Prepared in cooperation with the Wisconsin Department of Natural Resources

Sediment Characteristics of Northwestern Wisconsin's Nemadji River, 1973–2016

Open-File Report 2021–1003

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

Front cover. Photograph of the Nemadji River near County Highway C, July 12, 2016, by Molly Wick, formally of the Wisconsin Department of Natural Resources, used with permission.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.59	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton, short (2,000 lb) (ton)	0.9072	metric ton (Mt)
ton, short (2,000 lb) (ton)	0.9072	megagram (Mg)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
	Mass rate	
ton, short (2,000 lb) per day (ton/d)	0.9072	metric ton per day (Mt/d)
ton, short (2,000 lb) per day (ton/d)	0.9072	megagram per day (Mg/d)
ton, short (2,000 lb) per year (ton/yr)	0.9072	metric ton per year (Mt/yr)
ton, short (2,000 lb) per year (ton/yr)	0.9072	megagram per year (Mg/yr)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Supplemental Information

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

ANCOVA	analysis of covariance
*Adj*TSS	adjusted total suspended solids
AOC	Area of Concern
EWI	equal-width-increment
GCLAS	Graphical Constituent Loading Analysis System
MODEIN	modified Einstein procedure
MPCA	Minnesota Pollution Control Agency
SSC	suspended-sediment concentration
TSS	total suspended solids
USGS	U.S. Geological Survey
WDNR	Wisconsin Department of Natural Resources

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Abstract

In 2015–16, a comparison study of stream sediment collection techniques was done for a U.S. Geological Survey streamgage on the Nemadji River near South Superior, Wisconsin (U.S. Geological Survey station number 04024430) to provide an adjustment factor for comparing suspended-sediment rating curves for two historical periods 1973–86 and 2006–16. During 1973–1986, the U.S. Geological Survey used the equal-width-increment technique to collect suspended-sediment concentration data (EWI SSC). The Wisconsin Department of Natural Resources and Minnesota Pollution Control Agency collected grab samples for total suspended solids (grab TSS) concentration starting in 2006 and continuing beyond 2016. In addition to the comparison study of suspended-sediment concentrations, bedload and bed material samples were collected in 2015–16, and the modified Einstein procedure was run to further characterize total sediment loads. The 2015–16 study indicated that the EWI SSC and grab TSS concentrations were different, but not as much as expected, especially on the high end where grab TSS concentrations were sometimes higher than EWI SSC concentrations, possibly due to a combination of a high percentage of fines in suspension and higher concentrations in the center of the channel than the margins. The 2015–16 measured bedload made up a small percentage of total sediment load, and bedload and streambed particle sizes are 90 to 100 percent sand sized or smaller. The relative proportion of measured bedload to total load decreased with increased streamflow, and for streamflows greater than 1,800 cubic feet per second, the suspended load made up 98 percent of the total load. Calculated 2015–16 instantaneous total sediment loads from the modified Einstein procedure were up to 70 percent of the measured loads for flows less than 1,000 cubic feet per second and near or more than 100 percent for flows greater than 1,000 cubic feet per second. The sediment rating curve developed for the 2006–16 adjusted grab TSS data had a similar slope but a lower intercept than its 1973–86 EWI SSC counterpart, indicating that for a given streamflow, suspended-sediment concentrations were lower for 2006–16 compared to 1973–86. The negative offset equates to estimates of annual suspended-sediment loads in 2006–16 being on average 87 percent of the 1973–86 loads. Over the period 2009–16, annual suspended-sediment loads ranged from a low of about 21,000 tons per year in 2015 to a high of 167,000 tons per year in 2012 with a mean of 85,000 tons per year. However, reductions in suspended-sediment concentrations are likely obscured by large loads during years with flooding.

Introduction

The Nemadji River (fig. 1) is part of the U.S. Environmental Protection Agency's St. Louis River Area of Concern (AOC). One of the beneficial use impairments is excessive loading of sediment and nutrients (St. Louis River Alliance, 2015). A major goal of the AOC cleanup is to reduce sediment loads in the Nemadji River (LimnoTech, 2013), which is estimated to be one of the largest contributors of sediment to Lake Superior (Robertson, 1996). The Nemadji Basin Plan (Natural Resources Conservation Service, 1998) estimated the mean annual suspended-sediment load at the mouth of the Nemadji to be about 130,000 tons per year (tons/yr).

A U.S. Geological Survey (USGS) streamgage has been operating on the Nemadji River near South Superior (not shown), Wisconsin (USGS station number 04024430; hereafter referred to as "the streamgage"), since 1973 (fig. 1; U.S. Geological Survey, 2017). Beginning in 1973, sediment samples were collected and analyzed with two different sets of standard sampling and laboratory methods used by the USGS and State agencies. From 1973 through 1986, the USGS used a depth-integrated isokinetic sampler with an equal-width-increment technique (EWI) and suspended-sediment concentration (SSC) laboratory methods (Edwards and Glysson, 1999; Gray and Landers, 2014). The Wisconsin Department of Natural Resources (WDNR) and Minnesota Pollution Control Agency (MPCA) began using the grab sampling method and total suspended solids (TSS) laboratory methods in 2006. State agencies adopted the grab samples for total suspended solids (hereafter referred to as grab TSS) procedure over the equal-width-increment depth-integrated sampling with suspended-sediment concentration analyses (hereafter referred to as EWI SSC) because the grab TSS procedure is faster and less expensive and was thought to be adequate for assessing sediment-related impairments and other water quality issues (Ellison and others, 2014). Previous studies of grab TSS and

EXPLANATION

—— · · —— · · Watershed boundary

▲04024430 U.S. Geological Survey streamgage and identifier

Figure 1. Map showing the location of the Nemadji River streamgage (U.S. Geological Survey station number 04024430) and its watershed.

EWI SSC have shown that grab TSS samples are usually biased negatively compared to EWI SSC samples, especially when the suspended sediment contained more than 20 percent sand (Gray and others, 2000; Ellison and others, 2014; Groten and Johnson, 2018). These studies conclude that the negative bias for grab TSS could be caused by the sampling, laboratory procedure, or both.

For the Nemadji River, the time gap in suspended-sediment data collection combined with the different types of sampling and laboratory methods required the development of an adjustment factor in order to be able to compare the two datasets. Additionally, it is commonly difficult to separate upstream changes in suspended-sediment supply because of year-to-year hydrologic variability (Warrick, 2014). Comparison of suspended-sediment rating curves has been helpful for distinguishing whether there were changes in suspended-sediment supply potentially associated with upland management practices (Warrick, 2014), and this method was applied for the Nemadji River.

During 2015 through 2016, the USGS, in cooperation with the WDNR, conducted a methods and laboratory comparison study for suspended sediment collected at the Nemadji River streamgage. In addition to suspended sediment, bedload and bed material samples also were collected. These data were used to help describe total sediment loads and provide an adjustment factor for comparison of the historical suspended-sediment data. The results from the comparison will be used by the WDNR to identify if sediment loading from the Nemadji River to Lake Superior has increased, decreased, or stayed the same. This study was part of a larger assessment of the Excessive Loading of Sediment and Nutrients beneficial use impairment in the Nemadji watershed, funded by the U.S. Environmental Protection Agency in 2015, which also included evaluation of macroinvertebrate and fish communities in the Lower Nemadji River and modeling historical sediment loads (Minnesota Pollution Control Agency and Wisconsin Department of Natural Resources, 2015).

Purpose and Scope

This report describes four main study objectives related to sediment data collected at the Nemadji River streamgage. The first objective was to develop an adjustment factor between EWI SSC and grab TSS data collected during 2015 and 2016 that could be used to compare two sets of historical suspended-sediment concentration data collected and analyzed with different methods. The second objective was to describe total instantaneous sediment loads at the streamgage, which was done by collecting physical bedload samples in 2015 and 2016 and comparing physically measured bedloads to bedloads calculated using the modified Einstein procedure. The third objective was to compare the EWI SSC suspended-sediment rating curves for 1973–86 with adjusted grab TSS-based curves for 2006–16 and determine if there was a potential change in suspended-sediment concentrations. The fourth objective was to estimate annual suspended and total sediment loads for the 2009–16 period using raw and adjusted suspended-sediment concentration data and the Graphical Constituent Loading Analysis System (GCLAS) and a suspended to total sediment load relation developed from the 2015–16 data.

The scope of the report describes the results for 12 sets of suspended, bedload, and bed material samples collected at the Nemadji River streamgage for 11 sampling events from July 2015 through July 2016. For each event, two types of suspended-sediment samples were collected including a grab sample from the middle of the river (grab) and a composite EWI depth-integrated sample from a representative cross section of the river (EWI). Grab and composite EWI samples were submitted for SSC and TSS laboratory analyses, resulting in four combinations of sampling types and laboratory methods. The resulting four types of concentration data were used to help describe relations between EWI SSC and grab TSS. Bedload and bed material samples also were collected during the sampling events and submitted to the laboratory for particle-size analyses. The modern (2006–16) suspended-sediment concentrations relations were used to compare historical (1973–86) sediment curves and loads.

Physical Setting

The Nemadji River drains 430 square miles and empties into Lake Superior in Superior, Wisconsin (fig. 1). The watershed straddles eastern Minnesota and northwestern Wisconsin. The USGS streamgage is 2 miles south of Superior, Wisconsin, and the river has a drainage area of 420 square miles at the streamgage. The streamgage has operated continuously from 1973 to present (2020).

The steep, mainly forested Nemadji River watershed is known for problems with flashy runoff and large sediment loads (Robertson, 1996; Natural Resources Conservation Service, 1998). The mean slope of the river is 2 feet per mile, but the thick clayey glacio-lacustrine deposits that cover much of the watershed promote rapid runoff during rainfall events (Natural Resources Conservation Service, 1998; Reidel and others, 2001; 2005). Mass wasting and channel incision along deeply incised stream valleys contribute a large part of the load (Natural Resources Conservation Service, 1998; Reidel and others, 2001; 2005).

Methods

Methods included gathering published historical and ongoing sediment concentration, streamflow, and sediment load data collected by the USGS, WDNR, and the MPCA at the Nemadji River streamgage. Additional comparative measurements of suspended sediment, bedload, and bed material were collected by the USGS from July 2015 through

July 2016 and analyzed by the USGS Kentucky Sediment Laboratory and Wisconsin State Laboratory of Hygiene. Instantaneous total sediment loads for 2015–16 were calculated from the sums of measured suspended-sediment load and bedload. Total sediment loads were also estimated using the modified Einstein procedure. Sediment data processing followed four main steps: tabulation, evaluation, editing, and verification, following guidelines in Guy (1969), Porterfield (1972), and the USGS Office of Surface Water Memorandum 91.15. Simple linear regression models were developed for suspended-sediment concentration, streamflow rating curves, and comparison of MPCA and WDNR grab TSS samples. Analysis of covariance (ANCOVA) was used for comparing sediment concentration-streamflow rating curves. Data on concentrations and loads, as well as linear regression models developed for this study, are available as a USGS data release (Fitzpatrick, 2021).

Streamflow Characteristics

Streamflow data have been collected at the Nemadji River streamgage since 1973 (U.S. Geological Survey, 2017). Potential changes in streamflow characteristics for the period of record were examined by plotting mean annual flows and flood-frequency statistics using data retrieved from the USGS National Water Information System (U.S. Geological Survey, 2017). A 10-year moving mean was calculated for the annual mean flows (the mean of the last 10 years of annual mean flows, including the year of interest). Flood-frequency characteristics were calculated using the USGS PeakFQ program based on Bulletin 17B procedures (Flynn and others, 2006; Interagency Advisory Committee on Water Data, 1982) for four consecutive approximately 30-year periods for the 1-percent and 95-percent annual exceedance probability. The four periods included 1973–99 (27 years), 1975–2004, 1980–2009, and 1985–2014. One-sided confidence limits were also computed and are based on the sample set mean, standard deviation, and a confidence coefficient based in part on a weighted skew coefficient (Flynn and others, 2006).

Historical Suspended-Sediment Data Mining

Historical suspended-sediment data at the Nemadji River streamgage included EWI SSC data collected and analyzed by the USGS from 1973 through 1986 and grab TSS collected and analyzed by the WDNR and MPCA from 2006 through 2016. Data were gathered from the USGS National Water Information System database (U.S. Geological Survey, 2017) and the WDNR Surface Water Integrated Monitoring System and included EWI SSC, instantaneous streamflow, and instantaneous suspended-sediment loads. The grab TSS data were collected by either the WDNR or MPCA on a monthly plus events basis for a total of about 30 to 40 samples per year.

2015–16 Sediment Data Collection and Laboratory Analyses

From July 2015 through July 2016, 12 suspended-sediment, bedload, and bed material samples were collected by the USGS at the Nemadji River streamgage along with ongoing streamflow measurements during 11 sampling events (table 1, fig. 2). Streamflow measurements are routinely collected as part of existing funding from WDNR and the USGS Cooperative Water Program to run the realtime continuous-record streamgage (https://waterdata.usgs.gov/usa/nwis/uv?site_no=04024430). Sediment samples were collected from streamflows ranging from about 300 to more than 12,000 cubic feet per second (ft^3/s). The sampling was spread among seasons, except for the winter months of December through March when the river was frozen. The July 2016 flood had an annual exceedance probability of less than 0.2 percent (Fitzpatrick and others, 2017).

Suspended Sediment

Cross-sectional composite samples of suspended sediment were collected with a depth-integrating model D–74 or D–96 sampler using standard USGS methods, including EWI at equal transit rates (Edwards and Glysson, 1999; Gray and Landers, 2014). Stream water was collected at 15 to 20 verticals across the channel cross section with a distance between verticals of about 5 feet. The resulting composite sample accounted for the horizontal and vertical variability of SSC in the water column. These methods were similar to the techniques used by the USGS to collect suspended-sediment data from 1973 through 1986. The exact type of depth-integrating sampler used in 1973 is not known.

A grab sample of suspended sediment was collected from stream water using a weighted open-bottle sampler, replicating sampling methods used by WDNR and MPCA. The grab sample was collected from approximately 1 to 3 feet below the water surface in the centroid of flow. The WDNR was able to get a grab sample on July 12, 2016, close to the peak of the extreme flood of 15,600 ft^3/s (Fitzpatrick and others, 2017), whereas the USGS could not get to the site as fast because of nearby flood-related road closures.

The EWI and the grab sample were each split into two samples using a churn splitter. One set of samples was analyzed for SSC and particle-size determinations at the Kentucky Water Science Center Sediment Laboratory using standard filtration methods (Guy, 1969) under a quality assurance plan (Shreve and Downs, 2005). The particle-size determinations included a sand-fine split, or that portion of the sample greater than 0.063 millimeter (mm). The second set of samples were analyzed for TSS at the Wisconsin State Laboratory of Hygiene using standard methods for the examination of water and waste-water method: 2540D (American Water Works Association, 2012). In hindsight, the churn splitter added

Table 1. Date, instantaneous streamflow, and associated sediment samples collected by the U.S. Geological Survey at the Nemadji River streamgage near Superior, Wisconsin (U.S. Geological Survey station number 04024430), from July 2015 to July 2016.

[MM, month; DD, day; YY, year; EWI, equal-width-increment; SSC, suspended-sediment concentration]

Date (MM/DD/YY)	Instantaneous streamflow during EWI SSC sample collection (cubic feet per second)	Type of samples collected
07/07/15	2,590	Suspended, bedload, and bed material
07/08/15	1,350	Suspended, bedload, and bed material
10/28/15	388	Suspended, bedload, and bed material
11/06/15	298	Suspended, bedload, and bed material
11/17/15	698	Suspended, bedload, and bed material
11/18/15	1,990	Suspended, bedload, and bed material
03/31/16	1,990	Suspended, bedload, and bed material
04/25/16	4,820	Suspended, bedload, and bed material
04/26/16	4,830	Suspended only
05/31/16	247	Suspended, bedload, and bed material
07/12/16	15,300	Suspended-sediment grab only
07/13/16	5,930	Suspended only

another possible source of error to the sediment concentration results, because biases have been documented, both positive and negative, associated with the settling-velocity of the particles and the amount of sand (Barr, 2018).

The four types of concentration data from the 2015–16 sampling events (EWI SSC, grab SSC, EWI TSS, and grab TSS) were compared using simple linear regression plots. The concentration, particle-size data, and simple linear regression results are available in a USGS data release (Fitzpatrick, 2021).

The instantaneous streamflow at the time of sampling and the results from the concentration analyses were used to compute an instantaneous suspended-sediment load using the equation:

$$Qs = Qw \times Cs \times K \qquad (1)$$

where

Qs is the suspended-sediment load, in tons (English short tons) per day;

Qw is the instantaneous streamflow, in cubic feet per second;

Cs is suspended-sediment concentration, in milligrams per liter; and

K is a coefficient (0.0027) used to convert the units of measurement of streamflow and SSC or TSS into loads of tons per day and assumes a specific gravity of 2.65 (Porterfield, 1972).

Sometimes the instantaneous streamflow for the EWI samples was slightly different from the grab samples if the flow conditions were changing during sampling. The EWI samples generally took about 45 minutes to collect, whereas the grab sample took less than 1 minute to collect.

Bedload and Bed Material

Bedload and bed-material samples were collected by the USGS at the same verticals as the EWI suspended-sediment samples (Edwards and Glysson, 1999). Bedload samples were collected with a BL–84 sampler. A sample bag mesh size of 0.125 mm was used for all events. The more standard 0.250-mm mesh bag was used for the first two cross-sectional passes of the first event, followed by two additional passes with a sample bag with a mesh size of 0.125 mm. The sampler was held on the bottom for 30 seconds at each vertical. Bed-material samples were collected with a BM–54 or BMH–60 sampler at each of the verticals using methods described in Edwards and Glysson (1999).

The composited bedload and bed-material samples were dried at 105 degrees Celsius for 24 hours, weighed, and sieved for 60 minutes for sand and gravel sizes at the preparatory laboratory at the USGS Upper Midwest Water Science Center. Bedload mass, bedload, and bed-material particle-size results are available in a USGS data release (Fitzpatrick, 2021).

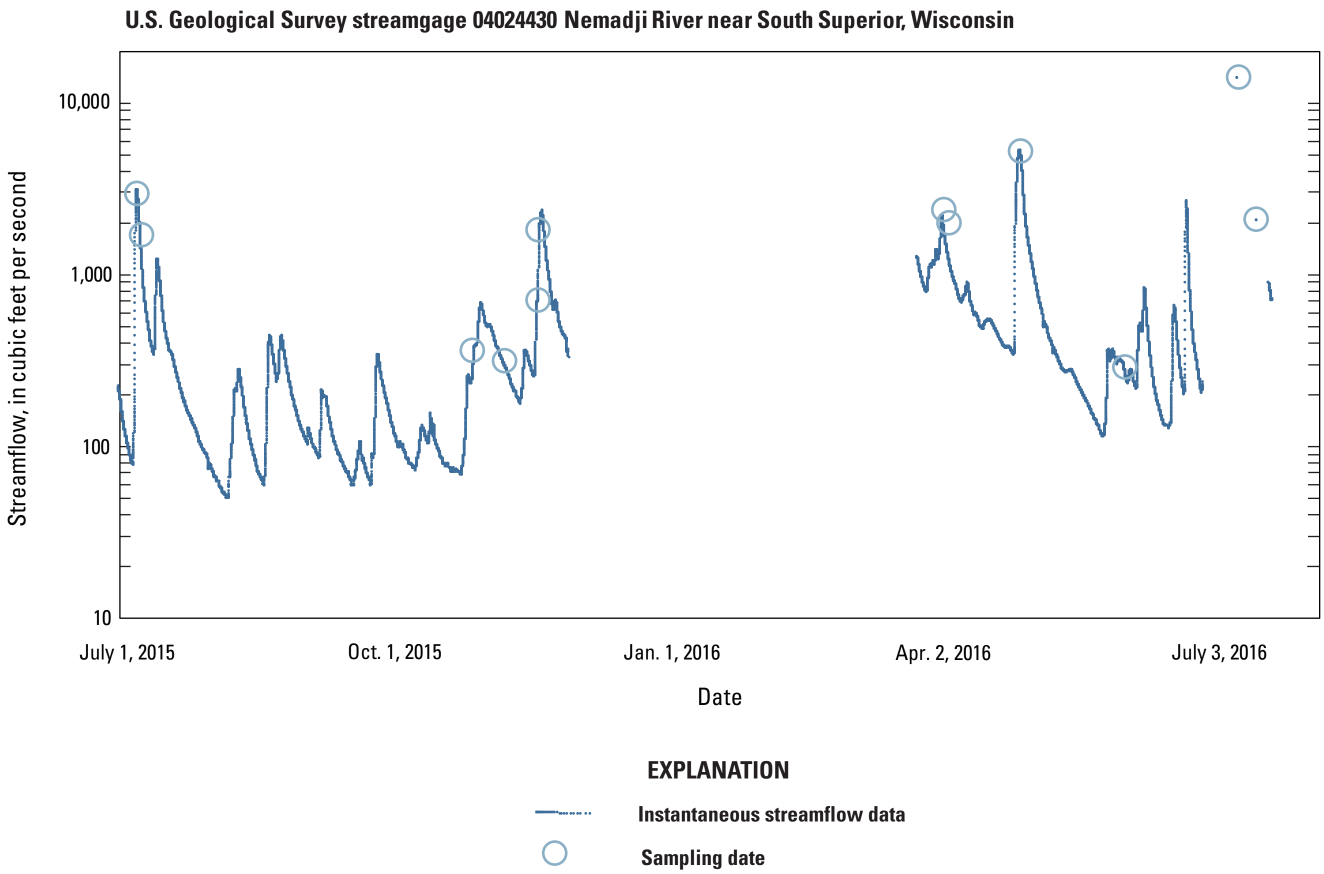

Figure 2. Hydrograph showing instantaneous streamflow for the Nemadji River streamgage near South Superior, Wisconsin, during the study period from July 2015 to July 2016 (U.S. Geological Survey station number 04024430). Sediment sampling dates shown in gray circle symbols. Instantaneous streamflow data are not available for winter months and for a short time during the July 2016 flood. Data are from the National Water Information System (U.S. Geological Survey, 2017).

For computing bedload, the "total cross-section method" was used (Edwards and Glysson, 1999). This method requires that (1) the sample times at each vertical are equal, (2) the verticals were evenly spaced across the cross section, and (3) the first sample was collected at half the sample width from the starting bank or edge with active bedload transport. The measured bedload was calculated as:

$$Q_b = K \times (W/t) \times M \quad (2)$$

where

- Q_b is the instantaneous measured bedload, in tons per day;
- K is a conversion factor of 0.381 for the type of sampler (the BL–84 has a 3-inch wide opening);
- W is the total width of the channel from where the bedload samples were collected, in feet;
- t is the total time the sampler was on the bed, in seconds; and
- M is the total mass of sample collected from all verticals sampled in the cross section, in grams.

Instantaneous Measured Total Load

The instantaneous measured total load was estimated by:

$$Q_{Mts} = Q_b + Q_s \quad (3)$$

where

- Q_{Mts} is the instantaneous measured total sediment load, in tons per day;
- Q_b is the instantaneous measured bedload, in tons per day; and
- Q_s is the instantaneous measured suspended-sediment load, in tons per day.

The addition of measured bedloads and suspended-sediment loads for estimating instantaneous measured total sediment loads assumes 100 percent efficiency of the BL–84 bedload samples and that the bedload sampler is sampling the approximately 3-inch unsampled zone near the bed not reached by the suspended-sediment sampler (Edwards and Glysson, 1999).

Modified Einstein Procedure

The USGS program for the computation of total sediment load by the modified Einstein procedure (MODEIN) was used to estimate instantaneous total sediment loads for the 2015–16 events (Einstein, 1950; Colby and Hembree, 1955; Colby and Hubbell, 1961; Stevens, 1985). This procedure is appropriate for alluvial channels like the Nemadji River that have mixed sand and gravel beds with particle sizes less than 16 mm. Field data needed for the procedure included streamflow, mean water depth, top width of channel, water temperature, mean particle size of suspended sediment, mean particle size of bed material, and suspended-sediment concentration. Estimates of the instantaneous total sediment load and bedload from the Einstein procedure were used to confirm the results from the measured loads. Bedload was estimated by the Einstein procedure by:

$$Q_{Cb} = Q_{Cts} - Q_{Cs} \quad (4)$$

where

- Q_{Cb} is the instantaneous calculated bedload, in tons per day;
- Q_{Cts} is the instantaneous calculated total sediment load, in tons per day; and
- Q_{Cs} is the instantaneous calculated suspended load, in tons per day.

Summary data and descriptions for Einstein procedure-related input and output files are available in a USGS data release (Fitzpatrick, 2021).

Suspended-Sediment Rating Curves

Sediment rating curves for the suspended-sediment concentration data were constructed using standard procedures in Glysson (1987). These graphical based curves represent the fit of the relation between instantaneous streamflow (Q_w) and sediment concentration (C_s) and were used for all the sampling and laboratory analysis combinations. Ordinary least squares simple linear regression analyses were applied in Excel to the base-10 logarithm transformed concentration and streamflow data following methods used in Gray and others (2000) and Warrick (2014). The rating curves used in this study are of the power-law form:

$$C_s = a \times Q_{wb} \quad (5)$$

where

- C_s is the sediment concentration, in milligrams per liter;
- a is a fitted value for the intercept;
- Q_w is the streamflow, in cubic foot per second; and
- b is the slope of the rating curve.

When using a rating curve computed in log space, a bias may be introduced in the intercept. This potential bias was not quantified for this study, and to minimize the possible error, the rating curve should only be applied over the range of streamflow sampled in this study.

The regression technique was also used for comparison of base-10 logarithm pairs of EWI SSC, grab SSC, EWI TSS, and grab TSS data. The regression between EWI SSC and grab TSS was used to adjust the historical grab TSS data (*Adj*TSS) before comparison to the historical EWI SSC data.

The log-transformed EWI SSC and *Adj*TSS data were compared for statistically significant differences between the two datasets using the ANCOVA procedure (Clausen and Spooner, 1993) in the R Statistical Environment, R version 3.6.2 (R Core Team, 2019). A confidence level of 0.05 (α=0.05) for ANCOVA results was considered statistically significant. Historical datasets, companion suspended-sediment rating curves, and results from the ANCOVA are available in a USGS data release (Fitzpatrick, 2021).

Calculation of Annual Suspended and Total Sediment Loads 2009–2016

Annual suspended-sediment loads for 2009 through 2016 were calculated by summing daily mean suspended-sediment load computations from GCLAS (Porterfield, 1972; Koltun and others, 2006) based on 30 to 40 samples per year collected monthly plus events. The datasets were sparser than the daily sampling frequency recommended for GCLAS, and the suspended-sediment loads are considered estimates. Grab TSS data from 2006 through 2008 were too few to calculate mean daily or annual loads using this method. Additionally, and for comparison purposes, daily mean suspended-sediment loads were computed by applying the suspended-sediment rating curves for 1973 through 1986 EWI SSC and for 2006 through 2016 *Adj*TSS.

For estimating annual total sediment loads, the daily mean bedload was estimated from the linear regression fit of the 2015–16 percent of instantaneous suspended to total sediment load to streamflow (eq. 6) and added to the daily mean suspended-sediment load to calculate the daily mean total sediment load:

$$\%Q_s/Q_{ts} = a \times Q_w{}^b \quad (6)$$

where

$\%Q_s/Q_{ts}$	is the proportion of measured instantaneous suspended-sediment load to total load, in percent;
a	is a fitted value for the intercept;
Q_w	is the streamflow, in cubic foot per second; and
b	is the slope of the rating curve.

The annual suspended and total loads were based on the water year defined as the 12-month period from October 1 through September 30, designated by the calendar year in which it ends. Daily mean loads calculated with GCLAS and the sediment rating curves are available in a USGS data release (Fitzpatrick, 2021).

Streamflow Characteristics 1973–2016

A comparison of streamflow characteristics for the Nemadji River streamgage over the period of record confirmed that the streamflow differed over the two historical sediment sampling periods and helped to give context to the variability in the 2009–16 annual sediment loads. Annual mean streamflow from 2006 through 2016 during the grab TSS sampling was on mean 84 percent of annual mean streamflow from 1975 through 1986 during EWI SSC sampling (fig. 3; annual streamflow for 1973 and 1974 were not available). The annual mean streamflow was variable during the 1975–86 period and included the highest mean streamflow in 1986, which was about double the mean. In contrast, the lowest mean streamflow on record was in 2007 during grab TSS sampling; however, after 2010, higher mean streamflow years were more common.

Instantaneous annual peak streamflows were helpful for distinguishing years with large floods, even when annual mean streamflows were low (fig. 4). The 2006–16 period had three notably large floods including two large floods in 2011 and 2012 that were more than double any previous flood from 1980 onward. The July 2016 flood of 15,600 ft^3/s had an annual exceedance probability of less than 0.2 percent (Fitzpatrick and others, 2017).

Flood-frequency characteristics, calculated using the USGS PEAKFQ program (Flynn and others, 2006; Interagency Advisory Committee on Water Data, 1982) for four consecutive 30-year periods of streamgage record, indicate a potential (but not statistically significant within the 95-percent confidence interval) decrease in the size of low magnitude frequent floods (95-percent probability of occurring in any given year) and a statistically significant increase in high magnitude floods (1-percent probability of occurring in any given year) during the water years 1985–2014 period overlapping with the grab TSS sampling (fig. 5). The decrease in the size of small frequent floods for the 1980–2009 and 1985–2014 periods compared to previous periods is complementary to the decrease in annual mean flows over a similar time period (fig. 3). These decreases are reflective of a relatively dry period in the mid-1990s through the 2000s that also, in part, contributed to lower water levels in Lake Superior (Gronewold and others, 2013). The increase in the size of floods with a 1-percent probability for the 1985–2014 period is likely partially affected by the large floods in 2011 and 2012 (Czuba and others, 2012; fig. 4). The nonstationarity in annual mean flows and instantaneous peak flows over the same period with differing collection methods for suspended sediment preclude any direct interpretations from increasing or decreasing annual sediment loads without considering flow variability.

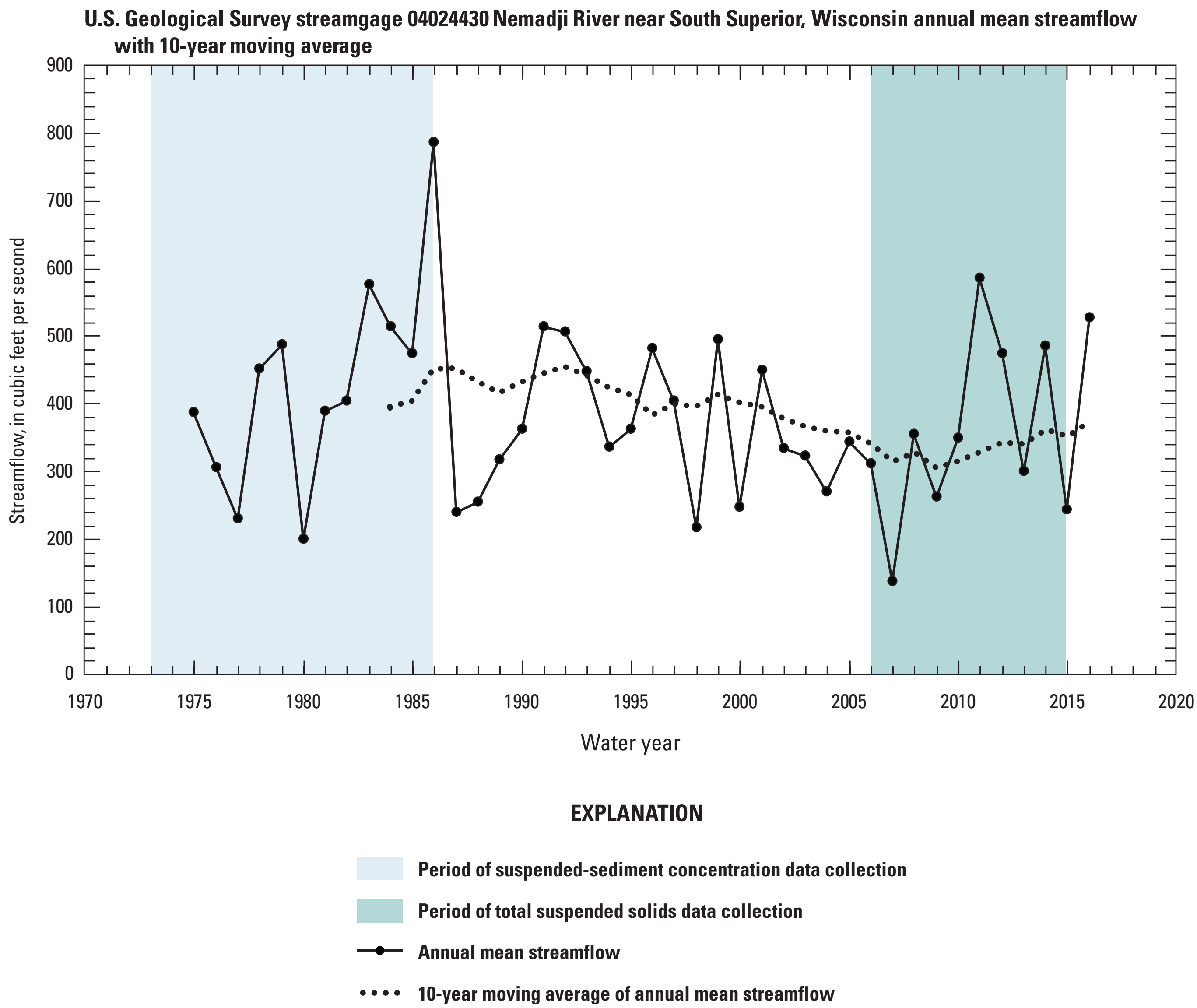

Figure 3. Graph showing annual mean streamflow for the Nemadji River streamgage near South Superior, Wisconsin, water years 1973–2016 (U.S. Geological Survey station number 04024430). Data from the National Water Information System (U.S. Geological Survey, 2017). Suspended-sediment concentration data were collected from 1973 to 1986 and total suspended solids were collected from 2006 to 2015.

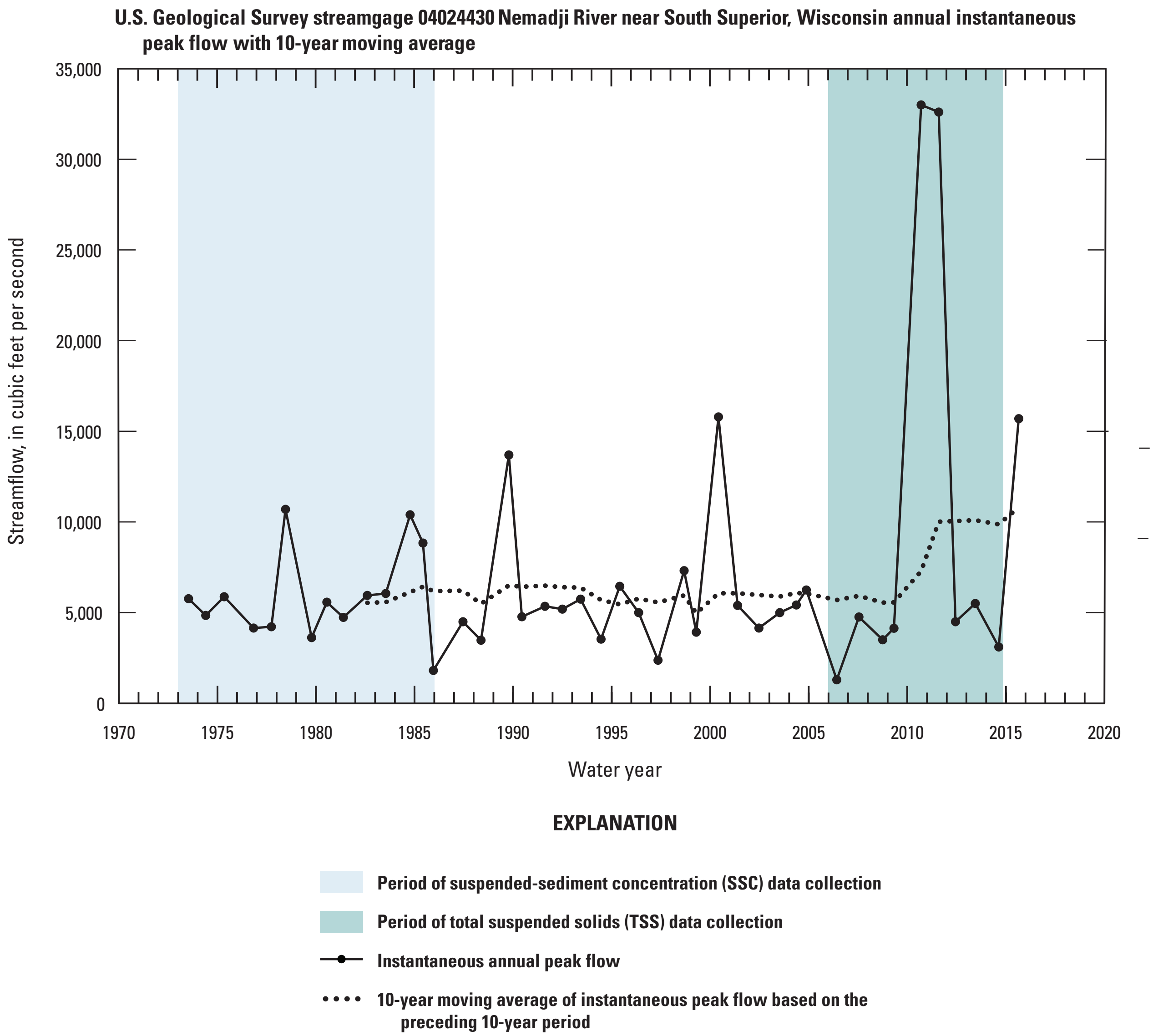

Figure 4. Graph showing the instantaneous annual peak flows for the Nemadji River streamgage near South Superior, Wisconsin, during the study period from water years 1973 to 2016 (U.S. Geological Survey station number 04024430). Data from the National Water Information System (U.S. Geological Survey, 2017). Suspended-sediment concentration data were collected from 1973 to 1986 and total suspended solids were collected from 2006 to 2015.

Sediment Characteristics 2015–16

The 2015–16 sediment sampling at the Nemadji River streamgage was mainly done to develop an adjustment factor that could be used for comparing the historical EWI SSC data with the more recent grab TSS data. The bedload and bed material sampling helped to characterize the proportion of bedload to total sediment loads and ultimately the estimated annual total sediment loads delivered to the lower St. Louis River estuary and AOC (fig. 1).

Comparison of Methods for Suspended-Sediment Concentration

Suspended-sediment concentration samples from July 2015 through July 2016 were collected from streamflows spanning three orders of magnitude, from a low flow of 250 ft^3/s to a flood flow of 15,300 ft^3/s (table 2; fig. 6). Across the four possible types of sampling and analyses combinations (EWI SSC, grab SSC, EWI TSS, and grab TSS), sediment concentrations also spanned three orders of magnitude from less than 11 mg/L to 2,000 mg/L.

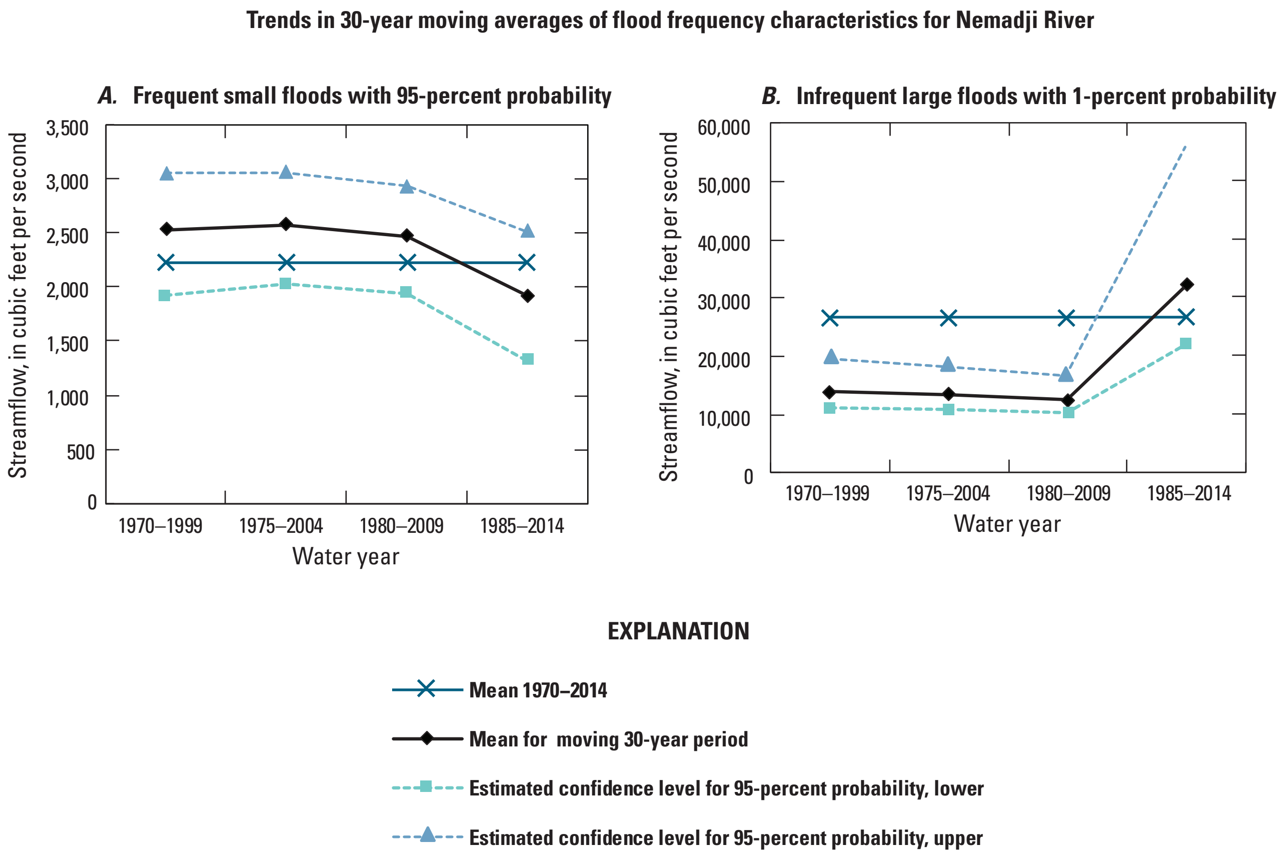

Figure 5. Graphs showing trends in 30-year moving means of flood-frequency characteristics for the Nemadji River streamgage near South Superior, Wisconsin, during the study period from water years 1973 to 2016 (U.S. Geological Survey station number 04024430). *A*, Frequent small floods with 95-percent probability. *B*, Infrequent large floods with 1-percent probability. Peak flow data from the National Water Information System (U.S. Geological Survey, 2017). Flood-frequency statistics calculated using the PEAKFQ program (Flynn and others, 2006) and confidence limits set at 95 percent.

Although concentrations of TSS were lower than SSC in all but four pairs (table 2), with a mean difference of 84 percent, the differences tended to be more for lower concentrations. For example, the spring runoff sample collected on April 25, 2016, had an EWI SSC value of 1,550 mg/L, whereas the grab TSS sample had a value of 1,790 mg/L (table 2, fig. 6A). Previous studies of three tributaries to Lake Michigan concluded that grab TSS values were almost always lower than EWI SSC values (Gray and others, 2000). Similarly, Ellison and others (2014) found EWI SSC values to be on average two times larger than paired grab TSS values for Minnesota streams.

Additionally, the Nemadji River data did not follow an expected pattern observed in the Gray and others (2000) and Ellison and others (2014) studies of increasing sand-sized material with increasing TSS to SSC ration (table 2, fig. 7). In the Gray and others (2000) study, if sand-sized material exceeded about 25 percent of the sediment dry weight, the EWI SSC values tended to exceed their corresponding paired grab TSS values. For the Nemadji River, the highest percentages for sand-size material ranged from 12 to 16 percent for samples collected during low flow, except for a sample on April 26, 2016, that had relatively high streamflow but low suspended-sediment concentration. This sample was collected on the receding limb of a spring rainfall event. The high proportion of fine-grained (silt and clay) suspended sediment in the Nemadji River may be the cause for this departure from the other studies where the studied streams had a higher proportion of suspended sand. This characteristic might also help to explain the similar concentrations of EWI SSC and grab TSS at high flows in the Nemadji River. The use of the churn splitter would not have biased these results.

A closer look at the plots of paired suspended-sediment data help to further describe differences or lack thereof of how sampling and analyses methods may have affected results for instantaneous suspended-sediment concentrations (fig. 6). Differences in EWI SSC and grab TSS concentrations (fig. 6A) could potentially come from differences in both sampling and laboratory analyses. At relatively low concentrations, EWI SSC was higher than grab TSS, but for high concentrations, EWI SSC was lower than grab TSS. The lower EWI SSC values for July 7 and 8, 2015, may have been caused by the time offset between the two samples or that the centroid of flow where the grab TSS was collected had higher

Table 2. Suspended-sediment concentration and total suspended solids data collected in 2015–16 at the Nemadji River streamgage near South Superior, Wisconsin, using two field sampling methods. A composite sample from an equal-width-increment equal depth interval was collected as well as a grab sample from the centroid of flow.

[MM, month; DD, day, YY, year; EWI, equal-width-increment; ft^3/s, cubic feet per second; SSC, suspended-sediment concentration; mg/L, milligram per liter; TSS, total suspended solids; mm, millimeter; --, no sample; *, outliers (lower than expected)]

Date and time (MM/DD/YY)	Sampling method, 10=EWI and 60=grab	Streamflow, instantaneous (ft^3/s)	SSC (mg/L)	TSS, water, unfiltered (mg/L)	TSS to SSC ratio	Percent greater than 0.063 mm in SSC sample
07/07/15, 18:33	10	2,590	297	271	0.91	7
07/07/15, 18:54	60	2,560	269	344	1.28	--
07/08/15, 15:45	10	1,350	135	150	1.11	3
07/08/15, 16:20	60	1,330	128	161	1.26	--
10/28/15, 11:10	60	385	34	27	0.79	--
10/28/15, 13:30	10	388	61	13	*0.21	15
11/06/15, 11:40	60	298	25	23	0.92	--
11/06/15, 12:54	10	298	33	27	0.82	16
11/17/15, 14:22	10	698	139	11	*0.08	14
11/17/15, 14:50	60	704	121	111	0.92	--
11/18/15, 12:12	60	1,980	482	298	0.62	--
11/18/15, 13:26	10	1,990	419	282	0.67	6
03/03/16, 14:21	60	2,010	286	262	0.92	--
03/31/16, 14:41	10	1,990	298	270	0.91	8
04/04/16, 15:15	60	4,750	2,000	1,790	0.90	--
04/04/16, 17:02	10	4,820	1,550	1,320	0.85	6
04/25/16, 17:03	10	4,820	1,450	1,240	0.86	4
04/26/16, 13:25	10	4,830	461	372	0.81	12
05/31/16, 15:31	60	248	32	33	1.03	--
05/31/16, 15:58	10	247	33	29	0.88	2
07/12/16, 17:10	60	15,300	1,970	1,840	0.93	--
07/13/16, 16:10	10	5,930	510	458	0.90	4

suspended-sediment concentrations than the full cross section included in the EWI SSC sample. For the comparison of EWI SSC and EWI TSS, concentrations of TSS were particularly low compared to SSC from two pairs with outliers (table 2), likely because the TSS laboratory method may not have captured a representative aliquot (fig. 6B). The relation between EWI SSC and grab SSC (fig. 6C) was similar to the EWI SSC and grab TSS (fig. 6A), and the grab SSC and grab TSS pairs had close to a 1:1 relation (fig. 6D), further pointing toward the sampling method as the most likely cause for differences in the EWI SSC and grab TSS concentrations.

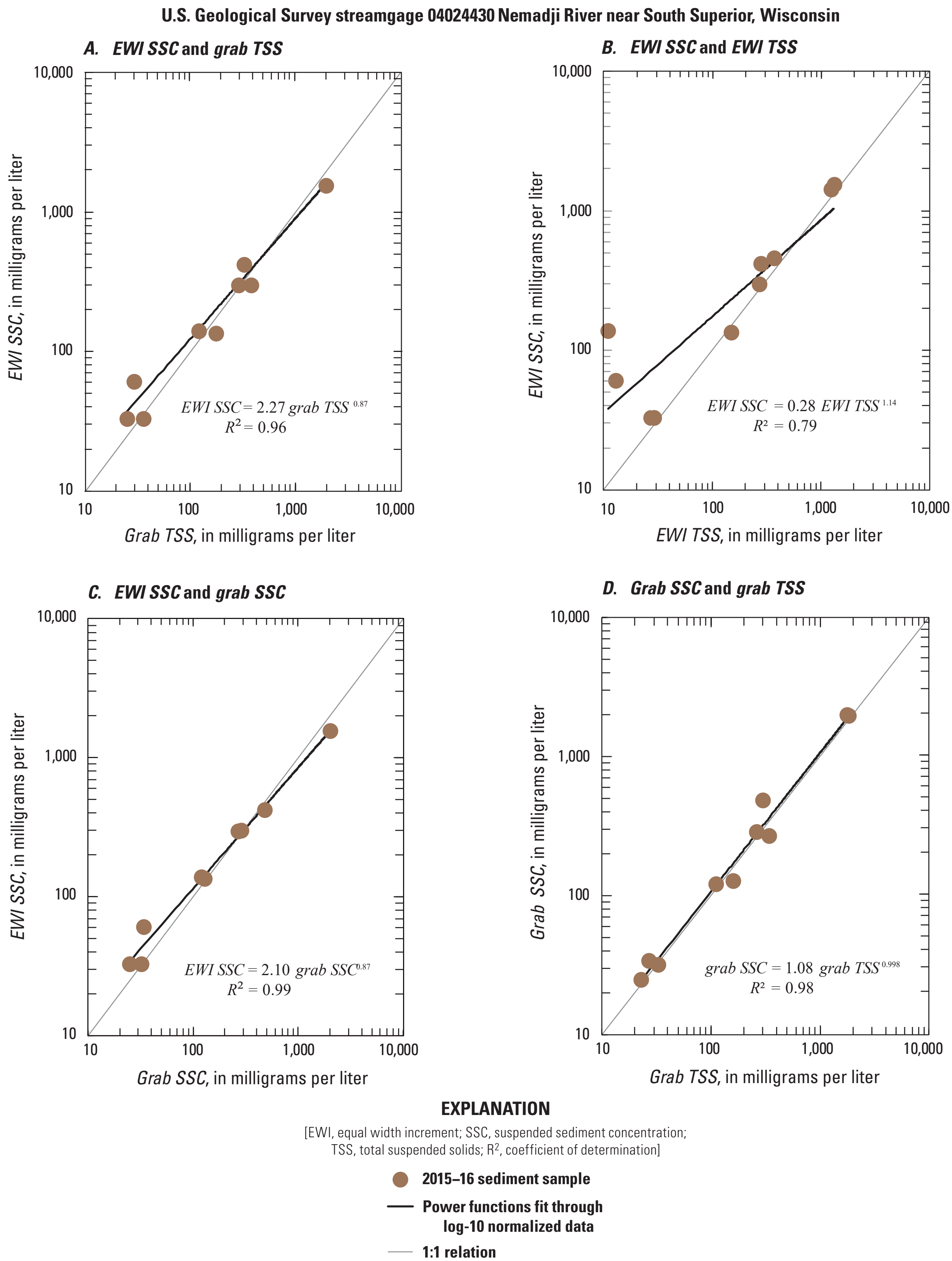

Figure 6. Graphs showing the comparison of paired suspended-sediment concentration (SSC) and total suspended solids (TSS) data for 2015–2016 for the Nemadji River streamgage near South Superior, Wisconsin (U.S. Geological Survey station number 04024430). *A*, Equal-width-increment (EWI) SSC and grab TSS. *B*, EWI SSC and EWI TSS. *C*, EWI SSC and grab SSC. *D*, grab SSC and grab TSS. The line for a 1:1 relation is shown in gray. Data are in table 2.

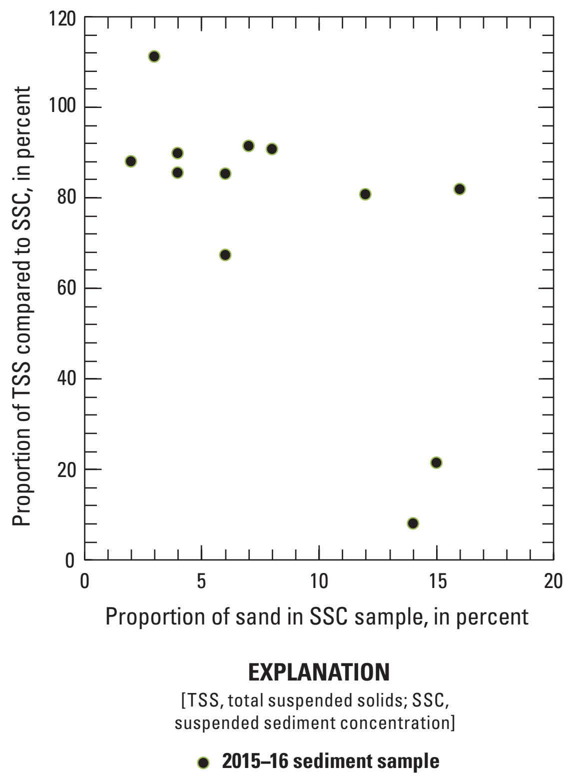

Figure 7. Graph showing the proportion of total suspended solids compared to suspended-sediment concentration compared with sand concentration in the suspended-sediment concentration samples for Nemadji River streamgage near South Superior, Wisconsin, 2015–16 (U.S. Geological Survey station number 04024430).

Bedload and Bed Material

The measured bedload ranged from 5 to 62 tons/day and was less than 1 to 47 percent of the total sediment load for the nine events sampled during 2015–16 (table 3). The highest proportions of bedload (and lowest proportions of suspended-sediment load) were measured during low streamflow (fig. 8). The April 26, 2016, event was not sampled for bedload because of time constraints, and the July 12 and July 13, 2016, events were not sampled because of difficulties getting equipment to the site due to road closures from area-wide flooding (table 1). When streamflows were greater than 1,800 ft^3/s, the instantaneous suspended-sediment load made up 98 percent of the total sediment load, similar to findings for the 1978 data collected by Rose (1980).

The measured particle-size distribution of the bedload and bed material was mainly sand in the 0.125- to 1-mm size range (fig. 9). The calculated bedload component from the modified Einstein procedure also was mainly composed of sand (table 3). The fraction greater than 1 mm was less than 10 percent in all but one sample. The mesh size used for the bedload sampler was 0.125 mm except the first two passes on July 7, 2015, when the more traditional 0.250-mm mesh was used. The mesh size was changed to 0.125 mm because sediment could be seen emptying from the bag during retrieval. Whereas silt- and clay-sized particles tend to have a uniform vertical distribution through the water column, the sand-sized particles may be more prevalent in the lower part of the water column, especially for the 0.125- to 0.25-mm sizes (Colby, 1963).

Instantaneous Total Sediment Loads

Instantaneous total sediment loads for the 2015–16 event samples were compared with two approaches (table 3). The first approach was to sum the field measurements of suspended-sediment load and bedload. The second approach was to estimate a total load from the MODEIN. Suspended-sediment loads calculated from the MODEIN were similar to measured suspended-sediment loads (table 3). For streamflows less than about 1,000 ft^3/s, MODEIN-based total loads were less than the measured values, and for streamflows greater than about 1,000 ft^3/s, MODEIN-based total loads were similar to or higher than the measured loads (table 3, fig. 10). The three sampled events with less than 1,000 ft^3/s streamflows had less calculated suspended sediment than measured sediment. Data for two events sampled in 1978 by Rose (1980) were similar. The November 2015 (115 percent) and March 2016 (145 percent) samples had more calculated than measured bedload. On average, the calculated total sediment load was 99 percent of the measured total sediment load.

Table 3. Results for equal-width-increment suspended-sediment and bedload measurements and modified Einstein procedure load calculations for 2015–16 for the Nemadji River streamgage near South Superior, Wisconsin (U.S. Geological Survey station number 04024430).

[MM, month; DD, day; YY, year; ft^2, square foot; ft, foot; ft/s, foot per second; ft^3/s, cubic foot per second; EWI SSC, equal-width-increment suspended-sediment concentration; mg/L, milligram per liter; ton/d, ton per day; mm, millimeter; <, less than; --, no data]

Characteristic	Date of sediment sampling (MM/DD/YY)								
	07/7/15	07/8/16	10/28/15	11/6/15	11/17/15	11/18/15	03/31/16	04/25/16	05/31/16
Field measurements									
Channel wetted width (ft^2)	110	99	71	75	79	89	68	203	71
Mean water depth (ft)	10.0	7.6	3.4	3.3	4.7	8.1	7.2	9.3	3.1
Channel wetted area (ft^2)	1,100	747	240	245	373	720	489	1,890	222
Mean velocity (ft/s)	2.7	2.1	1.6	1.2	1.8	2.6	4.0	2.5	1.1
Mean discharge for EWI SSC sample (ft^3/s)	2,960	1,540	385	300	654	1,870	1,950	4,790	250
Mean discharge for bedload (ft^3/s)	2,750	1,490	385	300	689	1,970	2,030	4,755	248
EWI SSC concentration (mg/L)	297	135	61	33	139	419	298	1,550	33
EWI SSC suspended-sediment load (ton/day)	2,374	561	63	27	245	2,116	1,569	20,046	22
Bedload (ton/day)	62	25	42	24	58	28	32	41	5
Measured total sediment load (ton/day)	2,436	586	105	50	303	2,143	1,601	20,087	28
Percent of measured suspended sediment to total sediment load	97	96	60	53	81	99	98	100	80
Modified Einstein procedure calculated suspended-sediment load (ton/day)									
0.0020–0.0625 mm size range	2,159	529	50	21	202	1,942	1,400	18,612	20
0.0625–0.1250 mm size range	77	8	4	2	14	62	76	594	<1
0.1250–0.2500 mm size range	53	6	3	1	12	41	30	396	<1
0.2500–0.5000 mm size range	28	3	2	1	5	21	15	198	0
0.5000–1.0000 mm size range	5	0	<1	<1	2	0	0	0	0
1.0000–2.0000 mm size range	0	0	0	0	0	0	0	0	0
2.0000–4.0000 mm size range	0	0	0	0	0	0	0	0	0
Calculated suspended-sediment load (ton/d)	2,322	545	59	24	234	2,066	1,522	19,799	21

Table 3. Results for equal-width-increment suspended-sediment and bedload measurements and modified Einstein procedure load calculations for 2015–16 for the Nemadji River streamgage near South Superior, Wisconsin (U.S. Geological Survey station number 04024430).—Continued

[MM, month; DD, day; YY, year; ft^2, square foot; ft, foot; ft/s, foot per second; ft^3/s, cubic foot per second; EWI SSC, equal-width-increment suspended-sediment concentration; mg/L, milligram per liter; ton/d, ton per day; mm, millimeter; <, less than; --, no data]

	Date of sediment sampling (MM/DD/YY)								
Characteristic	07/7/15	07/8/16	10/28/15	11/6/15	11/17/15	11/18/15	03/31/16	04/25/16	05/31/16
Modified Einstein procedure calculated total sediment load (ton/day)									
0.0020–0.0625 mm size range	2,230	547	55	26	216	2,057	1,532	18.945	22
0.0625–0.1250 mm size range	93	41	5	3	18	90	146	646	<1
0.1250–0.2500 mm size range	101	9	5	3	18	103	169	526	<1
0.2500–0.5000 mm size range	140	14	5	4	18	149	304	440	<1
0.5000–1.0000 mm size range	84	4	5	1	13	55	127	164	0
1.0000–2.0000 mm size range	5	<1	0	0	0	2	34	6	0
2.0000–4.0000 mm size range	<1	0	0	0	0	0	4	<1	0
Calculated total sediment load (ton/day)	2,653	615	75	36	282	2,456	2,316	20,728	23
Comparison of calculated and measured results for total sediment load									
Difference between calculated and measurement (ton/day)	217	29	−30	−14	−21	313	715	641	−5
Percent difference between calculated and measured	109	105	71	71	93	115	145	103	82
Mean percent difference between calculated and measured	99	--	--	--	--	--	--	--	--

Comparison of Suspended-Sediment Rating Curves 1973–86 and 2006–16

Trend analysis requires continuous datasets, but an alternative approach was needed because this study included historical data grouped into two datasets with different collection methods, different analytical methods, and a 20-year data gap. In this study, suspended-sediment rating curves (Gray and Simões, 2008; Warrick, 2014) were used to help determine whether land use changes caused differences in sediment loading from the watershed. The assumption for this method is that the suspended-sediment concentrations are supply-limited and not transport-limited. For this study, results from the 2015–16 methods comparison provided the adjustment factor that was needed to be able to compare the 2006–16 grab TSS-based rating curves to the 1973–86 EWI SSC-based rating curves. Furthermore, an additional check was done to make sure that the 2006–16 grab TSS values were not biased by individual State agency methods (fig. 11). Rating curves developed with MPCA and WDNR data were similar despite the MPCA data covering a higher range of streamflows and having about double the number of samples.

Sediment rating curves for 1973–86 EWI SSC and 2006–15 grab TSS data illustrate how the rating for grab TSS data shows lower values than EWI SSC values for lower streamflow (fig. 12A). This relation follows a similar pattern seen in the EWI SSC and grab TSS comparison (fig. 6A). There were more samples for EWI SSC (330) than grab TSS (230), but like the 2015–16 dataset, the two historical datasets

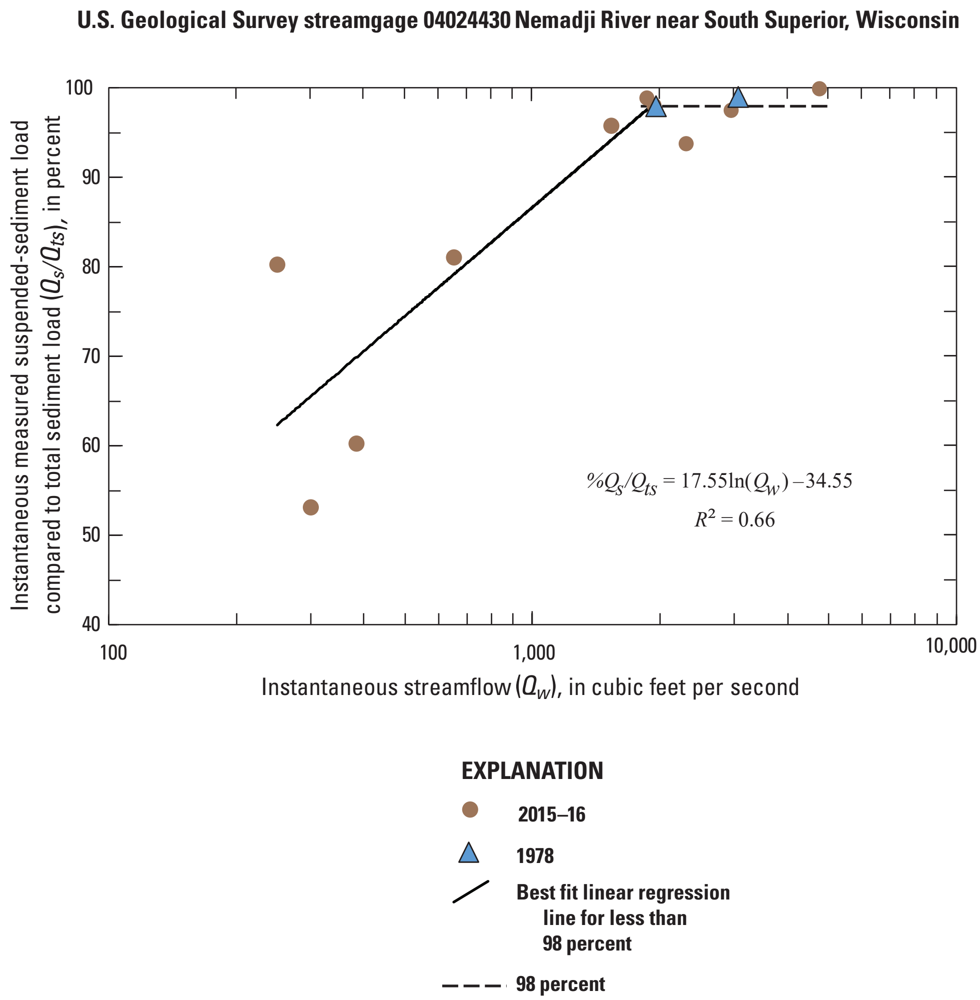

Figure 8. Graph showing the comparison of the proportion of measured instantaneous suspended-sediment load to total sediment load with instantaneous streamflow for nine events sampled in 2015–16 and two events in 1978 at the Nemadji River streamgage near South Superior, Wisconsin, 1973–2016 (U.S. Geological Survey station number 04024430). The fitted simple linear regression (solid line) extends to a streamflow of about 1,800 cubic feet per second. At streamflows greater than 1,800 cubic feet per second, the percentage of suspended-sediment load was assumed to be 98 percent of the total load (dashed line). Data from 1978 from Rose (1980).

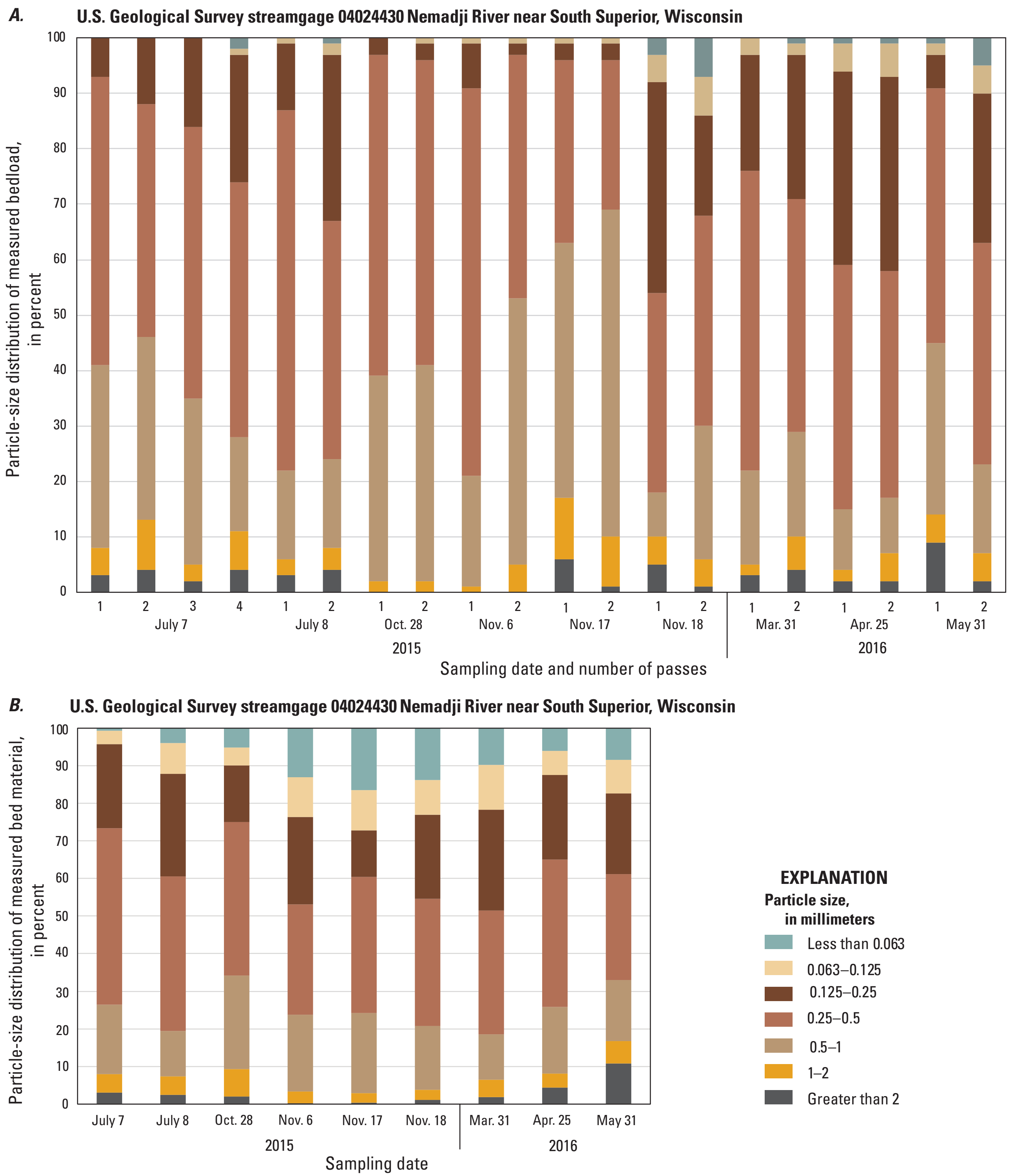

Figure 9. Graphs showing particle-size distribution of measured bedload. *A,* from multiple passes. *B*, bed material samples from the 2015–16 sampling events at the Nemadji River streamgage near South Superior, Wisconsin, 1973–2016 (U.S. Geological Survey station number 04024430). Bedload sampler mesh size was 0.125 millimeter except for July 7, 2015, passes 1 and 2, which had a mesh size of 0.25 millimeter.

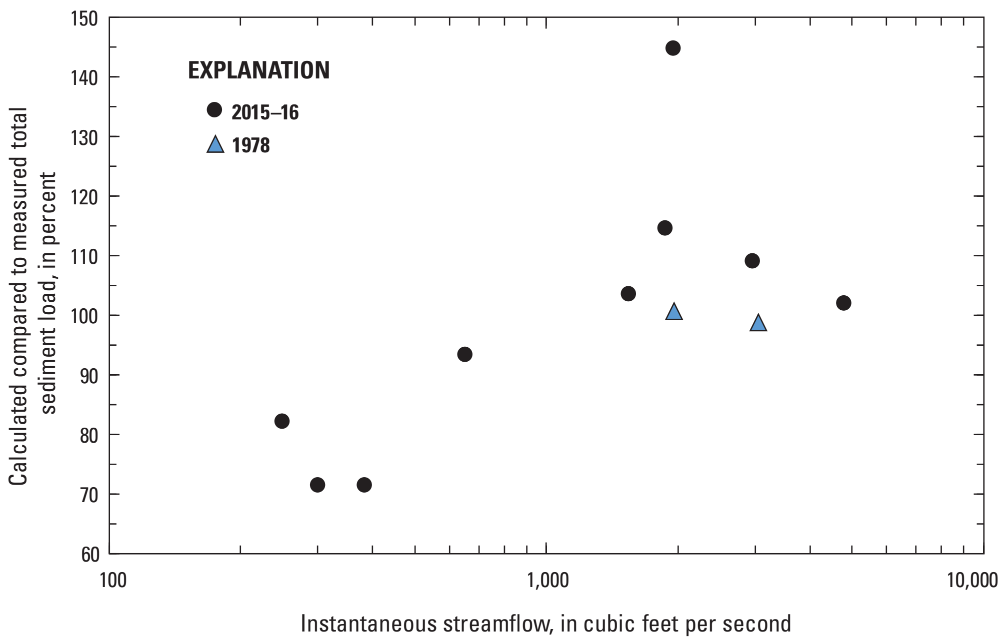

Figure 10. Graph showing the calculated compared to measured total sediment load, in percent, for 2015–16 and 1978 at the Nemadji River streamgage near South Superior, Wisconsin, 1973–2016 (U.S. Geological Survey station number 04024430). The 1978 data are from Rose (1980).

covered three orders of magnitude of concentrations (10 mg/L to more than 1,000 mg/L) and streamflow (50 to almost 10,000 ft^3/s).

After the 2015–16 methods, the comparison-based adjustment factor is applied to the grab TSS values:

$$AdjTSS = 2.27 \times TSS^{0.87} \quad (7)$$

where

AdjTSS is the grab TSS concentration, adjusted for use in comparison to EWI SSC, in milligrams per liter; and

TSS is the grab total suspended solids concentration, in milligrams per liter.

The 2006–16 *Adj*TSS rating curve continued to have a negative offset compared to the 1973–86 EWI SSC rating curve (fig. 12B). Results from an ANCOVA analysis indicated that the negative offset was statistically significant at the 99-percent confidence level (p-value = 0.0068; table 4). This offset indicates that less suspended sediment was transported for equivalent streamflows in the 2006–15 period compared to the 1973–86 period.

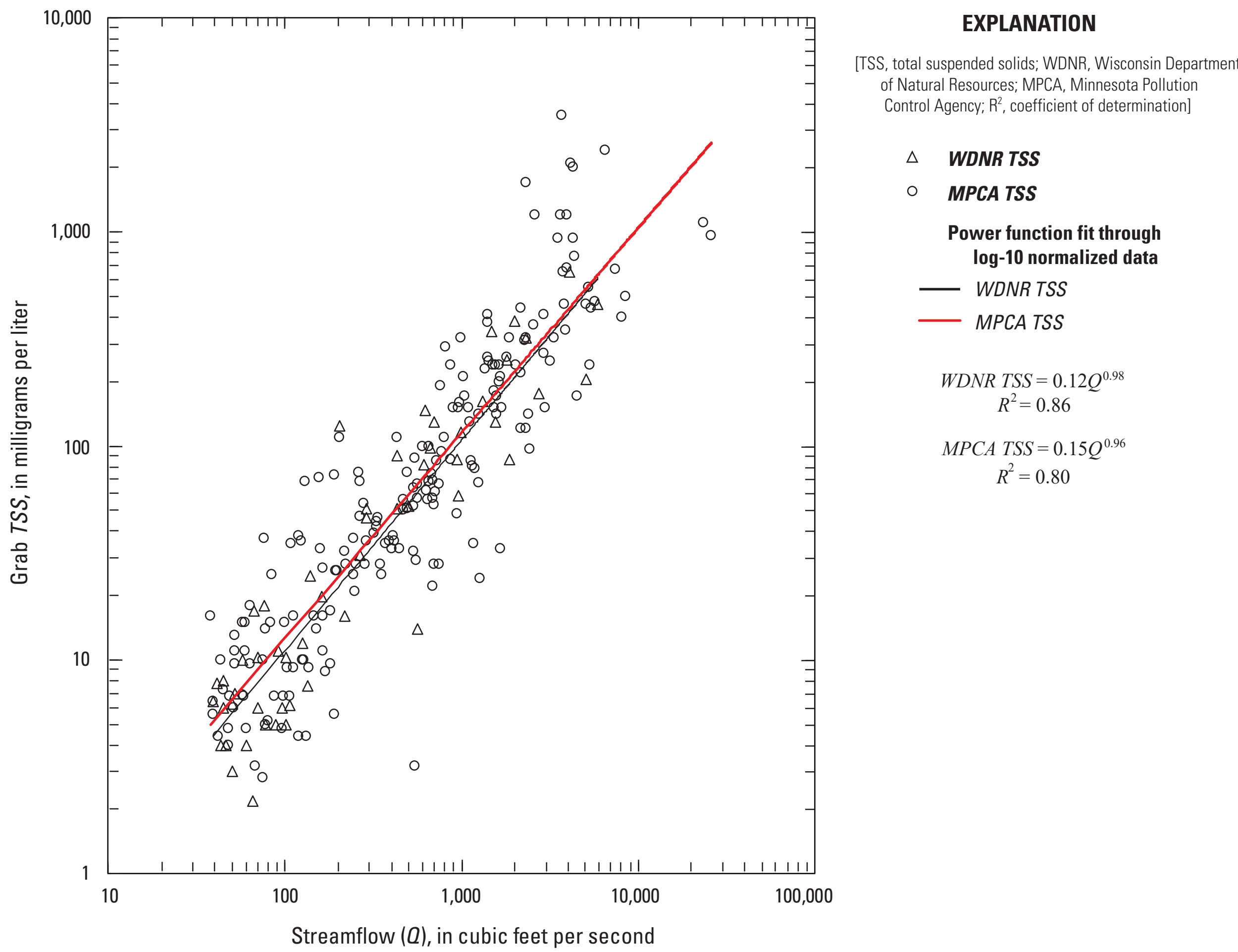

Figure 11. Graph showing grab total suspended solids collected by the Wisconsin Department of Natural Resources and the Minnesota Pollution Control Agency with streamflow from 2006 to 2015 for Nemadji River streamgage near South Superior, Wisconsin (U.S. Geological Survey station number 04024430). Lines are power functions fit through log-10 normalized data from each State agency.

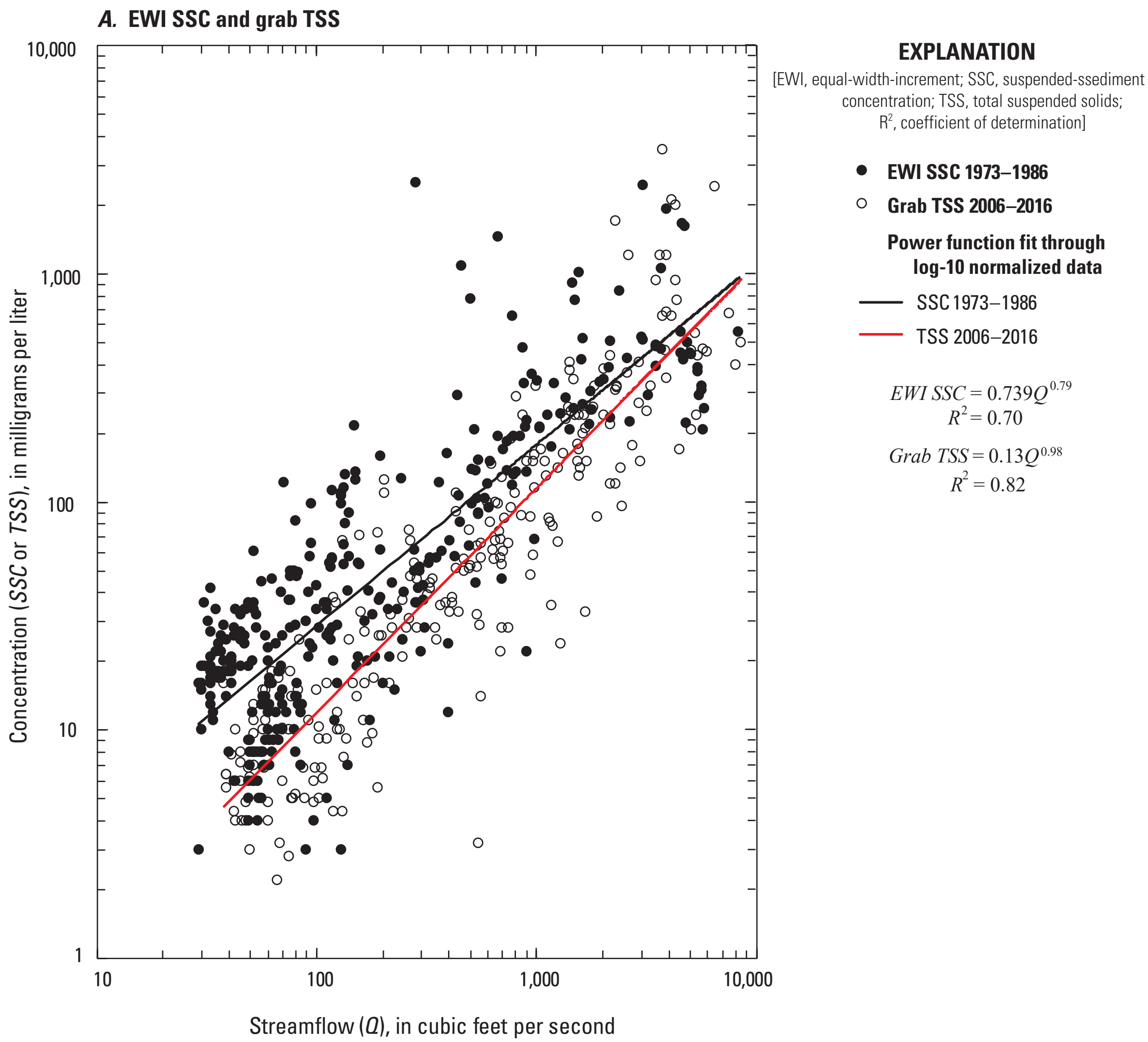

Figure 12. Graphs showing suspended-sediment rating curves for base-10 logarithms of equal-width-increment suspended-sediment concentration from 1973 to 1986. *A*, grab total suspended solids from 2006 to 2016. *B*, adjusted total suspended solids from 2006 to 2016 for Nemadji River streamgage near South Superior, Wisconsin (U.S. Geological Survey station number 04024430).

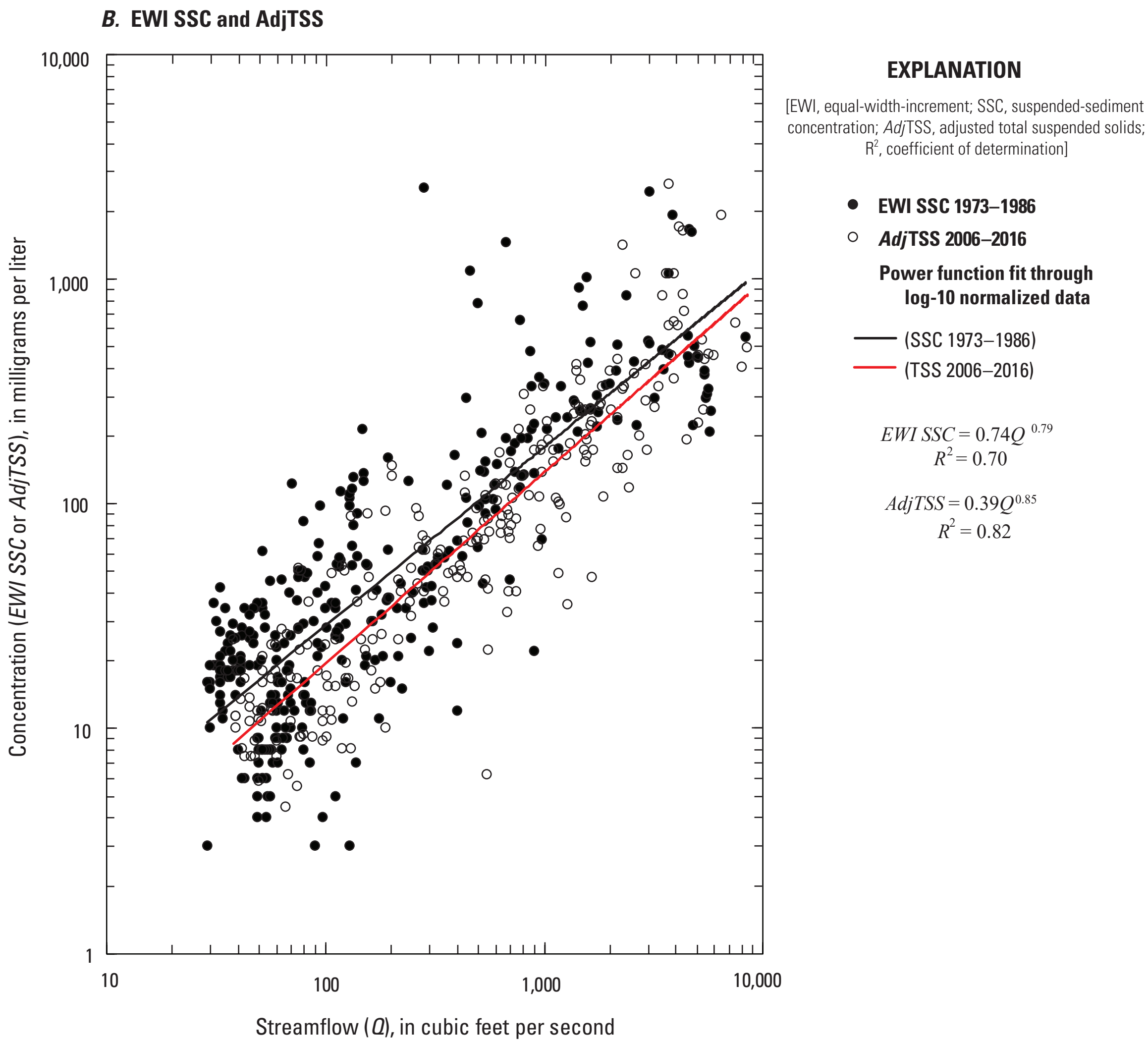

Figure 12. Graphs showing suspended-sediment rating curves for base-10 logarithms of equal-width-increment suspended-sediment concentration from 1973 to 1986. *A*, grab total suspended solids from 2006 to 2016. *B*, adjusted total suspended solids from 2006 to 2016 for Nemadji River streamgage near South Superior, Wisconsin (U.S. Geological Survey station number 04024430).—Continued

Estimates of Annual Suspended and Total Sediment Loads 2009–16

The 2009–16 period covered a wide range of hydrologic conditions, and the annual suspended and total sediment loads reflected the wide range annual streamflow (table 5, fig. 13). The annual suspended-sediment loads ranged from a low of about 21,000 tons per year in 2015 to a high of 167,000 tons per year in 2012, with a mean load of 85,000 tons per year. Annual suspended-sediment loads for 2009 through 2016 were estimated by summing the daily mean grab TSS and *Adj*TSS-based load values from GCLAS. In addition, rough estimates for annual total sediment loads were calculated by applying the 2015–16 relation between percent suspended of total sediment loads ($\%Q_s/Q_{ts}$) compared to streamflow (Q_w) (eq. 6, fig. 8). This equation was used for 2009–16 daily mean streamflow values of less than or equal to 1,800 ft³/s. For daily mean streamflow greater than 1,800 ft³/s, the suspended-sediment load was assumed to be 98 percent of the total sediment load (fig. 8).

Table 4. Analysis of covariance results for suspended-sediment rating curves from 1973 to 1986 equal-width-increment suspended-sediment concentration data and 2006–15 adjusted total suspended solids data for Nemadji River streamgage near South Superior, Wisconsin (U.S. Geological Survey, station number 04024430).

[Regression coefficients are log-transformed to meet the assumptions for the analysis of covariance results (ANCOVA). t, calculated difference represented in units of standard error; *, statistically significant at the α=0.05 level; <, less than; ***, statistically significant at the α=0.001 level; **, statistically significant at the α=0.01 level,. --, not applicable; R-squared, R-squared is the coefficient of determination]

Source	Result	Standard error	t value	Probability (greater than absolute value of t)
Intercept	−0.131	0.061	−2.147	0.032*
Slope	0.795	0.026	30.516	<2e–16***
Change in intercept	−0.281	0.103	−2.716	0.0068**
Change in slope	0.056	0.04	1.393	0.164
F-statistic	580.5	--	--	--
p-value	<2.2e–16	--	--	--
Degrees of freedom	3 and 571	--	--	--
R-squared	0.75	--	--	--
Number of observations	575	--	--	--

Table 5. Annual suspended and total sediment loads for 2009–16 based on total suspended solids concentrations and adjusted total suspended solids concentrations from daily mean summaries computed from the Graphical Constituent Loading System. The percentage of suspended to total sediment load is based on the 2015–16 suspended to total sediment load rating curve.

[ft^3/s, cubic foot per second; TSS, total suspended solids; ton/year, ton per year; *Adj*TSS, adjusted total suspended solids]

Water year	Annual cumulative streamflow (ft^3/s-days)	Grab TSS annual suspended-sediment load (ton/year)	*Adj*TSS annual suspended-sediment load (ton/year)	Proportion of grab TSS to *Adj*TSS suspended load (percent)	*Adj*TSS annual total sediment load (ton/year)	Proportion of *Adj*TSS suspended to total sediment load (percent)
2009	96,000	20,000	23,000	85	28,000	82
2010	128,000	33,300	37,000	88	42,000	88
2011	214,000	142,000	126,000	112	135,000	94
2012	174,000	202,000	167,000	120	176,000	95
2013	110,000	28,000	32,000	86	36,000	90
2014	177,000	158,000	155,000	102	163,000	95
2015	89,000	19,000	21,000	88	26,000	81
2016	193,000	131,000	120,000	109	127,000	94
Mean	148,000	91,000	85,000	99	92,000	90

Graph

The annual loads varied by an order of magnitude depending on hydrologic conditions in a given year, with the highest grab TSS loading being in 2012 (table 5), which included the flood of record (Czuba and others, 2012), followed by 2014. The grab TSS loads were higher than the *Adj*TSS loads in high-loading years, and the suspended-sediment load also made up a larger percentage of the total sediment load. Even though there was not a large flood in 2014, high annual streamflow resulted in large sediment loads, similar to the large flood years of 2011, 2012, and 2016. The mean annual grab TSS and *Adj*TSS suspended-sediment loads and *Adj*TSS total sediment load for 2009 through 2016 was 91,000, 85,000, and 92,000 tons/yr, respectively. The mean total sediment load is not much larger than the suspended-sediment loads, reflecting the predominance of suspended loads in this river. The percentage of annual bedload compared to annual suspended-sediment load depended on streamflow, with bedload representing about 20 percent of the total load in years with relatively low streamflow and only 5 to 6 percent in years with floods or high streamflow.

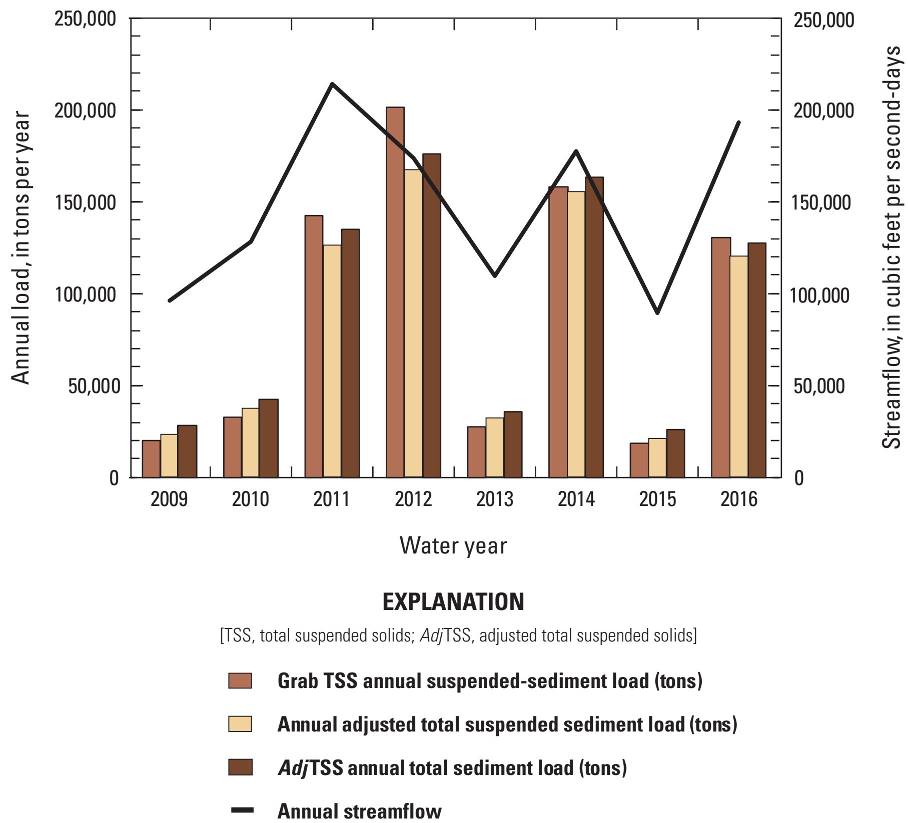

Figure 13. Graph showing annual streamflow, suspended-sediment load, and total sediment load for the Nemadji River streamgage near South Superior, Wisconsin, 2009–16 (U.S. Geological Survey station number 04024430). Suspended-sediment load calculated for grab total suspended solids and adjusted total suspended solids. Total sediment load calculated from adjusted total suspended-sediment daily mean loads and relation of the percentage of suspended-sediment load to total sediment load with streamflow (fig. 8).

Lastly, the 2009–16 annual *Adj*TSS GLCAS-based annual suspended-sediment loads were compared to annual suspended-sediment loads calculated from the 2006–16 *Adj*TSS and 1973–86 EWI SSC sediment rating curves (table 6, fig. 12*B*). The GCLAS-based loads are usually, but not always, lower than those based on the sediment rating curves, likely because the GCLAS method accounts for seasonal and runoff hydrograph (hysteresis) variations that are not possible with the suspended-sediment rating curve method. The negative offset between the two historical suspended-sediment rating curves resulted in the 2006–16 mean annual suspended-sediment loads being 87 percent of the 1973–86 mean annual loads.

Table 6. Comparison of 2009–16 annual adjusted total suspended solids loads based on mean daily summaries computed from the Graphical Constituent Loading System and 2006–16 and 1973–86 suspended-sediment rating curves.

[*Adj*TSS, adjusted total suspended solids; GCLAS, Graphical Constituent Loading System; ton/year, ton per year; EWI, equal-width-increment; SSC, suspended-sediment concentration]

Water year	*AdjTSS* GCLAS (ton/year)	2006–16 *Adj*TSS sediment rating curve (ton/year)	1973–86 EWI SSC sediment rating curve (ton/year)
2009	23,000	29,000	37,000
2010	37,000	54,000	65,000
2011	126,000	194,000	220,000
2012	167,000	232,000	257,000
2013	32,000	54,000	65,000
2014	155,000	127,000	150,000
2015	21,000	20,000	26,000
2016	120,000	130,000	152,000
Mean	85,000	105,000	121,000

Summary

A variety of sediment characteristics were examined at the U.S. Geological Survey Nemadji River streamgage in northwestern Wisconsin (U.S. Geological Survey station number 04024430), which has flow and sediment data starting in 1973 and continuing through 2016 and beyond. During 2015 through 2016, the U.S. Geological Survey, in cooperation with the Wisconsin Department of Natural Resources, conducted a methods and laboratory comparison study for suspended sediment collected at the Nemadji River streamgage. Even though available sediment data were collected with different sampling and laboratory methods with a time gap in between, the suspended-sediment rating curve approach was useful in comparing two historical periods with observed differences in patterns in annual streamflow and floods. Differences in equal-width-increment suspended-sediment concentration (EWI SSC) and grab samples for total suspended solids (grab TSS) concentrations were less than expected because of the predominance of fine grained (silt and clay) sized suspended sediment. The EWI SSC values were less than grab TSS samples for total suspended solids in some instances, perhaps because of concentrations differences horizontally across the channel cross section, with higher concentrations in the centroid of flow and lower concentrations along the margins.

For 2009 through 2016, annual suspended-sediment load ranged from a low of about 21,000 tons per year in 2015 to a high of 167,000 tons per year in 2012, with a mean load of 85,000 tons per year. The percentage of annual bedload compared to annual suspended-sediment load depended on streamflow, with bedload representing about 20 percent of the total load in years with relatively low streamflow and only 5 to 6 percent in years with floods or high streamflow. The proportion of bedload to total load likely drops as streamflow increases because of the potential for the abundance of fine-grained sediment in the Nemadji River to be transported in suspension during high streamflow. Instantaneous total sediment loads calculated from the modified Einstein procedure were up to 70 percent of measured loads for streamflows less than about 1,000 cubic feet per second and near or greater than 100 percent of measured for streamflows greater than about 1,000 cubic feet per second.

An adjustment factor based on a regression fit between the 2015–16 grab TSS and EWI SSC data was used for comparing suspended-sediment rating curves between the 1973–86 and 2006–16 periods. An analysis of covariance indicated that suspended-sediment rating curves for the two periods were statistically different at the 99-percent confidence level, and that concentrations of suspended sediment were lower in 2006–16 than 1973–86 for comparable streamflows.

Annual suspended and total sediment loads varied year-to-year by an order of magnitude during 2009 through 2016. The large amount of suspended sediment delivered to the mouth of the Nemadji River and eventually Lake Superior during extreme floods in 2011, 2012, and 2016 and the high annual streamflow in 2014 likely obscures the expected decrease in suspended-sediment concentrations and loads in the 2006–16 period compared to the 1973–86 period.

References Cited

American Water Works Association, 2012, Standard methods for the examination of water and wastewater (22d ed.): Washington, D.C., American Public Health Association, variously paged.

Barr, M.N., 2018, Evaluation of whole-water churn splitters for suspended-sediment sample collection and analysis: U.S. Geological Survey Scientific Investigations Report 2018–5126, 25 p., https://doi.org/10.3133/sir20185126.

Clausen, J.C., and Spooner, J., 1993, Paired watershed study design: U.S. Environmental Protection Agency Technical Report 841–F–93–009, 8 p.

Colby, B.R., 1963, Fluvial sediments—A summary of source, transportation, deposition, and measurement of sediment discharge: U.S. Geological Survey Bulletin 1181–A, 47 p.

Colby, B.R., and Hembree, C.H., 1955, Computations of total sediment discharge, Niobrara River, near Cody, Nebraska: U.S. Geological Survey Water-Supply Paper 1357, 187 p.

Colby, B.R., and Hubbell, D.W., 1961, Simplified methods for computing total sediment discharge with the modified Einstein procedure: U.S. Geological Survey Water Supply Paper 1593, 17 p.

Czuba, C.R., Fallon, J.D., and Kessler, E.W., 2012, Floods of June 2012 in northeastern Minnesota: U.S. Geological Survey Scientific Investigations Report 2012–5283, 42 p., with 3 app., accessed February 15, 2020, at https://pubs.usgs.gov/sir/2012/5283/.

Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 89 p.

Einstein, H.A., 1950, The bedload function for sediment transportation in open channel flows: U.S. Department of Agriculture Technical Bulletin no. 1026, 70 p.

Ellison, C.A., Savage, B.E., and Johnson, G.D., 2014, Suspended-sediment concentrations, loads, total suspended solids, turbidity, and particle-size fractions for selected rivers in Minnesota, 2007 through 2011: U.S. Geological Survey Scientific Investigations Report 2013–5205, 43 p., accessed July 17, 2020, at https://doi.org/10.3133/sir20135205.

Fitzpatrick, F.A., 2021, Selected sediment data and results from regression models, modified Einstein Procedure, and loads estimation for the Nemadji River, 1973–2016: U.S. Geological Survey data release, https://doi.org/10.5066/P9FX0X6Y.

Fitzpatrick, F.A., Dantoin, E.D., Tillison, N., Watson, K.M., Waschbusch, R.J., and Blount, J.D., 2017, Flood of July 2016 in northern Wisconsin and the Bad River Reservation: U.S. Geological Survey Scientific Investigations Report 2017–5029, 21 p., 1 app. [Also available at https://doi.org/10.3133/sir20175029.]

Flynn, K.M., Kirby, W.H., and Hummel, P.R., 2006, User's manual for program PeakFQ, annual flood-frequency analysis using Bulletin 17B guidelines: U.S. Geological Survey Techniques and Methods 4–B4, 42 p.

Glysson, G.D., 1987, Sediment-transport curves: U.S. Geological Survey Open-File Report 87–218, accessed April 7, 2020, at https://pubs.er.usgs.gov/publication/ofr87218.

Gray, J.R., Glysson, D., Turcios, L.M., and Schwarz, G.E., 2000, Comparability of suspended-sediment concentration and total suspended solids data: U.S. Geological Survey Water-Resources Investigations Report 2000–4191, 14 p, accessed March 1, 2020, at https://pubs.er.usgs.gov/publication/wri004191.

Gray, J.R., and Landers, M.N., 2014, Measuring suspended sediment, *in* Ahuja, S., ed., Comprehensive water quality and purification v. 1. Elsevier, Inc., p. 157–204. [Also available at https://doi.org/10.1016/B978-0-12-382182-9.00012-8.]

Gray, J.R., and Simões, F.J.M., 2008, Estimating sediment discharge, *in* Garcia, M., ed., Sedimentation engineering—Processes, measurements, modeling, and practice: American Society of Civil Engineers Manual 110, appendix D, p. 1065–1086, accessed March 1, 2020, at https://water.usgs.gov/osw/techniques/Gray_Simoes.pdf.

Gronewold, A.D., Fortin, V., Lofgren, B., Clites, A., Stow, C.A., and Quinn, F., 2013, Coasts, water levels, and climate change—A Great Lakes perspective: Climatic Change, v. 120, no. 4, p. 697–711. [Also available at https://doi.org/10.1007/s10584-013-0840-2.]

Groten, J.T., and Johnson, G.D., 2018, Comparability of river suspended-sediment sampling and laboratory analysis methods: U.S. Geological Survey Scientific Investigations Report 2018–5023, 23 p., accessed July 17, 2020, at https://doi.org/10.3133/sir20185023.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey, Techniques of Water-Resources Investigations, book 5, chap. C1, 59 p.

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood flow frequency: U.S. Geological Survey, Office of Water Data Coordination Bulletin 17B of the Hydrology Subcommittee, 190 p.

Koltun, G.F., Eberle, M., Gray, J.R., and Glysson, G.D., 2006, User's manual for the Graphical Constituent Loading Analysis System (GLCAS): U.S. Geological Survey Techniques and Methods, book 4, chapter C1, 51 p., accessed March 1, 2020, at https://water.usgs.gov/software/GCLAS/.

LimnoTech, 2013, St. Louis River area of concern implementation framework—Roadmap to delisting (Remedial action plan update): Minnesota Pollution Control Agency, 64 p., accessed March 1, 2020, at https://www.pca.state.mn.us/sites/default/files/wq-ws4-02a.pdf.

Minnesota Pollution Control Agency and Wisconsin Department of Natural Resources, 2015, St. Louis River Area of Concern, 2015 Remedial Action Plan: LimnoTech, St. Paul, Minnesota, 107 p, accessed on March 1, 2020, http://dnr.wi.gov/topic/greatlakes/documents/SLRAOCRAP2015.pdf.

Natural Resources Conservation Service, 1998, Nemadji River Basin Project Report: St Paul, Minn., U.S. Department of Agriculture, Natural Resources Conservation Service.

Porterfield, G., 1972, Computation of fluvial sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C3, 66 p.

R Core Team, 2019, R–A language and environment for statistical computing: Vienna, Austria, R Foundation for Statistical Computing web page, accessed March 1, 2020, at http://www.R-project.org/.

Reidel, M.S., Verry, E.S., and Brooks, K.N., 2001, Land use impacts on fluvial processes in the Nemadji River watershed: International Journal of Hydrology Science and Technology, v. 18, p. 197–206.

Reidel, M.S., Verry, E.S., and Brooks, K.N., 2005, Impacts of land use conversion on bankfull discharge and mass wasting: Journal of Environmental Management, v. 76, p. 326–337.

Robertson, D.M., 1996, Use of frequency-volume analyses to estimate regionalized yields and loads of sediment, phosphorus, and polychlorinated biphenyls to Lakes Michigan and Superior: U.S. Geological Survey Water-Resources Investigations Report 96–4092, 47 p.

Rose, W.J., 1980, Bedload in Northwestern Wisconsin's Nemadji River, *in* Andrews, S.C., ed., Impact of nonpoint pollution control on western Lake Superior—Red Clay Project final Part III: U.S. Environmental Protection Agency 905/9-79-002-C p. 378–384.

Shreve, E.A., and Downs, A.C., 2005, Quality-assurance plan for the analysis of fluvial sediment by the U.S. Geological Survey Kentucky Water Science Center Sediment Laboratory: U.S. Geological Survey Open-File Report 2005–1230, 28 p., accessed March 8, 2021, at https://pubs.er.usgs.gov/publication/ofr20051230.

St. Louis River Alliance, 2015, St. Louis River area of concern—2015 Progress Report: Wisconsin Department of Natural Resources, 3 p., accessed March 1, 2020, at https://dnr.wi.gov/topic/greatlakes/documents/StLouisRiverAllianceReportOfProgress2015.pdf.

Stevens, H.H., Jr., 1985, Computer program for the computation of total sediment discharge by the modified Einstein procedure: U.S. Geological Survey Water-Resources Investigations Report 85–4047, 77 p.

U.S. Geological Survey, 1991, Programs and plans—Guidelines for the analyses of sediment data: U.S. Geological Survey Office of Surface Water Technical Memorandum 91.15, accessed January 21, 2021, at https://water.usgs.gov/admin/memo/SW/sw91.15.html.

U.S. Geological Survey, 2017, USGS 04024430 NEMADJI RIVER NEAR SOUTH SUPERIOR, WI, in USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed May 15, 2017, at https://doi.org/10.5066/F7P55KJN. [Site information directly accessible at https://waterdata.usgs.gov/nwis/inventory/?site_no=04024430&agency_cd=USGS&amp.]

Warrick, 2014, Trend analysis with river sediment rating curves: Hydrological Processes, v. 29, p. 936–949.

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