Water Mission Area

Prepared in cooperation with the Teton Conservation District

Using Continuous Measurements of Turbidity to Predict Suspended-Sediment Concentrations, Loads, and Sources in Flat Creek through the Town of Jackson, Wyoming, 2019–20—A Pilot Study

Open-File Report 2022–1103

U.S. Department of the Interior
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U.S. Geological Survey, Reston, Virginia: 2022

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Suggested citation:
Alexander, J.S., Girard, C., Campbell, J., Ellison, C., Gosselin, E., and Smith, E., 2022, Using continuous measurements of turbidity to predict suspended-sediment concentrations, loads, and sources in Flat Creek through the town of Jackson, Wyoming, 2019–20—A pilot study: U.S. Geological Survey Open-File Report 2022–1103, 29 p., https://doi.org/10.3133/ofr20221103.

Associated data for this publication:
U.S. Geological Survey, 2021, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN.

ISSN 2331-1258 (online)

Acknowledgments

The authors thank the Teton Conservation District for their cooperation with this project.

The authors would like to thank Edward Kempema, Brian Remlinger, and David Rus (U.S. Geological Survey) for constructive peer review of earlier drafts of this document.

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
nanometer (nm)	3.93701×10^{8}	inch (in.)
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
	Mass	
metric ton (t)	1.102	ton, short [2,000 lb]

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

°F = (1.8 × °C) + 32.

Datum

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

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

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

Supplemental Information

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

Turbidity is given in formazin nephelometric units (FNU) or nephelometric turbidity units (NTU).

A water year is the period from October 1 to September 30 and is designated by the year in which it ends; for example, water year 2019 was from October 1, 2018, to September 30, 2019.

Abbreviations

BCF	bias correction factor
ECDF	empirical cumulative distribution function
LOI	loss on ignition
SSC	suspended-sediment concentration
SWE	snow-water equivalent
TCD	Teton Conservation District
TSS	total suspended solids
USGS	U.S. Geological Survey
WYDEQ	Wyoming Department of Environmental Quality

Using Continuous Measurements of Turbidity to Predict Suspended-Sediment Concentrations, Loads, and Sources in Flat Creek through the Town of Jackson, Wyoming, 2019–20—A Pilot Study

By Jason S. Alexander,[1] Carlin Girard,[2] James Campbell,[1] Chris Ellison,[1] Elyce Gosselin,[2] and Emily Smith[2]

Abstract

Flat Creek, a tributary to the Snake River in northwestern Wyoming, is an important source of irrigation water, fish and wildlife habitat, and local recreation. Since 1996, a section of Flat Creek within the town of Jackson has failed to meet Wyoming Department of Environmental Quality's surface-water-quality standards for total suspended solids and turbidity required by its State water-use classification. Wyoming Department of Environmental Quality water-quality standards prohibit increases of greater than 10 nephelometric turbidity units (NTU) because of human activities in streambodies of Wyoming. Sediment loading from urban stormwater runoff is hypothesized in previous publications to be the primary cause of impairment, but the relative fine sediment contributions from various sources have not been quantified.

In cooperation with the Teton Conservation District, the U.S. Geological Survey began a pilot study in the Flat Creek drainage basin to investigate the use of continuous turbidity measurements to predict suspended-sediment concentrations, loads, and sources through the town of Jackson, Wyoming. The predictions were based on turbidity measurements collected every 15 minutes during parts of water years 2019 and 2020. Analysis of differences in the more than 15,000 turbidity measurements coincident between upstream and downstream streamgages indicated that differences of 10 formazin nephelometric units (FNU) or greater composed about 1 percent of the total accepted measurements during the 2019 and 2020 measurement periods. The median difference in measured turbidity between coincident records at the upstream and downstream streamgages in 2019 was 0.20 FNU and the median difference in 2020 was 0.0 FNU.

Calculations of mean total sediment loads in Flat Creek during 2019 and 2020 indicate substantially more suspended-sediment was in Flat Creek below the town of Jackson than above town. Mean total calculated suspended-sediment loads at the upstream streamgage were 26 percent in 2019 and 21 percent in 2020 of the mean total suspended-sediment loads at the downstream streamgage. For measurements occurring at the same time (coincident), mean calculated suspended-sediment loads entering the town of Jackson from Flat Creek were 39 percent in 2019 and 35 percent in 2020 of those loads exiting town in Flat Creek. Incorporating statistical model uncertainty, mean differences between predicted suspended-sediment loads could potentially be zero. The annual period of operations of the South Park Supply Ditch, which diverts water into Flat Creek from the Gros Ventre River, constituted between 91 and 90 percent of the total calculated suspended-sediment load at the upstream streamgage, and between 88 and 87 percent of the loads at the downstream streamgage for coincident periods of record in 2019 and 2020, respectively. However, in the absence of simultaneous continuous monitoring and resulting measurements at the outlet of the South Park Supply Ditch, no robust method was available to quantify suspended-sediment loads from the ditch.

A moving average filter was used to identify and isolate short-duration (minutes to hours) spikes in turbidity at the downstream streamgage that were likely caused by overland flow and urban runoff. Suspended-sediment loads during urban runoff constituted about 8 and 10 percent of the total calculated suspended-sediment loads at the downstream streamgage (Flat Creek below Cache Creek, near Jackson, Wyoming; U.S. Geological Survey streamgage 13018350), and 6 and 4 percent of the loads calculated for the record coincident with the upstream streamgage in 2019 and 2020, respectively. Estimated suspended-sediment loads at the upstream streamgage during urban runoff events for the coincident period of record constitute 32 and 40 percent of the total estimated suspended-sediment loads at the downstream streamgage in 2019 and 2020, respectively, indicating sediment loads from urban runoff may contribute less than 10 percent, even as little as 5 percent, of the total sediment load exiting the town of Jackson on Flat Creek. Estimation of the proportion of suspended-sediment loads at the upstream site that originate from the South Park Supply Ditch or Cache

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[1] U.S. Geological Survey.

[2] Teton Conservation District.

Creek can only be done with assumptions but have the potential to be equivalent to or greater than calculated suspended-sediment loads associated with urban runoff.

Introduction

Sediment transport in rivers and streams is a natural physical process resulting from erosion of landscapes within a drainage basin (Wohl and others, 2015). Erosion and transport of sediment during floods is important for the disturbance, turnover, and renewal of aquatic and riparian habitats in streams and river bottoms (Junk and others, 1989; Scott and others, 1996; Wohl and others, 2015). Human activities on the landscape often alter sediment-transport processes and can cause water-quality impairments (Wood and Armitage, 1997; Dodds and Whiles, 2004). Grazing animals, for example, can compact soil and reduce riparian vegetation reinforcing riverbanks, thereby increasing sediment yields during snowmelt and rainfall-runoff events (Kauffman and Krueger, 1984; Fleischner, 1994; Trimble, 1994; Evans, 1998). Urbanization increases impervious surfaces within a drainage basin, quickening and increasing runoff, which can increase streambank erosion and increase fine sediment concentrations (Ogden and others, 2011; Blum and others, 2020). In cold urban regions, fine sediment is commonly mobilized by snowmelt and street sanding and can be deposited in receiving streams (Pierstorff and Bishop, 1980; Oberts, 1994; Marsalek and others, 2003). Transbasin diversions, which are common in the semiarid and arid western regions of the United States, also can increase sediment loads in receiving streams by increasing flow or directly delivering additional suspended-sediments (Dominick and O’Neill, 1998; Gaeuman and others, 2005; Bray and Kellerhals, 2021).

Flat Creek, a tributary to the Snake River in northwestern Wyoming (fig. 1*A*), is an important source of irrigation water, fish and wildlife habitat, and local recreation (Girard and others, 2019). Since 1996, a section of Flat Creek within the town of Jackson has failed to meet the Wyoming Department of Environmental Quality’s (WYDEQ) surface-water-quality standards for total suspended solids (TSS) and turbidity required by its State water-use classification (Remlinger, 2006; Girard and others, 2019). Although not equivalent, suspended-sediment may constitute large parts of the TSS load (Gray and others, 2000; Ellison and others, 2014), and turbidity can be strongly correlated to the concentration of suspended-sediment observed in streams (Rasmussen and others, 2009). Results from water-quality monitoring by the Teton Conservation District (TCD) and the town of Jackson has led to the working hypothesis that water-quality impairment of Flat Creek is the result of fine sediment (particles less than 2 millimeters [mm] in diameter) loading from urban stormwater runoff (Remlinger, 2006). However, the relative contributions of fine sediment loading from various sources have not been quantified, and thus, the primary sources of the impairment remain unclear.

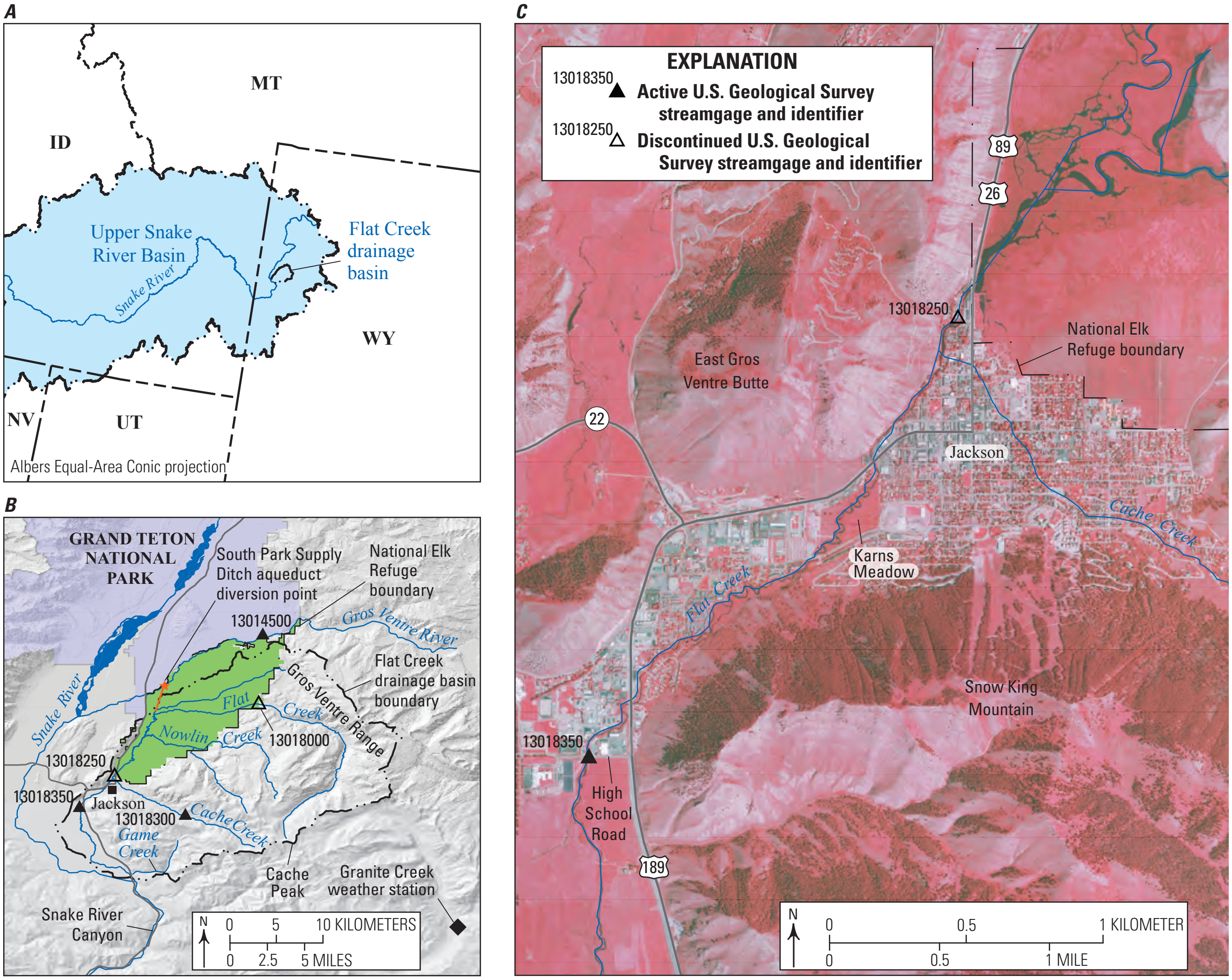
In cooperation with the TCD, the U.S. Geological Survey (USGS) began a pilot study to investigate the use of continuous turbidity measurements for quantifying suspended-sediment loads into and out of the town of Jackson. Quantifying sediment loads coming into and out of Flat Creek in Jackson is important for understanding the relative magnitude of contributions from various sources and identifying effective sediment mitigation strategies for reducing turbidity and TSS in Flat Creek. Discrete, paired measurements of turbidity and suspended-sediment concentration (SSC) were used to develop statistical models using turbidity as the independent variable. The statistical models were used to predict sediment loads at 15-minute time intervals based on measurements of turbidity and streamflow measured at streamgages on Flat Creek upstream and downstream from the town of Jackson. Sediment loads were partitioned by time periods of transbasin diversions and snowmelt and rainfall-driven urban runoff to examine the utility of the method for quantifying the relative loads of potential suspended-sediment sources.

Study Area

The area defined for the study described in this report is the Flat Creek drainage basin upstream from USGS streamgage 13018350, Flat Creek below Cache Creek, near Jackson, Wyo. (fig. 1*B*, *C*; U.S. Geological Survey 2021d). Flat Creek enters the town of Jackson (hereinafter “Jackson”) from the northeast and exits to the southwest. The primary focus area for the turbidity and sediment-transport analysis described in this report is the main channel of Flat Creek from USGS streamgage 13018250 (Flat Creek above Cache Creek, at Jackson, Wyo.; U.S. Geological Survey 2021b) to USGS streamgage 13018350 (fig. 1*A*–*C*). The discontinued streamgage 13018250 is near the upstream boundary of Jackson; the active streamgage 13018350 is near the downstream boundary of Jackson (fig. 1*A*–*C*). Precipitation and hydroclimatic data from the Flat Creek drainage basin upstream from streamgage 13018350, snowpack data observed in an adjacent drainage basin, and streamflow measurements from USGS streamgages 13018300 (Cache Creek near Jackson, Wyo.; U.S. Geological Survey 2021c) and 13014500 (Gros Ventre River at Kelly, Wyo.; U.S. Geological Survey 2021a) also were used in the analysis to provide hydroclimatic context and assist in the interpretation of results.

Physical and Hydroclimatic Characteristics of Flat Creek Drainage Basin

Flat Creek originates at an altitude of about 3,141 meters (m) near Cache Peak in the Gros Ventre Mountain Range and flows nearly 58 kilometers (km) to its confluence with the Snake River south of Jackson, descending more than 1,300 m along its course (Ryan and Dixon, 2007; Kempema and others, 2017). Flat Creek drains nearly 410 square kilometers



Base from U.S. Geological Survey-derived
30-meter digital elevation model
Universal Transverse Mercator, zone 12

False-color 2009 aerial image from
U.S. Department of Agriculture,
National Agricultural Information Program
Universal Transverse Mercator, zone 12

Figure 1. Regional location of (*A*) the Flat Creek drainage basin in Wyoming; (*B*) the Flat Creek drainage basin near the town of Jackson, Wyoming; (*C*) and Flat Creek within the town of Jackson, Wyo. The study area is Flat Creek drainage basin upstream from U.S. Geological Survey streamgage 13018350 (Flat Creek below Cache Creek, near Jackson, Wyo.; U.S. Geological Survey, 2021d).

of alpine and forested mountain slopes, wetlands, urban landscapes, and irrigated agricultural meadows (Ramirez and Armstrong, 1992; Girard and others, 2019). The three largest tributaries to Flat Creek by drainage basin area are Nowlin Creek, Cache Creek, and Game Creek (fig. 1*B*), which have their confluences upstream, within, and downstream from Jackson, respectively (Olsson Associates, 2016). The South Park Supply Ditch (fig. 1*B*), which has public and private adjudicated water rights totaling 1.6 cubic meters per second (m^3/s), delivers additional flow to Flat Creek from the adjacent Gros Ventre River Basin during the irrigation season, which generally runs from April through September (Gerber and others, 2012). Various diversions take water from Flat Creek and supply it to the National Elk Refuge (hereinafter “Elk Refuge”; fig. 1*B*) irrigated agricultural fields and areas within and downstream from Jackson (Remlinger, 2006).

Flat Creek flows through steep mountain valleys and lacustrine settings in its headwater segments before entering the fairly flat glacial plains and wetlands of the Elk Refuge (Ramirez and Armstrong, 1992; Pierce and others, 2018). Downstream from the Elk Refuge, Flat Creek is cobble bedded and flows through Jackson where it encounters a series of alternating urban encroachments and human-created riparian meadow and wetland settings (Hoffman, 2004). Within Jackson, the channel of Cache Creek is restricted by urban encroachments and intermittently contained within underground pipes divided into multiple flow paths. Downstream from Jackson's town center, Flat Creek flows through Karns Meadow (fig. 1*C*), one of the few sections of Flat Creek in Jackson with riparian flood plain connectivity. Karns Meadow also contains a human-constructed stormwater wetland complex (Olsson Associates, 2016). Below Karns Meadow, the channel of Flat Creek is generally narrow and fixed within urban encroachments until leaving the southern boundary of Jackson at High School Road (fig. 1*C*; Hoffman, 2004).

The Flat Creek drainage basin is described as a fully humid snow climate with cool summers by the Köppen-Geiger Climate classification (Kottek and others, 2006). Median daily temperature in the Flat Creek drainage basin varies from about −10 degrees Celsius (°C) in the winter to 16 °C in the summer (PRISM Climate Group, 2021). Most precipitation in the Flat Creek drainage basin falls as snow accumulation during the cold winter months, which gives the shape of the annual hydrograph a distinct snowmelt signal (Remlinger, 2006). Base flows in Flat Creek through Jackson occur from September through April and are maintained by groundwater and spring contributions from the Elk Refuge (Remlinger, 2006). The steady base flow of Flat Creek through Jackson, combined with cold winter temperatures, causes the creek to have complex ice formation and melt events throughout the winter; some of these formations and events have caused flooding (Daly, 2002; Kempema and others, 2017, 2019). Short-duration, intense summer rainfall events also can result in increased streamflow in Flat Creek (Girard and others, 2019).

Streamflow measurements in Flat Creek have been made at five streamgages operated off and on by the USGS over the past century (table 1). The USGS streamgage 13018350 is at the downstream boundary of the study area with a daily mean streamflow record over most of the past three decades (from May 17, 1989, to September 30, 1997; from October 1, 1999, to the present [2022]). Mean annual streamflow at streamgage 13018350 for the period of record between 2000 and 2020 varies from 1.7 to 3.8 m^3/s (U.S. Geological Survey, 2021d). Annual instantaneous high streamflows in Flat Creek observed at streamgage 13018350 between water years 1989 and 2020 have typically occurred between May and August and vary from 4 to 11 m^3/s (U.S. Geological Survey, 2021b). Annual instantaneous high streamflows commonly do not coincide with annual instantaneous high stages, which are commonly caused by winter ice formation and breakup (Kempema and others, 2017).

Hypothesized Sources of Fine Sediment in Flat Creek

WYDEQ water-quality standards prohibit increases of greater than 10 nephelometric turbidity units (NTU) resulting from human activities in Class 2AB streambodies of Wyoming (Girard and others, 2019). Previous investigations have observed increases in turbidity of more than 100 NTU on Flat Creek and Cache Creek through Jackson, Wyo. (Remlinger, 2006; Girard and others, 2019). These measurements have been used as evidence of sediment runoff from urban areas being the primary source of turbidity and TSS impairment. This evidence is rooted in the notion that turbidity is often a strong indicator of SSC (Rasmussen and others, 2009). However, these measurements of turbidity are discrete, and the relative contribution of fine sediment from Flat and Cache Creeks flowing through Jackson cannot be quantified based on these data. Another hypothesized source of sediment affected by human-management activities is suspended-sediment load from the Gros Ventre River carried through the South Park Supply Ditch into the segment of Flat Creek in the National Elk Refuge (fig. 1*B*) upstream from Jackson (Girard and others, 2019). Local residents also have observed increases in turbidity in the fall and winter when waterfowl are abundant in the wetlands of the elk refuge (Coburn, 2018).

Table 1. U.S. Geological Survey streamgages used for this study in northwestern Wyoming.

[USGS, U.S. Geological Survey; km^2, square kilometer; YYYY–MM–DD, year, month, day; present represents 2022; all information in table was obtained from U.S. Geological Survey, 2021a, b, c, d]

USGS station number (fig. 1*B*)	USGS station name[a]	Drainage area (km^2)	Daily records start date (YYYY–MM–DD)	Daily records end date (YYYY–MM–DD)	Description
13014500	Gros Ventre River at Kelly	622	1918–06–16	Present	Upstream from diversion for South Park Supply Ditch canal.
13018250	Flat Creek above Cache Creek, at Jackson	282	2018–10–03	2021–08–12	Near upstream boundary of town of Jackson.
13018300	Cache Creek near Jackson	27.5	1967–07–01	Present	About 4 kilometers upstream from town of Jackson.
13018350	Flat Creek below Cache Creek, near Jackson	334	1989–04–01	Present	Downstream end of town of Jackson municipal effect.

[a] All streamgages are within the State of Wyoming.

Purpose and Scope

The purpose of this report is to summarize findings of a pilot study to quantify suspended sediment loads in Flat Creek through Jackson, Wyo. Turbidity data were used in this study as a surrogate for SSCs in Flat Creek during calendar years 2019 and 2020. Turbidity and suspended-sediment data collected at two USGS streamgages, flow data from three streamgages, and daily precipitation data from published sources were used to test hypotheses regarding sources of suspended-sediment in Flat Creek. The study design did not include sediment monitoring at Cache Creek nor at the outlet for the South Park Supply Ditch and, thus, did not provide enough data for a complete sediment budget. Also, because of the danger of ice buildup in Flat Creek posed to monitoring equipment, sediment monitoring was limited to the non-ice season, which generally starts in March and ends in October or November.

Methods

Streamflow discharge (streamflow) and SSC are the two primary components required to quantify suspended sediment loads in streams and rivers (Glysson, 1987). This relation is a simple mass balance summarized by the following equation (Gray and Simões, 2008):

$$Q_s = Q_w C_s k, \tag{1}$$

where

Q_s is suspended-sediment load, in units of mass per time;
Q_w is streamflow, in units of volume per time;
C_s is concentration of suspended-sediment, in units of mass/volume; and
k is a unit conversion coefficient.

Streamflow is commonly measured in 15-minute intervals at streamgages across the Nation based on statistical relations between paired, discrete measurements of river water-surface elevation relative to an absolute or arbitrary datum (water stage) and streamflow measurements (Kennedy, 1984).

In rivers, streams, and creeks with fine sediment (particles with nominal diameters less than 2 mm) composing the bed material, streamflow is commonly strongly correlated to SSC, and streamflow is commonly used as a primary explanatory variable to predict SSC (Colby, 1956). Alternatively, in coarse-bed streams where the relation between streamflow and suspended-sediment is commonly weak, unstable, or complex, paired, discrete measurements of suspended-sediment “surrogates” and SSC have been used to develop statistical models to estimate SSC and sediment loads (Rasmussen and others, 2009; Griffiths and others, 2012; Landers and others, 2016). Turbidity, which is a measure of light scattering in the water column, has been widely used as a surrogate of suspended-sediment in the Nation’s waters (Rasmussen and others, 2009). Depending on field and hydrologic conditions and study design, continuous monitoring of turbidity has the potential to capture a large proportion of the natural variability of turbidity conditions in a stream and, thus, can be used to examine the variability of SSCs driven by different hydroclimatic processes and various sources of sediment on the landscape.

Continuous Monitoring of Streamflow and Turbidity

Two streamgages were used to continuously monitor turbidity and streamflow entering and exiting Jackson on Flat Creek. In the fall of 2018, the USGS established the Flat Creek above Cache Creek, at Jackson, Wyo. (13018250; fig. 1*C*) streamgage near the northern, upstream boundary of Jackson. USGS streamgage 13018250 was used as the upstream monitoring location for this study. Flat Creek, at this location, flows under a small bridge (fig. 2*A*), where the banks of the channel are armored by rip-rap. Just beyond the east bank is a parking area and storage facility, and the west bank abuts a mobile home park.

At the downstream boundary of Jackson, the Flat Creek below Cache Creek, near Jackson, Wyo. (13018350; fig. 1*C*) streamgage was used. Flat Creek at streamgage 13018350 flows under a bridge at High School Road (fig. 1*C*), and the channel banks are lined by grasses, shrubs, and rip-rap (fig. 2*B*). Just beyond the east bank is a parking lot, and beyond the west bank a sod yard surrounding a business complex. A storm sewer pipe about 30 centimeters in diameter enters the channel of Flat Creek on the east bank just upstream from streamgage 13018350 (fig. 2*B*).

Starting in the fall of 2018, turbidity sensors were suspended from the bridges near each of the two streamgages (fig. 2*A*–*D*). The sensors were housed in 10-centimeter diameter Teflon-coated aluminum tubes (fig. 2*C*), which were secured with a chain extending down into the water column (fig. 2*A* and *B*). Before April 2019, each station had an Analite NEP–5000 turbidity sensor (wavelength of 850 nanometers). After April 2019, a YSI 6136 turbidity sensor (wavelength of 860 nanometers) was installed at streamgage 13018350 because it was more compatible with the data-collection platform at this station. Both sensors conform to the International Organization for Standardization method 7027 (International Organization for Standardization, 2022) standards, having near-infrared wavelength beams and a single light detector oriented at 90-degrees from the incident light path. The sensors measured turbidity of the water column continuously and recorded and provided the provisional data to the public in 15-minute increments via the USGS National Water Information System database (https://doi.org/10.5066/F7P55KJN). Standard reporting units listed by manufacturers of both instruments are nephelometric turbidity units (NTU), but the reporting units in the National Water Information

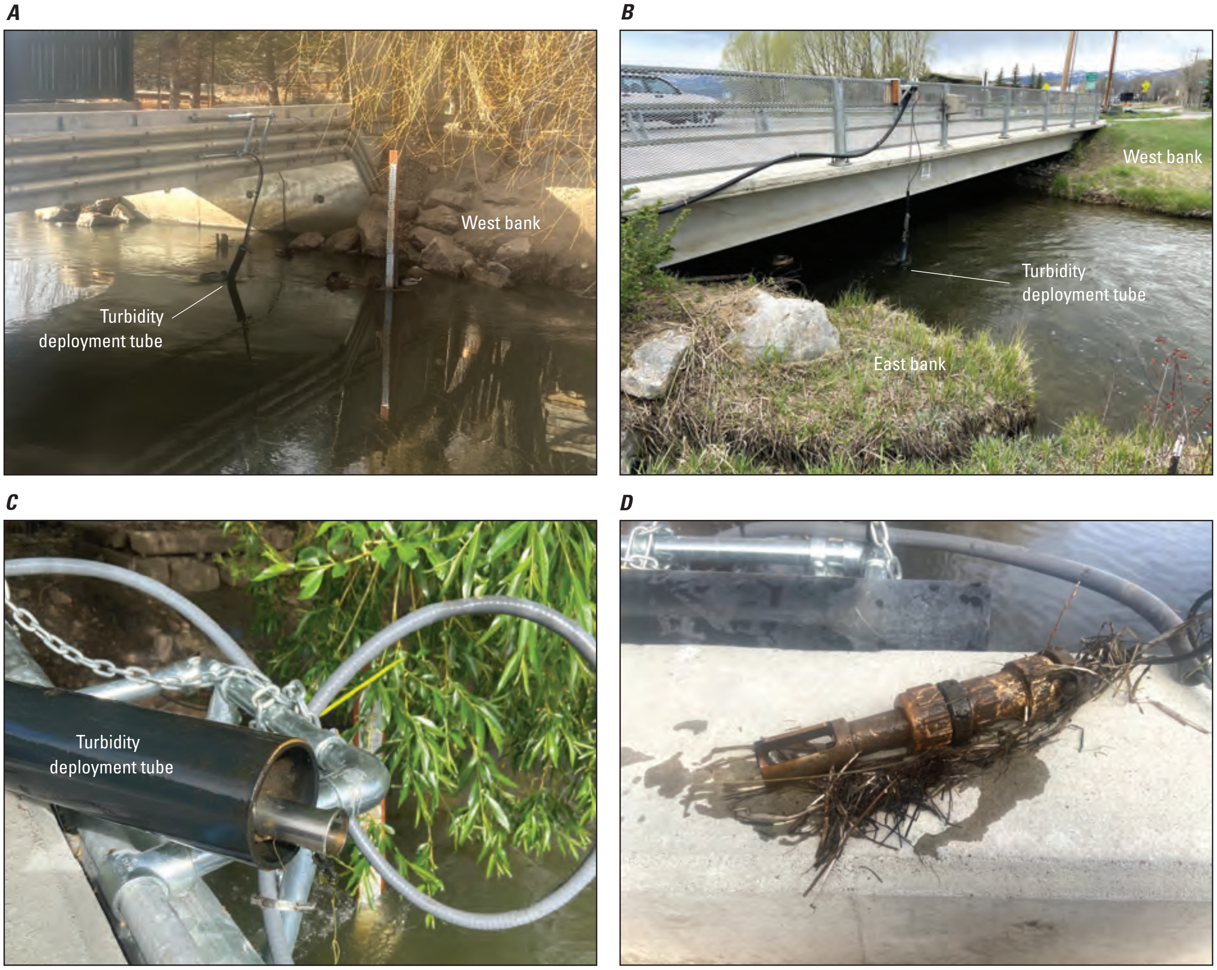


Figure 2. (*A*) Local environmental setting of U.S. Geological Survey (USGS) streamgage 13018250 (Flat Creek above Cache Creek, at Jackson, Wyoming; flow direction is right to left); (*B*) USGS streamgage 13018350 (Flat Creek below Cache Creek, near Jackson, Wyo.); (*C*) closeup of bottom end of Teflon-coated aluminum deployment tube with rock guard of the turbidity sensor protruding from the end; (*D*) closeup of Analite NEP–5000 turbidity sensor with entangled grasses, a typical result at the USGS streamgage 13018250 deployment. All photographs by Jason S. Alexander, USGS.

System database were in formazin nephelometric units (FNU), which are numerically equivalent to NTU (International Organization for Standardization, 2022).

Quality Control of Continuous Turbidity Monitoring

Biofouling (fig. 2*D*) and calibration checks of deployed turbidity sensors were made by USGS field personnel on visits typically made once every 6 weeks. These checks followed the methods described in Wagner and others (2006). Grasses and algae were often removed between USGS field visits by TCD personnel. Field turbidity sensors were used to check the relative accuracy of the deployed sensors. In 2019 and early 2020, a YSI 6136 was used as the field sensor. For most of 2020, an Analite NEP–5000 sensor was used as the field sensor. Both sensors are identical technology as those used in the site deployments. Flow in the channels at both sites was well mixed, but turbidity cross sections, which quantify any differences between turbidity measurements at the continuous monitor relative to the complete channel, were collected twice a year.

Characterization of Hydroclimatic Conditions

Suspended-sediment transport and sediment loads observed in any river or stream are driven by hydroclimatic processes over the measurement period. Hydroclimatic conditions in the Flat Creek study area were characterized based on published snowpack, streamflow, and precipitation data. Winter snowpack data were used as a broad measure of relative water supply in each water year. Snowpack data were obtained from the Granite Creek weather station (fig. 1*B*), which is about 30 km southeast of Jackson, in the Hoback

River Basin. The Granite Creek station was selected because it is the closest weather station to the study area within the same mountain range as the headwaters of Flat Creek with daily snow-water equivalent (SWE) records from 1988 to the present (2022) and is at an altitude of about 2,064 m, making these records broadly representative of the mid-to-high altitude regions of the Flat Creek drainage basin. Daily SWE records were obtained from the Natural Resources Conservation Service (U.S. Department of Agriculture-Natural Resources Conservation Service, 2021), which operates the station. To characterize relative water supplies over the winters of 2018–19 and 2019–20, daily SWE conditions at the Granite Creek station were compared to the 10th, 50th (median), and 90th quantiles of the period of record preceding the study period (1981–2018).

Streamflow data at USGS streamgage 13018350 were used to characterize daily streamflows, mean annual streamflow, annual instantaneous peak streamflow (annual peak streamflow), and the timing of onset of the annual snowmelt pulse over the study period. This streamgage was selected because it has the longest continuous period of record and is at the downstream end of the study area and, thus, fully integrates the hydrology of the study area. USGS streamgage 13018350 began operating in 1989, but not all streamflow statistics are available from the USGS for the entire period of record. Daily streamflow statistics were available from 1991 to 2022. Mean annual streamflow statistics at streamgage 13018350 were available for water years 2000 through the present. Annual peak streamflow timing and magnitude were available for 1989 through the present. The day of onset of snowmelt in Flat Creek was identified using the method of Cayan and others (2001) for 2019 and 2020 and compared to the available period of record. The method of Cayan and others (2001) requires mean daily streamflow data for an entire calendar year, and streamgage 13018350 only has available data from 2000 to 2022; therefore, statistics of snowmelt timing could only be compared for water years 2000 to 2022.

Daily precipitation was used to characterize the number and magnitude of rainfall events in the Flat Creek drainage basin over the study period relative to the period of precipitation record. Daily precipitation was obtained using the AN81d dataset from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) available from the PRISM Climate Group at Oregon State University (PRISM Climate Group, 2021). The AN81d daily precipitation dataset is available at no cost in a gridded format at a 4-km resolution and has a daily period of record spanning from January 1981 to the present. Gridded estimates of mean daily precipitation from the PRISM dataset were subset to two subbasins of the study area by converting the raster to point data using the "rasterToPoints" tool in the "raster" package (Hijmans, 2021) of language R, version 4.0.2 (R Core Team, 2021). Each point in the dataset was subset to one of two subbasins: (1) the drainage basin area upstream from USGS streamgage 13018250 (upstream subbasin) and (2) the drainage basin area upstream from USGS streamgage 13018350 but excluding the area upstream from streamgage 13018250 (downstream subbasin). The spatially averaged mean daily precipitation for each subbasin was taken as the simple arithmetic mean of the data points within each subbasin:

$$\langle P_j \rangle = \frac{\sum_{i_j=1}^{n_j} i_j}{n_j}, \tag{2}$$

where

$\langle P_j \rangle$ is the spatially averaged precipitation on a given day for basin *j*, in millimeters, and

n_j is the total number of data points *i* from the AN81d daily precipitation dataset within basin *j*.

The spatially averaged data were then compiled for each day to create a daily mean precipitation record for the calendar years 1981–2020.

Precipitation within the study area and over the study period was characterized by comparing daily precipitation from the 1981–2018 period of record to the same values in each subbasin for the 2019 and 2020 study periods. The precipitation analysis was used to quantify total precipitation, number of days with measurable precipitation, number of days with precipitation totals greater than the period-of-record median, and 90th percentile rainfall magnitudes. Because the study was done during the non-ice season, and snowmelt and rainfall was of primary concern for direct sediment runoff, the annual period when snowmelt and rainfall was most likely to occur was first defined (hereinafter referred to as the "warm season"). This definition was done using the AN81d daily temperature data from the PRISM dataset (PRISM Climate Group, 2021). In the same manner described previously for precipitation data, a daily record of average temperature was created by spatially averaging data subset to the study area boundary (fig. 1*A*):

$$\langle T_j \rangle = \frac{\sum_{i_j=1}^{n_j} i_j}{n_j}, \tag{3}$$

where

$\langle T_j \rangle$ is the spatially averaged temperature on a given day for basin *j*, in degrees Celsius.

The daily temperature record was used to extract median temperature values for each day of the year over the period of record preceding the study, 1981–2018. Using median daily temperature values over the period of record, the "warm season" was defined as beginning and ending on the first and last day that study area median temperatures were greater than 0 °C during the calendar year. Precipitation statistics were then extracted for the 1981–2018 period of record for the warm season, and the median and mean total for the warm season, median number of days of measurable precipitation, and median number of days with rainfall exceeding the warm season 50th and 90th percentiles of total daily precipitation were used as basic measures of precipitation for comparison with the 2019 and 2020 study periods.

Comparison of Turbidity Measurements Between Streamgages

As stated previously, the WYDEQ water-quality standards prohibit increases of greater than 10 NTU from human activities in Class 2AB waterbodies of Wyoming. Continuous monitoring of turbidity conditions in Flat Creek upstream and downstream from Jackson provided the opportunity to examine the frequency, direction, and magnitude of turbidity in an upstream to downstream manner.

The 15-minute records of turbidity for calendar years 2019 and 2020 were used to construct a record of differences in turbidity. A simple time-of-travel calculation was made to pair turbidity values between USGS streamgages 13018250 (upstream streamgage) and 13018350 (downstream streamgage) and quantify turbidity differences because a cell of surface water, and associated turbidity, observed at the upstream streamgage takes time (hours to days) to travel to the downstream streamgage. Mean time-of-travel of water between streamgages was estimated as the quotient of along-stream distance between streamgages and mean velocity of water throughout the channel width. The along-stream distance between streamgages was estimated using the “ruler” tool in Google Earth Pro software (Google Earth, 2021). Mean velocity in the channel was estimated by examining the summary statistics of mean velocities observed during streamflow measurements at each streamgage. The mean time-of-travel was then used as the time offset between the upstream and downstream turbidity measurement pairs, which were subsequently differenced for every available pair to quantify the magnitude, direction, and frequency of turbidity differences between streamgages.

Discrete Sampling of Suspended Sediment

From November 15, 2018, to October 19, 2020, discrete suspended-sediment samples were collected at the streamgages 13018250 and 13018350 by USGS and TCD personnel. For each sampling event, suspended-sediment samples were collected from the bridge deck using a US DH–81 depth-integrating water-quality sampler secured to a 3-m-long pole (Davis, 2005). Suspended-sediment samples were collected using the depth and velocity integrated 10-station equal width increment method (Edwards and Glysson, 1999). A total of 24 suspended-sediment samples were collected at each streamgage, 2 replicate samples for each of the 12 sampling events. Suspended-sediment sampling was targeted to represent the range of turbidity conditions observed in the continuous record. Replicate samples were collected to assure quality control of the data and to calculate average concentrations and standard errors.

Suspended-sediment samples were analyzed at the USGS Wyoming-Montana Water Science Center Sediment Laboratory in Helena, Montana, and the USGS Iowa Sediment Laboratory, in Iowa City, Iowa. Samples were analyzed for SSC and the percentage of the sample composed of grain sizes finer than 0.0625 mm (silt and clay) using the methods described in Guy (1969). Loss-on-ignition (LOI) analysis (Guy, 1969) was also completed on some samples to quantify the percentage of the sample composed of particulate organics. At the upstream site, 8 individual samples were analyzed for LOI; 10 individual samples from the downstream site were analyzed for LOI. The results of the LOI analysis were used to determine if some percentage of suspended material at the upstream site might be composed of organic materials derived from the wetlands of the Elk Refuge.

Statistical Modeling of Suspended-Sediment Concentrations in Flat Creek

Modeling of SSCs and loads in Flat Creek through Jackson, Wyo., closely followed the statistical procedures outlined in Rasmussen and others (2009). Outliers of discrete SSC data were identified by visual examination of scatter plots with turbidity (in FNU) plotted as the independent variable and SSC (in milligrams per liter) plotted as the dependent variable. Thresholds of 100-percent and 50-percent difference between paired, discrete samples were used to identify outliers in SSC for lower (<10 FNU) and higher (>10 FNU) values of turbidity, respectively. For most data pairs, the discrete value of turbidity was selected as the value measured closest in time to the discrete SSC sample time at each streamgage. In some cases, the continuous turbidity record was missing measurements at a time close to the discrete SSC sample time, typically because of biofouling, and the discrete value from the field turbidity instrument was used instead as the discrete value of turbidity. This substitution in turbidity value may introduce error or bias because of slight differences in turbidity readings between instruments and instrument technology (Rasmussen and others, 2009). Nonetheless, any error or bias introduced by this substitution is assumed to be minor relative to the reduction in model error caused by inclusion of additional, representative discrete turbidity measurements.

In addition to the number of paired samples, the accuracy of any predictive statistical model is dependent on data representative of the range of natural hydrologic conditions over the period of interest (Helsel and others, 2020). Discrete turbidity measurements associated with each discrete SSC sample were assessed for representation across the observed distribution by estimating their quantiles within the empirical cumulative distribution function (ECDF) of continuous turbidity records at each streamgage. The ECDF of the continuous turbidity records and the quantile estimates of discrete turbidity measurements within the ECDF were calculated using the “ecdf” function in R (R Core Team, 2021).

Sediment and flow conditions tend not to change over the short periods (less than 10 minutes) required for sample collection, and thus, samples that were collected closely spaced in time are often correlated (serial correlation). Such correlation can introduce bias in statistical models through overrepresentation of a narrow set of flow conditions within the sample set. Two samples of SSC were collected for every sampling event, but these individual samples are highly correlated, and thus, single-point values are desired for the purposes of representing average conditions during each event. For sample pairs that did not have either value identified as an outlier, the two values were averaged to represent a point estimate of average SSC.

Single-variable linear least-squares regression models of the following form were used to predict SSCs:

$$\log_{10}(SSC)=\beta_0+\beta_1\log_{10}(x_i), \quad (4)$$

where

β_0 and β_1 are the model intercept and slope coefficients, respectively, and

x_i is the ith measurement of the explanatory variable.

For the statistical models described in this report, x_i represents discrete measurements of turbidity, in FNU. The base-10 logarithm ($\log_{10}$) transformed model was used because exploratory analysis indicated this transformed model was more compliant with the fundamental assumptions of linear least-squares regression (for example, constant variance, normally distributed residuals, linear pattern of data across residual line) than nontransformed models.

Transformation of the response variable introduces bias when the predicted value is retransformed to standard units (Miller, 1951; Koch and Smillie, 1986). Transformed predictions of SSC using the model described previously were corrected for bias using the nonparametric bias correction factor (BCF) of Duan (1983):

$$BCF = \frac{\sum_{i=1}^{n} 10^{e_i}}{n}, \quad (5)$$

where

n is the number of samples i, and

e_i is the difference between each measured and estimated concentration, in $\log_{10}$ units (Rasmussen and others, 2009).

Retransformed predictions of SSC and associated prediction intervals were corrected for bias by multiplying by the BCF:

$$SSC = 10^{\beta_0} x_i^{\beta_1}(BCF). \quad (6)$$

Prediction intervals on predicted values of SSC were calculated using the "predict" function on each model in R (R Core Team, 2021).

Sediment loads were computed for all available pairs of continuous turbidity and streamflow data at each streamgage. Each turbidity measurement was used to predict SSC using the procedure described above, and a sediment load was calculated as follows:

$$SSL_i=SSC_i{*}Q_i{*}c_i, \quad (7)$$

where

SSL_i is the suspended-sediment load, in kilograms per second;

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

Q_i is streamflow for the ith value, in cubic meters per second; and

c_i is a constant for unit conversion.

Sediment loads over each 15-minute period were computed as follows:

$$SSL_n = \sum_{i=1}^{n} \frac{(SSC_i + SSC_{i-1}){*}(Q_i + Q_{i-1}){*}(t_i - t_{i-1})}{4} c_i, \quad (8)$$

where

SSL_n is the computed sediment load over the 15-minute time interval and

t_i is the time of the ith measurement.

Balancing and Partitioning Modeled Suspended-Sediment Loads in Flat Creek

For a given segment of stream, the term "sediment balance" refers to the mass continuity of sediment incoming from upstream relative to sediment exported at the downstream end of the segment. The sediment balance can be expressed as a simple mass continuity statement:

$$SSL_{upstream}-SSL_{downstream}+\Delta_{storage}=0, \quad (9)$$

where

$SSL_{upstream}$ is the mass of sediment incoming to the segment measured over some measurement period,

$SSL_{downstream}$ is the mass of sediment exported from the segment measured over the same measurement period, and

$\Delta_{storage}$ is the change in sediment storage.

The $\Delta_{storage}$ term refers to deposition or erosion of sediment within the stream segment. If unmeasured sediment tributaries bring sediment into the segment between the upstream and downstream measurement locations, the mass balance cannot be closed and the $SSL_{downstream}$ term may include sediment loads from tributaries in addition to sediments deposited or eroded between stations, such as sediments from the streambank.

To better understand sediment inputs from various sources, a mass balance of suspended-sediment loads was estimated for the study segment of Flat Creek using suspended-sediment loads calculated at the upstream (13018250) and downstream (13018350) USGS streamgages using the time-of-travel adjusted records. Sediment loads were examined for various sources by partitioning intervals of the suspended-sediment load time series at each streamgage. Model-predicted sediment loads were partitioned for three timescales: (1) total period of available record in each measurement year, (2) periods of record for the influx of transbasin water from the Gros Ventre River via the South Park Supply Ditch, and (3) periods of record for isolated daily precipitation events. Turbidity and SSC were not monitored on Cache Creek, and thus, sediment inputs from Cache Creek could not be isolated from other potential sources of sediment between the two streamgages on Flat Creek.

The total period of record for each measurement year was different for each streamgage. This difference was primarily due to periods when one turbidity sensor was biofouled and the other was not, but slight differences also resulted because of sensor installation and removal times. Consequently, the total available period of record sediment loads was calculated and compared in two ways. First, sediment loads were calculated for every approved 15-minute turbidity measurement at each streamgage. Loads calculated in this way include the total measured and model-predicted SSC and are thus the nearest, yet still incomplete, estimation of the total suspended-sediment loads over the measurement periods. Second, sediment loads were calculated for the minimum period of record when coincident 15-minute measurements were approved at both streamgages (hereinafter “coincident period-of-record”). Coincident period-of-record sediment loads, although less complete than the total observed sediment loads, were considered the most accurate way to examine the relative sediment balance of the study stream segment.

To examine potential sediment loads from the Gros Ventre River transbasin diversion via the South Park Supply Ditch, the timing of operations of the South Park Supply Ditch needed to be identified. Data documenting dates of operation of the South Park Supply Ditch or the amount of flow in the ditch at any given time could not be obtained. The influx of water from the South Park Supply Ditch typically results during the rising limb of the snowmelt hydrograph in most years and is indicated by a sudden rise in streamflow of as much as 1.6 m^3/s (the full adjudicated water allocation) (Brian Remlinger, Alder Environmental, written commun., 2021). The South Park Supply Ditch is typically shut off in mid-to-late September and is indicated by a sudden rise in the streamflow at streamgage 13018350. The rise in streamflow in Flat Creek when the ditch is shut off is counter intuitive because the South Park Supply Ditch provides additional water to Flat Creek. However, when the South Park Supply Ditch is shut off, other diversions upstream from streamgage 13018350 also are shut off, resulting in more water in the creek (Brian Remlinger, Alder Environmental, written commun., 2021). These two streamflow rises were used to identify signals in the hydrograph at streamgage 13018350 and isolate the timing of operations of the South Park Supply Ditch in both years of measurement.

Although relatively precise inference on the timing of operations of the South Park Supply Ditch could be made, partitioning the magnitude of suspended-sediment loads coming into Flat Creek in Jackson from the South Park Supply Ditch and Cache Creek, and diversions coming from urban runoff, required additional inference using available data. Cross-correlation analysis between 15-minute time series of the turbidity records at streamgages 13018250 and 13018350 and the coincident streamflow records from potential tributary sediment sources were used as a basic measure of likely sediment sourcing. Cross-correlation analysis was performed using the autocorrelation function in R (R Core Team, 2021), and the calculated maximum Pearson correlation coefficient of lagged records was used as the measure of strength of association. Use of correlation between turbidity and streamflow, although an imperfect measure of sourcing, is rooted in the hypothesis that the turbidity record at a measurement point would be expected to be most strongly correlated to the streamflow record of its primary sediment source. For streamgage 13018250, the turbidity record was cross-correlated with the streamflow record of that streamgage and the streamflow record at the Gros Ventre River at Kelly, Wyo. (USGS streamgage 13014500), which is the nearest streamgage upstream from the South Park Supply Ditch diversion point (fig. 1*B*). For streamgage 13018350, the turbidity record was cross-correlated with the streamflow record of that streamgage (13014500), and Cache Creek near Jackson (USGS streamgage 13018300; fig. 1*B*).

Examination of coincident turbidity records indicated the presence of short-duration (less than 2 hours) spikes in the turbidity record of the downstream streamgage (13018350) that were not typically observed at the upstream streamgage (13018250). These spikes were almost always coincident with precipitation events and, because of their short duration (less than 2 hours), were likely the consequence of urban runoff from impervious surfaces within Jackson. The short-duration spikes in turbidity at streamgage 13018350 were identified and isolated from the rest of the turbidity measurements using a moving average filter:

$$T_i \begin{cases} \mathit{urban\ runoff},\ 5 < T_i - \dfrac{\left(T_{(i-1)} + T_{(i-2)} + \ldots T_{(i-n)}\right)}{n}, \ or \\ \hline \mathit{other\ runoff},\ 5 > T_i - \dfrac{\left(T_{(i-1)} + T_{(i-2)} + \ldots T_{(i-n)}\right)}{n} \end{cases}, \qquad (10)$$

where

T_i is the ith 15-minute measurement of turbidity, in formazin nephelometric units;

n is the number of turbidity measurements preceding the ith measurement; and

$<, >$ are less than and greater than, respectively.

Trial and error with values of n resulted in the choice of 96, which equates to 24 hours if all 15-minute measurements are available in the data record. Deviation of more than 5 FNU from the 96-measurement moving average was selected as the criterion for classifying a measurement as urban runoff. The 5-FNU threshold was selected here because the magnitude of fluctuations under stable conditions (instrument precision) observed in the field was typically less than 5 FNU.

Lastly, the seasonal pattern of model predicted sediment concentrations relative to seasonal changes in streamflow was examined. Natural suspended-sediment loads measured in rivers commonly indicate hysteresis, whereby sediment loads for the same streamflow vary in time because of changes in upstream sediment supply, bed material grain size, and (or) bedform size (Topping and Wright, 2016). Coarse-bedded mountain streams commonly exhibit clockwise hysteresis, whereby SSCs are higher on the rising limb of the snowmelt hydrograph than on the receding limb of the hydrograph (Williams, 1989). Coincident period-of-record predicted SSCs were compared between the upstream and downstream streamgages for measurements classified as driven by urban runoff at the downstream streamgage based on the methods described previously. This comparison was done graphically and by calculating quantiles of the sediment concentrations relative to the broader population of predicted concentrations at each station.

Continuous Measurements of Turbidity to Predict Suspended-Sediment Concentrations, Loads, and Sources in Flat Creek Through the Town of Jackson, Wyoming, 2019–20

Hydrologic conditions over the study period were wetter than median conditions during the 2019 and 2020 measurements periods. Although sample size was low, statistical models were built that adequately describe relations between turbidity and suspended-sediment concentration in Flat Creek. Suspended-sediment loads estimated using the models indicate that as much as ten percent of the suspended-sediment load observed in Flat Creek at the downstream end of the study area may be coming from urban runoff in the town of Jackson, but potentially larger amounts of suspended-sediment may be coming from the Gros Ventre River transbasin diversion.

Hydroclimatic Conditions

Peak snowpack conditions in the Gros Ventre Mountains measured at the Granite Creek weather station (fig. 1*B*) during the 2019 and 2020 water years were above median peak conditions (fig. 3*A*, *B*). The median peak SWE at the Granite Creek weather station for the 1988 to 2018 period of record was 387 mm on March 18. SWE levels in water year 2019

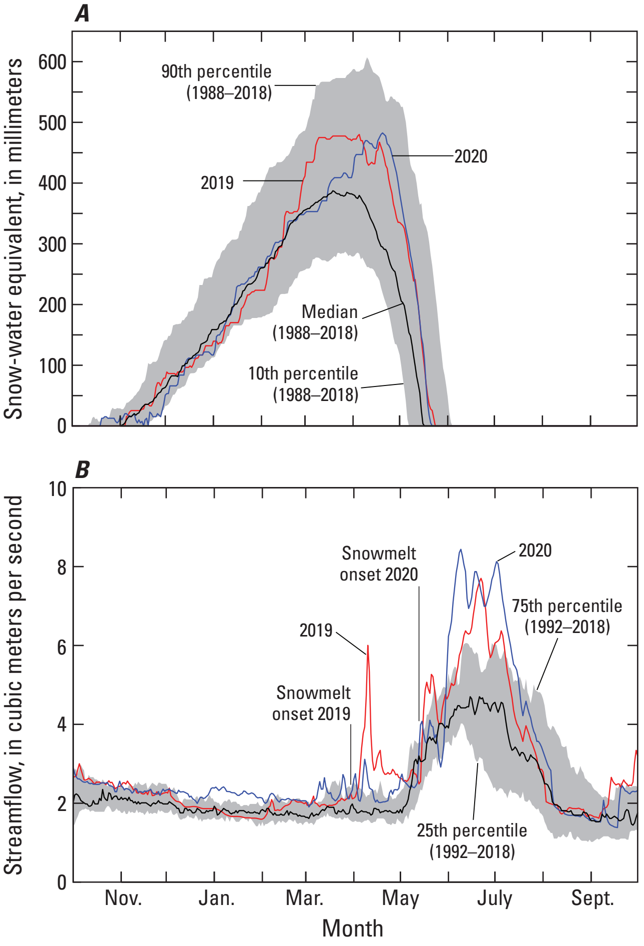


Figure 3. Time series of statistics and annual data for (*A*) 10th to 90th percentiles of snow-water equivalent for water years 1988–2018 and snow-water equivalent for water years 2019 and 2020 at the Granite Creek weather station in the Gros Ventre Mountain Range of northwestern Wyoming; (*B*) 25th to 75th percentiles of mean daily streamflow for water years 1992–2018 and mean daily streamflow for water years 2019 and 2021 at U.S. Geological Survey streamgage 13018350 (Flat Creek below Cache Creek, near Jackson, Wyoming). Snow-water equivalent data in *A* are from the U.S. Department of Agriculture-Natural Resources Conservation Service (2021). Streamflow data in *B* are available from the U.S. Geological Survey National Water Information System database (https://doi.org/10.5066/F7P55KJN). Snowmelt onset in *B* for 2019 and 2020 was calculated using the method of Cayan and others (2001).

fluctuated around median conditions until mid-February, when these levels increased substantially above the median and remained high until late April. The peak SWE in water year 2019 was 480 mm on April 4, 2019 (fig. 3*A*, *B*), ranking 12th in 34 years of record. The SWE in water year 2019 was 0 mm on May 22, 2019. In water year 2020, SWE conditions tracked median conditions for much of the winter but continued to increase beyond the median after mid-March (fig. 3*A*, *B*). The peak SWE in water year 2020 was 483 mm on April 19, 2020, ranking 11th out of 34 years of record. The SWE in water year 2020 was 0 mm on May 20, 2020.

Daily mean streamflows in Flat Creek measured at streamgage 13018350 were greater than median conditions for most days of water years 2019 and 2020, and peak flow conditions reflected the greater-than-median conditions of the snowpack measured at the Granite Creek weather station (figs. 1*B* and 3). Mean annual streamflow at streamgage 13018350 was 2.87 m^3/s in 2019, and 2.94 m^3/s in 2020, ranking 5th and 7th highest, respectively, out of 21 years of available statistics. The calculated day of snowmelt pulse initiation at streamgage 13018350 was April 3 for 2019 and May 11 for 2020. Those days ranked 5th and 17th earliest, respectively, relative to the 21 years of record. Peak streamflow in 2019 was 7.76 m^3/s on June 21; peak streamflow in 2020 was 8.55 m^3/s on June 7. The 2019 and 2020 peak streamflows ranked 7th and 3d highest, respectively, out of 29 years of record.

An analysis of the AN81d daily temperature dataset (PRISM Climate Group, 2021) identified April 10 and October 30 as the first and last days the period of record (1981–2018) median temperature in the Flat Creek drainage basin upstream from USGS streamgage 13018350 was greater than 0 °C (fig. 4*A*). This period of the calendar year is herein referred to as the "warm season," and precipitation during this period is assumed to be rainfall or snowmelt. The assumption is used to identify days of heavy rain (or exceedingly wet snow) during the study period that may be driven by urban runoff and create short-duration (hours) spikes in SSC.

The period-of-record (1981–2018) mean total precipitation in the study area during the warm season was 315 mm; the median total precipitation over the same period is 314 mm (table 2). The median number of days with precipitation during the warm season in the study area is 107. Over the period of record, median (50th percentile) magnitude of rainfall on days with rain was 1.45 mm, and the 90th percentile magnitude was 8.00 mm. The median number of days exceeding these percentiles over the period of record was 54 and 11, respectively.

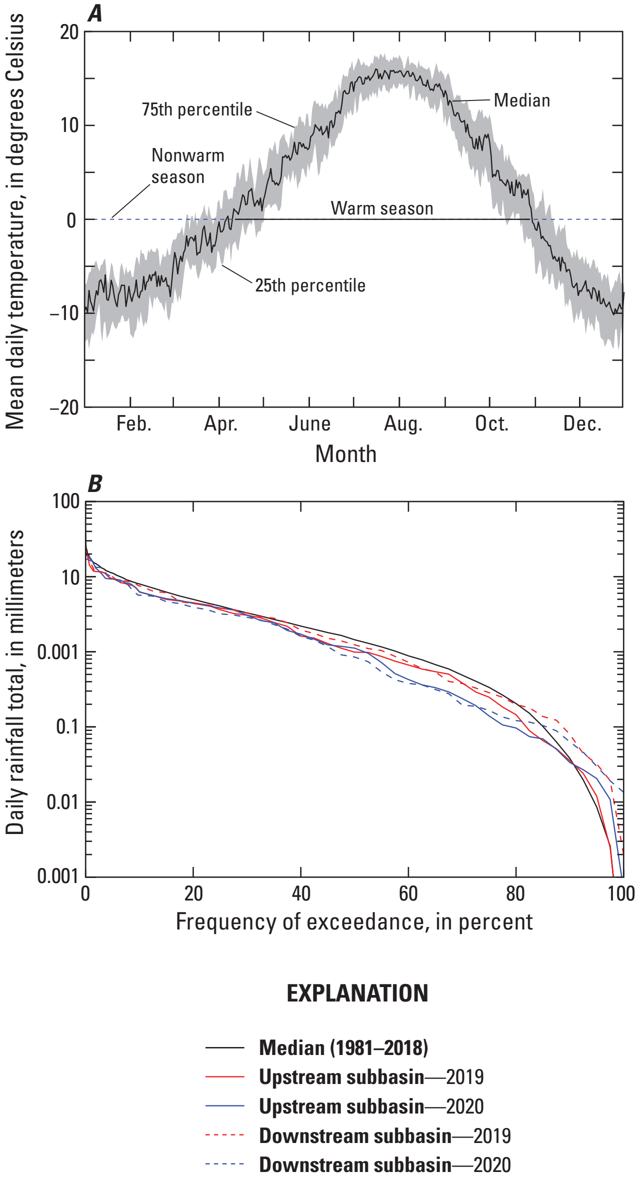


Figure 4. (*A*) Time series of statistics of mean daily temperature for the Flat Creek study area, northwestern Wyoming, for the 1981–2018 period of record; (*B*) frequencies of daily precipitation totals for the Flat Creek study area, northwestern Wyoming, over the 1981–2018 period of record and for the 2019 and 2020 water years within two subbasins of the Flat Creek study area. All data are derived from the AN81d dataset, available from PRISM Climate Group (2021).

The terms "upstream subbasin" and "downstream basin," again, refer to the drainage basin area upstream from USGS streamgage 13018250 and the drainage basin area upstream from USGS streamgage 13018350 but excluding the area upstream from 13018250, respectively. During the warm season in 2019, total precipitation, the number of days with precipitation, and the number of days with rainfall exceeding the median and 90th percentile magnitudes were greater than the period-of-record mean and median conditions in both subbasins (table 2). Except for the total number

Table 2. Statistics of daily precipitation in the Flat Creek study area, northwestern Wyoming, during the warm season.

[All data are from the AN81d PRISM climate dataset (PRISM Climate Group, 2021). The warm season is defined herein as April 10–October 30, which are the first and last days when the long-term median daily temperature in the study area is above freezing. PPT, precipitation (assumed to be mostly liquid); mm, millimeter; POR, period of record, defined as 1981–2018, which is the period preceding the 2019 and 2020 study periods; USGS, U.S. Geological Survey]

Location and period	Total PPT (mm)	Number of PPT days[a]	Number of days exceeding POR percentile[b]	
			50th (1.45 mm)	90th (8.00 mm)
Study area (1981–2018)[c]	314	107	54	11
Upstream subbasin[d]				
Warm season 2019	350	139	60	11
Warm season 2020	274	109	47	10
Downstream subbasin[d]				
Warm season 2019	339	124	58	12
Warm season 2020	249	104	44	8

[a] Number of days during warm season with recorded precipitation greater than 0.0 mm.

[b] Percentiles are defined as the percentiles of mean daily rainfall during the warm season over the 1981–2018 period of record.

[c] Period-of-record data are shown as the median value for the warm season over the period of record.

[d] The upstream subbasin is defined as the area upstream from USGS streamgage 13018250 (Flat Creek above Cache Creek, at Jackson, Wyoming); the downstream subbasin defined as the basin area upstream from USGS streamgage 13018350 (Flat Creek below Cache Creek, near Jackson, Wyo.), not including the upstream subbasin.

of precipitation days in the upstream subbasin, the 2020 hydrologic/environmental conditions for the same set of metrics were below period-of-record mean and median conditions (table 2). Empirical cumulative distribution curves of total daily rainfall for 2019 and 2020 relative to the period-of-record median empirical cumulative distribution indicate that light daily rainfall totals (less than about 0.2 mm) were more frequent than typical, and moderate rainfall totals (between about 0.2 and 1 mm) were less frequent than typical, and heavier rainfall totals were about as common as the period-of-record median values (fig. 4*B*).

Continuous Turbidity Records in Flat Creek, 2019–20

Turbidity sensors were initially installed at USGS streamgages 13018250 (upstream streamgage) and 13018350 (downstream streamgage) in October 2018 and were removed in November 2018 before winter ice formation. At both streamgages, biofouling and calibration problems hindered the creation of a turbidity record for the fall of 2018. Because a data record could not be created for the fall of 2018 at either streamgage, a turbidity measurement from the field sensor (YSI 6136) made at the time of the suspended-sediment measurement was paired with the measured SSC value (fig. 5*A*).

Turbidity monitoring at the upstream streamgage on Flat Creek (13018250) in calendar year 2019 began on April 2 and ran through November 15. Between the beginning and end of the 2019 record, a total of 21,773 potential data points (measurements) were available at the 15-minute recording interval. Of those, 15,432 data points (71 percent) from the 2019 continuous record met the data-approval criteria set forth in Wagner and others (2006). Most of the missing data values in the record are from the early spring flood and a part of the rising limb of the snowmelt hydrograph. Turbidity values within the 2019 continuous record ranged from 0.4 to 78.2 FNU, and the peak recorded value was measured on April 4, during an early spring snowmelt runoff event (fig. 5*A*). Two additional turbidity peaks were recorded at the upstream streamgage in 2019, one during the rising limb of the snowmelt hydrograph in early June, and one in early November during gradually declining base flows. Peak turbidity recorded during the snowmelt hydrograph at the upstream streamgage in 2019 was 44.3 FNU and was measured on June 9; peak turbidity during the November increase was 61.7 FNU and was measured on November 3.

Turbidity monitoring at the upstream streamgage in calendar year 2020 began on April 6 and ended on October 19. The 15-minute record between start and finish during this time had 18,819 potential data points (measurements), of which 15,824 (81 percent) for the 2020 continuous record met the data-approval criteria set forth in Wagner and others (2006). Because of sensor fouling, most of the missing data points in

2020 occurred during the rising limb of the snowmelt hydrograph. Turbidity values ranged from 0.9 to 88.3 FNU, and the maximum recorded value was measured on May 30 during the rising limb of the snowmelt hydrograph. A smaller peak in turbidity, potentially associated with timing of onset of water deliveries from the South Park Supply Ditch, resulted just before the onset of the large snowmelt peak. Peak turbidity during this earlier rise was 31.1 FNU and was measured on May 21.

Turbidity monitoring at the downstream streamgage on Flat Creek (13018350) in calendar year 2019 began on April 3 and extended to November 15. During that time, the 15-minute record had 21,683 potential data points (measurements), and 21,516 data points (99 percent) met the data-approval criteria set forth in Wagner and others (2006). Turbidity values in the 2019 record at the downstream streamgage ranged from 0.3 to 282 FNU, and the peak value was measured as an intermittent (about 2 hours) spike on April 24 during the recessional limb of the early spring snowmelt (fig. 5*B*). More sustained rises in

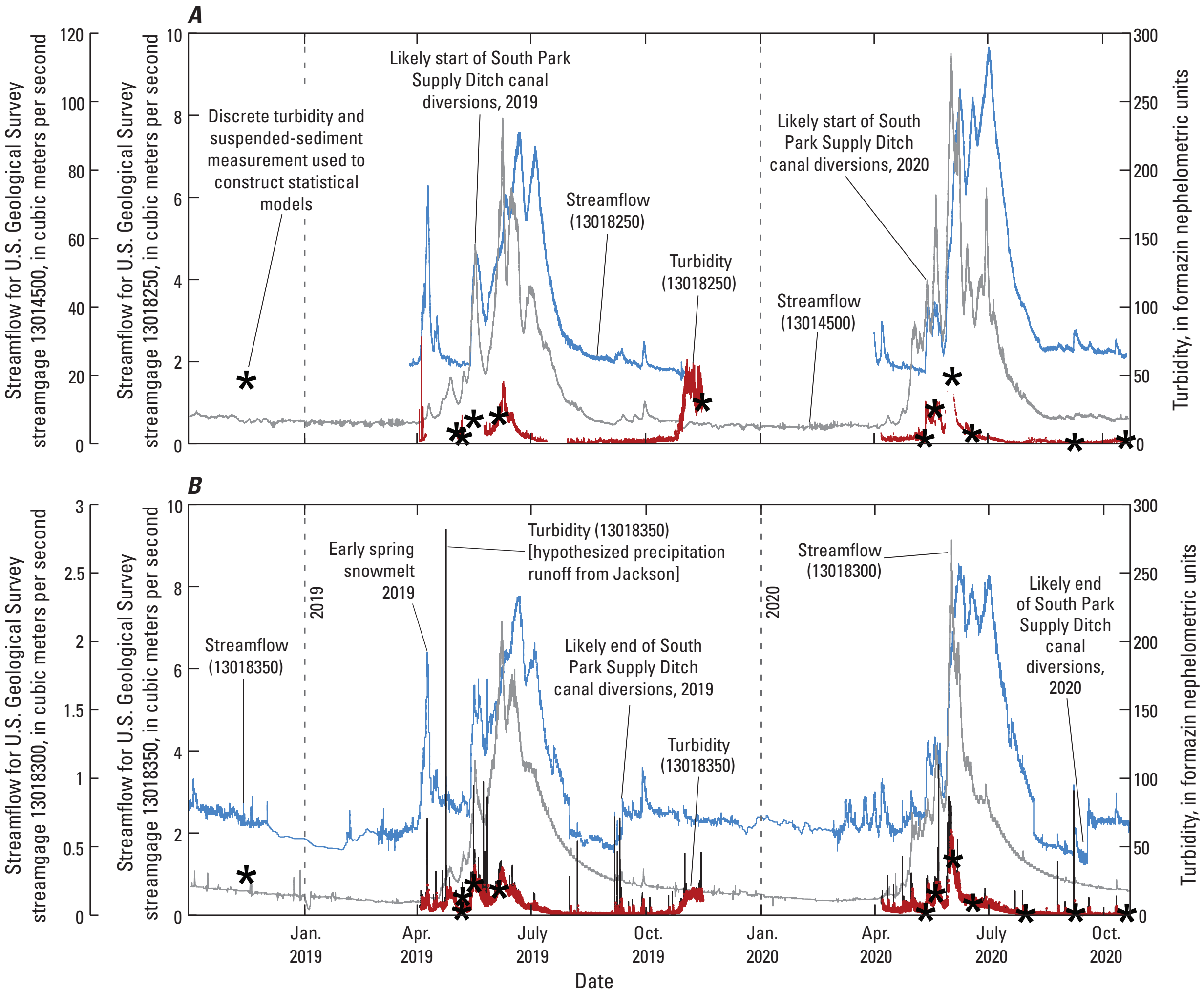


Figure 5. Time series from November 2018 to October 2020. (*A*) The 15-minute streamflow and turbidity record for U.S. Geological Survey (USGS) streamgage 13018250 (Flat Creek above Cache Creek, at Jackson, Wyoming; U.S. Geological Survey, 2021b), including timing and magnitude of discrete field turbidity measurements, and 15-minute streamflow for the same years at USGS streamgage 13014500 (Gros Ventre River at Kelly, Wyo.; U.S. Geological Survey, 2021a); (*B*) 15-minute streamflow and turbidity record for USGS streamgage 13018350 (Flat Creek below Cache Creek, near Jackson, Wyo.; U.S. Geological Survey, 2021d), including timing and magnitude of discrete field turbidity measurements, and 15-minute streamflow for the same years at USGS streamgage 13018300 (Cache Creek near Jackson, Wyo.; U.S. Geological Survey, 2021c). Black lines represent magnitudes of turbidity for hypothesized precipitation runoff events from the town of Jackson; (*C*) differences between upstream and downstream turbidity relative to assumed instrument error of plus or minus 5 formazin nephelometric units; and (*D*) study period mean daily precipitation and temperature for the Flat Creek Drainage Basin upstream from USGS streamgage 13018350.

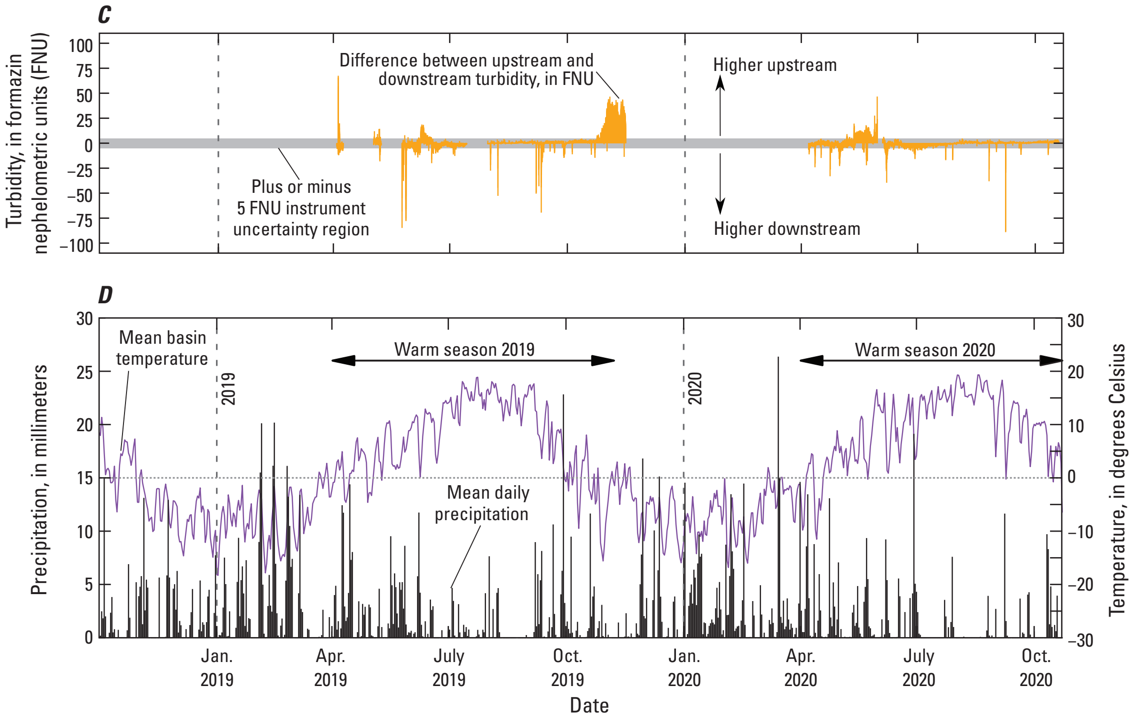


Figure 5. Time series from November 2018 to October 2020. (*A*) The 15-minute streamflow and turbidity record for U.S. Geological Survey (USGS) streamgage 13018250 (Flat Creek above Cache Creek, at Jackson, Wyoming; U.S. Geological Survey, 2021b), including timing and magnitude of discrete field turbidity measurements, and 15-minute streamflow for the same years at USGS streamgage 13014500 (Gros Ventre River at Kelly, Wyo.; U.S. Geological Survey, 2021a); (*B*) 15-minute streamflow and turbidity record for USGS streamgage 13018350 (Flat Creek below Cache Creek, near Jackson, Wyo.; U.S. Geological Survey, 2021d), including timing and magnitude of discrete field turbidity measurements, and 15-minute streamflow for the same years at USGS streamgage 13018300 (Cache Creek near Jackson, Wyo.; U.S. Geological Survey, 2021c). Black lines represent magnitudes of turbidity for hypothesized precipitation runoff events from the town of Jackson; (*C*) differences between upstream and downstream turbidity relative to assumed instrument error of plus or minus 5 formazin nephelometric units; and (*D*) study period mean daily precipitation and temperature for the Flat Creek Drainage Basin upstream from USGS streamgage 13018350.—Continued

turbidity were recorded at the downstream streamgage in 2019 during the likely onset of water influx from the South Park Supply Ditch in mid-May (fig. 5*B*), during the rising limb of the snowmelt hydrograph in late May and, as with measurements at the upstream streamgage in 2019, during late October and early November (fig. 5*B*). Intermittent rises were detected in 2019 throughout the summer, most of which appeared to be directly associated with rainfall events (fig. 5*B*, *D*).

Turbidity monitoring at the downstream streamgage on Flat Creek in calendar year 2020 began on April 6 and extended to October 19. During this period, a total of 18,790 potential data points were possible in the 15-minute record, of which 18,766 (99.9 percent) met the data-approval criteria set forth in Wagner and others (2006). Turbidity measurements in the 2020 record at the downstream streamgage ranged from 0.1 to 110 FNU, and the peak value was measured on May 22 during a flow peak in mid-May preceding the larger snowmelt peak. This peak may be associated with the influx of water from the South Park Supply Ditch (fig. 5*B*). A more sustained large rise in turbidity resulted 1 week later with the larger snowmelt peak. This second peak was at 86.7 FNU on May 30. Intermittent peaks resulted in 2020 throughout the summer, most of which seemed to coincide with rainfall events (fig. 5*B*, *D*).

The estimated along-stream distance between the upstream and downstream streamgages on Flat Creek through Jackson was measured as 5.1 km. Mean channel velocity from the 11 available flow measurements at the upstream streamgage was about 0.28 meter per second (m/s). Mean channel velocity from the 241 available measurements at the downstream streamgage was about 0.66 m/s. Using these two flow values as guidance, a value of 0.5 m/s was used as a reasonable approximation of mean channel velocity, resulting in an estimated mean time of travel of 170 minutes between the upstream and downstream streamgages. Based on the 0.5 m/s flow value, a time-of-travel offset of 11 data points in the mutual 15-minute records of the upstream and downstream streamgages was used to pair turbidity values of the upstream and downstream streamgages. An initial examination of the data indicated that the offset had negligible effects on the statistical distribution of turbidity differences between streamgages relative to using no time-of-travel offset. Nonetheless, the time-of-travel offset was used because it incorporates some accounting for mass-balance calculation.

Quantification of differences in turbidity measurements between upstream and downstream streamgages on Flat Creek indicated that increases of greater than 10 FNU were rare over the study period. Of the more than 15,000 coincident turbidity measurements in each year, 83 percent were within the plus or minus 5 FNU minimum assumed sensor uncertainty range in calendar year 2019, and 90 percent were within that range in calendar year 2020 (fig. 5*C* and fig. 6*A* and *B*). Increases of 10 FNU or greater between the upstream and downstream streamgages composed about 1 percent of the total number of measurements in 2019 and 2020. The median difference in turbidity between the upstream and downstream streamgages in 2019 was 0.20 FNU, and the inner 95 percent of values (2.5–97.5 percentiles) was between −7.2 and 20.2 FNU, indicating that higher turbidity values were more commonly measured at the upstream streamgage that year (fig. 6*A*). The median difference in turbidity between the upstream and downstream streamgages in 2020 was 0.0 FNU, and the inner 95 percent of values was between −5.5 and 6.3 FNU, indicating that turbidity values were generally similar (fig. 6*B*).

Examination of time series of turbidity differences between streamgages (fig. 5*C*) indicates that increases of 10 FNU or greater between upstream and downstream measurements typically result as intermittent spikes and are commonly coincident with precipitation events. Similarly, measurements of relatively large downstream increases in turbidity were made during the fall when flow in Flat Creek abruptly increases at the downstream streamgage (fig. 5*B*), an event assumed to be the shutdown of irrigation ditches. This abrupt increase in flow possibly mobilizes deposits of fine sediment in the channel. Time series of turbidity differences between streamgages also indicate that there are periods when turbidity is substantially higher upstream than downstream, such as the early spring runoff of 2019, base flows in late fall of 2019, and the rising limb of the snowmelt hydrograph in 2020.

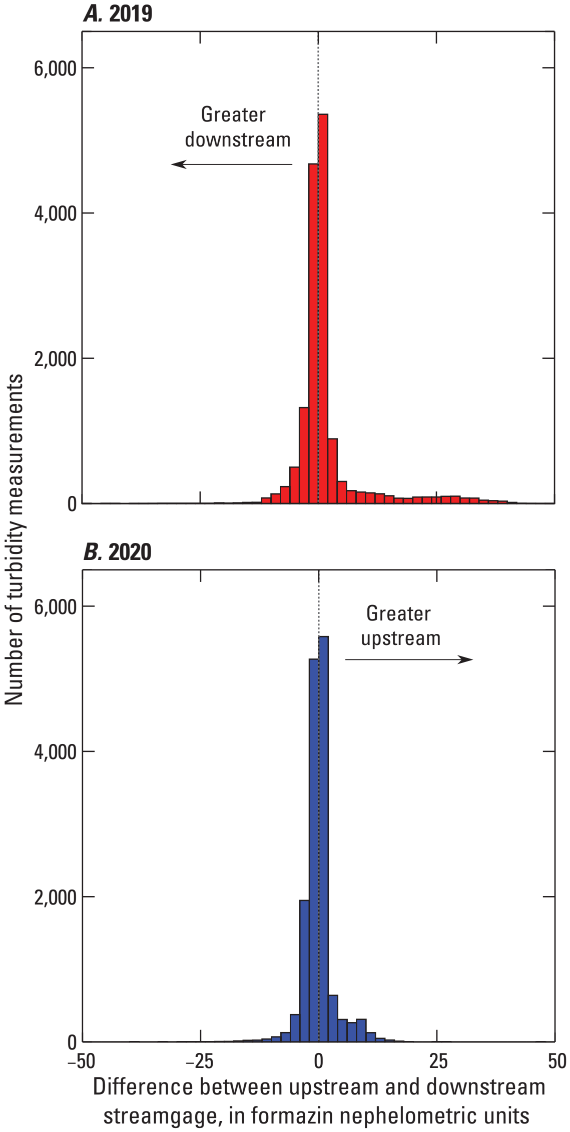


Figure 6. Frequency and magnitude of differences in measured turbidity values between the U.S. Geological Survey (USGS) streamgage near the upstream boundary of the Jackson, Wyoming (USGS streamgage 13018250, Flat Creek above Cache Creek, at Jackson; U.S. Geological Survey, 2021b), and the USGS streamgage near the downstream boundary of Jackson (USGS streamgage 13018350, Flat Creek below Cache Creek, near Jackson; U.S. Geological Survey, 2021d) for (*A*) calendar year 2019 and (*B*) calendar year 2020.

Suspended-Sediment Samples

A total of 24 discrete samples (12 replicate pairs) of suspended-sediment were collected at each streamgage location across a range of flow and turbidity conditions during the study period. Sampled SSCs ranged from 0.5 to 50 milligrams per liter (mg/L) at the upstream streamgage and from 2 to 70 mg/L at the downstream streamgage. One sample at the upstream streamgage had a concentration identified as an outlier; that sample had an SSC of 266 mg/L, which was more than five times greater than the SSC measured in the replicate sample collected at nearly the same time (50 mg/L). The sample SSC of 266 mg/L was deemed the outlier of the two samples because, not including those samples, the mean ratio of turbidity to SSC in the other 22 samples at the upstream streamgage was calculated as 1.2 FNU per milligram per liter, and the maximum calculated ratio was 2.2 FNU per milligram per liter.

Loss on ignition (LOI) analysis of select suspended-sediment samples indicates that most of the mass in samples was composed of mineral sediments, but at lower

Table 3. Results of suspended-sediment sample loss-on-ignition analyses, Flat Creek, near Jackson, Wyoming. See figure 1*C* for streamgage locations.

[YYYY–MM–DD, year, month, day; mg/L, milligram per liter; USGS, U.S. Geological Survey; all information in table was obtained from U.S. Geological Survey, 2021b, d]

Date of sample (YYYY–MM–DD)	Time of sample (24 hours)	Suspended-sediment concentration (mg/L)	Loss on ignition of suspended solids (mg/L)	Percentage of sample as mineral sediment
Flat Creek above Cache Creek, at Jackson (USGS streamgage 13018250)				
2019–05–16	11:25	18	3	83
2019–06–05	15:13	13	2	85
2020–05–11	14:28	6	3	50
2020–05–19	15:45	22	4	82
2020–06–02	14:05	50	5	90
2020–06–18	12:24	5	1	80
2020–09–08	14:20	1	1	0
2020–10–19	13:07	1	0.5	50
Flat Creek below Cache Creek, near Jackson (USGS streamgage 13018350)				
2019–05–16	12:10	36	5	86
2019–06–05	15:46	30	5	83
2020–05–11	15:07	13	2	85
2020–05–19	16:30	36	5	86
2020–06–02	15:10	71	11	85
2020–06–18	11:45	12	2	83
2020–07–30	16:04	4	2	50
2020–07–30	16:16	3	2	33
2020–09–08	13:30	2	1	50
2020–10–19	10:50	10	1	90

concentrations (less than 5 mg/L), more than one-half of the sample could be composed of other particulate materials (table 3). Of the 24 samples collected at the upstream streamgage (13018250), 8 were analyzed for LOI, and 7 of those samples ranged from 50- to 90-percent mineral particles. One sample, which had a concentration of 1 mg/L, was determined to be 0 percent mineral particles. At the downstream streamgage (13018350), 10 of the 24 samples were analyzed for LOI and ranged from 33- to 90-percent mineral particles; 7 of those samples had percentages of mineral sediment greater than or equal to 83 percent (table 3). Two of the samples collected at the downstream streamgage had only 33 and 50 percent of the sample as mineral sediment but, as described previously, were collected at low concentrations (3 and 2 mg/L, respectively). These data indicate potential for overestimation of suspended-sediment loads, particularly at lower concentrations. However, there is substantial variability in the percentages of mineral sediment and, in the absence of LOI analysis for every sample, no robust way of accurately accounting for SSCs relative to other solids. Thus, for the development of statistical models described in the next section, all samples are treated as 100-percent mineral sediment.

Predictive Modeling of Suspended-Sediment Concentration

Statistical modeling was used to predict suspended-sediment concentrations using selected continuous turbidity measurements. Although the number of discrete pairs of turbidity and suspended sediment samples used to generate the models was relatively small, the samples were broadly representative of the range of conditions observed in Flat Creek over the study period.

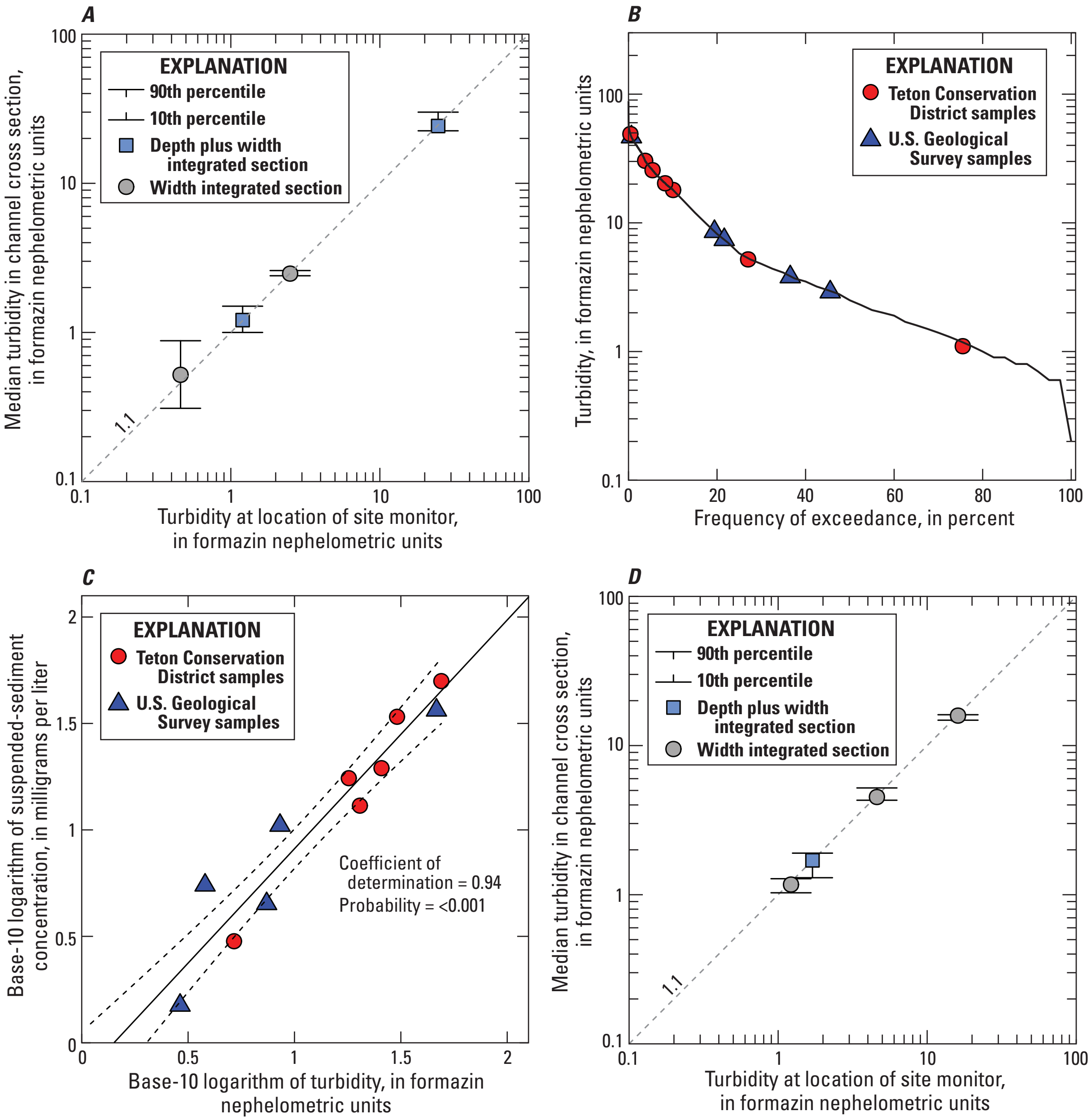


Figure 7. Quality-control and data models for turbidity and suspended-sediment in Flat Creek upstream (Flat Creek above Cache Creek, at Jackson, Wyoming; U.S. Geological Survey streamgage 13018250) and downstream (Flat Creek below Cache Creek, near Jackson, Wyo.; U.S. Geological Survey streamgage 13018350) from the town of Jackson, Wyo. (*A*) Comparison of turbidity measurements made at the continuous monitor at the upstream streamgage relative to multiple measurements made at the full cross section of the stream. Error bars indicate the full range of values measured in the cross section; (*B*) cumulative distribution of discrete samples of turbidity associated with suspended-sediment samples at the upstream streamgage relative to the full empirical cumulative distribution of continuous turbidity measurements observed over the study period; (*C*) data model of turbidity and suspended-sediment concentration for the upstream streamgage. Plots *D*, *E*, and *F* show the same data as *A*, *B*, and *C* for the downstream streamgage.

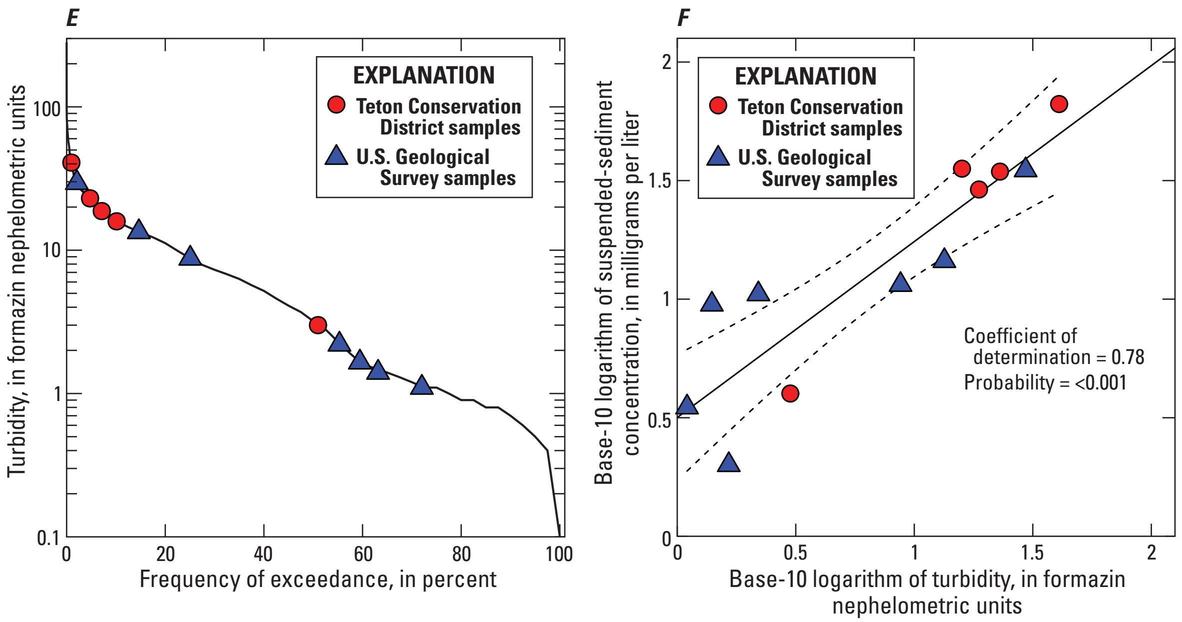


Figure 7. Quality-control and data models for turbidity and suspended-sediment in Flat Creek upstream (Flat Creek above Cache Creek, at Jackson, Wyoming; U.S. Geological Survey streamgage 13018250) and downstream (Flat Creek below Cache Creek, near Jackson, Wyo.; U.S. Geological Survey streamgage 13018350) from the town of Jackson, Wyo. (*A*) Comparison of turbidity measurements made at the continuous monitor at the upstream streamgage relative to multiple measurements made at the full cross section of the stream. Error bars indicate the full range of values measured in the cross section; (*B*) cumulative distribution of discrete samples of turbidity associated with suspended-sediment samples at the upstream streamgage relative to the full empirical cumulative distribution of continuous turbidity measurements observed over the study period; (*C*) data model of turbidity and suspended-sediment concentration for the upstream streamgage. Plots *D*, *E*, and *F* show the same data as *A*, *B*, and *C* for the downstream streamgage.—Continued

Representation of Continuous Measurements

Quality-control sampling at each monitoring site indicates that the point measurements (measurements) made with the continuously deployed turbidity sensors were accurately representing average turbidity conditions in the channel at each streamgage (fig. 7*A, D*). At the upstream streamgage (13018250), turbidity samples were collected along cross sections during four events over the study period, of which samples during two events were collected using equal width increments and samples during the two other events were collected using equal depth and width increments. At the downstream streamgage (13018350), turbidity samples were collected along cross sections during four events over the study period, samples during three events were collected using equal width increments and samples during the fourth event were collected using equal depth and width increments. As expected, variability of measured turbidity in the broader cross sections increased with increasing streamflow at both sites, but the Pearson's correlation coefficient (Pearson's R) between measurements at the continuously deployed sensors and those measurements in the broader channel were 0.99 at both streamgages, indicating near-perfect correlation (1:1 correlation).

At the upstream streamgage (13018250), turbidity values associated with suspended-sediment samples ranged from 1.1 to 49 FNU, spanning from the 1st to 75th exceedance percentiles of measurements made with the continuous monitor over the study period (fig. 7*B*). At the downstream streamgage (13018350), turbidity values associated with suspended-sediment samples ranged from 1.0 to 42.2 FNU, spanning the 1st to 78th exceedance percentiles of measurements made with the continuous monitor over the study period (fig. 7*E*). These data and statistical results indicate that, although the sample size is statistically small, the data broadly represent the range of natural environmental conditions observed over the study period, particularly those conditions when the bulk of the suspended-sediment load is being transported (SSC values greater than 0.5 mg/L).

Table 4. Summary of linear least-squares regression models of turbidity and suspended-sediment concentration, Flat Creek, Wyoming.

[USGS, U.S. Geological Survey; mg/L, milligram per liter; R^2, coefficient of determination; *p*, probability; BCF, Duan's bias correction factor (Duan, 1983); *SSC*, suspended-sediment concentration; *T*, turbidity, in formazin nephelometric units; <, less than]

USGS station number (fig. 1*B* and *C*)	USGS station name	Number of samples[a]	Regression model (mg/L)	R^2	*p*-value	BCF
13018250	Flat Creek above Cache Creek, at Jackson	12	$SSC=0.69*T^{1.1}$	0.94	<0.001	1.05
13018350	Flat Creek below Cache Creek, near Jackson	12	$SSC=3.2*T^{0.74}$	0.78	<0.001	1.12

[a]Value shown is the average of two replicate samples (one-half of total samples collected).

Predictive Statistical Models of Suspended-Sediment Concentration

Statistical model parameters and diagnostics indicate that the linear, least-squares regression models between discrete log-transformed samples of turbidity and log-transformed SSC adequately represent the general relation of SSC relative to turbidity in Flat Creek through Jackson (table 4). At the upstream streamgage (13018250), model parameters were determined to be significant. The model coefficient of determination indicates that log-transformed turbidity explains 94 percent of the variance in SSC, and Duan's BCF (Duan, 1983) indicates low model bias (plus 5 percent). Model performance at the downstream streamgage (13018350) was lower than model performance at the upstream streamgage, and the coefficient of determination at the downstream streamgage indicated that log-transformed turbidity explains 78 percent of the variance in SSC. Model parameters for the downstream streamgage were still significant, and Duan's BCF indicated about a 12-percent bias in predictions. Although parameters for both models were significant, the small sample size makes determining the cause of differences in magnitude of the parameters between models difficult.

Estimated Suspended-Sediment Loads and Sources

Prior to conducting any load calculations, suspended-sediment loads in Flat Creek through Jackson are hypothesized to be greater downstream than upstream because of unmeasured contributions from Cache Creek and along-stream increases in drainage area between streamgages. Mean total calculated loads in 2019 and 2020 indicate substantially more suspended-sediment exited Jackson than entered it from Flat Creek. Mean total calculated suspended-sediment loads at the upstream streamgage (13018250) were, respectively, 26 percent and 21 percent of the total calculated at the downstream streamgage for 2019 and 2020 (table 5). At least part of the calculated difference in suspended-sediment loads resulted from the number of accepted turbidity measurements at each streamgage. USGS streamgage 13018250 had 32 percent and 25 percent fewer accepted turbidity measurements than streamgage 13018350 in 2019 and 2020, respectively, but coincident periods of record also show substantial increases in suspended-sediment loads downstream (table 5). For coincident measurements, mean calculated suspended-sediment loads entering Jackson in 2019 and 2020 were 39 and 35 percent of those loads exiting respectively.

The relative quality of model fit at each streamgage adds complexity to interpretation of calculated differences in mean predicted suspended-sediment loads through Jackson. The weaker model fit at the downstream streamgage produced much larger prediction intervals than the model at the upstream streamgage. The differences in mean total calculated suspended-sediment loads for coincident measurements between streamgages were 5,876 and 5,521 metric tons in 2019 and 2020, respectively. However, in both years, the predicted mean total suspended-sediment load at the upstream streamgage was within the 95-percent prediction interval of the downstream streamgage, but the predicted mean total suspended-sediment load at the downstream streamgage was not contained by the 95-percent prediction interval of the upstream streamgage. This result indicates that, because of model uncertainty, there is a chance the predicted difference in sediment loads is zero. Additional measurements could allow refinement of the suspended-sediment statistical models and develop more confidence in the mean predicted values at each streamgage.

South Park Supply Ditch Operations

Examination of the hydrograph at streamgages 13018250 and 13018350 indicated abrupt increases in streamflow of nearly 1.5 m^3/s on May 13, 2019, and May 12, 2020 (fig. 5*B*). These streamflow increases were used as markers for the beginning of operations of the South Park Supply Ditch diverting water from the adjacent Gros Ventre River into Flat Creek. At streamgage 13018350, abrupt increases in streamflow on September 28, 2019, and September 17, 2020, were used as markers for the end of South Park Supply Ditch operations in each year. These time periods strongly overlap with the period

Table 5. Predicted suspended-sediment loads for select streamgages and periods of record on Flat Creek, Wyoming.

[*n*, number of 15-minute measurements used to make prediction; USGS, U.S. Geological Survey; total, sediment load calculated using all 15-minute measurements in period of record; coincident, sediment load calculated for 15-minute measurements in period of record common to both streamgages]

Time period of interest	*n*	Predicted sediment load and 95-percent prediction interval (metric tons)		
		Lower bound	Mean	Upper bound
Flat Creek above Cache Creek, at Jackson (USGS streamgage 13018250)				
April 2, 2019, through November 15, 2019				
Total	14,196	1,955	3,969	8,729
Total—coincident	13,511	1,840	3,729	8,202
South Park Supply Ditch canal season—total[a]	10,100	1,727	3,511	7,714
South Park Supply Ditch canal season—coincident[a]	9,797	1,671	3,399	7,468
No precipitation spikes identified	13,162	1,729	3,491	7,682
Precipitation spikes identified	488	84	179	392
April 6, 2020, through October 19, 2020				
Total	13,913	1,567	3,018	6,641
Total—coincident	13,840	1,563	3,010	6,624
South Park Supply Ditch canal season—total[b]	8,613	1,383	2,728	5,987
South Park Supply Ditch canal season—coincident[b]	8,586	1,380	2,722	5,975
No precipitation spikes identified	13,597	1,500	2,876	6,330
Precipitation spikes identified	280	59	127	279
Flat Creek below Cache Creek, near Jackson (USGS streamgage 13018350)				
April 3, 2019, through November 15, 2019				
Total	20,861	4,636	15,519	52,438
Total—coincident	13,511	2,881	9,605	32,433
South Park Supply Ditch canal season—total[a]	12,793	3,337	11,192	36,606
South Park Supply Ditch canal season—coincident[a]	9,797	2,547	8,499	28,689
No precipitation spikes identified—total[c]	20,190	4,237	14,154	47,760
Precipitation spikes identified—total[c]	902	345	1,185	4,076
No precipitation spikes identified—coincident	13,162	2,674	8,902	30,044
Precipitation spikes identified—coincident	488	164	559	1,908
April 6, 2020, through October 19, 2020				
Total	18,694	4,222	14,136	48,198
Total—coincident	13,840	2,612	8,531	28,567
South Park Supply Ditch canal season—total[b]	12,215	3,704	12,547	42,806
South Park Supply Ditch canal season—coincident[b]	8,586	2,241	7,428	24,791
No precipitation spikes identified—total[c]	18,164	3,815	12,678	42,966
Precipitation spikes identified—total[c]	615	388	1,394	5,018
No precipitation spikes identified—coincident	13,597	2,508	8,183	27,388
Precipitation spikes identified—coincident	280	94	319	1,080

[a] Period of South Park Supply Ditch operation defined as May 13, 2019, at 21:00 to September 28, 2019, at 03:15.

[b] Period of South Park Supply Ditch operation defined as May 12, 2020, at 05:00 to September 17, 2020, at 03:15.

[c] Value not calculated for streamgage 13018250 because precipitation spikes were identified using record at streamgage 13018350.

of snowmelt runoff in each year (fig. 3*A*) and are, therefore, reasonably representative of suspended-sediment loads during that period as well.

Calculated total mean suspended-sediment loads during South Park Supply Ditch operations, respectively, represented 89 and 90 percent of total loads at the upstream streamgage (13018250) in 2019 and 2020 (table 5). At the downstream streamgage (13018350), the period of South Park Supply Ditch operations represented 72 and 89 percent of the total suspended-sediment loads in 2019 and 2020, respectively. For periods of record coincident between streamgages, the part of the measurements made during the South Park Supply Ditch operations constituted nearly 91 and 90 percent of the total calculated suspended-sediment load at the upstream streamgage and 88 and 87 percent of the loads at the downstream streamgage in 2019 and 2020, respectively.

In the absence of simultaneous continuous monitoring at the outlet of the South Park Supply Ditch and the mouth of Cache Creek, a robust method was not available to quantify how much of the suspended-sediment loads measured at each streamgage in 2019 and 2020 originated from those sources. However, suspended-sediment loads commonly are at similar scales with streamflow in many creeks and rivers. Cross-correlation analysis of the turbidity record at streamgage 13018250 indicates a much stronger correlation with the streamflow of the Gros Ventre River than with the streamflow record at that streamgage (table 6). Similarly, cross-correlation of the turbidity record at streamgage 13018350 indicates a stronger correlation with the streamflow of the Gros River and Cache Creek than the streamflow record at that streamgage (table 6). Although not definitive evidence, the stronger correlation of turbidity measured at Flat Creek streamgages with tributary sources of water indicate the effect from these sources on suspended-sediment transport in Flat Creek.

Urban Runoff

Analysis of suspended-sediment loads during days identified to have urban runoff indicates that sediment transport from these events constituted less than 10 percent of the total measured suspended-sediment at the downstream streamgage (13018350). The moving average algorithm, which was only applied to the turbidity record at the downstream streamgage, identified turbidity spikes constituting 4 and 3 percent of total measurements in 2019 and 2020, respectively, and 3 and 2 percent, respectively, of measurements coincident with the upstream streamgage (table 5). Events hypothesized to be driven by urban runoff constituted 8 and 10 percent of the total estimated suspended-sediment load at the downstream streamgage in 2019 and 2020, respectively, and 6 and 4 percent of the load for the record coincident with the upstream streamgage. At the upstream streamgage, measurements coincident with precipitation events constituted 5 and 4 percent, respectively, of the total suspended-sediment loads measured for coincident measurements in 2019 and 2020.

Sediment concentration hysteresis loops at the upstream and downstream streamgages in both years followed clockwise directions, and the highest concentrations were measured in the rising limb and peak runoff months of May and June and declines (lowest) in concentrations relative to streamflow were measured during the recessional limb of the hydrograph (fig. 8*A*–*D*). In both monitoring years (2019–20), the decline in sediment concentration on the recessional limb of the snowmelt hydrograph was followed by a rise in concentration beginning in September. This effect caused hysteresis loops to be complete, closed, clockwise circles. This effect was particularly pronounced in 2019, when monitoring persisted into November, and sediment concentrations were persistently high at relatively low streamflows (less than 10 m^3/s) at both streamgages (fig. 8*A*–*D*). In 2020, concentrations were

Table 6. Correlation between coincident unit records of streamflow and turbidity for select streamgages in the Flat Creek drainage basin, northwestern Wyoming, water years 2019 and 2020.

[USGS, U.S. Geological Survey; --, no data or not applicable]

USGS station number (fig. 1*B*)	USGS station name[a]	Pearson correlation coefficient with turbidity (Pearson's R)[b]	
		Flat Creek above Cache Creek, at Jackson (USGS streamgage 13018250)	Flat Creek below Cache Creek, near Jackson (USGS streamgage 13018350)
13014500	Gros Ventre River at Kelly[c]	0.77	0.68
13018250	Flat Creek above Cache Creek, at Jackson	0.27	--
13018300	Cache Creek near Jackson	--	0.70
13018350	Flat Creek below Cache Creek, near Jackson	--	0.47

[a] Stations listed below “USGS station name” represent streamflow records; stations to the right represent turbidity records.

[b] Correlation coefficient was only calculated between turbidity and upstream or at the streamgage.

[c] Gros Ventre River at this location is considered upstream from Flat Creek because of transbasin diversion.

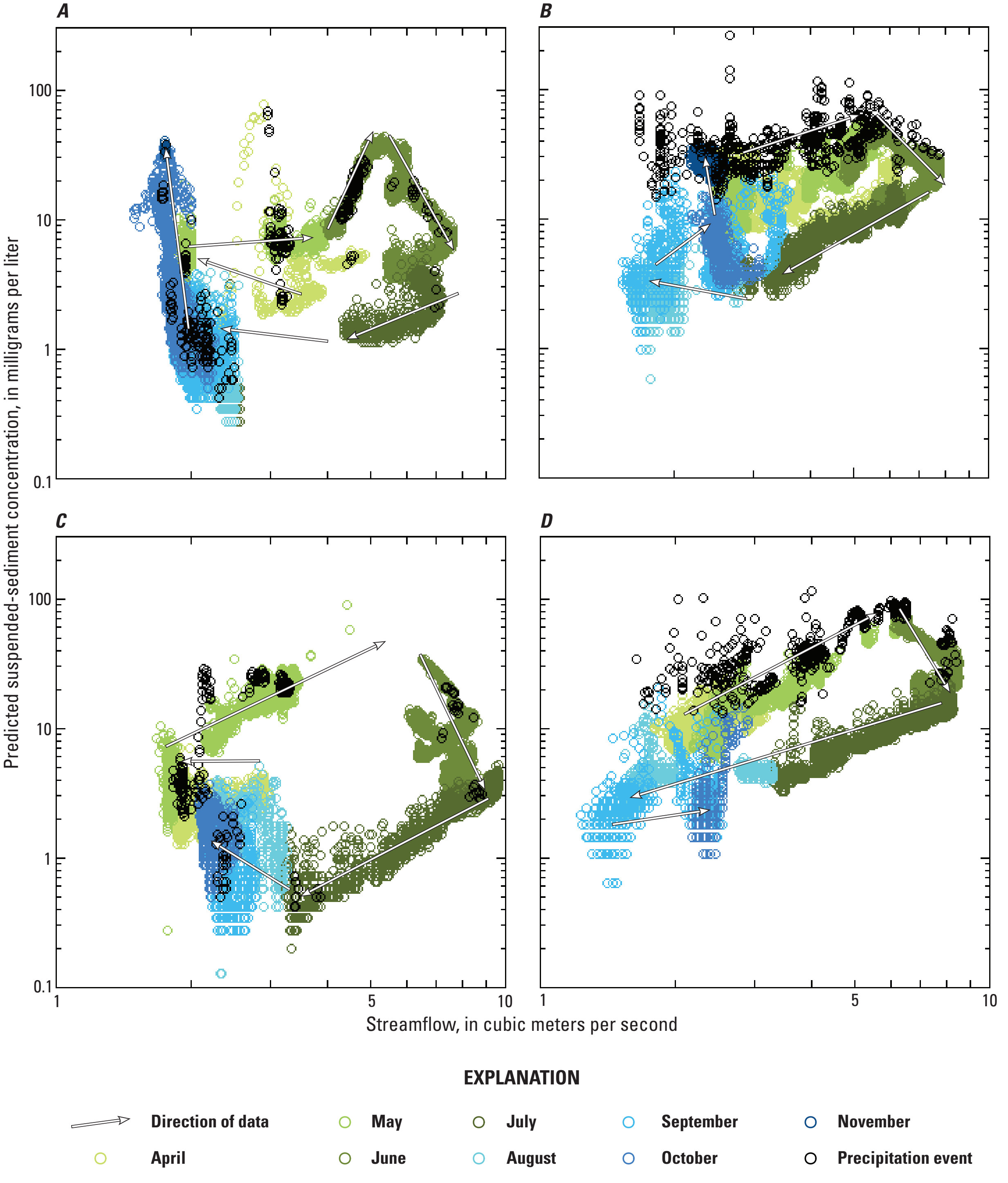


Figure 8. Predicted suspended-sediment concentration relative to streamflow, month of measurement, and events classified as being driven by urban runoff events in Flat Creek, 2019–20. (*A*) Measurements made at U.S. Geological Survey (USGS) streamgage 13018250 (Flat Creek above Cache Creek, at Jackson, Wyoming) in 2019; (*B*) measurements made at USGS streamgage 13018350 (Flat Creek below Cache Creek, near Jackson, Wyo.) in 2019; (*C*) measurements made at USGS streamgage 13018250 in 2020; (*D*) measurements made at USGS streamgage 13018350 in 2020. Arrows indicate progression of sediment through time and are shown for guidance only. See figure 1*B* for streamgage locations.

beginning to rise in the fall, but monitoring only persisted into late October, and it is unknown if the same abrupt concentration rise measured in early November 2019 would have resulted.

Despite observing similar percentages of total estimated suspended-sediment loads for measurements identified as affected by urban runoff events, sediment concentration hysteresis plots indicate that sediment concentrations during those events were appreciably lower at the upstream streamgage (13018250) compared to concentrations at the downstream streamgage (13018350) (fig. 8*A–D*). At the upstream streamgage, estimated SSCs during precipitation events (identified as spikes in turbidity at the downstream streamgage) in 2019 and 2020 had minimum values near the 4th percentile, mean values near the 67th and 69th percentiles, and maximum values at the 100th and 93d percentiles of the complete SSC distribution predicted at the upstream streamgage. At the downstream streamgage, SSCs during precipitation events in 2019 and 2020, respectively, had minimum values at the 63d and 60th percentiles, mean values at the 92d percentile, and maximum values at the 100th percentile of the complete SSC distribution predicted at the downstream streamgage. In combination with the hysteresis plots, this result indicates that concentrations during precipitation events at the upstream streamgage, although slightly elevated relative to non-precipitation events, followed the expected snowmelt-driven supply-limited pattern, whereas those concentrations at the downstream streamgage tended to deviate and were elevated relative to the expected pattern of concentrations across the measurement period.

Statistical Model Precision and Limitations and Accuracy of Sediment Budgets

Results of this pilot study provide the most detailed description of suspended-sediment dynamics in Flat Creek to date (as of 2020), but the discrete data used as input to the sediment concentration models are sparse, and substantial parts of the continuous turbidity record are missing for the important spring runoff period at the upstream streamgage (13018250). These two factors, respectively, limit model precision and sediment budget accuracy and make robust accounting of sediment loads in Flat Creek through Jackson over the measurement period impossible. Nevertheless, some inference can be made through examination of the more complete turbidity record at the downstream streamgage (1308350) and relative proportions of sediment loads for coincident periods of record at both streamgages. About 70 to 90 percent of the total estimated suspended-sediment loads at the downstream streamgage were transported during active operations of the South Park Supply Ditch in the 2019 and 2020 measurement periods, which strongly overlapped with the snowmelt-runoff period, and as much as 10 percent of the estimated loads was coincident with events hypothesized to be precipitation-driven urban runoff (table 5). Although 10 percent of the total suspended-sediment load is relatively small, these urban runoff measurements represent only about 4 percent of the total measurements in 2019 and 2020, respectively and are, thus, disproportionately large sediment-transport events.

Determination of the relative contributions of urban runoff and the South Park Supply Ditch to the total estimated suspended-sediment loads in Flat Creek is complex and requires some assumptions to make inference. Estimated suspended-sediment loads at the upstream streamgage for the coincident period of record constitute 32 and 40 percent of the total estimated suspended-sediment loads at the downstream streamgage during hypothesized urban runoff events in 2019 and 2020, respectively. These values indicate that the percentage of estimated suspended-sediment loads associated with urban runoff events may be smaller than 10 percent, even as little as 5 percent. However, direct translation of these percentages to the complete record at the downstream streamgage is difficult because the sediment loads calculated for the coincident period of record represent less than one-half of the total estimated load during events hypothesized as urban runoff in both years at that streamgage (table 5).

The proportion of suspended-sediment loads at the upstream site that originate from the South Park Supply Ditch can only be estimated. Cross-correlation analysis indicates that the turbidity at the upstream streamgage is better explained by Gros Ventre River streamflow than by streamflow in the ditch (table 6). The fact that this strong correlation persists to the downstream streamgage would indicate that a potentially large proportion of Flat Creek suspended-sediment may originate in the South Park Supply Ditch. If even one-half of the suspended-sediment load estimated at the upstream streamgage originated from the Gros Ventre River, it would be equivalent to the total suspended-sediment loads from hypothesized urban runoff estimated at the downstream streamgage and would be more than double for the estimates made for those events in the coincident records. Similarly, the contributions of suspended-sediment from Cache Creek cannot be quantified with the current data and analysis presented here. The strong correlation between turbidity at the downstream streamgage and streamflow in Cache Creek indicates that Cache Creek is a likely source of suspended-sediment load measured at the downstream streamgage. Given that predicted loads at the downstream streamgage were at least 60 percent larger than upstream loads, and loads associated with hypothesized urban runoff accounted for less than 10 percent of total loads calculated at the downstream streamgage, Cache Creek is likely a relatively large source of suspended-sediment measured at the downstream streamgage. Additional data could allow accurate isolation and estimation of suspended-sediment loads from the South Park Supply Ditch and Cache Creek.

Additional uncertainty in the results is added by the LOI analysis. Results of this analysis indicated that the organic content, particularly at concentrations less than 6 mg/L, can compose a large proportion (percentage) of the suspended material. In the absence of LOI data for every sample, there is no robust method to build separate statistical models to estimate sediment loads in Flat Creek. The LOI analysis indicates that the sediment loads estimated and presented here are likely biased high, particularly those estimated during low concentrations. Statistical modeling indicated that most of the suspended-sediment transport in Flat Creek resulted during the high-flow season when SSCs were higher than other times of the measurement periods and, thus, any bias is likely less than 15 percent (table 3). Additional data collection and LOI analysis could support more accurately resolved model bias from organic material on suspended-sediment loads in Flat Creek, but the relative proportion (percentage) of the sediment loads from various sources may be unaffected at the low concentrations of organic material indicated in table 3.

Analyses and modeling results completed as part of this study also demonstrate the potential pitfalls of using turbidity as a water-quality compliance parameter for sediment, particularly if those data are discrete. Only 1 percent of the more than 30,000 continuous, coincident measurements of turbidity upstream and downstream from Jackson in 2019 and 2020 exceeded the 10-FNU increase restriction, and median differences in 2019 indicated higher turbidity values were more commonly measured upstream from Jackson that year. This result differs from previous results where discrete turbidity data were used to indicate an average increase of about 7.7 FNU between measurements made upstream and downstream from Jackson. These data were collected solely during storm events (Girard and others, 2019), and sources of sediment were not isolated for that analysis. In the analysis completed for this study, between 2 and 3 percent of coincident measurements were identified as likely resulting because of precipitation-driven urban runoff. The disparity between the percentage of time a downstream increase in turbidity was observed and the percentage of time sediment loads associated with urban runoff were observed highlights the importance of using suspended-sediment load analysis as a more accurate indicator of sediment inputs from human sources to a stream.

Summary

Flat Creek, a tributary to the Snake River in northwestern Wyoming, is an important source of irrigation water, fish and wildlife habitat, and local recreation. Since 1996, a section of Flat Creek within Jackson, Wyoming, has failed to meet the Wyoming Department of Environmental Quality's surface-water-quality standards for total suspended solids and turbidity required by its State water-use classification. The Wyoming Department of Environmental Quality water-quality standards prohibit increases of greater than 10 nephelometric turbidity units (NTU) because of human activities in streambodies of Wyoming. Data collected during previous studies led to the working hypothesis that the water-quality impairment of Flat Creek is due to fine sediment loading from urban stormwater runoff, but the relative contributions of fine sediments from various sources have not been quantified. In cooperation with the Teton Conservation District, the U.S. Geological Survey began a pilot study to investigate the potential for quantifying suspended-sediment loads into and out of Jackson along Flat Creek. Paired discrete measurements of turbidity and suspended-sediment concentration (SSC) were used in the study to develop statistical models to predict sediment concentration and loads at streamgages upstream (Flat Creek above Cache Creek, at Jackson, Wyo.; 13018250) and downstream (Flat Creek below Cache Creek, near Jackson, Wyo.; 13018350) from Jackson for parts of calendar years 2019 and 2020. Sediment loads were partitioned by time periods of transbasin diversions and precipitation-driven urban runoff to examine the utility of the method for quantifying the relative loads of hypothesized suspended-sediment sources.

In most years, Flat Creek has heavy winter ice cover. Turbidity monitoring began in each year when open water conditions were persistent and ended before formation of winter ice. Not all turbidity measurements at each streamgage were deemed acceptable for the final data record, and the downstream streamgage had the most complete record over the monitoring periods. Analysis of differences in the more than 15,000 turbidity measurements coincident between upstream and downstream streamgages on Flat Creek in each year indicated that 83 percent were within the plus or minus 5 formazin nephelometric units (FNU) minimum assumed sensor uncertainty range in 2019, and 90 percent were within that range in 2020. Increases of 10 FNU or greater between the upstream and downstream streamgages composed about 1 percent of the total accepted measurements in 2019 and 2020. The median difference in turbidity between the upstream and downstream streamgages in 2019 was 0.20 FNU and the median difference in 2020 was 0.0 FNU. Time series of turbidity differences between streamgages indicated that increases of 10 FNU or greater between upstream and downstream locations typically resulted as intermittent spikes commonly associated with precipitation events.

A total of 24 discrete samples (12 replicate pairs) of suspended sediment were collected at each streamgage location across a range of flow and turbidity conditions during the study period. At the upstream streamgage (13018250), turbidity values associated with suspended-sediment samples ranged from 1.1 to 49 FNU, spanning from the 1st to the 75th exceedance percentiles of accepted continuous measurements. At the downstream streamgage (13018350), turbidity values associated with suspended-sediment samples ranged from 1.3 to 42.2 FNU, spanning the 1st to 78th exceedance percentiles of accepted continuous measurements. Loss-on-ignition analysis of select suspended-sediment samples indicated that most of the mass in most samples was composed of mineral sediments, but at concentrations less than 6 mg/L, more than one-half of the sample could be composed of other particulate materials.

Model parameters and diagnostics indicate that the linear, least-squares regression models between discrete log-transformed samples of turbidity and log-transformed SSC are most appropriate to represent the general relation of suspended-sediment loads relative to turbidity in Flat Creek through Jackson. Mean total calculated loads in 2019 and 2020 indicate substantially more suspended-sediment moving by way of Flat Creek after passing through Jackson. Mean total calculated suspended-sediment loads at the upstream streamgage (13018250) were, respectively, 26 percent and 21 percent of the total calculated at the downstream streamgage (13018350) for 2019 and 2020. For coincident measurements, mean calculated suspended-sediment loads entering Jackson on Flat Creek in 2019 and 2020 were 39 percent and 35 percent of loads exiting town on Flat Creek, respectively. However, in both years, the predicted mean total suspended-sediment load at the upstream streamgage was within the 95-percent prediction interval of the downstream streamgage, but the predicted mean total suspended-sediment load at the downstream streamgage was not contained by the 95-percent prediction interval at the upstream streamgage. This result indicates that model uncertainty includes a chance the predicted difference in sediment loads between the upstream and downstream streamgages is zero.

The South Park Supply Ditch diverts water from the Gros Ventre River into Flat Creek upstream from Jackson. Calculated mean suspended-sediment loads during South Park Supply Ditch operations, respectively, represented 89 and 90 percent of total observed loads at the upstream streamgage in 2019 and 2020. At the downstream streamgage, the period of South Park Supply Ditch operations represented 72 and 89 percent of the total observed suspended-sediment loads in 2019 and 2020, respectively. For periods of record coincident between streamgages, the time period of South Park Supply Ditch operations constituted nearly 91 and 90 percent of the total calculated suspended-sediment load at the upstream streamgage, and between 88 and 87 percent of the loads at the downstream streamgage in 2019 and 2020, respectively. Cross-correlation analysis indicated that the turbidity records at each streamgage had much stronger correlation to streamflow in the Gros Ventre River than streamflow observed at the upstream and downstream streamgages. Similarly, turbidity measured at the downstream streamgage had a stronger correlation to streamflow in Cache Creek than streamflow measured at the Cache Creek streamgage. However, in the absence of simultaneous continuous monitoring at the outlet of the South Park Supply Ditch and in Cache Creek, no robust method was available to quantify suspended-sediment loads from those sources.

A moving average filter was used to identify and isolate short-duration (minutes to hours) spikes in turbidity at the downstream streamgage that were hypothesized to be precipitation-driven urban runoff. Suspended-sediment loads during urban runoff constituted about 8 and 10 percent of the total calculated suspended-sediment loads at the downstream streamgage (13018350) in 2019 and 2020, respectively, and 6 and 4 percent of the loads calculated for the record coincident with the upstream streamgage (13018250). Sediment concentration hysteresis plots indicate that sediment concentrations during urban runoff events were not critically high at the upstream streamgage relative to the high concentrations observed at the downstream streamgage. At the upstream streamgage, estimated SSCs during urban runoff events in 2019 and 2020 had minimums at the 4th percentile of all measurements, mean values in the 60th percentile, and maximum values equal to or greater than the 99th percentile. At the downstream streamgage, SSCs during urban runoff events in 2019 and 2020 had minimum values greater than the 30th percentile of all measurements, mean values at the 92d percentile, and maximum values at the 100th percentile.

Results of this pilot study provide the most detailed description of suspended-sediment dynamics in Flat Creek to date (as of 2020). Estimated suspended-sediment loads at the upstream streamgage during urban runoff events for the coincident period of record constitute 32 and 40 percent of the total estimated suspended-sediment loads at the downstream streamgage in 2019 and 2020, indicating sediment loads from urban runoff may contribute less than 10 percent, even as little as 5 percent of the total load exiting Jackson on Flat Creek. Estimation of the proportion of suspended-sediment loads at the upstream streamgage that originate from the South Park Supply Ditch can only be done with appreciable assumptions but have potential to be equivalent to calculated suspended-sediment loads associated with urban runoff. Additional data and analysis may allow accurate isolation and estimation of suspended-sediment loads from the South Park Supply Ditch and Cache Creek.

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Publishing support provided by the
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Alexander and others—**Using Continuous Measurements of Turbidity to Predict Suspended-Sediment Concentrations, Loads, and Sources in Flat Creek**—OFR 2022–1103

ISSN 2331-1258 (online)
https://doi.org/10.3133/ofr20221103