Prepared in cooperation with Sauk-Suiattle Indian Tribe

Suspended Sediment, Turbidity, and Stream Water Temperature in the Sauk River Basin, Western Washington, Water Years 2012–16

Scientific Investigations Report 2017–5113

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

Cover

Front: Photograph showing the confluence of the Suiattle River, a glacier-fed tributary (chalky colored inflow at left) and the main stem Sauk River at river kilometer 21, Skagit County, Washington, August, 2013. Photograph by Chris Curran, U.S. Geological Survey.

Back:

Photograph showing the confluence of the tributary Whitechuck River (chalky colored inflow at right) and the main stem Sauk River at river kilometer 45, Snohomish County, Washington, July, 2013. Photograph by Chris Curran, U.S. Geological Survey.

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U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	0.2642	gallon (gal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
metric ton (t)	1.102	ton, short (2,000 lb)
ton per day (t/d)	1.102	ton per day (ton/d)
ton per day per square kilometer [$(t/d)/km^2$]	2.8547	ton per day per square mile [$(ton/d)/mi^2$]

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

$$°F = (1.8 \times °C) + 32.$$

Datums

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

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

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

Abbreviations

BCF	Bias correction factor, used to account for bias introduced by parameter transformation during regression analysis
CVO	U.S. Geological Survey Cascades Volcano Observatory
ED	equal-discharge increment
ENSO	El Niño-Southern oscillation
EPA	U.S. Environmental Protection Agency
EWI	equal-width increment
MSPE	model standard percentage error
MV	multiple verticals
NIST	National Institute of Standards and Technology
NRCS	Natural Resources Conservation Service
NSD	natural systems design
NWIS	National Water Information System
OLS	ordinary least squares
PI	prediction interval
PDO	Pacific decadal oscillation
PSD	particle-size diameter
RI	recurrence interval
RKM	river kilometer
SSC	suspended-sediment concentration
SSC_f	fine suspended-sediment concentration
SSIT	Sauk-Suiattle Indian Tribe
SSL	suspended-sediment load
SSL_f	fine suspended-sediment load
SSY	suspended-sediment yield
SWE	snow-water equivalent
USGS	U.S. Geological Survey
WY	water year (October 1 through September 30)
ybp	years before present (2016)

Suspended Sediment, Turbidity, and Stream Water Temperature in the Sauk River Basin, Western Washington, Water Years 2012–16

By Kristin L. Jaeger[1], Christopher A. Curran[1], Scott W. Anderson[1], Scott Morris[2], Patrick W. Moran[1], and Katherine A. Reams[1]

Abstract

The Sauk River is a federally designated Wild and Scenic River that drains a relatively undisturbed landscape along the western slope of the North Cascade Mountain Range, Washington, which includes the glaciated volcano, Glacier Peak. Naturally high sediment loads characteristic of basins draining volcanoes like Glacier Peak make the Sauk River a dominant contributor of sediment to the downstream main stem river, the Skagit River. Additionally, the Sauk River serves as important spawning and rearing habitat for several salmonid species in the greater Skagit River system. Because of the importance of sediment to morphology, flow-conveyance, and ecosystem condition, there is interest in understanding the magnitude and timing of suspended sediment and turbidity from the Sauk River system and its principal tributaries, the White Chuck and Suiattle Rivers, to the Skagit River.

Suspended-sediment measurements, turbidity data, and water temperature data were collected at two U.S. Geological Survey streamgages in the upper and middle reaches of the Sauk River over a 4-year period extending from October 2011 to September 2015, and at a downstream location in the lower river for a 5-year period extending from October 2011 to September 2016. Over the collective 5-year study period, mean annual suspended-sediment loads at the three streamgages on the upper, middle, and lower Sauk River streamgages were 94,200 metric tons (t), 203,000 t, and 940,000 t streamgages, respectively. Fine (smaller than 0.0625 millimeter) total suspended-sediment load averaged 49 percent at the upper Sauk River streamgage, 42 percent at the middle Sauk River streamgage, and 34 percent at the lower Sauk River streamgage.

Suspended-sediment loads in the Sauk River Basin exhibited clear seasonal trends and substantial inter-annual variability that reflected the variability in discharge conditions and the relative importance of individual precipitation events and the timing of snow melt conditions among the three streamgages. Fall (October–December) suspended-sediment load, on average, accounted for more than one-half of the total annual suspended-sediment load at all three streamgages (55 percent at the upper Sauk River streamgage, 67 percent at the middle Sauk River streamgage, and 62 percent at the lower Sauk River streamgage). Summer suspended-sediment load was the smallest at the upper and middle Sauk River streamgages (6 and 7 percent, respectively), but were higher at the lower Sauk River streamgage (16 percent). Higher summer suspended-sediment load at the lower Sauk River streamgage was attributed to a relatively high suspended-sediment load associated with the late summer glacial melt season in the tributary river, the Suiattle River, which joins the Sauk River downstream of the middle Sauk River streamgage. Inter-annual variability in annual suspended-sediment loads was large, and was primarily related to the frequency and intensity of autumn and early winter precipitation events that caused high discharge.

A mass-balance analysis indicates that the Suiattle River accounts for about 80 percent of the total suspended-sediment load at the lower Sauk River streamgage. About 60 percent of the load in the Suiattle River is attributed to sediment production from the glacial and pro-glacial regions of Chocolate and Dusty Glaciers on the eastern flank of Glacier Peak. The remaining load was partitioned evenly between the inputs from the upper Sauk River and White Chuck River Basins. Mean annual suspended-sediment yield over the entire Sauk River Basin was about 510 tons per square kilometer per year [(t/km^2)/yr]; yields in the Suiattle River Basin were about 680 (t/km^2)/yr over the 5-year period, which was more than twice the yields for the upper Sauk River and White Chuck River Basins, which were estimated to be 240 and 300 (t/km^2)/yr, respectively.

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[1]U.S. Geological Survey.

[2]Sauk-Suiattle Indian Tribe.

The relation between daily discharge and sediment loads varied substantially over the study period, indicating seasonal and inter-annual variability in the amount of in-channel sediment available for transport, referred to as “sediment availability.” In percentage terms, suspended-sediment loads per unit discharge were highest in the summer because of glacial processes that provided abundant sediment during periods of low discharge. Relative availability decreased sharply in the fall as glacial sediment production ceased and discharges increased with the onset of the fall storm season. Sediment availability continued to decrease over the fall, winter, and spring, likely related to the progressive accumulation of a seasonal snowpack that insulated the landscape against erosion and the exhaustion of glacial material deposited during the summer. Sediment availability increased substantially in fall 2015, which is attributed to an outburst flood on the eastern flank of Glacier Peak. Sediment transport during the fall 2015 storms is estimated to have been on the order of 1 million tons higher as a result of these events, which is the equivalent of 21 percent of the total suspended load over the 5-year record.

Water temperature exhibited characteristic seasonal and downstream trends. Median daily temperatures averaged for each month were highest in August (14.1 °C, 14.8 °C, and 15.1 °C at the upper, middle, and lower Sauk River streamgages, respectively) and lowest in January (3.5 °C, 3.7 °C, and 4.1 °C at the upper, middle, and lower Sauk River streamgages, respectively). Variability in water temperature was generally correlated with variations in air temperature, but was modulated by seasonal snowmelt in the spring and late summer; years with small snow packs and low runoff over the May–July time period experienced warmer water temperatures than would have been expected based on air temperatures alone. The snow-pack influence generally peaked around mid-July and modulated temperatures by as much as ±3 °C.

An additional analysis to evaluate how turbidity and stream water temperature could affect Chinook salmon (*Oncorhynchus tshawytscha*) life cycles was done. Identified periods-of-concern of elevated water temperature and turbidity values that could impair Chinook salmon at various life stages were rare at the Sauk River streamgages and accounted for less than 1 percent of the study period.

Introduction

The Sauk River is one of the few remaining large, glacier-fed rivers in western Washington that is unconstrained by dams and that drains a mountainous landscape that is relatively undisturbed by development activities (fig. 1). The river is federally designated as a Wild and Scenic River and is a major tributary to the Skagit River, the largest river that enters Puget Sound. The headwaters of the Sauk River drain the northern and western flanks of Glacier Peak, one of three glaciated stratovolcanoes of the North Cascade Mountain Range. Stratovolcanoes are steep, conical volcanoes formed by layers of explosively erupted lava flows, tephra, and pyroclastic flows. In Washington State, glaciated stratovolcanoes are dominant sources of regional sediment loads and can have significant consequences on morphology, flow-conveyance, and ecosystems in downstream rivers and estuaries (Czuba and others, 2010; 2012). Additionally, glaciated mountain basins have been shown to be sensitive to climatic change, which can alter the areal extent and advance/retreat rates of glaciers, the seasonal extent of snowpacks and flood hydrology, all of which may affect water, sediment, and temperature regimes in these basins (Beamer, 2005; Finger and others, 2012; Micheletti and Lane, 2015; Lane and others, 2017). As warming trends continue to drive glacier retreat and reduce periods of snow cover throughout the world (Roe and others, 2017), there is an increasing need to develop baseline understanding of sediment loads and temperature regimes in these systems to properly understand potential influences on rivers and the ecosystems they support.

The Sauk River and its tributaries are important spawning and rearing habitats for several salmonid species, including endangered Chinook salmon (Beamer and others, 2005; National Marine Fisheries Service, 2005, 2007), threatened bull trout (*Salvelinus confluentus*), and threatened steelhead (*Oncorhynchus mykiss*), all of which are part of the greater Skagit River system. The health of sensitive salmonid populations are critically important to local communities including the Sauk-Suiattle Indian Tribe (SSIT). There is interest in understanding how river conditions including suspended-sediment loads, turbidity, and water temperature currently influence sensitive salmonid populations. Particularly, there is concern that sedimentation associated with glacial melt periods may adversely affect spawning Chinook salmon in the Sauk River and lower Skagit River Basin (Beamer and others, 2000, 2005, 2010). There is additional concern about future effects on spawning and rearing habitat from potential elevated suspended-sediment loads, turbidity, and water temperature as short-term responses to climate change (Knight and Harrison, 2009). To address concerns pertaining to salmonid habitat conditions in the Sauk River, the SSIT requested that the U.S. Geological Survey (USGS) conduct this study to characterize suspended sediment, turbidity, and water temperature regimes in the Sauk River and its principal tributaries, the Suiattle and White Chuck Rivers.

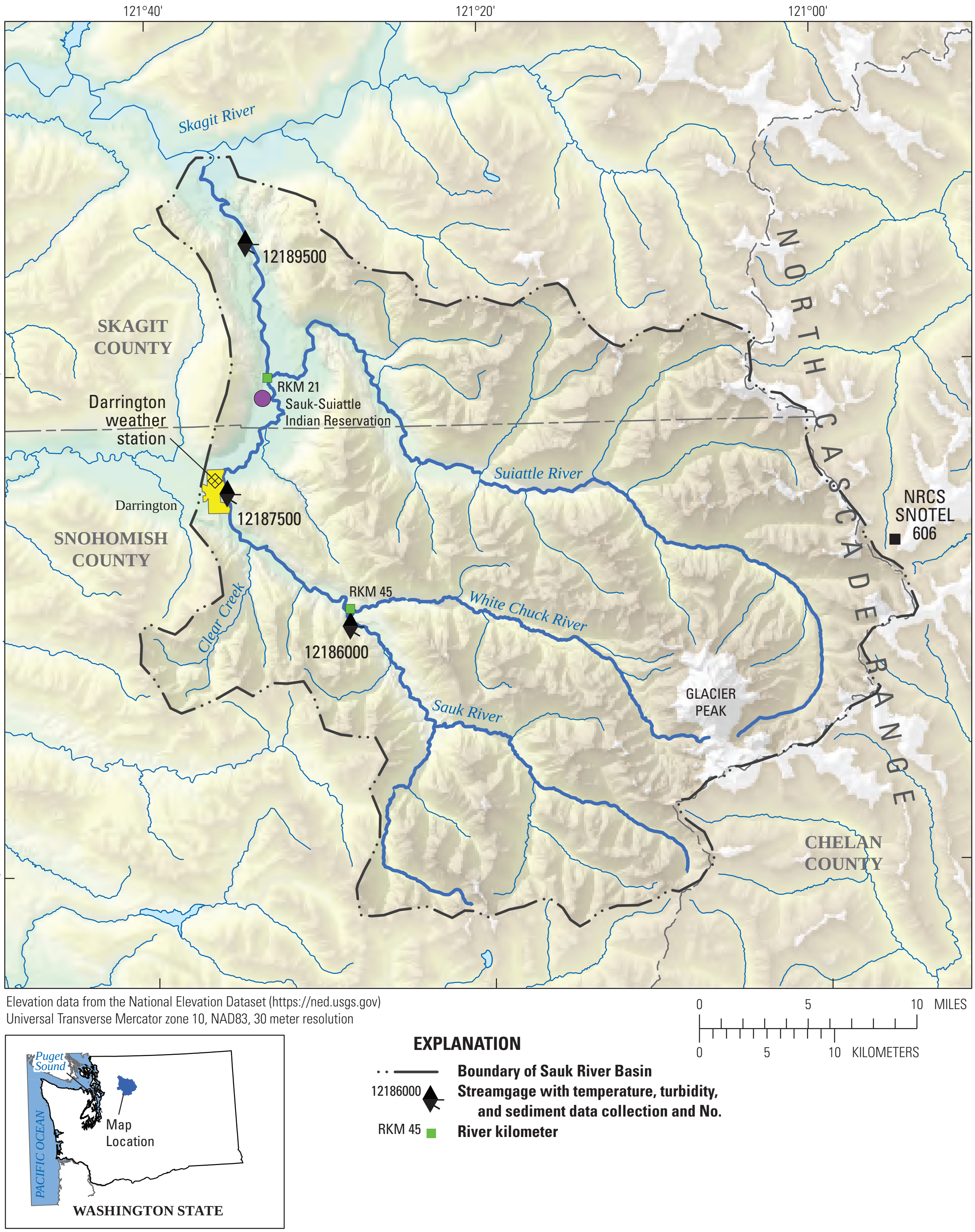


Figure 1. Location of streamgages used for discharge, sediment, turbidity, and water temperature data collection on the Sauk River including its principal tributaries, the Suiattle and White Chuck Rivers, western Washington.

Purpose and Scope

This report provides the results of a suspended-sediment and water temperature study in the Sauk River Basin to improve understanding of the magnitude and timing of suspended sediment and turbidity from the Sauk River and its tributaries to the Skagit River, and offers interpretation of sediment production regimes characterized by seasonal timing and source. This report also provides analytical results of suspended-sediment characteristics, specifically particle-size diameter (PSD). Water-quality conditions of turbidity and water temperature were evaluated in the context of potential implications on Chinook salmon life cycles.

Description of Study Area

The study area was the Sauk River Basin (drainage area 1,896 km^2) including its two principal tributaries, the Suiattle River (drainage area 890 km^2) and White Chuck River (drainage area 222 km^2) in the North Cascades Mountain Range, Washington (fig. 1). The Suiattle River drains the northern and eastern flanks of Glacier Peak and flows into the Sauk River at river kilometer (RKM) 21. The White Chuck River drains the western flanks of Glacier Peak and joins the North and South Forks of the Sauk River in the upper basin at RKM 45.

Geology, Geomorphology, and Land Cover

The basin geology can be broadly partitioned with respect to the north-south-trending Straight Creek Fault, a major geological structure in the North Cascade Mountain Range that results in distinct east-west divisions in the Sauk River Basin (fig. 2) (Vance, 1957; Brown and others, 1987; Tabor and others, 2002). East of the fault, the underlying geology is composed of intrusive and high-grade metamorphic units; west of the fault is composed of a diverse combination of intrusive, sedimentary, tertiary volcanic, and metasedimentary and metavolcanic units. River valleys originating from Glacier Peak are composed of Quaternary volcanics and lahars. Glacial drift comprises the non-glacial north and south forks of the Sauk River and tributary canyons of the Suiattle River. Unconsolidated alluvium, mass wasting, and glacial drift comprise the lower Sauk River valley.

The basin is heavily influenced by volcanism, glacial epochs, and post-glacial processes (Dragovich and others, 2000; Beechie and others, 2001, Booth and others, 2002; Collins and Montgomery, 2011). The basin experienced rapid incision into valley-filling glacial sediments following Cordilleran ice sheet retreat about 16,000 years before present (ybp), which resulted in lowering valley floors and the formation of terraces (Beechie and others, 2001; Collins and Montgomery, 2011). Prior to the Pleistocene glacial epochs (2.58 Ma to about 12,000 ybp), the Sauk and Suiattle Rivers formed a part of the Stillaguamish River Basin to the west of the Sauk River Basin. The Sauk River basin was altered by a valley-filling lahar from Glacier Peak around 12,500 ybp, which formed a low drainage divide near the town of Darrington and re-directed the Sauk north into the Skagit River (Dragovich and others, 2000; Beechie and others, 2001; Booth and others, 2002; Collins and Montgomery, 2011).

The longitudinal profiles of the river channels of the Sauk River main stem and the tributaries derived from digital elevation models (DEMs) follow characteristic concave profiles that reflect steep headwater channels with decreasing channel gradient in the downstream direction (fig. 3). The abrupt change in channel slope at approximately RKM 70 in the Sauk River upstream of the confluence of the White Chuck River corresponds to a sharp steepening of the channel as it emerges from the upper reaches of the basin and enters the main glacial river valley.

The headwater channels of the contemporary channel network emerge from the proglacial regions of Glacier Peak, transitioning from unstable, colluvial channels to steep mountain channels that are coarse-bedded with areas of exposed bedrock. Headwater channels are steep (slope 0.2 m/m) and small (bankfull width <5 m) (Beechie and others, 2001). Channel slopes rapidly decrease as they flow through terraces. Channel slopes typically range from 0.01 to 0.08 m/m, with slopes of less than 0.01 m/m on floodplains (Beechie and others, 2001).

The Sauk and Suiattle Rivers main stem channels are generally coarse-grained, single-thread meandering, pool-riffle morphology. The Sauk River valley widens downstream of Middle Sauk (12187500), and the channel shifts from a narrow, meandering planform to a wider planform with large exposed gravel bars reflecting an active channel migration in this part of the lower river. Interspersed multi-threaded reaches generally correspond to widened areas of the river valley where the channel flows through sections of floodplain forest and in-channel large wood has accumulated. The Sauk River channel narrows upstream of the confluence of the Suiattle River, the alluvial fan of which appears to constrain the Sauk River main stem floodplain.

Land cover in the Sauk River Basin is mostly forested (75 percent), of which one-half is designated wilderness (Natural Systems Design, 2014). The remaining forested parts are commercial forests owned by private individuals, Washington State Department of Natural Resources, or U.S. Forest Service. Approximately 17 percent of the Sauk River Basin has been logged since the later 1800s as part of the non-native settlement period, with the most intense harvest period occurring from the 1940s to 1980s, although timber harvest activities are currently on-going (U.S. Forest Service, 1996, 2004a, 2004b). Urban development accounts for less than 1 percent of the Sauk River basin.

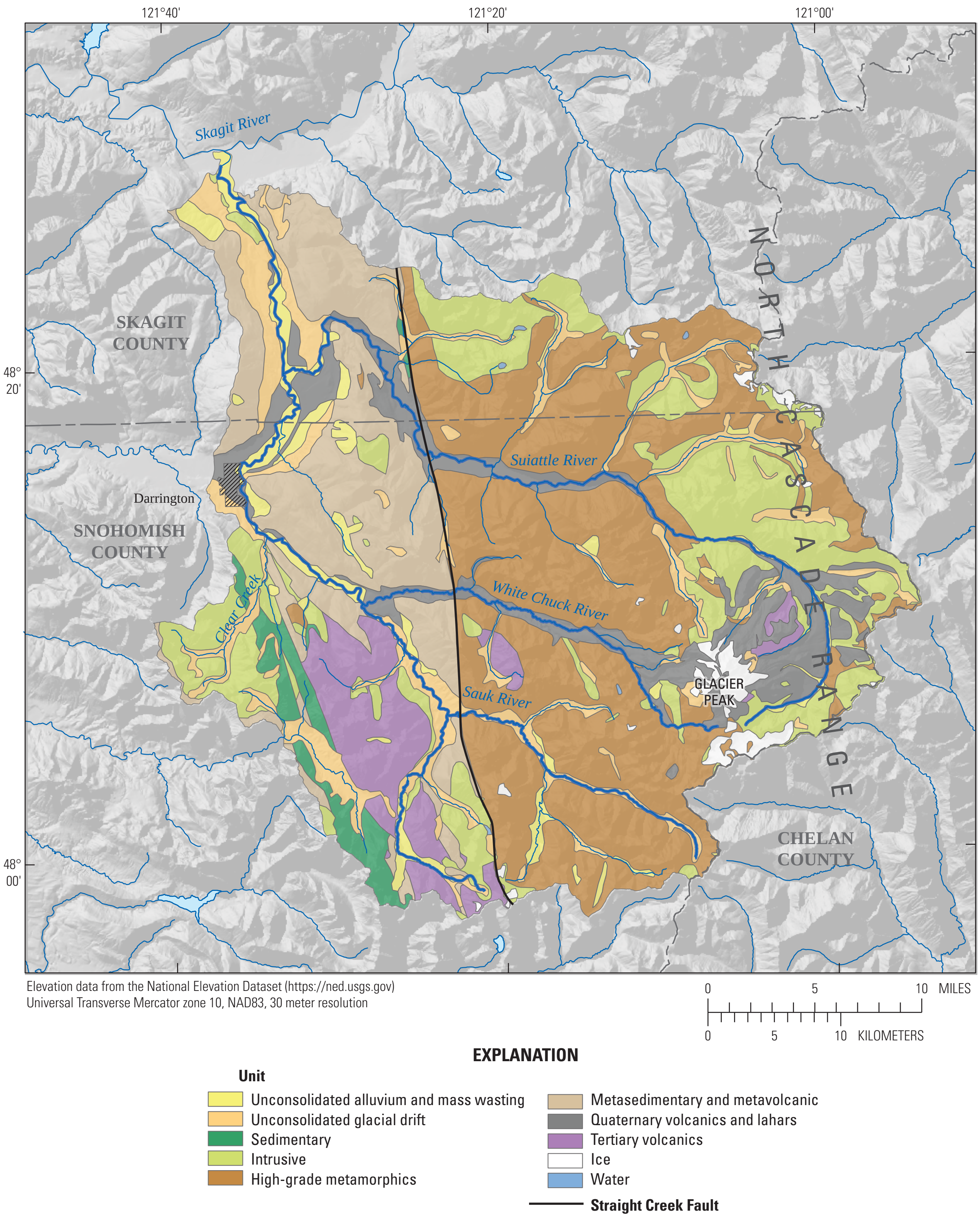


Figure 2. Surficial geology for the Sauk River Basin, western Washington.

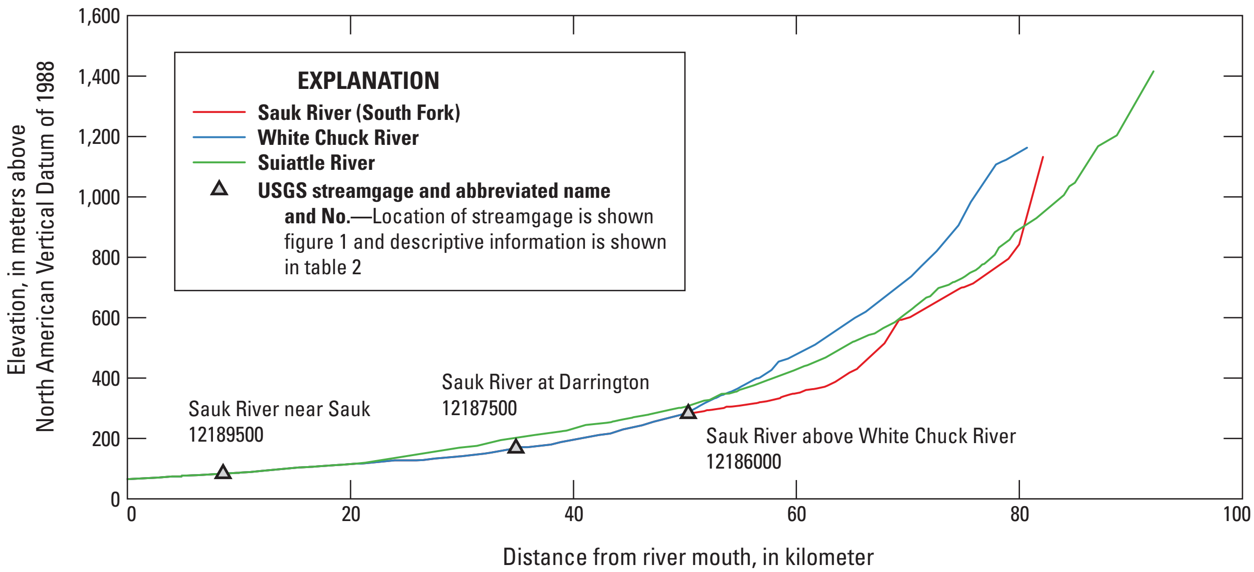


Figure 3. Sauk River and its principal tributaries, the White Chuck and Suiattle Rivers, western Washington.

Climate and Hydrology

The hydrology in the Sauk River Basin is driven by a maritime climate buffered by the North Cascades Mountain Range from the colder continental climate generated on the eastern side of the mountains, resulting in comparatively mild wet winters and cool dry summers (fig. 4). Precipitation follows a strong elevation gradient, with snow dominating the high elevations and rain in low elevation river valleys. Average annual precipitation ranges from 80 cm in the lowlands to more than 460 cm in the Glacier Peak area (Beechie and others, 2001).

Streamflow varies seasonally and reflects a bi-modal hydrograph of high discharge magnitudes in response to fall-winter precipitation and spring snowmelt (fig. 4). Fall-winter precipitation typically takes the form of low-intensity, long-duration frontal storms. However, the largest peak-flow magnitudes tend to be associated with atmospheric river events, which are narrow bands in the atmosphere that carry very high levels of water vapor from low-latitude, tropical regions to the north, making landfall along the North American Pacific Coast, including the Pacific Northwest (Zhu and Newell, 1994; Neiman and others, 2011). Atmospheric river events can result in high precipitation over concentrated regions that cause peak-flood magnitudes. Indeed, all peak flows with a recurrence interval greater than 5 years are associated with atmospheric rivers in the Sauk River for 1980–2009 (Neiman and others, 2011). Late summer base flows include glacial melt.

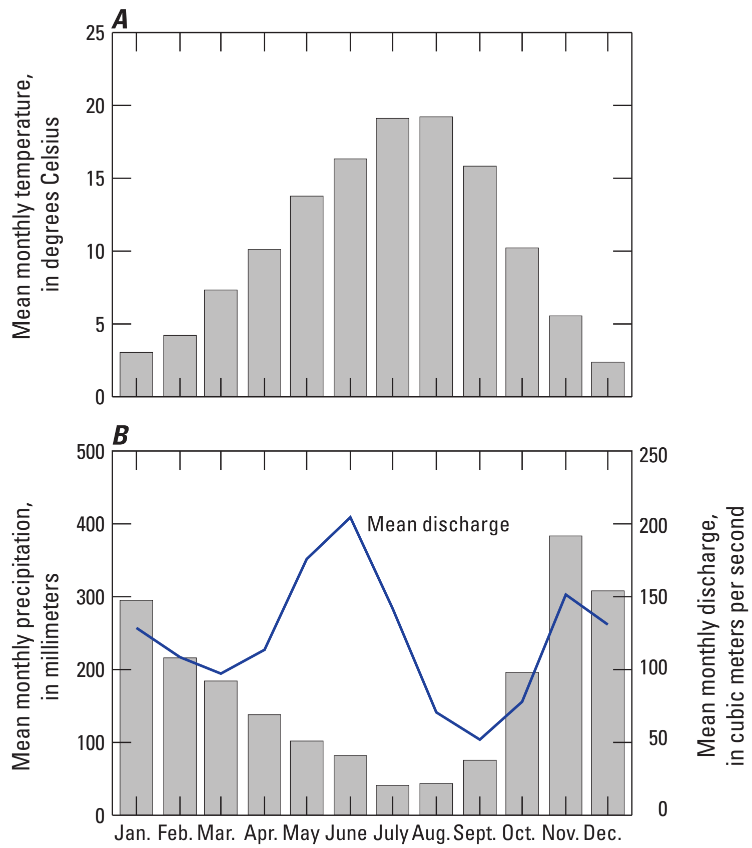


Figure 4. (*A*) 30-year normal (1980–2010) mean monthly air temperature, and (*B*) 30-year normal (1980–2010) mean monthly precipitation at Darrington weather station and mean monthly discharge (1980–2010) for U.S. Geological Survey streamgage Sauk River near Sauk (Lower Sauk, 12189500), Sauk River, western Washington. Locations of weather station and streamgage are shown in figure 1, and descriptive information for streamgages is shown in table 2.

The flood hydrology in the Sauk River Basin varies significantly from year to year as a result of the particular sequence of storms that affect the basin (fig. 5). The distribution of storms over a period of years is influenced by regional 20–30-year-long phases of the Pacific Decadal Oscillation (PDO) (Mantua and others, 1997; Mantua and Hare, 2002) and shorter fluctuations of the El Niño-Southern Oscillation (ENSO) (Hamlet and Lettenmaier, 2007). In the Sauk River Basin, the magnitude of the largest floods has increased since the late 1970s, coincident with the shift from a cool to warm phase in the PDO (fig. 5*A*). This shift in the late-1970s was particularly notable for the fall flood seasons (fig. 5*B*); prior to 1976, maximum fall daily discharges greater than 1,100 m^3/s occurred once in 45 years, or about 3 percent of the time. Since 1976, maximum fall discharges greater than 1,100 m^3/s have occurred 10 times in 41 years, or about 25 percent of the time. In combination with a modest increase in the frequency of fall storms since 1976, the overall activity of the fall storm season has been notably higher in the past decades than prior to the 1970s (fig. 5*C*). The fall storm season activity level is characterized in this report as the total volume of water transported (or 'flow volume') on days where the mean daily discharge is greater than 390 m^3/s. This metric is conceptually similar to geomorphically effective flow volumes (for example, Rickenmann, 1997) or the peaks-over-threshold approach to characterizing flood hydrology (Lang and others, 1999), in order to summarize a hydrograph with multiple distinct, relatively high-flow events and capture information about both the frequency and intensity of those events. The threshold value of 390 m^3/s represents the 2-percent exceedance flow based on the daily discharge record at the USGS streamgage Sauk River near Sauk (Lower Sauk, 12189500), and is a moderately high flow that is exceeded most years.

For all three flood hydrologic metrics, *t*-tests indicate that population of values prior to 1976 are statistically distinct from values after 1976 (table 1). No statistically significant linear trends were detected for any of the metrics over the two periods from 1929–1975 and 1976–2016. These results indicate that the positive linear trend in all three metrics for the 1929–2016 time period, which is nominally significant, is likely a spurious result caused by the abrupt shift in 1976 and not an indication of a true trend.

Discharge in the Sauk River Basin, Water Years 2012–16

Monitoring occurred at three USGS streamgages in the Sauk River. For ease of discussion in this report, the USGS streamgages are referenced in terms of the relative location of each streamgage along the river—Sauk River above White Chuck River, near Darrington (12186000; Upper Sauk); Sauk River at Darrington (12187500; Middle Sauk); and Sauk River near Sauk (12189500; Lower Sauk.) Upper Sauk and Lower Sauk are considered long-term streamgages with continuous streamflow record lengths of 93 and 89 years, respectively, through water year (WY) 2016, and the Middle Sauk streamgage was installed specifically as part of this study. The location of USGS streamgages are shown in figure 1, and the periods of operation for each streamgage are shown in table 2.

Streamflow during the 5-year study was characterized by a typical bi-modal hydrograph, although the study included substantial inter-annual variability (fig. 6*A*). The hydrographs for the three Sauk River streamgages are well correlated (Pearson's *r* more than 0.95 among the three streamgages) (fig. 6*B*), and descriptions of the seasonal and inter-annual characteristics of the hydrology during this period apply to all three streamgages equally. Differences in the magnitude of discharge between Upper and Middle Sauk are attributed to the contribution of the White Chuck River, which flows into the Sauk River main stem immediately downstream of the Upper Sauk streamgage. Differences in magnitude of discharge between the Middle and Lower Sauk streamgages are attributed to the contribution of the Suiattle River, which flows into the Sauk River main stem between the Middle and Lower Sauk streamgages.

Mean daily discharge did not vary substantially between years, with the exception of WY 2015 (table 3), which was a regional drought year. However, the distribution of that discharge varied substantially among the 5 years (fig. 6*A*). The first 3 years of record experienced relatively calm flood seasons, with average monthly mean discharges but relatively few large floods. Annual peak discharges were low (about 600 m^3/s at Lower Sauk) relative to the average over the long-term record (890 m^3/s at Lower Sauk). Discharges during the spring snow-melt season for the first 3 years were generally 20 percent greater than the long-term average (mean daily discharge of 212 m^3/s compared to 173 m^3/s). WY 2015, the fourth year of the study, had a relatively wet fall and winter, with above-average monthly mean discharges, and a sequence of fall and winter floods that were similar to the long-term median values. Mean daily discharge decreased to record lows and was approximately one-half the long-term average mean daily discharge during spring and summer 2015 (90 and 43 m^3/s, respectively), as the region experienced drought conditions (National Oceanic and Atmospheric Administration (2017). Fall 2016 was characterized by numerous large flood events, with three events exceeding the 2-year recurrence interval (RI) of 880 m^3/s, and one event exceeding the 5-year RI of 1,360 m^3/s in the Lower Sauk (fig. 6*B*, table 3). In total, there were 10 days in the fall of WY 2016 where the daily mean discharge exceeded 390 m^3/s, resulting in WY 2016 ranking third out of the 98-year period of record for most days above this threshold. In terms of the total flow volume for days with mean discharge greater than 390 m^3/s, the fall of WY 2016 was the fifth-most active fall over the long-term record (fig. 5*C*).

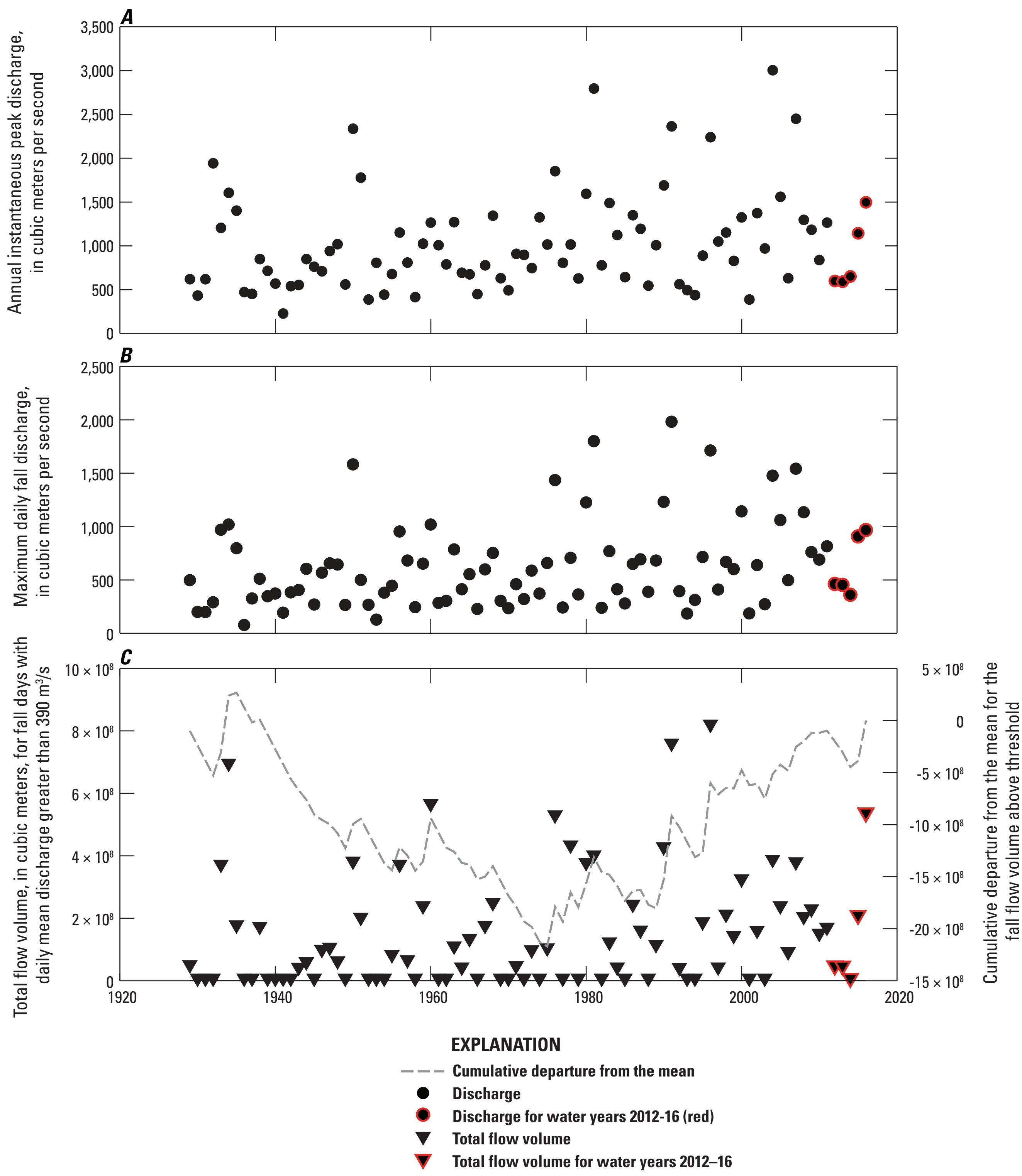


Figure 5. Annual instantaneous peak discharge (*A*), maximum daily discharge (October–December) (*B*), and total flow volume for fall days with daily mean discharge greater than 390 m³/s (*C*), for U.S. Geological Survey streamgage Sauk River near Sauk (Lower Sauk, 12189500), western Washington, water years 1928–2016. Location of streamgage is shown in figure 1, and descriptive information is shown in table 2.

Table 1. Statistical analyses of flood hydrologic metrics for U.S. Geological Survey streamgage Sauk River near Sauk (12189500), western Washington.

[Location of streamgage is shown in figure 1 and descriptive information is shown in table 2. **Abbreviation**: m^3/s, cubic meter per second]

Flood hydrologic metric	P-value for statistical test			
	t-test	Linear trend		
	1929–1975 and 1976–2016	1929–75	1976–2016	1929–2016
Annual instantaneous peak discharge	0.008	0.944	0.707	0.025
Maximum daily fall discharge	0.002	0.827	0.997	0.005
Total flow volume, in cubic meters, for fall days with daily mean discharge greater than 390 m^3/s	0.014	0.683	0.782	0.054

Table 2. Description of U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington.

[Locations of streamgages are shown in figure 1. **Abbreviation**: km^2, square kilometer]

USGS sreamgage name and No.	Abbreviated streamgage name	Drainage area (km^2)	River kilometer	Period of operation for streamflow	Period of record for this study
Sauk River above White Chuck River, near Darrington, 12186000[1]	Upper Sauk	393	50.3	Oct. 1, 1917–present	Oct. 1, 2011–Sept. 30, 2016
Sauk River near Darrington, 12187500	Middle Sauk	759	34.8	July 1, 1914–Sept. 30, 2016	Oct. 20, 2011–Sept. 30, 2016
Sauk River near Sauk, 12189500[1]	Lower Sauk	1,849	8.6	Apr. 1, 1911–present	Oct. 1, 2011–Sept. 30, 2016

[1]Long-term USGS streamgage that is in operation beyond study period date.

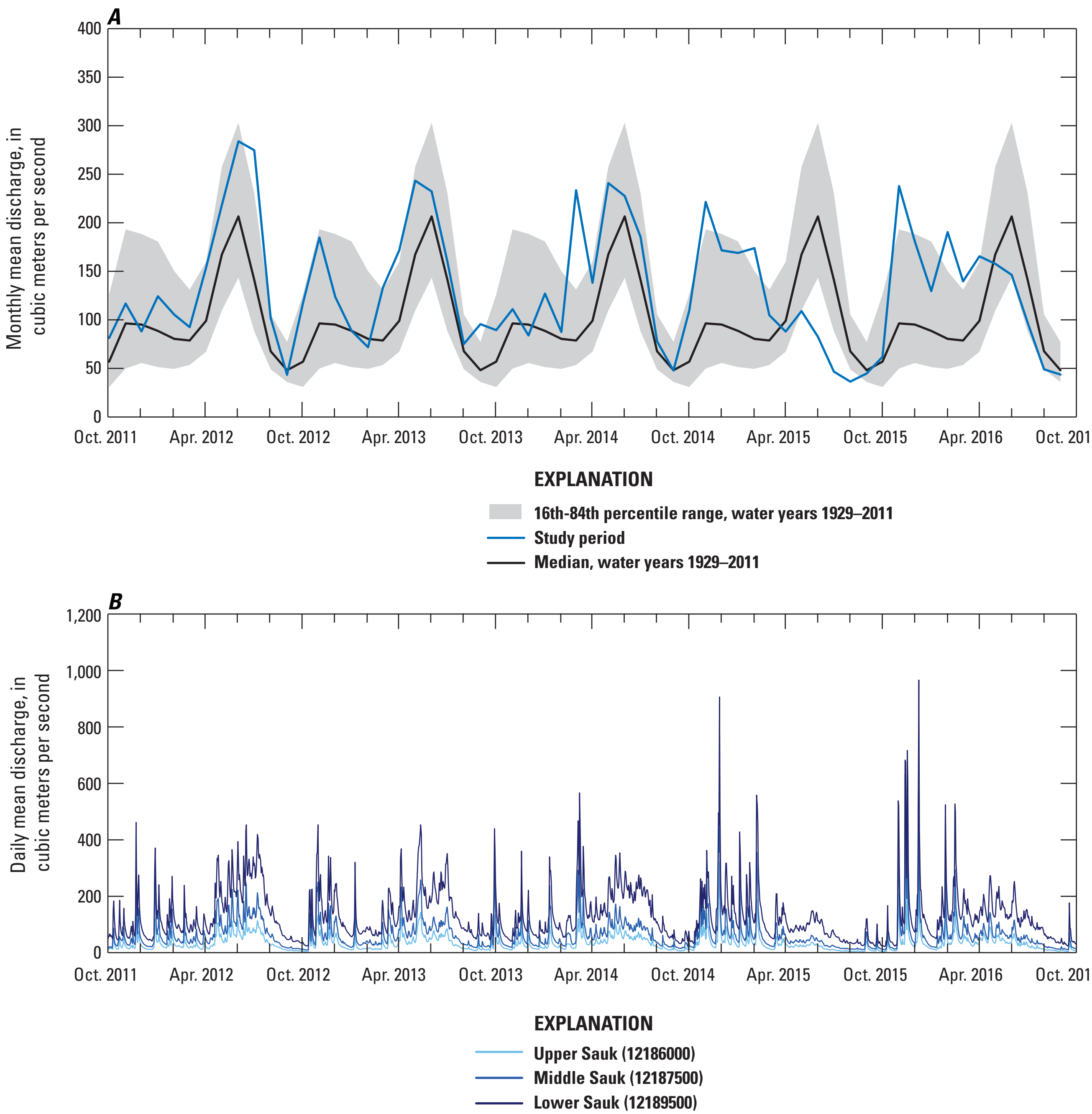


Figure 6. (*A*) Monthly mean discharge for water years 2012–16 for U.S. Geological Survey streamgage Sauk River near Sauk (Lower Sauk,12189500), and (*B*) time-series graphs showing daily mean discharge at U.S. Geological Survey streamgages on the Sauk River, western Washington, water years 2012–16. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Table 3. Summary statistics for discharge at U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, water years 2012–16.

[Locations of streamgages are shown in figure 1 and descriptive information is shown in table 2. **Abbreviations**: m³/s, cubic meter per second; >, greater than; –, not available]

USGS streamgage with sediment monitoring and No.	Abbreviated streamgage name	Water year	Mean daily discharge (m^3/s)	Minimum 7-day mean discharge (m^3/s)	Discharge of three largest events (m^3/s)			Recurrence interval for peak discharge (years)
Sauk River above White Chuck River, near Darrington, 12186000	Upper Sauk	2012	36.7	6.55	168	164	140	1.2
		2013	35.6	4.22	202	171	170	1.4
		2014	34.8	6.58	200	146	131	1.4
		2015	30.6	4.15	411	257	230	4.5
		2016	36.6	4.49	566	535	433	8.5
Sauk River near Darrington, 12187500	Middle Sauk	2012	69.0	13.7	453	391	289	–
		2013	67.7	10.1	445	365	328	–
		2014	64.1	15.7	462	343	311	–
		2015	56.3	11.1	875	612	487	–
		2016	65.8	11.2	>1,138	>1,138	756	–
Sauk River near Sauk, 12189500	Lower Sauk	2012	140	37.5	597	496	487	1.3
		2013	142	25.1	589	555	513	1.3
		2014	138	34.2	648	515	453	1.4
		2015	113	26.8	722	603	436	2.9
		2016	133	23.3	1,495	1,283	1,124	6.4

Previous Studies

The geology of the Sauk River Basin has been described by Beget (1982) and Tabor and others (2002). Glacier Peak volcanic history that includes eruptions, lahar activity, and debris flows have also been described by Dragovich and others (2000) and Slaughter (2004). Additionally, glaciers on Glacier Peak are included in the North Cascades Glacier Climate Project (Pelto and Hedlund, 2001; Pelto and Reidel, 2001).

The geomorphic processes of Sauk River Basin have been described within the context of the greater Skagit River system by Beechie and others (2001) and Booth and others (2002). Both works emphasize the importance of the post-glacial processes, notably large scale, post-glacial valley deposition and subsequent rapid incision, in shaping the contemporary landscape of the Sauk River Basin and greater Skagit River. Beechie and others (2001) provide a historical analysis of the influence of post-glacial geomorphic processes, non-native settlement, and recent land-use changes in the last 150 years on salmonid habitat in Skagit River system, with a focus on coho salmon (*Oncorhynchus kisutch)*. Beechie and others (2001) concluded that the main river valleys and floodplain sloughs on valley floors of the Skagit system support the majority of anadromous salmonid habitat. However, historical habitats that include channels and ponds, have been removed or substantially altered through extensive floodplain alteration via dredging, ditching, and diking (Beechie and others, 2001).

Natural Systems Design (2014) conducted a flood and erosion hazard assessment on the Sauk River with a focus on an approximately 3.2-km alluvial section of the river that flows through the SSIT reservation and the town of Darrington and is referred to as the Middle Sauk River reach. The objective of the study was to evaluate climate change effects on channel migration behavior that could affect SSIT infrastructure on and near the Sauk River floodplain. The report summarizes history of timber harvest activity, historical trends in hydrology, and potential future trends that may be associated with climate change. Analysis of historical channel migration (1949–2011) identifies that the channel morphology of the Middle Sauk River reach is active, but is trending towards a dominantly single-channel system from a multi-threaded morphology. Channel sinuosity is decreasing, although the channel remains relatively wide with exposed gravel bars and a meandering low-flow channel.

Projected increased peak flow magnitudes for the USGS streamgage Sauk River near Sauk (Lower Sauk, 12189500) for the 2080s were used to evaluate floodplain inundation in the Middle Sauk River reach. The report proposed that observed recent changes of reduced sinuosity and shifts from a multi-threaded to a single-thread planform morphology in the Middle Sauk River reach may be a result of channel adjustment to historical river incision following historical in-channel large wood removal and changes to the riparian forest. The dynamic channel morphology in this section of the river also may be attributed to the influence of the Suiattle River alluvial delta and its ability to create a backwater area upstream of the confluence in the Sauk River main stem and thus an aggradational zone that promotes sediment deposition and rapid channel migration (Natural Systems Design, 2014). The report documents increased channel migration rates (12 m/yr, 2004–11 relative to 6 m/yr 1949–1974), although this could be a function of limited aerial photograph analysis that did not capture channel change in intervening years. Their analysis indicates that the SSIT reservation is located in the channel migration zone and is at high risk for damage associated with climate-change driven peak flood magnitudes.

Additional studies include geomorphic analyses on the Sauk River main stem along an approximately 17-km reach that extends from Clear Creek to the Suiattle River confluence (Devries, 2008; DeVries and Madsen, 2008). Watershed analyses were conducted by the U.S. Forest Service for the Sauk River and Sauk River Forks (1996), the Suiattle River (2004a), and the White Chuck River (2004b). The Suiattle River channel was mapped by Skagit River System Cooperative for the U.S. Forest Service (Ramsden and Smith, 2010). The study included an analysis of historical aerial photographs extending from 1942 to 2007 to (1) identify a “historical channel zone,” (2) estimate channel migration rates, and (3) assess potential effects to Forest Road 26 from bank erosion activities in the Suiattle River. The 2010 report identifies that the Suiattle River is actively migrating along the valley floor with some select reaches that can be considered stable. Areas of highest channel migration rates (3–12 and 1.5–9 m/yr) are associated with the widest floodplains and the greatest channel change has occurred in the most recent interval of analysis, 1998–2007 (Ramsden and Smith, 2010).

The hydrological record of Lower Sauk (12189500) also has been the focus of several USGS studies as part of the larger Skagit River system (Herron, 1916; Stewart and Bodhaine, 1961; Mastin and others, 2016). Most recently, Mastin and others (2016) identified a positive, but weak, trend in flood-frequency analysis of Lower Sauk for the period extending to 2014.

Potential changes to the greater Skagit River system associated with climate change are of major regional interest and, therefore, the Sauk River, as a major tributary to the Skagit River that represents unregulated flow and a relatively long period of record (more than 90 years), has been included in several studies that evaluate climate change effects on hydrological and sediment regimes (for example, Lee and Hamlet, 2011; Mauger and others, 2015).

Data-Collection and Processing Methods

Sediment data were collected over a range of discharge, turbidity, and water temperature conditions at three USGS streamgages on the Sauk River. All USGS streamgages were operated and maintained per USGS methods (Rantz and others, 1982), and 15-minute discharge records were calculated based on a stage-discharge relation and reviewed and approved for the period of record per USGS methods (Rantz and others, 1982). All discharge data collected during this study are available online through the USGS National Water Information System (NWIS) Website (U.S. Geological Survey, 2017a).

Suspended Sediment

Most suspended-sediment samples were collected using either the equal-width-increment (EWI) method or the equal-discharge-increment method (EDI) in which depth-integrated samples are collected from 5 to 10 locations in the cross section and composited together (Edwards and Glysson, 1999) to ensure that sample concentrations were representative of the channel cross section. Exceptions occurred on three occasions (October 22, 2014, at Middle Sauk; September 5, 2013, and November 28, 2014, at Lower Sauk) when sampling conditions prohibited full EWI measurements and instead consisted of multiple verticals (MV), and on one occasion (January 10, 2012, at Middle Sauk) when the observed turbidity conditions were very low and only a grab sample was obtainable. All samples identified as MV or grab samples were, in the judgment of the hydrographer, considered representative of channel conditions at the time of collection. Suspended-sediment samples obtained by EWI, EDI, and MV methods were collected most of the time using a standard USGS bridge crane with variable-speed motor, and, in all cases, various depth-integrated samplers approved for isokinetic sampling by the Federal Interagency Sedimentation Project (FISP) and routinely used by USGS personnel (Davis, 2005) (fig. 7). All sediment samples were collected at vehicle bridges nearest in proximity to streamgages. As for Lower Sauk, samples were collected approximately 2.1 km upstream of the USGS streamgage Sauk near Sauk (12189500) and discharge-weighted time-of travel adjustments ranging from 0.2 to 1.15 h were applied when comparing sample results to discharge information recorded at the streamgage. Most cross-section samples were collected in duplicate (A and B sets) and if the suspended-sediment concentration (SSC)

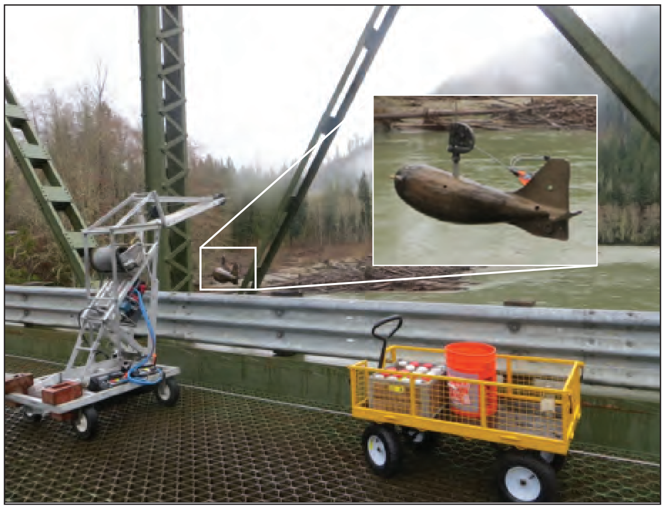


Figure 7. D-74 suspended-sediment sampler (inset) lowered from a crane at U.S. Geological Survey streamgage Sauk River near Sauk (Lower Sauk, 12189500), western Washington. Location of streamgage is shown in figure 1, and descriptive information is shown in table 2. Photograph by Karen Payne, U.S. Geological Survey, March 13, 2013.

results of A and B sets were within 20 percent of the average of both samples, the average SSC was reported. All sediment samples were analyzed at the USGS sediment laboratory at the Cascades Volcano Observatory (CVO) 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”). Some samples with high SSC were analyzed for full particle-size distribution (appendix A). All discrete suspended-sediment sample data collected for the Sauk River are available through the National Water Information System (NWIS), USGS Water-Quality Data for Washington, as “Field/Lab samples” (U.S. Geological Survey (2017b)

Turbidity

Turbidity was continuously monitored at each of the three USGS streamgages from October 1, 2011, to September 30, 2015 (with the exception of intermittent periods when instrument failure, excessive sedimentation, or fouling occurred), and at Middle Sauk (12187500), at which turbidity monitoring began on October 20, 2011. Additionally, turbidity was also monitored at Lower Sauk during WY 2016. Turbidity was measured at each streamgage using a DTS-12 Nephelometric Turbidity Sensor (Forest Technology Systems, Ltd., 2014) enclosed within a 2-in. diameter protective pipe (fig. 8*A*). 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. After the first year of deployment, mounting pipes were replaced within 3-in. diameter pipe to allow easier access to sensors for calibration checks and periodic sensor replacement. Turbidity data for each streamgage were recorded at 15-minute intervals and transmitted hourly via satellite from the streamgage to the USGS Automated Data Processing System and are available through NWIS, USGS Water-Quality Data for Washington, as “Historical Observations” (U.S. Geological Survey, 2017b). The nominal operational range of the DTS-12 sensor stated by the manufacturer is 0–1,600 FNU (Forest Technology Systems, Ltd., 2014); however, individual sensors have unique maximum-measurable limits that are reported by the manufacturer and these values can exceed 1,600 FNU. In this study, turbidity values exceeding 1,600 FNU were considered valid provided that these values did not exceed maximum values determined with calibration standards prior to deployment. Although deployed sensors were calibrated and met acceptance criteria as outlined by Wagner and others (2006) over the range of 0–1,600 FNU, the quality of turbidity data greater than 1,600 FNU is unknown and these data are considered poor with increased uncertainty. The USGS protocols for the operation and maintenance of continuous water-quality instruments were otherwise followed as outlined by Wagner and others (2006), and the time-series data were processed, reviewed, and approved according to established USGS policy for continuous water-quality data (Wagner and others, 2006).

Suspended-Sediment Concentration and Load

At each of the streamgages, time-series suspended-sediment concentration (SSC) was determined using turbidity and (or) discharge as a surrogate, following the methods outlined by Rasmussen and others (2009). Regression equations for estimating SSC and the concentration of “fine” suspended sediment (SSC_f; silt-size and finer sediment, less than 0.0625 mm in size) were developed from the SSC of samples and concurrently measured turbidity and (or) discharge at each streamgage and the upper and lower prediction intervals for individual estimates of SSC were calculated at the 90-percent level (Rasmussen and others, 2009). A time-series record of SSC and SSC_f was computed for each site using the appropriate regression equation and the 15-minute turbidity, and (or) discharge, time-series record. For sites where measured turbidity was greater than 1,600 FNU (greater than nominal operating range), the 15-minute regression-computed SSC and SSC_f values were reported and qualified as having a greater degree of uncertainty, and the computed SSC and SSC_f for turbidity equal to 1,600 FNU were reported to reflect minimum estimates. Time gaps in 15-minute turbidity data were estimated by interpolation provided that these gaps were equal to or less than 60 minutes duration.

Figure 8. U.S. Geological Survey streamgage and turbidity sensor installations on the Sauk River, western Washington. (*A, B*) Sauk River above White Chuck River (Upper Sauk, 12186000); (*C, D*) Sauk River at Darrington (Middle Sauk,12187500); and (*E, F*) Sauk River near Sauk (Lower Sauk, 12189500). Photographs by Chris Curran, U.S. Geological Survey, September 20, 2011. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Calculation of SSL, sometimes referred to as “suspended-sediment discharge,” requires concurrent measurements of both discharge and SSC. The equation by Guy (1969) was used for calculating SSL:

$$L_s = Q \times C_s \times k \quad (1)$$

where,

L_s is SSL, in metric tons (t) per day;
Q is discharge, in cubic meters per second;
C_s is SSC, in milligrams per liter; and
k is an International System of Units conversion equal to 0.0864 t-L-s/m^3-mg-day.

Using equation 1, the 15-minute records of discharge and computed SSC at each gaging station were used to generate a 15-minute record of SSL at each site, and daily values of SSL were obtained by summing the 15-minute SSL data for each day and dividing by 96 (the number of 15-minute values per day). The 15-minute data of SSC, SSC_f, associated upper and lower prediction intervals, and daily SSL are available in Curran and others (2017).

Water Temperature

Stream water temperature was monitored concurrently with operational turbidity sensors at all streamgages using the built-in DTS-12 thermistors that have the primary purpose of providing temperature correction data for the turbidity sensors rather than being primarily designed to measure water temperature. Thermistors in the DTS-12 sensors have a manufacturer reported operational range of -40–60 °C, and meet USGS precision criteria for primary thermistors with an accuracy of ±0.2 °C (Forest Technology Systems, Ltd., 2014). Independent measurements of quality assurance and quality control of the water temperature data were verified during annual manufacturer calibrations when the DTS-12 temperature was confirmed in ± 0.2 °C against a National Institute of Standards and Technology (NIST)-certified thermistor.

Suspended Sediment, Turbidity, and Stream Water Temperature in the Sauk River Basin

Suspended-Sediment Samples

A total of 20–26 cross-section representative samples of suspended sediment were collected at each of three USGS streamgages on the Sauk River over a broad range of turbidity and discharge conditions throughout the study. For each streamgage, the sample times, methods, stream conditions (discharge and turbidity), and laboratory results are shown in table 4. The SSC for samples ranged from 2 to 644 mg/L at Upper Sauk, 5 to 1,360 mg/L at Middle Sauk, and 11 to 4,320 at Lower Sauk. On average, the percentage of fine sediment (size <0.0625 mm) in samples was 58 percent at Upper Sauk, 55 percent at Middle Sauk, and 54 percent at Lower Sauk.

Turbidity Monitoring

Turbidity was measured continuously for most of the study at the three USGS streamgages on the Sauk River (fig. 9). Exceptions occurred at Upper Sauk, where turbidity data were missing for an extended period (April–September 2012) due to sensor burial during high flows (after which the sensor was relocated), and for November 6, 2014, to September 30, 2015, when deposition of sediment in and around the sensor housing caused elevated turbidity levels which, after closer inspection, were deemed unrepresentative of the river conditions for this period. On average, turbidity levels increased between streamgages in the downstream direction. In WYs 2012–14, when all turbidity sensors were operational, the mean turbidity at Lower Sauk (23.6 FNU) was about 2.5 times greater than the mean turbidity at Middle Sauk (8.6 FNU) and Upper Sauk (9.3 FNU). During this 3-year period, turbidity exceeded 100 FNU more frequently at Lower Sauk (6 percent of time) than at Upper and Middle Sauk (1.1 and 0.4 percent of time, respectively). These findings indicate the influence of the Suiattle River, the principal glacier-fed tributary between Middle and Lower Sauk, on the increased magnitude and frequency of turbidity events observed in the lower Sauk River. The turbidity sensor deployment periods and a summary of turbidity data measured at each streamgage are shown in table 5.

Seasonal Variability in Turbidity at Lower Sauk

The turbidity time series at Lower Sauk exhibits seasonal patterns that may reflect glacial melt processes that are distinct from non-glacial processes (fig. 10). During the non-glacial melt period, which extends from late fall through spring (November–March), turbidity values tend to scale with discharge and generally increase with increasing discharge magnitude (fig. 10*B*). However, the summer glacial melt period (July–September) exhibits several patterns that include diurnal signals, episodic pulses, and a first flush phenomenon. Diurnal signals are represented by small-scale daily fluctuations that correspond with changes in snowmelt-derived discharge (fig. 10*C*). Episodic pulses are very high pulses of turbidity (more than 2,000 FNU) that occur in late summer and, in contrast to winter season turbidity patterns, are not coherent with discharge. Finally, a first-flush signal is evident during which small precipitation-driven discharge events in late summer and early fall result in very high pulses of turbidity (more than 2,000 FNU).

Table 4. Sample data for suspended-sediment concentrations collected at U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, 2011–16.

[Data are available through the National Water Information System (U.S. Geological Survey, 2017b). Locations of streamgages are shown in figure 1 and descriptive information is shown in table 2. **Sampling method**: EDI, equal-discharge increment; EWI, equal-width increment (EWI); MV, multiple vertical. **SSC**, suspended-sediment concentration. **SSC$_f$**, fine suspended-sediment concentration. **SSL**, suspended-sediment load. **SSL$_f$**, fine suspended-sediment load. **Abbreviations**: FNU, Formazin Nephelometric Unit; m^3/s, cubic meter per second; mg/L, milligram per liter; t/d, ton per day]

USGS streamgage name and No.	Date	Start time	End time	Discharge (m^3/s)	Turbidity (FNU)	Sampling method	SSC (mg/L)	SSC$_f$ (mg/L)	SSL (t/d)	SSL$_f$ (t/d)
Sauk River above White Chuck River, near Darrington, 12186000	09-21-11	9:45	10:19	12	–	EDI	4	2	4	2
	10-19-11	10:40	11:04	13	1	EDI	2	1	2	1
	11-23-11	14:27	15:12	156	120	EWI	283	150	3,809	2,021
	02-22-11	11:38	12:10	79	62	EWI	64	51	435	344
	06-18-12	16:06	16:32	114	–	EDI	48	19	467	189
	07-10-12	17:30	17:45	96	–	EDI	23	10	190	81
	08-17-12	14:25	14:47	19	–	EDI	2	2	4	3
	10-15-12	15:47	16:32	42	15	EDI	18	13	65	46
	10-31-12	14:45	15:30	119	59	EDI	78	40	802	409
	01-09-13	15:38	16:28	75	37	EDI	61	48	396	314
	03-20-13	15:33	16:09	48	25	EDI	36	31	149	131
	05-08-13	12:46	13:23	107	17	EDI	51	19	472	176
	07-02-13	14:52	15:40	76	8	EDI	26	11	170	72
	08-30-13	15:59	16:15	29	11	EDI	16	11	40	27
	09-06-13	16:30	16:46	19	11	EDI	14	12	23	19
	09-30-13	15:03	15:18	106	93	EDI	122	29	1,122	262
	03-06-14	10:13	10:43	128	280	EDI	273	140	3,007	1,548
	10-22-14	14:12	15:26	108	198	EWI	323	211	2,999	1,963
	12-10-14	14:15	14:55	90	–	EWI	61	33	472	255
	01-05-15	10:29	11:19	131	–	EWI	556	266	6,280	3,010
	02-06-15	14:08	14:36	215	–	EDI	644	231	11,935	4,292
Sauk River at Darrington, 12187500	01-10-12	12:00	12:05	66	4	Grab	5	–	29	–
	01-31-12	9:46	10:48	112	5	EWI	9	6	87	59
	02-22-12	13:15	14:06	151	31	EWI	49	36	638	474
	05-22-12	10:00	11:00	190	27	EWI	94	46	1,541	748
	06-18-12	14:06	15:00	151	47	EWI	113	41	1,471	538
	07-10-12	15:15	16:15	157	47	EWI	117	74	1,582	1,010
	08-17-12	13:56	14:57	35	7	EWI	14	7	41	23
	10-15-12	14:03	14:56	86	21	EWI	76	26	565	192
	10-31-12	13:05	14:10	220	31	EWI	224	44	4,264	831
	01-09-13	14:57	15:56	172	29	EWI	87	40	1,285	599
	05-08-13	15:15	16:05	185	16	EWI	62	20	992	323
	07-02-13	15:09	16:22	144	25	EWI	80	49	996	611
	08-30-13	14:35	15:19	61	47	EWI	84	72	440	378
	09-06-13	14:48	15:36	44	130	EWI	172	165	646	620
	09-30-13	16:17	16:44	208	23	EWI	104	34	1,870	616
	03-06-13	11:30	12:08	306	70	EWI	260	121	6,884	3,201
	07-17-14	14:00	14:45	67	12	EWI	25	15	145	88
	08-13-14	12:20	13:05	78	330	EWI	677	644	4,552	4,331
	10-22-14	16:58	17:15	225	125	MV	567	210	11,034	4,094
	11-28-14	12:04	12:56	801	370	EDI	1,360	641	94,174	44,392

Table 4. Sample data for suspended-sediment concentrations collected at U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, 2011–16.—Continued

USGS streamgage name and No.	Date	Start time	End time	Discharge (m^3/s)	Turbidity (FNU)	Sampling method	SSC (mg/L)	SSC_f (mg/L)	SSL (t/d)	SSL_f (t/d)
Sauk River near Sauk, 12189500	09-21-11	12:37	13:01	45.6	–	EDI	11	9	41	35
	11-23-11	12:07	13:03	595	172	EWI	1,480	320	76,148	16,462
	05-22-12	15:20	16:11	363	25	EWI	189	39	5,906	1,222
	06-18-12	11:33	12:48	459	86	EWI	483	114	19,151	4,539
	07-10-12	10:35	11:45	405	118	EWI	523	199	18,288	6,982
	08-17-12	11:51	12:52	104	24	EWI	44	34	395	306
	10-04-12	14:47	15:09	30.9	15	EDI	26	22	68	60
	10-15-12	11:33	12:48	203	117	EWI	343	214	6,019	3,760
	10-31-12	10:27	11:33	470	75	EWI	574	144	23,322	5,830
	01-09-13	13:00	13:58	374	50	EWI	348	69	11,243	2,245
	03-13-13	14:28	15:17	238	21	EWI	112	27	2,300	561
	05-08-13	12:45	13:50	351	31	EWI	274	51	8,316	1,537
	07-02-13	11:10	12:36	337	72	EWI	236	111	6,874	3,235
	08-30-13	12:43	14:00	148	292	EWI	727	611	9,324	7,838
	09-05-13	15:19	15:54	59.8	98	EWI	318	223	1,640	1,154
	09-06-13	12:35	13:39	131	1,820	EWI	3,615	3,108	40,966	35,225
	09-30-13	10:32	11:29	363	62	EWI	669	127	20,959	3,982
	03-06-14	13:22	14:42	513	110	EWI	777	193	34,400	8,531
	07-17-14	11:13	12:30	188	36	EWI	79	57	1,280	922
	07-21-14	15:25	16:15	132	108	MV	383	301	4,378	3,438
	07-24-14	12:15	13:00	206	83	EWI	504	227	8,956	4,028
	08-05-14	11:41	12:42	96.9	415	EWI	1,305	1,024	10,924	8,575
	08-13-14	14:12	15:30	164	1,415	EWI	4,320	2,894	61,221	41,018
	11-28-14	14:40	15:32	1,142	572	MV	2,880	922	284,077	90,905
	08-14-15	13:50	14:58	37.7	1,480	EWI	2,485	2,410	8,089	7,847
	01-28-16	13:15	14:27	748	405	EWI	2,690	672	173,847	42,430
	09-29-16	13:34	14:22	32.6	14	EWI	15	13	42	38

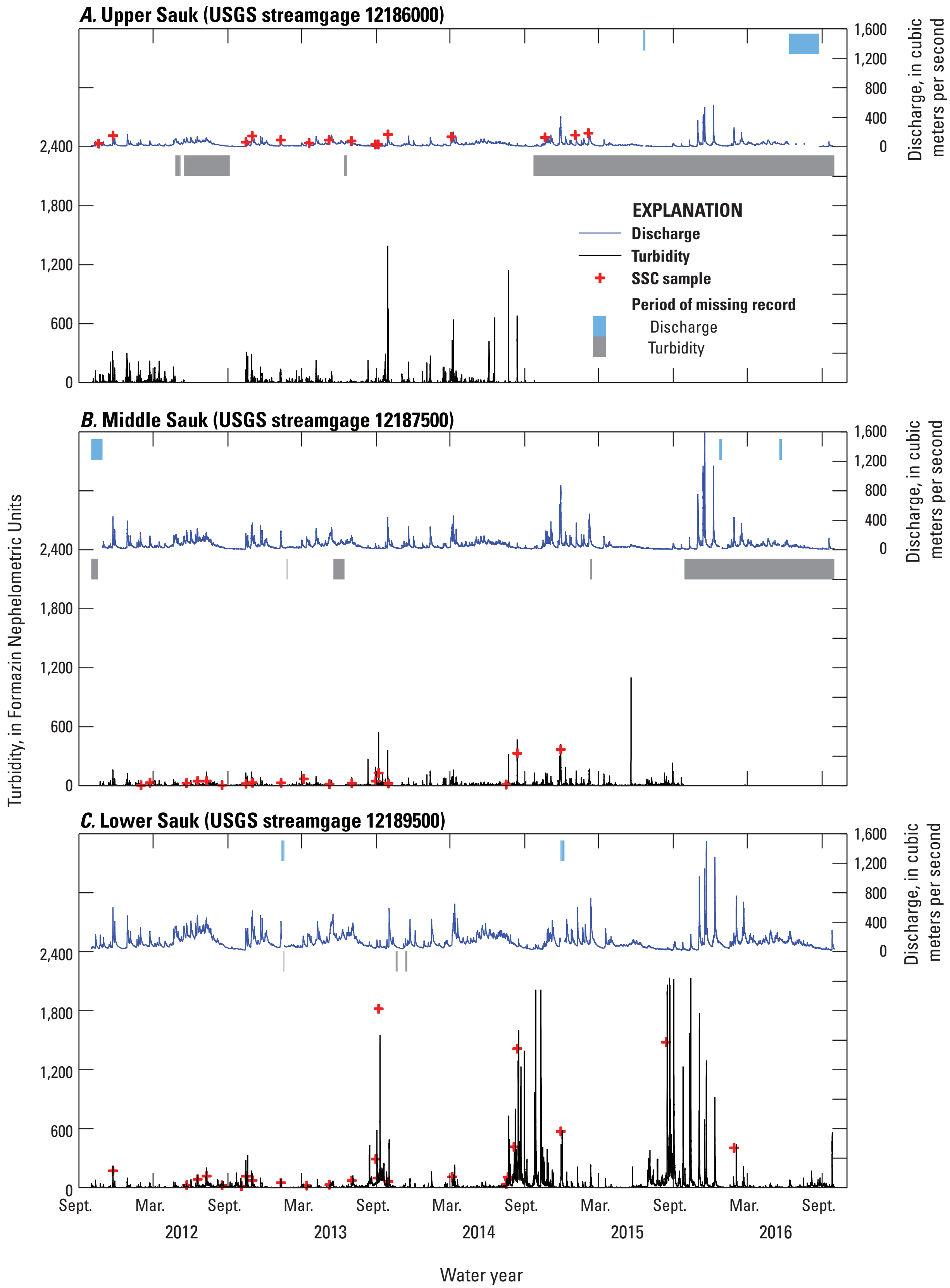


Figure 9. Discharge, turbidity, and suspended-sediment concentration sampling periods at U.S. Geological Survey streamgages on the Sauk River, western Washington, water years 2012–16. Samples of suspended-sediment concentrations are plotted as the concurrent turbidity or discharge value they were paired with in the development of regression models. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Table 5. Summary of continuous (15-minute) turbidity data measured at U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, 2011–16.

[Locations of streamgages are shown in figure 1 and descriptive information is shown in table 2. **Percent utilization**: A ratio of the number of valid recorded values to the total number of possible 15-minute values during the sensor deployment period.]

USGS streamgage name and No.	Period of turbidity sensor deployment	Number of valid 15-minute values	Percent utilization	Turbidity, in Formazin Nephelometric Units		
				Range	Median	Mean
Sauk River above White Chuck River, near Darrington, 12186000	Oct. 1, 2011–Sept. 30, 2015	125,105	89.2	0.1–2,190	4.1	24.5
Sauk River near Darrington, 12187500	Oct. 20, 2011–Sept. 30, 2015	135,225	97.7	0.3–1,330	4.9	12
Sauk River near Sauk, 12189500	Oct. 1, 2011–Sept. 30, 2016	174,256	99.3	0.5–2,130	7.0	29

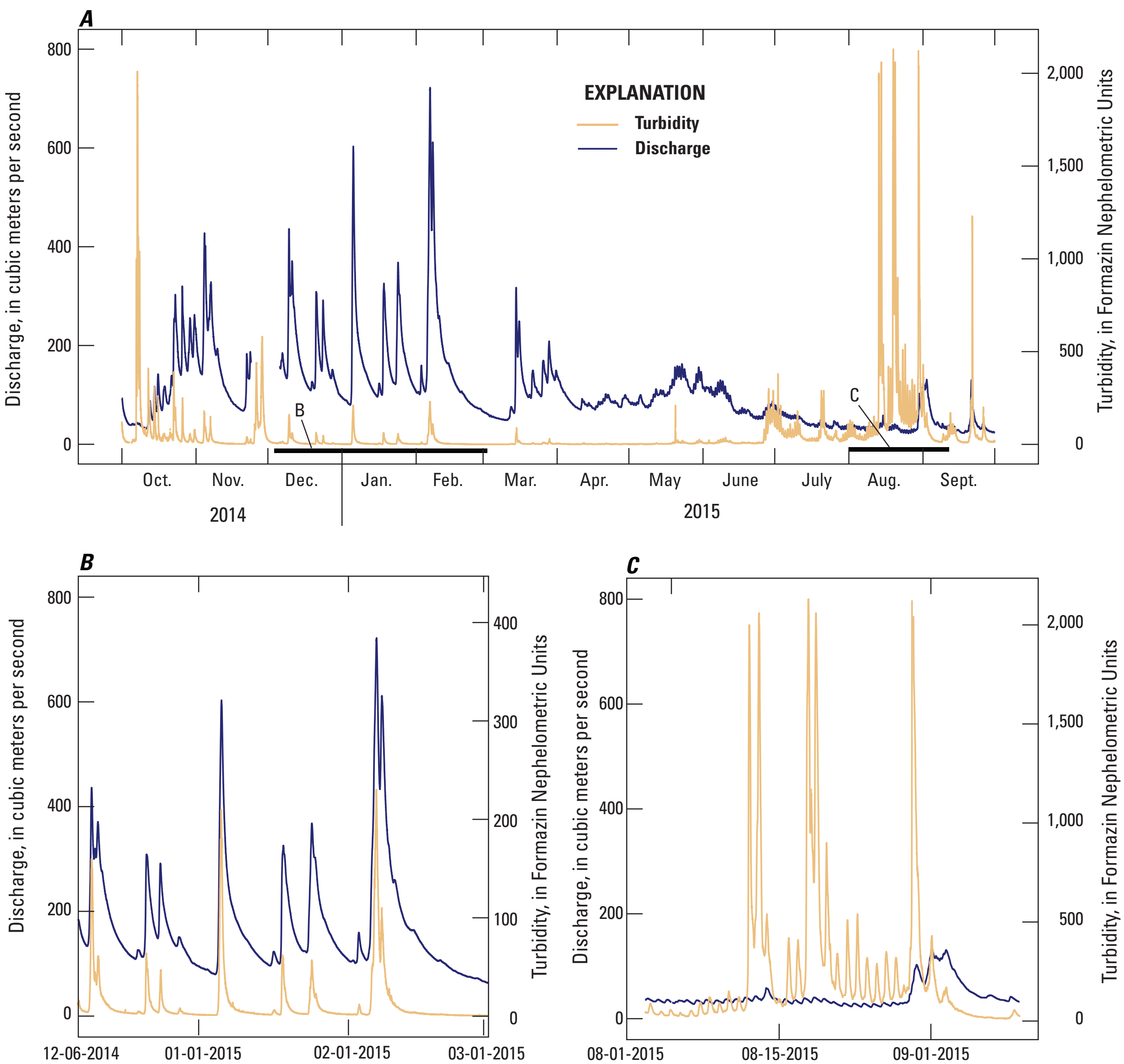


Figure 10. Discharge and turbidity (15-minute interval) at the U.S. Geological Survey streamgage Sauk River near Sauk (Lower Sauk,12189500), western Washington. (*A*), water year 2015; (*B*), December 2014–February 2015 to illustrate fall-winter storm turbidity values; and (*C*), August–early September 2015 to illustrate summer glacial melt processes. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

These first-flush events may correspond to residual glacial flour and fines built up throughout the catchment as summer base-flow conditions develop that are mobilized during small discharge events. Late-summer residual fines, once flushed, are depleted, and subsequent increases in discharge magnitudes do not result in corresponding increases in turbidity values. The temporary supply-limited condition for fines ends in the fall and the onset of larger magnitude discharge events.

The turbidity patterns observed during the summer glacial melt period may reflect hydrogeomorphic conditions occurring elsewhere in the basin that include landslides, slope failures, and debris flows, which can markedly elevate turbidity values. Although episodic pulses and first flush phenomenon were present in most years during the study, the magnitude of turbidity values for these events were highest during summer 2015 (fig. 9).

Turbidity as a Surrogate for Suspended-Sediment Concentration

Prior to developing regression models for estimating SSC, simple scatterplots of SSC versus turbidity and discharge were used to assess the strength of correlations between variables (fig. 11). A comparison of the SSC of samples relative to turbidity and discharge conditions at the time of sample collection (fig. 11 *A*–*D*) indicates that, whereas SSC and SSC_f were well-correlated with turbidity for all sites (Pearson's r >0.86), correlations for SSC and SSC_f with discharge were weaker at all sites (r = 0.13–0.79). Correlation was poor to modest (Pearson's r <0.001–0.47) between SSC and water temperature (fig. 11*E*), and correlations between SSC_f and water temperature were similar (Pearson's r 0.16–0.51; fig. 11*F*).

At each site, a series of regression equations was developed for estimating SSC and SSC_f from either turbidity or discharge, or both (table 6). Linear-versus log-models and single versus multiple explanatory variables were determined following the model selection methods described by Rasmussen and others (2009), wherein regression statistics such as the coefficient of determination (R^2), adjusted coefficient of determination (*adjR²*; which adjusts for the number of variables used in the model), and the Model Standard Percentage Error (*MSPE*; an expression of the root-mean square error as a percentage) are examined, and both residual and normal quantile plots are considered. In all cases, the log-transformation of variables improved regression models (*adjR²* increased and the MSPE was lower), and models for estimating SSC at both Middle Sauk and Lower Sauk were improved when both discharge and turbidity were used as explanatory variables. At Upper Sauk, because the turbidity record had extensive gaps during deployment caused by sensor burial, discharge was used as the only explanatory variable in the regression for estimating both SSC and SSC_f. Similarly, because turbidity was discontinued at Middle Sauk at the end of WY 2015, the daily suspended-sediment load (SSL) for WY 2016 was estimated from the daily mean discharge using a regression equation developed based on daily SSL and discharge determined for WYs 2012–15.

Table 6. Models used to estimate suspended-sediment concentration from turbidity and discharge at U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, 2011–16.

[Locations of streamgages are shown in figure 1 and descriptive information is shown in table 2. ***bcf***, bias correction factor; *n*, number of observations; $_{adj}R^2$, adjusted coefficient of determination; ***% MSPE***, model standard percentage error; *SSC*, suspended-sediment concentration, in milligrams per liter; SSC_f, fine portion of suspended-sediment concentration less than 0.0625 mm, in milligrams per liter; *Tu*, turbidity, in Formazin Nephelometric Units; *Q*, discharge, in cubic meters per second; *SSL*, suspended-sediment load (not applicable during periods of intense glacier melting or discharge greater than 300 m³/s), in tons per day. <, less than]

USGS streamgage and sediment monitoring site and No.	Abbreviated streamgage name	Model No.	Model	bcf	n	$_{adj}R^2$	p-value	% MSPE, lower	% MSPE, upper
Sauk River above White Chuck River, near Darrington, 12186000	Upper Sauk	1.1	$SSC=0.0276Q^{1.77}\ bcf$	1.27	21	0.81	< 0.001	-52	109
		1.2	$SSC_f=0.0343Q^{1.58}\ bcf$	1.37	21	0.70	< 0.001	-58	138
		1.3	$SSC=2.21Tu^{0.905}\ bcf$	1.06	14	0.94	< 0.001	-29	41
		1.4	$SSC_f=1.61Tu^{0.839}\ bcf$	1.06	14	0.92	< 0.001	-32	46
Sauk River near Darrington, 12187500	Middle Sauk	2.1	$SSC=0.35Tu^{0.968}Q^{0.442}\ bcf$	1.06	20	0.93	< 0.001 (*Tu*) 0.0021 (*Q*)	-30	43
		2.2	$SSC_f=1.07Tu^{1.08}\ bcf$	1.01	20	0.98	< 0.001	-16	20
		2.3	$SSC=2.06Tu^{1.08}\ bcf$	1.10	20	0.89	< 0.001	-37	58
		2.4	$SSL_{daily}=7.57 \times 10^{-5}Q_{daily}^{3.22}\ bcf$	1.25	368	0.74	< 0.001	-41	105
Sauk River near Sauk, 12189500	Lower Sauk	3.1	$SSC= 0.323Tu^{0.928}Q^{0.533}\ bcf$	1.06	26	0.94	< 0.001 (*Tu,Q*)	-30	44
		3.2	$SSC_f=1.23Tu^{1.07}\ bcf$	1.02	26	0.98	< 0.001	-20	25
		3.3	$SSC=4.77Tu^{0.962}\ bcf$	1.18	26	0.82	< 0.001	-46	87
		3.4	$SSL_{daily} = 0.0034Q_{daily}^{2.35}\ bcf$	1.67	366	0.73	<0.001	-61	155

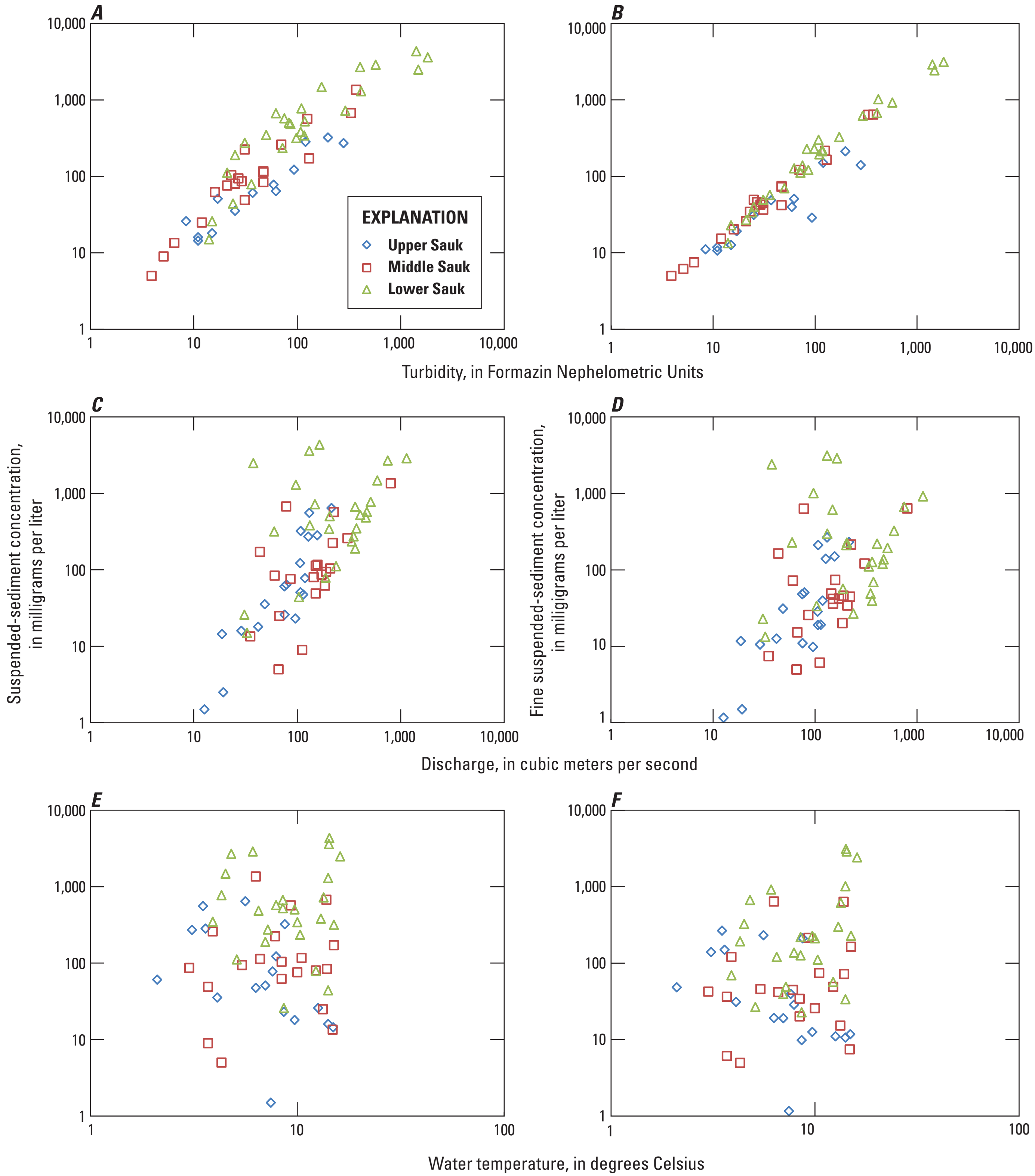


Figure 11. Suspended-sediment concentration and turbidity (*A* and *B*), suspended-sediment concentration and discharge (*C* and *D*), suspended-sediment concentration and water temperature (*E* and *F*) for the three streamgages on the Sauk River, western Washington. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

The most basic regression model (model numbers 1.3, 2.3, and 3.3 in table 6) for estimating SSC from turbidity at the three streamgages was used to identify periods during which turbidity conditions could affect Chinook salmon during specific life stages.

Suspended-Sediment Load Estimates

Cumulative SSL values partitioned by sand and fines at each of the three streamgages are shown in figure 12.

The cumulative SSL computed for Upper and Middle Sauk for the 5-year monitoring period is 471,000 t (±126,000 t) and 1,010,000 t (±140,000), respectively. Mean annual SSL for Upper and Middle Sauk were 94,000 t (±25,000 t) and 202,000 t (±28,000 t), respectively (table 7). The cumulative SSL for Lower Sauk is substantially higher at 4,700,000 t (±632,000 t), with a mean annual SSL of 940,000 t (±126,000 t). As a percentage of total SSL, fine (<0.625 mm) SSL averaged 53 percent at Upper Sauk, 42 percent at Middle Sauk (for WYs 2012–15), and 34 percent at Lower Sauk.

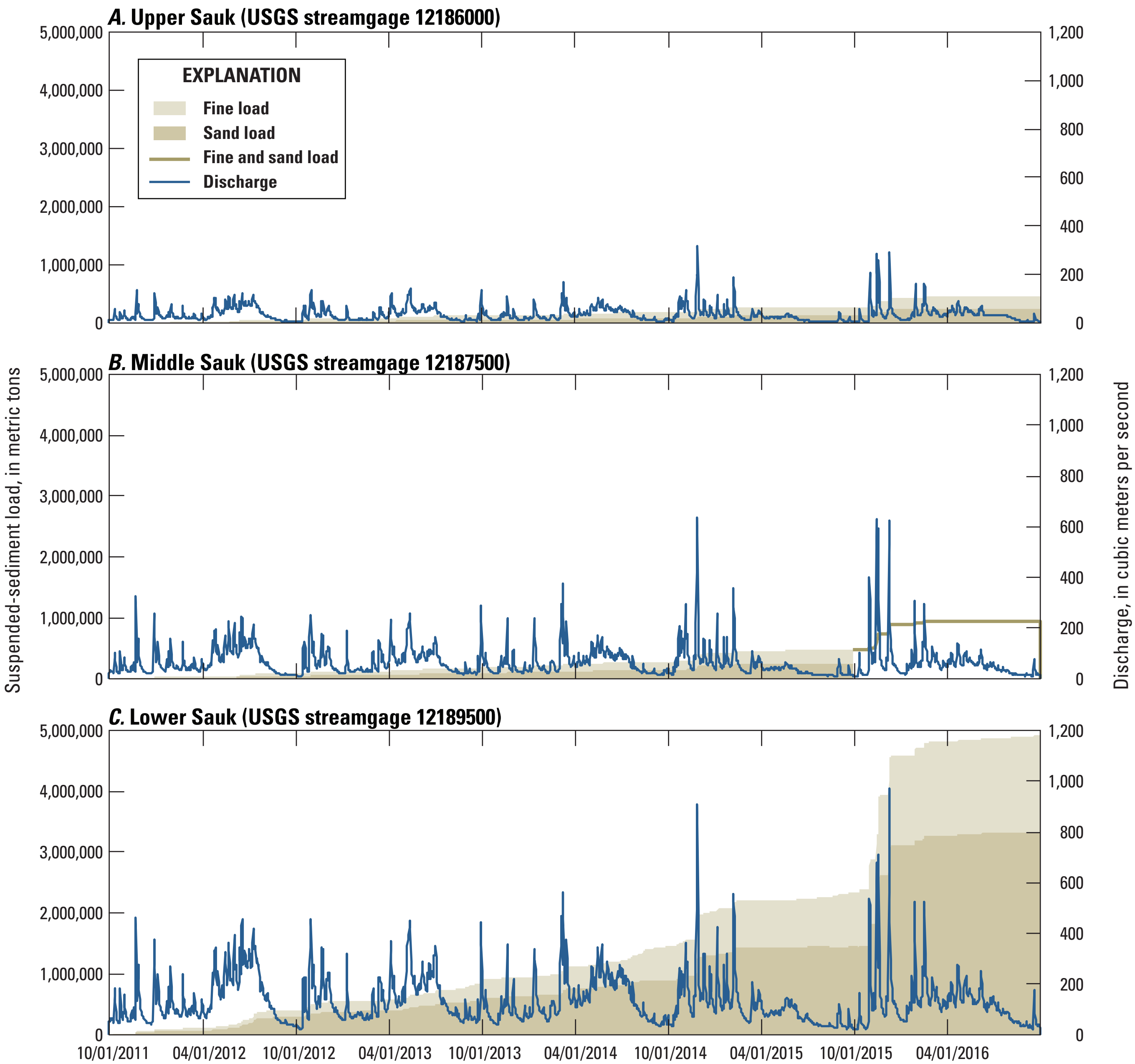


Figure 12. Daily discharge and cumulative suspended-sediment loads at U.S. Geological Survey (USGS) streamgages on the Sauk River western Washington, water years 2012–16. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Table 7. Annual suspended-sediment load estimates for the three streamgages on the Sauk River, water years 2012–16, and mean suspended-sediment annual load computed over the period of record for each streamgage, western Washington.

[All values are in metric tons. Locations of streamgages are shown in figure 1 and descriptive information is shown in table 2]

Abbreviated streamgage name	Annual load estimates for each water year					Mean annual load for period of record
	2012	2013	2014	2015	2016	
Upper Sauk	65,500 (±13,000)	65,500 (±13,000)	50,300 (±10,000)	94,100 (±27,000)	196,000 (±70,000)	94,200 (±25,200)
Middle Sauk	96,300 (±11,500)	116,000 (±13,000)	88,900 (±9,860)	246,000 (±47,000)	469,000 (±64,000)	203,000 (±28,000)
Lower Sauk	404,000 (±52,000)	500,000 (±52,000)	525,000 (±51,000)	719,000 (±82,000)	2,550,000 (±470,000)	940,000 (±126,000)

The median daily SSL for the three streamgages was 27 t at Upper Sauk, 34 t at Middle Sauk, and 242 t at Lower Sauk. The maximum daily SSL for the three streamgages was 30,200 t at Upper Sauk, 98,600 t at Middle Sauk, and 415,000 t at Lower Sauk. Maximum SSL were associated with a series of high discharge events in November 2015. Maximum SSL at Upper and Lower Sauk both occurred on November 17, 2015, during which peak discharge for that day was 357 m^3/s at Upper Sauk and 1,495 m^3/s at Lower Sauk. Maximum SSL at Middle Sauk occurred a few days prior on November 13, 2015, when peak discharge was 756 m^3/s.

Variability in Suspended-Sediment Loads

Suspended-sediment loads in the Sauk River Basin exhibit clear seasonal trends and substantial inter-annual variability that strongly reflect the variability in discharge conditions and the relative importance of individual precipitation events and the timing of snow melt conditions among the three streamgages (figs. 12 and 13). Suspended-sediment loads tend to be largest during fall (September–December) and to correspond to intense or long-duration rain events that generate high discharge. Fall SSL, on average, accounts for more than one-half of the total annual suspended-sediment load at all three streamgages (55 percent at Upper Sauk, 68 percent at Middle Sauk, and 62 percent at Lower Sauk). The spring snowmelt period contributes on average 23 percent of the total SSL at Upper Sauk. In contrast, average seasonal SSL at Lower Sauk tended to be smallest during spring, accounting on average for 9 percent of the total annual SSL. Summer suspended-sediment loads tend to be smallest at Upper and Middle Sauk (6 and 7 percent, respectively). Average summer SSL are approximately the same as winter SSL (16 and 14 percent, respectively) at Lower Sauk, and is attributed to the relatively high SSL in the Suiattle River that are associated with the summer glacial melt season during summer base flows.

Suspended-sediment loads are highly variable from year to year and appear to largely be driven by atmospheric rivers and other fall and early winter precipitation events that cause high discharge. Water years 2012–14 collectively account for only approximately one-third of the total 5-year load at all three streamgages (39 percent at Upper Sauk, 29 percent at Middle Sauk, and 30 percent at Lower Sauk). However, WY 2016 accounted for a substantially larger percentage of the total 5-year load (41 percent at Upper Sauk, 47 percent at Middle Sauk, and 54 percent at Lower Sauk). Lower SSL in the Sauk River Basin over the first 3 years of the study is attributed to the fact that WYs 2012–14 were relatively unremarkable water years, particularly at Lower Sauk at which no peak flows exceeded the 1-year RI (256 m^3/s). In contrast, WY 2016 was characterized by a series of four fall precipitation events that resulted in SSL that was two times the next highest fall SSL for the study period at Upper and Middle Sauk and almost four times the next highest fall SSL for the study period at Lower Sauk. Each individual event, which occurred over a 4–6 day period, generated 18–28 percent of the WY 2016 fall SSL and collectively generated 95 percent of fall WY 2016 SSL. The high SSL generated during fall WY 2016 demonstrates that a substantial amount of the fall load can be generated from a single precipitation event (fig. 12) and that consecutive events in the same season cumulatively drives variability between years (figs. 12 and 13).

Spring and summer SSL were less than average in WY 2015, particularly at Upper Sauk, which experienced SSL that was 9 and 6 percent of the mean SSL for the spring and summer, respectively. Water year 2015 experienced a regional drought that resulted in low snowpack and summer precipitation. Suspended-sediment loads during spring and summer were also lower than the mean for spring and summer at Middle Sauk for WY 2015 (23 and 29 percent, respectively) and for spring at Lower Sauk (30 percent). However, summer SSL at Lower Sauk was less reduced at 63 percent of the mean SSL for this season, even though mean daily discharge for this season was 46 percent of the average for the 5-year study period. Higher SSL for summer 2015 compared to the upstream monitoring locations in the Sauk River main stem may reflect increased availability of suspended sediment delivered from the Suiattle River.

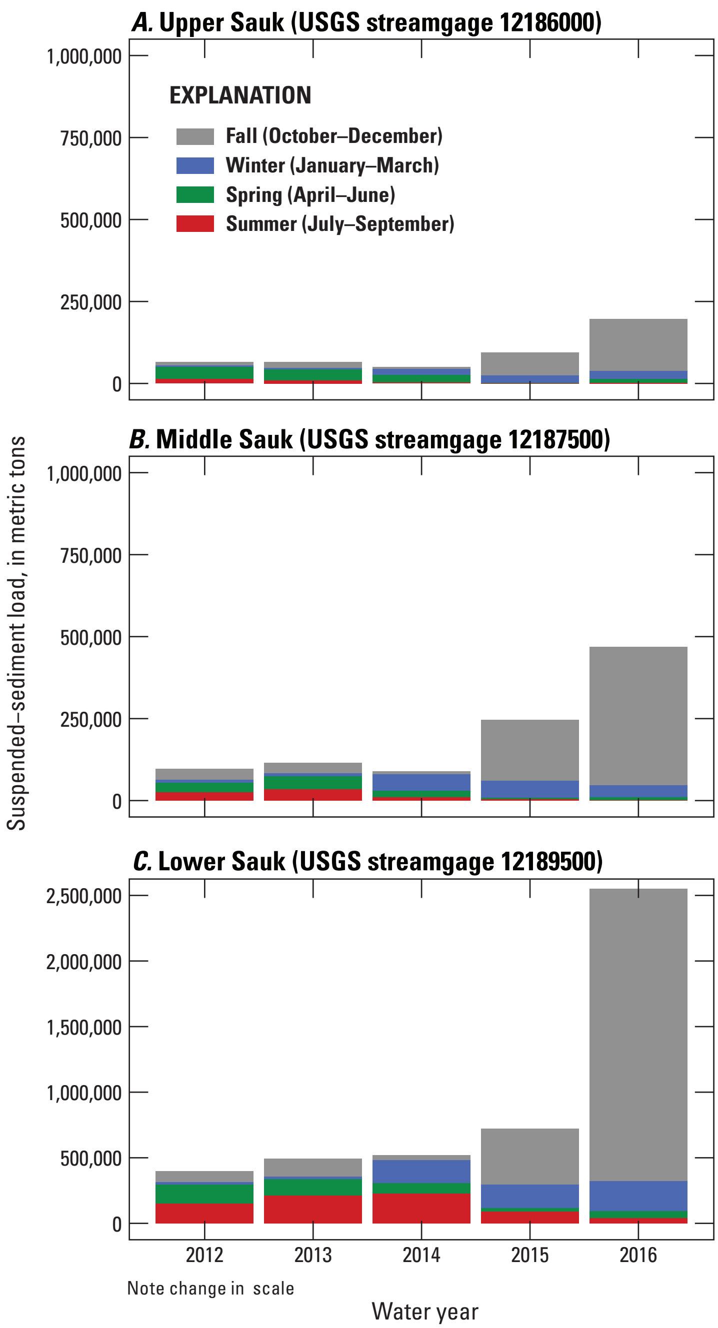


Figure 13. Suspended-sediment load by season at U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, water years 2012–16. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Variability in Sand Versus Fine Load

The relative contribution of sand (0.0625–2 mm) and fines (< 0.0625 mm) to the total SSL varies seasonally and inter-annually depending on the monitoring location (fig. 14). At Upper Sauk, the proportion of fine sediment did not vary substantially among seasons, ranging from 48 to 59 percent (fig. 14*A* inset). In contrast, the fine sediment load at the Lower Sauk was relatively large for summer, accounting for 56 percent of the SSL, but was only about 30 percent of the SSL in fall, winter, and spring (fig. 14*B* inset). Over the 5-year study period, the proportional contribution of fines to the seasonal SSL at Upper Sauk generally remained consistent between seasons and from year-to-year with a mean of 60 percent. Exceptions occurred in WY 2015 spring and summer and WY 2016 summer, during which the seasonal SSL was very low, but the contribution of fine sediment was 71 to 73 percent. At Lower Sauk, the proportional contribution of fine sediment to the year-to-year seasonal SSL was generally consistent for fall and winter, but was more variable for spring and summer SSL during the 5-year study period (fig. 14*B*). Particularly, summer 2015 SSL, which corresponds to the regional drought period, was estimated to be entirely composed of fine sediment.

At all three streamgages, the fraction of sand-sized material in suspension increased with discharge up to about three times the mean annual discharge, but appeared to plateau at around 60–80 percent sand for discharges higher than three times the mean annual discharge (fig. 15). This relation generally indicates that the transport of sand in suspension is limited by transport capacity at low flows, but is increasingly entrained with higher discharges. The sand fraction in high-discharge SSC samples, between 60 and 80 percent, is similar to the sand-fraction of the cumulative SSL over the 5 years of study (51, 58, and 67 percent for the Upper, Middle, and Lower Sauk, respectively), and may indicate the background abundance of the two size classes in the active channel.

At Lower Sauk, the relation between percent sand and discharge appears to separate by season. Samples collected in the summer show a linear increase in percent sand with increasing discharge, while samples collected in the late fall through spring had a consistent sand fraction of between 70 and 80 percent. For the limited number of samples collected at discharges between two and four times the mean annual discharge, the summer samples generally had a lower percent sand than the other seasons' samples. SSC samples collected in the early fall appear to straddle these two populations.

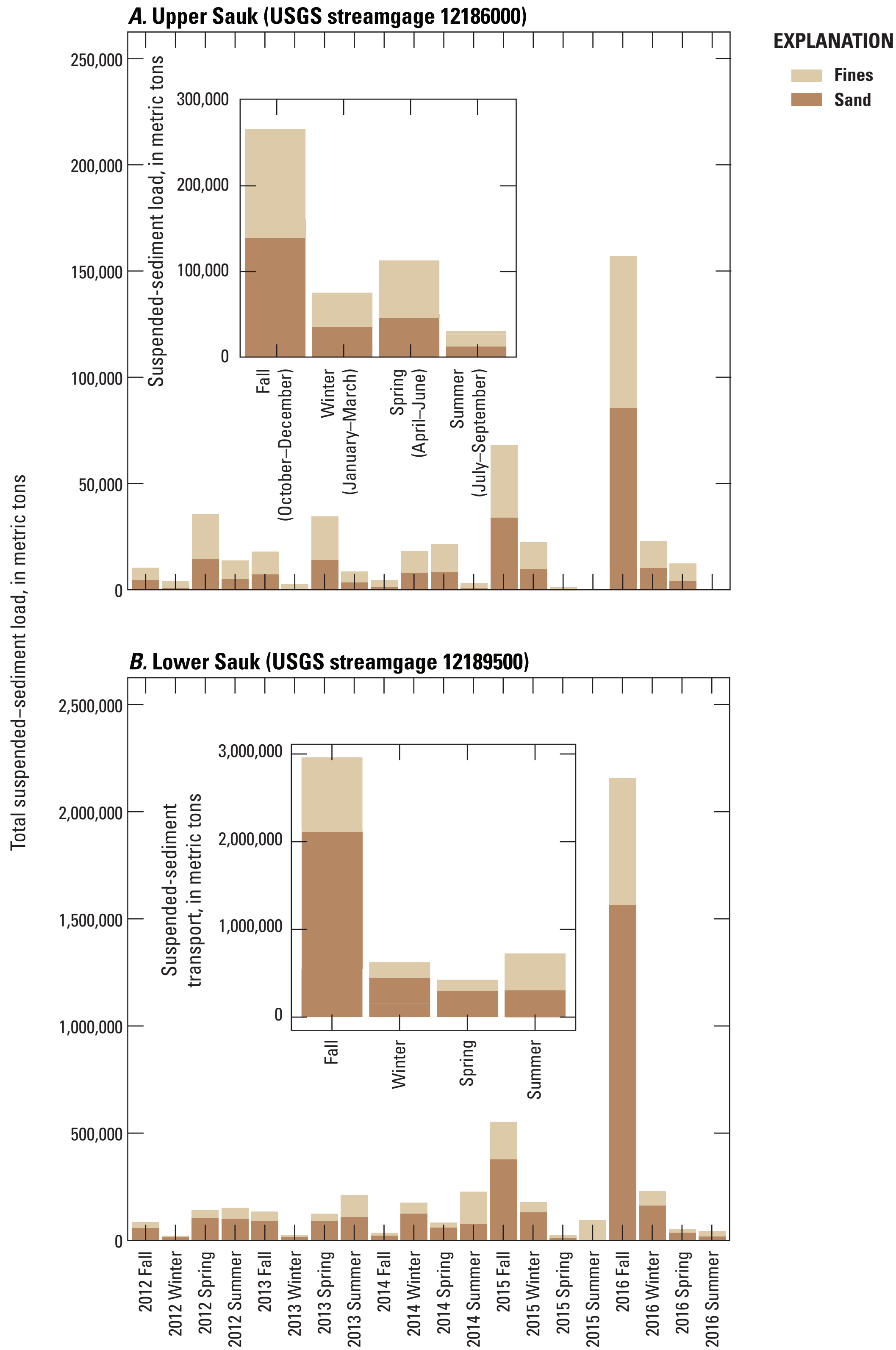


Figure 14. Suspended-sediment load partitioned by fines (<0.0625 millimeter [mm]) and sand (0.0625–2 mm) summed by season for two U.S. Geological Survey streamgages on the Sauk River western Washington, water years 2012–16. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

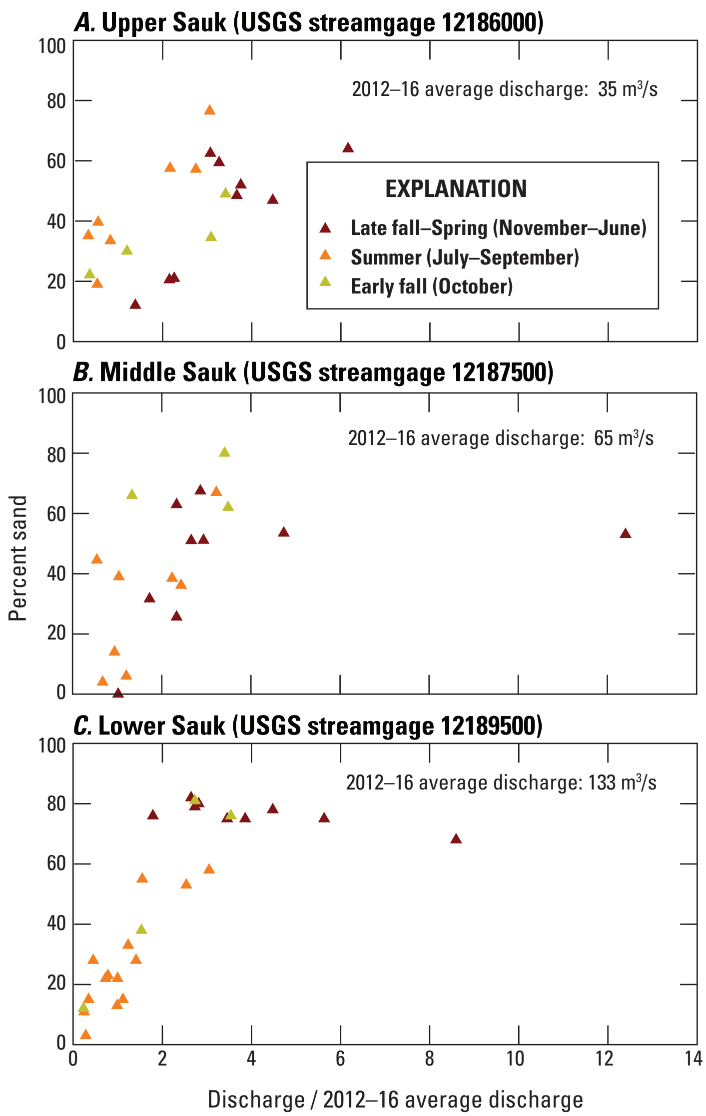


Figure 15. Suspended-sediment concentration measurements plotted as percent sand versus discharge at the time of measurement at the three U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, water years 2012–16. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Given that this seasonal separation was not apparent at the other sites, this may be an artifact of inherent noise and a limited number of samples. Alternately, this separation may indicate that the abundant but finite fine-sediment supply in the lower river becomes seasonally exhausted, as glacier sediment production shuts off in the early fall and the accumulated fine material in the channel is rapidly exported out of the basin. Under this scenario, the fraction of sand in suspension may stay relatively consistent over the late fall, winter, and spring regardless of discharge. More SSC samples made at low discharges outside of the glacial melt period would be needed to determine if the observed separation is physically meaningful or is an artifact.

Water Temperature in the Sauk River Basin

Water temperature was measured continuously and concurrently with turbidity using the DTS-12 turbidity sensor at the three USGS streamgages on the Sauk River for WYs 2012–16 (fig. 16). Periods of missing water temperature data are concurrent with missing periods of the turbidity data (fig. 9), with the exception of the period of November 6, 2014, to September 30, 2015, at Upper Sauk, which corresponds to when sediment deposition in and around the sensor housing that affected the turbidity data during this period. However, inspection of the temperature data indicated that sediment deposition did not appear to affect the temperature data (fig. 16). Temperature data at all three streamgages had more than 96 percent utilization (table 8). Manufacturer confirmation that the DTS-12 temperature was within ± 0.2 °C occurred on average within 9 months (standard deviation 11 months) pre- and post-deployment of each sensor during annual calibration checks. Seven out of a total of 25 DTS-12 sensor deployments had manufacturer confirmation dates in excess of 1 year; however, in all cases, pre- and post-deployment manufacturer checks confirmed DTS-12 temperatures to be within ± 0.2 °C. Manufacturer checks are for a single point using a NIST-certified thermistor versus a multi-point calibration approach. Therefore, as a conservative measure, the temperature uncertainty is increased to ±0.5 °C from the ±0.2 °C accuracy typically associated with DTS-12 thermistors. Water temperature data are available in Curran and others (2017).

Water temperature in the Sauk River over the 5-year monitoring period exhibited characteristic seasonal and downstream trends. Mean monthly temperatures were at a maximum in August (14.4 °C at Upper Sauk, 14.9 °C at Middle Sauk, and 15.1 °C at Lower Sauk) and minimum in January (3.3 °C at Upper Sauk, 3.6 °C at Middle Sauk, and 4.0 °C at Lower Sauk). Maximum monthly temperatures were highest in August at Upper and Middle Sauk (21 °C and 20.9 °C, respectively) and in July at Lower Sauk (20.8 °C); average daily maximum temperatures did not increase in the downstream direction.

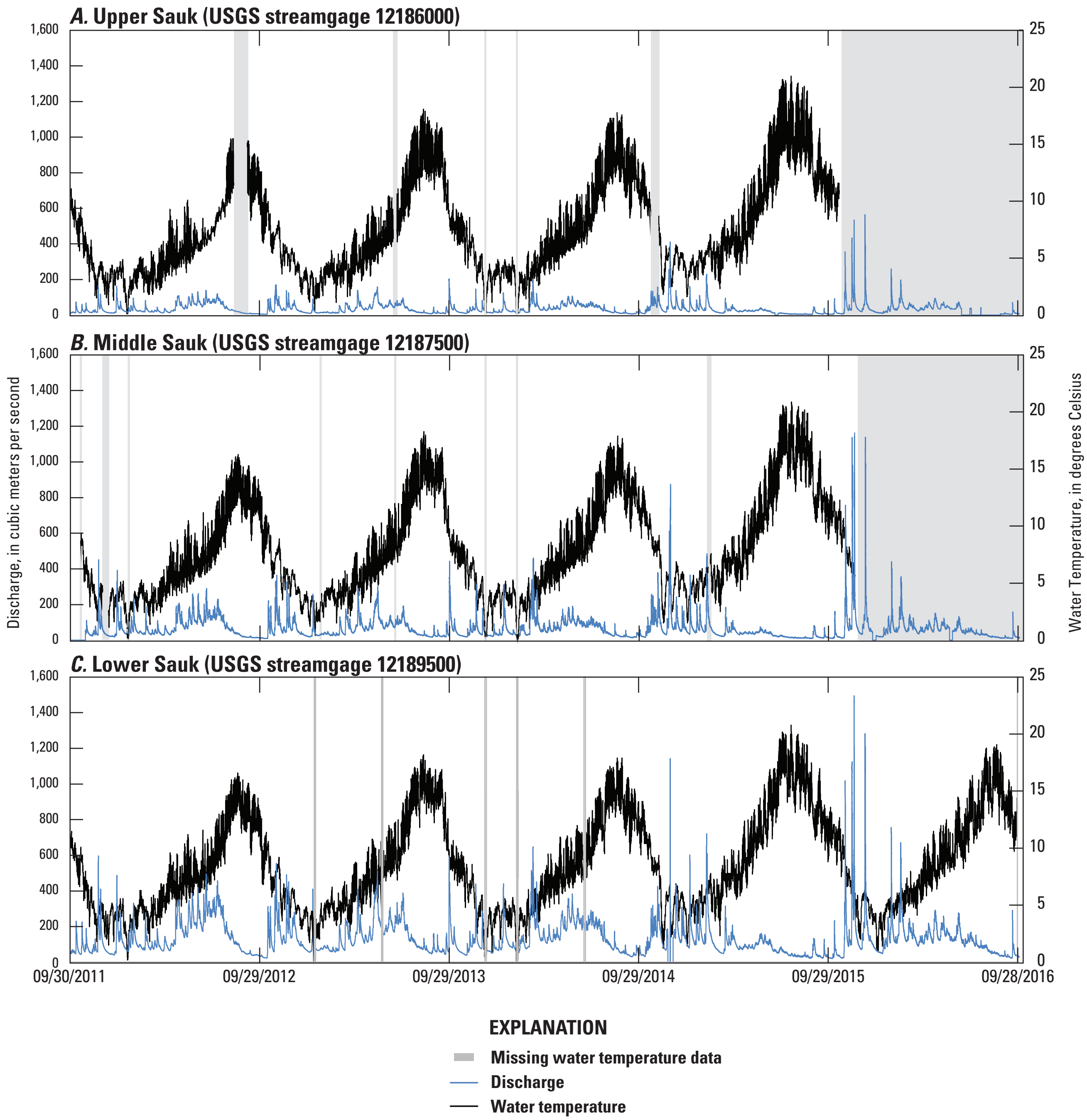


Figure 16. Water temperature and discharge data (15 minute) recorded by DTS-12 turbidity sensors at U.S. Geological Survey streamgages on the Sauk River, western Washington, water years 2012–16. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Table 8. Continuous (15-minute) water temperature data collected at U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, 2011–16.

[Locations of streamgages are shown in figure 1 and descriptive information is shown in table 2. **Percent utilization**: A ratio of the number of valid recorded values to the total number of possible 15-minute values during the sensor deployment period]

Streamgage name and No.	Abbreviated streamgage name	Period of thermistor deployment	Number of valid 15-minute values	Percent utilization	Water temperature (degrees Celsius)		
					Range	Median	Average
Sauk River above White Chuck River, near Darrington, 12186000	Upper Sauk	Oct. 1, 2011–Sept. 30, 2015	135,427	96.6	0.1–21.0	6.3	7.4
Sauk River near Darrington, 12187500	Middle Sauk	Oct. 20, 2011–Sept. 30, 2015	144,911	98.3	0.1–20.9	7	8
Sauk River near Sauk, 12189500	Lower Sauk	Oct. 1, 2011–Sept. 30, 2016	174,046	99.2	0.1–20.8	7.7	8.5

Suspended-Sediment Budget for the Sauk River Basin

The records of SSL at various locations in the Sauk River Basin were used to construct a basin-scale sediment budget using a mass balance approach that allowed for estimation of suspended-sediment production and subsequent SSL from different sources within the basin. The location of the streamgages was selected so that the mass imbalance between streamgages could be used to estimate the suspended-sediment input from the two major tributaries (fig. 17); the difference in the SSL between Upper and Middle Sauk is a proxy for the SSL from the White Chuck River, and the difference between the Middle and Lower Sauk is a proxy for the SSL for the Suiattle River. The White Chuck River Basin (222 km^2) accounts for 61 percent of the difference in drainage area between Middle and Upper Sauk. The Suiattle River basin (891 km^2) is 82 percent of the drainage area difference between Lower and Middle Sauk. These estimates of SSL indicate that the Suiattle River is the predominant source of suspended sediment to the Lower Sauk, accounting for an average of about 80 percent of the annual load for the entire basin (fig. 17). The remaining load was split evenly between the inputs from the Upper Sauk River and White Chuck River Basins, both of which contributed about 10 percent of the SSL in any given year during the 5-year study.

Dividing SSL at each site by the corresponding drainage area provides the suspended-sediment yield (SSY), which is a metric for sediment production (table 9). Yields for the two major tributaries were estimated by dividing the inferred SSL by the difference in drainage area between the downstream and upstream streamgages, representing the drainage area that was unique to the more-downstream streamgage. The annual SSY over the entire Sauk River Basin ranged from 220 (t/km^2)/yr in WY 2012 to 1,370 (t/km^2)/yr in WY 2016, and averaged 510 (t/km^2)/yr over the 5-year study (table 9). These values are similar to average SSYs estimated for other major basins draining stratovolcanoes, including the Nooksack River [580 (t/km^2)/yr; Wise and others, 2007], the Puyallup River [350 (t/km^2)/yr; Czuba and others, 2012], and the lower Skagit River, which includes the Sauk River Basin [300 (t/km^2)/yr; Curran and others, 2016]. Average SSYs in the White Chuck River and Upper Sauk River Basins were 300 and 240 (t/km^2)/yr, respectively, while average SSY in the Suiattle River Basin was about 680 (t/km^2)/yr (table 9).

The substantial difference in average sediment production between the White Chuck River and Suiattle River Basins, which share similar geologies and valley-floor compositions, is likely related to the high sediment production from the eastern flank of Glacier Peak carried by the Suiattle River. Although the White Chuck River also drains glaciated terrain on Glacier Peak, a visual comparison of the pro-glacial areas feeding into the two basins shows that the White Chuck River source areas are generally more vegetated and do not appear as active as the east-facing basins draining into the Suiattle River (fig. 17). A rough estimate of the influence of those active, east-facing, pro-glacial areas was made by comparing the Suiattle River SSL estimated from the mass-balance to an estimated “background SSL rate,” which is defined here as the expected load if the basin was producing fine sediment at a rate of 270 (t/km^2)/yr, the average yield for Middle Sauk, which incorporates both the Upper Sauk River and White Chuck River Basins (table 9). The difference between the Suiattle River SSL and the estimated background SSL rate is then interpreted as a measure of how much extra suspended sediment can be attributed to the geomorphically active pro-glacial basins. The estimated background SSL rate in the Suiattle River Basin was about 290,000 t/yr over the 5 years of study. Therefore, about 450,000 t/yr, or about 60 percent, of the SSL from the Suiattle River is estimated to be attributable to the eastern flank of Glacier Peak (fig. 18). Sediment from the eastern flank of Glacier Peak may then contribute about 50 percent of the sediment load for the entire Sauk River Basin in any given year. Additional research that is outside the scope of this study is needed to determine if this additional sediment is continually produced on a year-to-year basis by erosion from sub-glacial and pro-glacial sediments, or if a history of mass failures and high sediment production over decades or millennia has made the entire system sediment-rich.

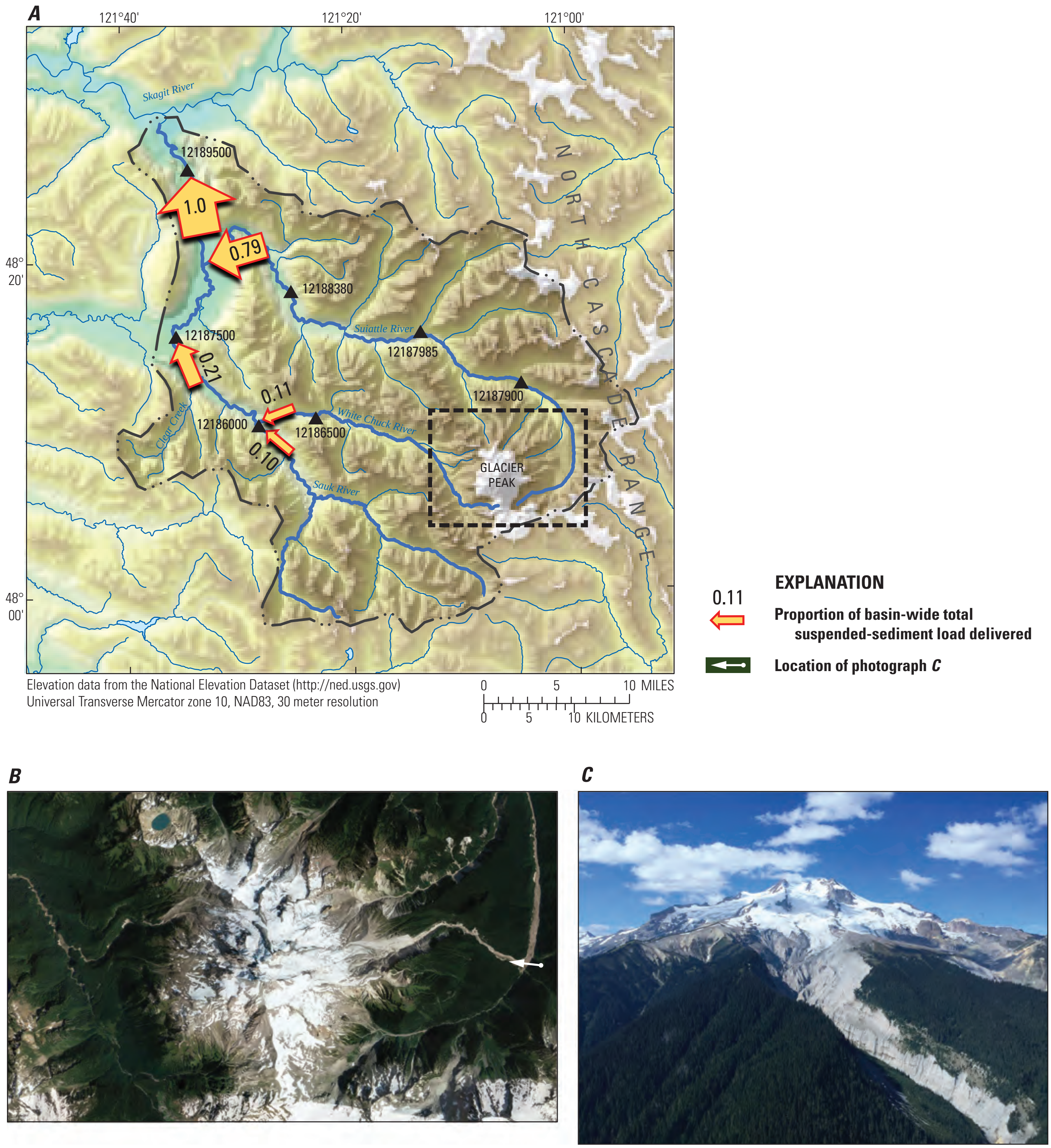
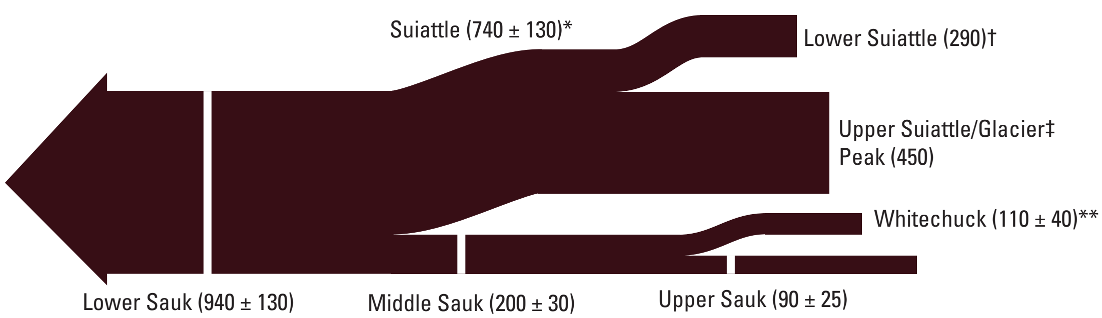


Figure 17. Suspended-sediment loads in Sauk River Basin (*A*); aerial imagery of Glacier Peak; the eastern flank is substantially more geomorphically active in appearance (*B*); and oblique image of Glacier Peak with the Chocolate Creek Valley in the foreground (*C*), western Washington. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Table 9. Suspended-sediment yields in the Sauk River Basin, western Washington, water years 2012–16.

[Locations of streamgages are shown in figure 1 and descriptive information is shown in table 2. Mass-balance estimated suspended-sediment yields are calculated as the difference in load between streamgages divided by the unique drainage area to a given streamgage. The relative contribution of Glacier Peak's eastern flank is estimated by assuming that all of the unique area for the Sauk River near Sauk (12189500) streamgage has a yield equal to the yield at the Sauk River near Darrington, and is considered the "background" sediment production rate for the entire Sauk River Basin. Sediment loads above this background rate were attributed to pro-glacial "point" sources. **Abbreviation**: (t/km^2)/yr, metric ton per square kilometer per year]

Water year	Suspended-sediment yield [(t/km^2)/yr]			Mass-balance estimated suspended-sediment yields [(t/km^2)/yr]		Estimated fraction of total suspended-sediment load at Lower Sauk derived from Glacier Peak, eastern flank
	Sauk River above White Chuck River (Upper Sauk, 12186000)	Sauk River near Darrington (Middle Sauk, 12187500)	Sauk River near Sauk (Lower Sauk, 12189500)	Middle Sauk - Upper Sauk (White Chuck River)	Lower Sauk - Middle Sauk (Suiattle River Basin)	
2012	160	130	220	80	280	0.4
2013	160	150	270	140	350	0.4
2014	130	120	280	110	400	0.6
2015	240	320	390	420	430	0.2
2016	490	610	1,370	750	1,910	0.6
Average (2012–16)	240	270	510	300	680	0.5



EXPLANATION

The width of the arrows is scaled by the magnitude of the suspended-sediment load. Values in parentheses indicate the mean annual suspended-sediment load, in thousands of metric tons, for the 5-year study.

* Estimated by conservation of mass (Lower Sauk - Middle Sauk)
** Estimated by conservation of mass (Middle Sauk - Upper Sauk)
† Estimated sediment yield of 270 (t/km^2)/yr
‡ Difference between Suiattle and Lower Suiattle (Suiattle - Lower Suiattle)

Figure 18. Suspended-sediment budget for the Sauk River Basin, western Washington. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

Suspended-sediment yields in the White Chuck River Basin were similar to yields in the Upper Sauk Basin, despite the fact that the White Chuck River drains glaciated terrain on Glacier Peak while the Upper Sauk River does not. This similarity may indicate that the amount of sediment inputs from the glaciated western flank of Glacier Peak are not different from sediment inputs elsewhere within the White Chuck River Basin. The similarity in yields, despite differences in modern glaciation, may also be a function of the different geologies in the White Chuck River and Upper Sauk River Basins (fig. 2). Below Glacier Peak, the White Chuck River Basin is predominantly underlain by erosion-resistant high-grade metamorphics, while the Upper Sauk River Basin is underlain by more erodible low-grade metavolcanic or meta-sedimentary material, along with tertiary volcanic material. The generally weaker and less coherent geologies in the Upper Sauk River Basin may produce more sediment than the more erosion-resistant material in most of the White Chuck River Basin, offsetting the influence of glacially-sourced sediment in the White Chuck River Basin.

Hydroclimatic and Geomorphic Controls on Suspended-Sediment Loads

The 5 years of monitoring at Lower Sauk encompass a range of annual hydroclimatic conditions (figs. 5 and 6, table 2), providing an opportunity to assess the response of suspended-sediment loads. With respect to seasonal response, the fall, winter, and spring, year-to-year variations in sediment loads were primarily a function of hydrology, and specifically the frequency and intensity of days with high discharge (fig. 19). For fall and winter, this was characterized as the total volume of water carried at discharges greater than 390 m^3/s in a given season, a metric that describes both the number of storms and the intensity of those storms. For a given discharge, suspended-sediment concentrations were generally higher in the fall than in the winter, indicating that more sediment was transported in the fall than in the winter for floods of the same size (fig. 19*A*). Suspended-sediment loads in the spring scaled with the intensity and duration of the snow-melt hydrology. Similar to the threshold metric of 390 m^3/s, intensity and duration of snow-melt hydrology was characterized as the total flow volume for days where the daily discharge exceeded 235 m^3/s. This value reflects the 20-percent flow exceedance value for the spring season (fig. 19*B*) and represents a moderately high magnitude discharge for the spring snowmelt season, which typically has reduced discharge magnitudes relative to fall storm floods. These relations between seasonal hydrology and sediment loads are not sensitive to the threshold value used.

In the summer, inter-annual variability in sediment loads at Lower Sauk approximately scaled with metrics of discharge, but was most strongly related to average August–September temperature (fig. 19*C*). Physically, this may be related to higher delivery rates by the Suiattle River of sediment-rich meltwater from the glaciers caused by higher temperature.

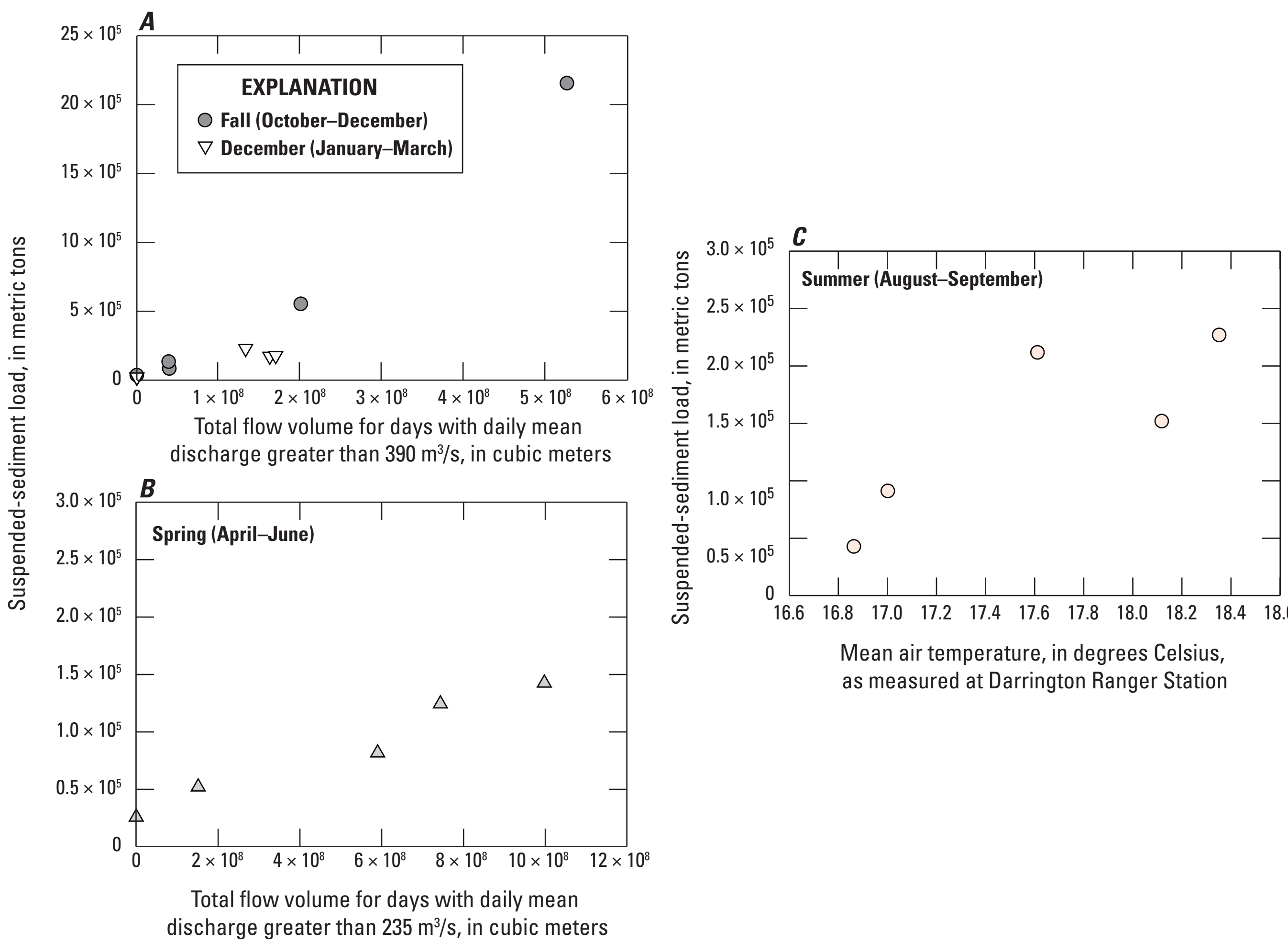


Figure 19. Seasonal suspended-sediment loads and their relation with various metrics of discharge or temperature at U.S. Geological Survey streamgage Sauk River near Sauk (Lower Sauk, 12189500), Sauk River Basin, Washington, 2011–16.

Discharge-Sediment Load Relations and Changing Sediment Availability

Suspended-sediment loads at Lower Sauk generally scale with discharge. The exact relation between SSL and discharge is a function of how much sediment is readily available to be transported, which may change substantially over seasonal, annual, or decadal time periods (Horowitz, 2003; Warrick and Rubin, 2007; Warrick and others, 2013; Bywater-Reyes and others, 2017). These sorts of variations in the sediment supply introduce substantial scatter in plots of daily SSL versus discharge. In the lower Sauk River, the scatter is particularly apparent in the summer, when glacial sediment is transported with little to no relation to discharge.

The potential influence of variations in sediment availability over seasonal or inter-annual time periods was assessed by first defining a baseline (or "typical") relation between daily SSL and daily mean discharge in the lower Sauk River (fig. 20). This was accomplished by fitting a power-law equation to the data for only November–May, when the relation between discharge and sediment loads was generally well-defined, using Ordinary Least Squares (OLS) regression on the log-transformed values. The load reported for a given day was then compared against what was expected based on this regression; days in which the load was higher than the baseline regression would have predicted are interpreted as having relatively high sediment availability, and days in which the load was lower are interpreted as having relatively low sediment availability. This comparison was made for all days during the study period, including June–October; the residuals for these days then indicate how much sediment was transported during these periods relative to days with similar discharges during the late fall, winter, and spring. The results were reported two ways; first, as the regression residuals using the log-transformed units, which provided an indication of when sediment availability was relatively high or low in terms of the percent deviation (fig. 21*A*). This allowed variations in relative sediment availability to be compared across periods of very different absolute loads. However, residuals in log-space are often high in cases where the absolute loads are small (for example, if the discharge-regression predicted 1 metric ton but the measured load was 100 metric tons), resulting in a minimal effect on annual load estimates. In order to describe how variations in sediment availability influenced loads over annual time scales, the results were transformed back into linear space and, after applying a bias correction factor (Duan, 1983), the daily-load residuals calculated in untransformed units. These residuals were then cumulatively summed, so that periods with positive slope indicate periods of above-average sediment availability and periods with negative slopes indicate below-average sediment availability (fig. 21*B*).

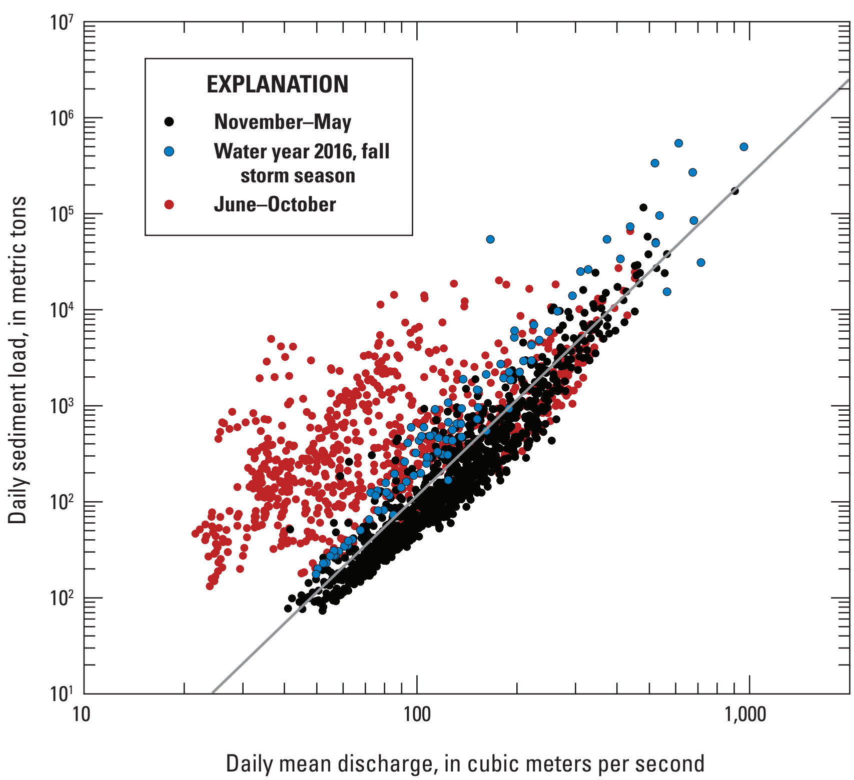


Figure 20. Daily suspended-sediment load versus daily mean discharge for U.S. Geological Survey streamgage Sauk River near Sauk (Lower Sauk, 12189500), western Washington. Location of streamgage is shown in figure 1, and descriptive information is shown in table 2.

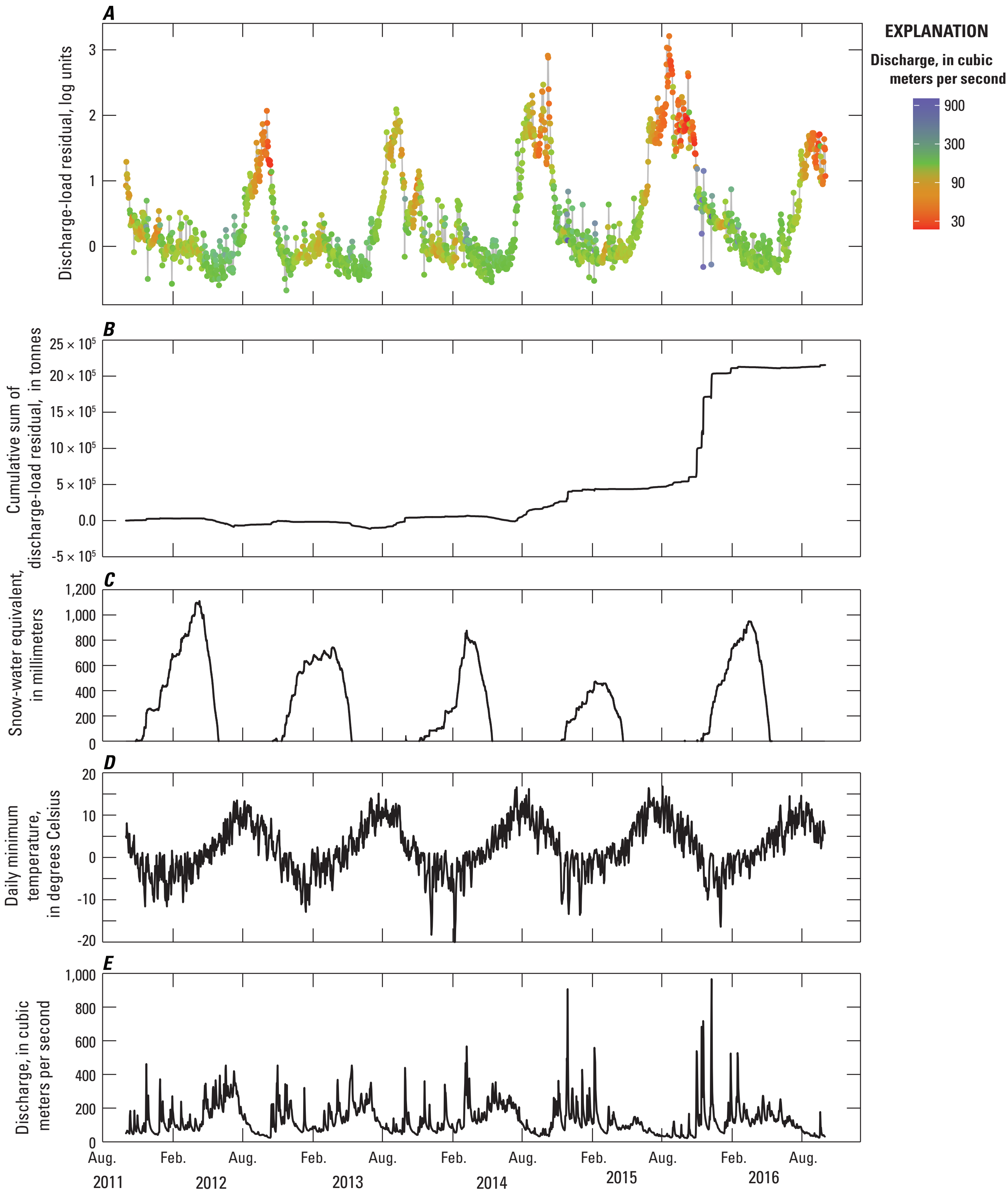


Figure 21. (*A*) Residuals from the power-law regression shown in figure 20, (*B*) the cumulative sum of residuals, (*C* and *D*) the snow-water equivalent and the daily minimum temperature at the Lyman Lake NRCS Snotel Site (NRC SNOTEL 606), and (*E*) discharge at U.S. Geological Survey streamgage Sauk near Sauk (12189500). Residuals are interpreted as an indication of periods of higher sediment availability (positive residuals) or lower sediment availability (negative residuals). Locations of streamgage are shown in figure 1, and descriptive information is shown in table 2.

The total vertical change over a given period then provides an approximate measure of how much more or less sediment was transported as a function of changes in sediment availability, independent of the discharge over that period. In all cases, these residuals are relative to average conditions during the 5-year study for fall, winter, and spring seasons over which the baseline regression was fit.

When plotted in log units, the dominant feature of the residuals is the annual cycle of high positive values during the glacier melt period (fig. 21*A*), indicating high sediment availability in summer relative to conditions during other seasons. This high availability is attributed to sediment sourced from sub-glacial and pro-glacial areas. The transition to higher relative sediment availability typically started in late June or early July, after the seasonal snowpack had melted out and discharges began to decrease to summer lows. Over these periods of increasing residuals, the actual mass of sediment in transport was typically steady or slightly decreasing; the seasonal increase in the residuals is therefore an indication that a relatively consistent mass of sediment was being transported by progressively less and less discharge. Physically, this is likely related to the progressive decrease of clear water inputs from snowmelt, which likely diluted the sediment-rich glacial inputs. The timing and nature of the increase in the residuals is inferred to be an indication of when snowmelt ceased to dilute the glacial sediment production signal, and not an indication of how and when glacial sediment production increased over this period.

Log-unit residuals, and therefore inferred sediment availability, typically remained high during the first fall storms (fig. 21*A*), when glacially derived sediment accumulated in the stream was flushed out of the basin. Sediment availability then decreased rapidly after several days of high discharge exhausted the readily available in-stream sediment supply. Residuals generally continued to decrease over late fall and winter, and reached the lowest values in a given year during spring snowmelt. The progressive decrease in relative sediment availability may be related to the accumulation of a seasonal snowpack, which limits the potential for heavy rains to cause surficial erosion or mass wasting. The trend may also be related to the continued exhaustion of glacial material deposited the previous summer. Spring snowmelt provides a steady supply of water, but was not typically associated with high peak discharges or rapid erosion, likely explaining the low residuals and inferred sediment availability during this period. In any given year, the details of the climatic conditions might cause deviations from these general patterns. For example, sediment availability was low in fall 2012 (start of WY 2013) (fig. 21*A*), which experienced early and rapid accumulation of seasonal snowpack (fig. 21*C*) and associated cold weather (fig. 21*D*); relative sediment availability then actually increased during the subsequent winter, in which warm-weather storms were as likely to bring rain as snow.

When plotted in terms of the cumulative absolute residuals, the seasonal cycle of high relative sediment availability appears much more muted (fig. 21*B*), because the absolute loads during the summer are typically a small part of the annual load (fig. 13). Instead, the dominant feature of the record was the high sediment availability during fall 2015 (start of WY 2016). Daily loads for that time period plot above the baseline discharge-sediment load regression over the full range of measured discharges (fig. 20). Between October 9 and December 15, 2015, a sequence of five floods transported about 2.2 million metric tons of suspended sediment. Based on the cumulative sum of the residuals, this was about 1 to 1.5 million metric tons more sediment than would have been expected based on the average relation between sediment and discharge during the 5-year study (fig. 21*B*). The annual load for WY 2016 was therefore large both because of the relatively active fall storm season (fig. 5), and because the sediment load per unit discharge was high for those storms relative to the 4 years prior.

High sediment availability in fall 2015 was attributed to an outburst flood and associated debris flow that occurred in the Chocolate Creek Basin, on the eastern flank of Glacier Peak. The outburst event was recorded in the turbidity record at Lower Sauk, which spiked to nearly 2,000 NTU on August 13, 2015, independent of any change in discharge or precipitation event (fig. 10*C*). Over the following 2 weeks, there were three more spikes greater than 2,000 NTU, and the maximum and minimum turbidity values over the diurnal cycle, excluding the prominent peaks, were at least three times higher than for the period prior to August 13. The absence of similar turbidity spikes in the Middle Sauk turbidity record indicates that the source was in the Suiattle River Basin. The likely source of this turbidity signal was identified through differencing of two topographic surveys of the Suiattle River headwaters. The surveys indicated that the valley-floor immediately down-valley of the Chocolate Glacier terminus eroded between 3 and 8 m over about 700 m sometime in the 2014–16 interval. Glacial outburst floods are relatively common occurrences on Cascade stratovolcanoes, and Chocolate Glacier has been particularly prone to such events (Richardson, 1968; Slaughter, 2004).

The high turbidity spikes in mid- to late August indicate the rapid arrival of high concentrations of silt and clay associated with the outburst events, but represented a relatively small amount of material in terms of total mass. A substantial amount of sand and silt associated with that outburst flood was only delivered to the lower Sauk River after large fall storms re-worked and re-mobilized that material. The estimate of “extra” sediment introduced by this outburst flood over the Fall 2015 flood season, about 1 million metric tons, represented about 20 percent of all suspended sediment mobilized past Lower Sauk over the 5 years of monitoring. The frequency and intensity of these stochastic geomorphic events likely play a significant role in the timing and overall magnitude of sediment exiting the basin.

Controls on Inter-Annual Variability of Water Temperatures

A comparison between mean daily water temperature for WYs 2012–16 and the average water temperature of that day of the year over the 5-year record illustrates inter-annual variability in water temperatures at Lower Sauk (fig. 22*A*). Deviations from the 5-year mean were most notable in the spring and early summer of WY 2012, when water temperatures were cooler than average, and in the spring and early summer of 2015, when water temperatures were substantially warmer than average. These records were compared to daily air temperature records at the Darrington Ranger Station (fig. 22*B*). Over most of the record, periods of water temperature above or below the 5-year mean generally corresponded to air temperatures that were also above or below the 5-year mean, respectively (fig. 22*C*). The water temperature response to short-term periods of seasonably warm or cold weather was generally more muted than the air temperature. However, there were several periods where the water temperature behavior was not correlated with air temperature, most notably in the summer of 2012 and the spring of 2015; the summer of 2015 also was one of the few times when the water temperature anomaly exceeded the air temperature anomaly.

The deviations from the typical air-water temperature relations were characterized by fitting a line to the scatterplot of daily air temperature anomalies versus daily water temperature anomalies. This regression describes how much warmer or colder than average water temperatures are expected to be as a function of how much warmer or cooler the air temperature was than average on any given day. The degree to which the water temperature anomaly on any given day falls above or below this line is an indication of how much, and in what direction, water temperature at Lower Sauk was responding to processes other than air temperature. A plot of these residuals shows a large negative departure in the spring and early summer of 2012, indicating that water temperatures were not only colder than average, but were also colder than expected based on air temperature alone (fig. 22*D*). Conversely, the large positive deviations in the spring and summer of 2015 indicate that water temperatures were warmer than expected when based on air temperatures alone. Although less prominent, minor negative deviations are also present during the snow-melt seasons in WY 2013 and WY 2014, and a minor positive deviation occurred in the snow-melt season of WY 2016.

The direction and magnitude of the observed seasonal departures correspond to inter-annual variability in snowpack accumulations and snow-melt discharge. WY 2012 was a large snow year (fig. 22*D*), and spring monthly discharges were well above the long-term (1929–2011) average (fig. 6*A*). Conversely, WY 2015 was a very low snow year, and experienced exceptionally low flows over the spring and summer. Negative air-water temperature deviations in WY 2013 and WY 2014 correspond to years with spring discharges above the long-term average. In WY 2016, the peak snow accumulation was the second highest behind WY 2012, but a warm spring caused the snow pack to melt rapidly, and discharge in the late spring and early summer was relatively low. This corresponded to a positive temperature departure, indicating that the timing of melt-out is important in addition to the total flow volume. Overall, the correlation between the mean May–July discharge and the maximum deviation from the air temperature-water temperature regression in that year is -0.995, indicating a near-perfect (negative) linear relation (table 10).

These results are an indication of the influence of relatively cold snow-melt water as a control on water temperatures over the summer; specifically, large snow packs and the steady supply of cool water over the spring and early summer act to slow the rate of water temperature warming relative to air temperature. The relative amount of snow, and the timing of the melt-out period, therefore modulates the degree to which changes in air temperature influence spring and summer water temperatures. The magnitude of the temperature deviations that could not be explained by air temperature was as much as ±3.5 °C, indicating that variations in snow pack depth and timing of melt-out are likely a significant control on summer water temperature trends.

Table 10. Spring-summer mean discharge in relation to anomalously warm or cool water temperatures.

[Air-water temperature residual values are from 15-day moving average presented in figure 22*D*. **Abbreviation:** m^3/s, cubic meters per second]

Water year	Mean May–July discharge (m^3/s)	Maximum spring/ summer air-water temperature residual (degrees Celsius)
2012	259	-2.9
2013	212	-1.5
2014	218	-1.5
2015	79	3.7
2016	134	1.5

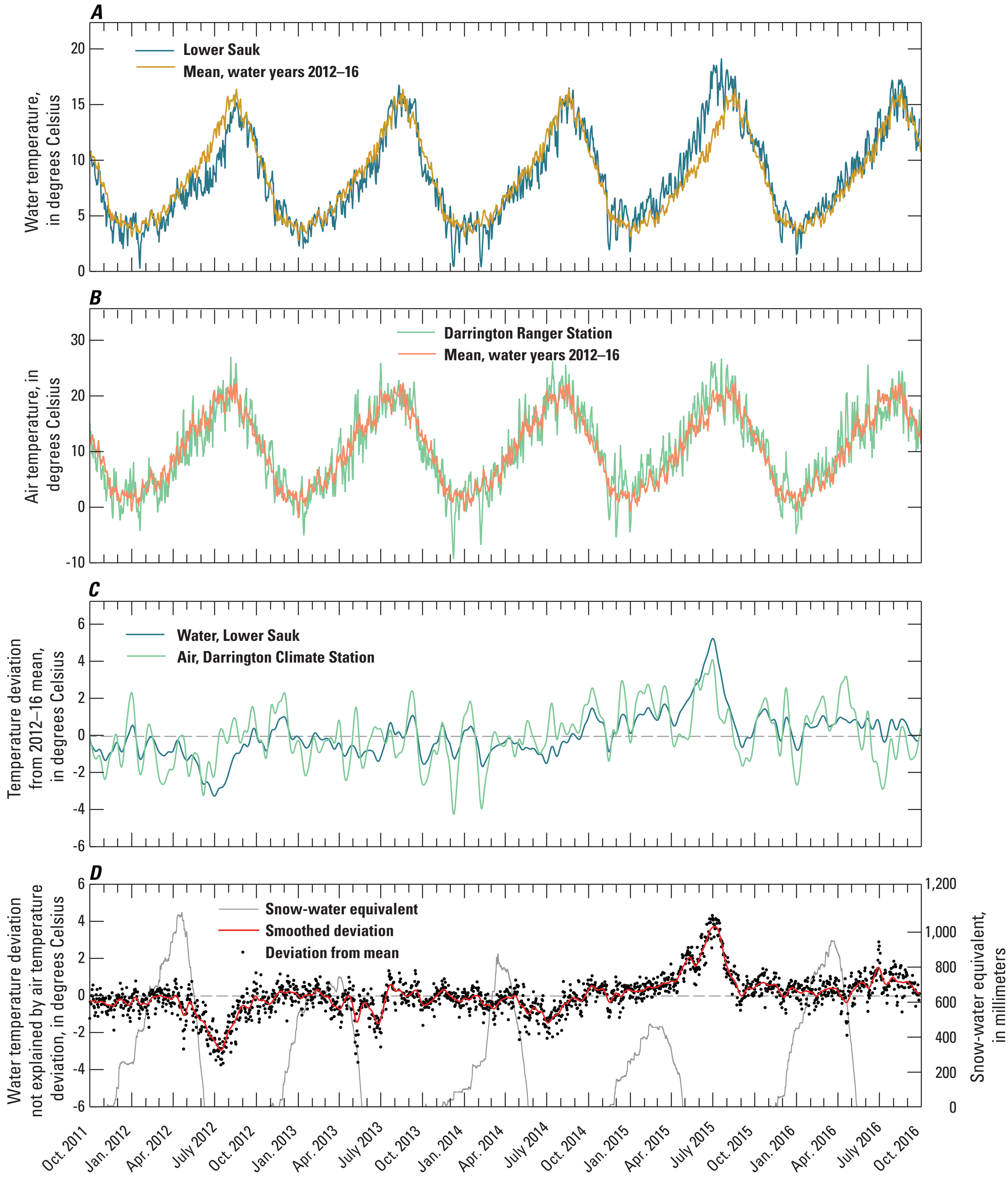


Figure 22. Water and air temperature, temperature deviations from the mean (water and air), and snow-water equivalent in the Sauk River Basin, western Washington, water years 2012–16. (*A*) Mean daily and daily mean water temperature for water years (WYs) 2012—16 study at U.S. Geological Survey (USGS) streamgage Sauk River near Sauk (Lower Sauk, 12189500); (*B*) Mean daily and daily mean air temperature at Darrington weather station for WYs 2012–16; (*C*) Daily temperature deviations relative to WYs 2012–16 means for both air temperature at Darrington and water temperature at Lower Sauk; (*D*) daily water temperature deviation not explained by the air temperature deviation, and daily snow-water equivalent at Lyman Lake NRCS Snotel Site (606). Both lines in (*C*) are 15-day moving averages over the daily record. Locations of streamgage are shown in figure 1, and descriptive information is shown in table 2.

Implications of Turbidity and Water Temperature on Chinook Salmon

The main stem sections of the Sauk River, which the three streamgages discussed in this report represent, are most likely to be used by ESA-listed Chinook salmon and steelhead for migration, spawning, and rearing. Temperature requirements for Chinook salmon are lower than those of steelhead (Ruckelshaus, 2006); therefore, Chinook salmon temperature thresholds were used for assessment of temperature periods of concern as a conservative measure. However, care should be taken when applying a common Chinook threshold to all three sections of the Sauk River main stem (Upper, Middle, and Lower Sauk), as Rucklelshaus and others (2006) suggested that adaptation to a particular temperature regime to be a key factor in population differentiation, and temperature tolerance and suitability is somewhat variable even in Puget Sound Chinook. Monthly temperature thresholds were obtained from McCollough and others (2001) and selected for different life stage of spring and summer run Chinook in the Sauk River main stem and summarized in table 11. When there were overlapping thresholds from different runs, the lower of the two values was selected. Maximum daily temperature values were compiled from the long-term record as a point of comparison to the life-stage threshold values in order to indicate temperature periods of concern.

High turbidity can also influence Chinook and steelhead life-history stages, although identifying particular levels of concern is challenging. Turbidity as a stressor to aquatic communities can be thought of as both a “pulse” (for example, short-term) and “press” (for example, long-term) type stressor. The Washington State water-quality standards definition of a background level and subsequent departure from background level that could be considered a stressor allows for some interpretation. Usually, press-type, long-term effects are observed at lower, average concentrations (Newcombe and Jensen, 1996). While a longer or even seasonal time period might be warranted for defining a press-type of stress caused by elevated turbidity (a proxy for SSC), the seasonal variation in turbidity conditions may necessitate that seasonal background levels be defined for particular species and settings of interest. Instead, departure from background as discussed in Washington State standards is most often assessed on an instantaneous basis; for example, above and below an instream activity. However, turbidity data and turbidity conditions in streams are known to be highly variable, even in pristine systems. Very high values can occur briefly from natural disturbances, which can occur locally from, for example, bank erosion or river bed disturbance from animal activity near the measuring site or more widely as a result of erosional processes that include slope failures, landslides, or debris flows common to mountain river systems, or seasonally as from snowmelt and glacial erosion. Despite this variability, identifying threshold values of turbidity levels that would be considered a pulse-type stressor is more tenable than determining turbidity levels that would be considered a press-type stressor.

Table 11. Sauk River Chinook-temperature thresholds for spring and summer runs.

[From McCoullough and others (2001)]

Month	Life stage	Temperature threshold (degrees Celsius)	Impact of concern
January	Gravel incubation	14	Poor egg survival
February	Gravel incubation	14	Poor egg survival
March	Fry emergence	14	Poor egg survival
April	Smoltification	15	Impaired smoltification
May	Smoltification	15	Impaired smoltification
June	Smoltification	15	Impaired smoltification
July	Adult migration	20	Disease, reduced swimming ability, migration blockage
August	Adult migration	20	Disease, reduced swimming ability, migration blockage
September 15th	Spawning	13	Poor adult gamete development
October	Spawning	13	Poor adult gamete development
November	Spawning	13	Poor adult gamete development
December	Gravel incubation	14	Poor egg survival

Specifics regarding data to define a pulse-type stress from turbidity were reviewed from the literature. Particularly, Newcombe and Jensen (1996) address the complex issues of concentration, duration and severity of effects on several fish species by using empirical data to generate a model matrix of taxa specific effects that have step changes with duration and concentration. “Lethal” and “non-lethal” effects of suspended sediment on various life stages of salmonids are then summarized by Newcombe and Jensen (1996; table A1). A SSC of 1,097 mg/L extending over a 48- to 96-hour period was identified as a consistent, reliable, short-term modeled “lethal” or “paralethal” level, hereinafter referred to as “threshold values.” Turbidity threshold values corresponding to 1,097 mg/L are 893 FNU for Upper Sauk, 306 FNU for Middle Sauk, and 242 FNU for Lower Sauk based on regression models developed for SSC and turbidity (model numbers 1.3, 2.3, and 3.3, respectively, in table 6). The corresponding turbidity threshold value of 893 FNU at Upper Sauk is more than three times the turbidity threshold values at Middle and LoweR Sauk, and represents an extrapolation beyond the SSC and turbidity values measured at the Upper Sauk. As a result, there is greater uncertainty associated with the turbidity threshold value of 893 FNU. Therefore, an average of the Middle Sauk and Lower Sauk turbidity threshold values (274 FNU) is used as a point of comparison to values reported in the literature.

The average modeled value of 274 FNU is similar to the most sensitive 96-hour lethal concentration (LC50) value for Chinook salmon (Newcombe and Jensen,1996, appendix A1), of 488 mg/L derived from Mt. St. Helens volcanic ash. However, Lloyd (1987) concluded that a “moderate level of protection to clear-water aquatic habitats” is 25 NTU above natural conditions for Washington streams. Unit values are roughly equivalent between NTU and FNU if Formazin standards are used during turbidity sensor calibration, which is assumed for the purposes of this analysis. Twenty-five NTU corresponds to 80 mg/L, the average of the three SSC values computed from the regression models for the three streamgages. Given this ambiguity about effects from lower turbidity levels, both the modeled SSC value of 1,097 mg/L from Newcombe and Jensen (1996), and Lloyd’s (1987) “moderate level of protection” value of 100 mg/L were selected to identify 48-hour periods-of-concern when mortality to salmonids might begin to be observed, assuming those concentrations were unavoidable by fish. It is important to note that avoidance of turbid waters by salmonids is also well documented (Lloyd, 1987; Newcombe and Jensen, 1996; Robertson and others, 2006), which can result in fish displacement at suspended-sediment concentrations lesser than the identified threshold values.

The Upper and Middle Sauk streamgages experienced limited turbidity and temperature periods-of-concern over the study period for which data exist. Additionally, at a given site, turbidity and temperature periods-of-concern did not occur at the same time. At Upper Sauk, daily maximum temperatures exceeded the thresholds in table 11 on 12 dates, which occurred in late September 2014 and late June 2015 and persisted for approximately one week at a time (fig. 23*A*). Threshold values for turbidity were exceeded on a single day, September 29th, 2013, and no 48-hour periods-of-concern were observed at the Upper Sauk streamgage. Middle Sauk experienced elevated temperature that exceeded threshold values on six dates during June 2015 (fig. 23*B*). Turbidity periods-of-concern maintained for 48 hours did not occur at Middle Sauk and elevated turbidity values rarely approached threshold values.

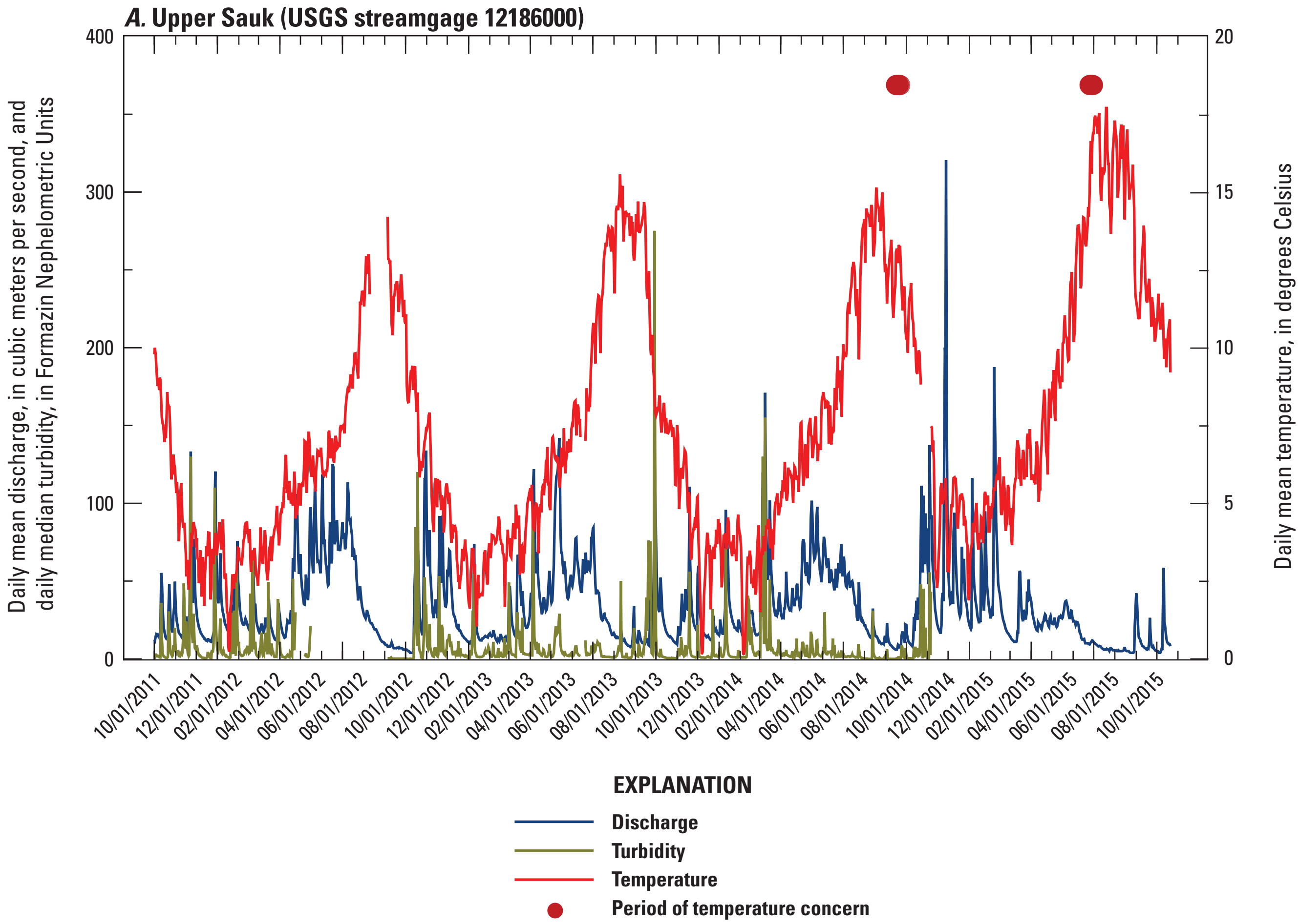


Figure 23. Daily mean discharge, median turbidity, and median temperature at U.S. Geological Survey (USGS) streamgages on the Sauk River, western Washington, water years 2012–16. Periods of concern are when turbidity and water temperature exceeds identified impairment levels for individual Chinook life stages. Locations of streamgages are shown in figure 1, and descriptive information is shown in table 2.

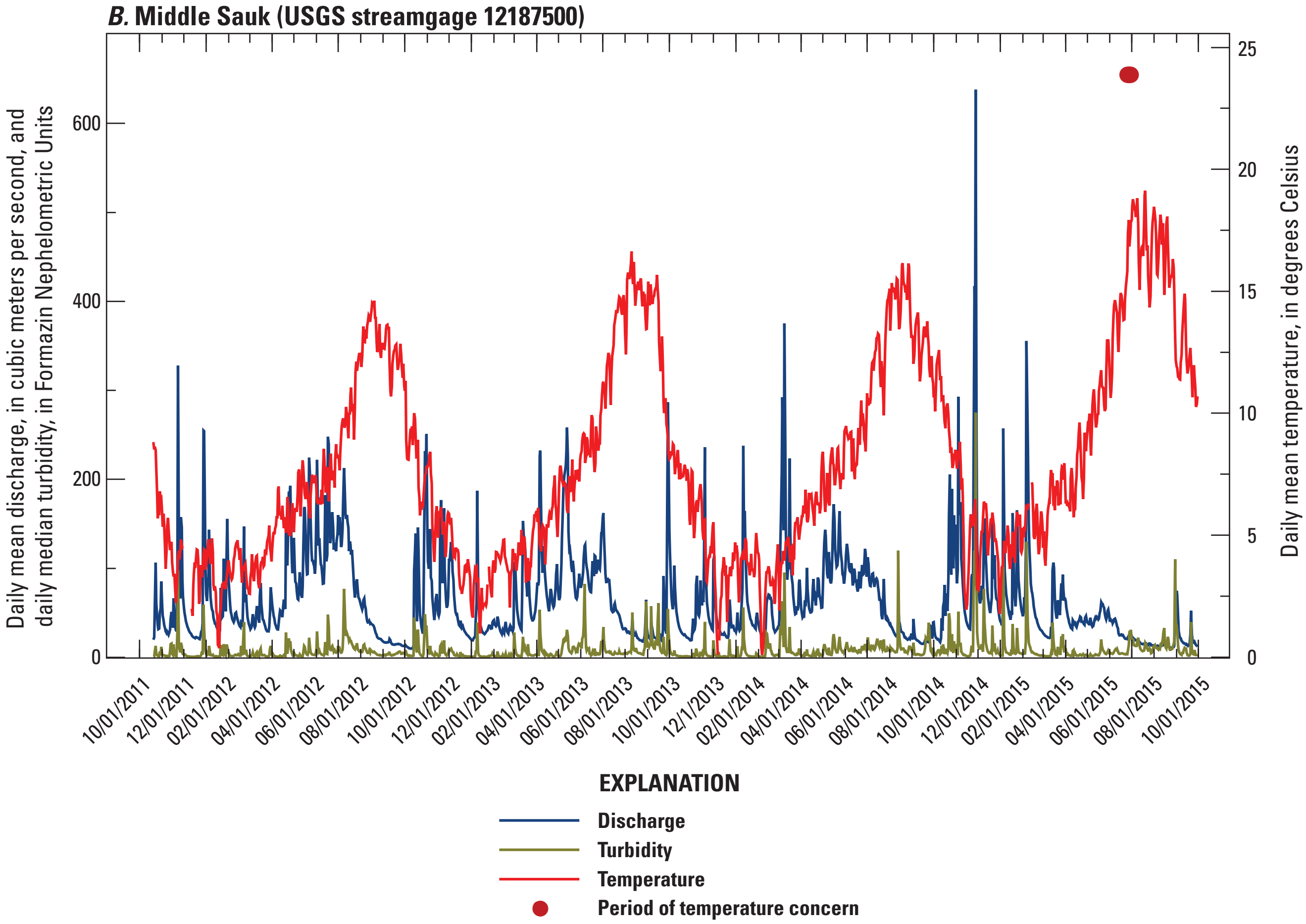


Figure 23.—Continued

The Lower Sauk had the highest daily temperature and turbidity values of the three streamgages. However, daily maximum temperatures exceeded the threshold values in table 11 during just 2 weeks of the 5-year study and corresponded to the drought period of June 2015. Daily median turbidity exceeded the site-specific threshold values on 232 dates between 2011 and 2016; however, concentrations were elevated for 48 hours or longer on only 8 of those dates. The identified periods-of-concern translates to less than 0.1 percent of the 48-hour periods measured, which typically occurred during mid-August and October. The period-of-concern for elevated turbidity at Lower Sauk did not co-occur with a temperature period of concern (fig. 23*C*).

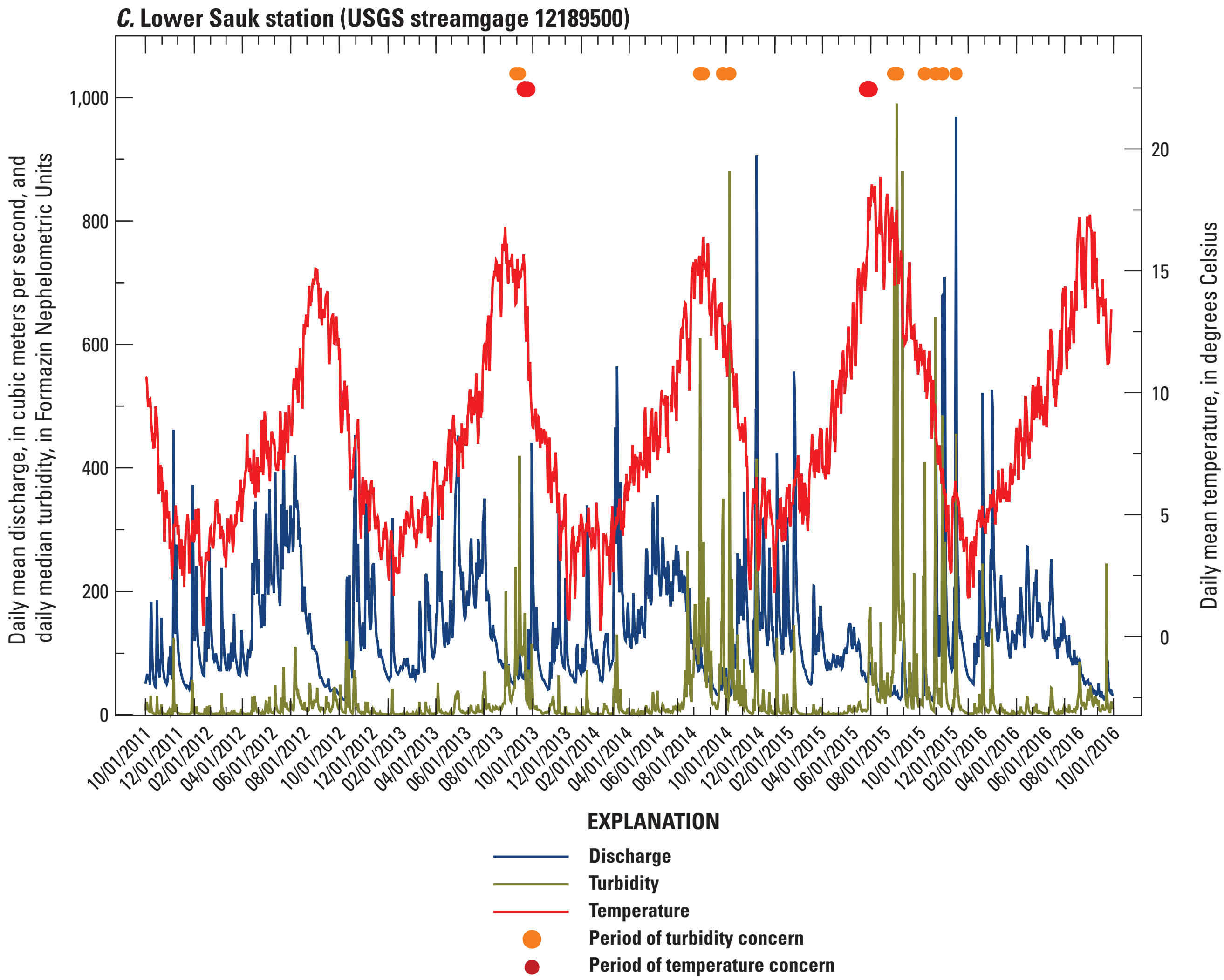


Figure 23.—Continued

During the 5 years of data collection in this study, potential temperature stress to fish in the Sauk River was more commonly and consistently observed during late summer and early fall, compared to periods-of-concern from turbidity. The longer term effects of either of these stressors to salmonids in this system, especially turbidity, should be the subject of future study. Only pulse-type turbidity stress was reviewed and defined in this study. A press-type stressor, for example, from elevated turbidities contributing to increase sedimentation in the channel, would be an important topic for future study. In particular, the ability, severity, and frequency of elevated turbidity to result in fine sediment deposition and the sedimentation of salmonid eggs and (or) alevins, particularly in known spawning and incubation sections of the river and times of the year, would be a likely mechanism, often discussed in reviews (Lloyd, 1987; Newcombe and Jensen, 1996; Robertson, 2006) worthy of future investigation. Additionally, this dataset, with perhaps some close scrutiny of particular events, provides an excellent example of what background might be for this and (or) other regional rivers with regards to Washington State water-quality standards.

Summary

This report provides the results of a 5-year suspended-sediment and water temperature study in the Sauk River Basin. The purpose of this study was to improve understanding of the magnitude and timing of suspended sediment and turbidity from the Sauk River and its tributaries to the Skagit River. Additionally, this report provides interpretation of sediment production regimes in the basin and provides an analysis on how turbidity and water temperature conditions may affect Chinook salmon life-cycles. Fluvial sediment data were collected over a range of discharge, turbidity, and water temperature conditions at three USGS streamgages in the Sauk River, previously identified as Upper, Middle, and Lower Sauk. Data were collected at all three streamgages for water years 2012–15; data were also collected at Lower Sauk for water year 2016.

The SSL computed for Upper and Middle Sauk for the 5-year study period is 471,000 t (±126,000 t) and 1,010,000 t (±140,000), respectively. Average annual SSL for Upper and Middle Sauk are 94,000 t (±25,000 t) and 203,000 t (±28,000 t), respectively. The cumulative SSL for Lower Sauk is substantially higher at 4,700,000 t (±632,000 t), with an average annual SSL of 940,000 t (±126,000 t). The maximum daily SSL for the three streamgages was 30,200 at Upper Sauk, 98,600 t at Middle Sauk, and 415,000 t at Lower Sauk. Maximum SSL were associated with a series of high discharge events in November 2015. Suspended-sediment loads in the Sauk River Basin exhibit clear seasonal trends and substantial inter-annual variability that strongly reflect the variability in discharge conditions and the relative importance of individual precipitation events and the timing of snow melt conditions among the three streamgages. Fall (September–December) SSL, on average, accounts for more than one-half of the total annual suspended load at all three streamgages (55 percent at Upper Sauk, 67 percent at Middle Sauk, and 62 percent at Lower Sauk). Suspended-sediment loads are highly variable from year to year and appear to largely be driven by the occurrence of atmospheric rivers and other fall and early winter precipitation events that cause high discharge. WY 2016 was characterized by a series of fall season precipitation events following a record drought summer that resulted in SSL that were three times the mean fall SSL at all three streamgages.

The relative contribution of sand (0.0625–2 mm) and fines (< 0.0625 mm) to the total SSL varies seasonally and inter-annually depending on the monitoring location. At Upper Sauk, the proportion of fine sediment did not vary substantially among seasons, ranging from 48 to 59 percent. In contrast, the fine load at the Lower Sauk was relatively large for the summer season, accounting for 56 percent of the SSL, but was only about 30 percent of the SSL in fall, winter, and spring.

At all three streamgages, the fraction of sand-sized material in suspension increased with discharge up to about three times the mean annual discharge, but appeared to plateau at around 60 to 80 percent sand for discharges higher than three times the mean annual discharge. This relation generally indicates that the transport of sand in suspension is limited by transport capacity at low flows, but is increasingly entrained with higher discharges. At Lower Sauk, the relation between percent sand and discharge appears to separate by season. Samples collected in the summer show a linear increase in the percent sand with increasing discharge, while samples collected in the late fall through spring had a consistent sand fraction of between 70 and 80 percent. This separation could be an artifact of the limited number of samples collected during winter low flow periods. Alternately, this separation may reflect seasonal shifts in the supply of fine versus sand-size sediment as a consequence of reduced glacier sediment production in the early fall that exhausts fine sediment supply and facilitates greater representation of sand-sized sediment in suspended-sediment concentrations.

Mean monthly temperatures were at a maximum in August (14.4 °C at Upper Sauk, 14.9 °C at Middle Sauk, and 15.1 °C at Lower Sauk) and minimum in January (3.3 °C at Upper Sauk, 3.6 °C at Middle Sauk, and 4.0 °C at Lower Sauk). Maximum monthly temperatures were highest in August at Upper and Middle Sauk (21 °C at Upper Sauk and 20.9 °C, respectively) and in July at Lower Sauk (20.8 °C), although average daily maximum temperatures did not increase in the downstream direction.

The records of SSL at various locations in the Sauk River Basin were used to construct a basin-scale sediment budget using a mass balance approach. The Suiattle River appears to be the predominant source of suspended sediment at Lower Sauk, accounting for an average of 80 percent of the annual load for the entire basin. The remaining load was split evenly between the inputs from the Upper Sauk River and White Chuck River Basins, both of which contributed about 10 percent of the SSL in any given year over the 5 year monitoring period. Additionally, about 450,000 t/yr, or about 60 percent, of SSL from the Suiattle River is estimated to be attributable to the eastern flank of Glacier Peak. Sediment from the eastern flank of Glacier Peak may contribute about 50 percent of the sediment load for the entire Sauk River Basin in any given year.

In fall, winter, and spring, year-to-year variations in sediment loads were primarily a function of hydrology, and specifically the frequency and intensity of days with high discharge. In the summer, inter-annual variability in sediment loads approximately scaled with metrics of discharge, but was most strongly related to average August–September temperature. Physically, this is likely related to higher rates of sediment-rich meltwater from the glaciers caused by higher temperature. Suspended-sediment concentration and sediment loads typically scale with discharge. However, the particular relation between sediment load and discharge is a function of the sediment availability in the system. Sediment availability typically remained high during the first fall storms, when glacial sediment accumulated over the summer was flushed out of the watershed. Indeed, a dominant feature of the record was the high sediment availability during the fall storms of 2015 (start of WY 2016); during which a sequence of five fall floods transported about 1.5 million metric tons more sediment than would have been expected based on typical relations between sediment load and discharge during the study.

Identified periods-of-concern of elevated water temperature and turbidity values that could impair Chinook salmon at various life stages were rare at the Sauk River streamgages accounting for less than 1 percent of the monitoring period. Additionally, identified periods-of-concern for temperature and turbidity, when they did take place, did not occur at the same time at a given site. This multi-year dataset provides an opportunity to effectively determine what the background level might be for this and (or) other regional rivers with regards to Washington State water-quality standards.

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Appendix A. Particle-Size Distribution for Suspended-Sediment Samples Collected at Three Streamgages on the Sauk River, Western Washington, 2012–14

Appendix A is a Microsoft® Excel file and is available for download at https://doi.org.10.3133/sir20175113.

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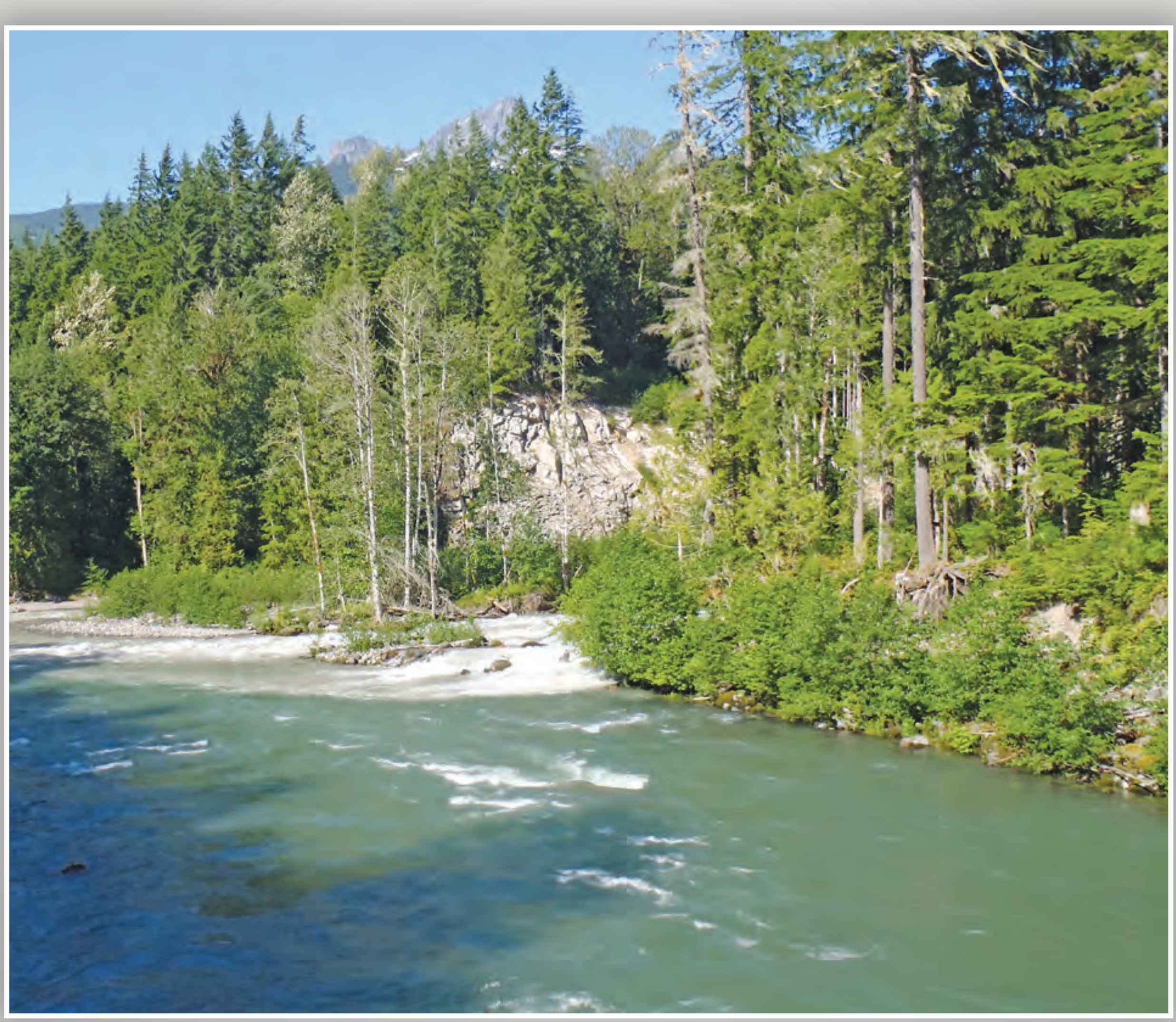

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