National Water Quality Program and Water Availability and Use Science Program

Prepared in cooperation with the Bureau of Reclamation San Joaquin River Restoration Program

Sediment Transport in Two Tributaries to the San Joaquin River Immediately Below Friant Dam—Cottonwood Creek and Little Dry Creek, California

Scientific Investigations Report 2023–5023

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

Cover. Little Dry Creek and Cottonwood Creek in January and February of 2017. Photographs taken by Mathieu D. Marineau.

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We would also like to thank Amber Powell from the U.S. Geological Survey for all of the field assistance in the early part of the study.

Contents

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Tables

Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
micrometer (µm)	0.00003937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.81402	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)
	Flow rate	
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]
metric ton (t)	0.9842	ton, long [2,240 lb]

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

$$°F = (1.8 \times °C) + 32.$$

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).

Elevation, 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).

Abbreviations

CDEC	California Data Exchange Center
CTK	Cottonwood Creek streamgage
D_{50}	median grain diameter
LDC	Little Dry Creek streamgage
GSD	grain-size distribution
GPS	Global Positioning System
Q	streamflow
Q_s	sediment load
RTN	real-time network
SSC	suspended-sediment concentration
SJR	San Joaquin River streamgage
USGS	U.S. Geological Survey
WSE	water-surface elevation
WY	water year (October 1 to September 30)

Sediment Transport in Two Tributaries to the San Joaquin River Immediately Below Friant Dam—Cottonwood Creek and Little Dry Creek, California

Dan R.W. Haught[1], Mathieu D. Marineau[1], Justin Toby Minear[2], Scott A. Wright[3], and Joan V. Lopez[1]

Abstract

Two tributaries to the greater San Joaquin River watershed, Cottonwood and Little Dry Creeks, in California's Central Valley, were assessed for sediment and streamflow dynamics between October 1, 2011, and September 30, 2019. The two systems deliver sediment to the San Joaquin River below Friant Dam, California. Dams create downstream discontinuities in streamflow and sediment transport and therefore influence fish habitat and sediment dynamics. Because these two creeks are directly downriver from Friant Dam, they become the most upstream source of sediment to the San Joaquin River below Friant Dam.

The quality and quantity of spawning habitat for fish in the gravel-bedded reach of the San Joaquin River relies on a range of bed material particle size suitable for redd structure. The effects of coarse-sand to fine-gravel supply on salmonid habitat depends primarily on the size of the sediment and the timing of its addition from tributaries to the San Joaquin River; thus, understanding the timing, quantity, and size of sediment supplied from these two tributaries is critical to the management of ecological and biological sustainability.

Streamflow from Cottonwood and Little Dry Creeks, along with streamflow from the San Joaquin River below Friant Dam, were compared to continuously measured water-surface elevations to quantify the timing and direction of streamflow. Suspended-sediment samples were collected with multiple automatic samplers and analyzed for concentration and grain-size distribution. Measured suspended-sediment concentrations and streamflows were used to develop sediment rating curves and compute continuous estimates of suspended-sediment load for each tributary. Satellite imagery was used to qualify spatial and temporal dynamics through the lower watersheds and support more quantitative sediment-load estimates.

Computed annual sediment loads ranged from 1.32×10^{1} to 2.68×10^{4} metric tons for Little Dry Creek and 9.82 to 1.98×10^{3} metric tons for Cottonwood Creek. Sediment loads computed during the study period for both watersheds show that annual loads were highest during water year 2017 (October 1, 2016, to September 30, 2017). Sediment transport primarily occurred between the months of January and March. In both tributaries, grain-size distributions of suspended sediment were predominantly coarse-sized sand and were finer than the remnant bed material.

Both creeks demonstrate backwater effects from the San Joaquin River, but the more tortuous stream channel and historical mining pits within Little Dry Creek provide more capacity for sediment storage compared to the less complex stream network of Cottonwood Creek. Because loads were computed based on upstream streamgages and not at the confluence of each tributary to the San Joaquin River, annual load estimates do not represent direct flux into the San Joaquin River; instead, these results indicated that in Little Dry Creek, particularly, the lowest portion of the watershed stores sediment before it reaches the San Joaquin River.

Introduction

Dams disrupt the downstream transport of water and sediment in rivers. Dam management can influence the magnitude and duration of the hydrograph, often reducing peak streamflows while increasing hydrograph duration. Reduction of peak streamflows can affect sediment transport and morphology of the river downstream by decreasing the energy available for transporting size-specific sediment (Sklar and others, 2009; Humphries and others, 2012; Nelson and others, 2015). Additionally, dams create discontinuities in sediment transport by capturing sediment behind the dam and preventing it from transporting downstream below the dam. Sediment captured by the dam creates a channel bed below the dam that becomes increasingly coarser as fine sediment is transported downstream without being replenished (Kondolf, 1997). Therefore, dams often reduce the streamflows capable of moving coarser sediment while also preventing sediment from resupplying the downstream reaches, resulting in sorting and armoring of the bed sediment that was in place before dam construction.

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In gravel-bedded rivers, increasing the supply of relatively coarse sand to fine gravel (1 millimeter [mm] sand to 10 mm gravel) has been shown to increase the partial transport of coarser gravels and smaller cobble (Whiting and others, 1988; Dietrich and others, 1989; Wilcock and Crowe, 2003; Venditti and others, 2010a, b). Herein, fine sediment is defined as that finer than 0.063 mm, sand-size sediment is defined as a range from 0.063 to 2 mm, gravel sediment is defined as larger than 2 mm, whereas cobble is defined as sediment greater than 64 mm. Increased supply occurs when coarse sand to fine gravel is trapped in between the framework of coarser sediment (coarse gravel and cobble). Trapped sediment smooths the bed and increases shear velocities (Johnson and others, 2015), increasing the force on larger sediment and initiating motion if the forces are greater than the resistance of the larger particle. Miwa and Parker (2017) showed how a coarse sand fraction of 40 percent is a threshold value for gravel transport (that is, as the sand fraction increases to 40 percent, gravel transport increases and then declines once the sand fraction exceeds 40 percent). Fractions of coarse sand and fine gravel—above 40 percent—can cement larger particles, thus reducing transport.

Additionally, the increase of coarse sand to fine gravel (less than 10 mm) within the matrix can have substantial biological effects, such as preventing dissolved-oxygen exchange and reducing intragravel flow (Kondolf, 2000). These complex transport processes indicate that coarse sand and fine gravel interacting with a coarse gravel bed substrate can have positive (increase mobility of the armor layer, exposing generally finer bed material underneath) and negative effects (potential to clog the matrix) on sediment transport and bed characteristics with respect to habitat quality.

Coarse sand and fine gravel can have two consequences on the stream reach: (1) with increased coarse sand to fine gravel, the bed becomes finer by the evacuation of relatively coarser surface sediment, exposing the generally finer subsurface bed material and (2) with too much coarse sand to fine gravel, the bed can ‘lock’ coarse gravel in place by filling the matrix with fine material. Thus, these studies indicated that the grain-size distribution (GSD) of transported material introduced to a coarse, previously stable, bed can influence the transport of the bed’s parent material.

One of the main concerns with tributary sediment supply to the San Joaquin River downstream from Friant Dam is the potential adverse effect on salmonid rearing habitat. The effects of fine-sediment supply on salmonids depend primarily on the size of the sediment and the timing of its addition to the channel (Chapman, 1988; Kondolf, 2000). Though coarse sediment between 10 and 55 mm is needed for spawning by adults (Chapman, 1988; Kondolf and Wolman, 1993) and for cover by juveniles (Kondolf, 2000), fine gravel and sand can have a detrimental effect on emergence and juvenile rearing quality (Chapman, 1988; Kondolf, 2000; Suttle and others, 2004). In particular, the timing of sediment supply is important because the eggs must incubate for several months before emergence (Chapman, 1988). If sand and fine gravel are supplied after egg deposition, sediment can filter down through the framework of coarser sediment to plug pore spaces, decreasing permeability and inhibiting the flow of oxygenated water to eggs or alevins in the redd (Kondolf, 2000). Relatively small proportions of fines (10–30 percent) can decrease incubation survival and emergence rates (Chapman, 1988). Generally, sediment less than 1 mm substantially decreases survival of incubating eggs (Kondolf, 2000), but sediment sizes up to 9.5 mm have been found to decrease survival rates (Chapman, 1988).

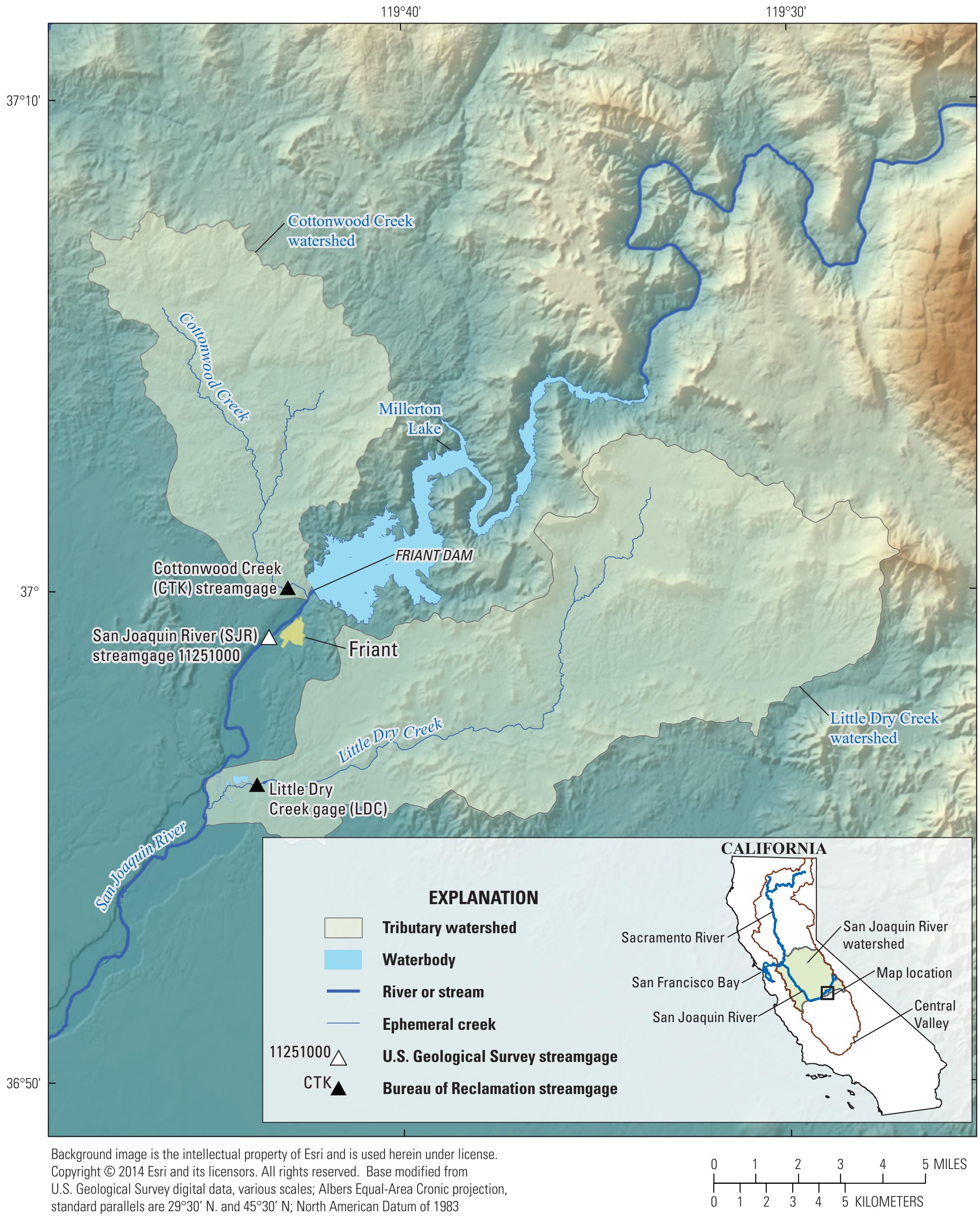
The U.S. Geological Survey (USGS), in cooperation with the Bureau of Reclamation (Reclamation) San Joaquin River Restoration Program, focused on quantifying the sediment inputs from Little Dry and Cottonwood Creeks, two naturally flowing tributaries that enter the San Joaquin River immediately below Friant Dam. These tributaries have sediment loads that could influence sediment dynamics and habitat quality on the main stem of the San Joaquin River below the dam. The objective of the study was to quantify the rate, timing, and GSD of sediment entering the main stem of the San Joaquin River from these two tributaries. As part of this objective, we also examined sediment continuity in the tributaries.

Purpose and Scope

In this report, a combination of streamflow (Q), sediment data, and aerial imagery were used to assess sediment transport and morphologic evolution in Cottonwood and Little Dry Creeks. Streamflow and water-surface elevation data were used to examine the impact of San Joaquin River streamflow on Cottonwood Creek and Little Dry Creek hydrodynamics. The impact of stream connectivity and storage on sediment transport was evaluated from water year (WY) 2012 to WY 2019 by developing a sediment rating curve for each tributary, which allowed for continuous estimates of suspended-sediment concentration (SSC). A WY is defined as the period from October 1 of one year through September 30 of the following year and is categorized by the year in which it ends. Streamflow and SSCs are used to compute suspended-sediment loads within the lower tributary watersheds. Hydrodynamic and sediment transport results are related to the more qualitative assessment of geomorphic evolution to identify watershed storage. Finally, the size of the bed material was compared to the size of material in suspension to assess what size of material was transporting through each tributary. The scope of this report is limited to sediment transport within the lower tributary watershed during the period of investigation.

Study Area

The San Joaquin River watershed is located in the Central Valley of California (fig. 1), draining to the Sacramento–San Joaquin Delta (not shown) where it joins with the Sacramento River and flows into San Francisco Bay, California. In the following text, we describe the San Joaquin River watershed briefly, while providing a detailed description of the Little Dry Creek and Cottonwood Creek watersheds.



 Base modified from U.S. Geological Survey digital data, various scales; Albers Equal-Area Cronic projection, standard parallels are 29°30′ N. and 45°30′ N; North American Datum of 1983

Figure 1. Little Dry Creek and Cottonwood Creek watersheds, San Joaquin Valley, near Friant Dam, California. Site location data available from Haught and Marineau (2023), and U.S. Geological Survey streamgage site information and data are available from U.S. Geological Survey (2022).

San Joaquin River Watershed above Little Dry Creek

The confluence of the San Joaquin River with Little Dry Creek (fig. 1) is roughly 11.1 kilometers (km) downriver from Friant Dam. The closest USGS streamgage is the San Joaquin River below Friant Dam (USGS station number 11251000; U.S. Geological Survey, 2022). The USGS streamgage is approximately 2.5 km downstream from Friant Dam, whereas the Cottonwood Creek confluence with the San Joaquin River is roughly 0.34 km downstream from the dam. The San Joaquin River watershed, above this streamgage, is 4,340 square kilometers (km^2) and receives a mean annual precipitation of 1,001 mm (table 1). The mean slope of the watershed is 9.47 percent and has a mean annual runoff of 37.4 cubic meters per second (m^3/s). About 64.5 percent of area is above the snowline (1,828 meters [m]), resulting in watershed hydrology driven by precipitation in the form of snowfall and rainfall. Friant Dam, built in 1942, is 97 m high and stores about 0.642 cubic kilometers (km^3) at capacity.

Little Dry Creek and Cottonwood Creek

Little Dry and Cottonwood Creeks are tributaries to the San Joaquin River, entering the main stem of the San Joaquin River just below Friant Dam (fig. 1). Figure 2 shows photographs of Little Dry Creek in the vicinity of the confluence with the San Joaquin River, illustrating the variability in bed sediment, geomorphology, and vegetation found in the lower watershed.

Little Dry and Cottonwood Creeks are ephemeral and can experience long periods of very low or no flow. Table 1 shows the watershed characteristics. The drainage area of the Little Dry Creek watershed more than doubles the drainage area of the Cottonwood Creek watershed. Mean annual precipitation is similar for the two watersheds, whereas average watershed slope is smaller in Little Dry Creek. Both watersheds are below the snowline such that the hydrology is controlled by rainfall-runoff processes, leading to flashy, short-duration flow events.

Little Dry Creek has been more anthropogenically influenced than Cottonwood Creek, in industrial and residential contexts. In particular, a CEMEX aggregate processing facility (https://www.cemexusa.com/) is located adjacent to the Little Dry Creek study site near the confluence with the main stem of the San Joaquin River (fig. 3). Farther up the watershed, an approximately 3-m high dam creates a discontinuity in elevation and has some control on sediment delivery to the lower section of Little Dry Creek. Additionally, there are several small residential communities within the watershed, primarily around the town of Prather, Calif. (not shown). A golf course also is located within the watershed outside of Friant, Calif. Industrial and residential activity can have some impact on the timing and magnitude of hydrologic and sediment delivery to the system. More importantly, the watershed has been influenced by gravel mining, and the mining pits can still be seen from satellite imagery (courtesy of Digital Globe Inc., https://www.digitalglobe.com/company/about-us/).

Table 1. Watershed characteristics for Cottonwood Creek, Little Dry Creek, and the San Joaquin River below Friant Dam, California. Data available from USGS StreamStats application (Gotvald and others, 2012; Ries and others, 2017).

[USGS, U.S. Geological Survey; km^2, square kilometer; mm, millimeter; m, meter; NAVD88, North American Vertical Datum of 1988]

Characteristic	Little Dry Creek[1]	Cottonwood Creek[1]	San Joaquin River below Friant Dam (USGS streamgage 11251000)[1]
Drainage area (km^2)	2.05E+02	9.51E+02	4.34E+03
Mean annual precipitation (mm)	4.47E+02	4.37E+02	1.00E+03
Mean watershed slope (percent)	9.47E+00	1.70E+01	3.06E+01
Mean channel slope (percent)	7.80E−01	1.34E+00	1.74E+00
Percent area above 1,828 m above NAVD88	0.00E+00	0.00E+00	6.45E+01

[1]Data estimated from USGS StreamStats (Gotvald and others, 2012; Ries and others, 2017).

Little Dry Creek has two confluences with the San Joaquin River; one is the natural channel (fig. 3*B*) and the other is a water supply/intake canal (referred to herein as “Canal”) that bisects the natural stream channel (fig. 3). The Canal is used by the CEMEX aggregates processing facility to draw water from the main stem of the San Joaquin River. The historical Little Dry Creek channel connects to the San Joaquin River farther to the south (downstream, on the main stem of the San Joaquin River) and west of the CEMEX facility. The channel flows next to several mining pits on a tortuous path before reconnecting to the main stem (fig. 3).

Cottonwood Creek is the first tributary to the San Joaquin River below Friant Dam. Figure 3*A* shows the study area, along with the locations of the Reclamation streamgage at Cottonwood Creek (CTK) and the sampling site upstream from the Bureau Road bridge (‘U/S Bridge’). The watershed and floodplain are mostly grass-covered rolling hills with less obvious anthropogenic impacts relative to the Little Dry Creek watershed. Figure 4 shows images of the vegetation and geologic material found in the Cottonwood Creek watershed.

Figure 2. Little Dry Creek channel between the confluence with the San Joaquin River and North Friant Road, near Friant, California. See Haught and Marineau (2023) for site location information.

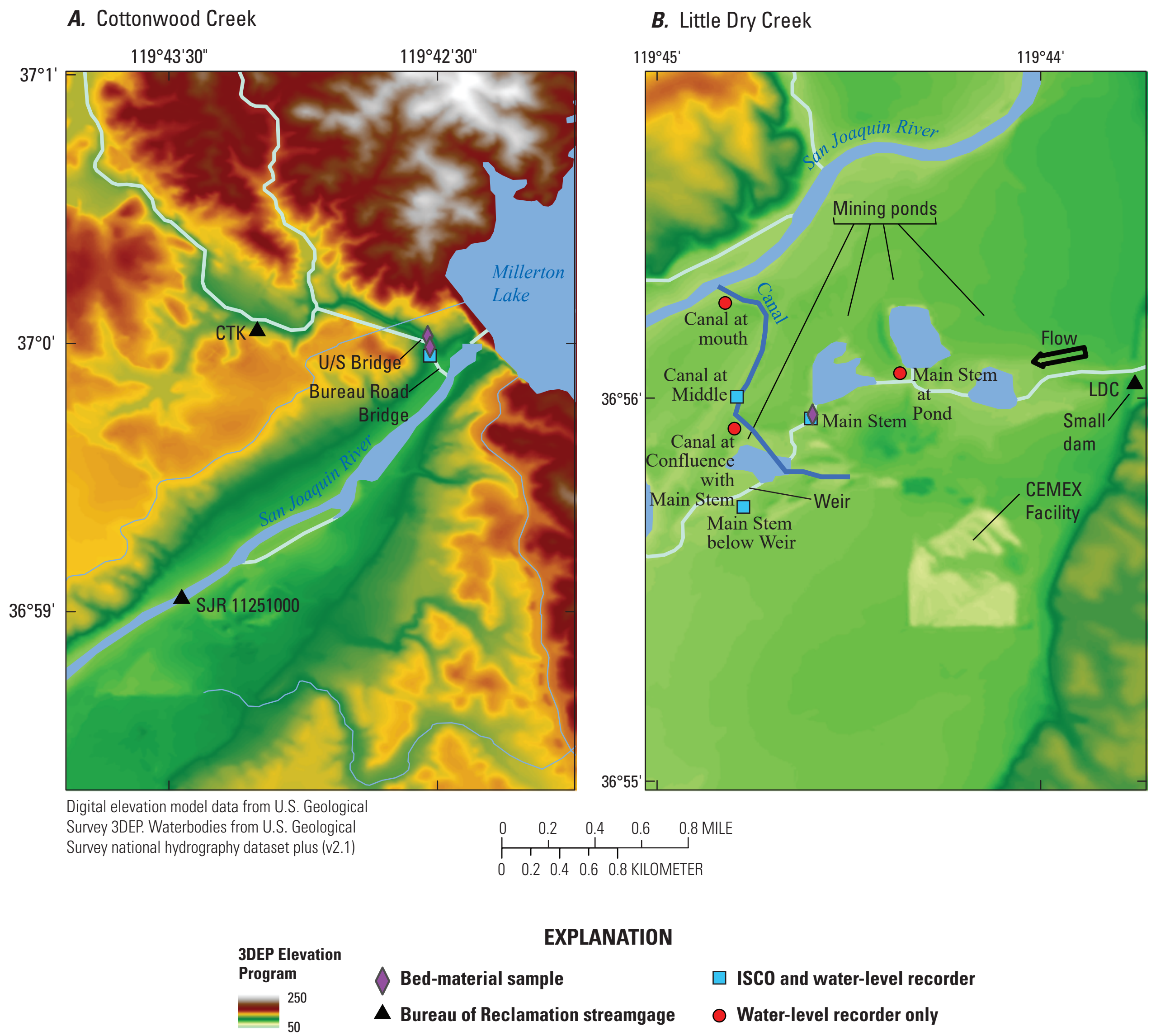


Figure 3. Study areas within the *A*, Cottonwood Creek watershed and *B*, Little Dry Creek watershed, California. Streamflow data available from the California Data Exchange Center (California Department of Water Resources, 2020; http://cdec.water.ca.gov/). Abbreviations: CTK, Cottonwood Creek streamgage; LDC, Little Dry Creek streamgage; SJR, San Joaquin River streamgage (U.S. Geological Survey station number 11251000; U.S. Geological Survey, 2022); U/S, upstream. More information about the 3D Elevation Program (3DEP) is available at https://www.usgs.gov/3d-elevation-program and in Lukas and Baez (2021). See Haught and Marineau (2023) for site location and instrument information.

Cottonwood Creek streamgage (CTK)

Upper Cottonwood Creek near San Joaquin River confluence

Figure 4. Cottonwood Creek channel near the confluence with the San Joaquin River, California. Photographs taken by Mathieau Marineau and Joan Lopez, U.S. Geological Survey, August 8, 2019. (CTK; California Department of Water Resources, 2020; http://cdec.water.ca.gov/)

Geology

Little Dry Creek and Cottonwood Creek watersheds predominantly contain Mesozoic granite, quartz monzonite, granodiorite, and quartz diorite (fig. 5). The primary differences between the watersheds are that Cottonwood Creek watershed has more metamorphic rock, whereas the Little Dry Creek watershed has relatively more metavolcanic rock, along with lake deposits and Pliocene sandstones (sedimentary rock). Overall, the two watersheds can be differentiated by Cottonwood Creek watershed having more hard rock and Little Dry Creek watershed having relatively more loosely consolidated rock.

Hydrology

Streamflow data for the San Joaquin River downstream from Friant Dam are available from the streamgage operated by the USGS (station 11251000 San Joaquin River below Friant Dam; U.S. Geological Survey, 2022) and also are available through the California Department of Water Resources California Data Exchange Center (CDEC; California Department of Water Resources, 2020; http://cdec.water.ca.gov/) using the station identifier “SJR.” Streamflows in both tributary creeks are monitored by streamgages operated by Reclamation, and data are available through the CDEC (California Department of Water Resources, 2020; http://cdec.water.ca.gov/). The streamgage at Cottonwood Creek (CDEC station identifier CTK) is approximately 1.2-km upstream from the confluence with the San Joaquin River. The streamgage at Little Dry Creek (CDEC station identifier LDC) is approximately 2.3-km upstream from the confluence with the San Joaquin River. Streamflow data from these three streamgages between WYs 2011 and 2019 are shown on figure 6. The largest runoff events occurred during WY 2017, and some smaller runoff events occurred during WY 2019.

The hydrographs for the Cottonwood Creek and Little Dry Creek watersheds show steep rising and falling limbs common to small, rainfall-runoff driven watersheds (fig. 6). Flow occurs in late winter to late spring, and CTK tends to respond more quickly than LDC. Table 2 shows the predicted flood-frequency hydrology from the USGS StreamStats program (Gotvald and others, 2012; Ries and others, 2017). Comparison of the flow data with the estimated flood-frequencies indicates that streamflow at CTK exceeded the 2-year-return period in only 1 year of the study (WY 2017), whereas streamflow at LDC exceeded the 5-year-return period twice between WYs 2011 and 2019.

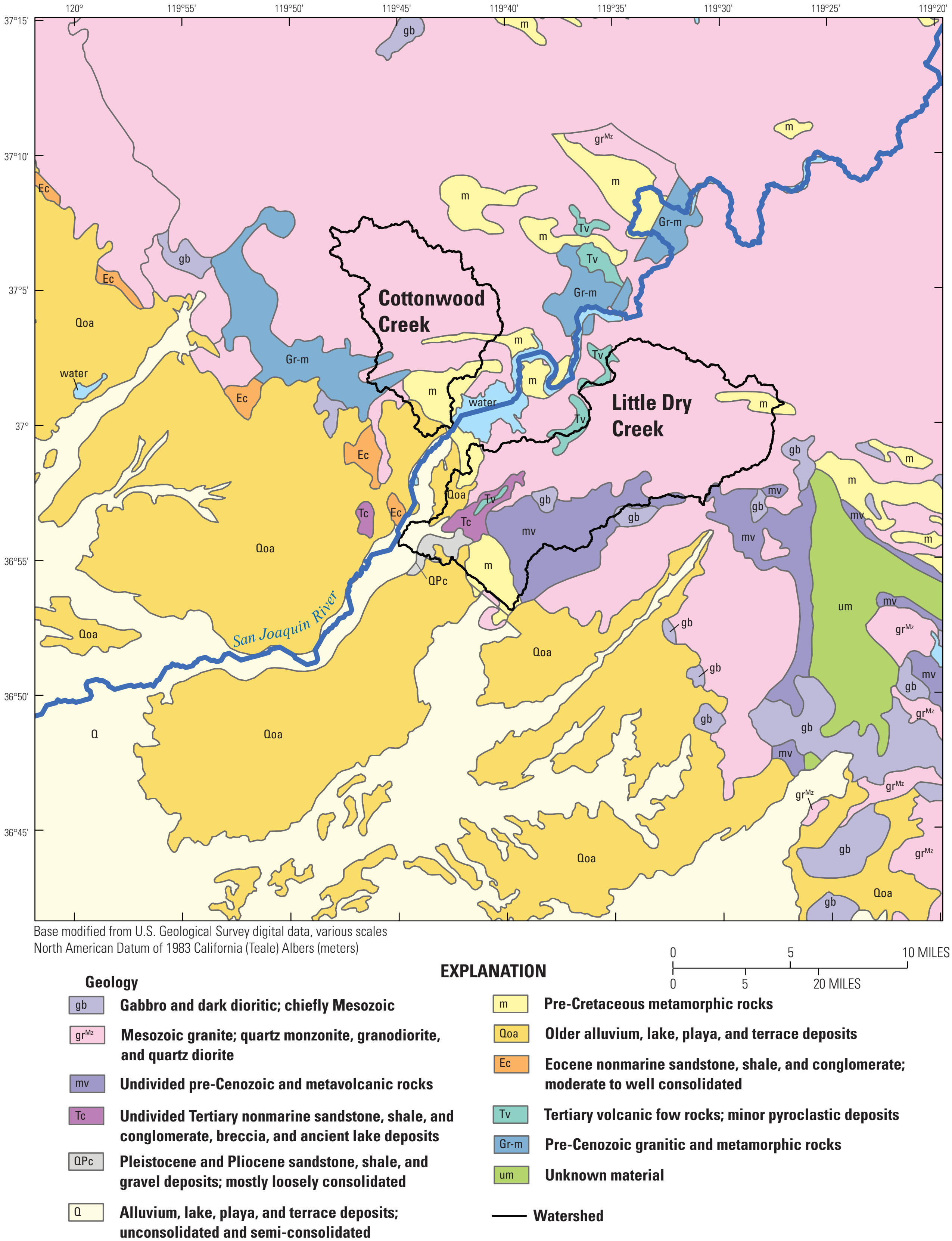


Figure 5. Geologies of the Cottonwood Creek and Little Dry Creek watersheds, California. Data available from California Geological Survey (1977).

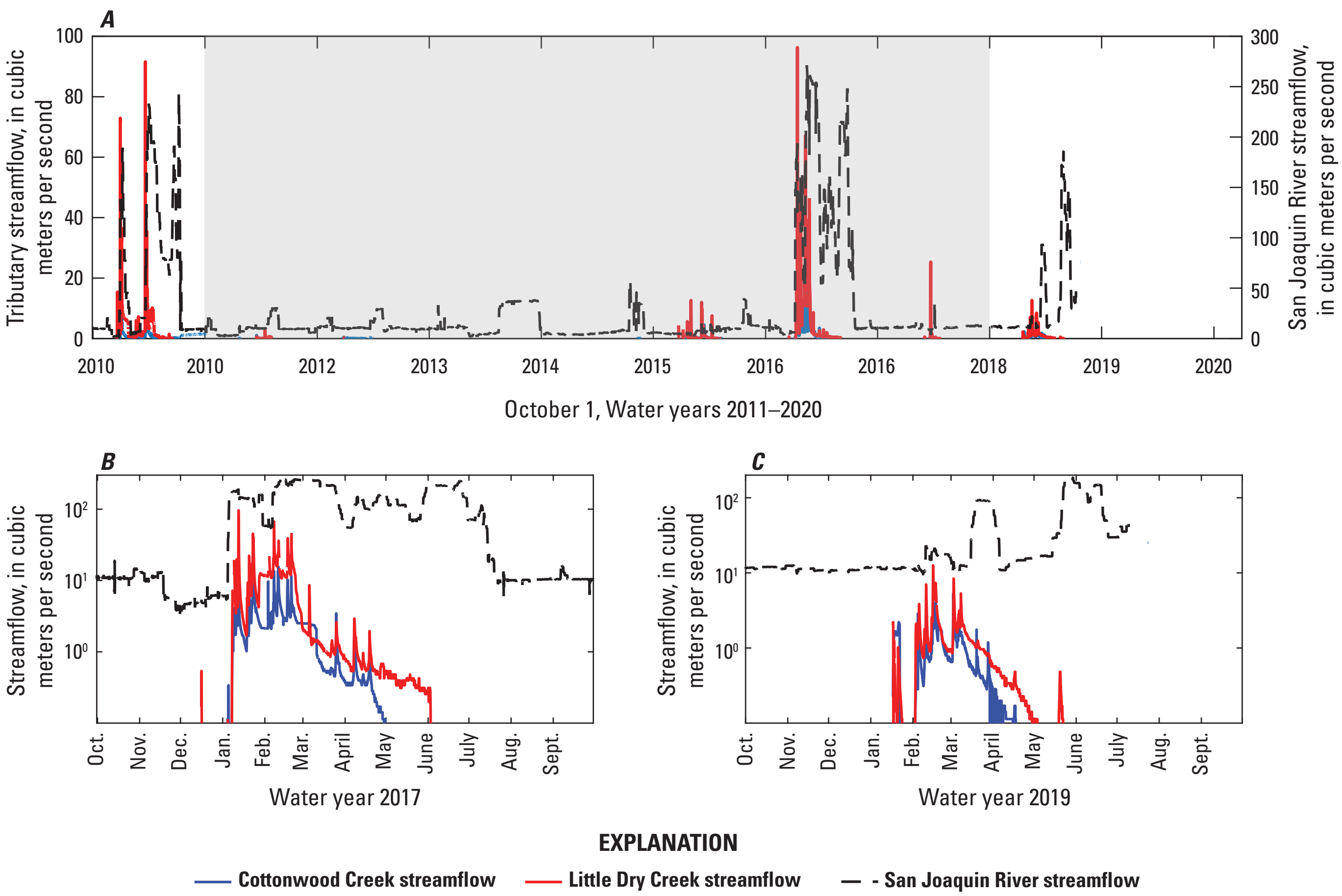


Figure 6. Streamflow hydrographs for Cottonwood Creek (CTK; California Department of Water Resources, 2020; http://cdec.water.ca.gov/), Little Dry Creek (LDC; California Department of Water Resources, 2020; http://cdec.water.ca.gov/), and the San Joaquin River (SJR; California Department of Water Resources, 2020; http://cdec.water.ca.gov; U.S. Geological Survey station number 11251000; U.S. Geological Survey, 2022), California, showing *A*, the hydrograph for water years (WYs) 2011–19, with the shaded region indicating the study period and subsets of the same data highlighting; *B*, a high flow (WY 2017); and *C*, a low-flow (WY 2018) water year.

Table 2. Recurrence intervals and return periods for Little Dry and Cottonwood Creeks near Friant, California. Data available from U.S. Geological Survey StreamStats application (Gotvald and others, 2012; Ries and others, 2017).

[m^3/s, cubic meter per second; USGS, U.S. Geological Survey]

Recurrence interval (percent)	Return period (years)	Cottonwood Creek discharge[1] (m^3/s)	Little Dry Creek discharge[1] (m^3/s)
50	2-year peak flood	8.30E+00	1.73E+01
20	5-year peak flood	2.31E+02	4.73E+02
10	10-year peak flood	3.60E+01	7.28E+01
4	25-year peak flood	5.35E+01	1.08E+02
2	50-year peak flood	6.85E+01	1.37E+02
1	100-year peak flood	8.44E+01	1.69E+02
Mean flow	Mean flow	1.00E−01	3.00E−01

[1]Data computed from USGS StreamStats application (Gotvald and others, 2012; Ries and others, 2017).

Methods

The following section describes the equipment and methods used to collect data and samples during this study (WYs 2011–19). Water-level data were collected in several locations (fig. 3) during the study using self-logging, submersible pressure transducers. Water-surface elevation and topographic data for key locations were collected using Global Positioning System (GPS) survey gear. Bed-material samples were collected in the main stems of Little Dry and Cottonwood Creeks. Suspended-sediment samples also were collected throughout the lower watersheds, but at Little Dry Creek, samplers were set up in multiple locations because of the complex flow paths in the lower 2.3 km of the creek. Historical satellite imagery was utilized to assess geomorphic changes during the study period.

Topographic Surveying

A Trimble R10 GPS receiver with corrections from a real-time network (RTN) was used to measure water-surface elevations and instrumentation locations at the Little Dry Creek and Cottonwood Creek pressure gage sites. Survey elevation data were referenced to the North American Vertical Datum of 1988 (NAVD 88). The RTN provides horizontal and vertical accuracy of about 1–2 centimeters (cm) and was referenced to the North American Datum of 1983 (NAD 83).

Water-Level Measurements

Pressure transducers were deployed between WYs 2014 and 2019. Pressure transducer data were collected with two types of transducers: (1) Onset HOBO U20 and (2) TruBlue 255, and they were submersible, non-vented, pressure transducers. To correct for atmospheric pressure changes, one or more additional pressure transducers were installed on dry land nearby (within 10 km) and out of the channel. In-channel pressure transducer data were converted to water depth using the barometric corrections from the on-land pressure transducers. Both types of transducers were deployed similarly in that they were connected to a rebar stake and set to collect data at 15-minute intervals throughout the deployment (fig. 7). Water depths were then converted to water-surface elevations (WSE) by collecting RTN GPS elevation measurements of the water surface at the location of the pressure transducer while the pressure transducer was submerged and collecting data. Pressure transducers have a depth resolution of about 1 cm, but water-surface elevations have a measurement uncertainty of 1–2 cm because of the resolution of the GPS RTN measurements used to convert the pressure transducer data. Henceforward, we use the term ‘water-level recorder’ to represent the instruments once the conversion to depth or WSE has been computed. In Cottonwood Creek, the water-level recorder is located at the “U/S Bridge” location shown on figure 3 (Haught and Marineau, 2023), whereas in Little Dry Creek, water-level recorders were deployed at several locations (fig. 3; ‘Water-level recorder only’ and ‘ISCO and water-level recorder’).

Figure 7. An example of the water-level pressure transducer installation used at Little Dry and Cottonwood Creeks, California.

Bed-Sediment Sampling

Bed-sediment samples were collected in Cottonwood Creek on several dates during WY 2017. Samples were collected at and upstream from the U/S Bridge site (fig. 3), both in the channel and from recently deposited sediment on the floodplain. Bed-sediment samples were collected within the Little Dry Creek watershed on 3 days in WY 2017, at locations between the main stem at Little Dry Creek weir (Main Stem below Weir on fig. 3) and the confluence with the San Joaquin River.

Samples were processed in the USGS sediment laboratory in Santa Cruz, Calif., for GSD using a series of dry sieves ranging from 1 to 45 mm at increments ranging from 0.5 to 1 phi (Guy, 1969). Particles smaller than the 1 mm sieve were processed in a LS 13-320 Particle Size Analyzer (Beckman Coulter Inc., 2009) with an Aqueous Liquid Module following the methods described in Marineau and Wright (2017). The LS 13-320 uses a mixing chamber and sonic probe to ensure primary particles instead of conglomerates are analyzed for size. The operating range for the LS 13-320 is 0.4–2,000 micrometers (µm). Figure 8 provides an example of a location where bed sediment was collected to represent the material either deposited or entrained by flood flows. Specific times of sample collections for each tributary are described in the “Results” section.

Suspended-Sediment Sampling

Automated pump samplers (Teledyne ISCO Inc., 2012) were deployed in WYs 2016 and 2017 to collect point samples to be analyzed for suspended-sediment concentration (SSC) and GSD. In WY 2016, 114 samples were collected in Little Dry Creek, and 32 samples were collected in Cottonwood Creek. During WY 2017, 69 samples were collected at the Little Dry Creek ISCO sites (fig. 3*B*), and 15 samples were collected at the Cottonwood Creek ISCO site (fig. 3*A*). Sample collection locations are shown on figure 3 (ISCO and water-level recorder). Each automatic pump sampler held a set of 24 1-liter (L) bottles. The automated samplers were deployed at the start of the wet season and checked after major runoff events. The samplers were deployed on the upper floodplain with the intake line extended to a rebar stake placed within the channel (fig. 9). Liquid level actuators (wet/dry sensor) were used to trigger sampling when water reached an elevation determined by the placement of the actuator. Actuators were attached to a 30-cm piece of rebar that was hammered into the bed. Actuators generally were placed 10 cm above low-water levels. Once triggered, samples were collected every 1–6 hours, depending on location, until all 24 sample bottles were filled, or the sampler was deactivated by the water receding to below the actuator.

Figure 8. Freshly deposited sediment from Little Dry Creek, California, 2017.

A. ISCO suspended-sediment sampler in Little Dry Creek

B. ISCO Sampler in Cottonwood Creek

Figure 9. Examples of automatic pump sampler (ISCO) installations at *A*, Little Dry Creek; and *B*, Cottonwood Creek, California.

Samples were retrieved and processed in the USGS sediment laboratory in Santa Cruz, Calif., for total suspended-particle matter and SSC (that is, without organic material). Herein, we only analyze results based on SSC, thereby excluding organic material. During WY 2016, 54 and 15 samples were processed for grain-size distribution in Little Dry and Cottonwood Creeks, respectively. During WY 2017, 109 and 13 were analyzed for GSD in Little Dry and Cottonwood Creeks, respectively. Samples were processed for SSC using two methods: (1) evaporation and (2) filtration. Filtered samples followed USGS standard operating procedures (Guy, 1969) and were run through a 1.2-µm filter and pneumatic pump. The evaporation method (Guy, 1969) allows for samples to be further processed for GSD characteristics. The evaporation method entails decanting the clear liquid from the settled sediment, drying the sample at 85-degrees Celsius (°C) for 12–24 hours, and then drying for an additional 1 hour at 105 °C. Lastly, the sample was cooled in a desiccator for 2 hours. All samples were processed to determine the organic content using the Loss of Ignition method (Heiri and others, 2001), though not reported henceforth. Evaporated samples were then processed for GSD using the LS 13 320 Particle Size Analyzer.

Suspended-Load Computation

Estimates of SSC (milligrams per liter [mg/L]) and streamflow from the streamgage for the respective time of SSC sampling were used to compute a least-squares regression model between streamflow and measured SSC (Rasmussen and others, 2009). Continuous SSC was then estimated from streamflow using the regression model. Using estimated, continuous SSC and streamflow, Q, from the respective Reclamation streamgages, sediment loads were computed from their product:

$$Q_s = Q * SSC \qquad (1)$$

where

Q_s is the sediment load in units of mass/time,

Q is the streamflow, and

SSC is the suspended-sediment concentration.

Sediment-load records were then integrated through time to estimate the annual sediment loads per water year. This method assumes that during high-flow conditions, the cross-section averaged SSC can be approximated by point samples collected by the automated samplers, and thus, assumes the system is well-mixed. This assumption is supported by the fact these systems tend to be flashy (fig. 6); thus, most of the flow (and associated shear stress) moves quickly through the relatively steep watersheds. Additionally, in steep, gravel-bedded streams, sand transport tends to move in suspension or by saltation (Church, 2002).

Satellite Imagery

Satellite imagery (courtesy of Digital Globe Inc., https://www.digitalglobe.com/company/about-us/) collected between September 24, 2009, and August 23, 2018, was used to assess streamflow paths and planform changes to the channels. There were 10 images that were downloaded and compared as part of this assessment. Although this approach has limitations, such as the lack of elevation and streamflow stage information, the assessment provides supporting information to the more quantitative study.

Results

The following sections provide results for the hydrology, sediment transport and annual loads, and the morphological changes assessed in Little Dry Creek and Cottonwood Creek watersheds. The sediment and water-level results from this report are available in Haught and Marineau (2023).

Streamflows and Water Levels

Below, water-level data (depth and WSE) were evaluated by their response to San Joaquin River flow and the respective upstream Reclamation streamgages. Additionally, flow direction was assessed from water-surface elevation among the sites for Little Dry Creek.

Cottonwood Creek

Flow direction and water levels in Cottonwood Creek were relatively straightforward to interpret because Cottonwood Creek enters the San Joaquin River through a single channel (compared to Little Dry Creek; as described in the next section). The largest hydrologic response came in the winter of WY 2017, when depths at the water-level recorder reached 1.8 m and CTK streamflow peaked at 20.5 cubic meters per second (m^3/s; fig. 10). Events in WY 2016 had shorter durations and smaller peak streamflows, whereas two events in WY 2019 had longer durations than WY 2016 but were shorter and smaller than events in WY 2017. Water levels tended to track streamflow events well, and in years with higher streamflow, water levels receded well after streamflows at CTK (fig. 10). In some cases, Cottonwood Creek flow depths exceeded the duration of streamflow gage upstream (figs. 10*A*–*B*), whereas SJR (USGS station 11251000; U.S. Geological Survey, 2022) showed increased streamflow, which indicated a backwater effect at the water-level gage.

Little Dry Creek

Flow paths and water levels in the lower 2 km of Little Dry Creek are more complex than in Cottonwood Creek because of the Canal, historical mining pits, and a concrete weir (referred to herein as "Weir") separating the Canal from the downstream (natural) creek channel (fig. 3). Figure 11 shows depths at several sites monitored (sites on fig. 3) during the study period. Some of the water-level recorders were buried throughout the study and did not have a complete or continuous record of data; therefore, only shorter periods were assessed based on data availability (Haught and Marineau, 2023).

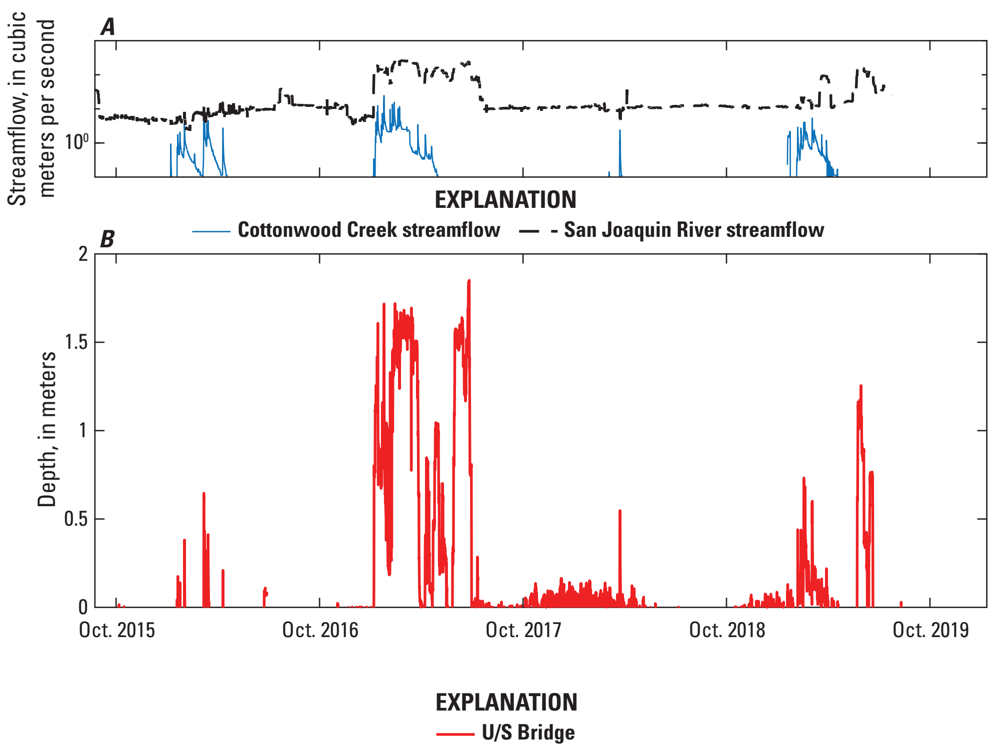


Figure 10. *A*, Streamflow from the Bureau of Reclamation in Cottonwood Creek (CTK; California Department of Water Resources, 2020; http://cdec.water.ca.gov/) and the San Joaquin River below Friant, California (SJR; California Department of Water Resources, 2020; http://cdec.water.ca.gov/; U.S. Geological Survey station 11251000; U.S. Geological Survey, 2022) streamgages; and *B*, water depth for Cottonwood Creek, California. Abbreviation: U/S, upstream.

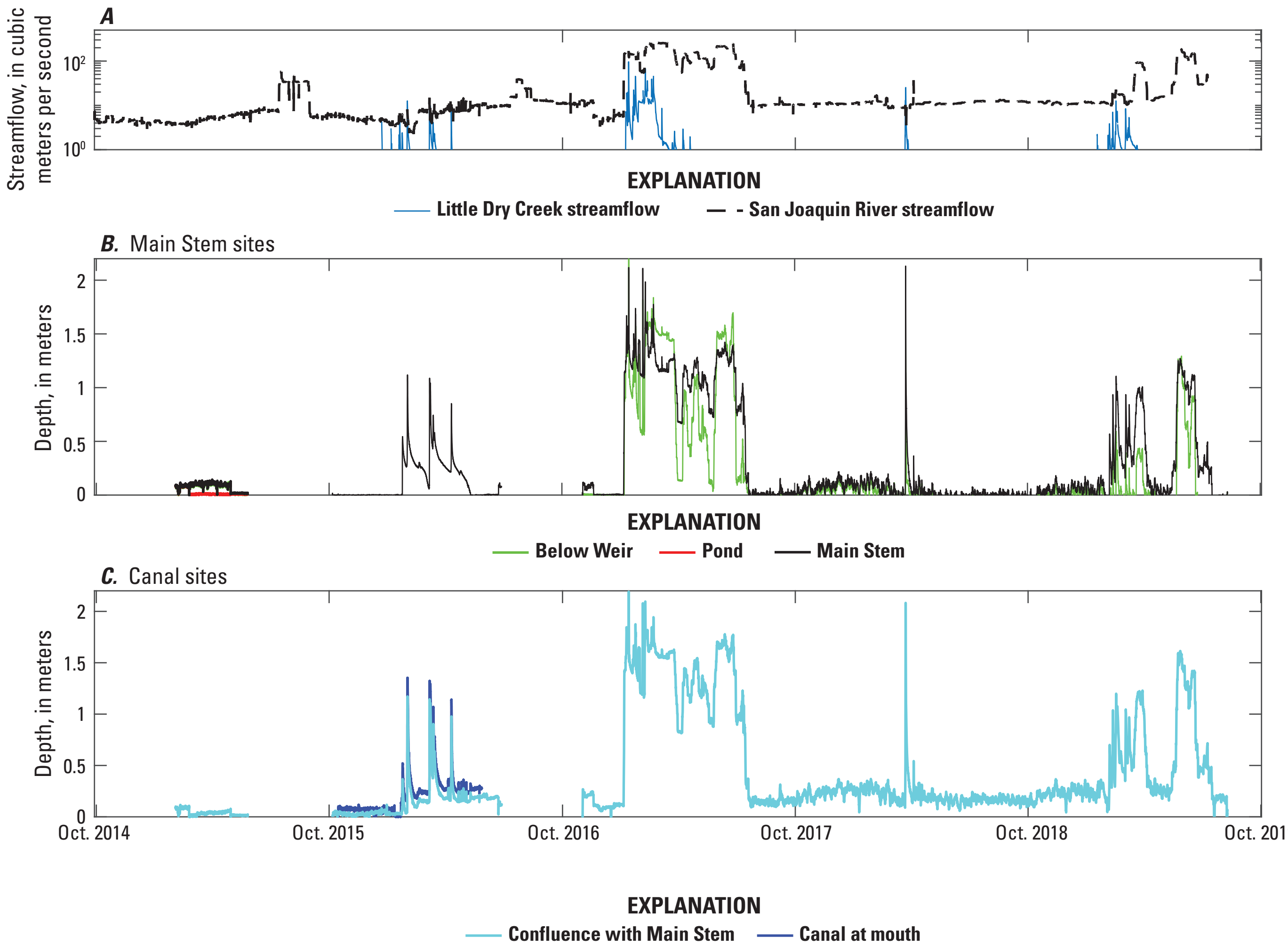


Figure 11. *A*, Streamflow from the Bureau of Reclamation Little Dry Creek (LDC) and the U.S. Geological Survey San Joaquin River (SJR; California Data Exchange Center; California Department of Water Resources, 2020; http://cdec.water.ca.gov/; U.S. Geological Survey station number 11251000; U.S. Geological Survey, 2022) streamgages; *B*, water depths in Main Stem Little Dry Creek; and *C*, water depths in Little Dry Creek Canal, California. See figure 3 for site locations. Water-surface elevation and site data are available from Haught and Marineau (2023).

The sites used to assess flow direction are the Main Stem at Pond, Canal at Middle, Canal at Confluence with Main Stem, Main Stem, and Main Stem below Weir (next to the CEMEX facility; fig. 3). The Main Stem at Pond is the most upstream site, whereas the Main Stem below Weir site indicates when the water passes over the Weir and down the main channel out the mouth (the top of the Weir is 88 m above NAVD 88). The Canal at Confluence with Main Stem and the Canal at Middle sites identify the direction of flow in the Canal. Water-surface elevations can indicate whether streamflow enters from the San Joaquin River through the Canal or the main channel of Little Dry Creek, assuming the WSEs are accurate enough to indicate flow direction.

Figure 11 indicates that there were three substantial events where water depths exceeded about 0.5 m. To assess the direction and temporal lag of water-level response, we examined the events in January 2017 and February 2019. Data were insufficient to determine flow direction during the January 2016 event. In WY 2016, changes in stream depths corresponded with changes in streamflow at LDC (California Data Exchange Center; California Department of Water Resources, 2020; http://cdec.water.ca.gov/), whereas in WYs 2017 and 2019, changes in stream depths corresponded with changes in streamflow at SJR (USGS station 11250000; U.S. Geological Survey, 2022) and LDC.

Figure 12 shows the WSE response of the Canal at Confluence with Main Stem, the Canal at Middle, and the Main Stem below Weir to that of LDC for the WY 2017 event. Water-surface elevations during WY 2017 indicated water was flowing from the Canal mouth toward the CEMEX facility throughout the event because the elevation at the Canal at Middle site was consistently higher than that at the Canal at Confluence with Main Stem site. Figure 12 also shows that at times, the flow may reverse when WSE at the Canal at Confluence with Main Stem is momentarily higher than the Canal at Middle. Water-surface elevation and site data are available from Haught and Marineau (2023).

The response of the Main Stem below Weir WSE to streamflow shows streamflow increases before the WSE responds, which indicates a counterclockwise hysteresis, meaning there is a lag between streamflow at LDC and WSE—some of which has to do with the Reclamation streamgage being upstream from this site (fig. 3). The lag demonstrates the influence of the Weir on water level in that it backs up before it breaches the Weir. Lastly, streamflow at SJR (USGS station 11251000) appeared to control the pattern of the WSE response, whereas the streamflow at LDC seemed to control only the minor deviations or peaks in streamflow, indicating a backwater effect in the lower watershed (that is, the portion below the Reclamation streamgage).

Figure 13 shows the same locations as figure 12 but for the smaller streamflow event in WY 2019. Canal sites responded similarly, until streamflow at SJR (USGS station number 11251000) increased when the Canal at Middle had a higher WSE than the Canal Confluence with Main Stem, indicating streamflow was moving from the San Joaquin River through the Canal to the Little Dry Creek main stem. Relative to WY 2017, Main Stem below Weir showed a much more muted response. Additionally, WSEs tracked the streamflows at LDC more than at SJR (USGS station number 11251000), until high streamflows occurred at SJR (USGS station number 11251000)—which was particularly evident at the Weir.

Figure 14 shows WSEs plotted against one another for the two Canal sites and the Weir for WYs 2017 and 2019. During the larger streamflow event of WY 2017, the Canal at Middle site had a rising limb that responded linearly to the Canal at Confluence with Main Stem site but lagged behind the Canal at Confluence with Main Stem site during the receding limb, indicating a backwater effect, most likely from San Joaquin River streamflows (fig. 14*A*). During the lower streamflow event in 2019, both Canal sites responded linearly and along the line of equality (1:1; fig. 14*B*) with no obvious lag. The Main Stem below Weir site (figs. 14*C–D*) showed a non-linear counterclockwise response to that of the Canal at Confluence with Main Stem site, indicating that once the lower Little Dry Creek channel (below the Weir) is activated, it recedes slower than that of the Canal. A WSE response does not occur until the Canal at Confluence with Main Stem reaches, roughly, an elevation of 88 m, which is the average elevation of the Weir.

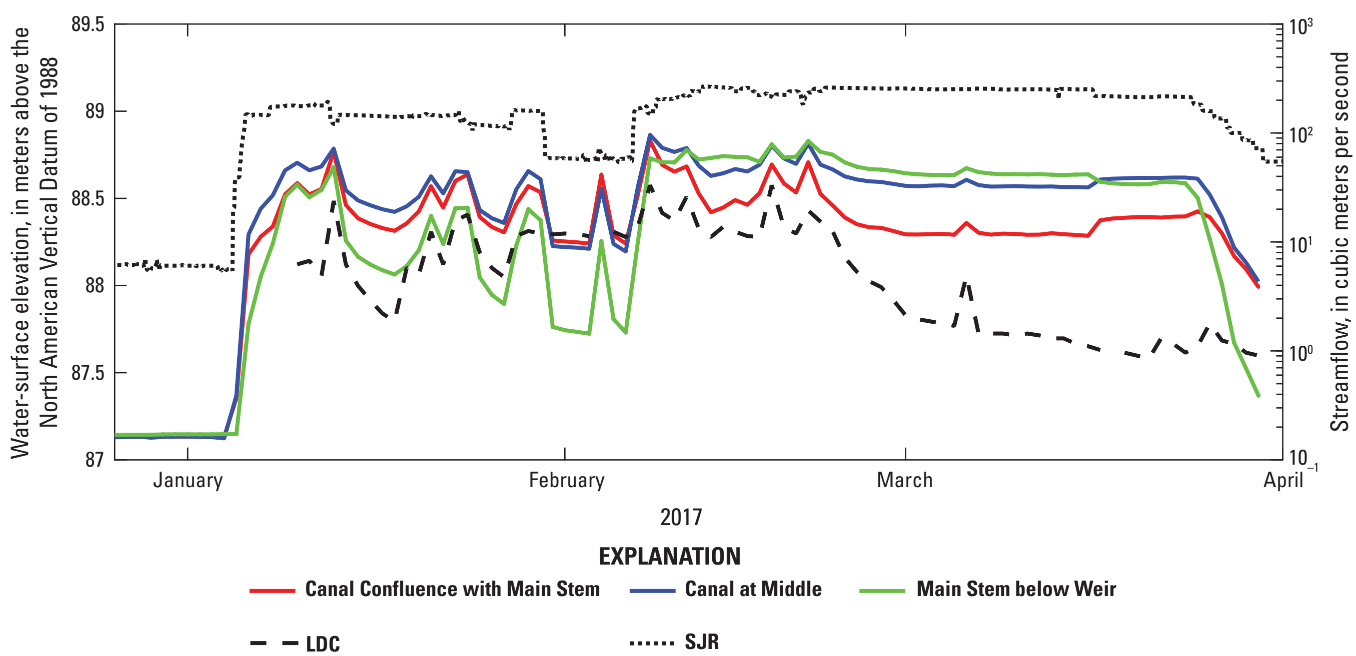


Figure 12. Water-surface elevation at three sites along Little Dry Creek and the water supply/intake canal (Canal) and streamflow at streamgages on Little Dry Creek (LDC; California Department of Water Resources, 2020; http://cdec.water.ca.gov/) and San Joaquin River below Friant Dam, California (SJR; California Department of Water Resources, 2020; http://cdec.water.ca.gov/; U.S. Geological Survey station number 11251000; U.S. Geological Survey, 2022), during the 2017 event. See figure 3 for site locations. Water-surface elevation data are available from Haught and Marineau (2023).

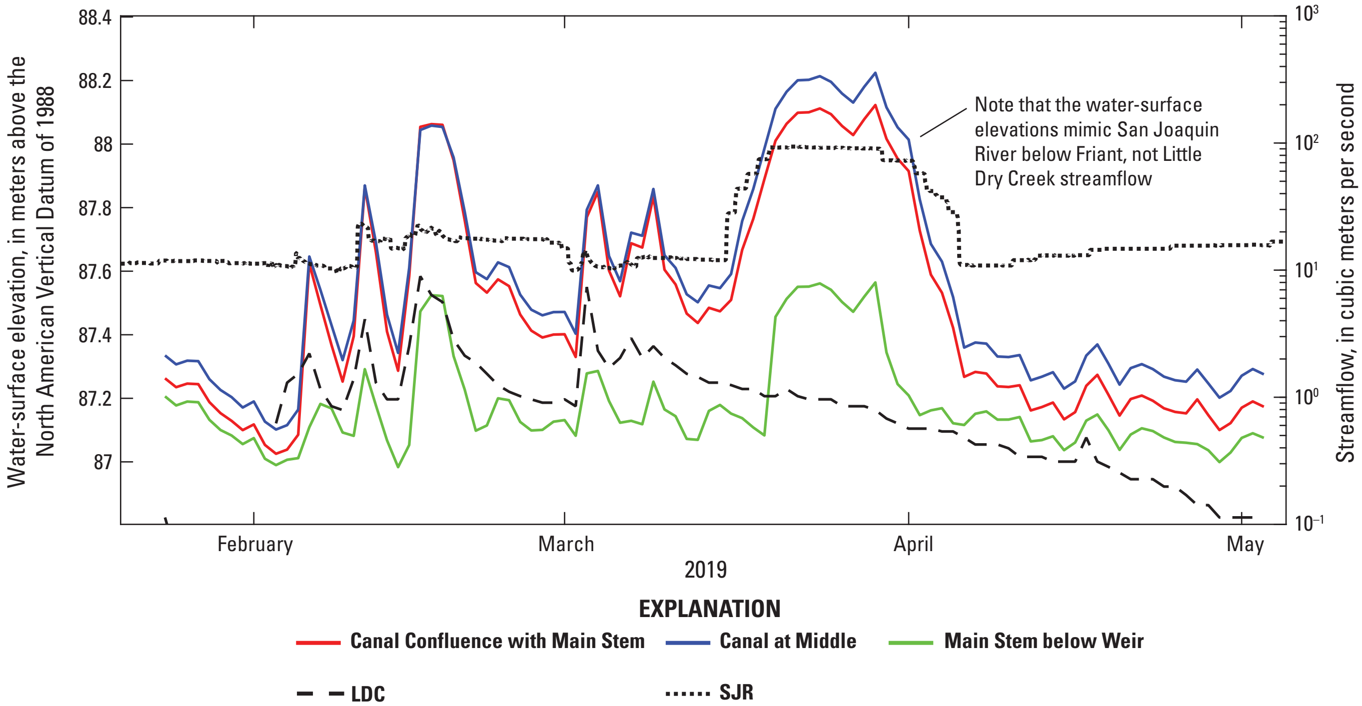


Figure 13. Streamflows for Little Dry Creek (LDC; California Data Exchange Center; California Department of Water Resources, 2020; http://cdec.water.ca.gov/) and San Joaquin River below Friant, California (SJR; California Data Exchange Center; California Department of Water Resources, 2020; http://cdec.water.ca.gov/; U.S. Geological Survey station number 11251000), and water-surface elevations from selected Little Dry Creek sites during the 2019 event. See figure 3 for site locations. Water-surface elevation data are available from Haught and Marineau (2023).

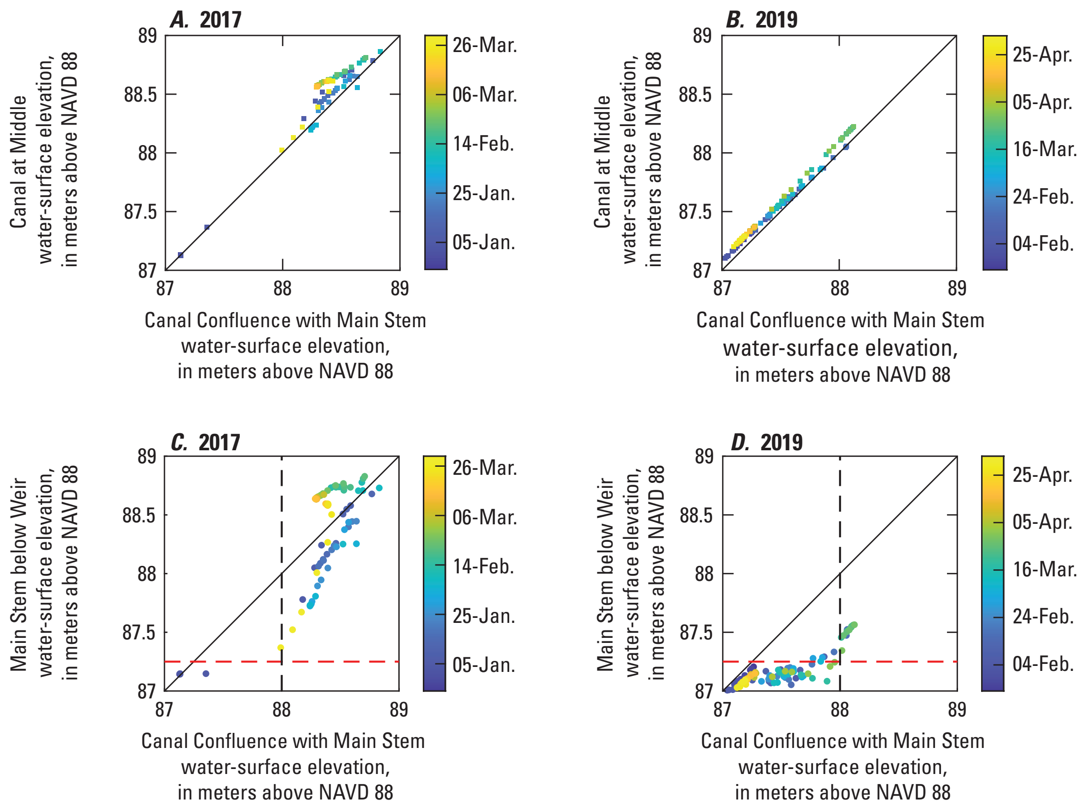


Figure 14. Water-surface elevation plotted for the Canal at Middle versus the Canal Confluence with Main Stem during *A*, water year (WY) 2017; and *B*, WY 2019, along with the Main Stem below Weir versus the Canal Confluence with Main Stem during; *C*, WY 2017; and *D*, WY 2019. The vertical dashed black line represents an elevation of 88 meters (m) above the North American Vertical Datum of 1988 (NAVD 88), which is the elevation of the Little Dry Creek Weir, whereas the horizontal dashed red line represents an elevation of 87.25 m, which is the median elevation of the cross-section below the Weir. The diagonal line is the line of equality. See figure 3 for site locations. Water-surface elevation data and site information are available from Haught and Marineau (2023).

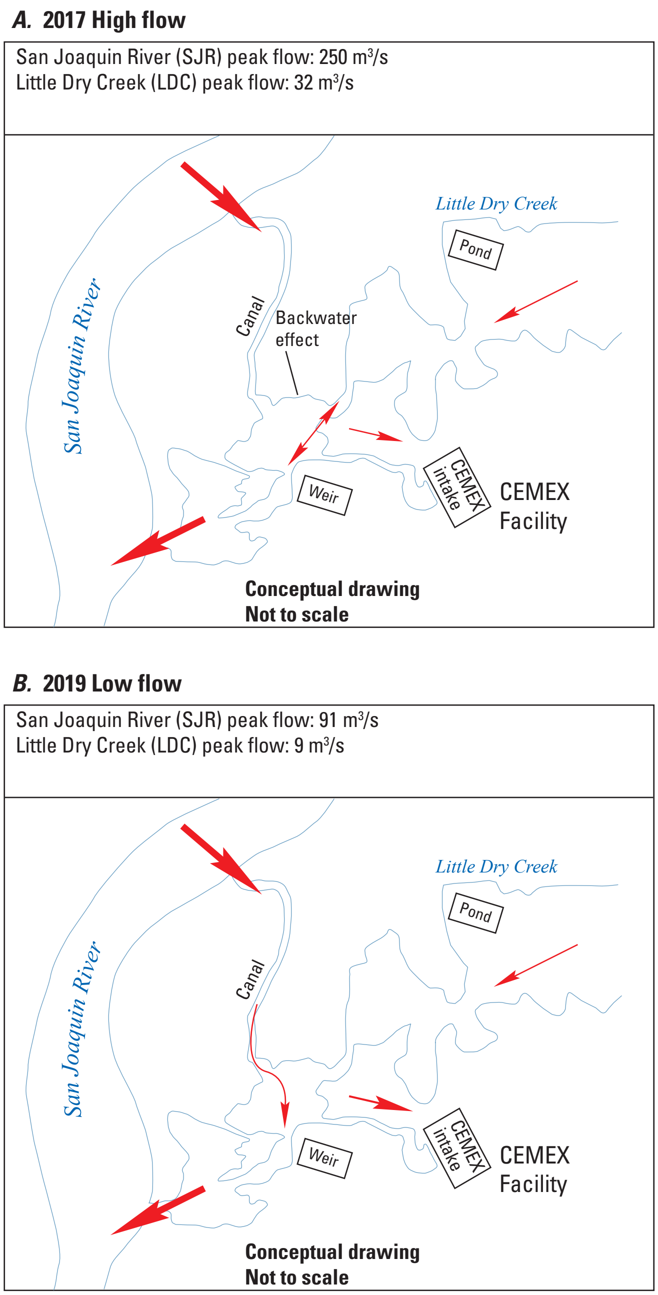


Figure 15. Conceptual flow diagram of the Little Dry Creek lower watershed during the *A*, water year (WY) 2017 high-flow; and *B*, WY 2019 low-flow events shown on figures 12 and 13, respectively. Streamflow data for the Little Dry Creek streamgage (LDC) are available from the California Data Exchange Center (California Department of Water Resources, 2020; http://cdec.water.ca.gov/). Streamflow data for San Joaquin River streamgage (SJR; U.S. Geological Survey station number 11251000) are available from the California Data Exchange Center (California Department of Water Resources, 2020; http://cdec.water.ca.gov/) or from U.S. Geological Survey (2022). Abbreviation: m³/s, cubic meters per second.

During smaller streamflow events in WY 2019, WSEs in the Canal showed a minimal response above the elevation of the bed, a median value of 87.25 m, which coincided with the streamflow seen in the San Joaquin River (fig. 13). Coinciding responses indicate the water is transported from the San Joaquin River through the Canal and down the main stem of Little Dry Creek, in addition to being transported to the intake at CEMEX. SJR flows moving through the Canal could cause a localized backwater effect at the confluence of the Canal and Little Dry Creek main stem, depending on streamflows at LDC.

Figure 15 shows a conceptual diagram of the lower 2 km of Little Dry Creek and the Canal. We used arrows to roughly scale streamflow and flow direction with respect to the two events in 2017 and 2019 described earlier. The major differences between the two events shown in the diagrams are that when streamflow is high at SJR and low at LDC, the Canal acts as a bypass channel. When streamflow is high at SJR and LDC, like in WY 2017, the channel tends to backwater at the confluence of the Canal and the Main Stem of Little Dry Creek because of high streamflows at SJR and LDC. During lower LDC streamflows, water levels backwater at the Weir until higher WSE allows streamflow to move down the main Little Dry Creek channel and back into San Joaquin River. This latter condition also causes streamflow to move toward Canal at mouth if SJR streamflows are low.

Sediment Transport

The subsections that follow this paragraph describe the concentration, timing, and load of sediment transport in lower Cottonwood Creek and Little Dry Creek. We also compared bed material and suspended-sediment GSD to distinguish the size of the material moving through the two creeks. Lastly, we provided the computed annual loads for each creek.

Bed-Sediment Grain Size

Analysis of Cottonwood Creek grain-size distributions (table 3; fig. 16) indicates that the sediment is primarily coarse sand (1–2 mm). However, these samples were likely biased toward finer material that was transported and not the coarser historical remnants shown on figure 4. Results from Little Dry Creek GSD analyses (table 4; fig. 17) indicated that the bed sediment primarily is coarse sand and very fine gravel (2–4 mm).

Table 3. Grain-size distribution characteristics for bed-sediment samples collected in Cottonwood Creek near Friant, California. Sediment data and site information are available from Haught and Marineau (2023).

[dd-mmm-yy, day-month-year; mm, millimeter; D_{10}, 10th percentile of grain-size distribution; D_{50}, median diameter; D_{90}, 90th percentile of grain-size distribution; CTK, Cottonwood Creek]

Sample	Date (dd-mmm-yy)	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)	Percent gravel	Percent sand	Percent silt	Percent clay
CTK-1	01-Nov-16	0.51	1.24	2.02	10.2	88.8	1.8	0.2
CTK-2	01-Nov-16	0.14	1.26	16.2	35.7	59.6	4.3	0.4
CTK-Left bank 1	30-Jan-17	0.16	1.02	3.9	24.8	71.6	3.1	0.5
CTK-Left bank 2	30-Jan-17	0.32	1.2	3.47	22.4	76.1	1.3	0.2
CTK-3	28-Feb-17	0.41	1.57	19.3	46.3	52.6	0.9	0.2
CTK-Left bank 3	15-May-17	0.49	1.14	1.91	5.6	93.4	0.8	0.2

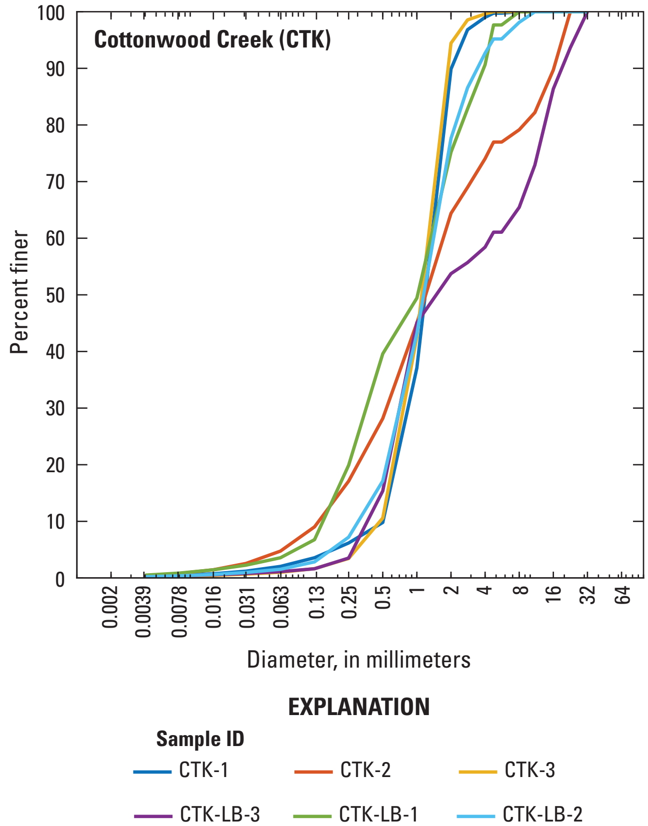


Figure 16. Grain-size distributions for bed-sediment samples collected at the Cottonwood Creek Bureau of Reclamation streamgage (CTK; California Data Exchange Center; California Department of Water Resources, 2020; http://cdec.water.ca.gov/). Grain-size diameters ranging from 1 to 2 millimeters represent coarse sands. See figure 3 for site location and table 3 for more information on specific samples. Sample identifiers listed in the figure "Explanation" are included in table 3, and sediment data are available from Haught and Marineau (2023). Abbreviation: LB, left bank.

Table 4. Grain-size distribution characteristics for bed-sediment samples collected in the Little Dry Creek watershed near Friant, California. Sediment data and site information are available from Haught and Marineau (2023).

[dd-mmm-yy, day-month-year; mm, millimeter; D_{10}, 10th percentile of grain-size distribution; D_{50}, median diameter; D_{90}, 90th percentile of grain-size distribution; LDC, Little Dry Creek]

Sample	Date (dd-mmm-yy)	D_{10} (mm)	D_{50} (mm)	D_{90} (mm)	Percent gravel	Percent sand	Percent silt	Percent clay
LDC-001	01-Nov-16	0.41	1.29	6.46	32.3	66.5	1	0.2
LDC-002	01-Nov-16	0.49	1.17	1.99	9.6	89.3	0.9	0.2
LDC-1	17-Jan-17	0.028	1.18	18.6	39	43.6	15.6	1.8
LDC-2	17-Jan-17	0.026	1.28	22.7	44.9	37.2	16	1.9
LDC-3	17-Jan-17	0.025	1.09	4.16	28.9	53.9	15.3	1.9
LDC-4	17-Jan-17	0.023	1.21	22.6	38.1	45.4	14.3	2.2
LDC-5	17-Jan-17	0.045	1.09	2.73	16.8	71.3	10.5	1.4
LDC Grab sample 1	16-Jan-17	0.51	1.13	1.98	9.2	89.9	0.7	0.2
LDC Grab sample 2	16-Jan-17	0.44	1.1	1.83	0.9	97.8	1.1	0.2

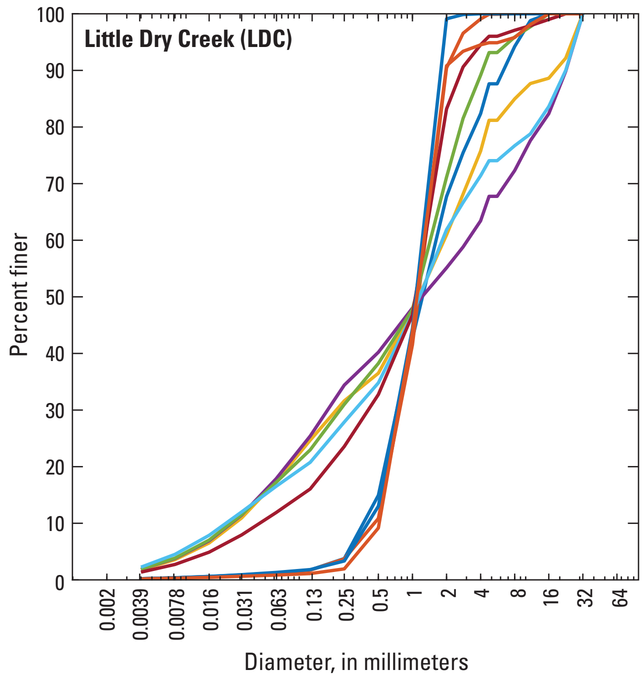


Figure 17. Grain-size distributions for bed-sediment samples collected near the Little Dry Creek Bureau of Reclamation streamgage (LDC; California Data Exchange Center; California Department of Water Resources, 2020; http://cdec.water.ca.gov/). Grain-size diameters ranging from 1 to 2 millimeters represent coarse sands. See figure 3 for site location and table 4 for more information on specific samples. Sample identifiers listed in the figure “Explanation” are included in table 4, and sediment data are available from Haught and Marineau (2023).

Suspended-Sediment Concentration and Grain Size

Figure 18 shows the suspended-sediment concentrations (SSCs, colored by median grain size) for all sites during WYs 2016 and 2017 and the time series of streamflow from the respective Reclamation streamgages (not all samples were run for GSD). In WY 2016, CTK had streamflows below 10 m^3/s and SSCs ranging from 10 to 100 mg/L. In WY 2017, CTK had streamflows an order of magnitude higher that resulted in SSCs ranging from 100 to 1,000 mg/L.

In WY 2016, SSCs in Little Dry Creek ranged from 5 to 300 mg/L when LDC streamflows were below 20 m^3/s. In WY 2017, SSCs in Little Dry Creek ranged from 10 to 10,000 mg/L, with outliers as high as $2x10^6$ mg/L, when LDC streamflows reached 100 m^3/s. Bedload sediment, or sediment saltating very near the bed, may have been sampled by the automatic sampler intake and contributed to the high SSC values (defined as being greater than 10,000 mg/L). In 2017, higher SSCs lagged peak streamflows at LDC (fig. 18*D*).

Figure 19 shows SSCs plotted as a function of streamflow for all samples collected in each watershed. Between streamflows of 1 and 10 m^3/s, SSC is highly correlated—with respect to the 95-percentile bounds—with streamflow at LDC (fig. 19*B*). Above streamflows of approximately 30 m^3/s, Little Dry Creek SSC values show more variability, with SSC values above 10,000 mg/L likely being caused by bedload. Two models (linear and non-linear) were used for predicting SSC from streamflow. The Little Dry Creek model was fit to data without outliers using non-linear (power-law) least-squares regression. A least-squares linear model was used for the Cottonwood Creek model. There were 10 outliers removed from Little Dry Creek data because of suspicions that the intake pump had contact with the bed, and 1 outlier was removed from the Cottonwood Creek data (fig. 19, red circles). Outliers for Little Dry Creek were determined by the order of magnitude that separated them from the lower SSC values (greater than 10,000 mg/L), along with the larger median grain size, whereas the Cottonwood Creek outlier was determined by Grubb's test for outliers (Grubbs, 1969).

Table 5 shows the model parameters for Cottonwood Creek and Little Dry Creek regression models. The coefficient of determination (R^2=0.54) for the Little Dry Creek model resulted from a power-law relation, whereas the R^2 value (0.56) for the Cottonwood Creek model resulted from a linear relation. Streamflows at CTK did not exceed 15 m^3/s during sediment sampling, possibly limiting the accuracy of the model at higher SSC values. The coefficient of determination for the Cottonwood Creek model demonstrates the large variability in SSC during streamflows that ranged from 0.6 to 1.0 m^3/s, whereas the coefficient of determination for the Little Dry Creek model shows more scatter when LDC streamflows were above 15 m^3/s. Table 5 provides the lower flow limit to the model, which was applied to the daily average time-series data (from the model) to limit days with no flow at a concentration of 0 mg/L.

At Cottonwood Creek, median grain diameter (D_{50}) ranged from 0.013 to 0.040 mm, with the sediment being predominantly silt sizes for WY 2016. In WY 2017, D_{50} ranged from 0.023 to 0.862 mm, with most of the samples having a median diameter in the medium- to- coarse sand size range (0.5–2 mm; fig. 20).

In the main stem of Little Dry Creek (fig. 20*B*), the D_{50} of the SSC samples exhibited a large range, with sediment being generally coarser in WY 2017 than in WY 2016. Some of this coarsening is attributed to sampling of bedload sediment when the automatic pump intake was close to the bed. In WY 2016, the Little Dry Creek main channel D_{50} ranged from 0.007 to 0.510 mm, whereas in WY 2017, the D_{50} ranged from 0.023 to 0.805 mm. At the Canal at Middle site (fig. 20*C*), WY 2016 D_{50} values ranged from 0.017 to 0.097 mm, whereas in WY 2017, D_{50} ranged from 0.016 to 0.040 mm. Thus, the Canal at Middle site shows an opposite pattern to that of Cottonwood and Little Dry Creeks in that it was finer during the larger streamflow events of WY 2017, indicating that the sediment may be sourced from San Joaquin River streamflow.

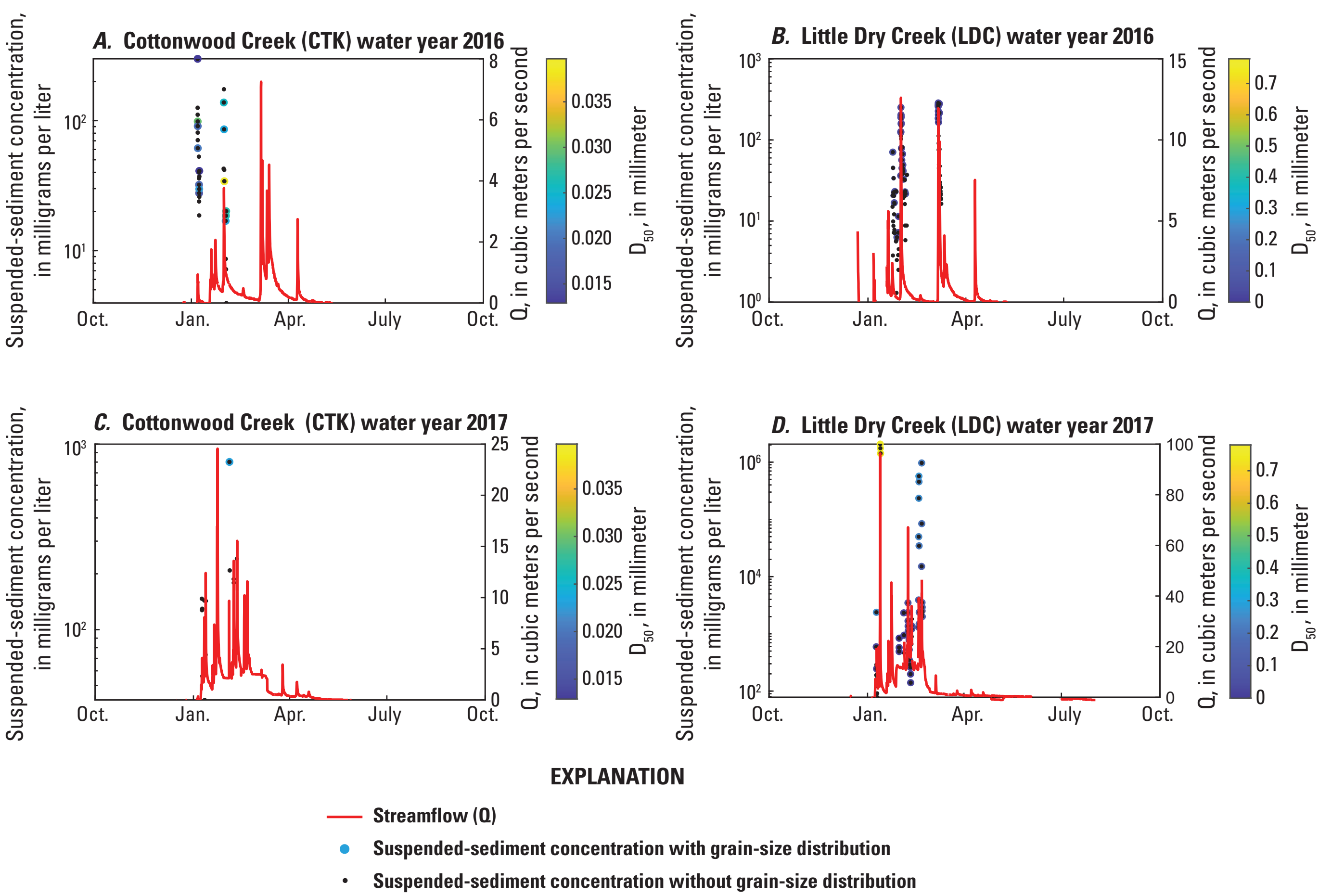


Figure 18. Time-series of streamflow and suspended-sediment samples, along with the median grain size in Cottonwood Creek (*A*, *C*) and Little Dry Creek (*B*, *D*), California. Q is streamflow. Water-surface elevation data are available from Haught and Marineau (2023), and streamflow data for the Cottonwood Creek (CTK) and Little Dry Creek (LDC) streamgages are available from the California Data Exchange Center (California Department of Water Resources, 2020; http://cdec.water.ca.gov/). Abbreviation: D_{50}, median grain size.

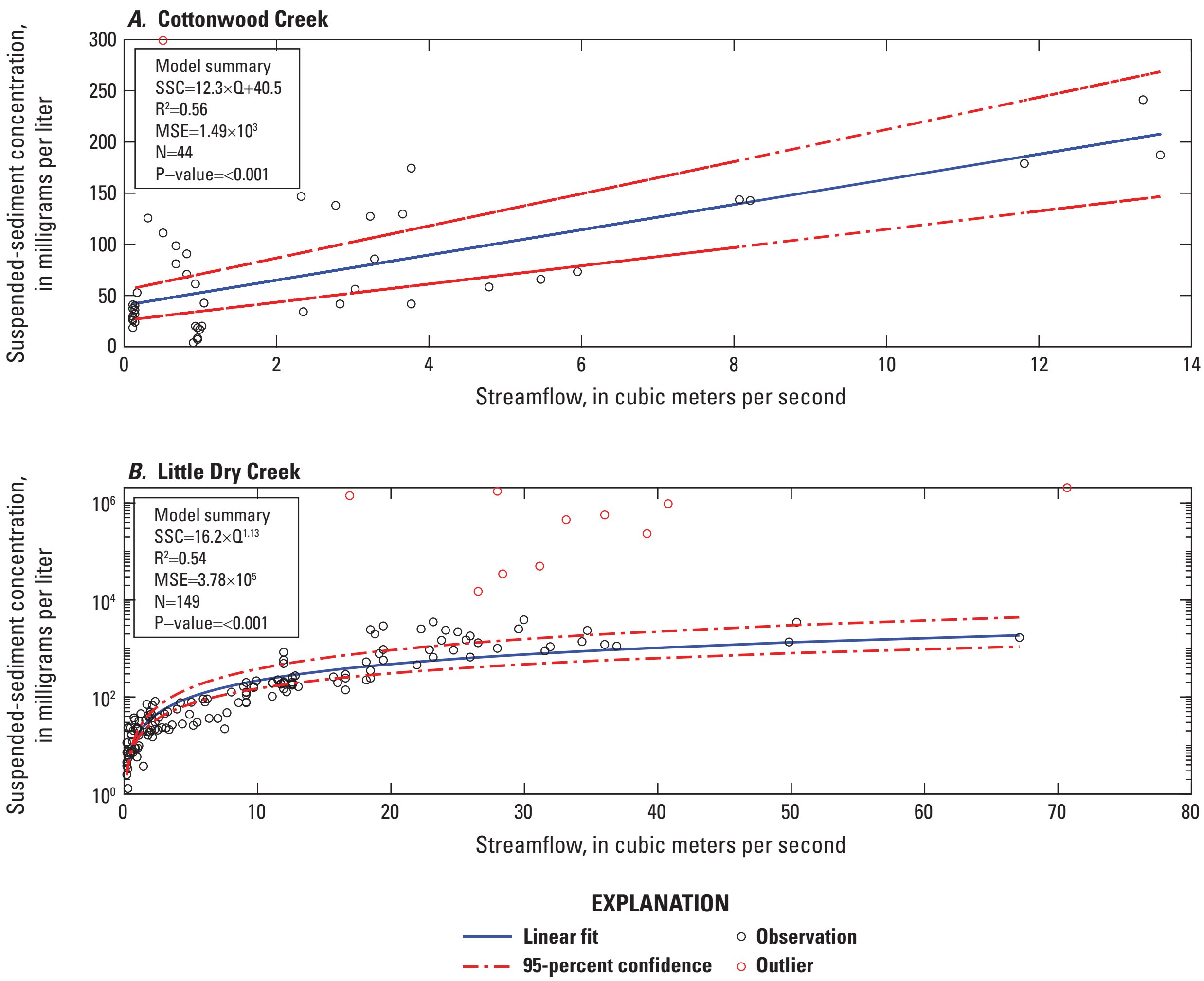


Figure 19. Suspended-sediment concentration (SSC) as a function of streamflow for *A*, Cottonwood Creek; and *B*, Little Dry Creek, California, along with models used to predict suspended-sediment concentration (table 5). Dashed lines are the 95-percent confidence bounds. Sediment data are available from Haught and Marineau (2023). Streamflow data for the Cottonwood Creek (CTK) and Little Dry Creek (LDC) streamgages are available from the California Data Exchange Center (California Department of Water Resources, 2020; http://cdec.water.ca.gov/). See table 5 for model statistics. R^2 is the coefficient of determination, MSE is mean squared error, and N is the number of observations.

Table 5. Suspended-sediment models derived from relations between suspended-sediment concentrations (SSCs) from discrete samples and measured streamflows for Cottonwood Creek (CTK) and Little Dry Creek (LDC), near Friant, California. Streamflow data are available from the California Data Exchange Center (CDEC; California Department of Water Resources, 2020; http://cdec.water.ca.gov/). Sediment data are available from Haught and Marineau (2023). Confidence bounds were determined with a level of significance (α) of 0.05.

[Confident bounds determined with a level of significance (α) of 0.05. **Abbreviations**: SSC, suspended-sediment concentration; N, number of observations; R^2, coefficient of determination; %, percent; m^3/s, cubic meter per second; a, the intercept; b, the slope; Q, discharge; CTK, Cottonwood Creek; LDC, Little Dry Creek]

Model form	SSC model	Coefficients	N	R^2	p-value	95% Confidence bounds	Lower flow limit (m^3/s)
				Watershed CTK			
Linear	SSC=b*Q+a	a=12.30	44.00	0.56	Less than $1e^{-3}$	a=[8.90, 15.69]	0.11
		b=40.47				b=[25.69, 55.25]	
				Watershed LDC			
Power	SSC=a*Q^b	a=16.23	149.00	0.54	Less than $1e^{-3}$	a=[13.52, 19.48]	0.2
		b=1.128				b=[1.044, 1.213]	

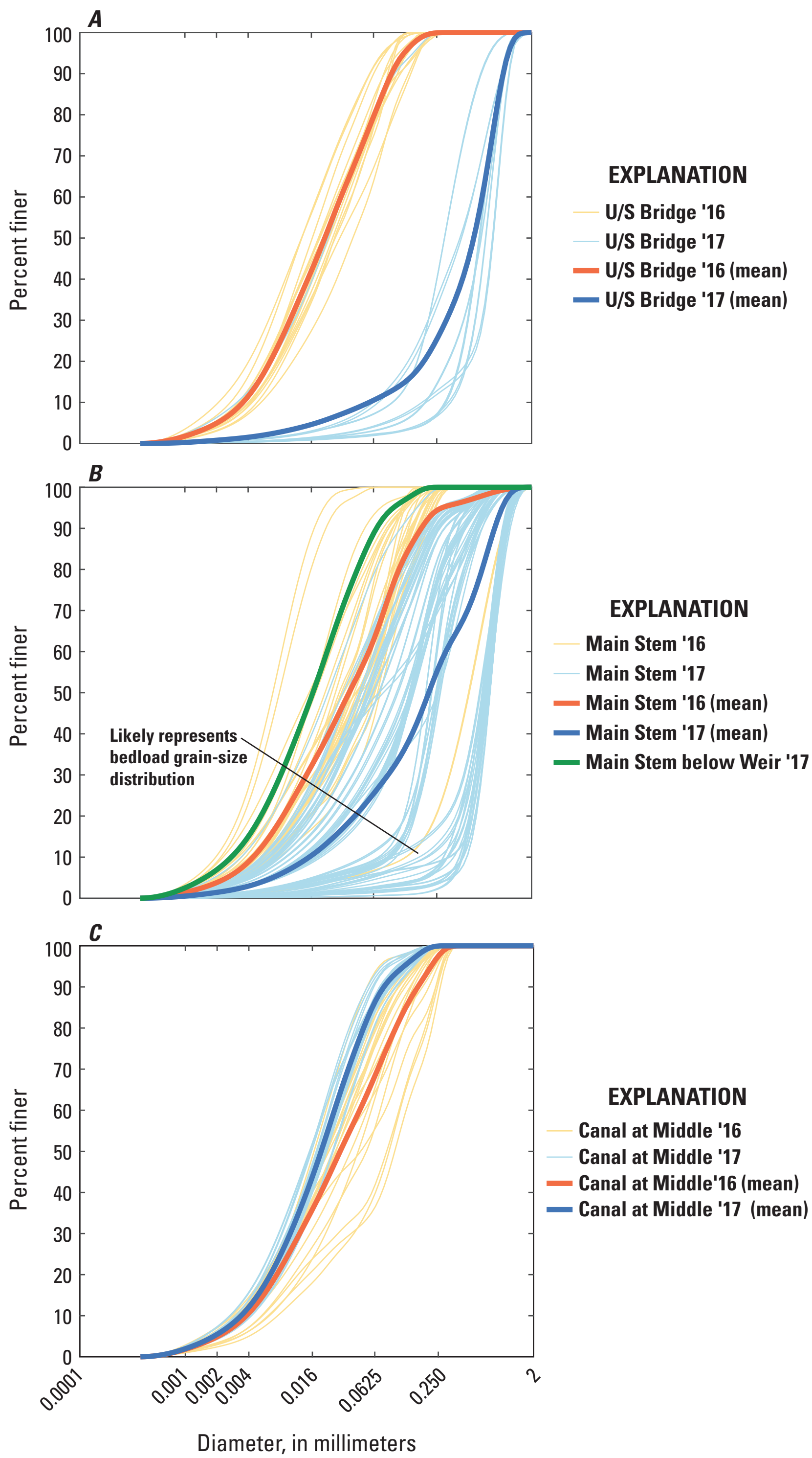


Figure 20. Suspended-sediment sample grain-size distributions for water years 2016 and 2017 from *A*, Upstream Bridge (U/S); *B*, Main Stem and Main Stem Below Weir; and *C*, Canal at Middle. Sediment data and site information are available from Haught and Marineau (2023).

Suspended-sediment GSDs have D_{10} (that is, the 10th percentile of the GSD) that ranges from 1 to roughly 125 µm (fig. 20) for all sites, which is finer than that of the bed material, which ranges from 23 to 510 µm for Little Dry Creek and from 140 to 510 µm for Cottonwood Creek. These differences in D_{10} values indicates that the finer suspended material passes through the system and is not retained in the bed. However, bed-material samples are limited in quantity and spatial distribution. Additional samples collected throughout a broader spatial distribution would help confirm the interpretation of these results.

Suspended-Sediment Loads

Suspended-sediment loads, Q_s, were calculated for Little Dry and Cottonwood Creeks from the product of streamflow and SSC (eq. 1). Continuous sediment concentrations were computed from the models summarized in table 5. Figure 21 shows daily averaged sediment loads for Little Dry and Cottonwood Creeks for the wet season of WY 2017. The continuous sediment-load time series for each water-year was integrated through time to compute the annual load (fig. 22; table 6). Figure 21 also shows the daily standard deviation bounds (with respect to the average), whereas figure 22 provides the error in the annual load estimates associated with the 95-percent confidence bounds provided in table 5.

Geomorphology

This section discusses the use of aerial imagery to infer sediment transport effects on morphology of the lower watersheds to support the more quantitative assessment described in the "Sediment Transport" section. The inferences listed in this section are based solely on changes of the images through time and not physical measurements.

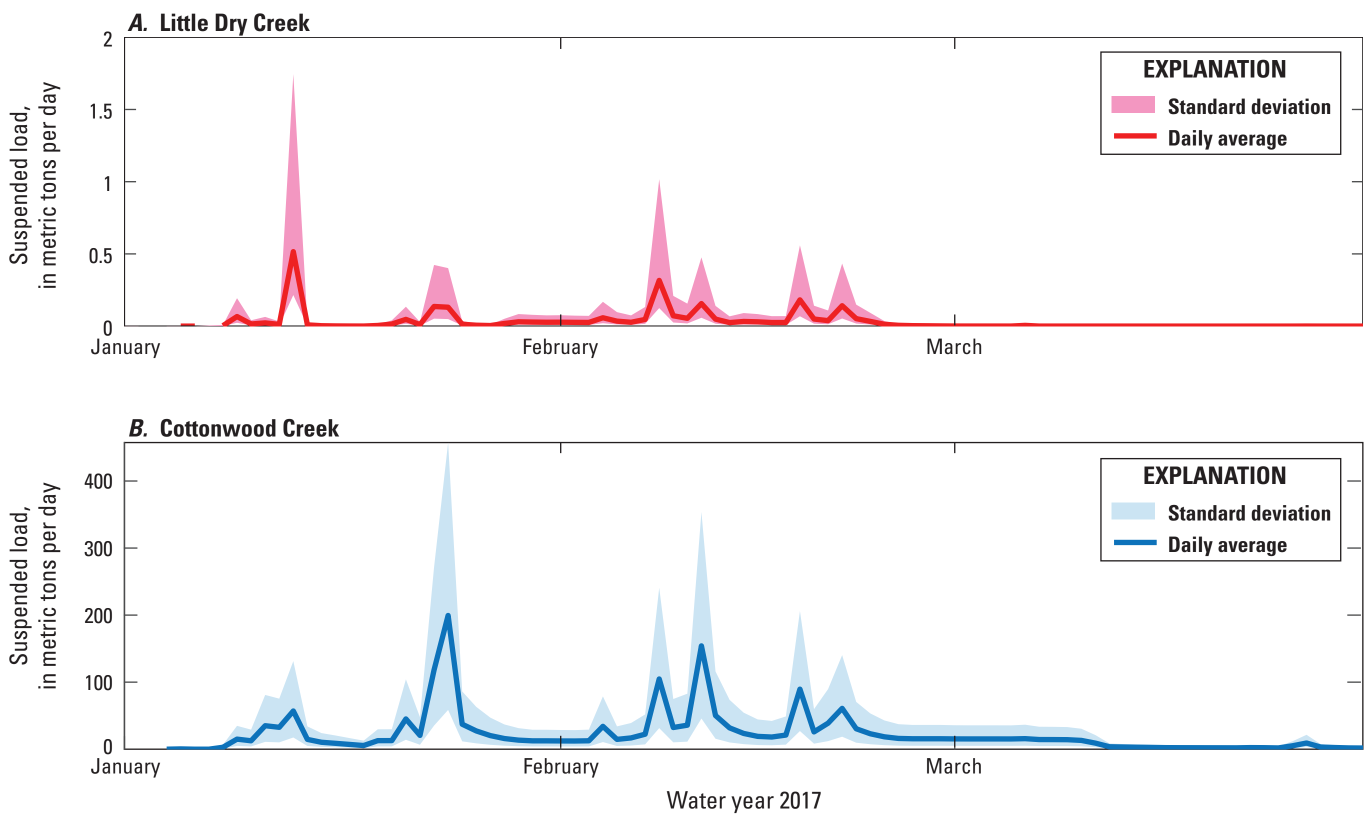


Figure 21. Computed loads for the 2017 water year (WY 2017), showing the daily averaged and daily standard deviation bounds for *A*, Little Dry Creek; and *B*, Cottonwood Creek, California. Sediment data are available from Haught and Marineau (2023), and streamflow data for the Little Dry Creek (LDC) and Cottonwood Creek (CTK) streamgages are available from the California Data Exchange Center (California Department of Water Resources, 2020; http://cdec.water.ca.gov/). Abbreviation: metric tons/day, metric tons per day. Little Dry Creek sediment loads represent sediment samples from all ISCO sites.

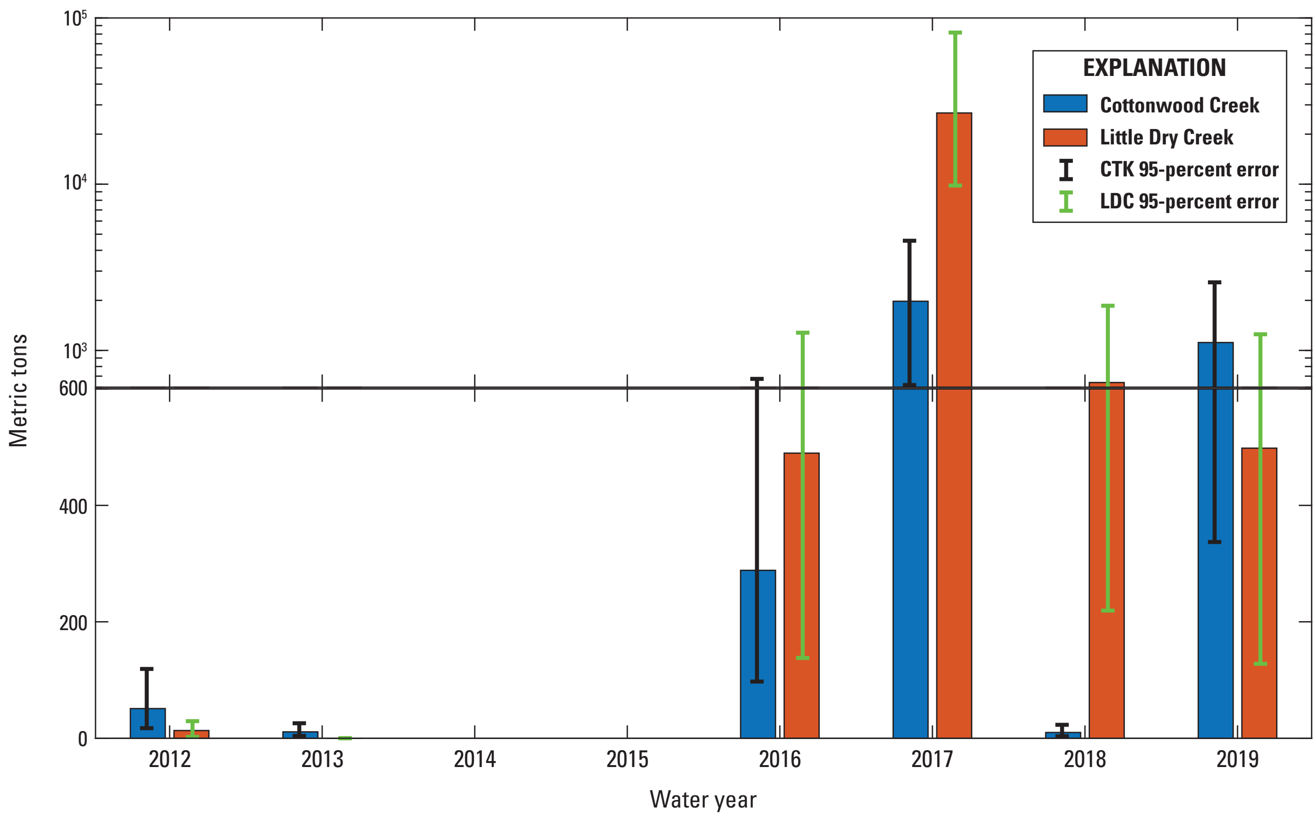


Figure 22. Annual suspended-sediment loads computed by water year (October 1 to September 30, named for the calendar year in which the period ends) for the Cottonwood Creek (CTK) and Little Dry Creek (LDC) streamgages, California. Error bars based off 95-percent confidence bounds. Note that the lower panel y-axis is linear, whereas the upper panel is logarithmic. Sediment data are available from Haught and Marineau (2023), and streamflow data are available from the California Data Exchange Center (California Department of Water Resources, 2020; http://cdec.water.ca.gov/). Little Dry Creek sediment loads represent sediment samples from all ISCO sites.

Table 6. Annual suspended-sediment loads (in metric tons) for water years 2012–18, at the Cottonwood Creek (CTK) and Little Dry Creek (LDC) streamgages, California. A water year is the period from October 1 through the following September 30 that is named for the calendar year in which the period ends. Sediment data are available from Haught and Marineau (2023), and streamflow data are available from the California Data Exchange Center (California Department of Water Resources, 2020; http://cdec.water.ca.gov/).

[WY, water year; %, percent; Q, streamflow; m^3, cubic meter; —, no data]

WY	Cottonwood Creek load (metric ton)				Little Dry Creek load (metric ton)			
	95% Low bound	Fit	95% High bound	Total Q (m^3)	95% Low bound	Fit	95% High bound	Total Q (m^3)
2012	3.37×10^1	5.09×10^1	6.81×10^1	1.49×10^4	1.09×10^1	1.32×10^1	1.61×10^1	3.94×10^5
2013	6.98×10^0	1.09×10^1	1.48×10^1	3.89×10^5	—	—	—	—
2014	—	—	—	—	—	—	—	—
2015	—	—	—	—	—	—	—	—
2016	1.91×10^2	2.88×10^2	3.85×10^2	4.72×10^6	3.52×10^2	4.89×10^2	7.88×10^2	6.27×10^6
2017	1.36×10^3	1.98×10^3	2.59×10^3	1.97×10^7	170×10^2	2.68×10^4	5.49×10^4	5.06×10^7
2018	6.44×10^0	9.82×10^0	1.32×10^1	2.19×10^5	4.21×10^2	6.41×10^2	1.22×10^3	2.65×10^6
2019	7.88×10^2	1.12×10^3	1.45×10^3	5.35×10^6	3.70×10^2	4.98×10^2	7.52×10^2	8.33×10^6

Little Dry Creek

Figure 23 shows a series of five images from March 18, 2015, to August 23, 2018, that illustrate the evolution of the Main Stem at Pond geomorphology. The March 2015 image shows a protruding delta into the pond, with substantial vegetation in the channel. Figure 23*B* shows the channel in March 2017 when LDC streamflow was approximately 0.9 m^3/s (fig. 6). The flood peaked in January 2017 at 86 m^3/s, and the only previous storm occurred in March 2016, with a peak streamflow of 10 m^3/s (fig. 6). The March 2017 image indicates that the active channel had less vegetation or vegetation that had been buried, whereas the floodplains appear to have freshly deposited sediment. The August 2017 imagery (fig. 23*C*) shows the pond still full of water with the channel dry and less vegetation than prior to the flooding (fig. 23*A*). There were no large fluvial events between the flood in 2017 and February 2018. Between February (fig. 23*D*) and August 2018 (figs. 23*D–E*), a flood with a peak of 22 m^3/s occurred (fig. 6). The channel showed no signs of new or altered deposits—if anything, there was an increase in vegetation—suggesting that streamflows may need to be larger and longer than the March 2018 event (approximately 25 m^3/s) to induce major channel evolution at this location.

Figure 24 shows imagery from Little Dry Creek below the Weir collected in March 2015 (fig. 24*A*) and March 2017 (fig. 24*B*). The largest flood during the study period receded in mid-March 2017, so the imagery on figure 24*B* was collected during the falling limb of the hydrograph when streamflow was approximately 0.8 m^3/s at LDC (figs. 3, 6). Water levels indicate that the Weir disconnects streamflow from the main channel below the Weir and redirects it to the Canal (see the “Streamflows and Water Levels” section). Substantial deposition occurred between March 2015 and March 2017, indicating that below the Weir, deposition occurs after larger events and the bed is active once streamflows reach the threshold to overtop the Weir. Figure 25 further shows the discontinuity of sediment transport at the Weir. Deposition of sand-sized sediment is apparent upstream from the Weir, whereas downstream bed sediment consists of coarse gravel and cobble until streamflow overtops the Weir and transports sediment downstream to the San Joaquin River. Figures 24 and 25 further demonstrate the complex sediment transport that occurs through this area during flood streamflows.

Cottonwood Creek

Satellite imagery of Cottonwood Creek (fig. 26) provides limited information about channel deposition or erosion, with one exception. The image on figure 26*B* was taken shortly after the 2017 high-flow event that had a peak streamflow of 25 m^3/s (fig. 6) on January 26, 2017, where changes in bed material were observed between the two photographs. The channel was heavily vegetated in 2015 (fig. 26*A*), but after the 2017 event, sandy deposits appeared in the channel as bars (fig. 26*B*). After 2017, the channel appears to have revegetated. This process can be seen consistently in imagery throughout the entire watershed.

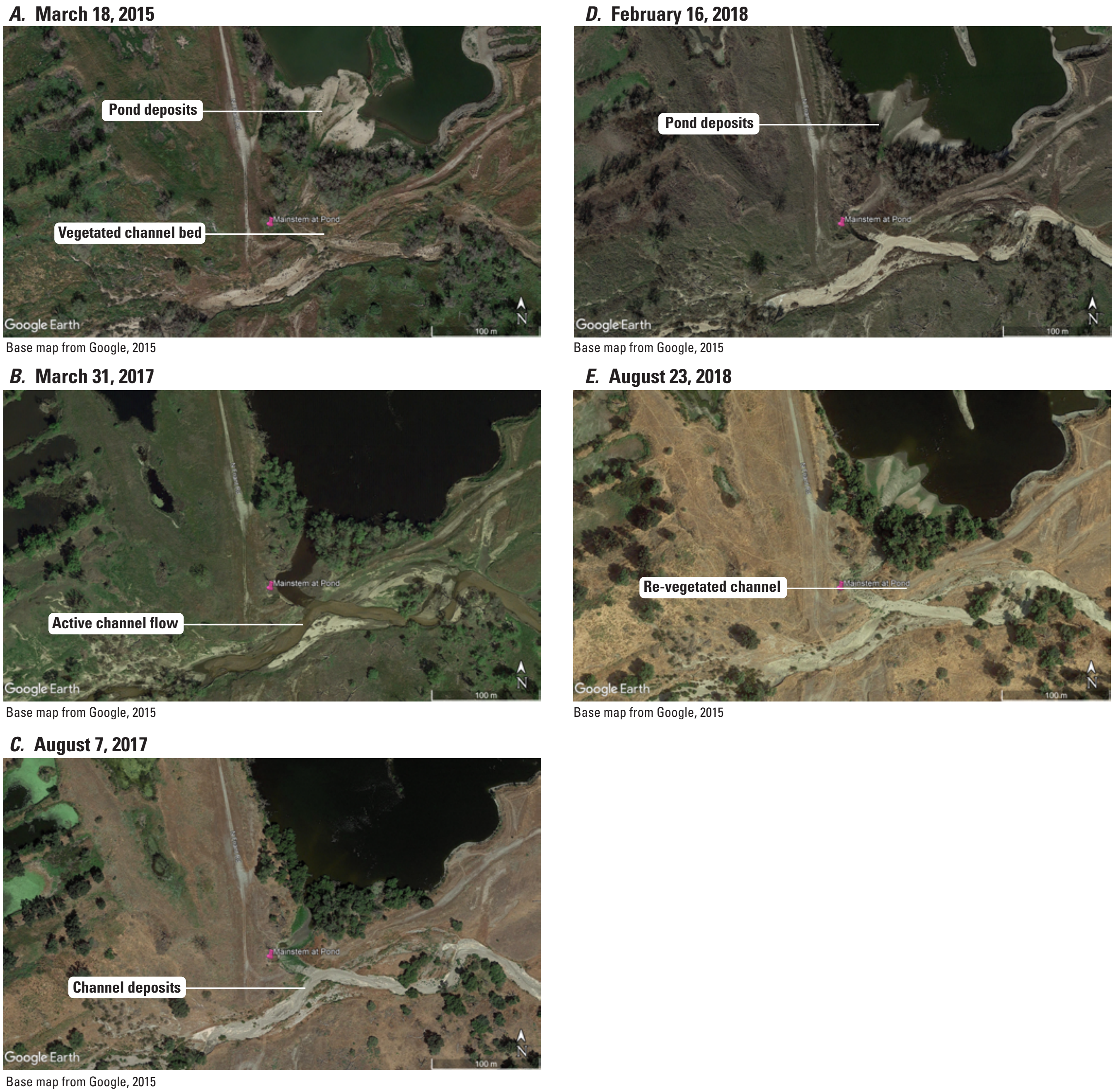
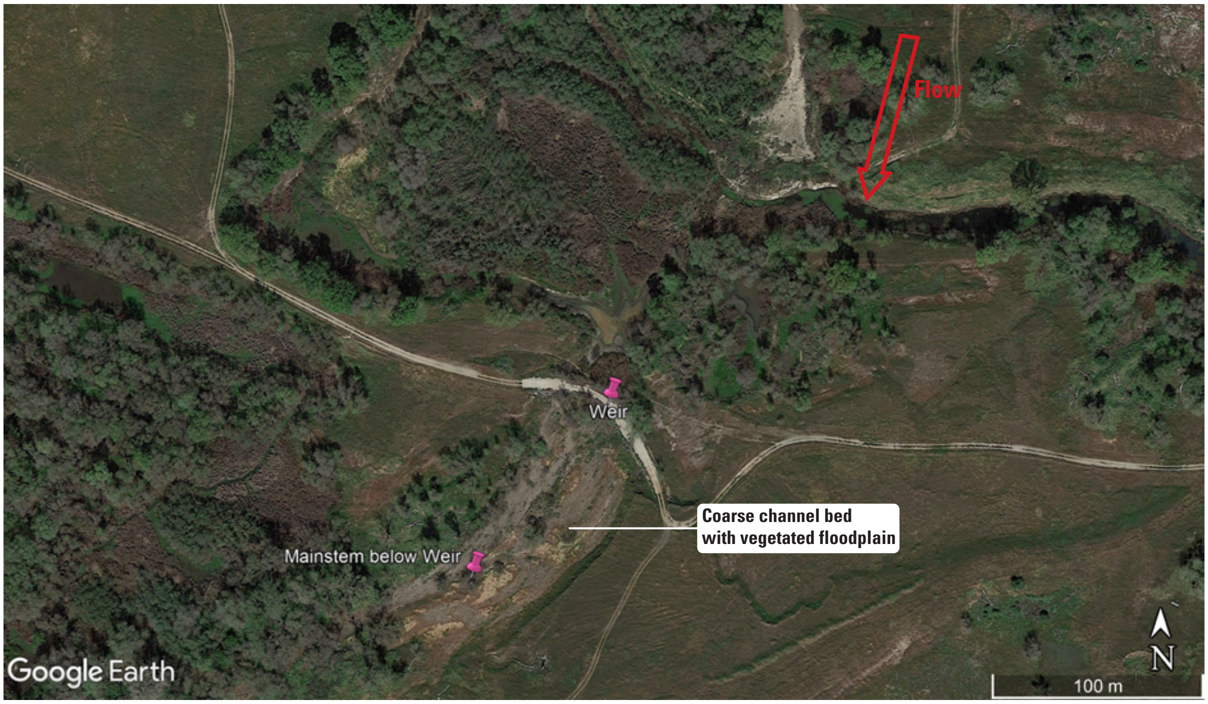


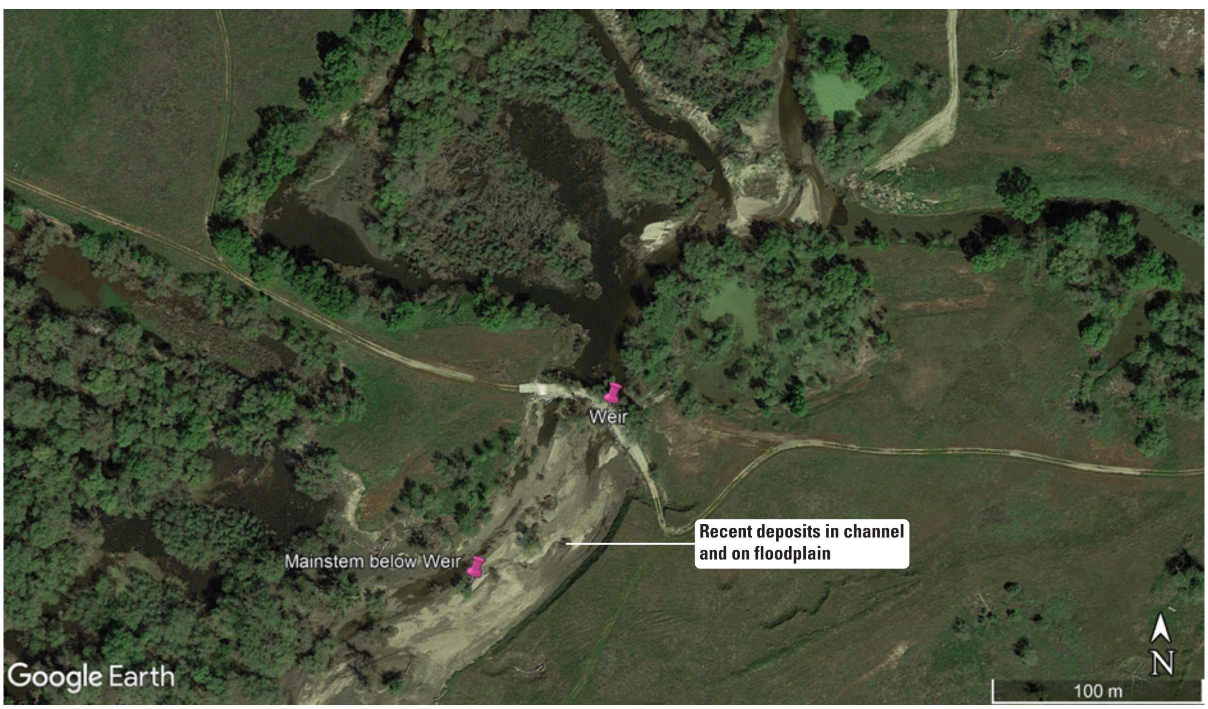
Figure 23. Channel evolution depicted from a series of plan-view Google Earth imagery on *A*, March 18, 2015; B, March 31, 2017; *C*, August 7, 2017; *D*, February 16, 2018; and *E*, August 23, 2018, in Little Dry Creek, California. Imagery courtesy of Digital Globe Inc., (https://www.digitalglobe.com/company/about-us/).

A. **March 18, 2015**



Base map from Google, 2015

B. **March 31, 2017**



Base map from Google, 2015

Figure 24. The Main Stem below Weir at Little Dry Creek, California, for *A*, March 18, 2015; and *B*, March 31, 2017. Imagery courtesy of Digital Globe Inc. (https://www.digitalglobe.com/company/about-us/).

A. **Looking downstream from Little Dry Creek weir toward San Joaquin River**

B. **Looking upstream from Little Dry Creek weir toward Canal**

Figure 25. The Main Stem at Weir facing *A*, downstream, showing coarse bed material and little-to-no deposition; and *B*, upstream, showing substantial sand deposition, in Little Dry Creek, California. Figure photographs demonstrate the influence the Weir has on upstream suspended-sediment transport. See figure 3 for site location.

A. **March 18, 2015**

Base map from Google, 2015

B. **March 31, 2017**

Base map from Google, 2015

Figure 26. Cottonwood Creek, near Friant, California, approximately 200 meters upstream from the confluence with the San Joaquin River on *A*, March 18, 2015; and *B*, March 31, 2017. The Cottonwood Creek water-level logger was located just upstream from the bridge seen in this image. See figure 3 (CTK) for site location. Imagery courtesy of Digital Globe Inc., (https://www.digitalglobe.com/company/about-us/).

Implications of Tributary Loads on San Joaquin River Habitat

Water year 2017 was the second wettest WY on record (1901–2019) for the San Joaquin River watershed (California Department of Water Resources, 2020), which allowed for a wide range of SSC samples across a large range of streamflow observations. Because of the substantial range in streamflow at SSC sampling—specifically in WY 2017—the sediment rating curve developed herein represents a broad range of streamflow conditions. Most high-flow events, and therefore sediment laden events, occurred in late winter to early spring. High-flow events tend to last relatively longer in Little Dry Creek than Cottonwood Creek. However, the overall flashiness of these systems likely limits channel-forming streamflows or restructuring of the bed—which limits the movement of material coarser than sand and small gravel—to short durations and distances. Therefore, morphological evolution of Little Dry and Cottonwood Creeks likely occurs at the intra-annual scale.

Cottonwood Creek and Little Dry Creek suspended-sediment GSDs show that transported sediment ranged from silts to coarse sands, with the coarsest sediment (1- to 2-millimeter sand) likely indicating more bedload transport than suspended transport (fig. 20*B*). Between WYs 2016 and 2017, the main stems of Cottonwood and Little Dry Creeks showed coarsening in suspended sediment during high-flow years. The Canal showed the opposite trend, with increasing fines from WYs 2016 to 2017. Suspended-sediment size indicates that the source sediment in the Canal during 2017 was from the San Joaquin River and not Little Dry Creek because finer sediment may be sorted as it enters the Canal from the San Joaquin River.

Annual sediment loads for the Little Dry Creek and Cottonwood Creek watersheds were largest in WY 2017. For Little Dry Creek, WY 2018 had the second largest annual suspended-sediment loads followed by WYs 2019 and 2016. The suspended-sediment loads show that Cottonwood Creek annual loads were generally an order of magnitude smaller than Little Dry Creek, with WY 2019 being the exception, when Cottonwood Creek had a greater annual load than Little Dry Creek. In WY 2018, Cottonwood Creek had substantially less total load and an order of magnitude less total streamflow, but in WY 2019, Cottonwood Creek had an order of magnitude greater load than Little Dry Creek. Additionally, Little Dry Creek had more total streamflow but less total load in 2016 than in 2018, whereas Cottonwood Creek loads increased with increased total streamflow. These differences demonstrate the importance of streamflow-event duration per WY.

Because sediment concentration is estimated as a function of streamflow, load computations are sensitive to any error in streamflow estimated at each tributary streamgage. Additionally, estimated sediment loads do not indicate changes in sediment supply in the system. Lastly, the load estimates described earlier are partially estimated (that is, the streamflow part of eq. 1) at the Reclamation streamgages where streamflow is measured (fig. 3), and sediment loads that pass these streamgages may not represent what enters the San Joaquin River. Though these streamgages are not located at the most downstream end of each watershed, the unmeasured downstream portion is small relative to the size of the watersheds (3.3 percent and 2.4 percent for Cottonwood and Little Dry Creeks, respectively).

In the lower Cottonwood Creek (that is, below the streamgage), the channel is narrow relative to Little Dry Creek, which likely limits the available storage in the lower Cottonwood Creek watershed. This hypothesis is further supported by the lack of observed deposits in field visits and in satellite imagery, indicating that suspended-sediment loads downstream from the CTK streamgage reach the San Joaquin River. Downstream from the LDC streamgage, there are at least three mining pits (or ponds), the Weir, and the water-supply Canal that delivers water to CEMEX (and bisects the historical channel). Therefore, the channel discontinuities and larger available storage in Little Dry Creek likely inhibits sediment loads from entering the San Joaquin River relative to Cottonwood Creek; this is supported by observation of delta deposits at the mouth of the Little Dry Creek Pond (fig. 23) and buried instrumentation. These observations demonstrate that the Little Dry Creek main stem and the mining pits act as water and sediment sinks that trap sediment moving down Little Dry Creek before the sediment reaches the Canal and Weir.

The Canal and Weir—depending on streamflows at LDC and SJR (USGS station number 11251000)—can further induce suspended-sediment deposition when the Weir causes backwater conditions. Relatively finer sediment may only pass over the Weir at higher streamflows because coarser material falls out of suspension in the relatively slower velocity water immediately upstream from the Weir; therefore, the suspended material entering the San Joaquin River is selectively sorted. The composition of the single sediment sample collected below the Weir in January 2017 supports the idea that only fine sediment passes over the Weir (fig. 20*B*); however, additional samples are needed to verify this hypothesis. Downstream from the Weir, sediment is actively transported from the streambed only when streamflows reach the threshold to overtop the Weir. Therefore, these discontinuities in streamflow and sediment transport, along with the upstream sediment sinks, can influence the timing and amount of potential sediment delivered to the San Joaquin River.

CEMEX maintains the Canal and excavates sediment from it after wet winters when Little Dry Creek (or the San Joaquin River) fills in the Canal with sediment. Excavation of the Canal likely reduces the quantity of stored sediment to transport downstream to the San Joaquin River.

Summary and Conclusions

In this report, the U.S. Geological Survey cooperated with the Bureau of Reclamation San Joaquin River Restoration Program to examine the suspended-sediment load, timing, continuity, and grain size of the transported material from Cottonwood and Little Dry Creeks and assess potential sediment contributions to the San Joaquin River. Sediment loads and grain size affect sediment transport processes and salmonid spawning habitat. The following are the key findings of this study:

- Annual suspended-sediment loads generally were higher in the Little Dry Creek watershed compared to the Cottonwood Creek watershed. Water year 2017 had the highest annual loads among Little Dry and Cottonwood Creeks during the period of study. Computed annual sediment loads ranged from 1.32x10^{1} to 2.68x10^{4} metric tons for Little Dry Creek and from 9.82 to 1.98x10^{3} metric tons for Cottonwood Creek.

- Transport of suspended sediment occurred in the Little Dry Creek and Cottonwood Creek watersheds primarily between January and March. Transport events were flashy and affected by backwater caused by the San Joaquin River, which likely influenced deposition.

- Grain-size distribution of the bed material and suspended material indicate that clay, silts, and fine sand may pass through the systems, with coarse sand dominating the suspended-sediment at the highest streamflows. Sand of this size is within the range of material that can be detrimental to incubating salmonid eggs and can influence the transport of coarser bed material.

- Little Dry Creek had more potential for storage of sand-sized material because of tortuous channel paths, backwater effects from the San Joaquin River, and mining ponds. Additionally, the bisecting Canal and Weir creates discontinuities in streamflow and sediment transport.

Although this study has provided annual loads and grain-size distributions within the lower two tributaries, a better understanding of the hydrodynamics near the confluences of Cottonwood and Little Dry Creeks to the San Joaquin River would provide clarity regarding the influence of the backwater effect and channel continuity with respect to how much sediment enters the San Joaquin River. Because of the tortuous nature of streamflow in lower Little Dry Creek, a two-dimensional hydraulic (and maybe sediment-transport) model could be used to identify more transport patterns at a wider breadth of flow conditions.

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