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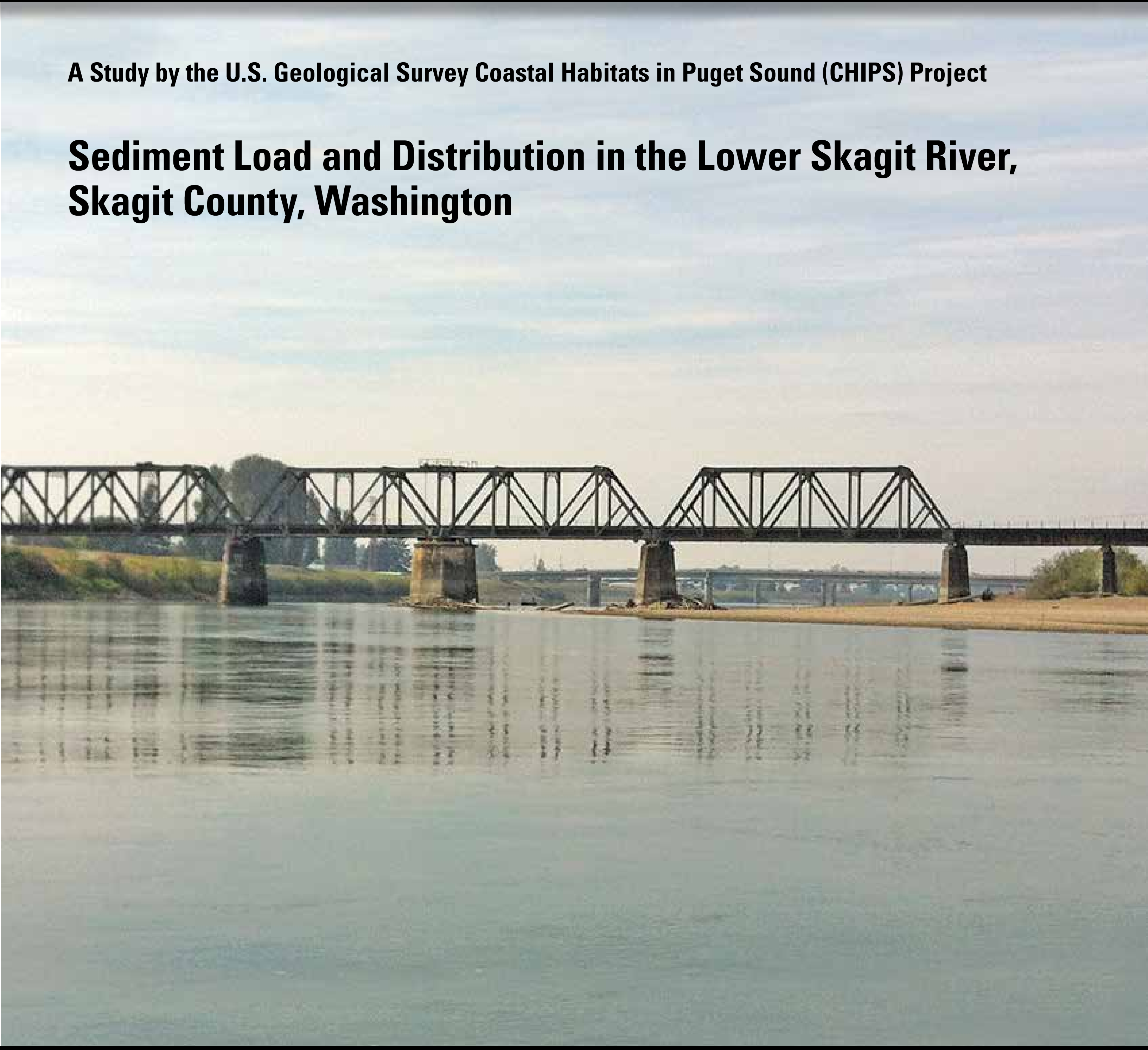
Sediment Load and Distribution in the Lower Skagit River, Skagit County, Washington



Scientific Investigations Report 2016–5106

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

Front Cover: Downstream view of the Skagit River near Mount Vernon, Washington, September 28, 2012. Photograph by Eric Grossman, U.S. Geological Survey.

Back Cover: Downstream view of the North Fork Skagit River at the bifurcation near Skagit City, Washington, September 14, 2012. Photograph by Eric Grossman, U.S. Geological Survey.

Sediment Load and Distribution in the Lower Skagit River, Skagit County, Washington

By Christopher A. Curran, Eric E. Grossman, Mark C. Mastin, and
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SALLY JEWELL, Secretary

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

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram per day (Mg/d)	1.102	ton per day (ton/d)
megagram per year per square kilometer [(Mg/yr)/km^2]	2.8547	ton per year per square mile [(ton/yr)/mi^2]
megagram per year (Mg/yr)	1.102	ton per year (ton/yr)
teragram (Tg)	1,102	ton, short (2,000 lb)
teragram per year (Tg/yr)	1,102	ton per year (ton/yr)

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

$$°F = (1.8 \times °C) + 32.$$

Datums

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

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

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

Supplemental Information

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

Abbreviations

AWTP	Anacortes Water Treatment Plant
EDI	equal discharge increment
EWI	equal width increment
GCLAS	Graphical Constituent Loading Analysis System
MSPE	model standard percentage error
NASQAN	National Stream Quality Accounting Network
FNU	Formazin Nephelometric Unit
RK	river kilometer
SSC	suspended-sediment concentration
SSL	suspended-sediment load
USGS	U.S. Geological Survey

Sediment Load and Distribution in the Lower Skagit River, Skagit County, Washington

By Christopher A. Curran, Eric E. Grossman, Mark C. Mastin, and Raegan L. Huffman

Abstract

The Skagit River delivers about 40 percent of all fluvial sediment that enters Puget Sound, influencing flood hazards in the Skagit lowlands, critically important estuarine habitat in the delta, and some of the most diverse and productive agriculture in western Washington. A total of 175 measurements of suspended-sediment load, made routinely from 1974 to 1993, and sporadically from 2006 to 2009, were used to develop and evaluate regression models of sediment transport (also known as "sediment-rating curves") for estimating suspended-sediment load as a function of river discharge. Using a flow-range model and 75 years of daily discharge record (acquired from 1941 to 2015), the mean annual suspended-sediment load for the Skagit River near Mount Vernon, Washington, was estimated to be 2.5 teragrams (Tg, where 1 Tg = 1 million metric tons). The seasonal model indicates that 74 percent of the total annual suspended-sediment load is delivered to Puget Sound during the winter storm season (from October through March), but also indicates that discharge is a poor surrogate for suspended-sediment concentration (SSC) during the summer low-flow season. Sediment-rating curves developed for different time periods revealed that the regression model slope of the SSC-discharge relation increased 66 percent between the periods of 1974–76 and 2006–09 when suspended-sediment samples were collected, implying that changes in sediment supply, channel hydraulics, and (or) basin hydrology occurred between the two time intervals. In the relatively wet water year 2007 (October 1, 2006, through September 30, 2007), an automated sampler was used to collect daily samples of suspended sediment from which an annual load of 4.5 Tg was calculated, dominated by a single large flood event that contributed 1.8 Tg, or 40 percent of the total. In comparison, the annual load calculated for water year 2007 using the preferred flow-range model was 4.8 Tg (+6.7 percent), in close agreement with the measured value.

Particle size affects sediment transport, fate and distribution across watersheds, and therefore is important for predicting how coastal environments, particularly deltas and beaches, will respond to changes in climate and sea-level. Particle-size analysis of winter storm samples indicated that about one-half of the suspended-sediment load consisted of fines (that is, silt- and clay-sized particles smaller than 0.0625 mm in diameter), and the remainder consisted of mostly fine- to medium-sized sand (0.0625–0.5 mm), whereas bedload during winter storm flows (about 1–3 percent of total sediment load) was predominantly composed of medium to coarse sand (0.25–1 mm). A continuous turbidity record from the Anacortes Water Treatment Plant (water years 1999–2013), used as a surrogate for the concentration of fines ($R^2 = 0.93$, $p = 4.2\text{E-}10$, $n = 17$), confirms that about one-half of the mean annual suspended-sediment load is composed of fines.

The distribution of flow through the delta distributaries (that is, the channels into which the main stem splits as it approaches the delta) is dynamic, with twice as much flow through the North Fork of the Skagit River relative to the South Fork during low-flow conditions, and close to equal flows in the two channels during high-flow conditions. Turbidity, monitored at several locations in the lower river in spring 2009, was essentially uniform among sites, indicating that fines are well mixed in the lower Skagit River system (defined as the Skagit River and all its distributaries downstream of the Mount Vernon streamgage). A strong relation ($R^2 = 0.95$, $p = 3.2\text{E-}14$, $n = 21$; linear regression) between the concentration of fines and turbidity measured at various locations in summer 2009 indicates that turbidity is an effective surrogate for the concentration of fines, independent of location in the river, under naturally well-mixed fluvial conditions. This relation is especially useful for monitoring suspended sediment in western Washington rivers that are seasonally dominated by glacier meltwater because glacial melting typically produces suspended-sediment concentrations that are not well correlated with discharge. These results provide a comprehensive set of tools to estimate sediment delivery and delta responses of interest to scientists and resource managers including decision-makers examining options for flood hazard mitigation, estuary restoration, and climate change adaptation.

Introduction

The Skagit River in northwestern Washington (fig. 1) is the largest river entering Puget Sound. It is also the predominant source of fluvial sediment to the Skagit River delta, which is a valuable agricultural resource, as well as an important estuarine habitat for fish, birds, invertebrates, and plants. Like other river deltas, the Skagit River delta is shaped by the dynamic fluvial and tidal processes that control sediment transport and deposition. These processes, combined with fluvial sediment characteristics, ultimately control delta geomorphology and estuarine mixing, both of which sustain habitat structure. Detailed understanding of the ways in which sediment characteristics, delivery, and transport mechanisms are influenced by hydrology, land use, and flood control is important for making informed decisions regarding habitat restoration and flood hazard mitigation in the delta. Information relating the transport, fate, and distribution of sediments through watersheds is also important for predicting how coastal environments, particularly deltas and beaches, will respond to climate change and sea-level rise (Church and White, 2011).

The lower Skagit River system is defined herein as the area of the Skagit River drainage basin that encompasses its primary distributaries located downstream of the USGS streamgage at Mount Vernon. Previous efforts to quantify sediment delivery in the lower Skagit River include a study by Collins (1998), who conducted the calculations using data derived from suspended-sediment samples collected from 1974 to 1993 by the U.S. Geological Survey (USGS) at the USGS streamgage near Mount Vernon, Washington (12200500) as part of the National Stream Quality Accounting Network (NASQAN) (Alexander and others, 1996). The data were obtained from 160 measurements of suspended-sediment load (computed by multiplying the suspended-sediment concentration by the river discharge) that were made on a monthly or bi-monthly basis, mostly during low- to medium-flow conditions (<1,000 m^3/s [35,300 ft^3/s]). These measurements were used by Collins (1998) to estimate a mean annual suspended-sediment load of 1.5 teragrams (Tg) for the lower Skagit River, using linear regression, for water years[1] 1980–91. In 2008, as part of a flood-hazard reduction study, the U.S. Army Corps of Engineers used a combination of geomorphic and hydrologic methods—including NASQAN data—to estimate a mean annual sediment load for the basin that ranged from 0.7 to 3.5 Tg (U.S. Army Corps of Engineers, 2008).

Purpose and Scope

This report documents the results of a multi-year study involving sediment and discharge data collection at various locations in the lower Skagit River in Skagit County and provides regression models for using these data to estimate suspended-sediment concentration and the partitioning of discharge and suspended-sediment load. The goals of this study were twofold: (1) to quantify the suspended-sediment load delivered by the Skagit River to Puget Sound, and (2) to determine the distribution of water and sediment through the lower river bifurcation that forms the North and South Forks of the Skagit River. The data used for this study were derived from suspended-sediment samples collected from 2006 to 2009 by the USGS over a range of flow conditions at several sites on the lower Skagit River system. These data were combined with historical USGS suspended-sediment and water-discharge measurements made at the Mount Vernon streamgage (during water years 1974–93) to refine the sediment-rating curves and the estimates of the mean annual suspended-sediment load at the Mount Vernon streamgage. Sediment-rating curves were examined for seasonal patterns and long-term temporal changes, and model-derived suspended-sediment loads were compared with loads determined from daily samples obtained in water year 2007. Sediment characteristics such as particle size were examined by hydrologic season and during individual winter storm flows. A 15-year record of continuous turbidity data collected by the City of Anacortes at the Anacortes Water Treatment Plant (water years 1999–2013) was used to estimate the fine fraction (<0.0625 mm) of the suspended-sediment load. Discharge measurements and concurrent suspended-sediment samples were collected in the North Fork and South Fork Skagit River and used to develop regression models for estimating the distribution of water and suspended sediment over a range of flow conditions in the lower river system. Turbidity, monitored at five USGS sites in the lower river system and one site in Skagit Bay during spring 2009, was examined as a surrogate for the suspended-sediment concentration.

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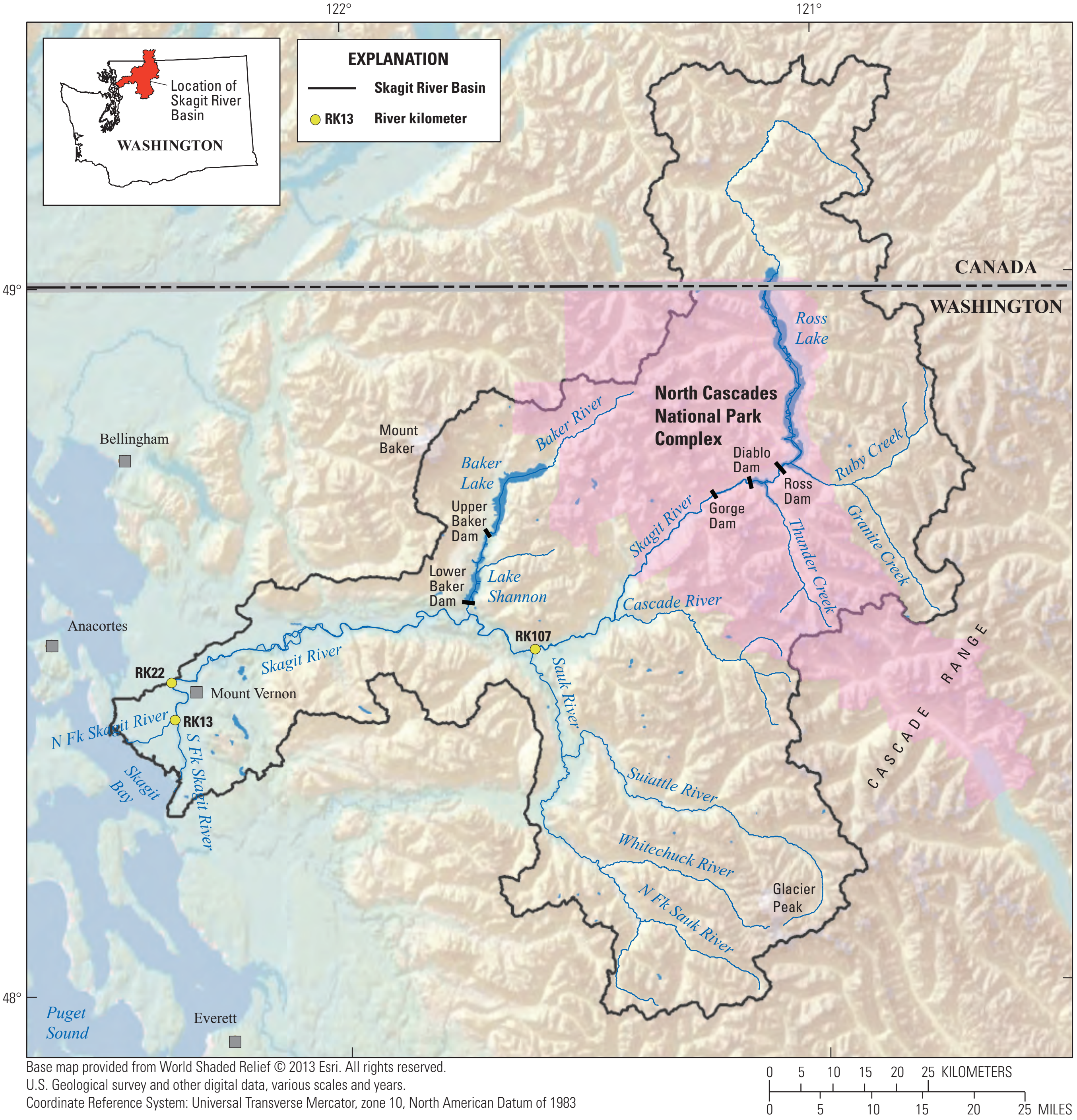
[1] A water year is defined as the 12-month period October 1, for any given year through September 30, of the following year, and is designated by the calendar year in which it ends.



Base map provided from World Shaded Relief © 2013 Esri. All rights reserved.
U.S. Geological survey and other digital data, various scales and years.
Coordinate Reference System: Universal Transverse Mercator, zone 10, North American Datum of 1983

Figure 1. Location of the Skagit River Basin in northwestern Washington and southwestern Canada.

Description of Study Area

The Skagit River Basin (fig. 1), located in northwestern Washington and southwestern Canada, encompasses an area of about 8,280 km^2 and ranges in elevation from sea level to 3,286 m (the top of Mount Baker above the North American Vertical Datum of 1988 [U.S. Geological Survey, 2016a]), with a mean elevation of about 1,100 m. The basin receives an average of 2.44 m of precipitation annually (PRISM, 2010), much of which is in the form of snow. Most of the basin (65 percent) is covered by forest and has a slope greater than 30 percent (Multi-Resolution Land Characteristics Consortium, 2001); 78 percent of the basin has surficial geology that, for purposes of hydrogeologic characterization, can be classified as bedrock (Vaccaro and others, 1998). The Skagit River Basin contains many glaciers in the headwaters that are important for maintaining summer and autumn flows in the river and that contribute fine sediment to the lower river system. Post and others (1971) counted 396 glaciers in the Skagit River Basin with a combined glacier area of 166.8 km^2. Granshaw (2006) estimated a 7.0 percent decrease in glacier area within the North Cascades National Park Complex (which contains 30 percent of the Skagit River basin) from 1958 to 1998.

Discharge from one-half of the Skagit River Basin is controlled to a large degree by the operation of dams, which were constructed primarily for generating hydroelectric power. A series of three dams (Gorge, Diablo, and Ross Dams) located on the Skagit River mainstem (fig. 1) regulate flow from a combined catchment area of about 3,240 km^2 and have been operated by Seattle City Light since 1924 (Gorge Dam), 1936 (Diablo Dam), and 1952 (Ross Dam) (Seattle City Light, 2012). Lower and Upper Baker Dams (fig. 1), located on the Baker River (a tributary to the Skagit River), have a combined catchment area of about 770 km^2 and have been operated by Puget Sound Energy since 1925 and 1959, respectively. (Puget Sound Energy, 2012). The Sauk River (fig. 1) is a tributary of the Skagit River and is the largest unregulated (free-flowing) river in the basin. It has a catchment area of 1,900 km^2 (about 23 percent of the total basin area) that includes an active volcano (Glacier Peak) and enters the Skagit River at river kilometer (RK) 107. The lower Skagit River serves as the primary water source for the City of Anacortes and its surrounding area; on average, 0.7 m^3/s (24.7 ft^3/s) of water is withdrawn from the river at RK 22, treated by the Anacortes Water Treatment Plant (AWTP), and distributed for residential, commercial, and industrial use (City of Anacortes, 2013).

Despite regulation of its flows by multiple dams, the seasonal pattern of daily mean discharge of the Skagit River near Mount Vernon (fig. 2) is typical of large rivers in western Washington. High flows typically occur from mid-October to March as a result of precipitation, and from April to mid-July as a result of snowmelt; the annual low-flow period generally is from mid-July to mid-October.

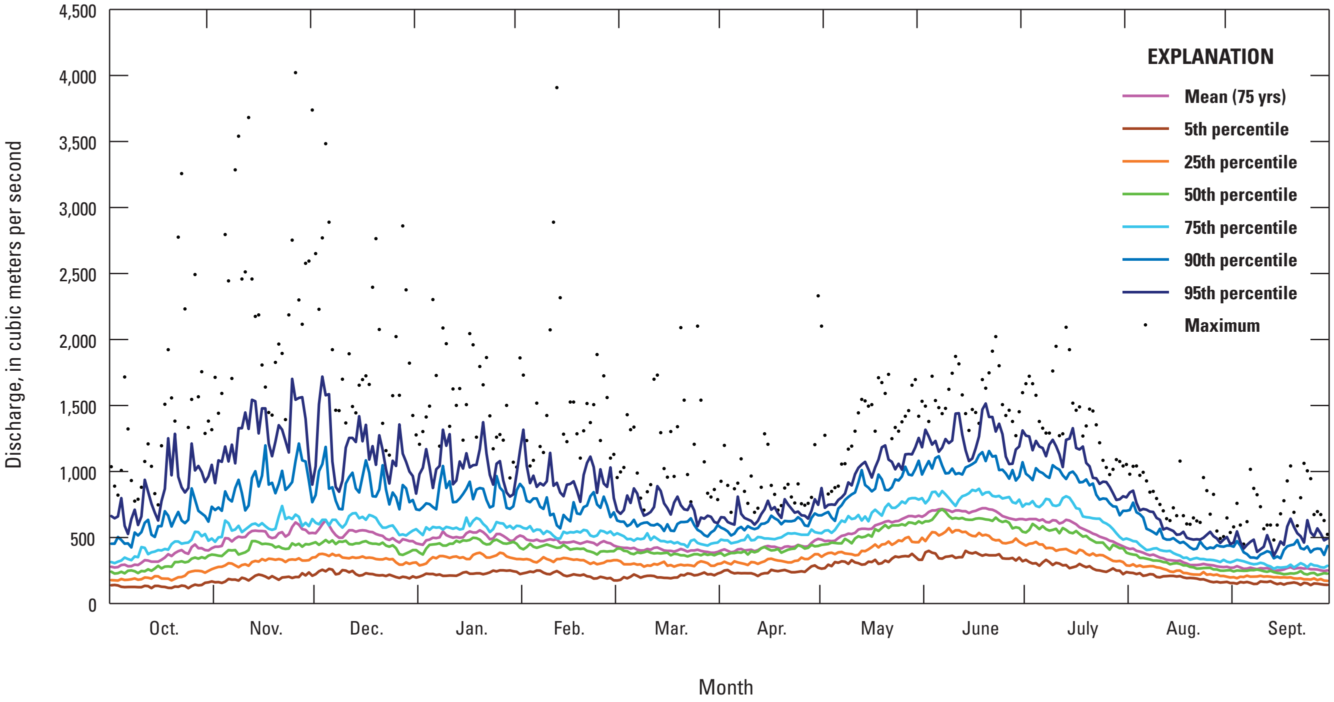
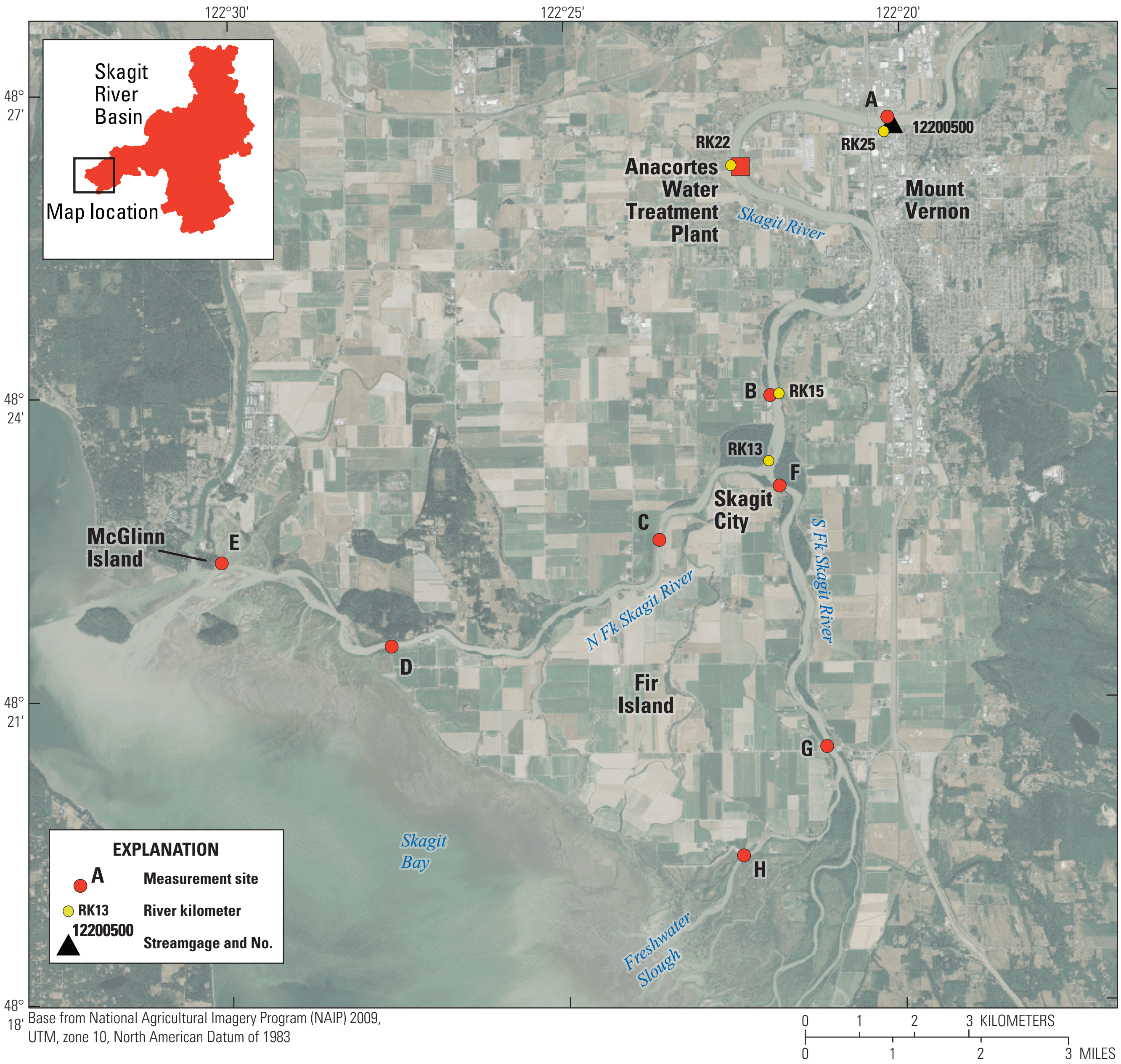


Figure 2. Daily mean discharge and percentile of daily mean and maximum discharge, based on 75 years of record (water years 1941–2015) for the Skagit River near Mount Vernon, Washington (USGS streamgage12200500).

At RK 25, which represents the upstream extent of the lower Skagit River system (fig. 3), the Skagit River is about 210 m wide and flows west at the start of a large, symmetric, S-shaped meander (curvature radius about 0.8 km) that begins the southward turn of the river toward Puget Sound. Throughout the meander (about 9 river km in length), the river is bounded by levees on both banks that provide flood protection for the City of Mount Vernon and surrounding agricultural lands. The levee system then straightens the river for 3 km until it reaches a bifurcation upstream of Fir Island, where the North and South Forks of the Skagit River separate at about RK 13. The North Fork flows southwest and then west and feeds a series of smaller delta distributaries before it enters Skagit Bay. The South Fork flows south and, before discharging into southern Skagit Bay, splits into several distributaries that are larger than those on the North Fork. Historical descriptions indicate that the South Fork distributaries once allowed the passage of large ships (Collins, 1998). Currently, these channels have filled with sediment to the extent that only small boats can navigate them during high tides.



Base from National Agricultural Imagery Program (NAIP) 2009, UTM, zone 10, North American Datum of 1983

Figure 3. Principal distributaries and measurement sites where sediment samples were collected and (or) turbidity was monitored, lower Skagit River system, Skagit County, Washington.

Data-Collection and Data-Processing Methods

This study involved the collection of data on suspended-sediment concentrations, bedload, and water quality in the lower Skagit River system, and the use of the resulting data to compute sediment loads and the distributions of water and suspended sediment in the system.

Measurement and Computation of Suspended-Sediment Load

From September 2006 to October 2009, suspended-sediment samples were collected sporadically at seven sites in the lower Skagit River system (fig. 3; sites A–D and F–H) over a range of discharges and seasons using the equal discharge increment (EDI) method of sampling. This method requires an initial measurement of discharge on-site to determine the locations of 5–7 depth-integrated sample verticals along the channel cross section (Edwards and Glysson, 1999). At all sites, discharge was measured using a boat-mounted 600-kHz acoustic Doppler current profiler (fig. 4), in accordance with USGS measurement protocols to limit measurement variability to approximately ± 5 percent (Mueller and Wagner, 2008). During a storm in November 2006, when discharge exceeded 3,500 m^3/s (124,000 ft^3/s), discharge measurements at the Mount Vernon streamgage (fig. 3; site A) were made using a Price AA current meter from the Riverside Drive bridge, 50 m upstream of the streamgage. Suspended-sediment samples were collected immediately following the discharge measurements using various depth-integrating isokinetic samplers approved by the Federal Interagency Sedimentation Project (Davis, 2005). To quantify variability in the sampling results, all manually collected samples were obtained in duplicate. All samples were analyzed for suspended-sediment concentration and, for most samples, the mass percentage of fines (that is, sediment smaller than 0.0625 mm in diameter) also was determined.

From March 2006 to September 2007, daily suspended-sediment samples were collected with an Isco® automated sampler at the Mount Vernon streamgage. A second Isco® sampler at the same site was used periodically during this time to collect hourly samples during storm events. Both sampler intakes were located at the base of a riprap-armored levee on the north bank of the river (fig. 5*A*), approximately 60 m downstream of the Riverside Drive bridge (where EDI samples were collected), close to the stage sensor used by the streamgage. The Isco® samplers were housed in a wheeled shelter (fig. 5*B*) that could be moved to the top of the dike during extreme flood events. During the study period, both samplers collected a total of 422 suspended-sediment samples. To account for any bias in sample concentration associated with the location of the sampler intake, the concentrations measured in the Isco® samples were adjusted with respect to the mean cross-section concentrations obtained with the EDI method. Using the Graphical Constituent Loading Analysis System (GCLAS), a USGS computer program designed to compute daily loads in a river, the suspended-sediment concentrations of samples collected by the Isco® samplers were used with the 15-minute unit value record of discharge at the streamgage to calculate daily suspended-sediment load and annual load as described by Porterfield (1972) and Koltun and others (2006).

Figure 4. Boat-mounted acoustic Doppler current profiler (ADCP), used with davit and reel for sediment sampling with a D-74 sampler, on the Skagit River near Skagit City, Skagit County, Washington.

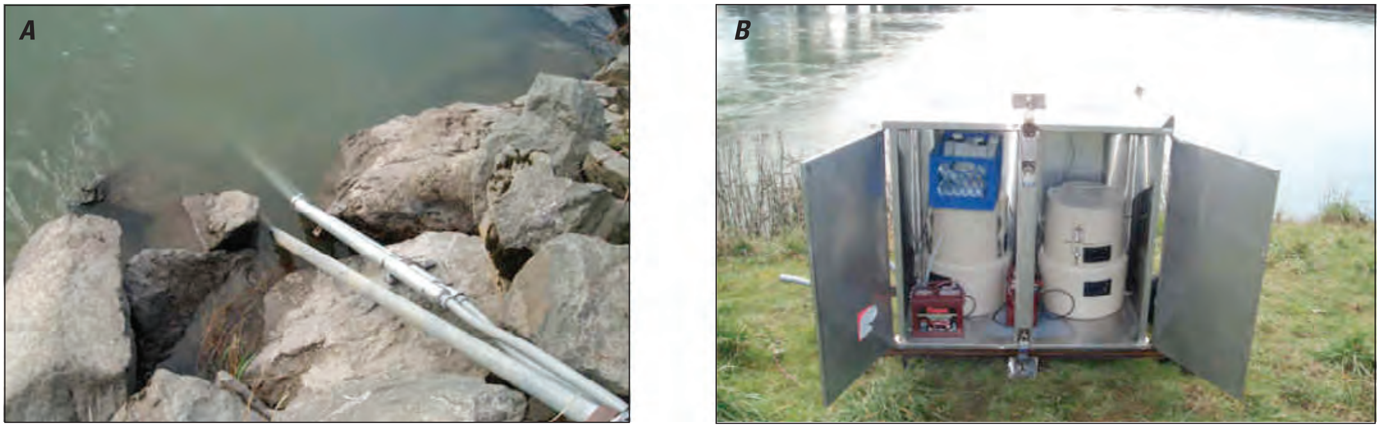


Figure 5. (*A*) Isco® sampler intake and (*B*) Isco® sampler at the Skagit River near Mount Vernon (USGS streamgage 12200500), Washington.

The daily suspended-sediment loads were calculated as follows (after Porterfield, 1972):

$$L_s = C_s Q k \qquad (1)$$

where

L_s is suspended-sediment load per day, in megagrams;

C_s is suspended-sediment concentration, in milligrams per liter;

Q is discharge, in cubic meters per second; and

K is a constant equal to 0.0864 for converting units to megagrams per day.

All concentration and particle-size analyses of the suspended-sediment samples (EDI and Isco® samples) collected during this study were performed using either gravimetric or filtration methods by the USGS Cascades Volcano Observatory Sediment Laboratory in Vancouver, Washington.

Measurement and Computation of Bedload

Bedload was measured in the Skagit River near Mount Vernon (fig. 3; site A) during two storm events—one in November 2008 and another in January 2009. Measurements of bedload were made using an Elwha-style sampler (fig. 6) with a 0.1 × 0.2 m-intake nozzle, an expansion ratio of 1.40 and a 0.5 mm-mesh sample bag. Although sediment particles smaller than 0.5 mm often constitute a significant proportion of the total bedload, retention of bedload finer than the mesh size of the sampler bag may occur if the mesh openings become clogged—effectively reducing the mesh size—or as a result of asymmetric particle shapes (J.R. Gray, U.S. Geological Survey, written commun., 2013). The bedload sampler was deployed on the downstream side of the Riverside Drive bridge using a standard USGS bridge crane and motorized E-reel. The equal width increment (EWI) method of sampling was used to collect a series of 10 samples at evenly spaced locations along the cross section (Edwards and Glysson, 1999). At each location, samples were collected by resting the sampler on the channel bed for 60 s with the intake facing upstream. The sampler was kept in position on the channel bed with a tether line that was attached to the sampler and controlled by a technician standing 20 m upstream on the upstream side of the bridge. Samples collected for each cross section were composited prior to analysis. All bedload samples were analyzed for dry weight and grain-size distribution by the USGS Cascades Volcano Observatory sediment laboratory in Vancouver, Washington. To calculate bedload from the measurements, the following equation was used:

$$L_b = \left(k W M\right) / \left(t N_w\right) \qquad (2)$$

where

L_b is the bedload mass per day, in megagrams,

k is a constant equal to 0.0864 for converting units to megagrams per day;

W is the total width of the stream cross section, in meters;

M is the total mass of the sample collected in the cross section, in grams;

t is the total time the sampler was on the bed, in seconds; and

N_w is the sampler width, in meters (Edwards and Glysson, 1999).

Figure 6. U.S. Geological Survey Elwha-style bedload sampler used on the Skagit River near Mount Vernon (USGS streamgage 12200500), Skagit County, Washington. Photograph by Raegan L. Huffman, U.S. Geological Survey, November 8, 2008.

Turbidity Monitoring

From May to October 2009, turbidity was monitored at five sites in the lower Skagit River system (fig. 3; sites A, B, D, G, and H) and at one site in Skagit Bay (site E). At all sites, a YSI 6136 turbidity sensor was installed. The manufacturer's reported accuracy of the sensor is ± 0.3 Formazin Nephelometric Units (FNUs) or ± 2 percent, whichever is greater, within the range of 0–1,000 FNU. Inspections were made twice per month to clean the sensors and check for instrument drift and bio-fouling using an identical calibrated field meter, in accordance with USGS protocols (Wagner and others, 2006). At all monitoring sites in the river, turbidity sensors were mounted at the edge of the bank inside a 5-cm diameter PVC pipe. To verify that turbidity conditions at the edge of the river also were representative of the channel cross section, cross-channel measurements of turbidity were made using either the EDI or the EWI method (Edwards and Glysson, 1999). To establish a relation between turbidity and suspended-sediment concentration, measurements of turbidity were made during the course of the suspended-sediment sampling over a range of discharges. Using this relation, continuous turbidity data were used to compute time series of suspended-sediment concentration, following the guidelines outlined by Rasmussen and others (2009).

Turbidity data collected at the AWTP were examined as a possible surrogate for fine suspended-sediment loads at the Mount Vernon streamgage. Since 1998, turbidity has been monitored in the influent to the AWTP by the City of Anacortes as part of a standard operating protocol designed to comply with state and Federal water-treatment standards. The plant uses an in-line, nephelometric turbidity sensor (Hach Surface Scatter 7 sc turbidimeter) to continuously measure and record influent turbidity, and the data are made available by request (Jamie LeBlanc, City of Anacortes, oral commun., 2009). The manufacturer's reported accuracy of the sensor is ± 0.1 FNU or ± 5 percent, whichever is greater, within the range of 0–2,000 FNU. Because the sensor optics do not contact the water sample in this flow-through system, sensor fouling is minimized (Hach Company, 2007).

Sediment Load in the Skagit River near Mount Vernon

During this study, 17 cross-sectional measurements of suspended-sediment concentrations (SSC) (calculated using either the EWI or the EDI method) were made at the Mount Vernon streamgage from 2006 to 2009 (table 1). These measurements were made over a range of discharges (159–73,770 m^3/s [5,610–133,000 ft^3/s]) that significantly extended the range of previous measurements made during water years 1974–93 (119–1,190 m^3/s [4,200–42,000 ft^3/s]). For water year 2007, daily discharge ranged from 102–3,530 m^3/s (3,600–125,000 ft^3/s), and mean discharge was 13 percent above the long-term average value (for water years 1941–2013). Daily suspended-sediment concentrations

Table 1. Discharge and suspended-sediment measurements made at Skagit River at Mount Vernon, Washington (USGS streamgage 12200500), water years 2006–09.

[Results in *italics* represent the average of the preceding pair of measurement (shaded). **Abbreviations:** m^3/s, cubic meter per second; mg/L, milligram per liter; Mg/day, megagram per day; –, no data]

Date	Time	Discharge (m^3/s)	Suspended-sediment concentration (mg/L)	Sediment < 0.0625 mm (percent)	Suspended-sediment load (Mg/d)
03-09-06	1330	456	136	–	5,360
05-11-06	1208	312	79	5	2,130
05-19-06	1321	1,220	498	50	52,500
07-24-06	1931	391	155	–	5,200
11-06-06	1423	1,830	1,400	46	221,000
11-06-06	1533	1,930	1,610	49	268,000
11-06-06	*1458*	*1,880*	*1,500*	*48*	*244,000*
11-07-06	0840	3,000	2,560	67	664,000
11-07-06	1500	3,740	2,030	71	656,000
11-07-06	1530	3,770	2,130	76	694,000
11-07-06	*1515*	*3,760*	*2,080*	*74*	*676,000*
03-12-07	1403	1,920	1,650	–	274,000
06-05-07	1457	385	534	–	17,800
09-12-07	1228	159	27	–	371
11-08-08	1500	1,220	545	–	57,400
01-08-09	1415	2,170	1,220	55	228,000
06-25-09	1050	447	66	18	2,550
07-16-09	1215	368	58	16	1,850
08-02-09	0945	374	105	59	3,390

during water year 2007 ranged from 16 to 2,200 mg/L, and the annual suspended-sediment load was 4.5 Tg (U.S. Geological Survey, 2008). As expected, daily SSC was significantly correlated with daily discharge (Pearson's $r = 0.82$, $p<10^{-3}$, $n = 365$). Approximately 40 percent of the annual suspended-sediment load for water year 2007 (1.8 Tg) was transported during a single rainfall-driven flood event that occurred from November 4 to 10, 2006. This indicates that a significant proportion of annual sediment load may be delivered during the highest flows and over relatively short periods. Bedload discharge was measured on two occasions in water year 2009 at the Mount Vernon streamgage during typical winter storms: 1,940 Mg/d (or 3.4 percent of the total sediment load, suspended-sediment load and bedload) was measured on November 8, 2008, when discharge was 1,220 m^3/s (43,100 ft^3/s), and 3,030 Mg/d (or 1.3 percent of the total sediment load) was measured on January 8, 2009, when discharge was 2,240 m^3/s (79,100 ft^3/s). On both occasions, concurrent measurements of bedload and suspended-sediment load were added to determine the total sediment load.

Sediment-Rating Curves

Five approaches were evaluated to select the most appropriate model for estimating long-term averages of suspended-sediment load for the USGS streamgage on the Skagit River at Mount Vernon. Each approach was used with the combined suspended-sediment data (water years 1974–93 and 2006–09) to develop empirical relations between suspended-sediment concentration and discharge, referred to as "sediment-rating curves." Models for each approach then were evaluated based on regression metrics (if appropriate), the apparent model fit over the range of the data, and comparison with the annual load determined from daily samples in water year 2007 (table 2). The regression metrics included the coefficient of determination (R^2, representing the percentage of variability that is explained by the model), the distribution of the model residuals (which represent the differences between the observed and estimated values), and the model standard percentage error (*MSPE*; Rasmussen, 2009). Of the five approaches, four used standard linear-regression methods (Helsel and Hirsch, 1992; Horowitz, 2003) and one used a group-average method (Glysson, 1987; Julien, 1998). The different approaches used for computing sediment-rating curves were (1) ordinary least-squares regression with log-transformed variables (OLS-log), (2) polynomial least-squares regression with log-transformed variables (Poly-log), (3) seasonally applied regressions, (4) time-interval applied regressions, and (5) group-averaged data by flow range (fig. 7*A*–*D*). Where log-transformed variables were used in regressions, the sediment loads were adjusted using bias correction methods (Duan, 1983; Ferguson, 1986; Helsel and Hirsch, 1992).

Table 2. Model equations and performance metrics for five suspended-sediment-rating curves developed for estimating suspended-sediment concentration from discharge at the streamgage, Skagit River at Mount Vernon, Washington (12200500).

[Shaded areas refer to components of models 3, 4, and 5. ***bcf***, bias correction factor. ***R*²**, coefficient of determination. ***n*,** number of observations. ***MSPE***, model standard percentage error. **Abbreviations**: SSL, suspended-sediment load; Tg, teragram; WY, water year; *SSC*, suspended-sediment concentration; *Q*, discharge in cubic meters per second; m³/s, cubic meter per second; mg/L, milligram per liter; –, not applicable]

Model No.	Description	Conditions	Model	*bcf*	R^2	*p*	*n*	*MSPE* (upper/lower)	Model SSL, 2007 WY (Tg)
1	Ordinary least squares	Any	$SSC = 0.0180Q^{1.34} bcf$	1.15	0.46	4.4E-25	175	121 / -55	3.0
2	Polynomial least squares	Any	$SSC = Q^{(1.01 \log Q-4.18)} 5.37E+5\ bcf$	1.13	0.50	7.8E-5	175	113/ -53	5.2
3	Seasonal	By month of year	Composite of 3a, 3b and 3c	–	–	–	175	–	4.0
3a	Winter-storm season	October–March	$SSC = 0.00249Q^{1.67}\ bcf$	1.10	0.69	7.7E-23	85	97 / -49	3.4
3b	Spring-freshet season	April–June	$SSC = 0.00171Q^{1.67}\ bcf$	1.10	0.49	3.3E-7	41	91 / -48	0.42
3c	Summer low-flow season	July–September	$SSC = 3.87Q^{0.433} bcf$	1.17	0.05	0.11	49	134 / -57	0.19
4	Time interval	By time intervals	Composite of 4a, 4b and 4c	–	–	–	175	–	–
4a	Initial-sample interval	1974–1976 WY	$SSC = 0.142Q^{0.921} bcf$	1.04	0.74	1.5E-10	33	29 / -23	–
4b	Middle-sample interval	1977–1993 WY	$SSC = 0.0343Q^{1.23} bcf$	1.15	0.31	3.4E-11	127	125 / -56	–
4c	Recent-sample interval	2006–2009 WY	$SSC = 0.0109Q^{1.53} bcf$	1.03	0.96	2.6E-10	15	35 / -26	6.3
5	Flow range	By flow range	Composite of 5a, 5b and 5c	–	–	–	175	98 / -98	4.8
5a	Low flow range	$Q <$ or $= 850$ m³/s	$SSC = 0.0336Q^{1.27}$	–	–	–	158	84 / -84	1.2
5b	Medium flow range	850 m³/s $< Q <$ 1,900 m³/s	$SSC = 3.11E\text{-}6Q^{2.65}$	–	–	–	15	34 / -34	1.7
5c	High flow range	$Q >$ or $= 1,900$ m³/s	$SSC = 31.4Q^{0.513}$	–	–	–	3	–	1.9

Model No.	Description	Conditions	Model	Percent difference in SSL from measured 2007 WY value	Range of model SSC in 2007 WY (mg/L)	Mean annual SSL, 1974–93, 2006–09 WY (Tg)	Mean annual SSL, 1941–2013 WY (Tg)
1	Ordinary least squares	Any	$SSC = 0.0180Q^{1.34} bcf$	-33	10–1,180	1.8	1.8
2	Polynomial least squares	Any	$SSC = Q^{(1.01 \log Q-4.18)} 5.37E+5\ bcf$	16	29–4,650	2.1	2.1
3	Seasonal	By month of year	Composite of 3a, 3b and 3c	-11	6–2,320	1.9	1.9
3a	Winter-storm season	October–March	$SSC = 0.00249Q^{1.67}\ bcf$	-8.1	6–2,320	1.4	1.2
3b	Spring-freshet season	April–June	$SSC = 0.00171Q^{1.67}\ bcf$	-24	38–260	0.37	0.48
3c	Summer low-flow season	July–September	$SSC = 3.87Q^{0.433} bcf$	-12	40–89	0.19	0.20
4	Time interval	By time intervals	Composite of 4a, 4b and 4c	–	–	1.8	–
4a	Initial-sample interval	1974–1976 WY	$SSC = 0.142Q^{0.921} bcf$	–	–	–	–
4b	Middle-sample interval	1977–1993 WY	$SSC = 0.0343Q^{1.23} bcf$	–	–	–	–
4c	Recent-sample interval	2006–2009 WY	$SSC = 0.0109Q^{1.53} bcf$	40	13–3,010	–	–
5	Flow range	By flow range	Composite of 5a, 5b and 5c	6.7	12–2,080	2.5	2.5
5a	Low flow range	$Q <$ or $= 850$ m³/s	$SSC = 0.0336Q^{1.27}$	8.9	12 –173	1.1	1.1
5b	Medium flow range	850 m³/s $< Q <$ 1,900 m³/s	$SSC = 3.11E\text{-}6Q^{2.65}$	-14	180–1,180	0.87	1.1
5c	High flow range	$Q >$ or $= 1,900$ m³/s	$SSC = 31.4Q^{0.513}$	32	1,590–2,080	0.49	0.35

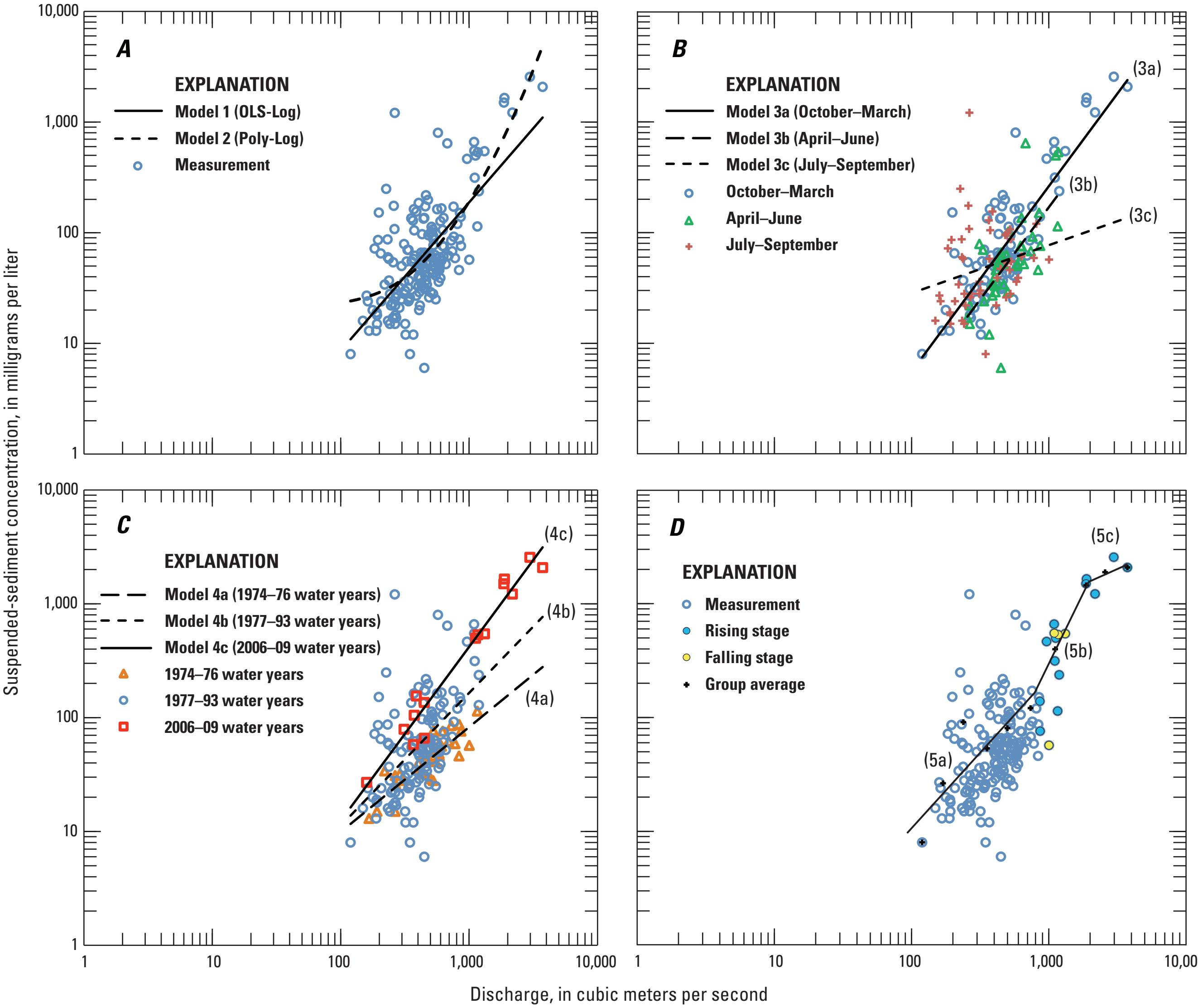


Figure 7. Suspended-sediment-rating curves derived from 175 measurements made at the Skagit River near Mount Vernon (streamgage 12200500), Washington, water years 1974–93 and 2006–09. (*A*) Ordinary least-squares (OLS) and polynomial regression (models 1 and 2, respectively); (*B*) OLS regression by hydrologic season (models 3a–c); (*C*) OLS regression by time-interval (models 4a–c); and (*D*) group-averaged data by flow-range (models 5a–c).

Ordinary (Model 1) and Polynomial (Model 2) Least-Squares Regression with Log-Transformed Variables

For the OLS-log and Poly-log models (models 1 and 2, fig. 7*A*), regression equations were developed using base-10 logarithmic transformed values of SSC and discharge, and regression metrics such as R^2, *p*-value, and *MSPE* were also determined. Log-transformed equations were then reexpressed (untransformed) back into original units and bias correction factors (*bcf*), equal to 1.15 and 1.13, respectively, were used to calculate sediment loads (table 2). For both the OLS-log and Poly-log models, the R^2 values (0.46 and 0.50 respectively) indicate that the models explain only about one-half the observed variation in SSC, and the *MSPE* (-55 to +121 percent, and -53 to +113 percent, respectively) indicates a large range of uncertainty in estimating SSC. Whereas the model residuals for the Poly-log model exhibited a near-normal distribution, suggesting an acceptable fit between the measured and simulated values (Helsel and Hirsch, 1992), this was not the case for the OLS-log model. Most sediment data (90 percent) were collected at discharges less than 850 m^3/s (30,000 ft^3/s). Consequently, this flow range exerted a disproportionately high influence on the slope of the OLS-log model, resulting in a poorer fit between predicted and observed SSC values at the higher values of SSC and discharge. In most cases at these higher values, the OLS-log model underestimated the observed SSC values.

Because these higher values of SSC and discharge represent conditions during which a significant amount of sediment is transported, the OLS-log model is likely to substantially underestimate annual sediment load, as well as sediment transport during individual storms. Closer agreement was observed between estimated and measured values of SSC for the Poly-log model, but the slope of the curve increases with increasing discharge, indicating a greater potential for overestimation of SSC—relative to the OLS-log model—during high flows. Consistent with these expectations, in comparison with the annual suspended-sediment load computed from the daily sediment record for water year 2007, the OLS-log model underestimated the measured value by 33 percent, whereas the Poly-log model overestimated the measured value by 16 percent.

Seasonal Models (Models 3a–c)

Another approach for estimating SSC from discharge included separate models developed for the three hydrologic seasons (approximately defined) that generally occur in western Washington, each of which is associated with different water-supply processes in the Skagit River Basin: winter-storm season (October–March), spring-freshet season (April–June), and summer low-flow season (July–September). The data were grouped according to hydrologic season, and a regression model was developed for each season using log-transformed variables and *bcf* values (table 2; fig. 7*B*). The R^2 and *MSPE* for the winter-storm and spring-freshet seasonal models showed closer agreement between simulated and measured SSC values than was the case for the OLS-log and Poly-log models (table 2). In contrast, the summer low-flow model exhibited much poorer agreement between simulated and measured values, indicating that discharge is a poor surrogate for SSC during this season. Compared with the measured daily sediment record for water year 2007, the combined seasonal models underestimated the annual suspended-sediment load by 11 percent and underestimated the corresponding seasonal loads by 8.1–24 percent. Using the three seasonal models and the corresponding record of discharge, a mean annual suspended-sediment load of 1.9 Tg (table 2) was calculated for the discharge record concurrent with the sampling period (water years 1974–93 and 2006–09). The proportions of the total load for the winter-storm, spring-freshet, and summer low-flow seasons for this period were 74, 26, and 10 percent, respectively. For the relatively wet water year 2007, the contributions to the total load for the winter-storm, spring-freshet, and summer low-flow seasons were 85, 10, and 5 percent, respectively.

Time Interval Models (Models 4a–c)

Over extended periods, changes in sediment and water supply can cause fundamental shifts in sediment-rating curve models (Warrick, 2014). To assess this possibility, separate models (models 4a–c, fig. 7*C*) were used to examine SSC-discharge relations for three different time intervals during which suspended-sediment sampling occurred: the initial-sample interval (1974–76), the middle-sample interval (1977–93), and the recent-sample interval (2006–09). These time intervals were selected following an examination of apparent trends in the SSC-discharge relation for the data and, for simplicity, were limited to three continuous periods, albeit of different lengths, during the water year. The R^2 and *MSPE* values indicated considerably closer agreement between the simulated and measured SSC values for the initial- and recent-sample interval models than for the middle-sample interval, which contained most of the data ($n = 127$; table 2). The slopes of the regression lines increased during the course of the three time intervals, with an increase of 66 percent (from 0.921 to 1.53) between the initial- and recent-sample intervals (table 2; fig. 7*C*). Previous studies of sediment transport curves also have identified shifts in regression-model slope over time, attributing them to factors such as changes in sediment supply, channel hydraulics, or basin hydrology (Warrick and Rubin, 2007; Yang and others, 2007; Warrick, 2014). Using the time-interval models (models 4a–c), the mean annual suspended-sediment load for 1974–93 and 2006–09 was calculated to be 1.8 Tg (table 2). For water year 2007, however, the model overestimated the measured sediment load by 40 percent.

Flow-Range Models (Models 5a–c)

For the flow-range model (models 5a–c, fig. 7*D*), data were grouped uniformly across the range of measured flow and the average SSC for each group was determined (Glysson, 1987; Julien, 1998). Based on the average for each group, a segmented curve (fig. 7*D*) was developed for estimating SSC over three ranges of discharge (similar to the approach used by Holnbeck, 2005): low flow (<850 m^3/s [30,000 ft^3/s]), medium flow (850–1,900 m^3/s [30,000–67,100 ft^3/s]) and high flow (>1,900 m^3/s [67,100 ft^3/s]). Although standard regression metrics could not be computed for the flow-range model, the *MSPE* values were comparable to those for the other models (table 2). An advantage of this model is that it closely fit the highest measured values of SSC and discharge, which may account for a significant amount of the annual sediment load. The annual suspended-sediment load (SSL) calculated for the comparatively wet water year 2007 using the flow-range model was 4.8 Tg, which was closer to the measured load (6.7 percent higher) than the values computed using any of the other models. The range of SSC for the flow-range model (12–2,080 mg/L) in water year 2007 also was in close agreement with the value computed from the measured water year 2007 record (16–2,200 mg/L; U.S. Geological Survey, 2008). For these reasons, the flow-range model is preferred over other models for estimating SSC for the Skagit River at the Mount Vernon streamgage.

Using the record of daily mean discharge and the flow-range model (model 5), the mean annual SSL for the Skagit River was calculated to be 2.5 Tg, regardless of whether it was calculated using the long-term discharge record (water years 1941–2013, 73 years) or only the discharge record concurrent with the sampling period (water years 1974–93, 2006–09). This indicates that among the rivers entering Puget Sound, the Skagit River is the largest contributor of fluvial sediment and accounts for roughly 40 percent of the total fluvial sediment load to Puget Sound (Czuba and others, 2011). Averaged over the entire Skagit River Basin (8,280 km^2), this load is calculated to be 300 (Mg/yr)/km^2. However, because nearly one-half of the Skagit River Basin (about 4,010 km^2) is upstream of reservoirs that trap fluvial sediment (in addition to storing water), the total sediment yield from the basin, including sediment storage in reservoirs, is likely to be much higher.

Limitations

The use of sediment-rating curves with daily discharge records to estimate suspended-sediment load requires the assumption that sediment-supply and sediment-transport conditions are in equilibrium and that particle-size distribution is relatively constant during the period of interest (Wright and other, 2010). In contrast, apparent increases in the slope and offset between time-interval models of suspended-sediment transport for the Skagit River at Mount Vernon (for example, fig. 7*C*, models 4a and 4c) indicate that changes in sediment supply, hydraulic conditions, or both have occurred (Asselman, 2000). Thus, the use of a single model to estimate suspended-sediment load over a lengthy discharge record (75 years in this case) and outside the sampling periods also assumes that shifts in sediment-rating curves are cyclical, relatively short lived, and averaged out with time. Although the use of a single model to estimate the mean annual suspended-sediment load over a lengthy discharge record seems reasonable (for example, the calculated mean annual suspended-sediment loads for all models are consistent whether limited to sampling years or extended over the entire discharge record [table 2]), using the same model to estimate suspended-sediment load for shorter or specific periods of interest could result in larger errors (Walling, 1977).

Within the context of this study, hysteresis involves the observation of SSC values that, for a given discharge value, may be different between the rising and falling limbs of the hydrograph, especially at the upper end of many sediment-transport curves (high SSC and discharge). This phenomenon is caused by differences in the timing of SSC and discharge peaks and is also related to sediment source and availability (Guy, 1970; Glysson, 1987; Julien, 1998). The potential for hysteresis was evaluated in the flow-range model by identifying the timing of the collection of SSC samples when discharge was greater than 850 m^3/s (30,000 ft^3/s), relative to the timing of the flood peak (that is, relative to the rise, the peak, or the recession). However, because of the lack of measurements during the recession following large peak flows, hysteresis, which likely occurs to some degree, was neither observed nor incorporated into the transport curve. Thus, additional measurements of SSC are needed, preferably during the rise and recession of large, individual runoff-events for discharges greater than 850 m^3/s (the transition point from low to medium flow for the flow-range models 5a–c; fig. 7*D*).

Particle Size and Seasonality

Particle size is an important factor controlling sediment delivery and deposition—both of which, in turn, influence flood hazards and water quality, as well as habitat structure and function. Detailed particle-size analyses of suspended-sediment samples collected during high-flows on November 14, 2008 (1,030 m^3/s [36,400 ft^3/s]) at the Skagit River near Skagit City (RK 15) and January 8, 2009 (2,180 m^3/s [77,000 ft^3/s]), at the Mount Vernon streamgage (fig. 8*A*) showed that about one-half of the suspended-sediment load for these flow conditions consisted of fine sediment (that is, silt- and clay-sized particles smaller than 0.0625 mm) and most of the remainder consisted of fine- to medium-sized sand (0.0625–0.5 mm). By comparison, a similar analysis of bedload samples collected on November 8, 2008 (1,220 m^3/s [43,100 ft^3/s]), and January 8, 2009 (2,240 m^3/s [79,100 ft^3/s]), at the Mount Vernon streamgage showed that for these flow conditions, sediment transported along the river bed was predominantly medium- to coarse-sized sand (0.25–1 mm; fig. 8*B*) and represented only about 1–3 percent of the total sediment load (the sum of suspended-sediment load and bedload) by mass. Sediments finer than the mesh size of the sampler bag (<0.5 mm) represented about one-half of the bedload in both samples, and medium-sized sand (0.25–0.5 mm) was the largest component of bedload in both samples (fig. 8*B*).

To examine seasonal variations in particle size, the relations between the percentage of SSL represented by fines in each sample and the discharge at the time of sample collection, with each data point coded according to one of the three previously defined hydrologic seasons (fig. 9). Whereas the percentage of fines was slightly correlated with increasing discharge during the winter storm season (Pearson's $r = 0.55$, p-value = 1.47E-7, $n = 77$), the same correlation was weaker, although still significant (at 95 percent confidence), during the spring freshet season (Pearson's $r = 0.46$, p-value = 0.0038, $n = 38$). During the summer low-flow season, when flow is dominated by glacier meltwater, the data indicate a slight negative correlation (Pearson's $r = -0.31$, p-value = 0.047, $n = 42$) between the percentage of fines and discharge. This indicates that glacier-derived suspended-sediment load can yield high concentrations during summer low-flow periods, but concentrations may be diluted with increased discharge such as from rainfall-runoff during summer storms or upstream reservoir releases. Overall, discharge was a poor surrogate for explaining variability in the percentage of fines ($R^2 \leq 0.30$ for all seasons), and explanatory variables other than discharge were examined.

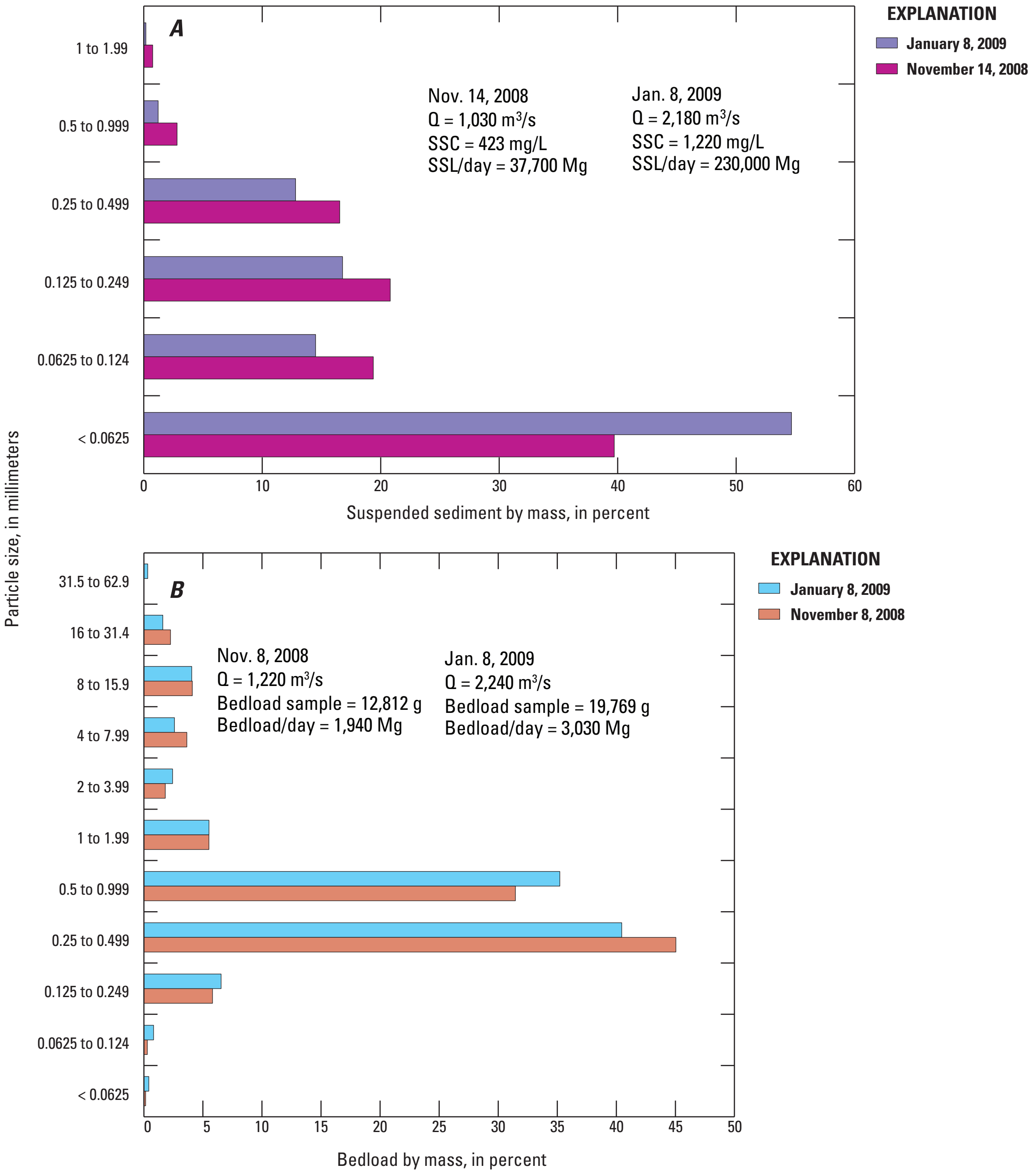


Figure 8. Particle-size distributions of suspended-sediment concentration (SSC) and bedload samples collected at selected sites along the Skagit River, Washington. (*A*) Suspended-sediment samples collected November 14, 2008, at river kilometer 15 (upstream of the bifurcation of the North and South Forks Skagit River) and January 8, 2009 (at Skagit River at Mount Vernon [USGS streamgage 12200500]); and (*B*) bedload samples collected November 8, 2008, and January 8, 2009, at USGS streamgage 12200500. Q, discharge in cubic meters per second; SSC, suspended-sediment concentration; SSL/day, suspended-sediment load per day; Bedload/day, bedload per day.

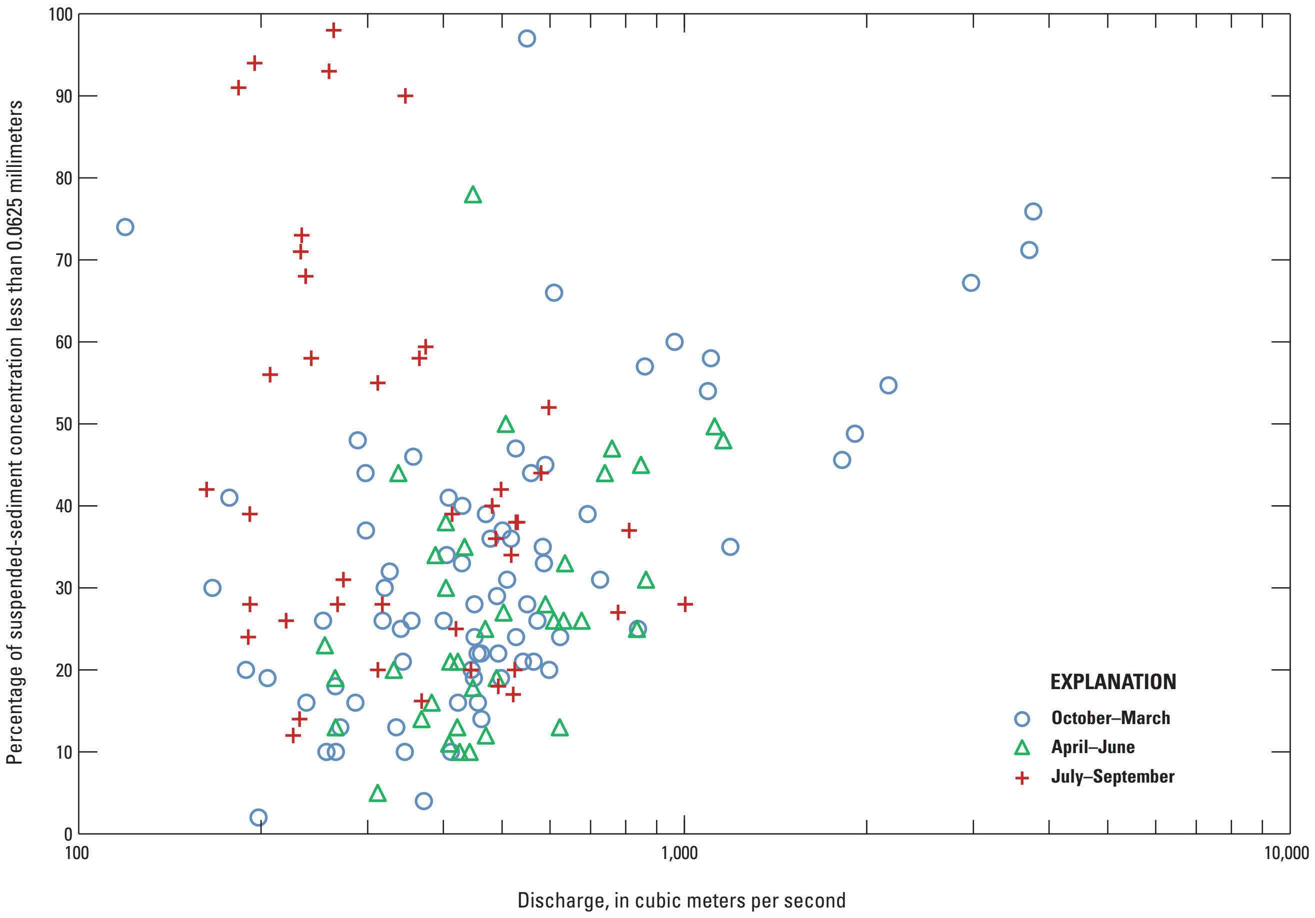


Figure 9. Percentage of suspended-sediment concentration with particle size smaller than 0.0625 millimeter in samples collected at Skagit River near Mount Vernon, Washington from water years 1974 to 2009 relative to discharge, classified according to three hydrologic seasons. Hydrologic seasons are winter storm season (October–March), spring freshet season (April–June), and summer low-flow season (July–September).

Turbidity Measured at Anacortes Water Treatment Plant to Estimate Fine Sediment Load

The concentration of fines determined from particle-size analysis of samples collected at the Mount Vernon streamgage and Skagit River near Skagit City (fig. 3, locations A and B, respectively) during 2006–09 had a strong correlation with the daily mean turbidity measured at AWTP and a linear regression model was developed after both variables were log transformed ($R^2 = 0.93$, $p = 4.2\text{E-}10$, $n = 17$; fig. 10). This indicates that turbidity measured at the AWTP is a useful surrogate for fine suspended-sediment concentration, providing an additional method for estimating the fine-sediment load contribution using the following equations:

$$C_f = 2.37Tu^{1.02}bcf \tag{3}$$

where

C_f is the fine suspended-sediment concentration, in milligrams per liter;

Tu is the turbidity at the AWTP, in FNU; and

bcf is the bias correction factor, equal to 1.12 (Duan, 1983).

$$L_f = 0.0864C_f Q_{SR} \tag{4}$$

where

L_f is the fine suspended-sediment load per day, in megagrams; and

Q_{SR} is the discharge, in cubic meters per second, at the Skagit River at Mount Vernon.

By applying equations 3 and 4 for the water years 1999–2013, the mean annual load of fine sediment was 1.2 Tg. This represented 48 percent of total mean annual suspended-sediment load (2.5 Tg) for this period, as estimated from the preferred sediment transport curve (see section, “Flow-Range Models (Models 5a–c)”).

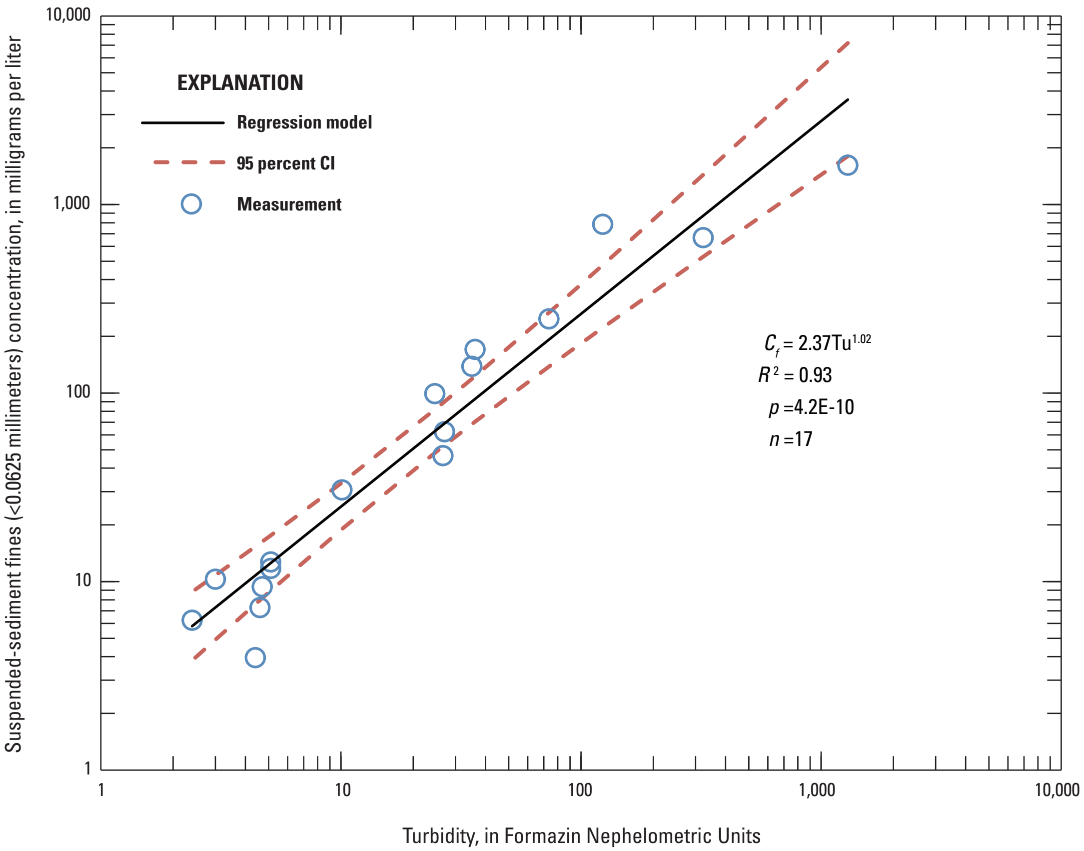


Figure 10. Fine suspended-sediment concentrations at the Skagit River at Mount Vernon (USGS streamgage12200500) and Skagit River near Skagit City (12200570) as a function of turbidity recorded at the Anacortes Water Treatment Plant, Skagit County, Washington, water years 2006–09. C_f, fine suspended-sediment concentration in milligrams per liter; Tu, turbidity at the Anacortes Water Treatment Plant in Formazin Nephelometric Units.

Water and Sediment Distribution Downstream of Mount Vernon

The distribution of water and suspended sediment from the main channel of the Skagit River to the North and South Forks of the Skagit River, and to Freshwater Slough (a distributary of the South Fork Skagit River), was measured over a range of discharges and seasons from 2006 to 2009 (table 3). From these discharge measurements, the following linear regression equations were developed to estimate discharge in these distributaries from the discharge measured in the main channel of the Skagit River, near Skagit City (fig. 11):

$$Q_{NF} = 0.503 Q_{SR} + 36.4 \left(R^2 = 0.99;\ p = 4.5\mathrm{E}{-9};\ n = 10 \right) \quad (5)$$

$$Q_{SF} = 0.503 Q_{SR} + 39.4 \left(R^2 = 0.99;\ p = 1.1\mathrm{E}{-11};\ n = 10 \right) \quad (6)$$

$$Q_{FS} = 0.223 Q_{SR} + 6.71 \left(R^2 = 0.99;\ p = 0.036;\ n = 3 \right) \quad (7)$$

where

Q_{NF}, Q_{SF}, and Q_{FS} are the discharges, in cubic meters per second, estimated for North Fork Skagit River, South Fork Skagit River, and Freshwater Slough, respectively; and

Q_{SR} is the discharge, in cubic meters per second in the main channel of Skagit River near Skagit City.

Table 3. Discharge measurements and suspended-sediment concentrations and loads at selected U.S. Geological Survey water-quality sites on the Lower Skagit River downstream of Mount Vernon, Skagit County, Washington, 2006–09.

[Location references are shown in figure 3. **Abbreviations:** m^3/s, cubic meter per second; Mg/d, megagram per day; mg/L, milligram per liter; mm, millimeter; –, no data; <, less than]

Water-quality sites	USGS Site Identifier	Location reference	Latitude (decimal degrees)	Longitude (decimal degrees)	Date	Time (Local)	Discharge (m^3/s)	Suspended-sediment concentration (mg/L)	Sediment < 0.0625 mm (percent)	Suspended-sediment load (Mg/d)
Skagit River near Skagit City, WA	12200570	B	48.401	-122.366	09-18-06	1434	166	8	78	115
					09-18-06	1550	102	–	–	–
					04-07-08	1613	235	18	–	365
					04-08-08	1240	255	22	47	485
					05-29-08	1233	1,030	382	26	34,000
					09-15-08	1300	244	12	–	253
					11-14-08	1330	1,030	423	40	37,600
					06-10-09	1145	683	97	32	5,720
					06-25-09	1300	453	44	29	1,720
					07-15-09	1645	411	28	26	994
					08-01-09	2000	379	73	66	2,390
					10-24-09	1215	657	290	48	16,500
North Fork Skagit River near Skagit City, WA	1220070310	C	48.384	-122.382	09-18-06	1244	121	7	–	73
					09-18-06	1602	31	–	–	–
					04-07-08	1817	131	–	–	–
					04-07-08	1824	120	–	–	–
					04-07-08	1832	109	–	–	–
					04-08-08	1425	168	–	–	–
					05-29-08	1435	547	262	35	12,400
					09-15-08	1610	149	14	–	181
					09-16-08	1245	165	–	–	–
					11-14-08	1445	547	378	46	17,900
North Fork Skagit River near Fish Town, WA	1220070360	D	48.359	-122.460	06-09-09	1230	380	98	28	3,210
					06-25-09	1645	265	38	44	870
					07-16-09	1010	261	29	30	655
					08-01-09	1645	176	56	89	854
South Fork Skagit River at Skagit City, WA	12200660	F	48.385	-122.364	09-18-06	1329	44	5	75	19
					09-18-06	1639	33	–	–	–
					04-07-08	1748	75	–	–	–
					04-08-08	1403	82	–	–	–
					05-29-08	1344	476	314	28	12,900
					09-15-08	1435	73	10	–	63
					11-14-08	1515	476	380	44	15,600
South Fork Skagit River at Conway, WA	12200675	G	48.342	-122.353	06-09-09	1430	295	113	30	2,880
					06-25-09	1415	191	45.5	36	751
					07-15-09	1505	168	34	32	494
					08-01-09	1815	134	52	88	602
Freshwater Slough near Milltown, WA	1220068050	H	48.324	-122.374	06-09-09	1530	152	162	32	2,130
					06-25-09	1515	110	64	44	606
					07-15-09	1225	97	18	45	151
					08-02-09	1735	49	–	–	–

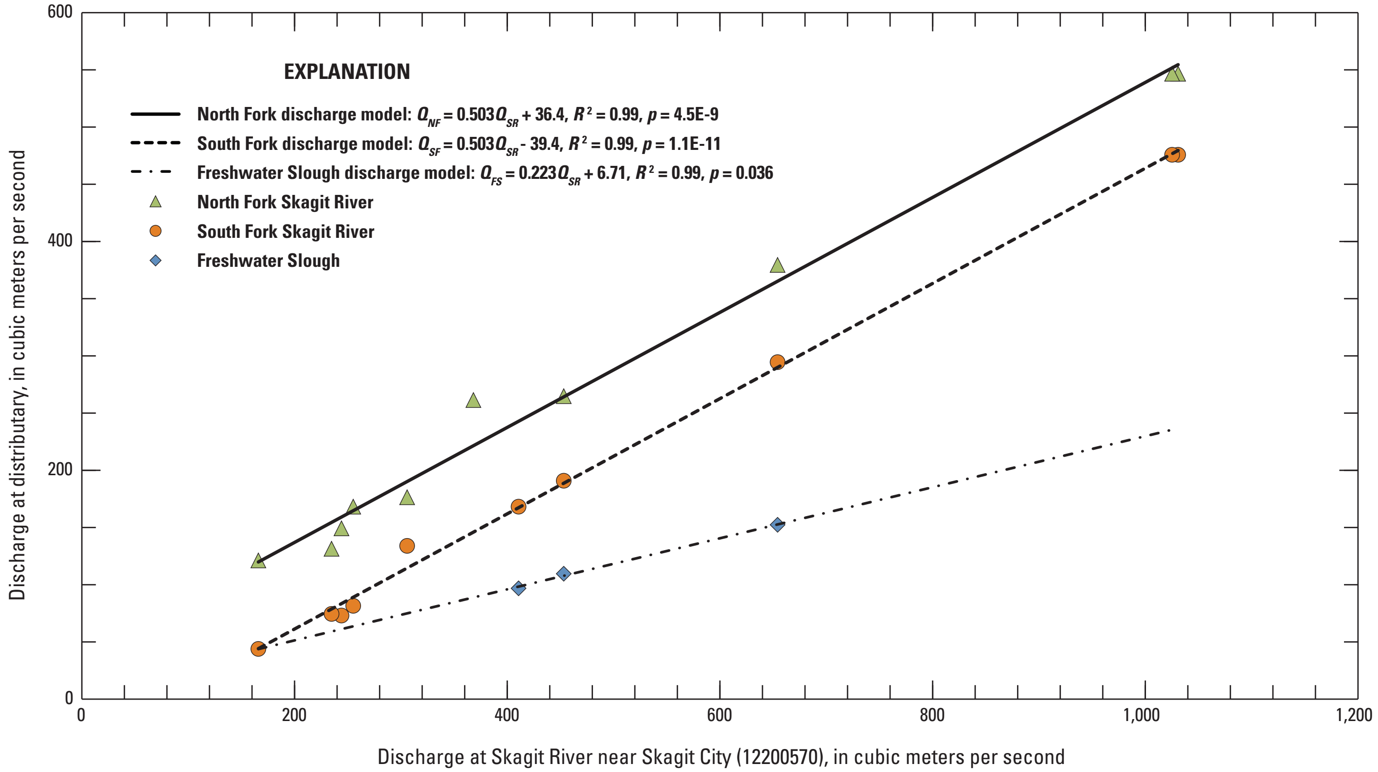


Figure 11. Discharge measurements at selected U.S. Geological Survey water-quality sites on the Lower Skagit River downstream of Mount Vernon, Skagit County, Washington, 2006–09.

Using the empirically derived equations 5 and 6, a mass balance of water from the main channel through the bifurcation was calculated as follows:

$$Q_{NF} + O_{SF} = Q_{SR} \tag{8}$$

By applying equation 8 over a range of discharges 200–2,000 m³/s (7,600–70,600 ft³/s) at Skagit River near Skagit City, discharge is conserved to within 99 percent and within the bounds of measurement error (5 percent).

Daily suspended-sediment loads in the main channel of the Skagit River and its distributaries (fig. 12) were estimated from the discharge values calculated using equations 5–7. The regression equations developed for this purpose are as follows:

$$L_{SR} = 1.48\text{E-}5Q_{SR}^{\;3.08} \quad \left[R^2 = 0.96; p = 2.8\text{E-}7; n = 10\right] \tag{9}$$

$$L_{NF} = 1.61\text{E-}5Q_{NF}^{\;3.25} \quad \left[R^2 = 0.93; p = 7.7\text{E-}5; n = 8\right] \tag{10}$$

$$L_{SF} = 4.90\text{E-}4Q_{SF}^{\;2.77} \quad \left[R^2 = 0.98; p = 7.6\text{E-}7; n = 8\right] \tag{11}$$

$$L_{FS} = 3.29\text{E-}9Q_{FS}^{\;5.43} \quad \left[R^2 = 0.84; p = 0.18; n = 3\right] \tag{12}$$

where

L_{SR}, L_{NF}, L_{SF}, and L_{FS} are the daily suspended-sediment load, in megagrams per day estimated for Skagit River near Skagit City, North Fork Skagit River, South Fork Skagit River, and Freshwater Slough, respectively.

A mass-balance analysis of SSLs upstream and downstream of the bifurcation of the Skagit River upstream of Skagit City was carried out by comparing the total SSL computed in the Skagit River (fig. 3; site B) with the sum of the SSLs computed in the North Fork Skagit River and South Fork Skagit River (fig. 3; sites C and F, respectively).

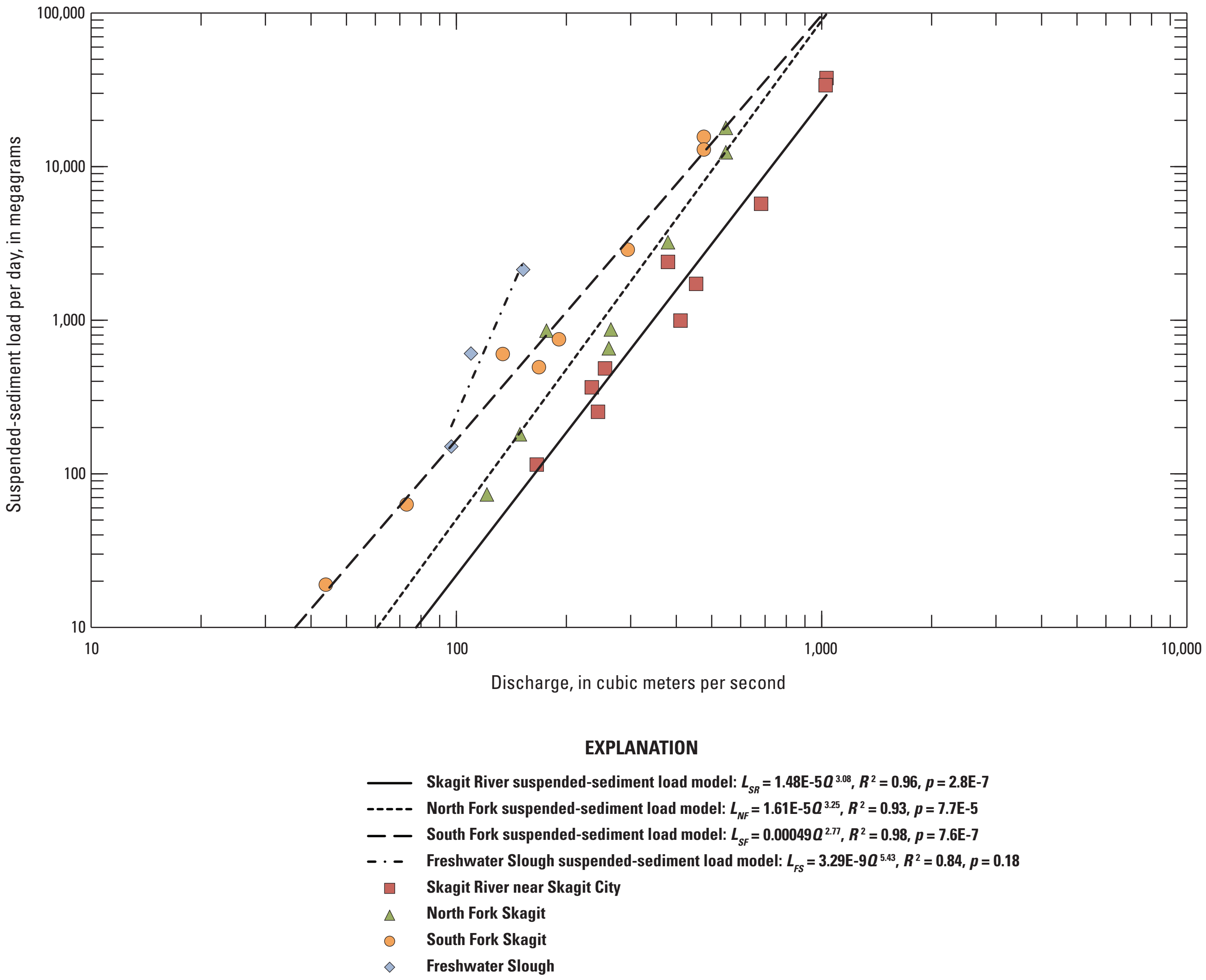


Figure 12. Relation of daily suspended-sediment load to discharge for the Skagit River near Skagit City (12200570), North Fork and South Fork Skagit River (1220070360 and 12200660, respectively), and Freshwater Slough (1220068050), Skagit County, Washington. Locations of measurement sites are shown in figure 3 as B, C, F, and H.

This was accomplished by (1) using equations 5 and 6 to compute Q_{NF} and Q_{SF}, respectively, assuming values of Q_{SR} over a range from 200–2,000 m³/s [7,060–70,600 ft³/s]; (2) using the resulting values and equations 9–11 to compute values of L_{SR}, L_{NF} and L_{SF}, respectively, for each Q_{SR} value; and (3) dividing the sum of L_{NF} and L_{SF} by L_{SR} for each Q_{SR} value. This analysis indicated that, within the flow range of 200–2,000 m³/s [7,060–70,600 ft³/s] in the main stem of the river, the fraction of SSL in the Skagit River lost at or near the bifurcation of the river ranged from -2 percent at Q_{SR} = 200 m³/s (7,060 ft³/s) to 10 percent at Q_{SR} = 2,000 m³/s (70,600 ft³/s). These losses are considered within the range of measurement error (estimated to be within 15 percent).

By further applying equations 5, 6, 10, and 11 over a range of Skagit River discharges (Q_{SR} = 200–2,000 m³/s [7,060–70,600 ft³/s]), it can be shown that, as discharge (Q_{SR}) increases, the ratios of distributary discharges (Q_{SF}/Q_{NF}) approaches unity but the ratio of sediment loads reaches a maximum of 0.98 at 1,000 m³/s (35,300 ft³/s) before gradually decreasing with increasing discharge (fig. 13). Thus, with increasing discharge in the main channel upstream of the bifurcation, the partitioning of discharge through the distributaries approaches equality, but at flows greater than 1,000 m³/s (35,300 ft³/s), the North Fork Skagit River carries an increasingly higher proportion of suspended sediment.

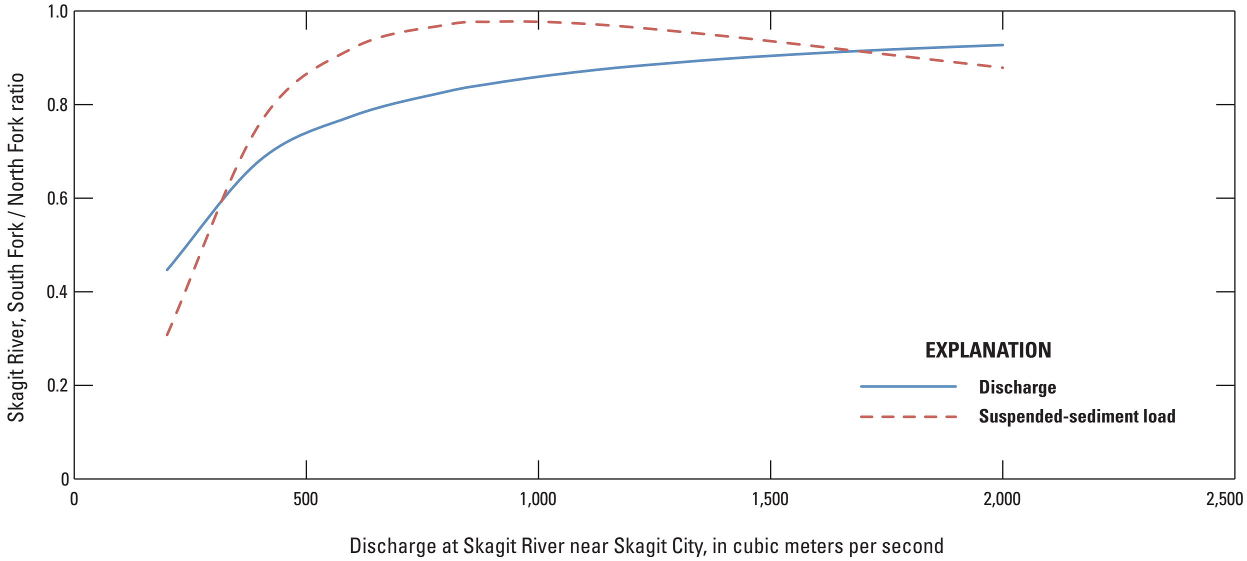


Figure 13. Ratios of discharges and suspended-sediment loads between the South Fork and North Fork Skagit Rivers, over a range of discharges at the Skagit River near Skagit City, Washington.

Turbidity as a Surrogate for Suspended-Sediment Concentration

In 2009, during the early part of the spring freshet season (May 21–June 22), turbidity was continuously monitored at five sites in the lower river system (fig. 3, sites A, B, D, G, and H) and at one site near McGlinn Island in Skagit Bay (fig. 3, site E). The daily time series (fig. 14) indicate a consistent pattern of turbidity between these sites and the turbidity recorded at the AWTP. In accord with basic hydraulic principles, turbidity at all these sites generally decreased as discharge decreased during the monitoring period.

A regression model was developed for turbidity and SSC at all the sites of interest (fig. 3; sites A, B, D, G, and H). The model exhibited an R^2 value of 0.78 (p = 3.9E-8; n = 22), which increased to 0.95 (p = 3.2E-14; n = 21) when only the concentration of fines (C_f, representing particles smaller than 0.0625 mm) was considered (fig. 15). This indicates that turbidity is a useful surrogate for the concentration of suspended clay and silt that is held within the water column. However, turbidity appears to be a less effective surrogate for suspended sand, for which the concentration tends to be more variable throughout the water column and higher near the streambed. The consistency in the C_f-turbidity relation for multiple sites (fig. 15) indicates that the suspended sediment in the lower river system is well mixed within the water column. This indicates that for certain sediment-transport regimes (for example, fine sediment derived from the melting of glaciers in late summer), a single relation between turbidity and C_f may prove to be suitable for most sites in the lower river system.

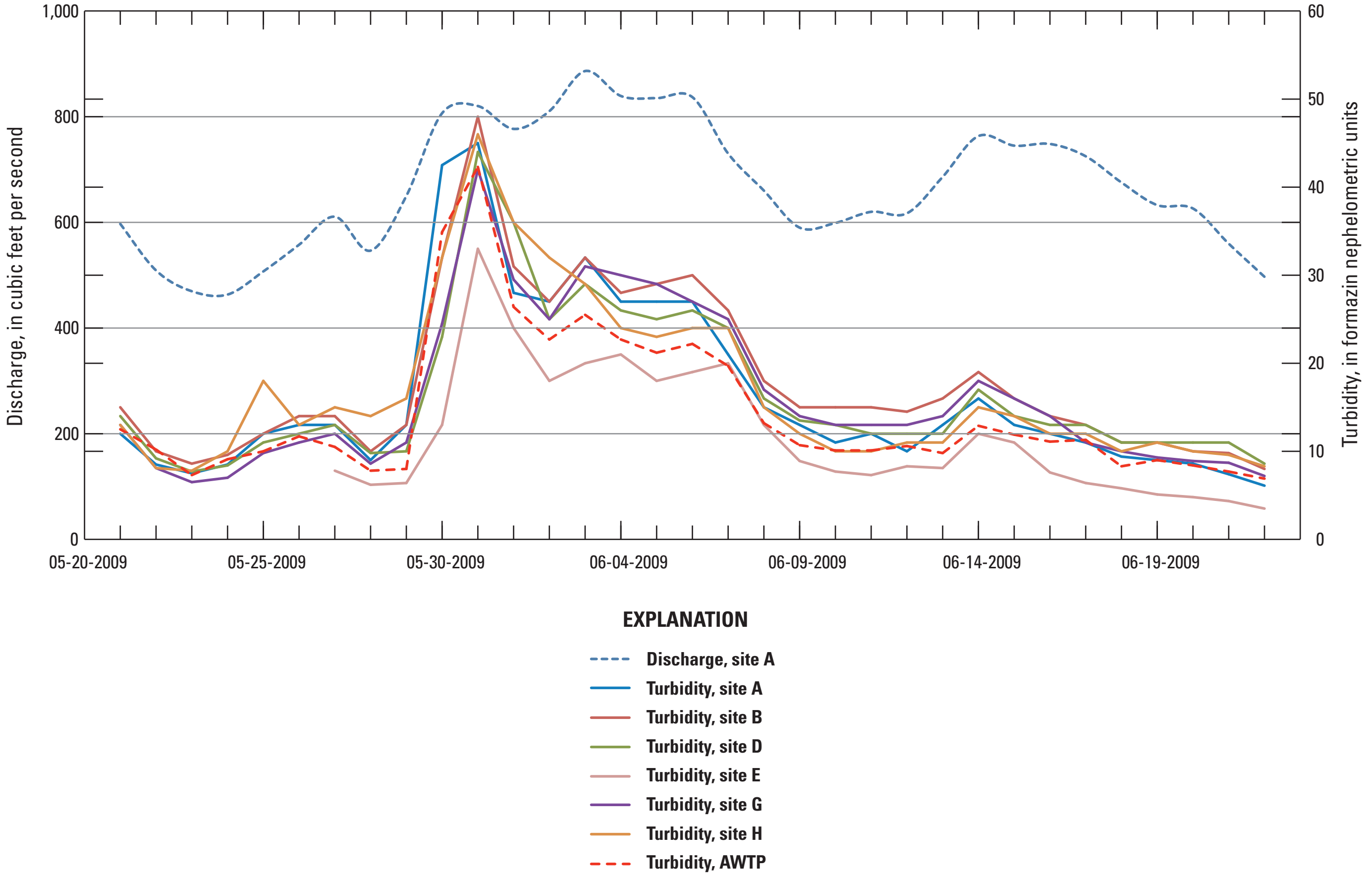


Figure 14. Daily turbidity monitored at five sites in the lower Skagit River system (sites A, B, D, G, and H), one site near McGlinn Island (site E), and at the Anacortes Water Treatment Plant (AWTP), Skagit County, Washington, May–October 2009. Locations of sites are shown in figure 3. The discharge at Skagit River near Mount Vernon (site A) is provided for reference.

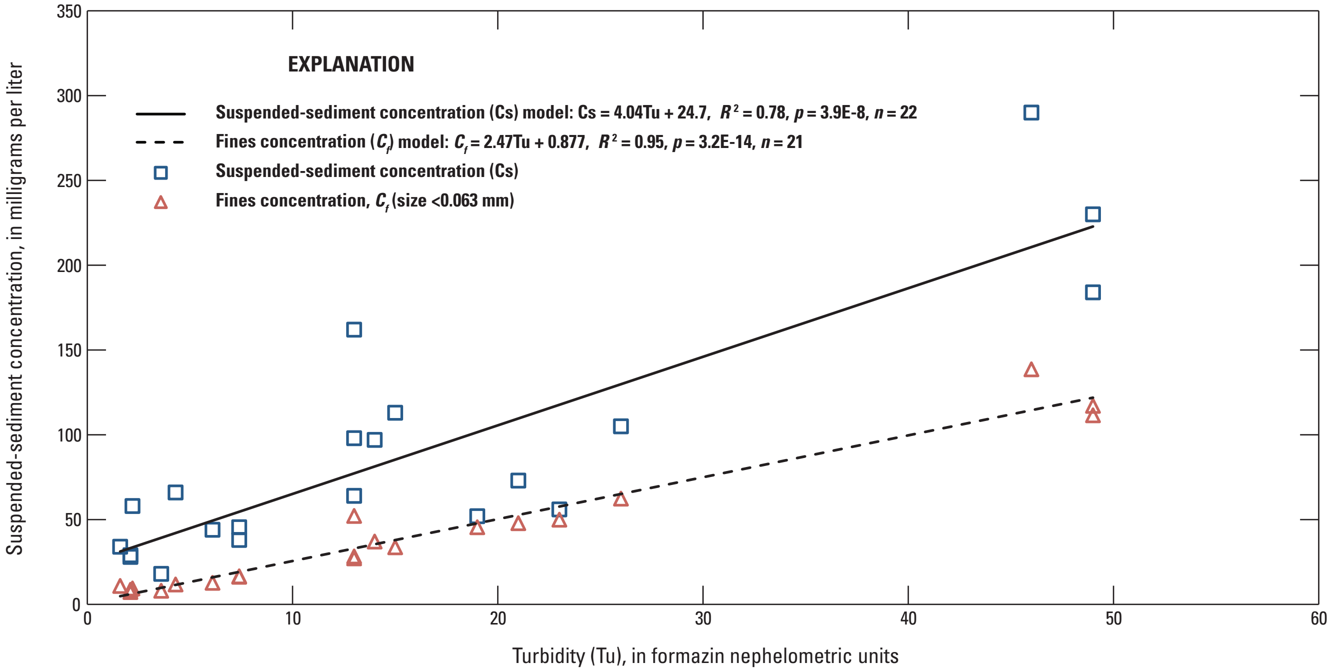


Figure 15. Relation between turbidity and suspended-sediment concentration at multiple sites (A, B, D, G, and H) in the lower Skagit River, Skagit County, Washington. Locations of sites are shown in figure 3.

Summary and Conclusions

Several approaches were explored to find the most appropriate model for relating discharge to suspended-sediment concentration (SSC) in the Lower Skagit River; a model that would make it possible to use the long record of discharge that is available for this area to estimate a corresponding record of suspended-sediment transport in the river over the same time interval. A flow-range model that apportioned the 175 measurements of SSC by different ranges of discharge provided the closest fit between estimated and measured SSC. Using this relation, in conjunction with 75 years of daily discharge record (1941–2015), a mean annual suspended-sediment load in the Skagit River of 2.5 teragrams (1 Tg = 1 million metric tons) was estimated, and individual large floods accounted for as much as 40 percent of annual sediment delivery. This was the case in 2007, an unusually wet year, when an annual load of 4.5 Tg was measured from daily suspended-sediment samples collected with an automated sampler. Whereas a flow-range based sediment-rating curve overestimated the suspended-sediment load for water year 2007 by 6.7 percent, seasonal rating curves underestimated the load by 11 percent. A summer low-flow model showed poor correlation between SSC values estimated from discharge and measured SSC values, indicating that discharge is a poor surrogate for SSC during this season, when flow in the river is dominated by glacial meltwater. A comparison of sediment-transport curve models for three time intervals revealed an overall increase of 66 percent in the slope of the SSC-discharge relation between the initial (water years 1974–76) and recent (water years 2006–09) sampling intervals, suggesting that changes in sediment supply, channel hydraulics, and (or) basin hydrology occurred between the earlier and the later periods. The use of a single model to estimate suspended-sediment load over a lengthy discharge record (75 years in this case) and outside the sampling periods assumes that shifts in sediment-rating curves are cyclical, relatively short-lived, and averaged-out with time. Particle size was an important factor controlling sediment delivery and deposition—processes that, in turn, influence flood hazards, habitat structure and function, and water quality. The percentage of fines generally increased with increasing discharge during the winter storm season. However, consistent with the relation between discharge and SSC, the percentage of fines was less strongly correlated with discharge during the summer low-flow season, indicating the predominant influence of glacier meltwater on sediment transport during summer. A daily turbidity record for the water years 1999–2013 provided by the Anacortes Water Treatment Plant was used to estimate a mean annual fine-sediment load of 1.2 Tg in the Skagit River, a value that represents 48 percent of the total mean annual suspended-sediment load for this period. On the basis of two measurements, bedload near Mount Vernon was determined to represent about 1–3 percent of the total sediment load and was predominantly composed of medium to coarse sand (0.5–1.0 mm).

Across a 15-km stretch of the lower river and delta, turbidity was generally uniform during summer, indicating that the lower river is well mixed with respect to fine sediments. Several regression equations were developed to relate suspended-sediment load to discharge, turbidity, and flow distribution through the principal distributaries of the Skagit River delta. These relations can be used to estimate sediment delivery and relative particle-size distribution in the river, both of which can be applied to support further sediment-related studies, to inform proposed delta restoration designs, and to simulate the ways in which coastal environments—particularly deltas and beaches—will respond to climate change and sea-level rise.

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