loads for the constituent of interest. The form of the regression equation used in the S-LOADEST model was described previously in equation 7.

Annual and Seasonal Suspended-Sediment Loads

Annual and seasonal suspended-sediment loads were estimated for 12 of the 14 sites for which continuous-record streamflow data were available or could be estimated using streamflow data from nearby streamgages. Loads were not estimated for Buffalo Creek and the Zumbro River because continuous streamflow data were not available; streamgages at these sites were taken out of service from December through March per MDNR/MPCA streamgaging procedures at the time (Lisa Pearson, Minnesota Department of Natural Resources, oral commun., November 2012).

For the data collected during this study, the S-LOADEST regression coefficients and R^2 for each site are presented in table 9. The R^2 value measures the variation in the data about the S-LOADEST models. High R^2 values indicate that the model is a good predictor of the observed sediment loads based on streamflow and time. The relation between suspended-sediment load and streamflow for all sites is illustrated in figure 11. The large R^2 values for most of the models indicate that the S-LOADEST models were successful in minimizing the observed variability in suspended-sediment loads (table 9). The annual loads for suspended sediment, TSS, suspended sands, and suspended fines computed with S-LOADEST along with upper and lower 95-percent confidence intervals are presented in table 10.

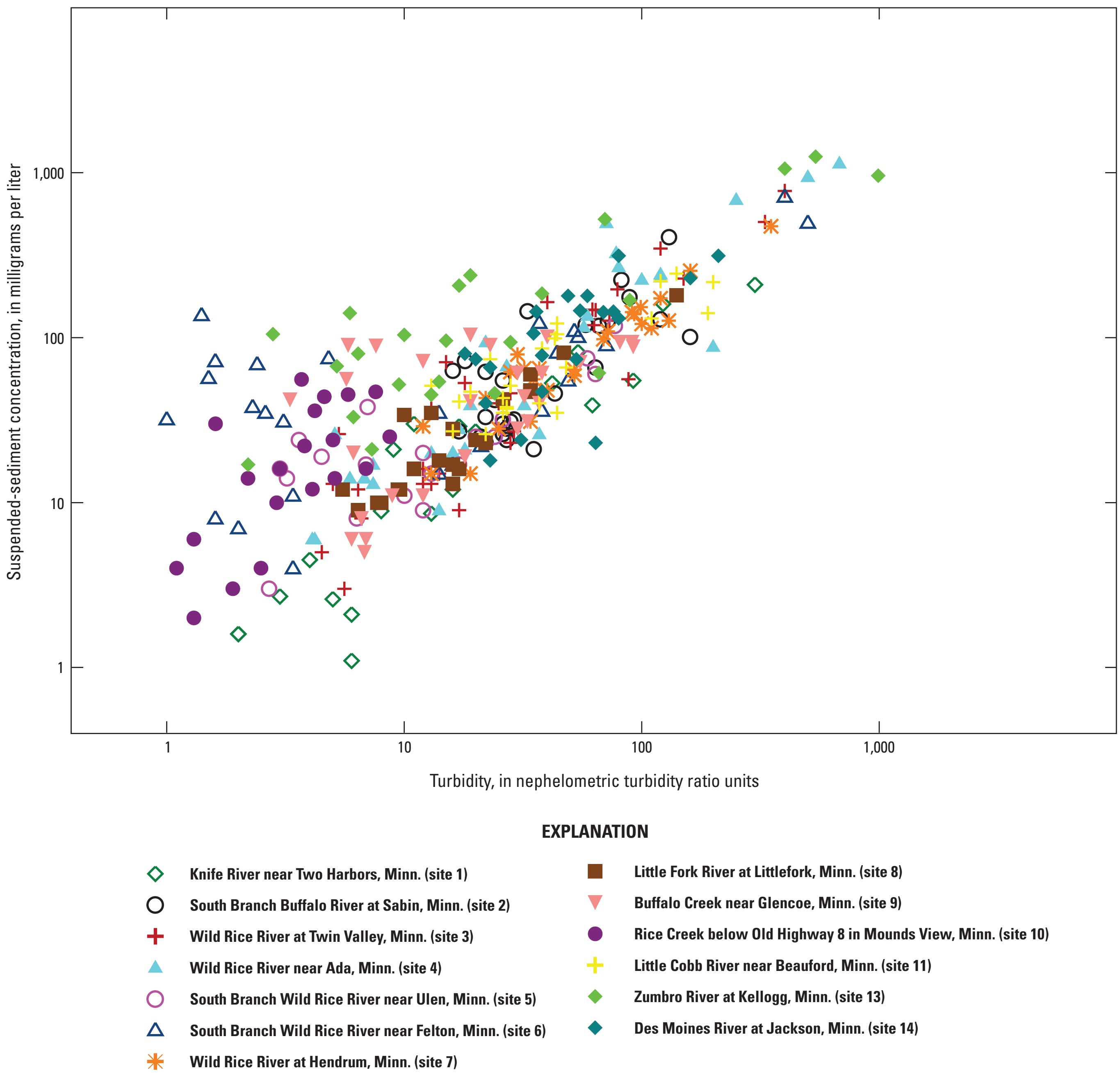


Figure 10. Relation between suspended-sediment concentration and turbidity for selected sites in Minnesota, 2007 through 2011.

Table 7. Summary of regression models to evaluate suspended-sediment concentrations using turbidity as the explanatory variable for selected sites in Minnesota, 2007 through 2011.

[mg/L, milligrams per liter; R^2, coefficient of determination; RPE, relative percent error between sample and model results; BCF, Duan's bias correction factor; Minn., Minnesota; *SSC*, suspended-sediment concentration; *Turb*, turbidity; <, less than]

Site number (figs. 1–4)	Station name	Number of samples used for regression	Regression model (mg/L)	R^2	RPE (percent)	Standard error residual (mg/L)	*p*-value	BCF
1	Knife River near Two Harbors, Minn.	20	$SSC = 3.452 \times Turb^{0.1686} \times (Turb^2)^{0.2821}$	0.87	4.7	7.5	<0.01	1.110
2	South Branch Buffalo River at Sabin, Minn.	27	$SSC = 2.520 \times Turb^{0.9061}$	0.54	-0.9	11.6	<0.01	1.156
3	Wild Rice River at Twin Valley, Minn.	29	$SSC = 1.6789 \times Turb^{1.0442}$	0.82	9.9	11.1	<0.01	1.184
4	Wild Rice River near Ada, Minn.	29	$SSC = 2.2175 \times Turb^{1.0041}$	0.85	8.1	24.8	<0.01	1.177
5	South Branch Wild Rice River near Ulen, Minn.	19	$SSC = 16.74 \times Turb^{-0.4312} \times (Turb^2)^{0.4518}$	0.57	49.8	3.8	<0.01	1.125
6	South Branch Wild Rice River near Felton, Minn.	26	$SSC = 50.37 \times Turb^{-0.531} \times (Turb^2)^{0.3827}$	0.50	0.1	25.3	<0.01	1.319
7	Wild Rice River at Hendrum, Minn.	26	$SSC = 2.261 \times Turb^{0.8979}$	0.86	11.0	12.9	<0.01	1.043
8	Little Fork River at Littlefork, Minn.	23	$SSC = 1.784 \times Turb^{0.9428}$	0.82	0.7	1.7	<0.01	1.056
9	Buffalo Creek near Glencoe, Minn.	27	$SSC = 10.43 \times Turb^{0.5468}$	0.25	10.1	6.1	<0.01	1.383
10	Rice Creek below Old Highway 8 in Mounds View, Minn.	20	$SSC = 3.487 Turb^{2.022}$	0.45	69.5	15.5	<0.01	1.266
11	Little Cobb River near Beauford, Minn.	23	$SSC = 4.765 \times Turb^{0.7351}$	0.70	0.5	7.0	<0.01	1.067
13	Zumbro River at Kellogg, Minn.	24	$SSC = 23.19 \times Turb^{0.6105}$	0.63	4.4	37.4	<0.01	1.261
14	Des Moines River at Jackson, Minn.	21	$SSC = 4.751 \times Turb^{0.8088}$	0.38	2.3	11.3	<0.01	1.164

Table 8. Summary of stepwise regression models to evaluate suspended-sediment concentration for selected sites in Minnesota, 2007 through 2011.

[mg/L, milligrams per liter; R^2, coefficient of determination; RPE, relative percent error between sample and model results; AIC, Akaike's Information Criteria; BCF, Duan's bias correction factor; Minn., Minnesota; *SSC*, suspended-sediment concentration; *Q*, daily mean streamflow; *Turb*, turbidity; <, less than]

Site number (figs. 1–4)	Station name	Number of samples used for regression	Model (mg/L)	R^2	RPE (percent)	Standard error residual (mg/L)	AIC	BCF	*p*-value
1	Knife River near Two Harbors, Minn.	19	$SSC = 1.39 \times Q^{0.258} \times Turb^{0.536}$	0.85	-1.8	3.7	1.28	1.127	<0.01
2	South Branch Buffalo River at Sabin, Minn.	23	$SSC = 6.03 \times Q^{-0.174} \times Turb^{0.920}$	0.65	6.5	10.5	1.02	1.090	<0.01
3	Wild Rice River at Twin Valley, Minn.	29	$SSC = 0.395 \times Q^{0.492} \times Turb^{0.602}$	0.90	2.2	12.8	1.21	1.089	<0.01
4	Wild Rice River near Ada, Minn.	29	$SSC = 1.069 \times Q^{0.244} \times Turb^{0.799}$	0.86	8.1	24.8	1.97	1.177	<0.01
5	South Branch Wild Rice River near Ulen, Minn.[a]	17	$SSC = 5.066 \times Q^{0.377}$	0.60	-8.9	3.4	0.582	1.133	<0.01
6	South Branch Wild Rice River near Felton, Minn.	26	$SSC = 50.37 \times Turb^{-0.531} \times (Turb^2)^{0.383}$	0.50	0.1	25.3	3.95	1.319	<0.01
7	Wild Rice River at Hendrum, Minn.	26	$SSC = 2.26 \times Turb^{0.898}$	0.86	11.0	12.9	0.501	1.043	<0.01
8	Little Fork River at Littlefork, Minn.	23	$SSC = 1.78 \times Turb^{0.943}$	0.82	0.7	1.7	0.438	1.056	<0.01
9	Buffalo Creek near Glencoe, Minn.	28	$SSC = 9.48 \times Turb^{0.547}$	0.26	7.2	6.9	2.21	1.257	<0.01
10	Rice Creek below Old Highway 8 in Mounds View, Minn.	20	$SSC = 0.565 \times Q^{0.568} \times Turb^{0.748}$	0.55	6.0	2.9	1.93	1.225	<0.01
11	Little Cobb River near Beauford, Minn.	23	$SSC = 3.94 \times Q^{-0.0673} \times Turb^{0.848}$	0.78	0.2	6.0	0.507	1.043	<0.01
12	Minnesota River at Mankato, Minn.	32	$SSC = 9.74 \times Q^{0.329}$	0.41	0.1	20.0	0.631	1.173	<0.01
13	Zumbro River at Kellogg, Minn.	17	$SSC = 16.2 \times Turb^{0.681}$	0.67	4.4	33.7	2.06	1.172	<0.01
14	Des Moines River at Jackson, Minn.	19	$SSC = 0.417 \cdot Q^{0.274} \times Turb^{0.925}$	0.65	0.2	9.5	1.077	1.039	<0.01

[a]Outliers removed.

Table 9. Regression coefficients and coefficients of determination for models used to estimate loads of suspended sediment, particle-size fractions, and total suspended solids for selected sites in Minnesota, 2007 through 2011.

[The form of the regression equation is described in equation 7. β_0, regression intercept; β_1, β_2, β_3, β_4, regression coefficients that remain constant with time; T_c, central value of time; Q_c, central value of flow; R^2, coefficient of determination and represents the amount of variance explained by the model; Minn., Minnesota]

Site number (fig. 1–4)	Station name	β_0	Regression coefficient				T_c	Q_c	R^2
			β_1	β_2	β_3	β_4			
	Suspended-sediment load								
1	Knife River near Two Harbors, Minn.	0.9796	1.8563	0.0616	-0.7016	-0.4983	2009.62	83.60	0.97
2	South Branch Buffalo River at Sabin, Minn.	3.4489	0.7687	-0.0355	0.1999	-0.3270	2009.62	214.2	0.81
3	Wild Rice River at Twin Valley, Minn.	3.6020	1.9908	-0.1729	-0.1909	0.0253	2008.61	303.1	0.95
4	Wild Rice River near Ada, Minn.	3.9741	2.0115	-0.2259	-0.4118	0.2441	2008.75	288.2	0.94
5	South Branch Wild Rice River near Ulen, Minn.	1.4725	1.0887	-0.0838	-0.0663	0.3691	2008.65	53.56	0.82
6	South Branch Wild Rice River near Felton, Minn.	1.9277	1.3610	-0.2777	-0.1997	-0.3228	2008.81	62.50	0.81
7	Wild Rice River at Hendrum, Minn.	4.1124	1.0585	0.0986	0.2631	-0.6690	2008.51	432.0	0.91
8	Little Fork River at Littlefork, Minn.	4.0711	1.4013	0.0348	0.1264	0.0107	2009.66	806.3	0.95
10	Rice Creek below Old Highway 8 in Mounds View, Minn.	1.2440	1.4678	0.6671	0.4623	-0.0395	2011.02	89.47	0.82
11	Little Cobb River near Beauford, Minn.	1.1281	1.1193	-0.1569	0.0280	-0.4602	2009.45	20.99	0.88
12	Minnesota River at Mankato, Minn.	7.8113	1.4160	-0.2088	0.0406	0.0676	2009.48	6,195	0.94
14	Des Moines River at Jackson, Minn.	4.8307	1.3134	0.0441	-0.2725	0.1798	2009.62	537.7	0.89
	Suspended-sands load								
1	Knife River near Two Harbors, Minn.	-0.8381	1.8043	-0.1297	-1.1525	-0.7351	2009.62	83.60	0.93
2	South Branch Buffalo River at Sabin, Minn.	0.7918	0.4308	-0.1040	0.2961	-0.1331	2009.62	177.7	0.42
3	Wild Rice River at Twin Valley, Minn.	1.1818	2.3420	0.1064	-0.1586	0.3976	2008.41	244.5	0.91
4	Wild Rice River near Ada, Minn.	2.1275	2.1007	-0.4281	-0.7021	0.6187	2008.40	235.9	0.85
5	South Branch Wild Rice River near Ulen, Minn.	-1.1231	0.4220	0.2804	0.2451	0.0874	2008.60	31.47	0.25
6	South Branch Wild Rice River near Felton, Minn.	0.5818	1.1749	-0.2012	0.0338	-0.3872	2008.48	58.36	0.71
7	Wild Rice River at Hendrum, Minn.	1.5826	1.2843	-0.1516	-0.2769	-0.4489	2008.40	435.1	0.81
8	Little Fork River at Littlefork, Minn.	2.1809	1.3956	0.0283	0.1085	0.6997	2009.66	804.9	0.82
10	Rice Creek below Old Highway 8 in Mounds View, Minn.	0.1755	2.0773	0.2479	0.0304	-0.6207	2011.02	89.47	0.84
11	Little Cobb River near Beauford, Minn.	-0.8645	1.1977	-0.7411	-0.8198	-0.5940	2009.61	27.55	0.78
12	Minnesota River at Mankato, Minn.	6.0976	1.1681	-0.0596	1.2525	0.6418	2009.76	5,823	0.94
14	Des Moines River at Jackson, Minn.	2.4466	1.7138	0.3661	0.0670	0.2877	2009.62	537.7	0.90

Table 9. Regression coefficients and coefficients of determination for models used to estimate loads of suspended sediment, particle-size fractions, and total suspended solids for selected sites in Minnesota, 2007 through 2011.—Continued

[The form of the regression equation is described in equation 7. β_0, regression intercept; β_1, β_2, β_3, β_4, regression coefficients that remain constant with time; T_c, central value of time; Q_c, central value of flow; R^2, coefficient of determination and represents the amount of variance explained by the model; Minn., Minnesota]

Site number (fig. 1–4)	Station name	β_0	Regression coefficient				T_c	Q_c	R^2
			β_1	β_2	β_3	β_4			
	Suspended-fines load								
1	Knife River near Two Harbors, Minn.	0.7713	1.7318	0.0709	-0.1687	-0.1350	2009.62	83.60	0.92
2	South Branch Buffalo River at Sabin, Minn.	2.9534	0.7819	0.0049	0.1577	-0.5830	2009.62	177.7	0.81
3	Wild Rice River at Twin Valley, Minn.	2.9597	1.9542	-0.2832	-0.1820	-0.0883	2008.41	244.5	0.94
4	Wild Rice River near Ada, Minn.	3.2218	1.9670	-0.5210	-0.5114	0.1976	2008.40	235.9	0.94
5	South Branch Wild Rice River near Ulen, Minn.	0.4373	1.1747	-0.1419	-0.1839	0.2400	2008.60	31.47	0.84
6	South Branch Wild Rice River near Felton, Minn.	1.4008	1.3796	-0.2013	0.0598	-0.3252	2008.48	58.36	0.81
7	Wild Rice River at Hendrum, Minn.	4.2969	1.3140	-0.2263	-0.3503	-0.4289	2008.40	435.1	0.92
8	Little Fork River at Littlefork, Minn.	3.7462	1.3628	0.0572	0.2227	-0.1673	2009.66	804.9	0.95
10	Rice Creek below Old Highway 8 in Mounds View, Minn.	0.6649	1.0224	0.8071	0.6464	0.3060	2011.02	89.47	0.73
11	Little Cobb River near Beauford, Minn.	1.3379	1.1107	-0.2213	-0.0660	-0.2484	2009.61	27.55	0.92
12	Minnesota River at Mankato, Minn.	7.0310	1.2764	-0.0017	0.1194	-0.2178	2009.76	5,823	0.95
14	Des Moines River at Jackson, Minn.	4.5491	1.1901	0.0010	-0.3039	0.0501	2009.62	537.7	0.83
	Total suspended solids load								
1	Knife River near Two Harbors, Minn.	0.2321	1.9323	-0.1028	-0.7604	-0.6400	2009.85	89.25	0.97
2	South Branch Buffalo River at Sabin, Minn.	2.8995	0.9970	-0.1278	0.1963	-0.5754	2010.15	293.1	0.88
8	Little Fork River at Littlefork, Minn.	3.4804	1.6663	0.0221	0.0517	-0.0819	2010.31	812.5	0.98
11	Little Cobb River near Beauford, Minn.	0.0912	1.1332	-0.0264	0.0003	-1.2374	2009.53	23.98	0.96
14	Des Moines River at Jackson, Minn.	4.7658	0.9197	0.0340	0.1016	-0.0145	2010.36	527.1	0.89

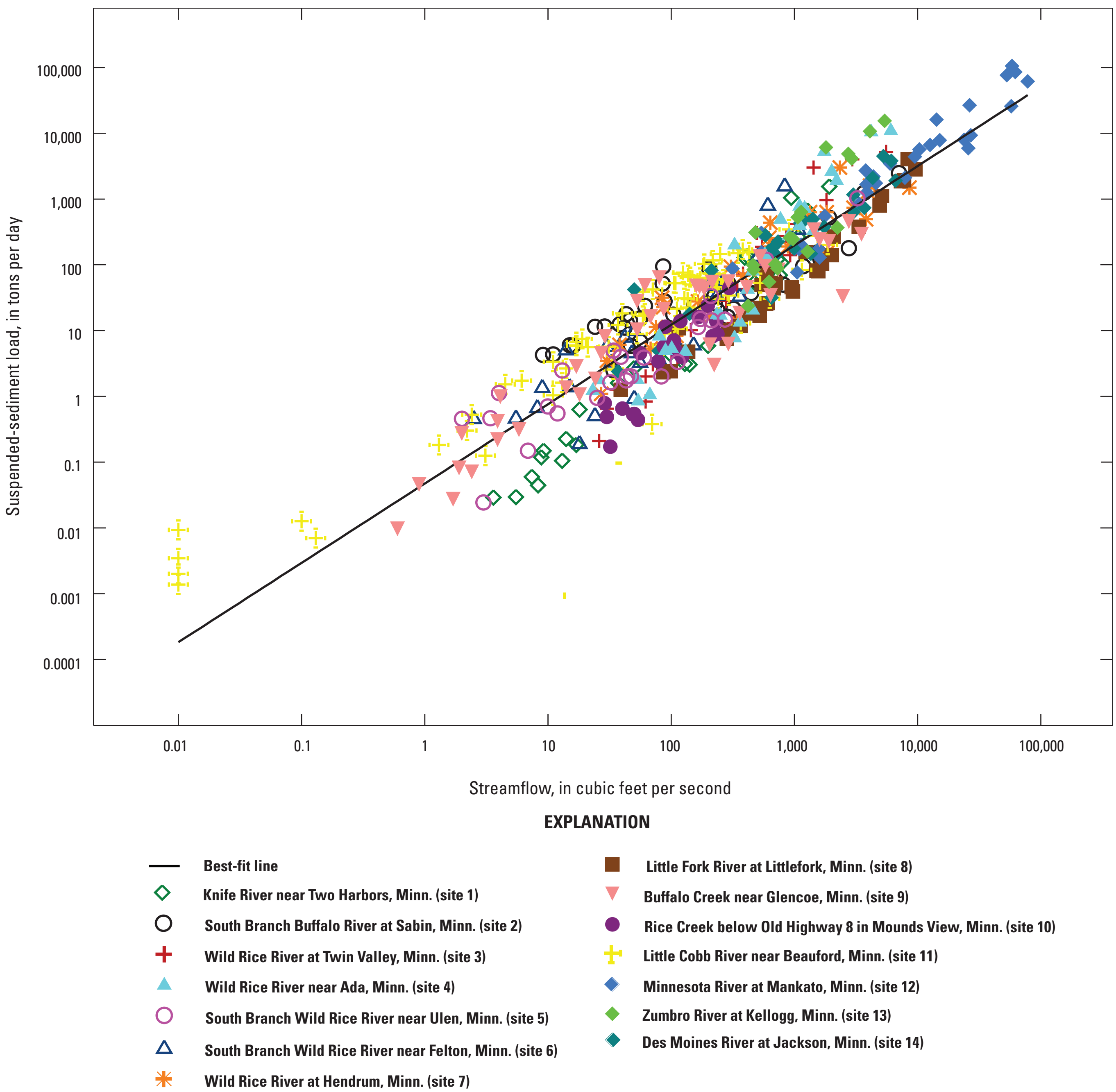


Figure 11. Relation between suspended-sediment load and streamflow for selected sites in Minnesota, 2007 through 2011.

Table 10. Estimated annual sediment loads for suspended sediment, total suspended solids, and particle-size fractions and 95-percent confidence intervals for selected sites in Minnesota, 2007 through 2011.

[Location of sites are shown in figs. 1–4; C.I., confidence interval; Minn., Minnesota; --, not measured]

Calendar year	Suspended-sediment load (tons) (95-percent C.I.)	Total suspended solids load (tons) (95-percent C.I.)	Suspended-sands load (tons) (95-percent C.I.)	Suspended-fines load (tons) (95-percent C.I.)
		Knife River near Two Harbors, Minn. (site 1)		
2007	6,338 (3,354–10,937)	4,614 (1,866–9,582)	2,108 (496–5,982)	4,587 (1,101–12,889)
2008	3,539 (2,027–5,757)	2,256 (1,000–4,411)	792 (248–1,922)	3,582 (982–9,381)
2009	2,451 (1,408–3,985)	1,254 (650–2,196)	433 (150–993)	2,892 (700–8,094)
2010	5,337 (2,715–9,472)	2,302 (945–4,726)	899 (199–2,627)	4,717 (954–14,433)
2011	4,750 (2,138–9,184)	2,013 (714–4,545)	643 (110–2,124)	3,833 (798–11,564)
		South Branch Buffalo River at Sabin, Minn. (site 2)		
2007	9,325 (5,188–15,504)	5,978 (2,122–13,482)	976 (304–2,378)	6,548 (3,745–10,660)
2008	11,801 (7,776–17,190)	7,238 (4,022–12,043)	1,041 (449–2,073)	8,652 (5,776–12,470)
2009	18,316 (12,134–26,566)	12,351 (7,443–19,318)	1,270 (601–2,373)	13,491 (9,014–19,430)
2010	13,607 (9,064–19,647)	7,055 (4,593–10,378)	1,043 (488–1,964)	10,334 (7,055–14,624)
2011	14,271 (8,642–22,236)	7,354 (4,091–12,229)	957 (405–1,929)	11,640 (7,189–17,857)
		Wild Rice River at Twin Valley, Minn. (site 3)		
2007	35,820 (18,327–63,341)	--	6,593 (1,592–18,466)	32,613 (15,318–61,269)
2008	42,409 (23,981–69,649)	--	11,707 (2,800–32,953)	31,591 (16,903–54,070)
2009	116,894 (61,125–203,467	--	61,355 (10,459–203,045)	75,903 (30,428–158,568)
2010	57,446 (27,887–105,466)	--	29,988 (3,427–116,728)	32,924 (10,945–77,251)
		Wild Rice River near Ada, Minn. (site 4)		
2007	59,141 (23,877–122,987)	--	19,052 (2,609–69,157)	46,641 (18,740–97,297)
2008	86,677 (36,264–176,097)	--	35,640 (3,457–147,100)	50,396 (20,450–104,454)
2009	206,743 (85,995–421,648)	--	51,400 (3,070–230,293)	80,061 (24,956–195,063)
2010	100,544 (40,215–210,353)	--	20,599 (796–109,824)	29,589 (7,381–81,491)
		South Branch Wild Rice River near Ulen, Minn. (site 5)		
2007	1,064 (442–2,171)	--	139 (21–481)	738 (304–1,515)
2008	2,060 (748–4,583)	--	234 (49–709)	1,422 (501–3,222)
2009	3,073 (1,105–6,876)	--	342 (54–1,169)	1,923 (620–4,598)
2010	2,632 (716–6,913)	--	407 (24–1,964)	1,611 (386–4,530)
		South Branch Wild Rice River near Felton, Minn. (site 6)		
2007	6,861 (1,534–19,983)	--	1,744 (249–6,221)	4,565 (802–14,901)
2008	8,706 (2,730–21,127)	--	2,040 (442–6,035)	5,232 (1,360–14,102)
2009	12,914 (2,705–38,838)	--	2,948 (235–12,979)	10,511 (1,073–42,609)
2010	8,546 (1,987–24,408)	--	1,822 (85–9,290)	5,596 (408–25,324)
		Wild Rice River at Hendrum, Minn. (site 7)		
2007	35,627 (20,593–57,543)	--	4,289 (1,214–11,038)	53,687 (28,403–92,654)
2008	48,036 (32,771–68,011)	--	5,939 (1,929–14,130)	72,806 (41,611–118,609)
2009	80,906 (47,384–129,366)	--	6,426 (1,737–16,957)	70,858 (36,913–123,674)
2010	83,386 (39,171–156,647)	--	5,610 (824–19,790)	63,564 (25,150–133,920)

Table 10. Estimated annual sediment loads for suspended sediment, total suspended solids, and particle-size fractions and 95-percent confidence intervals for selected sites in Minnesota, 2007 through 2011.—Continued

[Location of sites are shown in figs. 1–4; C.I., confidence interval; Minn., Minnesota; --, not measured]

Calendar year	Suspended-sediment load (tons) (95-percent C.I.)	Total suspended solids load (tons) (95-percent C.I.)	Suspended-sands load (tons) (95-percent C.I.)	Suspended-fines load (tons) (95-percent C.I.)
Little Fork River at Littlefork, Minn. (site 8)				
2007	23,190 (15,649–33,130)	15,283 (7,932–26,746)	4,341 (1,333–10,672)	16,355 (11,087–23,279)
2008	60,602 (43,103–82,867)	50,086 (29,574–79,586)	9,197 (3,861–18,646)	46,751 (32,919–64,470)
2009	58,640 (41,812–80,017)	45,573 (29,725–66,940)	10,272 (4,250–21,023)	45,249 (31,986–62,196)
2010	27,503 (21,132–35,193)	16,663 (12,910–21,168)	4,905 (2,143–9,681)	21,183 (16,263–27,125)
2011	81,448 (51,069–123,472)	72,420 (43,412–113,736)	12,221 (3,561–30,939)	65,662 (40,741–100,375)
Rice Creek below Old Highway 8 in Mounds View, Minn. (site 10)				
2010	534 (287–910)	--	206 (104–368)	341 (159–644)
2011	3,735 (1,959–6,486)	--	1,948 (939–3,593)	1,669 (773–3,163)
Little Cobb River near Beauford, Minn. (site 11)				
2007	14,826 (9,080–23,703)	3,335 (1,629–6,097)	9,323 (1,059–36,371)	13,509 (5,704–27,280)
2008	7,768 (5,148–11,263)	3,004 (1,918–4,489)	1,887 (624–4,444)	5,776 (3,514–8,967)
2009	2,270 (1,601–3,124)	800 (573–1,086)	282 (105–609)	1,729 (1,079–2,632)
2010	21,930 (13,463–33,805)	8,862 (5,767–13,042)	3,008 (522–9,876)	16,289 (9,004–27,215)
2011	14,151 (7,836–23,391)	6,870 (3,709–11,484)	638 (126–1,968)	9,193 (4,472–16,710)
Minnesota River at Mankato, Minn. (site 12)				
2007	1,847,372 (1,132,125–2,851,644)	--	--	--
2008	1,039,185 (700,293–1,486,280)	--	--	--
2009	669,854 (518,343–851,859)	--	--	--
2010	2,991,119 (2,077,934–4,171,650)	--	--	--
2011	2,526,270 (1,713,939–3,593,168)	--	--	--
Des Moines River at Jackson, Minn. (site 14)				
2007	67,523 (20,755–165,849)	46,216 (11,558–127,118)	5,914 (875–20,796)	51,108 (13,364–137,295)
2008	47,616 (27,546–76,856)	40,553 (18,287–78,357)	5,643 (2,229–11,904)	38,958 (20,822–66,732)
2009	34,626 (19,789–56,412)	33,559 (19,351–54,304)	3,805 (1,487–8,078)	28,250 (15,216–48,116)
2010	269,975 (119,303–528,849)	125,408 (77,434–192,440)	76,754 (19,802–207,677)	171,742 (69,518–356,546)
2011	207,024 (113,827–347,245)	119,750 (73,708–184,213)	97,108 (36,046–213,030)	132,405 (66,268–237,873)

For suspended sediment, 6 of 12 S-LOADEST models explained greater than 90 percent of the variability in the observed loads (R^2 values greater than 0.90), whereas the remaining 6 models explained 80–90 percent of observed variability. For suspended sands, 4 models explained greater than 90 percent of the observed variability, 4 models explained 80–90 percent of the observed variability, and 2 models explained 70–80 percent of the observed variability. Two models for suspended-sand loads, the South Branch Buffalo River and the South Branch Wild Rice River near Ulen, only explained 42 and 25 percent, respectively, of the observed variability. In contrast, 7 of 12 S-LOADEST models for suspended fines explained 90 percent or more of the observed variability, 4 models explained 80–90 percent of the observed variability, and 1 model (Rice Creek) explained 73 percent of the variability. Only five models were developed for TSS loads because either too few TSS data were available or TSS data were not collected for 7 of the 12 sites for which continuous streamflow data were available. For the 5 sites for which S-LOADEST models were developed to estimate TSS loads, 3 of the models explained 90 percent or more of the observed variability and 2 models explained 80–90 percent of the observed variability (table 3).

Annual suspended-sediment loads varied widely among sites and across years (table 10). The 95-percent upper and lower confidence intervals, determined in LOADEST, at some sites were substantial. Marked differences were determined between suspended-sediment and TSS loads. Although total suspended-sediment loads are the sum-total of sands and fines, the estimated suspended-sand and suspended-fine loads from S-LOADEST did not sum exactly to the total suspended-sediment load. The difference between the sum of the suspended-sands and fines loads and total suspended-sediment loads is attributed to differences in estimating loads from S-LOADEST models, which takes concentrations and transforms them into log space to make the residuals more symmetric, linear, and homoscedastic. The residual values in log space, which are used to develop the regression model, do not back-transform directly into their original residual values (Helsel and Hirsch, 2002; Dave Lorenz, U.S. Geological Survey, oral commun., March 18, 2013). The consequence is that the individual loads from sands and fines did not sum to the total suspended-sediment load (table 10).

For this study period, the Minnesota River had the largest annual sediment load among all sites. The Minnesota River produced an average of 1.8 million tons of sediment per year from 2007 through 2011. For the Red River watershed sites, the Wild Rice River near Ada transported the largest sediment loads, transporting an average of 110,000 tons per year from 2007 through 2010. The South Branch Buffalo River, located south of the Wild Rice River, transported an average of 13,000 tons per year from 2007 through 2011. In the Rainy River and the Western Lake Superior watersheds, the Little Fork River and the Knife River transported an average of 50,000 and 4,000 tons per year, respectively, from 2007 through 2011.

TSS loads were considerably lower than suspended-sediment loads. For example, from 2007 through 2011, the Knife River transported about 22,000 tons of suspended sediment compared to TSS loads of 12,000 tons (table 10), or a TSS load that was 45 percent smaller than suspended-sediment load. Notably smaller loads for TSS, in comparison to suspended sediment, were estimated for all sites. The South Branch Buffalo River, Little Fork River, Little Cobb River, and the Des Moines River had TSS loads that were 41, 20, 63, and 42 percent, respectively, smaller than suspended-sediment loads.

Seasonal loads for suspended sediment are illustrated in figure 12. For this analysis, winter is January through March, spring is April through June, summer is July through September, and fall is October through December. Seasonal loads generally were largest during spring snowmelt runoff (fig. 12). The magnitude of sediment loads is controlled by timing, magnitude, and frequency of streamflow, so the years with large or frequent precipitation events may on occasion generate higher loads during seasons other than spring. For example, the Knife River transported its largest suspended-sediment loads during the fall for years 2007 and 2010. For the South Branch Buffalo River, the Little Fork River, and the Minnesota River, the largest loads were transported during spring snowmelt runoff for the entire study period. At the Des Moines River at Jackson, the largest seasonal loads were transported during the spring for years 2007, 2008, and 2011, and during fall for years 2009 and 2010. For the Wild Rice River at Twin Valley and the Wild Rice River near Ada, the largest loads were transported during spring for years 2007, late winter/early spring for 2009 and 2010, and during fall for year 2008. For the Wild Rice River at Hendrum, the largest suspended-sediment loads were transported during spring for years 2007 through 2010. At the South Branch Wild Rice River near Ulen and Felton, the largest loads were transported during the spring in 2007, 2009, and 2010 and during fall for 2008. For the Little Cobb River, the largest loads were transported during spring snowmelt runoff for years 2007 through 2009 and in 2011, and during the summer for year 2010. Overall, the largest loads were transported during spring snowmelt runoff for 81 percent (42 out of 52 seasons) of the seasonal periods, during fall for 15 percent of the seasons (8 out of 52 seasons), and during summer for 4 percent (2 out of 52) of the seasons.

Sediment Yield by Watershed

Average annual basin yields for suspended sediment, suspended sands, and suspended fines are shown in figure 13. Comparing annual sediment yields among sites across Hydrologic Unit Code (HUC) Level 4 watersheds provides insight on erosion rates and describes the relative measure of degradation occurring on the landscape. For all sites, the Minnesota River had the largest mean annual sediment basin yield of 120 tons per year per square mile [(tons/yr)/mi^2]. Several sites had similar yields during the study period. For example, the Wild Rice River near Ada, Des Moines River at Jackson, and the Little Cobb River near Beauford had similar yields of 103, 100, and 94 (tons/yr)/mi^2, respectively. Each site has similar land use (extensive cultivation) in the watershed and low to moderately low relief, although the Little Cobb River has a much smaller drainage area (130 mi^2) than the Wild Rice River near Ada (1,100 mi^2) and the Des Moines River at Jackson (1,250 mi^2). The Knife River and South Branch Wild Rice River near Felton, which are relatively small watersheds in northeastern and northwestern Minnesota, also had similar basin yields of 53 and 51 (tons/yr)/mi^2, respectively. The Knife River watershed is heavily forested and the river flows through clay soils in steep terrain, whereas the South Branch Wild Rice River near Felton flows through cultivated cropland in a transition area of lake shore sands and gravels. Another pair of sites with smaller but similar yields were the South Branch Buffalo River and the Little Fork River, which are located in the northwestern and north-central part of the State, with yields of 29 and 30 (tons/yr)/mi^2, respectively. These sites are markedly different in land use, soil types, and drainage area size. The South Branch Buffalo River flows through cultivated cropland with clay

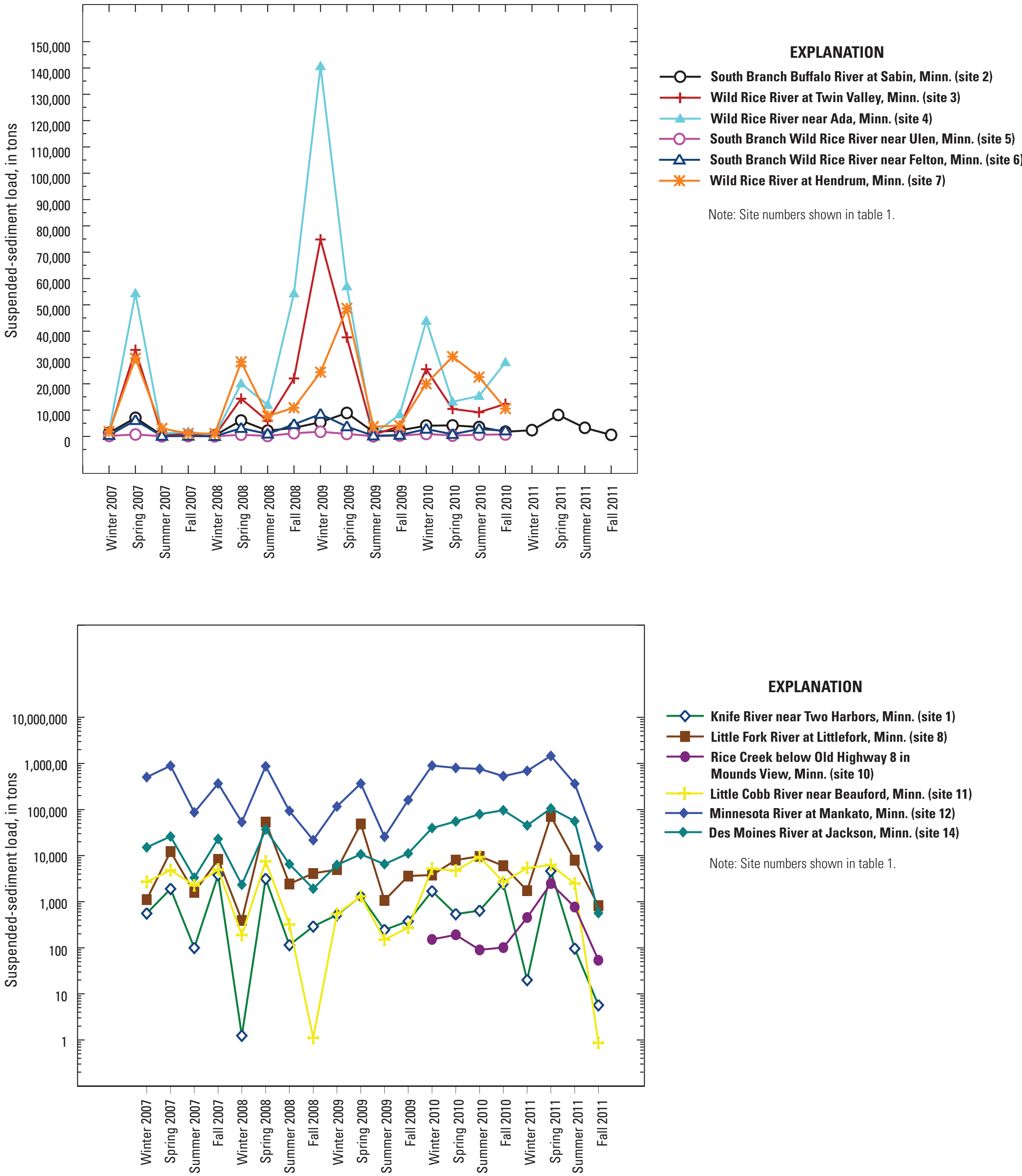


Figure 12. Seasonal suspended-sediment loads for selected sites in Minnesota, 2007 through 2011.

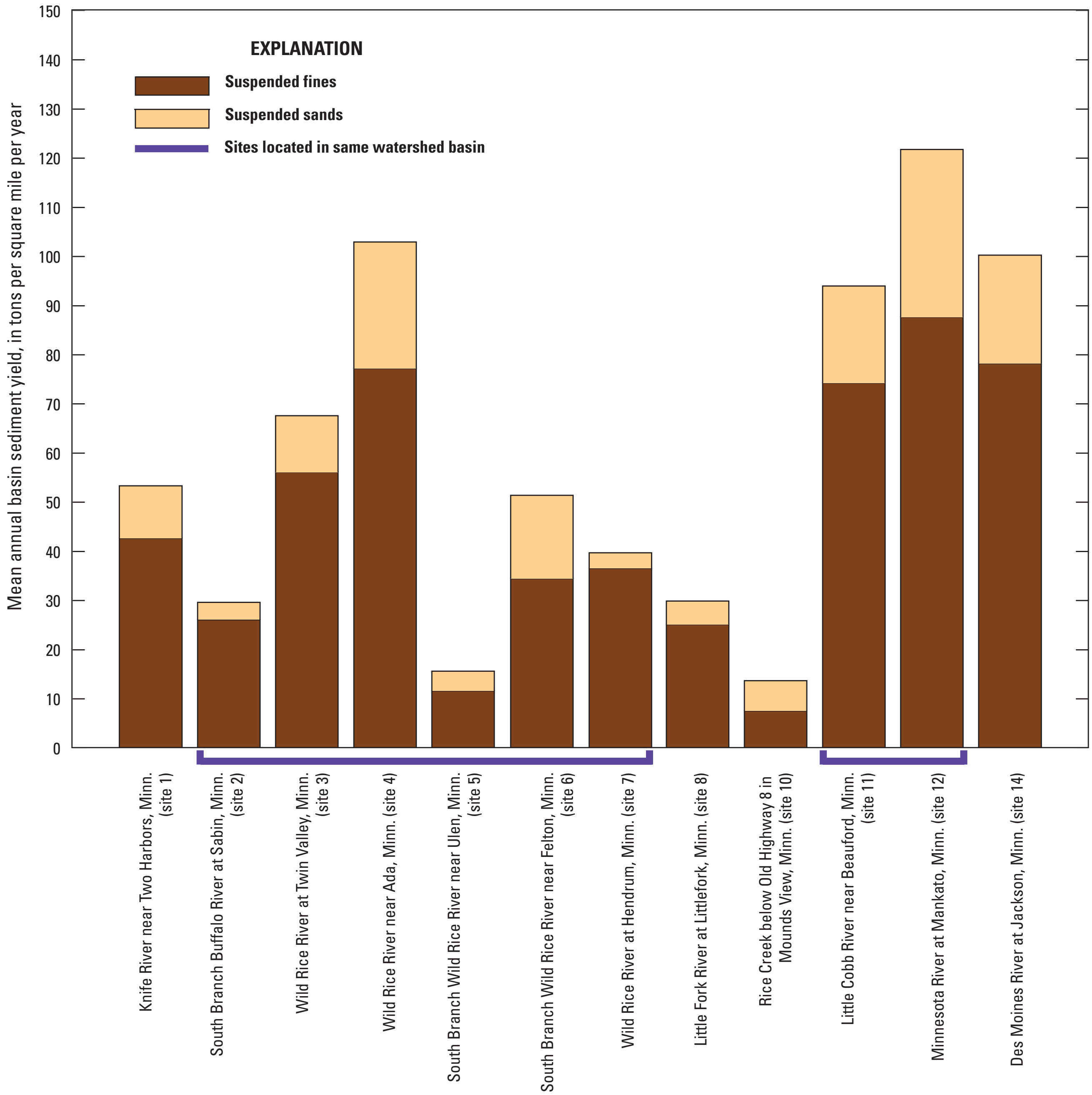


Figure 13. Mean annual basin yields of suspended sediment for selected sites in Minnesota, 2007 through 2011.

soils in extremely flat terrain, whereas the Little Fork River, which has a much larger drainage area, flows through remote forests and wetlands in peat and clay soils with moderate relief. The last two sites having similar yields were the South Branch Wild Rice River near Ulen and Rice Creek in the northern Minneapolis-St. Paul metropolitan area. These sites are among the smallest watersheds studied, are located in opposite corners (northwest and southeast) of the State, and had the smallest yields of all sites, with basin yields of 16 and 14 (tons/yr)/mi^2, respectively.

The Wild Rice River sites at Twin Valley, near Ada, and at Hendrum had average basin yields of 68, 103, and 40 (tons/yr)/mi^2 and transported 63,000, 110,000, and 62,000 tons of mean annual sediment loads, respectively. The large increase in yield and loads between Twin Valley and Ada is consistent with channel degradation and scour upstream from the Ada site (Minnesota Board of Soil and Water Resources, 2003). The substantial decrease in yield and loads between Ada and Hendrum is consistent with sediment deposition in the intervening stream reaches and provides evidence that aggradation is continuing downstream from Ada.

Quality Assurance

Quality-assurance samples were collected to estimate variation in the reproducibility in field sampling procedures. Sequential replicate samples were collected immediately after the primary sample at the same cross-section. In addition to providing a measure of the variability in sample collection procedures, sequential replicates also add the additional variability associated with short-term environmental fluctuation (Mueller and others, 1997). A total of 39 replicate samples were collected and analyzed for SSC (table 11). The overall mean absolute relative percent difference (RPD) between primary and sequential replicate samples was 16 percent, with some sites having noticeably higher RPDs than others. Sites with markedly higher differences between primary and replicate samples most likely are associated with unstable site conditions, which were indicated by weak relations between SSC and streamflow, and less attributable to variability in field sampling procedures. For example, the Little Cobb River had no statistically significant relation between SSC and streamflow (table 5), and the RPD between primary and replicate samples was the largest (50 percent) of all sites. The Wild Rice River at Hendrum, which had an RPD of 26 percent between the primary and replicate samples, also had a weak relation between SSC and streamflow. In contrast, sites with relatively strong correlations between SSC and streamflow had smaller RPDs between primary and replicate samples. The Knife River and the Little Fork River had small differences between primary and replicate samples and had corresponding strong relations between SSC and streamflow (tables 11 and 5).

Table 11. Results of quality-assurance samples for suspended-sediment concentration for samples collected at selected sites in Minnesota, 2007 through 2011.

[mg/L, milligrams per liter; RPD, relative percent difference; Minn., Minnesota]

Date (month/day/year)	Suspended-sediment concentration (mg/L)		RPD[a] (percent)
	Primary sample	Sequential replicate sample	
Knife River near Two Harbors, Minn. (site 1)			
04/16/2009	62	56	10.2
04/16/2009	46	51	-10.3
08/25/2009	16	16	0.0
08/20/2010	123	122	0.8
South Branch Buffalo River at Sabin, Minn. (site 2)			
04/13/2009	18	27	-40.0
04/13/2009	28	26	7.4
04/13/2009	25	26	-3.9
08/19/2009	66	67	-1.5
07/29/2010	33	21	44.4
Wild Rice River near Ada, Minn. (site 4)			
04/14/2009	196	271	-32.1
04/14/2009	326	329	-0.9
07/29/2010	136	134	1.5
South Branch Wild Rice River near Ulen, Minn. (site 5)			
04/13/2009	20	20	0.0
08/27/2009	8	7	13.3
South Branch Wild Rice River near Felton, Minn. (site 6)			
04/14/2009	35	33	5.9
07/28/2010	101	90	11.5
Wild Rice River at Hendrum, Minn. (site 7)			
04/14/2009	48	41	15.7
04/14/2009	57	40	35.1
Little Fork River at Littlefork, Minn. (site 8)			
04/15/2009	179	176	1.7
04/15/2009	177	172	2.9
10/23/2009	17	16	6.1
08/24/2010	16	15	6.5
Buffalo Creek near Glencoe, Minn. (site 9)			
03/27/2009	88	125	-34.7
08/13/2010	71	71	0.0
Rice Creek below Old Highway 8 in Mounds View, Minn. (site 10)			
08/11/2010	30	15	66.7
08/17/2011	14	17	-19.4

Table 11. Results of quality-assurance samples for suspended-sediment concentration for samples collected at selected sites in Minnesota, 2007 through 2011.—Continued

[mg/L, milligrams per liter; RPD, relative percent difference; Minn., Minnesota]

Date (month/day/year)	Suspended-sediment concentration (mg/L)		RPD[a] (percent)
	Primary sample	Sequential replicate sample	
Little Cobb River near Beauford, Minn. (site 11)			
05/02/2007	110	71	43.1
08/05/2010	105	60	54.5
04/13/2011	83	48	53.4
Minnesota River at Mankato, Minn. (site 12)			
07/21/2009	145	146	-0.7
06/22/2010	142	145	-2.1
03/19/2011	798	865	-8.1
05/02/2011	86	80	7.2
Zumbro River at Kellogg, Minn. (site 13)			
08/03/2010	45	70	-43.5
08/14/2010	961	1020	-6.0
Des Moines River at Jackson, Minn. (site 14)			
04/02/2009	103	101	2.0
08/04/2010	146	140	4.2
07/21/2011	75	71	5.5
07/21/2011	74	60	20.9

[a]RPD = $[(x_1 - x_2)/([x_1 + x_2]/2)] \times 100$, where x_1 is the suspended-sediment concentration in the primary sample, in milligrams per liter, and x_2 is the suspended-sediment concentration in the sequential replicate sample, in milligrams per liter.

Summary

Sediment-laden rivers and streams pose substantial environmental and economic challenges. Excessive sediment transport in rivers causes problems for flood control, soil conservation, irrigation, aquatic health, and navigation, and transports harmful contaminants like organic chemicals and eutrophication-causing nutrients. In Minnesota, more than 5,800 miles of streams are identified as impaired by the Minnesota Pollution Control Agency (MPCA) due to elevated levels of suspended sediment.

This report documents findings based on sediment data collected by the U.S. Geological Survey, in cooperation with the Minnesota Pollution Control Agency, on selected rivers in Minnesota from 2007 through 2011 to improve the understanding of fluvial sediment transport relations. Specifically, this study examines suspended sediment data to (1) describe suspended-sediment concentrations (SSC), total suspended solids (TSS), turbidity, and particle-size fractions for selected rivers across Minnesota's major watersheds; (2) quantify the difference between SSC and TSS; (3) develop relations among streamflow, SSC, suspended-sediment loads, TSS, and turbidity; and (4) estimate annual and seasonal suspended-sediment loads and basin yields.

Suspended-sediment samples collected from 14 sites during 2007 through 2011 indicated that the Zumbro River at Kellogg in southeast Minnesota's driftless region had the highest mean SSC of 226 milligrams per liter (mg/L) followed by the Minnesota River at Mankato with a mean SSC of 193 mg/L. The single highest SSC of 1,250 mg/L was measured at the Zumbro River during the 2011 spring runoff. The lowest mean SSC of 21 mg/L was observed at Rice Creek in the northern Minneapolis–St. Paul metropolitan area.

TSS and turbidity samples were collected concurrently with SSC samples at seven sites. TSS and turbidity followed similar spatial patterns as SSC. The Zumbro River, Wild Rice River near Ada, and the Minnesota River had the largest mean turbidity values, whereas Rice Creek had a very narrow range of values from 1 to 9 nephelometric turbidity ratio units.

For particle sizes, suspended fines (sediment smaller than 0.0625 millimeters) had higher percentages than suspended sands at nearly all sites, although the percentage of suspended sands comprised an appreciable amount of the total suspended-sediment concentration for many samples at many sites. The largest mean percentages of sand-sized particles in suspension were measured at Rice Creek, where an average of 45 percent of the material in suspension was sand-sized. Other substantial mean percentages of sands were measured at the Zumbro River, South Branch Wild Rice River near Felton, and the Minnesota River with 35, 33, and 28 percent, respectively.

The Wilcoxon signed-rank test was used to determine if there were differences between SSC and TSS at seven sites. For all sites, the test indicated significant differences between SSC and TSS, with SSC values being larger. The largest percent difference between SSC and TSS was measured at the South Branch Buffalo River at Sabin, and the smallest difference was observed at the Des Moines River at Jackson. Overall, it was determined that TSS concentrations were 50 percent smaller than SSC.

For relations among streamflow, SSC, TSS, and turbidity, the coefficient of determination (R^2) values and relative percent errors for regression models varied widely among sites. Strong correlations between SSC and streamflow were determined for the Knife River and the Wild Rice River at Twin Valley. The Wild Rice River near Ada, Little Fork River at Littlefork, and the Zumbro River had moderate R^2 values, whereas Rice Creek and the Minnesota River had modest R^2 values, and correlations between SSC and streamflow were significant for these sites; however, one-half of the sites had poor relations between SSC and streamflow. For three sites, the South Branch Wild Rice River near Ulen, Buffalo Creek, and the Little Cobb River, the correlation between SSC and streamflow was not signficant. Variation in SSC was noticeably smaller and R^2 values were improved for all sampling sites when using turbidity as the explanatory variable in comparison to using streamflow. Among the largest improvements in R^2 values was for the Wild Rice River at Hendrum, for which R^2 values increased from 0.16 using streamflow to 0.86 using turbidity.

Stepwise regression procedures were used to evaluate whether the simple linear regression of SSC with streamflow could be improved by including turbidity in a multiple linear regression to improve the results of the model. In only 2 of the 14 models, streamflow alone produced the best model. In five models, turbidity alone produced the best model, and in seven models, turbidity combined with streamflow produced the best models.

S-LOADEST models were successful in explaining the observed variability in suspended-sediment and particle-size fraction loads. For suspended-sediment loads, 6 of 12 S-LOADEST models explained greater than 90 percent of the observed variability, whereas 7 of 12 models for suspended fines explained 90 percent or more of the observed variability. For TSS, only five models were developed due to lack of TSS data. For TSS loads, three out of five models explained 90 percent or more of the observed variability.

The Minnesota River had the largest annual sediment load and the largest annual basin yield when compared to all sites, producing an average of 1.8 million tons of sediment per year with an average basin yield of 120 tons of sediment per year per square mile. For sites in the Red River watershed, the Wild Rice River near Ada transported the largest average sediment load of 110,000 tons per year for a total of 450,000 tons from 2007 through 2010. Suspended-sediment loads substantially were larger than TSS loads at all sites where SSC and TSS were sampled concurrently. Predominately, the largest suspended-sediment loads were transported during spring snowmelt runoff.

This study provides data from which to characterize suspended sediment across Minnesota's diverse geographical settings. The analysis improves understanding of sediment transport relations, provides information for improving sediment budgets and designing stream restoration, and documents baseline data to aid in understanding the effects of future land use/land cover on water quality. Additionally, the data provide insight from which to evaluate the effectiveness and efficiency of best-management practices at a large watershed scale.

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Appendix

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
Knife River near Two Harbors, Minn. (USGS station 04015330; site 1)					
05/24/2007	141	8	--	8.9	97
06/12/2007	31	--	--	4.4	--
06/18/2007	940	414	240	--	81
06/19/2007	1,070	92	--	55	72
08/21/2007	4	3	--	--	83
10/09/2007	761	34	21	--	63
10/18/2007	1,270	196	--	--	45
04/16/2008	783	51	--	--	31
07/23/2008	13	3	--	2.7	78
09/10/2008	6	2	2	1.6	82
10/09/2008	127	--	5.6	34	--
11/06/2008	187	54	39	82	95
04/16/2009	724	62	34	39	85
07/16/2009	17	4	2	4.5	87
08/20/2009	394	121	--	--	--
08/25/2009	37	16	6.8	12	99
09/10/2009	7	3	--	--	--
10/22/2009	97	17	11	29	98
03/29/2010	97	--	1.6	15	--
05/04/2010	32	--	1.4	12	--
06/23/2010	50	20	3.6	27	98
08/20/2010	412	123	71	160	92
10/07/2010	18	13	2.5	8.6	41
04/28/2011	473	42	13	53	97
05/06/2011	199	11	8	30	92
05/10/2011	129	9	4.4	21	88
06/22/2011	1,910	300	160	210	84
07/26/2011	14	6	1.2	2.1	61
08/31/2011	9	5	1	2.6	82
09/26/2011	8	2	2	1.6	79
10/19/2011	9	6	1	1.1	88
South Branch Buffalo River at Sabin, Minn. (USGS station 05061500; site 2)					
06/07/2007	810	23	--	22	99
06/19/2007	445	31	--	28	92
06/27/2007	61	144	--	--	77
07/11/2007	24	176	--	89	96
07/26/2007	15	149	--	--	89
04/09/2008	286	21	--	35	82
05/13/2008	144	--	--	21	--
06/09/2008	1,550	37	--	--	93
06/10/2008	1,180	30	16	26	76
06/19/2008	203	161	--	--	84
06/25/2008	85	224	87	82	92
07/08/2008	43	154	--	--	97
07/15/2008	56	101	--	--	80

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft³/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft³/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
South Branch Buffalo River at Sabin, Minn. (USGS station 05061500; site 2)—Continued					
07/24/2008	56	45	--	--	96
07/29/2008	16	137	--	--	56
08/05/2008	11	145	31	33	50
08/06/2008	9	174	--	--	88
09/09/2008	42	97	--	--	81
09/23/2008	28	--	28	26	--
10/15/2008	2,760	24	11	27	90
03/22/2009	3,650	126	69	72	99
03/25/2009	7,040	129	87	120	--
04/13/2009	1,630	28	21	27	93
06/18/2009	1,910	101	100	160	99
07/14/2009	38	120	64	58	92
07/23/2009	154	59	--	--	92
07/30/2009	29	147	34	--	82
08/19/2009	291	66	70	64	98
09/15/2009	46	115	16	--	--
10/27/2009	316	--	11	13	--
03/24/2010	669	26	22	26	99
05/05/2010	320	25	20	21	99
06/21/2010	88	118	58	66	99
07/29/2010	684	33	20	22	94
08/17/2010	236	32	20	29	97
10/06/2010	104	62	22	22	95
04/26/2011	586	63	16	16	85
05/04/2011	211	72	13	18	66
05/11/2011	223	55	27	26	94
06/21/2011	86	408	99	130	94
07/26/2011	226	42	24	24	87
08/24/2011	47	46	37	43	91
10/31/2011	34	27	15	17	74
Wild Rice River at Twin Valley, Minn. (USGS station 05062500; site 3)					
02/14/2007	26	3	--	5.6	94
03/22/2007	321	15	--	14	95
04/02/2007	1,430	775	--	400	89
04/12/2007	496	228	--	150	91
05/08/2007	395	40	--	25	87
06/04/2007	343	46	--	28	89
06/18/2007	2,940	502	--	330	89
08/01/2007	83	23	--	28	98
08/17/2007	36	13	--	13	94
10/15/2007	99	9	--	17	93
02/27/2008	62	5	--	4.5	91
04/08/2008	382	71	--	15	84
04/15/2008	547	127	--	73	93
05/28/2008	279	37	--	13	52

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
Wild Rice River at Twin Valley, Minn. (USGS station 05062500; site 3)—Continued					
06/09/2008	857	119	--	63	88
06/13/2008	923	56	--	88	71
07/08/2008	232	27	--	29	83
08/07/2008	71	16	--	12	79
08/27/2008	30	8	--	6.6	94
10/17/2008	1,190	164	--	40	43
02/23/2009	144	26	--	5.3	47
03/26/2009	5,530	347	--	120	--
04/14/2009	1,820	196	--	79	71
06/11/2009	316	13	--	5	94
08/04/2009	62	12	--	6.4	96
09/14/2009	112	13	--	12	97
11/02/2009	622	148	--	62	64
03/26/2010	1,050	147	--	64	--
05/05/2010	597	53	--	18	--
Wild Rice River near Ada, Minn. (USGS station 05063000; site 4)					
02/14/2007	26	26	--	5.1	70
03/22/2007	326	9	--	14	96
04/02/2007	1,740	1140	--	680	86
04/12/2007	327	232	--	120	61
05/08/2007	455	67	--	27	60
06/04/2007	415	39	--	19	86
06/18/2007	4,200	944	--	500	79
08/01/2007	80	39	--	32	92
08/17/2007	23	20	--	13	71
10/15/2007	101	20	--	16	88
02/27/2008	54	6	--	4.1	80
05/29/2008	235	28	--	17	71
06/09/2008	1,210	225	--	100	95
06/13/2008	1,430	88	--	200	61
07/08/2008	250	26	--	37	72
08/07/2008	90	21	--	18	86
08/27/2008	53	13	--	7.4	50
10/16/2008	2,000	496	--	71	33
02/23/2009	362	14	--	5.9	67
03/26/2009	6,050	685	--	250	--
04/14/2009	2,200	326	--	78	58
06/11/2009	458	17	--	7.4	90
08/04/2009	67	6	--	4.2	87
09/14/2009	130	14	--	6.8	89
11/01/2009	770	242	--	120	63
03/25/2010	1,100	268	--	80	--
05/06/2010	575	94	--	22	--
06/22/2010	903	116	--	57	--
07/29/2010	1,100	136	--	59	--

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft³/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft³/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
South Branch Wild Rice River near Ulen, Minn. (USGS station 05063340; site 5)					
03/14/2007	166	25	--	24	93
03/28/2007	44	17	--	17	98
04/03/2007	173	32	--	26	98
05/09/2007	39	38	--	7	--
06/15/2007	592	75	--	59	95
07/10/2007	12	17	--	6.9	82
09/07/2007	2	85	--	4.5	56
10/21/2007	43	15	--	13	97
12/17/2007	4	104	--	3	18
04/08/2008	83	9	--	12	70
05/14/2008	47	16	--	3	50
06/10/2008	212	25	--	20	95
06/24/2008	25	14	--	3.2	53
08/05/2008	3	3	--	2.7	84
09/22/2008	10	26	--	4	46
02/20/2009	13	70	--	3.1	59
03/25/2009	3,240	118	76	77	--
04/13/2009	273	20	12	12	84
06/19/2009	34	54	--	--	51
07/14/2009	3	51	--	4.6	56
08/27/2009	7	8	--	6.3	83
10/24/2009	32	19	--	4.5	77
10/31/2009	210	60	--	64	96
03/24/2010	113	11	--	10	93
05/05/2010	60	24	--	3.6	--
South Branch Wild Rice River near Felton, Minn. (USGS station 05063400; site 6)					
03/14/2007	215	110	--	52	79
03/28/2007	48	36	--	38	94
04/03/2007	223	81	--	44	81
05/09/2007	50	75	--	4.8	54
06/15/2007	834	715	--	400	57
07/10/2007	15	35	--	2.6	63
09/07/2007	3	69	--	2.4	82
10/21/2007	56	22	--	21	94
12/17/2007	6	32	--	1	5
04/08/2008	116	17	--	16	65
05/14/2008	50	7	--	2	58
06/10/2008	242	90	--	71	86
06/24/2008	30	72	--	1.6	39
08/05/2008	8	31	--	3.1	49
09/22/2008	24	8	--	1.6	51
10/14/2008	1,070	123	--	37	57
02/20/2009	14	137	--	1.4	80
04/14/2009	360	35	--	14	80
06/19/2009	42	71	--	--	54

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
South Branch Wild Rice River near Felton, Minn. (USGS station 05063400; site 6)—Continued					
07/14/2009	9	57	--	1.5	68
08/27/2009	18	4	--	3.4	100
10/24/2009	33	38	--	2.3	66
11/01/2009	235	55	--	49	89
03/25/2010	152	15	--	14	--
05/06/2010	88	11	--	3.4	--
07/14/2010	609	497	--	500	--
07/28/2010	504	101	--	54	--
Wild Rice River at Hendrum, Minn. (USGS station 05064000; site 7)					
02/14/2007	27	15	--	13	93
03/22/2007	340	15	--	19	99
04/02/2007	2,340	474	--	350	90
04/12/2007	636	254	--	160	95
05/08/2007	644	109	--	72	91
06/04/2007	622	153	--	99	95
06/18/2007	3,930	121	--	100	94
08/01/2007	84	139	--	93	97
08/17/2007	38	59	--	52	98
10/15/2007	110	28	--	25	92
03/04/2008	68	29	--	12	94
05/28/2008	384	65	--	37	95
06/09/2008	1,830	127	--	130	84
06/13/2008	3,020	90	--	330	90
07/08/2008	305	114	--	110	93
08/07/2008	75	56	--	35	84
08/27/2008	30	43	--	22	77
10/16/2008	4,120	143	--	91	95
02/24/2009	211	29	--	12	76
03/30/2009	8,560	64	--	52	95
04/14/2009	3,800	48	38	40	97
06/11/2009	482	65	--	32	95
08/05/2009	86	98	--	69	98
09/15/2009	165	62	--	28	96
11/02/2009	1,340	173	--	120	96
03/26/2010	1,850	31	--	34	--
05/06/2010	884	79	--	30	--
Little Fork River at Littlefork, Minn. (USGS station 05131500; site 8)					
05/23/2007	522	12	--	9.6	99
06/04/2007	1,560	19	--	--	90
06/05/2007	2,080	48	--	34	99
06/22/2007	988		--	--	--
08/15/2007	39	12	--	5.5	76
11/19/2007	608	16	--	--	70
04/24/2008	9,590	109	--	--	31
04/29/2008	7,740	92	--	--	93

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
Little Fork River at Littlefork, Minn. (USGS station 05131500; site 8)—Continued					
04/30/2008	7,320	94	--	--	89
05/30/2008	1,510	20	--	--	85
06/03/2008	2,000	26	--	--	95
06/24/2008	972	15	--	--	79
07/03/2008	1,670	23	21	22	97
08/04/2008	291	13	--	--	91
08/12/2008	137	13	--	16	94
10/31/2008	542	34	6	10	25
04/15/2009	8,280	181	150	140	89
06/30/2009	364	12	5.6	9.4	89
07/15/2009	115	35	5.6	13	95
08/26/2009	783	49	19	30	100
09/10/2009	215	23	--	--	--
10/23/2009	484	17	12	16	89
03/30/2010	678	24	14	20	90
05/03/2010	703	28	12	16	95
06/23/2010	1,230	47	34	34	95
08/24/2010	588	16	14	17	78
10/07/2010	948	18	10	14	82
04/27/2011	5,110	81	58	47	93
05/05/2011	4,910	60	48	34	81
05/11/2011	3,330	42	32	26	89
06/22/2011	590	46	8.8	12	36
07/20/2011	422	16	--	11	94
09/15/2011	86	10	4	8	95
09/29/2011	99	9	5.2	6.4	78
10/24/2011	282	10	6.8	7.7	90
Buffalo Creek near Glencoe, Minn. (USGS station 05278930; site 9)					
05/09/2007	170	101	--	40	82
05/23/2007	80	295	--	--	71
06/13/2007	61	298	--	--	88
07/13/2007	4	90	--	5.8	75
07/25/2007	--	37	--	--	65
09/12/2007	1	6	--	6	85
09/19/2007	2	51	--	--	63
05/01/2008	360	19	--	--	34
07/03/2008	53	198	64	--	57
07/10/2008	29	104	28	19	69
07/17/2008	18	22	--	--	68
08/05/2008	14	36	30	--	97
08/21/2008	2	16	--	--	93
08/22/2008	2	11	14	12	97
08/28/2008	17	62	11	--	68
09/16/2008	4	21	9.4	--	98
09/26/2008	6	20	20	--	96

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
Buffalo Creek near Glencoe, Minn. (USGS station 05278930; site 9)—Continued					
03/24/2009	525	94	80	91	91
03/27/2009	1,440	88	63	92	86
05/06/2009	68	89	11	7.6	67
06/11/2009	87	90	33	23	62
07/23/2009	2	6	2.8	6.9	91
08/08/2009	215	94	81	81	95
08/11/2009	184	88	--	--	--
08/24/2009	160	111	20	--	--
09/01/2009	53	72	18	12	60
09/22/2009	27	62	--	--	--
10/06/2009	580	61	58	38	86
11/16/2009	223	5	--	--	--
03/22/2010	2,470	5	5.6	6.8	87
04/02/2010	640	20	11	6.1	77
05/13/2010	290	8	12	6.6	97
06/14/2010	411	41	32	19	89
08/13/2010	291	71	65	55	97
09/27/2010	1,900	44	16	32	48
10/19/2010	205	11	--	8.9	94
03/23/2011	2,760	61	22	30	89
03/26/2011	3,500	31	18	33	84
05/16/2011	740	42	--	3.3	43
06/27/2011	1,600	56	9.2	5.7	50
08/30/2011	24	28	39	30	93
09/20/2011	4	40	40	37	--
10/25/2011	1	19	18	18	93
Rice Creek below Old Highway 8 in Mounds View, Minn. (USGS station 05288580; site 10)					
03/23/2010	167	36	--	4.2	64
04/01/2010	122	12	--	4.1	54
04/13/2010	87	24	--	5	62
06/07/2010	30	6	--	--	68
07/23/2010	49	4	--	1.1	44
08/11/2010	56	30	--	1.6	33
09/15/2010	32	2	--	1.3	60
10/21/2010	40	6	--	1.3	83
11/02/2010	54	3	--	1.9	64
11/11/2010	50	4	--	2.5	71
03/20/2011	118	44	--	4.6	95
03/25/2011	198	45	--	5.8	60
04/04/2011	296	56	--	3.7	17
04/24/2011	217	14	--	2.2	34
05/23/2011	233	22	--	3.8	43
08/17/2011	236	14	--	5.1	26
09/02/2011	110	16	--	6.9	44
09/08/2011	105	25	--	8.7	57

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
Rice Creek below Old Highway 8 in Mounds View, Minn. (USGS station 05288580; site 10)—Continued					
09/15/2011	90	47	--	7.6	63
09/22/2011	79	16	--	3	50
10/13/2011	29	10	--	2.9	69
Little Cobb River near Beauford, Minn. (USGS station 05320270; site 11)					
01/24/2007	17	145	--	--	--
02/27/2007	2	81	--	--	--
03/15/2007	240	47	--	--	--
04/17/2007	156	117	--	--	--
05/02/2007	61	110	--	--	--
05/23/2007	59	245	--	140	71
05/31/2007	185	206	--	--	--
06/05/2007	137	189	--	--	--
06/07/2007	124	227	120	--	--
06/12/2007	71	220	--	120	82
06/26/2007	17	128	79	--	--
06/27/2007	14	70	--	--	--
07/05/2007	3	15	--	--	--
07/17/2007	0	20	--	--	--
08/20/2007	206	131	--	110	97
08/21/2007	228	99	79	--	--
08/29/2007	213	93	--	--	--
09/12/2007	34	28	--	--	--
09/26/2007	136	82	--	--	--
05/22/2008	88	38	48	27	46
06/06/2008	171	137	--	--	82
06/13/2008	348	159	--	--	68
06/17/2008	381	166	45	22	36
06/20/2008	217	198	--	--	66
07/10/2008	19	145	--	--	81
07/11/2008	17	130	25	19	52
07/15/2008	11	113	--	--	27
08/04/2008	6	105	--	--	48
08/06/2008	5	125	--	--	87
08/26/2008	0	129	--	--	48
08/28/2008	0	47	21	19	72
09/30/2008	0	51	13	13	73
03/24/2009	0	346	--	--	98
05/29/2009	21	99	73	43	86
06/17/2009	37	122	61	44	99
07/22/2009	2	51	24	28	96
11/12/2009	31	68	--	7.3	73
03/20/2010	1,150	27	13	16	99
04/07/2010	108	41	25	17	99
05/13/2010	85	26	28	22	98
06/15/2010	187	86	64	38	89

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
Little Cobb River near Beauford, Minn. (USGS station 05320270; site 11)—Continued					
08/05/2010	59	105	52	44	93
09/23/2010	904	141	65	190	83
09/28/2010	1,860	40	14	37	73
10/29/2010	128	90	--	--	--
11/29/2010	111	72	--	--	--
12/28/2010	70	2	--	--	--
01/27/2011	40	169	--	--	--
02/23/2011	367	13	--	--	--
03/22/2011	1,540	66	36	48	87
03/29/2011	527	37	22	27	92
04/13/2011	265	83	--	--	--
05/04/2011	229	118	--	--	--
05/11/2011	143	58	--	--	--
05/19/2011	113	35	38	26	93
05/25/2011	236	72	--	--	--
06/09/2011	108	179	--	--	--
06/15/2011	249	217	170	200	98
06/27/2011	429	134	--	--	--
06/29/2011	294	43	--	26	92
07/11/2011	105	186	--	--	--
07/21/2011	630	18	--	--	--
07/27/2011	142	170	--	--	--
08/03/2011	53	62	--	--	--
08/11/2011	11	35	39	44	94
08/24/2011	13	46	--	--	--
09/01/2011	1	52	--	--	--
09/20/2011	0	74	18	23	88
Minnesota River at Mankato, Minn. (USGS station 05325000; site 12)					
01/03/2007	1,760	116	--	--	--
02/21/2007	540	106	--	--	--
02/21/2007	540	209	--	4.9	15
03/22/2007	26,400	373	--	170	--
05/17/2007	9,500	172	--	27	--
08/29/2007	3,780	264	--	73	--
04/03/2008	4,380	186	--	--	--
05/22/2008	10,300	204	--	--	--
07/09/2008	5,970	215	--	--	--
09/30/2008	314	103	--	--	--
10/30/2008	1,050	27	--	--	70
11/24/2008	1,130	66	--	--	--
02/25/2009	1,600	30	--	--	--
03/18/2009	4,570	141	--	--	--
04/01/2009	14,200	421	--	--	44
04/16/2009	12,600	195	--	--	--
07/29/2009	1,090	59	--	--	92

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
Minnesota River at Mankato, Minn. (USGS station 05325000; site 12)—Continued					
09/02/2009	1,010	65	--	--	98
03/18/2010	58,200	671	--	--	--
03/19/2010	61,800	513	--	--	--
04/07/2010	27,000	128	--	--	68
06/16/2010	15,100	191	--	--	79
08/26/2010	3,860	121	--	--	92
09/28/2010	78,100	290	--	--	--
02/04/2011	3,830	161	--	--	--
03/23/2011	52,900	531	--	--	63
03/29/2011	57,500	165	--	--	61
05/26/2011	23,800	124	--	--	71
06/30/2011	25,800	85	--	--	76
08/12/2011	7,900	99	--	--	85
09/20/2011	3,350	93	--	30	87
10/20/2011	1,570	41	--	--	85
Zumbro River at Kellogg, Minn. (USGS station 05374900; site 13)					
05/10/2007	--	141	--	5.9	14
06/05/2007	--	169	--	89	87
07/12/2007	--	39	--	--	65
08/02/2007	--	45	--	--	77
08/14/2007	--	275	--	--	96
08/15/2007	--	166	--	--	94
04/17/2008	2,230	61	--	66	28
06/11/2008	2,730	659	140	52	2
06/20/2008	--	258	--	--	71
07/11/2008	--	204	--	--	71
07/22/2008	--	130	--	--	66
07/30/2008	--	109	--	--	75
07/31/2008	483	239	64	19	27
08/06/2008	--	87	--	--	82
08/21/2008	--	117	--	--	57
09/18/2008	466	67	15	5.2	54
10/22/2008	--	17	7.4	2.2	56
06/26/2009	1,060	185	110	38	83
07/20/2009	460	80	14	6.4	89
09/14/2009	420	21	--	7.3	84
11/09/2009	921	104	29	10	51
03/21/2010	2,920	523	170	70	39
03/31/2010	1,280	46	61	24	39
05/11/2010	621	33	11	6.1	74
06/17/2010	970	94	72	28	73
08/03/2010	727	45	--	13	52
08/14/2010	4,100	961	580	990	91
09/16/2010	700	54	50	14	85
03/18/2011	1,800	1,250	1,100	540	75

Table 1–1. Summary of streamflow, suspended-sediment concentrations, total suspended solids, turbidity, and suspended fines for sampled sites in Minnesota, 2007 through 2011.—Continued

[ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligrams per liter; TSS, total suspended solids; NTRU, nephelometric turbidity ratio unit; Minn., Minnesota; USGS, U.S. Geological Survey; --, not measured]

Date	Streamflow, daily mean (ft^3/s)	SSC (mg/L)	TSS (mg/L)	Turbidity (NTRU)	Fines[a] (percent)
Zumbro River at Kellogg, Minn. (USGS station 05374900; site 13)—Continued					
03/21/2011	5,380	1060	610	400	65
05/17/2011	--	52	--	9.5	49
07/12/2011	1,130	207	--	17	64
08/31/2011	--	96	44	15	86
10/27/2011	--	105	9.2	2.8	90
Des Moines River at Jackson, Minn. (USGS station 05476000; site 14)					
05/04/2007	990	66	--	23	97
06/21/2007	580	179	--	59	95
07/19/2007	84	23	--	--	93
09/05/2007	212	144	--	76	98
04/10/2008	651	18	--	23	77
05/16/2008	1,360	40	--	22	43
07/11/2008	708	74	77	53	95
04/02/2009	690	103	130	--	98
05/15/2009	618	98	59	--	84
06/24/2009	736	113	71	--	98
09/03/2009	79	23	55	64	99
10/02/2009	141	47	51	38	98
03/20/2010	5,270	314	150	80	41
04/06/2010	3,000	144	76	36	58
05/12/2010	1,410	131	110	80	84
06/16/2010	1,590	--	130	81	--
08/04/2010	1,190	146	110	55	84
09/24/2010	6,100	230	63	160	65
03/22/2011	4,320	179	94	49	52
03/28/2011	6,600	106	42	35	47
05/09/2011	1,740	80	41	18	65
06/17/2011	3,010	78	68	38	70
07/21/2011	3,680	74	39	20	42
08/09/2011	1,110	143	130	69	92
09/21/2011	50	313	350	210	91
10/19/2011	37	24	46	31	90

[a]Fines are particle sizes less than 0.0625 millimeters.

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Ellison and others—**Sediment Concentrations, Loads, Total Suspended Solids, Turbidity, and Particle-Size Fractions for Rivers in Minnesota**—SIR 2013–5205

ISSN 2328–0328 (online)
http://dx.doi.org/10.3133/sir20135205