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Prepared in cooperation with the Sauk-Suiattle Indian Tribe

Suspended-Sediment Concentration in the Sauk River, Washington, Water Years 2012-13

By Christopher A. Curran[1], Scott Morris[2], and James R. Foreman[1]

[1] U.S. Geological Survey, Washington Water Science Center, Tacoma, Washington
[2] Department of Natural Resources, Sauk-Suiattle Indian Tribe, Darrington, Washington
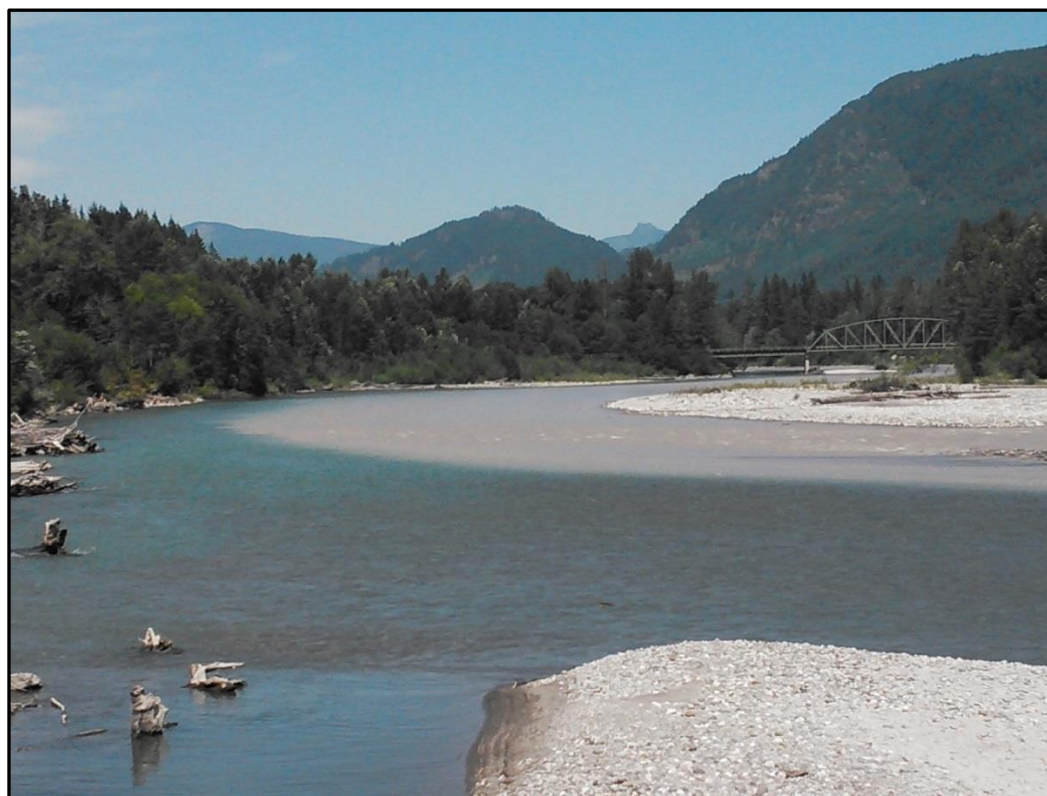
Photograph of glacier-derived suspended sediment entering the Sauk River immediately downstream of the Suiattle River mouth (August 5, 2014, Chris Curran).

Introduction

The Sauk River is one of the few remaining large, glacier-fed rivers in western Washington that is unconstrained by dams and drains a relatively undisturbed landscape along the western slope of the Cascade Range. The river and its tributaries are important spawning ground and habitat for endangered Chinook salmon (Beamer and others, 2005) and also the primary conveyors of meltwater and sediment from Glacier Peak, an active volcano (fig. 1). As such, the Sauk River is a significant tributary source of both fish and fluvial sediment to the Skagit River, the largest river in western Washington that enters Puget Sound. Because of its location and function, the Sauk River basin presents a unique opportunity in the Puget Sound region for studying the sediment load derived from receding glaciers and the potential impacts to fish spawning and rearing habitat, and downstream river-restoration and flood-control projects.

The lower reach of the Sauk River has some of the highest rates of incubation mortality for Chinook salmon in the Skagit River basin, a fact attributed to unusually high deposition of fine-grained sediments (Beamer, 2000b). The Suiattle River, a principal tributary to the Sauk River, is similarly impaired by sediment and Chinook have been observed to favor spawning sites in the relatively clearer mouths of tributary creeks (Beamer and others, 2005). In recent years the volcano's glacier-sediment pulses have appeared to coincide with spawning runs in late spring and summer, and the effects of this on fish health during the fry to smolt stages is unknown. The 2005 Skagit River Recovery Plan asserts that levels of sedimentation in the lower Sauk River have increased since 1991 (though data to support this is limited) and attributes this to accelerated glacial melting from Glacier Peak. Other, management-related, sediment sources such as mass-wasting events associated with forestry practices have increased

sediment loading in forested mountain watersheds, but the potential contribution from this source in the Sauk River basin is unknown. Increased sediment delivery from the Sauk River has downstream implications for human safety (flood control), economic interests (agriculture) and fisheries management associated with the Skagit River, which is Puget Sound's largest river and fish producer.

In cooperation with the Sauk-Suiattle Indian Tribe, the U.S. Geological Survey (USGS) was asked to monitor turbidity and calculate suspended-sediment concentrations and loads in the Sauk River beginning in October, 2011. During the project, USGS operated turbidity sensors at established streamflow gaging stations at three locations in the Sauk River (fig. 1) and collected suspended-sediment samples over a range of turbidity and flow conditions at each site. A relation between turbidity and suspended-sediment concentration was developed at each site, consistent with established USGS protocols (Rasmussen and others, 2009), to enable reporting of 15-min suspended-sediment concentration and calculation of daily suspended-sediment loads.

Purpose and Scope

This document contains calculations of total suspended-sediment concentration and concentration of suspended-sediment fines (particle sizes smaller than 0.0625 mm) and associated uncertainties at three sites in the Sauk River basin from October 1, 2011 to September 30, 2013. A time-series record of suspended-sediment concentration is reported using continuous turbidity data as a surrogate for suspended-sediment concentration.

Computation of Suspended-Sediment Concentration Time Series Record

Fluvial sediment data were collected at three USGS streamflow gaging stations on the Sauk River over a range of flows and turbidity values: Sauk River above Whitechuck River near Darrington (USGS Station Number 12186000), Sauk River near Darrington (12187500), and Sauk River near Sauk

(12189500) (fig. 1). Suspended-sediment samples were collected using either the equal-width-increment (EWI) method or the equal-discharge method (EDI) (Edwards and Glysson, 1999) to ensure that sample concentrations were representative of the channel cross section. Suspended-sediment samples were collected using a variety of depth-integrated samplers approved by the Federal Interagency Sedimentation Project (FISP) and routinely used by USGS personnel (Davis, 2005). All sediment samples were analyzed at the USGS sediment laboratory at the Cascades Volcano Observatory in Vancouver, Washington, to determine the total sediment concentration and percentage of fine-grained particles (generally silts and clays, less than 0.0625 mm in size and referred to as 'fines'). All discrete suspended-sediment sample data collected for the Sauk River are available through the National Water Information System (NWIS) at:

http://waterdata.usgs.gov/wa/nwis/nwisman/?site_no=12186000&agency_cd=USGS, for the Sauk River above Whitechuck River near Darrington (12186000);

http://waterdata.usgs.gov/wa/nwis/nwisman/?site_no=12187500&agency_cd=USGS, for the Sauk River near Darrington (12187500); and

http://waterdata.usgs.gov/wa/nwis/nwisman/?site_no=12189500&agency_cd=USGS, for the Sauk River near Sauk (12189500).

Turbidity was continuously monitored at each site during the period of sediment sampling (October 1, 2011 to September 30, 2013), with the exception of intermittent periods when instrument failure or excessive sedimentation or fouling occurred. Turbidity was measured at each site using a DTS-12 nephelometric turbidity sensor (Forest Technology Systems Ltd., 2014) enclosed within a protective pipe (Use of trade or brand names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey). This mounting arrangement allowed turbidity measurements in an actively flowing part of the river channel and decreased the likelihood of

debris build-up around the sensor face or on the mounting hardware. Turbidity data for each site were recorded at 15-minute intervals and transmitted hourly via satellite from the water-quality monitoring stations to the USGS Automated Data Processing System and are available through NWIS at:

http://waterdata.usgs.gov/wa/nwis/uv/?site_no=12186000&PARAmeter_cd=63680, for the Sauk River above Whitechuck River near Darrington (12186000);

http://waterdata.usgs.gov/wa/nwis/uv/?site_no=12187500&PARAmeter_cd=63680, for the Sauk River at Darrington (12187500); and

http://waterdata.usgs.gov/wa/nwis/uv/?site_no=12189500&PARAmeter_cd=63680, for the Sauk River near Sauk (12189500). The operational range of the DTS-12 sensor as suggested by the manufacturer is 0 - 1,600 FNU (Forest Technology Systems Ltd., 2014) and when turbidity values in the Sauk River exceeded 1,600 FNU, turbidity values were reported as ">1,600 FNU" and corresponding computed values of suspended-sediment concentration were censored and reported accordingly for each site. USGS protocols for the operation and maintenance of continuous water-quality instruments were followed as outlined by Wagner and others (2006), and the time-series data were processed and reviewed according to established USGS policy for continuous water-quality data.

Standard USGS guidelines were followed at all Sauk River sites for using turbidity as a surrogate measurement for suspended-sediment concentration (Rasmussen and others, 2009). At each site, regression equations were developed for estimating the concentration of total suspended sediment and the concentration of fines based on measured suspended-sediment concentrations from representative samples and concurrently measured turbidity. Upper and lower confidence intervals for regression models, as well as upper and lower prediction intervals for individual estimates of suspended-sediment concentration, were calculated at the 90-percent level (Rasmussen and others, 2009). A time-series record of suspended-sediment concentration was computed for each site by

applying the appropriate regression equation using 15-minute turbidity time-series data from October 1, 2011, to September 30, 2013. This reporting period brackets the dates when operational turbidity sensors were exchanged with replacement calibrated sensors and checked against standards following USGS protocol, thus ensuring integrity of the turbidity data (Wagner and others, 2006).

Results

For all Sauk River sites, regression model metrics such as R^2 and model standard percentage error (*MSPE*; Rasmussen and others, 2009) improved after applying logarithmic (base-10) transformations to turbidity and suspended-sediment concentration data (table 1). However, converting the log-transformed concentrations back into arithmetic space resulted in a bias (Helsel and Hirsh, 1992). To correct for the bias, a nonparametric "smearing" correction was used when transforming the estimates of suspended-sediment concentration and 90-percent prediction intervals back into arithmetic space (Duan, 1983; Rasmussen and others, 2009); see table 1 for a list of bias correction factors used. In developing the regression models for estimating the total suspended-sediment concentration and the fine-grained portion (<0.0625 mm) of suspended-sediment concentration, between 12 and 15 representative samples collected at each site during the study were used (appendix A). For each site, the regression models for estimating total suspended-sediment concentration and the concentration of fines were applied to the respective time-series record of 15-minute turbidity values from October 1, 2011, to September 30, 2013 using the methods outlined by Rasmussen and others (2009). Calculated suspended-sediment concentrations exceeded the highest measured suspended-sediment concentration at each of the three sites, and those concentrations have added uncertainty because they are extrapolated beyond the range of the regression.

Sauk River above Whitechuck River near Darrington (12186000)

For the Sauk River above White Chuck River near Darrington (12186000), twelve cross-section representative samples were used to generate a regression model (**fig. 2**) with total suspended-sediment concentration ranging from 2 to 283 mg/L and a median concentration of 43 mg/L (**table 2**). The computed suspended-sediment concentration of time-series data ranged from 0.4 to 990 mg/L with a median value of 7.3 mg/L, and the concentration of fines ranged from 0.2 to 510 mg/L with a median value of 4.3 mg/L (**table 2**). Uncertainty in predicted suspended-sediment concentration, reported as 90-percent prediction intervals, was significant and ranged from 1.4 to 5.1 mg/L when the turbidity was 1.0 FNU (predicted suspended-sediment concentration of 2.6 mg/L), and from 506 to 1,900 mg/L when the turbidity was 850 FNU (predicted suspended-sediment concentration of 990 mg/L). All suspended-sediment concentration values and uncertainties, for both total and fines, were calculated for each available 15-minute turbidity measurement and are available in **appendix B**.

A time-series plot of daily mean suspended-sediment concentration and water discharge in the Sauk River above Whitechuck near Darrington (12186000) shows that turbidity increases with increasing discharge (**fig. 5**). Data utilization, calculated as the percentage useable 15-minute values from the total number of possible values from October 1, 2011 to September 30, 2013, was 81.3 percent. From April 4, 2012 to May 7, 2012 the sensor was buried and recorded erroneous data. From May 16, 2012 to September 5, 2012, the sensor was damaged and not operational until it was replaced and the sensor location was moved 50 ft downstream. When the turbidity sensor was operational during 2012-13 water years, daily mean suspended-sediment concentrations were less than 200 mg/L with the exception of September 29-30, 2013 when daily mean concentration was 393 and 298 mg/L respectively (**fig. 5**).

Sauk River at Darrington (12187500)

For the Sauk River at Darrington (12187500), fifteen cross-section representative samples were used to generate a regression model with total suspended-sediment concentration ranging from 5 to 224 mg/L and a median concentration of 84 mg/L (**table 3**). The computed suspended-sediment concentration of time-series data ranged from 0.7 to 2,670 mg/L with a median value of 11 mg/L, and the concentration of fines ranged from 0.3 to 1,200 mg/L with a median value of 5.1 mg/L (**table 3**). Uncertainty in predicted suspended-sediment concentration, reported as 90-percent prediction intervals, was significant and ranged from 1.0 to 5.9 mg/L when the turbidity was 1.0 FNU (predicted suspended-sediment concentration of 2.4 mg/L), and from 1,090 to 6,540 mg/L when the turbidity was 750 FNU (predicted suspended-sediment concentration of 2,670 mg/L). All suspended-sediment concentration values and uncertainties, for both total and fines, were calculated for each available 15-minute turbidity measurement and are available in **appendix C**.

A time-series plot of daily mean suspended-sediment concentration and water discharge in the Sauk River at Darrington (12187500) shows that shows that in general turbidity increases with increasing discharge, although in late summer and early fall turbidity increases with decreasing discharge due to sediment from glacier-melt processes (**fig. 5**). Because the turbidity sensor was not installed until October 19, 2011, the time series of suspended-sediment concentration was shorter for this site relative to the other two sites. Data utilization from October 19, 2011 to September 30, 2013, was 97.5 percent. When the turbidity sensor was operational during 2012-13 water years, daily mean suspended-sediment concentrations were less than 300 mg/L with the exception of November 23, 2011 when daily mean concentration was 337 mg/L and September 6 and 28, 2013 when daily mean concentration was 420 and 346 mg/L respectively (**fig. 5**).

Sauk River near Sauk (12189500)

For the Sauk River near Sauk (12189500), fifteen cross-section representative samples were used to generate a regression model with total suspended-sediment concentration ranging from 26 to 1,480 mg/L and a median concentration of 343 mg/L (table 4). The computed suspended-sediment concentration of time-series data ranged from 2.5 to greater than 8,800 mg/L with a median value of 26 mg/L, and the concentration of fines ranged from 0.5 to 3,770 mg/L with a median value of 6.2 mg/L (table 4). Uncertainty in predicted suspended-sediment concentration, reported as 90-percent prediction intervals, was significant and ranged from 1.8 to 14.7 mg/L when the turbidity was 1.0 FNU (predicted suspended-sediment concentration of 5.0 mg/L), from 1,500 to 12,600 mg/L when the turbidity was 800 FNU (predicted suspended-sediment concentration of 4,370 mg/L), and from 3,030 to 25,300 mg/L when the turbidity was 1,600 FNU (or predicted suspended-sediment concentration of 8,800 mg/L). All suspended-sediment concentration values and uncertainties, for both total and fines, were calculated for each available 15-minute turbidity measurement and are available in appendix D.

A time-series plot of daily mean suspended-sediment concentration and water discharge in the Sauk River near Sauk (12189500) shows that in general turbidity increases with increasing discharge, although in late summer and early fall turbidity increases with decreasing discharge due to sediment from glacier-melt processes (fig. 5). Data utilization from October 1, 2011 to September 30, 2013, was 99.7 percent. From January 12, 2013 at 11:00am PST to January 14, 2013 at 2:15 pm PST, the sensor did not record turbidity due to equipment malfunction at the gaging station. When the turbidity sensor was operational during 2012-13 water years, daily mean suspended-sediment concentrations exceeded 300 mg/L on 41 days (5.6 percent of days) and the maximum daily-mean concentration was 2,340 mg/L on September 6, 2013 (fig. 5).

Acknowledgments

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Appendix A

Suspended-sediment sample data collected from October 1, 2011 to September 30, 2013 are presented for three water-quality monitoring sites on the Sauk River: Sauk River above Whitechuck River near Darrington, Washington (USGS station No. 12186000); Sauk River at Darrington, Washington (12187500); and Sauk River near Sauk, Washington (12189500). The data were used for regression model calibration and consist of the total suspended-sediment concentration and the concentration of fine suspended sediment (particle size <0.0625 mm) as well as the corresponding turbidity recorded at the monitoring site during sample collection.

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Appendix B

The 15-minute time-series record of turbidity and corresponding suspended-sediment concentration as computed by a regression model, are presented for the monitoring site Sauk River above Whitechuck River near Darrington, Washington (USGS station No. 12186000) for the period of October 1, 2011 to September 30, 2013. Also presented for each turbidity value are the concentration of fine suspended-sediment (particle size less than 0.0625 mm) as determined by regression and the associated uncertainty for each concentration value. Uncertainty is expressed as an upper and lower concentration representing, with 90 percent confidence, the range of expected concentration for a given turbidity value.

Appendix C

The 15-minute time-series record of turbidity and corresponding suspended-sediment concentration as computed by a regression model, are presented for the monitoring site Sauk River at

Darrington, Washington (USGS station No. 12187500) for the period of October 1, 2011 to September 30, 2013. Also presented for each turbidity value are the concentration of fine suspended-sediment (particle size less than 0.0625 mm) as determined by regression and the associated uncertainty for each concentration value. Uncertainty is expressed as an upper and lower concentration representing, with 90 percent confidence, the range of expected concentration for a given turbidity value.

Appendix D

The 15-minute time-series record of turbidity and corresponding suspended-sediment concentration as computed by a regression model, are presented for the monitoring site Sauk River near Sauk, Washington (USGS station No. 12189500) for the period of October 1, 2011 to September 30, 2013. Also presented for each turbidity value are the concentration of fine suspended-sediment (particle size less than 0.0625 mm) as determined by regression and the associated uncertainty for each concentration value. Uncertainty is expressed as an upper and lower concentration representing, with 90 percent confidence, the range of expected concentration for a given turbidity value.
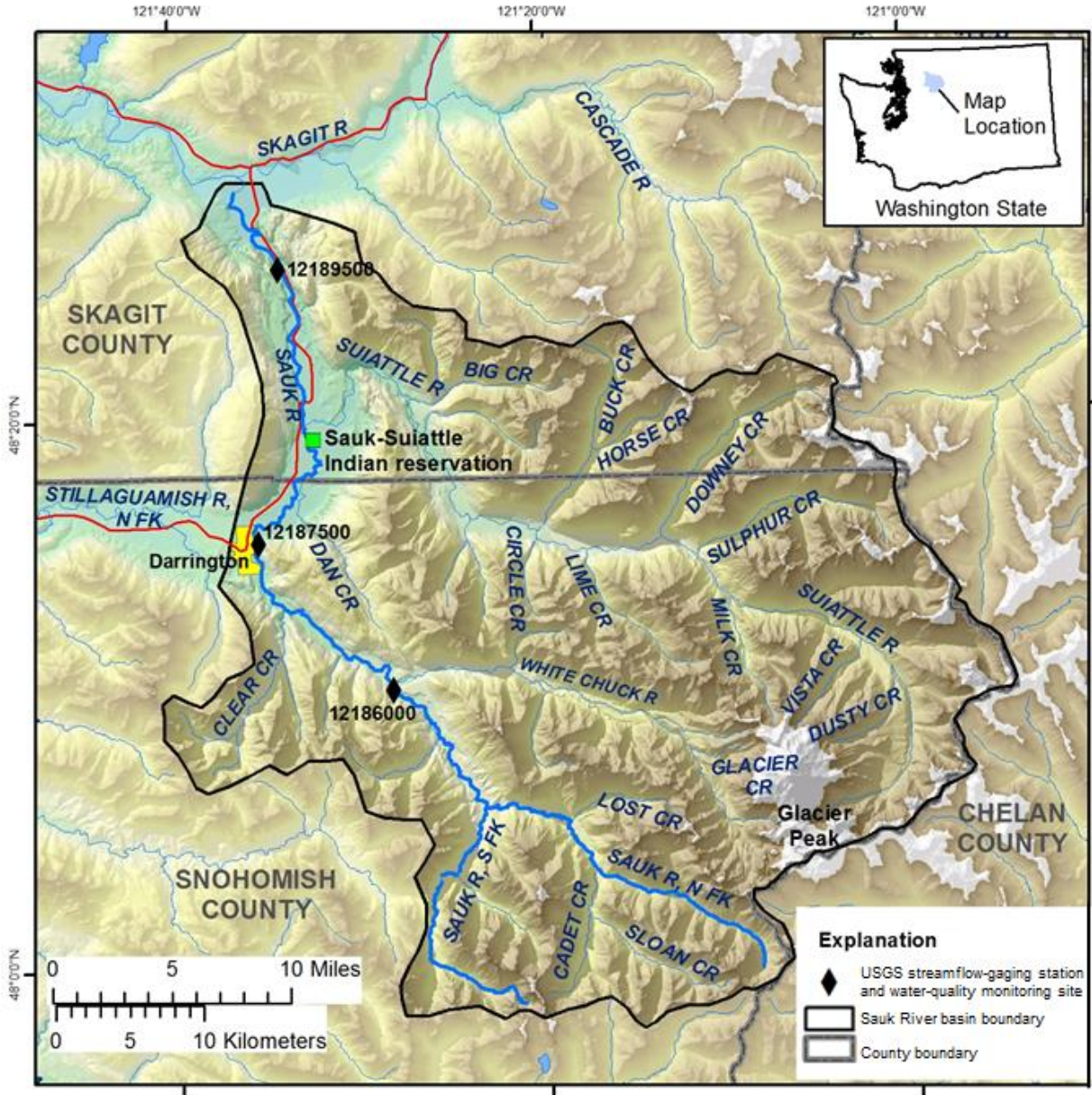
Figures

Figure 1. Map of Sauk River and tributaries in northwest Washington showing three discharge and sediment monitoring stations: Sauk River above Whitechuck River near Darrington (12186000), Sauk River at Darrington (12187500), and Sauk River near Sauk (12189500), where turbidity and suspended-sediment measurements were made.
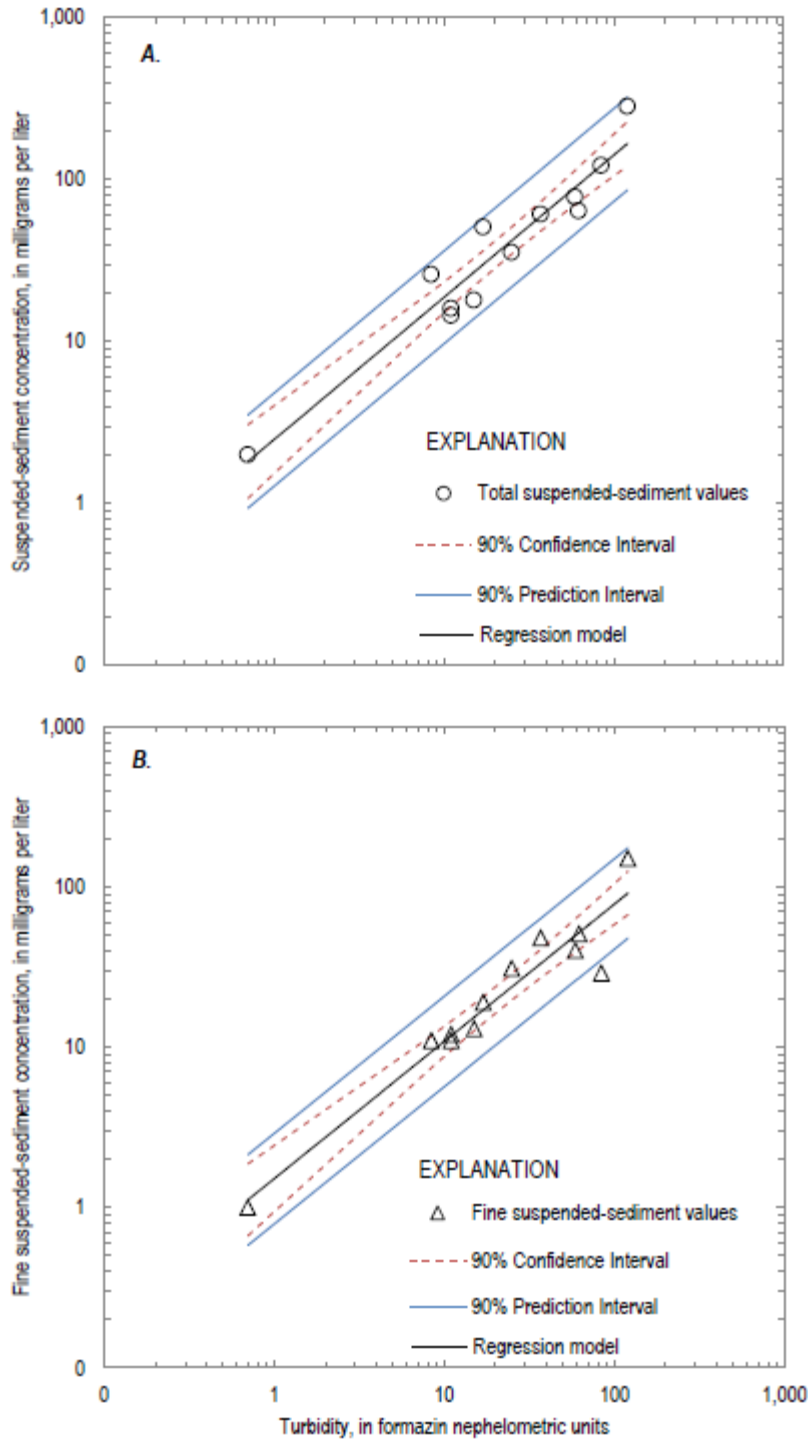
Figure 2. Graph showing log-log regression model in real units with 90 percent uncertainty intervals used to estimate (A) total suspended-sediment concentration and (B) fine suspended-sediment concentration from turbidity at U.S. Geological Survey water-quality monitoring station Sauk River above Whitechuck River near Darrington, Washington (12186000).
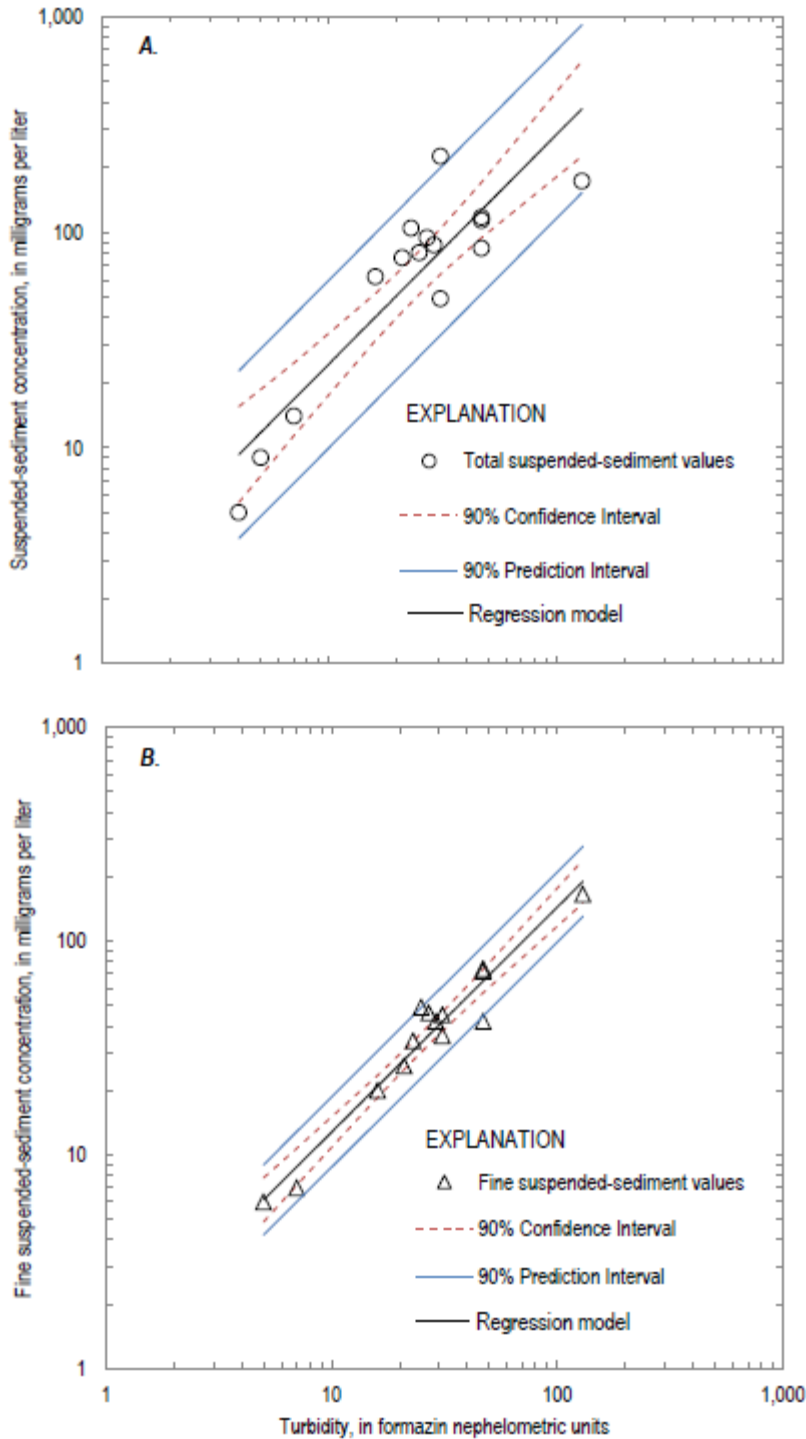
Figure 3. Graph showing log-log regression model in real units with 90 percent uncertainty intervals used to estimate (A) total suspended-sediment concentration and (B) fine suspended-sediment concentration from turbidity at U.S. Geological Survey water-quality monitoring station Sauk River at Darrington, Washington (12187500).
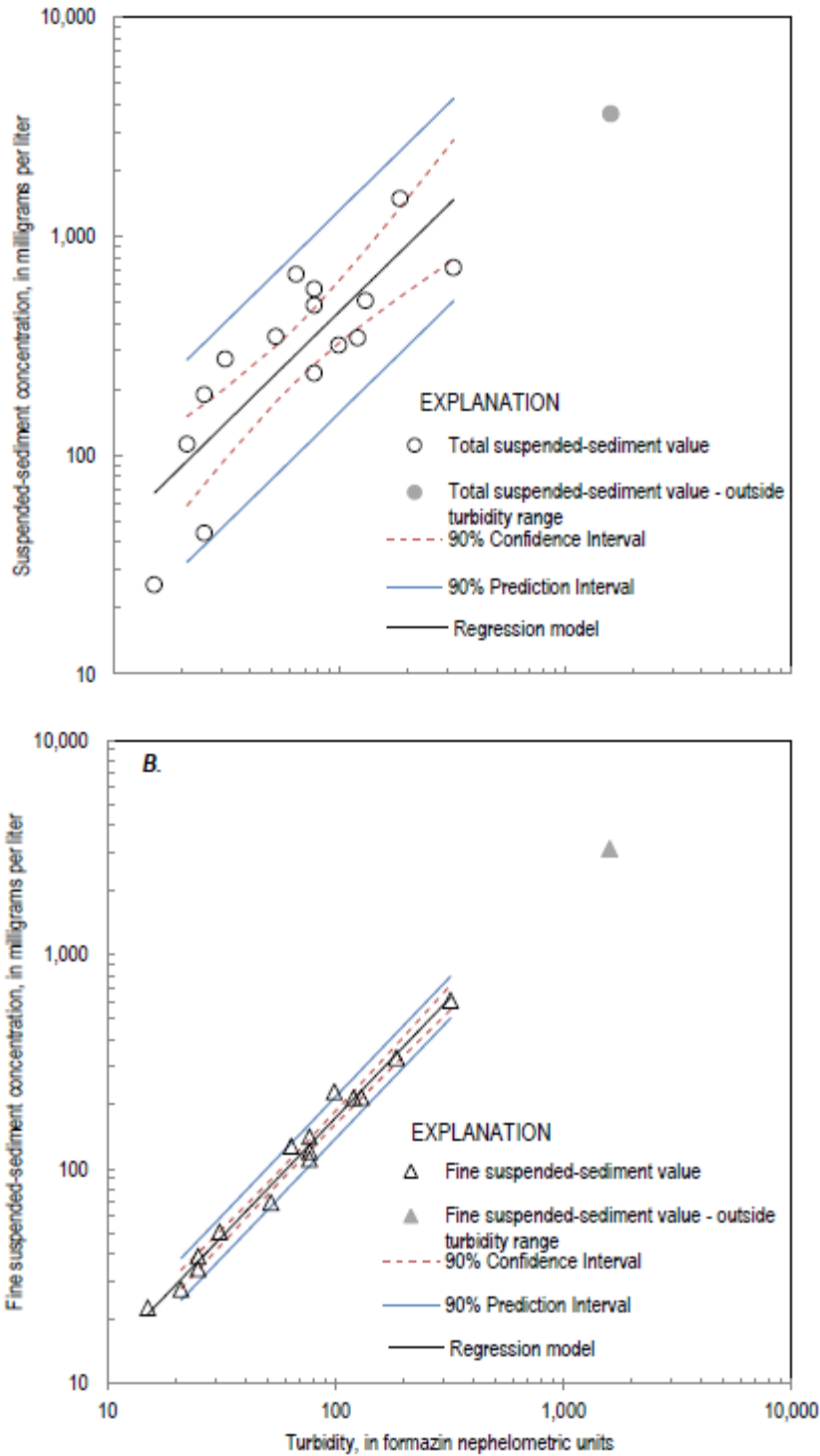
Figure 4. Graph showing log-log regression model in real units with 90 percent uncertainty intervals used to estimate (A) total suspended-sediment concentration and (B) fine suspended-sediment concentration from turbidity at U.S. Geological Survey water-quality monitoring station Sauk River near Sauk, Washington (12189500). Shaded points represent the suspended-sediment values for a sample collected when the measured turbidity was greater than 1,600 formazin nephelometric units and outside the sensor range; values not used in model development.
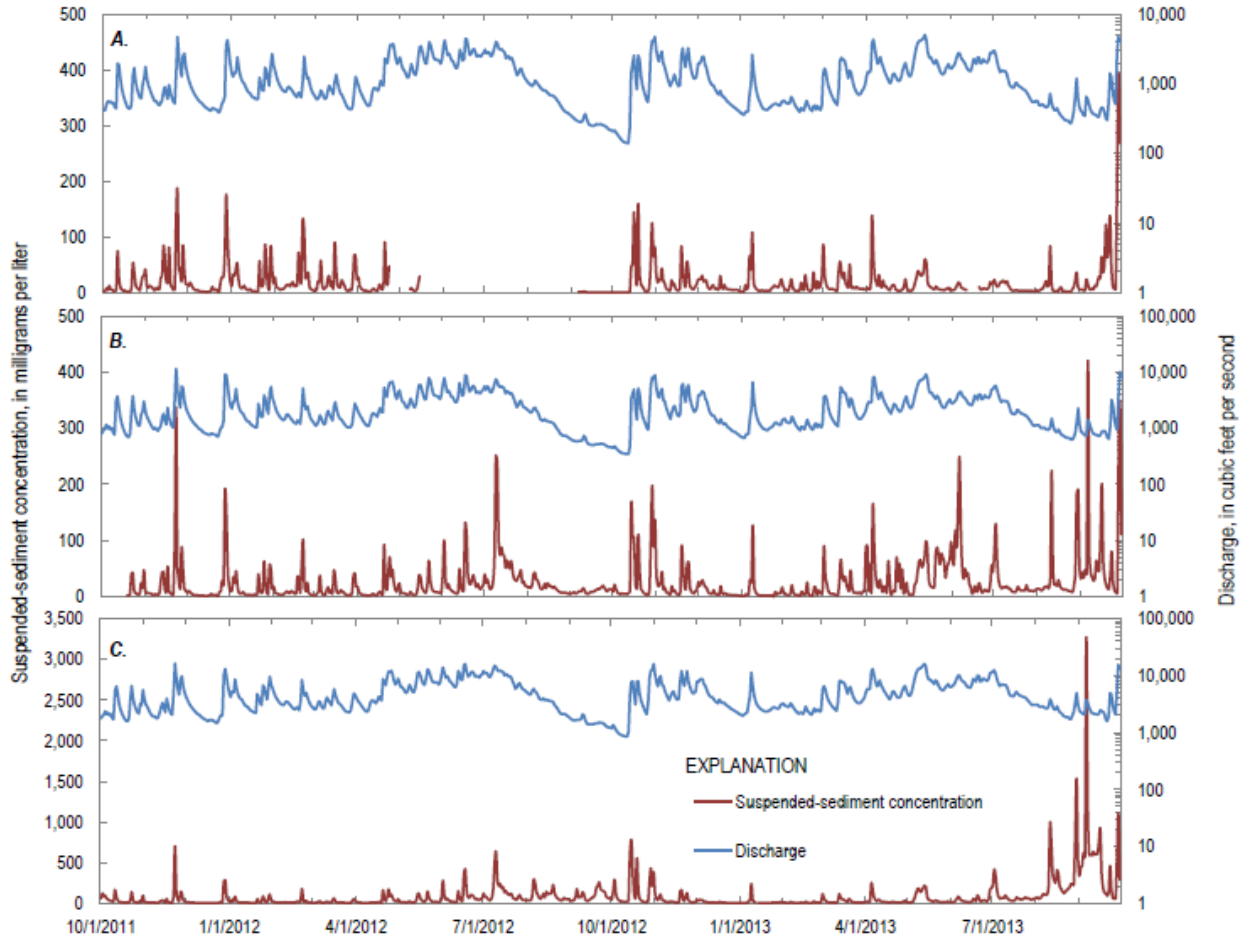
Figure 5. Daily mean suspended-sediment concentration and discharge from October 1, 2011 to September 30, 2013 at three water quality monitoring sites in western Washington: A) Sauk River above Whitechuck (12186000), B) Sauk River at Darrington (12187500), and C) Sauk River near Sauk (12189500.

Tables

Table 1. Regression models for estimating suspended-sediment concentration and the concentration of fine-suspended sediment (particle size less than 0.0625 mm) from nephelometric turbidity measurements for three sites in the Sauk River basin where turbidity was continuously monitored during 2012-13 water years. [**Abbreviations:** bcf, bias correction factor; n, number of observations; R^2, coefficient of determination; % MSPE, model standard percentage error; SSC, suspended-sediment concentration in milligrams per liter; fSSC, fine portion of suspended-sediment concentration less than 0.0625 mm in milligrams per liter; Tu, turbidity in formazin nephelometric units]

USGS Water Quality Monitoring Site	USGS Site Number	Model	bcf	n	R^2	% MSPE (upper/lower)
Sauk River above Whitechuck River near Darrington, Washington	12186000	$SSC = 2.48 \times Tu^{0.878} \times bcf$	1.06	12	0.92	44 / -31
		$fSSC = 1.51 \times Tu^{0.856} \times bcf$	1.05	12	0.92	43/ -30
Sauk River at Darrington, Washington	12187500	$SSC = 2.14 \times Tu^{1.06} \times bcf$	1.12	15	0.80	66/ -40
		$fSSC = 1.13 \times Tu^{1.05} \times bcf$	1.02	14	0.94	24/ -19
Sauk River near Sauk, Washington	12189500	$SSC = 4.36 \times Tu^{1.01} \times bcf$	1.17	15	0.65	83 / -45
		$fSSC = 1.04 \times Tu^{1.11} \times bcf$	1.01	15	0.98	14 / -12

Table 2. Statistical summary of model-calibration data set for U.S. Geological Survey water-quality monitoring station at the Sauk River above Whitechuck River near Darrington, Washington, October 2011-September 2013. [**Abbreviations:** mg/L, milligrams per liter; FNU, formazin nephelometric units]

Summary statistic	Calibration data set (12 samples)			Time-series data set (15-minute values)		
	Suspended-sediment concentration (mg/L)	Fine suspended-sediment concentration (mg/L)	Turbidity (FNU)	Suspended-sediment concentration (mg/L)	Fine suspended-sediment concentration (mg/L)	Turbidity (FNU)
Minimum	2	1	0.70	0.4	0.2	0.10
Maximum	283	150	120	990	510	850
Mean	64	35	38	19	10	8.6
Median	43	24	21	7.3	4.3	2.4
Standard deviation	77	40	37	38	20	25

Table 3. Statistical summary of model-calibration data set for U.S. Geological Survey water-quality monitoring station at the Sauk River near Darrington, Washington, October 2011-September 2013. [**Abbreviations:** mg/L, miligrams per liter; FNU, formazin nephelometric units]

Summary statistic	Calibration data set (15 samples)			Time-series data set (15-minute values)		
	Suspended-sediment concentration (mg/L)	Fine suspended-sediment concentration (mg/L)	Turbidity (FNU)	Suspended-sediment concentration (mg/L)	Fine suspended-sediment concentration (mg/L)	Turbidity (FNU)
Minimum	5	6	3.9	0.70	0.30	0.30
Maximum	224	165	130	2,670	1,200	750
Mean	86	48	33	26	12	8.9
Median	84	42	27	11	5.1	4.1
Standard deviation	59	39	30	61	28	19

Table 4. Statistical summary of model-calibration data set for U.S. Geological Survey water-quality monitoring station at the Sauk River near Sauk, Washington, October 2011-September 2013. [**Abbreviations:** mg/L, miligrams per liter; FNU, formazin nephelometric units; >, greater than]

Summary statistic	Calibration data set (15 samples)			Time-series data set (15-minute values)		
	Suspended-sediment concentration (mg/L)	Fine suspended-sediment concentration (mg/L)	Turbidity (FNU)	Suspended-sediment concentration (mg/L)	Fine suspended-sediment concentration (mg/L)	Turbidity (FNU)
Minimum	26	22	15	2.5	0.50	0.50
Maximum	1,482	611	320	>8,800	>3,770	>1,600[1]
Mean	421	156	88	>85	>26	>16
Median	343	120	77	26	6.2	5.0
Standard deviation	362	155	80	>230	>88	>42

[1]Turbidity exceeds the manufacturer's suggested threshold of 1,600 FNU for the DTS-12 sensor.