Description of Chronostratigraphic Units Preserved as Channel Deposits and Geomorphic Processes Following a Basin-Scale Disturbance by a Wildfire in Colorado

By John A. Moody and Deborah A. Martin

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Cover. Views of the mouth of Spring Creek looking upstream. South Platte River at the base of the photographs flows from left to right. Upper left, August 7, 1997, one year after the 1996 Buffalo Creek wildfire. Bottom right, June 10, 2014.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	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)

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)

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).

Description of Chronostratigraphic Units Preserved as Channel Deposits and Geomorphic Processes Following a Basin-Scale Disturbance by a Wildfire in Colorado

By John A. Moody and Deborah A. Martin

Abstract

The consequence of a 1996 wildfire disturbance and a subsequent high-intensity summer convective rain storm (about 110 millimeters per hour) was the deposition of a sediment superslug in the Spring Creek basin (26.8 square kilometers) of the Front Range Mountains in Colorado. Spring Creek is a tributary to the South Platte River upstream from Strontia Springs Reservoir, which supplies domestic water for the cities of Denver and Aurora. Changes in a superslug were monitored over the course of 18 years (1996–2014) by repeat surveys at 18 channel cross sections spaced at nearly equal intervals along a 1,500-meter study reach and by a time series of photographs of each cross section. Surveys were not repeated at regular time intervals but after major changes caused by different geomorphic processes. The focus of this long-term study was to understand the evolution and internal alluvial architecture of chronostratigraphic units (defined as the volume of sediment deposited between two successive surveys), and the preservation or storage of these units in the superslug. The data are presented as a series of 18 narratives (one for each cross section) that summarize the changes, illustrate these changes with photographs, and provide a preservation plot showing the amount of each chronostratigraphic unit still remaining in June 2014.

The most significant hydrologic change after the wildfire was an exponential decrease in peak discharge of flash floods caused by summer convective rain storms. In response to these hydrologic changes, all 18 locations went through an aggradation phase, an incision phase, and finally a stabilization phase. However, the architecture of the chronostratigraphic units differs from cross section to cross section, and units are characterized by either a laminar, fragmented, or hybrid alluvial architecture. In response to the decrease in peak-flood discharge and the increase in hillslope and riparian vegetation, Spring Creek abandoned many of the nearly horizontal erosional and depositional surfaces and left a landscape consisting of a series of cut-and-fill terraces as a legacy of this wildfire disturbance.

Introduction

Wildfires alter the interception of rainfall, the soil hydraulic properties, and the surface roughness of steep, forested basins (Moody and others, 2013). When these alterations are followed by sufficient rainfall over most of the basin, extreme runoff is generated that erodes hillslopes, channelizes drainages, and enlarges low-order, steep-gradient channels. The resulting sediment fluxes can surpass normal background fluxes by several orders of magnitude (Moody and Martin, 2001a, b), and sediment is often deposited in higher order, low-gradient channels that act as sediment reservoirs. These sediment deposits are often called pulses or sediment slugs (Nicholas and others, 1995; James, 2010).

There is a growing interest in understanding (1) the deposition and erosion processes that modify sediment slugs and (2) how much sediment is preserved in the slug. This interest is because some sediment may be contaminated (Malmon and others, 2002; Pizzuto, 2002; Walter and Merritts, 2008; James, 2013). Theoretical and modeling approaches generally have assumed that that fluxes of sediment in and out of the storage reservoirs are constant over time and that subsequent processes modifying the sediment slugs are in a steady state such that all particles in a given sediment unit of the same age are equally likely to be eroded (Bolin and Rodhe, 1973; Dietrich and others, 1982; Malmon and others, 2003). Previous studies (Dietrich and others, 1982; Bradley and Tucker, 2013) have focused on lateral depositional and erosional processes typical of meandering rivers, and a few (Lauer and Parker, 2008a, b) have dealt with vertical aggradation and incision processes. Modification of sediment slugs by steady-state processes has been documented (for example, Madej and Osaki, 1996; Sutherland and others, 2002), but modification by unsteady flow processes has not been documented thus far.

Purpose and Scope

The purpose of this report is twofold. First, is to describe basic topographic data from repeat surveys of channel cross sections and chronostratigraphic units deposited during the period between the surveys. Second, is to describe the geomorphic processes that altered a superslug that was deposited as the result of a wildfire disturbance (1996 Buffalo Creek wildfire) and a subsequent extreme flood. Erosional changes after the flood, of chronostratigraphic units (defined as the volume of sediment deposited between two successive surveys), were monitored at 18 channel cross sections along a 1,500-meter (m) reach of the Spring Creek tributary of the South Platte River in the Front Range Mountains of central Colorado from 1996 through 2014. Basic data are provided in Moody and Martin (2017).

Background

The 1996 Buffalo Creek fire (May 18–24, 1996) was a crown fire that burned a predominately ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) forest in the Buffalo Creek and Spring Creek basins (elevations 1,900–3,200 m) in the Pike National Forest located along the Front Range Mountains of Colorado (fig. 1). This high-intensity crown fire, driven by strong westerly winds, burned 21 percent of the Buffalo Creek basin (122.4 square kilometers [km^2]) and 79 percent of the Spring Creek basin (26.8 km^2); combusted the canopy, litter, and duff layers; and altered the soil hydraulic properties (Agnew and others, 1997; Moody and Martin, 2001b; Ebel and others, 2012). Soils on hillslopes are highly erodible (Blair, 1976), especially when the litter and duff layers are removed (Moody and Martin, 2001a, b). The unburned soil erodibility or K-factor (Foster and others, 1981; Renard and others, 1997) is 0.019 ton per hectare per megajoule per hectrare times millimeter per hour (t/ha/[{MJ/ha}{mm/h}]) (Moore, 1992; Foster and others, 1981).

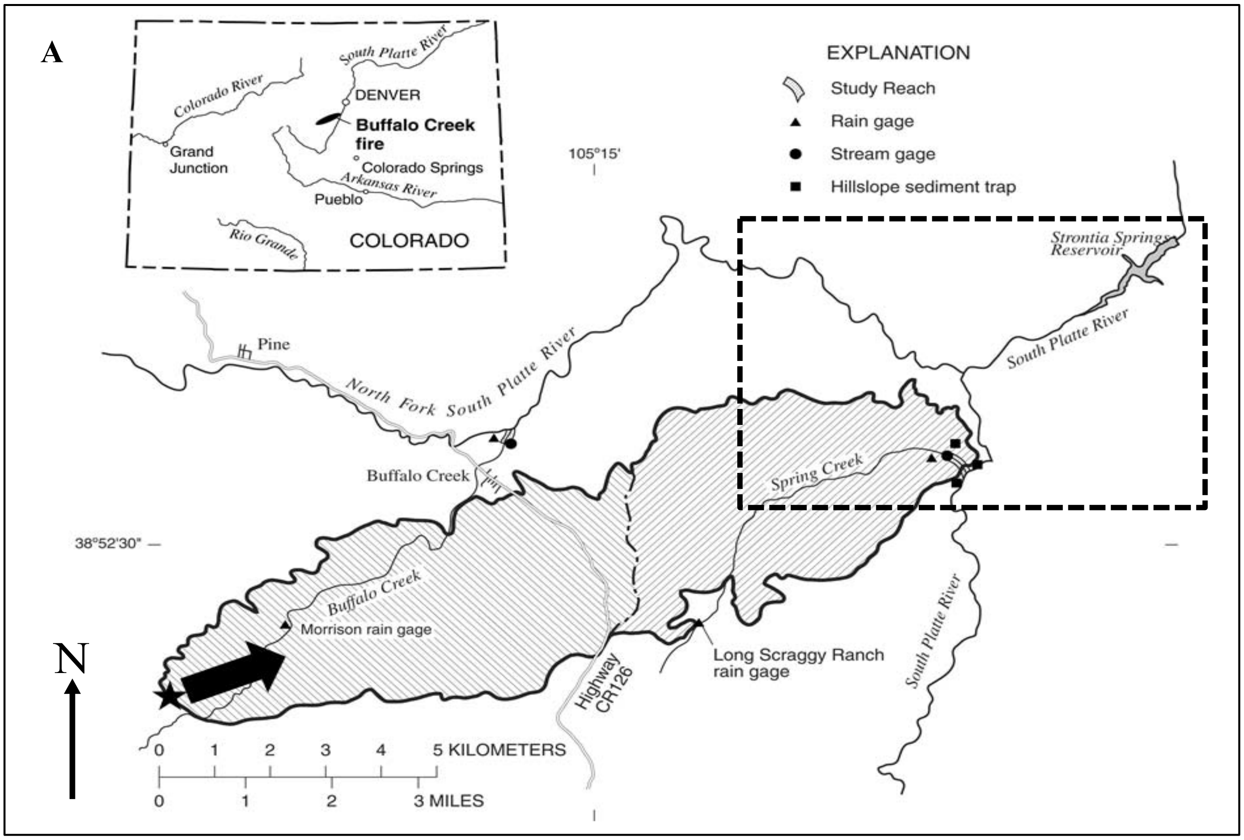

Figure 1. Area near Denver, Colorado, USA, that was burned by the 1996 Buffalo Creek fire and subsequently modified by flooding. *A*, Burned area, enlarged to show the portions of the Buffalo Creek basin (21 percent of 122.40 square kilometers [km^2]) and Spring Creek basin (79 percent of 26.80 km^2) that were burned by the wildfire. Buffalo Creek is shown by descending diagonal lines and Spring Creek is shown by ascending diagonal lines. The fire started at the black star and was driven eastward by strong winds (shown by large black arrow pointing northeastward) as a crown fire through the canopy of mostly ponderosa pine trees. Box with black dashed lines shows the approximate area of figure 1*B*.

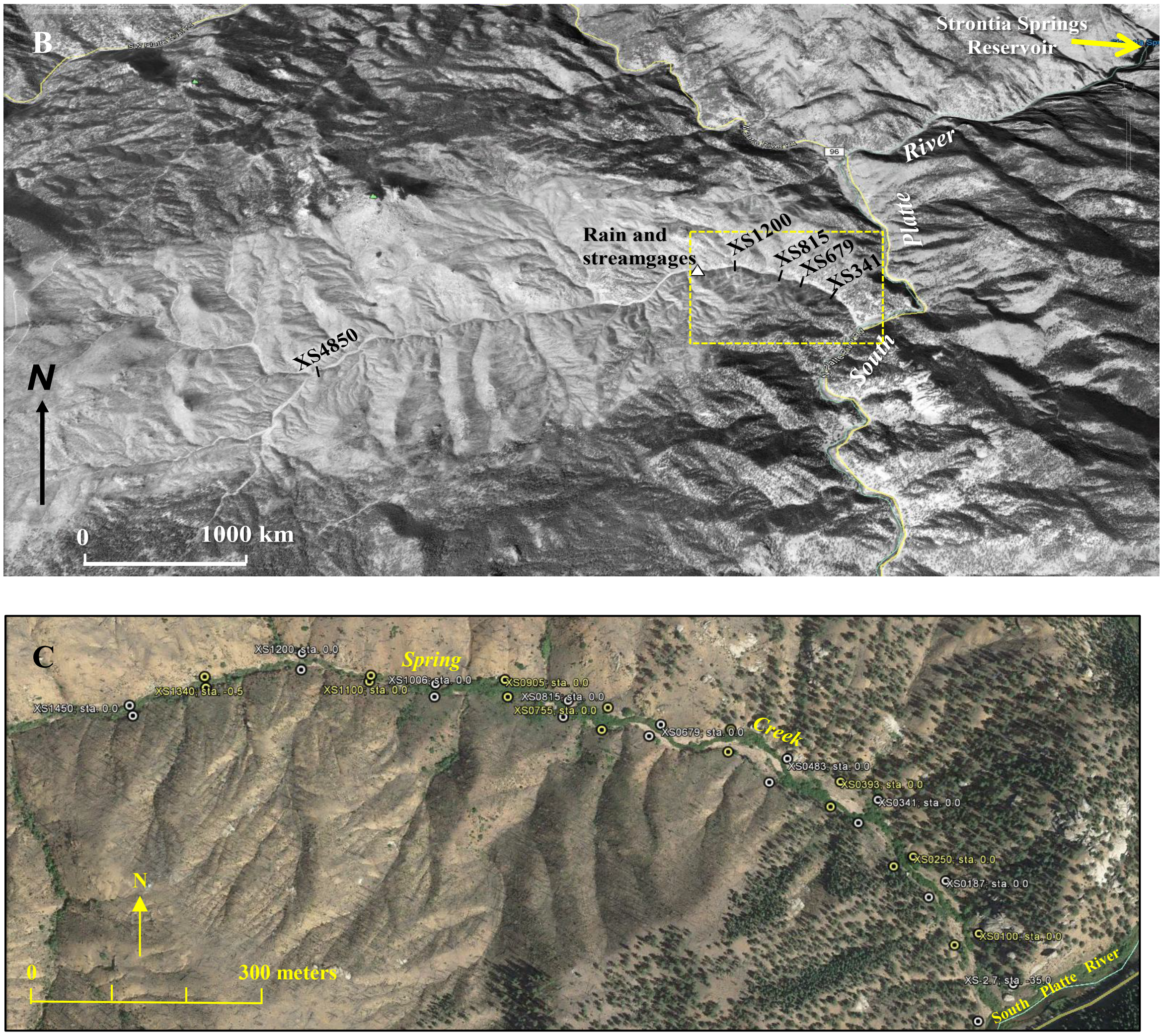

Figure 1. Area near Denver, Colorado, USA, that was burned by the 1996 Buffalo Creek fire and subsequently modified by flooding. *B*, Modified Google Earth image (October 4, 1999) showing the burned area of Spring Creek. Image was taken three years after the major flood on July 12, 1996, and the landscape still shows the burn scar and the extent of the sediment superslug consisting of white sand, gravel, and rocks occupying the main channel and most of the major tributary channels of the Spring Creek basin (especially the tributaries upstream from the location of cross section [XS] 4850). The primary study reach extends from the confluence of Spring Creek and the South Platte River to a rain and streamgage 1,500 meters (m) upstream. Data from the rain gage were used to determine rainfall-discharge relations (Moody, 2001; Moody and Martin, 2001a, b, c). Five of 18 channel cross section locations are shown. In each section label, the number following the "XS" is the distance in meters upstream from the confluence. Box with yellow dashed lines shows the approximate area of figure 1*C*. *C*, Google Earth image (September 8, 2016) showing close-up view of the primary study reach of Spring Creek shown in figure 1*B*. Flow in the creek is from west to east. Seventeen channel cross sections are shown. The most upstream cross section (XS4850, not shown) is about 3,000 m upstream from XS1450. The 0.0 station for each cross section is on the left bank of Spring Creek. Base map data from Google, DigitalGlobe 2015.—Continued

Only seven weeks after the wildfire, the Spring Creek basin received an intense 100-year-recurrence-interval rainstorm that caused extensive erosion of the burned hillslopes. On July 12, 1996, about 110 millimeters (mm) of rain fell in a single hour (Jarrett, 2001). This storm caused an extreme flood with a peak discharge of about 510 cubic meters per second (m^3/s). Peak discharge per unit drainage area was about 24 cubic meters per second per square kilometer ($m^3/s/km^2$) (Moody, 2001; Moody and Martin, 2001a, b), which eroded most of the steep Spring Creek basin (relief ratio 0.046, mean channel bed slope 0.041; Moody and Martin, 2001a, b) and deposited sediment in the channel network (fig. 1) (Moody and Martin, 2001b; Moody and Kinner, 2005). The estimate of the initial equivalent sediment thickness after the flood (measured cross-sectional area divided by the valley width) is 0.6 m based on pre- and postflood aerial photographs. Surficial bed sediment was relatively uniform, having a median particle diameter (D_{50}) ranging from 2.5 to 4.4 mm (Moody, 2001). Based on the criteria given by Nicholas and others (1995), this sediment deposit can be classified as a superslug because it involves a basin-scale sediment supply and was a major valley-floor adjustment of the base level. The superslug in Spring Creek contained sediments from several types of human activity such as grazing, timber harvest, and mining (Jack, 1900; Gilbert, 1917; Connaughton, 1938; Peterson, 1964; Haynes, 1965; Vance and Vance, 2016; U.S. Geological Survey, 2017). An estimated volume of 1.1 million cubic meters (m^3) of sediment was eroded from the Spring Creek basin (26.8 km^2) during the extreme flood. A volume of about 0.36 million m^3 was transported into and impacted the Strontia Spring water-supply reservoir on the South Platte River, which supplies the cities of Denver and Aurora, leaving 0.74 million m^3 of legacy sediment preserved in the Spring Creek basin (fig. 1) (Moody and Martin, 2001a, b).

Runoff and erosion after wildfires are generally driven by summer convective rainstorms in this mountainous region of Colorado (Moody and Martin, 2001a, b, c). During the period 1996–2014, summer (June through September) rainfall total was greatest during 1997 (383 mm), the first year after the wildfire and smallest in 2008 (157 mm) (fig. 2). Summer total rainfall had no significant trend (R^2=0.017) after the wildfire (1996–2014). The mean was 235 mm, which is 52 percent of the total annual precipitation.

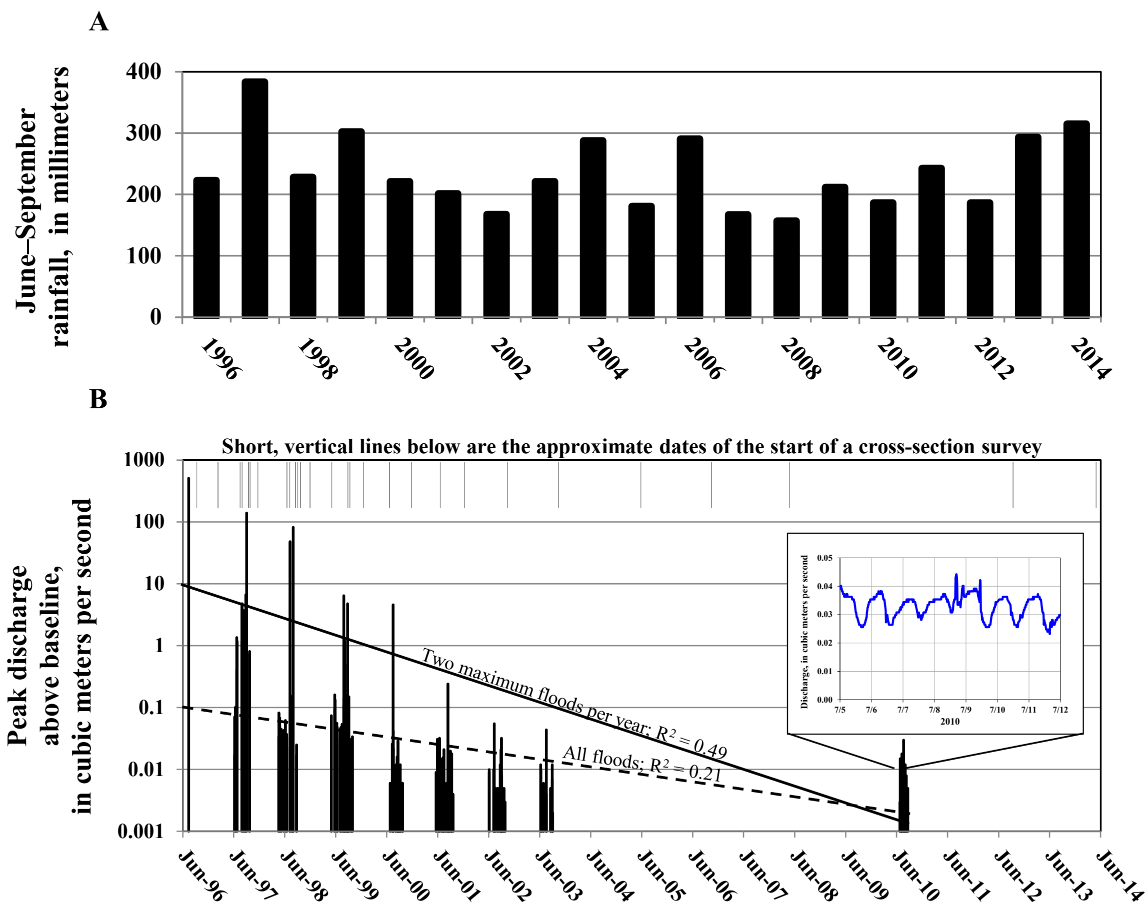

Figure 2. Annual rainfall and peak discharges for Spring Creek, 1996–2014. *A*, Annual summer (June through September) rainfall totals from 1996 through 2014. These rainfall data are from the National Oceanic and Atmospheric Administration National Weather Service station 050454 in Bailey, Colorado, located about 20 kilometers west of the mouth of Spring Creek. *B*, Peak water discharge for floods greater than 0.01 cubic meters per second [m^3/s] 1996–2014 (Moody and Martin, 2001a). These peak discharges have an exponentially decreasing trend for the two maximum floods each year (coefficient of determination [R^2]=0.49, solid-black line) and for all floods greater than 0.01 m^3/s (R^2=0.21, dashed black line). The inset hydrograph for July 5–12, 2010, shows the distinct diurnal fluctuations (amplitude of about 0.02 m^3/s) caused by evapotranspiration from willow species that recolonized the riparian zone and armored the bed with root mats as the number and magnitude of flash floods decreased. This is in contrast to the character of the discharge from episodic flash floods common from 1996 through about 2002. Spikes on the generally sinusoidal pattern of the hydrograph represent small floods. The length of each survey varied. The 18 cross sections described in this report were initially part of a larger set of about 100 cross sections so that the surveys took several days to complete. Later, the total number of cross sections was reduced as the spatial variability decreased in response to fewer and smaller magnitude flash floods, and the surveys could be done in a single day when there were only 18 cross sections. However, the last two surveys took several days because the willows had grown tall enough to obstruct the view and time was required to prune sight lines through the willows.

Methods

Channel Cross Sections

The primary study reach was established in 1996 to monitor changes in the lower end of the superslug through 2014. This reach (fig. 1) starts at the confluence of Spring Creek and the South Platte River where the valley is about 50 m wide and ends 1,500 m upstream at a streamgage (U.S. Geological Survey [USGS] Station Number 06701970, Spring Creek above mouth near South Platte, Colorado) where the valley is about 10 m wide (Moody and Martin, 2001a). Initially, channel cross-section (XS) locations were established and monumented every 10 m from the confluence to the streamgage, resulting in 150 cross-section locations (fig. 1; see also Moody and Martin, 2001a, fig. 5.2). Channel cross-sectional profiles were constructed from measurements of ground elevations at irregularly spaced distances from reference pins. These elevations corresponded to topographic highs, lows, and inflection points for features greater than about 0.1 m in relief (Moody and Martin, 2001a). They were measured (Nikon 720 Digital Terrain Model [DTM] and Wild level) after each geomorphic process (table 1) that eroded, transported, or deposited sediment. All cross sections were spatially tied together into a common coordinate system with Universal Transverse Mercator (UTM) coordinates and North American Vertical Datum 1988 (NAVD88) elevations using a survey-grade global positioning system (GPS; Trimble 4700 Rover and 4800 Base). Each cross-sectional profile is equivalent to a chronostratigraphic horizon at a given time. The unit volume of sediment (that is, the cross-sectional area per meter in the stream-wise direction) between two sequential horizons represents a chronostratigraphic unit. Because the wildfire altered soil hydraulic properties, subsequent floods were more frequent than if the Spring Creek basin had not been disturbed by wildfire. As the magnitude and number of floods decreased through time, the number of cross sections measured was reduced to a final set of 18 cross-section locations spaced about 100 m apart (the location of XS4850 is outside the primary study reach; fig. 1, table 1). This report contains descriptions of the different chronostratigraphic units and documents the geomorphic processes that modified these units at each of the 18 cross-section locations.

Table 1. List of survey dates and the cross sections along Spring Creek that were measured during each survey.

[Cross section numbers are based on the distance, in meters, upstream from the confluence of Spring Creek with the South Platte River on December 14, 1996; dates are given in DD–Mon–YY and DD–Mon format; for survey intervals longer than two weeks, the date of the survey of a cross section is shown in grey; black cells, cross section was surveyed; blank cells, cross section was not surveyed]

Survey			Cross-section numbers																	
No.	**Start**	**End**	**–2.7**	**100**	**187**	**250**	**341**	**393**	**483**	**567**	**679**	**755**	**815**	**905**	**1006**	**1100**	**1200**	**1340**	**1450**	**4850**
31	10–Jun–14	21–Oct–14	13–Jun	13–Jun	13–Jun	13–Jun	13–Jun	23–Sep	13–Jun	10–Jun	10–Jun	10–Jun	10–Jun	23–Sep	10–Jun	21–Oct	10–Jun	23–Sep		22–Jun
30	2–Jun–12	17–Oct–12	17–Oct				17–Oct		17–Oct	17–Oct	17–Oct	2–Jun	2–Jun							
29	7–May–11	7–May–11									■									
28	11–Oct–10	11–Oct–10									■									
27	7–Jul–10	7–Jul–10									■									
26	26–Sep–09	26–Sep–09	■						■	■	■	■	■							
25	5–May–08	5–May–08					■	■	■	■	■	■	■							
24	25–Oct–07	25–Oct–07	■								■	■					■			
23	14–Oct–06	14–Oct–06	■	■	■	■	■	■	■	■	■	■	■				■			
22	18–May–05	14–Jun–05			18–May		18–May	14–Jun	14–Jun	18–May	18–May	18–May					18–May			14–Jun
21	27–Sep–03	27–Sep–03	■	■	■	■	■	■	■	■		■	■	■	■		■	■	■	
20	21–Sep–02	21–Sep–02	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■
19	10–Nov–01	10–Nov–01	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	
18x	25–Oct–01	25–Oct–01																		■
18	19–May–01	19–May–01	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	
17	21–Oct–00	21–Oct–00	■	■	■	■	■	■	■	■	■	■	■	■	■		■	■	■	■
16	13–May–00	14–May–00	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
15	8–Nov–99	8–Nov–99	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
14x	11–Aug–99	11–Aug–99																		■
14	31–Jul–99	1–Aug–99	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
13	16–Jul–99	17–Jul–99	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
12	20–Mar–99	21–Mar–99	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
11	12–Oct–99	14–Oct–99	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
10	5–Aug–98	6–Aug–98	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
9x	18–Jul–98	18–Jul–98																		■
9	16–Jul–98	17–Jul–98	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
8	1–Jul–98	2–Jul–98		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
7	19–May–98	21–May–98	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
6	28–Apr–98	3–May–98	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
5	27–Sep–97	6–Oct–97	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
4x	4–Sep–97	4–Sep–97	■				■													
4	3–Aug–97	8–Aug–97	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
3	22–Jul–97	28–Jul–97	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
2	20–May–97	11–Jun–97		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
1	14–Dec–96	14–Dec–96					■													

Discharge

A streamgage was deployed in a narrow bedrock section of Spring Creek about 20 m upstream from XS1450 (fig. 1*A*) and was operated seasonally (March through November) from 1997 through 2003. This streamgage (Spring Creek above mouth near South Platte, Colorado, USGS station number 06701970) was a standard bubble gage (Accubar interfaced with Sutron 8210 Data Collection Platform [DCP]), which collected stage data and transmitted them via satellite at 15-minute intervals. Data for flood flows were transmitted at 5-minute intervals whenever a preset threshold for the rate of rise in stage was exceeded (Moody and Martin, 2001a). Data from the rain gage (fig. 1*A*) were measured at a smaller (5-minute) sampling interval than the daily data from the National Oceanic and Atmospheric Administration National Weather Service station (050454) at Bailey Colorado. Therefore, they were used to determine rainfall intensity, and these intensities were used to determine rainfall-discharge relations (Moody, 2001; Moody and Martin, 2001a, b, c) to help in interpreting the geomorphic processes.

During 2010, additional discharge measurements were made by using a 9-inch modified Parshall flume located 10 m downstream from XS0815 (fig. 1*B*). Stage was measured with a Global Water sensor (Model WL15–015) every 15 minutes, and discharge measurements were made approximately every month (with a Pygmy, open-cup current meter) to check the theoretical calibration of the flume (Grant, 1991).

Description of Chronostratigraphic Units and Geomorphic Processes

Between each pair of cross-section surveys was a geomorphic-process time interval with different flow regimes that determined the amount of sediment deposited as a chronostratigraphic unit and the amount of each previously deposited unit that was eroded. Discharge data from the streamgage (Spring Creek above mouth near South Platte, Colorado, USGS station number 06701970) and from the Parshall flume were used to determine the different flow regimes from 1997 through 2014.

Discharge

Peak flood discharges above base flow (179 floods) were separated into three categories. Minor floods (167) ranged from 0.001 to 1 m^3/s; major floods (10) ranged from 1 to 10 m^3/s; and extreme floods (2) were greater than 10 m^3/s. As the burned basin recovered, there was a substantial decrease in peak discharge from 1996 through 2010 (fig. 2*B*). The first extreme flood was on July 12, 1996, (about 510 m^3/s) and was equivalent to about 24 $m^3/s/km^2$, which places it among the world's largest recorded unit discharges (Moody and Martin, 2001c; Moody, 2012, 2016). By 2010, the water discharge showed a diurnal variation as the riparian vegetation recovered (fig. 2*B* inset).

Table 2. Flow conditions in Spring Creek for each survey interval from July 1996 to October 2014 and the corresponding colored symbols for each chronostratigraphic unit.

[Cross section numbers are based on the distance, in meters, upstream from the confluence of Spring Creek with the South Platte River on December 14, 1996; dates are given in DD–Mon–YY format with the oldest date starting at the bottom of the table; No., number; m^3/s, cubic meters per second; Major, flood discharge from 1 to 10 m^3/s; Extreme, flood discharge greater than 10 m^3/s; ~, approximate; &, and; blank cell, cross section was not surveyed; double hyphen, not applicable; single hyphen, surveyed but no measureable sediment. Special fill patterns: green irregular stipple, channel-bank dry ravel; black irregular stipple, cumulative effect of hillslope dry ravel; vertically dashed, after 2003 only selected cross sections were re-surveyed, and therefore the process interval varies in length of time so that all changes are lumped together and have this same symbol; white checkered, deposition in 2001 and 2002 at cross section 1450; orange checkered, deposition between August 11, 1999, and October 21, 2000, at cross section 4850; green cross hatched, deposition between July 18, 1998, and August 11, 1999, at cross section 4850; diagonally dashed, hillslope erosion followed by hillslope collapse; and f, first survey of the cross section; all other fill patterns identify a single chronostratigraphic unit.]

Survey			Flow conditions	Peak or range of water discharge (m3/s)	Type of flood	Cross-section number																	
No.	Start	End				-2.7	100	187	250	341	393	483	567	679	755	815	905	1006	1100	1200	1340	1450	4850
31	10–Jun–14	21–Oct–14	No streamgage in operation	--	--						-												-
30	2–Jun–12	17–Oct–12	No streamgage in operation	--	--					-		-	-	-		-							
29	7–May–11	7–May–11	Diurnal flow	0.02–0.06	--									-									
28	11–Oct–10	11–Oct–10	Diurnal flow	0.02–0.05	--									-									
27	7–Jul–10	7–Jul–10	Diurnal flow	0.02–0.04	--									-									
26	26–Sep–09	26–Sep–09	No streamgage in operation	--	--								-	-	-	-							
25	5–May–08	5–May–08	No streamgage in operation	--	--					-	-	-	-										
24	25–Oct–07	25–Oct–07	No streamgage in operation	--	--										-					-			
23	14–Oct–06	14–Oct–06	No streamgage in operation	--	--		-				-	-	-	-	-	-				-			
22	18–May–05	14–Jun–05	No streamgage in operation	--	--						-	-	-	-	-								-
21	27–Sep–03	27–Sep–03	Relatively steady flow	~0.02	--		-	-	-		-	-	-			-	-	-		-	-	-	
20	21–Sep–02	21–Sep–02	Relatively steady discontinuous flow	~0.02	--		-	-	-		-	-	-	-		-	-	-		-	-		-
19	10–Nov–01	10–Nov–01	Relatively steady discontinuous flow	~0.02	--		-	-	-	-		-	-		-	-		-					
18x	25–Oct–01	25–Oct–01	13–Aug–01 unsteady flood flow	0.24	--																		-
18	19–May–01	19–May–01	Relatively steady discontinuous flow	0.02–0.04	--			-	-	-		-	-					-		-	-		
17	21–Oct–00	21–Oct–00	16–Jul–00 unsteady flood flow	4.6	Major		-	-		-		-						-					
16	13–May–00	14–May–00	Relatively steady flow with cohesive banks	0.03–0.05	--	-		-	-	-	-							-	-	-			
15	8–Nov–99	8–Nov–99	4–Aug–99 unsteady flood flow	1.2	Major	-		-	-	-	-										-	-	
14x	11–Aug–99	11–Aug–99	Decreasing runoff	6.4–0.5	--																		
14	31–Jul–99	1–Aug–99	'29–Jul–99 unsteady flood flow	6.4	Major	-		-		-	-		-									-	
13	16–Jul–99	17–Jul–99	Relatively steady braided but discontinuous flow	~0.06	--	-	-		-	-	-	-		-		-			-	-		-	
12	20–Mar–99	21–Mar–99	Relatively steady flow with cohesive banks	~0.03	--	-		-		-	-	-	-				-	-	-	-	-	-	
11	12–Oct–99	14–Oct–99	Relatively steady braided but discontinuous flow	0.03–0.07	--	-	-	-		-	-	-					-	-	-		-	-	
10	5–Aug–98	6–Aug–98	31–Jul–98 unsteady flood flow	82	Major														-		-	-	
9x	18–Jul–98	18–Jul–98	Relatively steady braided but discontinuous flow	~0.10	--																		f
9	16–Jul–98	17–Jul–98	9–Jul–98 unsteady flood flow	48–58	Major	-			-	-		-	-	-			-		-	-	-	-	
8	1–Jul–98	2–Jul–98	Decreasing runoff	0.12–0.06	--				-	-	-		-	-	-		-	-	-	-	-	-	
7	19–May–98	21–May–98	Decreasing snowmelt runoff	0.15–0.12	--	-		-	-	-	-			-	-		-	-	-	-	-	-	
6	28–Apr–98	3–May–98	Relatively steady flow with cohesive banks	~0.2	--	-									-	-	-	-	-	-	-	f	
5	27–Sep–97	6–Oct–97	26– and 31–Aug–97 unsteady flood flows	6.6 & 140–180	Major & Extreme											-			-		-		
4x	4–Sep–97	4–Sep–97	Relatively steady braided but discontinuous flow	~0.07	--	-				-													
4	3–Aug–97	8–Aug–97	28–, 29– , and 31–Jul–97 unsteady flood flows	1.15, 4.76, & 3.55	3 Major	-													-		-		
3	22–Jul–97	28–Jul–97	21–Jun–97 unsteady flood flow	1.35	Major	f	-			-	-				-				-		-		
2	20–May–97	11–Jun–97	No streamgage in operation	--	--		f	f	f		f	f	f	f	f	f	f	f	f	f	f		
1	14–Dec–96	14–Dec–96	No streamgage in operation	--	--					f													
Before start of surveys			12–Jul–96 unsteady flood flow	~510	Extreme	Before start of surveys																	

Chronostratigraphic Units

Different flow regimes determined the amount of sediment deposited as a chronostratigraphic unit and the amount of each previously deposited unit that was eroded during the geomorphic-process time intervals between cross-section surveys. Flow regimes during some intervals between surveys included a single flood, some included several floods, and others included varying flow conditions (table 2). Chronostratigraphic units do not necessarily differ in lithology. Nor are they found at all cross sections, and may vary is amount at each cross section where they are found. Geomorphic Processes

Six geomorphic processes (floods, braided flow, percolation, winter aggradation, dry ravel, and vegetation trapping and armoring) were observed to alter the initial form of the superslug, which first underwent vertical aggradation and, later, incision (fig. 3). Flash floods (fig. 4*A*) were a primary geomorphic process in the first years after the deposition of the superslug when they were more frequent, had greater magnitudes, and transported substantial amounts of sediment. Each extreme and major flood generally resuspended the bed sediment, eliminating any channelization and vegetation regrowth, and redeposited the sediment as a level, planar cross-channel surface (fig. 4*B*) with a relatively steep down-channel slope (0.03–0.05; Moody, 2001). These conditions were ideal for braided, shallow (0.02–0.05 m) flow (fig. 4*B*), which tended to be steady but spatially discontinuous. Flow was often observed to transport larger sediment particles (about 10 mm) by rolling them on the relatively uniform bed surface composed of 1–2-mm particles. Surface flow was observed to percolate into the bed sediment in some channel reaches and to leave behind the sediment it had been transporting. This process formed in-channel fans (fig. 4*C*), but also caused sediment aggradation upstream from the in-channel fan where the bed slope was less. Aggradation was usually during late fall, winter, and early spring, when the bank sediments were frozen and, thus, cohesive, and is termed "winter aggradation". Flowing water was then only able to erode narrow, slot-like channels, and at times some winter and early spring flows exceeded the capacity of the small incised channels, spread onto the adjacent surface, and deposited sediment which refroze (fig. 4*D*). Dry ravel (Anderson and others, 1959; Gabet, 2003; Jackson and Roering, 2009; Lamb and others, 2011) supplied sediment from the adjacent hillslopes (fig. 4*E*). The dry ravel originated from the equatorial (south)-facing hillslopes in summer and also during the late fall, winter, and early spring when the freeze-thaw process was observed to deliver substantial quantities of sediment to the channel from equatorial-facing slopes but not from frozen, polar-facing hillslopes. Vegetation trapping increased as the frequency of major floods decreased and steadier flow conditions prevailed such that the riparian vegetation (for example sedges, grasses, willow species, and cottonwood trees) was able to reestablish itself (fig. 2*B* inset, fig. 4*F*). Multi-stemmed willows reduced the bed shear stress available for transporting sediment (Griffin and others, 2014). Their roots were observed to grow just under the bed surface and formed a root mat that essentially armored the bed surface and thus increased the bed shear stress required to erode the sediment (Prosser and others, 1995).

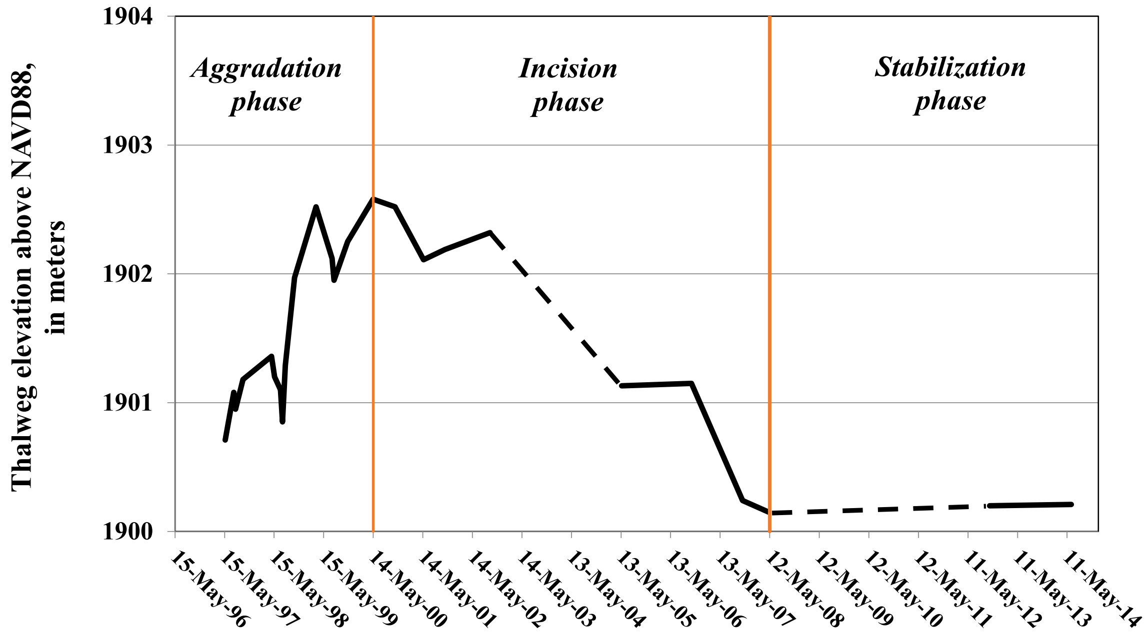

Figure 3. Three phases of the change in the thalweg elevation of the superslug at the location of cross section 679 ("XS0679" in figure 1*C*) following the extreme flood (about 510 cubic meters per second or about 24 cubic meters per second per square kilometer) on July 12, 1996. NAVD88 is the North American Vertical Datum of 1988.

Figure 4. Photographs showing six geomorphic processes that eroded, transported, and deposited sediment. These processes modified the initial form of the sediment superslug deposited in Spring Creek. *A*, Floods. View is looking upstream from a vantage point at the mouth of Spring Creek during the flood on July 29, 1997. *B*, Braided flow. View is looking downstream, with XS1200 across the center of the photograph. The width of the sand and gravel surface is about 20 meters (m). *C*, Percolation. View is looking upstream. This process was common where water transporting sediment percolated into the channel bed, leaving behind sediment and forming thick sediment deposits, sometimes referred to as in-channel fans. The downstream end of an in-channel fan is shown behind D. Wolf (about 1.8 m tall) in the photograph. Surface flow from upstream completely disappears into the fan and reappears downstream at approximately the location where D. Wolf is standing.

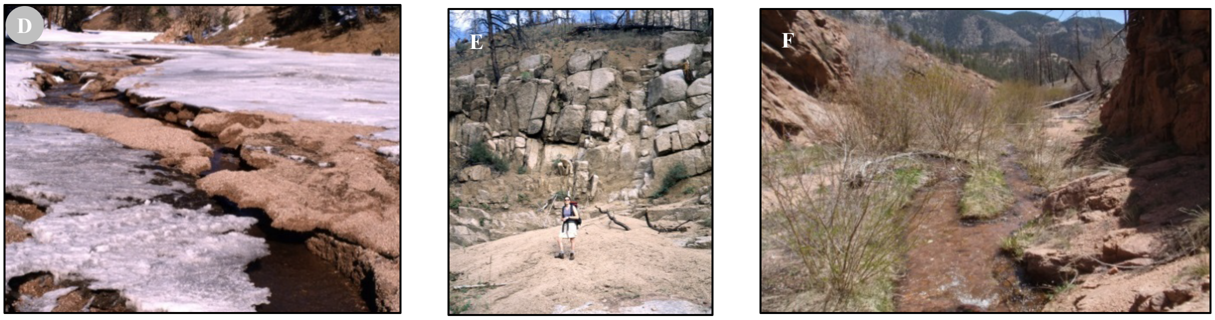

Figure 4. Photographs showing six geomorphic processes that eroded, transported, and deposited sediment. These processes modified the initial form of the sediment superslug deposited in Spring Creek. *D*, Winter aggradation. View is of an area upstream from XS0187, January 20, 1998. Sediment particles in the photograph are typically 2–4 millimeters in diameter and are derived from the weathered granite that underlies most of the Spring Creek basin (Blair, 1976). The channel is about 0.3 m wide. *E*, Dry ravel. Photograph shows a fan at the base of a hillslope between XS1340 and XS1450. The sediment in the fan was deposited in the bedrock channel by dry ravel during the summer, by the freeze-thaw process during the winter, and some hillslope runoff after a rain storm on August 13, 2001.The person in the photograph is about 1.8 m tall. *F*, Vegetation trapping and armoring. Photograph was taken on May 8, 2010 of the channel at XS0679. View is looking downstream and the water surface is about 1 m wide. The effects of vegetation trapping and armoring have produced an anabranching channel as the willows re-colonized the reach.—Continued

As the peak discharge decreased with time (fig. 2) and as the channel incised (fig. 3), many relatively level surfaces were abandoned. Vegetation of the basin has recovered progressively on hillslopes and in the riparian zone since the wildfire (see “Narratives” section). As of 2014, post-wildfire runoff from the hillslopes has decreased and the likelihood of extreme and major floods has decreased (fig. 2). In addition, the roots of the riparian vegetation have armored the bed, the stem densities have decreased flow velocities, and the leaves are transpiring water and decreasing the water discharge. Thus, the abandoned surfaces are essentially small terraces created in response to a disturbance.

Narratives

The following narratives for each of the 18 cross-section locations describe the changes in sediment storage of the superslug in Spring Creek from 1996 through 2014. Reference markers for each cross-section location are listed in appendix 1. Narratives are meant to stand alone, so some information may be repeated. Left and right banks of the cross sections are from the perspective of being viewed in a downstream direction. Narratives include photographs and a preservation plot showing the amount of each chronostratigraphic unit preserved as of October 2014 as polygons (see table 2 for a detailed explanation of polygon symbols). The net gain and loss of sediment is different for each cross-section location, but generally there was a net loss at cross-section locations near the mouth of Spring Creek and a net gain at cross-section locations midway between the mouth and the streamgage (fig. 5). Not all chronostratigraphic units were preserved at the location of each cross section because some units were not deposited during the process interval or because some units were completely eroded by subsequent geomorphic processes (see table 2).

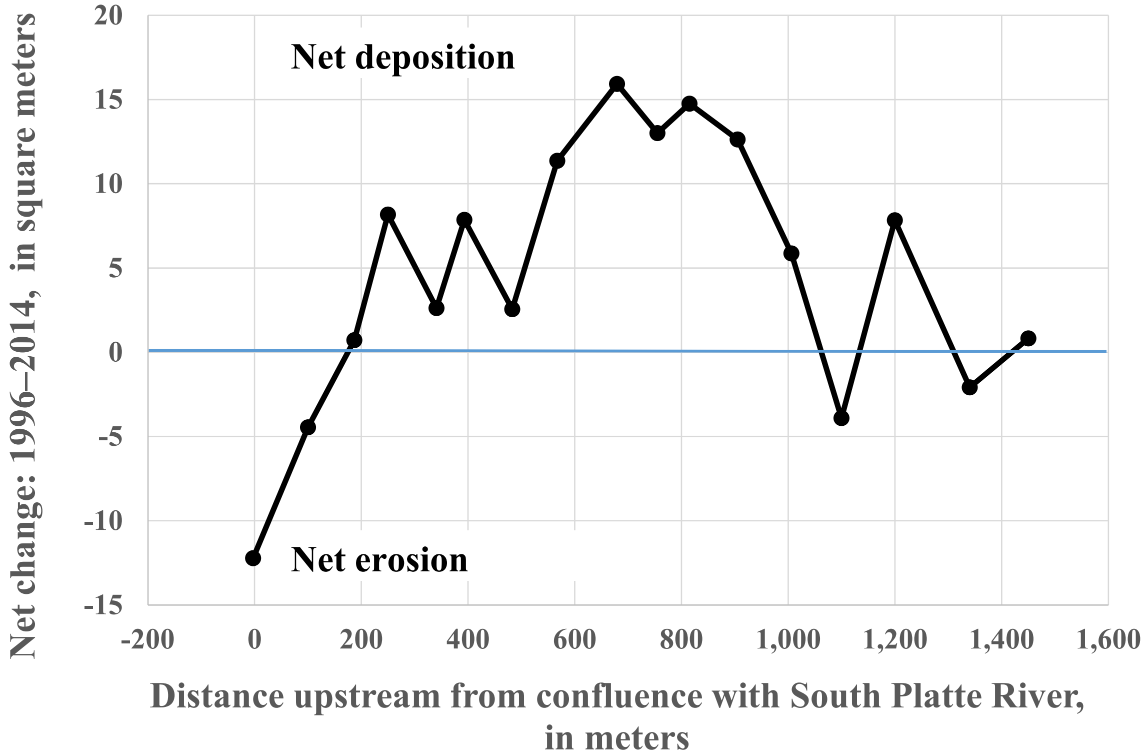

Figure 5. Net change in cross-sectional area at 17 cross-section locations of the Spring Creek superslug from 1996 through 2014.

Different combinations of units were preserved at each cross-section location. The geomorphic process response was complex (Schumm, 1981), but three primary alluvial architectures (laminar, fragmented, and hybrid) and two secondary architectures (erosional and dry ravel) were identified within the study reach (table 3). In preservation plots, laminar architecture is identified by nearly continuous, horizontal chronostratigraphic units, and fragmented architecture is identified by mainly discontinuous and irregularly shaped chronostratigraphic units. In hybrid architectures, the chronostratigraphic units are a mixture of horizontal layers and irregular shapes. Erosional architectures showed a net loss of sediment from the superslug from 1996 through 2014. The dry-ravel architecture also showed a net loss but with a substantial input of sediment from 1996 through 2014.

Table 3. Alluvial architecture identified at 18 cross sections of the superslug in Spring Creek.

[Cross-section number is the distance in meters upstream from the confluence of Spring Creek and South Platte River]

Cross-section number	Width (meters)	Architecture
–2.7	50.0	Laminar
100	36.0	Fragmented
187	34.0	Hybrid
250	32.9	Laminar
341	43.0	Fragmented
393	40.0	Fragmented
483	41.5	Fragmented
567	33.4	Hybrid
679	25.1	Laminar
755	34.2	Hybrid
815	25.5	Laminar
905	25.0	Hybrid
1006	18.7	Hybride
1100	9.7	Erosional
1200	24.2	Fragmented
1340	16.3	Dry ravel
1450	14.0	Erosional
4850	25.0	Laminar

XS-2.7 Narrative

Cross section -2.7 is one of the widest cross sections in the study reach. It is about 50 m wide (fig. 6) and was measured at the end of an expanding reach near the mouth of Spring Creek (figs. 6–7). During the extreme flood on July 12, 1996, (about 510 m^3/s) sediment (mostly sand and gravel) from Spring Creek was transported into the South Platte River. This dammed the South Platte until the river was able to breach the dam in a few hours and transport the sediment downriver to Strontia Springs Reservoir (Moody and Martin, 2001a, b). The Denver Water Board (operators of Strontia Springs Dam and Reservoir) graded some of the remaining sediment on the right bank of Spring Creek (see evidence in photographs taken December 6, 1996, and June 7, 1997; fig. 7*B*).

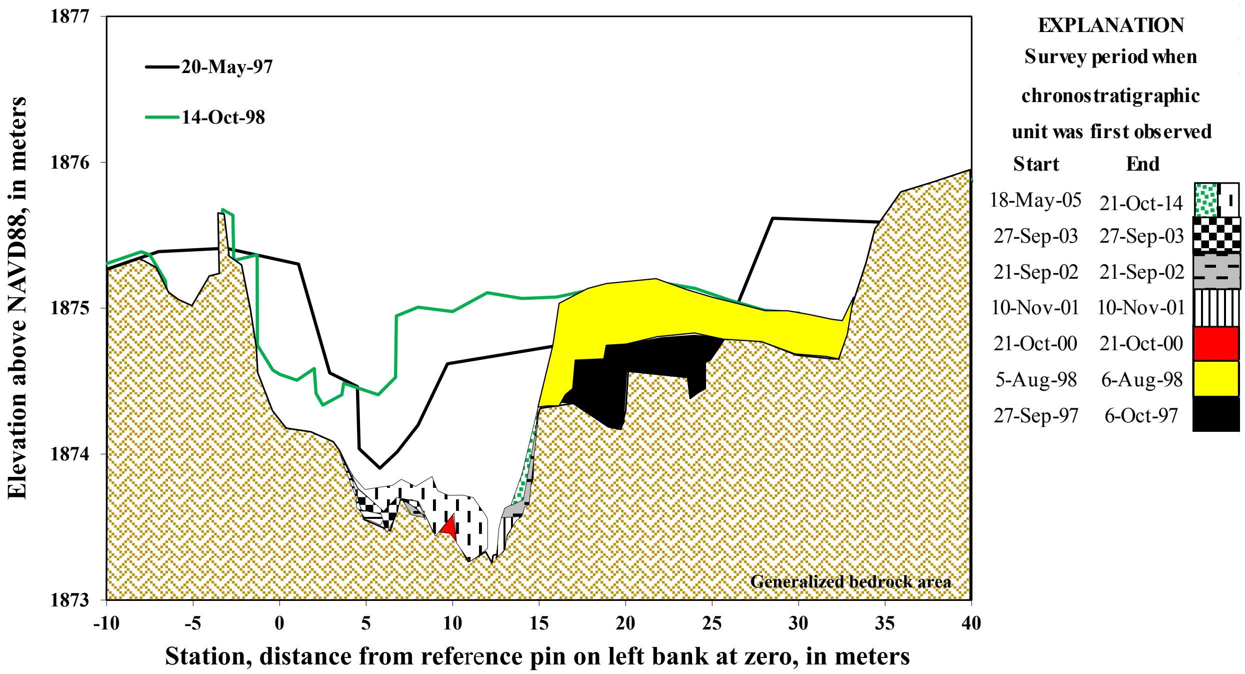

Figure 6. Preservation plot for cross section -2.7 (XS-2.7). Vertical exaggeration is 8.5×. The vertical relief near station -3 is a 1-meter-diameter boulder. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSECm2p7_SciBase.xlsx) for survey data. Green stippling indicates channel-bank dry-ravel deposits. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

Figure 7. Repeated views of the mouth of Spring Creek that include the location of cross section -2.7 (XS-2.7), 1996–2014. All views are looking upstream. The South Platte River at the base of the photographs flows from left to right. The yellow dashed line in each photograph indicates the approximate location of XS-2.7. *A*, December 6, 1996. *B*, June 7, 1997. Note the parallel tire ruts created by reshaping and grading of the original deposit of sediment from the extreme flood on July 12, 1996 (about 510 cubic meters per second [m^3/s]). *C*, August 7, 1997. *D*, September 1, 1997. *E*, September 30, 1997. Spring Creek is a braided stream in this photograph. *F*, December 18, 1997. Spring Creek is more incised, as the sand and gravel filling the channel are frozen and, thus, cohesive so that lateral erosion is difficult.

Figure 7. Repeated views of the mouth of Spring Creek that include the location of cross section -2.7 (XS-2.7), 1996–2014. All views are looking upstream. The South Platte River at the base of the photographs flows from left to right. The yellow dashed line in each photograph indicates the approximate location of XS-2.7. *G*, March 24, 1998. Sediment near the mouth of Spring Creek has been reworked by the floods on August 26, 1997 (6.6 m^3/s) and August 31, 1997 (140–180 m^3/s). *H*, May 19, 1998. After the flood on August 31, 1997, the sediment surface is smooth, and Spring Creek became a braided stream. *I*, August 1, 2000. Vegetation has recolonized the reach and the channel has begun to lose its braided character. *J*, November 19, 2000. *K*, April 6, 2001. *L*, May 18, 2001. Bare sand-and-gravel surface on the right-bank terrace contrasts with the green vegetation alongside the channel.—Continued

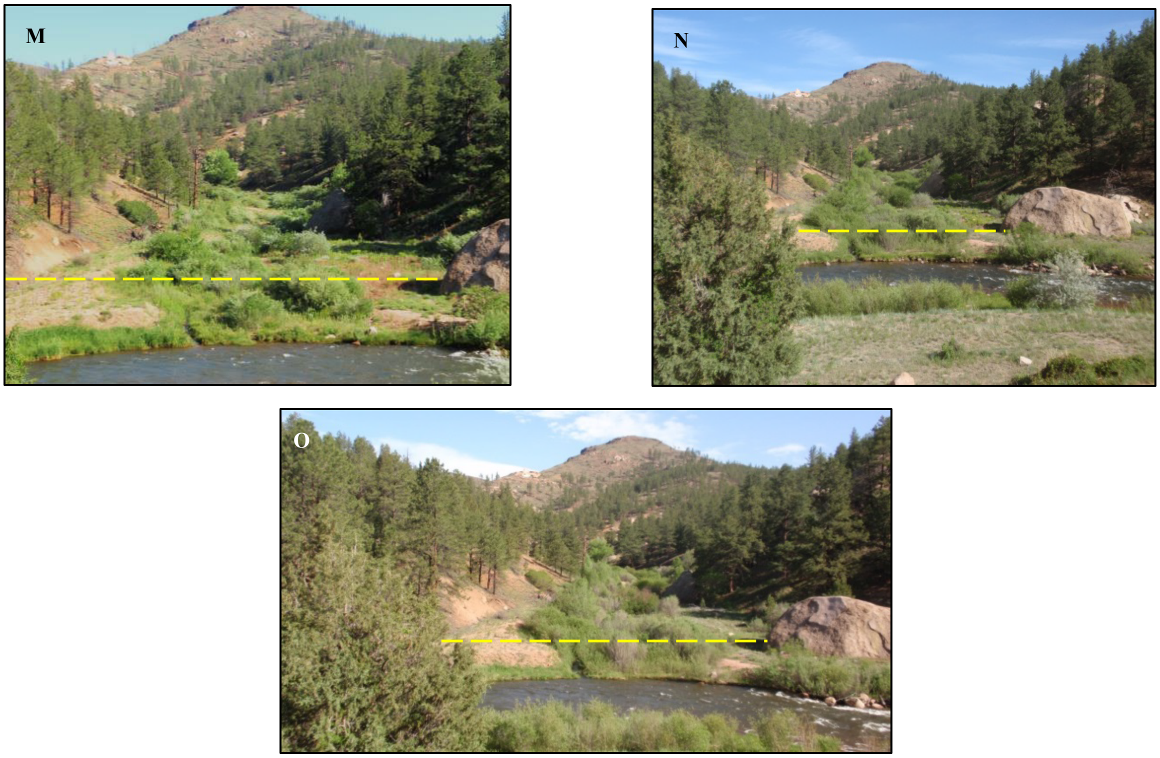

Figure 7. Repeated views of the mouth of Spring Creek that include the location of cross section -2.7 (XS-2.7), 1996–2014. All views are looking upstream. The South Platte River at the base of the photographs flows from left to right. The yellow dashed line in each photograph indicates the approximate location of XS-2.7. *M*, June 24, 2009. *N*, June 2, 2012. *O*, June 10, 2014.—Continued

Net change in cross-sectional area from 1996 through 2014 has been a loss of about 12 m^2 (fig. 5). The initial profile was surveyed on May 20, 1997, and showed an elevated deposit from the July 12, 1996, flood on the right bank between stations 25 and 35 (fig. 6). Major floods in 1997 on June 21; July 28, 29, and 31; and August 9, 26, and 31 eroded the original sediment deposited by the July 12, 1996, flood. Some of the chronostratigraphic unit deposited by the August 31, 1997, flood was eroded by the flood on July 31, 1998. However, some of the unit remained (black polygon in figure 6) and was covered and preserved by a new unit (yellow polygon) that formed the surface of a small terrace as of 2014.

A ponderosa pine tree is estimated to have germinated on this terrace between 2003 and 2005 (fig. 8). The vertical relief near station -3 m is an approximately 1-m-diameter boulder that appeared at the location of the cross section after the flood on July 9, 1998, (48–58 m^3/s) when the small channel to the left of the boulder was formed. After July 31, 1998, Spring Creek at XS-2.7 slowly eroded its channel down to the current level of the South Platte River. As of 2014, the surface was about 1 m lower than it was in 1998 (green line in figure 6).

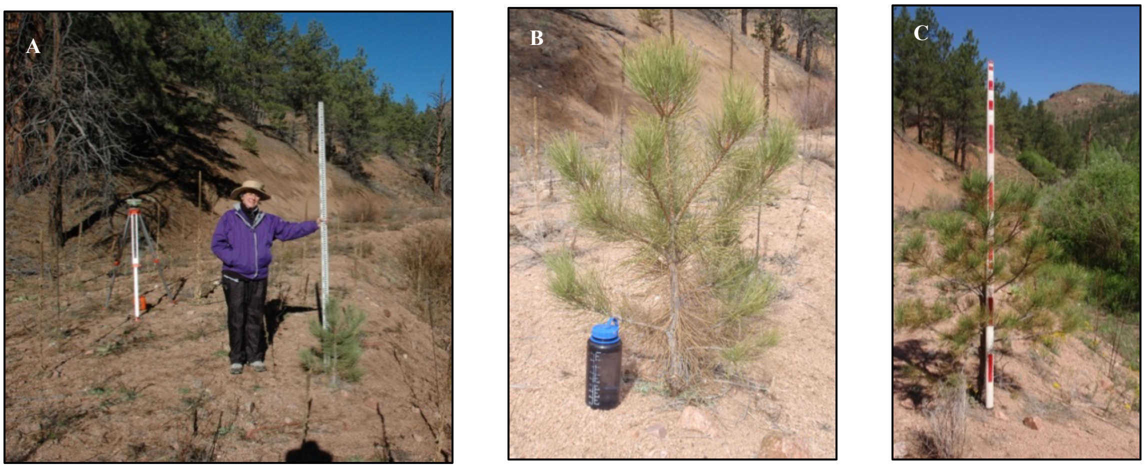

Figure 8. Photographs of the first ponderosa pine tree to colonize the right-bank terrace of cross section -2.7 (XS-2.7), 2007–2014. *A*, October 25, 2007. D. Martin is 1.7 meters (m) tall. *B*, March 9, 2009. *C*, June 13, 2014. Tree is 1.7 m tall.

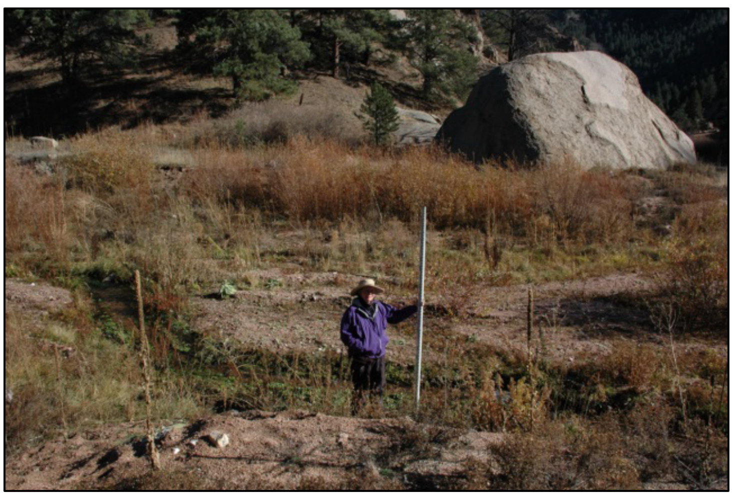

Figure 9. View from the right bank along the line of section for cross section -2.7 (XS-2.7), 2007. Photograph of D. Martin (1.7 meters tall) standing on the right-bank flood plain of Spring Creek, taken on October 25, 2007. Line of section passes through the leveling rod and between the small ponderosa pine tree and the large bedrock boulder on the left bank (background). The right-bank terrace is in the foreground.

By 2014, a new flood plain had formed among willows along the left bank (stations 4 to 12) that may have regrown from the roots of the original willows. These willows were dense enough by about 2000 (fig. 7*J*–*O*) to trap sediment, a process that formed this flood-plain surface. There were about ten major floods from 1996 through 2000, but chronostratigraphic units were preserved from only three floods (August 26 and 31, 1997, and July 31, 1998) at the location of cross section -2.7. No sediment is preserved from the original flood on July 12, 1996. The thalweg elevation at this cross-section location in June 2014 (1,873.4 m) was 0.5 m lower than the thalweg elevation measured during the May 20, 1997, survey after the extreme flood on July 12, 1996 (fig. 6).

XS0100 Narrative

Cross section 100 was measured within an expanding reach that begins near XS0250 and extends to the mouth of Spring Creek (fig. 10). Repeated survey measurements through 2014 indicate a net loss of sediment in this cross-section location since the extreme flood on July 12, 1996 (about 510 m^3/s). However, sediments in the area of this cross section aggraded periodically as chronostratigraphic units (fig. 11) were deposited by major floods (>1 m^3/s) on July 28, 29, and 31, 1997 (wavy-line polygon); August 26 and 31, 1997 (black polygon); July 9, 1998 (green polygon); and July 31, 1998 (yellow polygon).

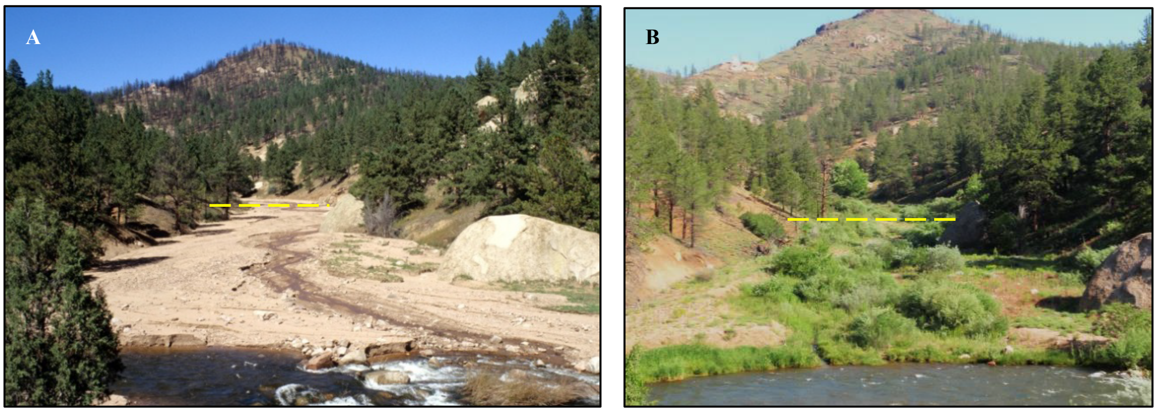

Figure 10. Repeated views of the mouth of Spring Creek that include the location of cross section 100 (XS0100), 1997–2009. Both views are looking upstream. The South Platte River at the base of the photographs flows from left to right. The yellow dashed line in each photograph indicates the approximate location of XS0100. *A*, September 30, 1997. *B*, June 24, 2009.

The July 9, 1998, flood unit is preserved only at the locations of six cross sections (XS0100, XS0187, XS0393, XS0755, XS0815, and XS1006), whereas units deposited by the larger floods on August 26 and 31, 1997, and July 31, 1998, are preserved at 13 of the 18 cross-section locations (from XS1200 through XS-2.7, except XS0815 for the August 26 and 31 flood).

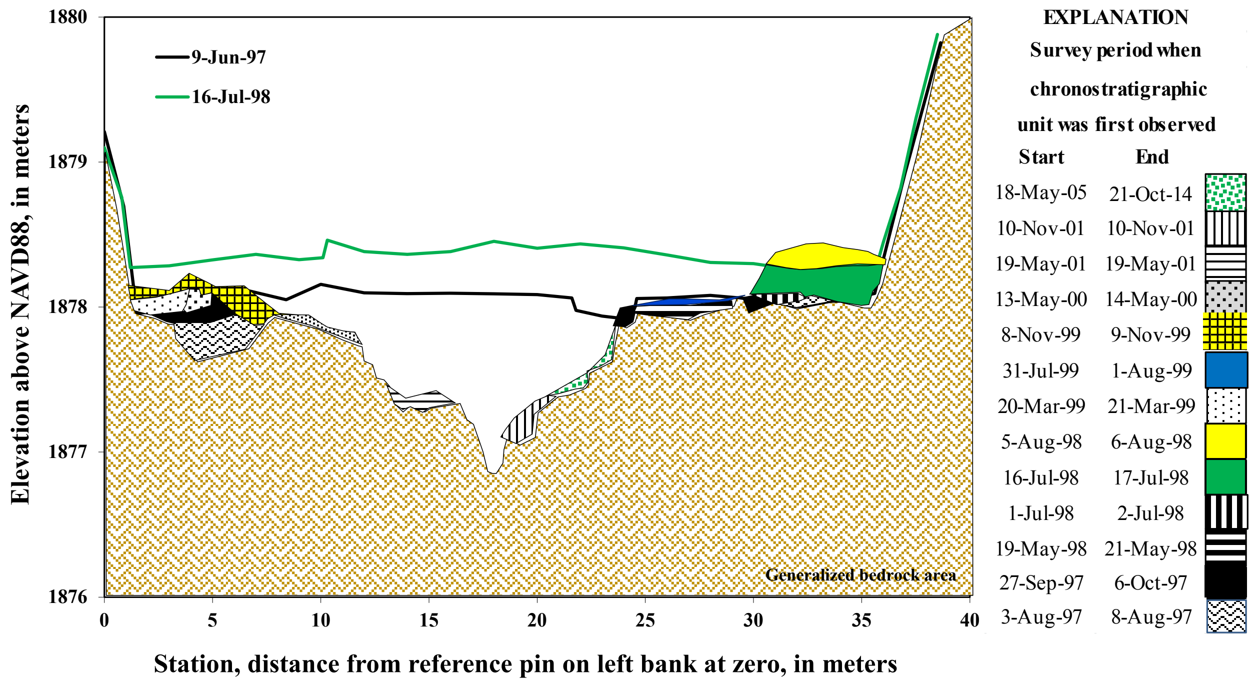

Figure 11. Preservation plot for cross section 100 (XS0100). Vertical exaggeration is 6.7×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0100_SciBase.xlsx) for survey data. (Green stippling indicates channel-bank dry-ravel deposits. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

After the initial aggradation of 1997–1998, the general trend was erosional and the overall net change in cross-sectional area from 1996 through 2014 was a loss of about 4.5 m^2 (fig. 5). By 2014, Spring Creek had eroded more than 1 m below the original surface of 1997 (black line in figure 11) and formed a narrow channel about 0.5 m wide. Only the major floods on July 29, 1999, (blue polygon in figure 11) and August 4, 1999, (yellow checkered polygon in figure 11) were high enough to deposit the sediment as chronostratigrahic units that have been preserved during subsequent erosional intervals. The unit deposited on August 4, 1999, consisted of braided-stream deposits, which formed when multiple threads of shallow water deposited bedload as levees. These levees caused flow paths to alter directions, leaving the deposits to accumulate. After the maximum aggradation in 1998 (green line in figure 11), gradual incision lowered the average elevation by about 0.6 m over the course of two years along a broad area (about 16 m wide) on the left side of the cross section. By the time of the May 13–14, 2000, survey, a narrow incision about 4 m wide and about 0.7 m deep had developed near station 18 (fig. 11) with a single-thread channel.

As of 2014, at cross section 100, chronostratigraphic units from nine of the thirteen major floods have been preserved. Most of these units reside in one terrace on the left bank and two terraces on the right bank about 1 to 1.5 m above the water level. Thalweg elevation in 2014 (1,876.9 m) was substantially lower than that measured in 1997 (0.9 m) after the extreme flood on July 12, 1996 (fig. 11).

XS0187 Narrative

Cross section 187 was measured within an expanding reach that begins near XS0250 and extends to the mouth of Spring Creek. Since the extreme flood on July 12, 1996 (about 510 m^3/s), the net area of deposition has essentially balanced the net area of erosion at the cross section from 1996 through 2014. The net change in cross-sectional area during this 18-year period was an increase of about 1 m^2 (fig. 5). Aggradation reached a maximum in March 1999; thereafter, erosion lowered the elevation of the thalweg to about 0.8 m below the original level of deposition in 1997 (black line in figure 12). The bulk of the sediment preserved was deposited as chronostratigraphic units by major floods (>1 m^3/s) on July 28, 29, and 31, 1997 (wavy-line polygon in figure 12); July 9, 1998 (green polygon in figure 12); and August 26 and 31, 1997 (black polygon in figure 12). In total, units from six major floods were preserved.

The July 9, 1998, flood unit is preserved only at six cross-section locations (XS0100, XS0187, XS0393, XS0755, XS0815, and XS1006), whereas flood units are preserved at 13 of the 18 cross-section locations for floods on August 26 and 31, 1997, and at 14 of 18 cross-section locations for the flood on July 31, 1998. The winter aggradation process happened when the sediment composing the channel banks was frozen and, thus, cohesive. Flowing water was then only able to erode a narrow, slot-like channel, and at times, some winter and early spring flows exceeded the capacity of the small, incised channel, spread onto the adjacent surface, and deposited sediment, which refroze (white densely stippled polygon in figure 12; see also figs. 13, 41, 45).

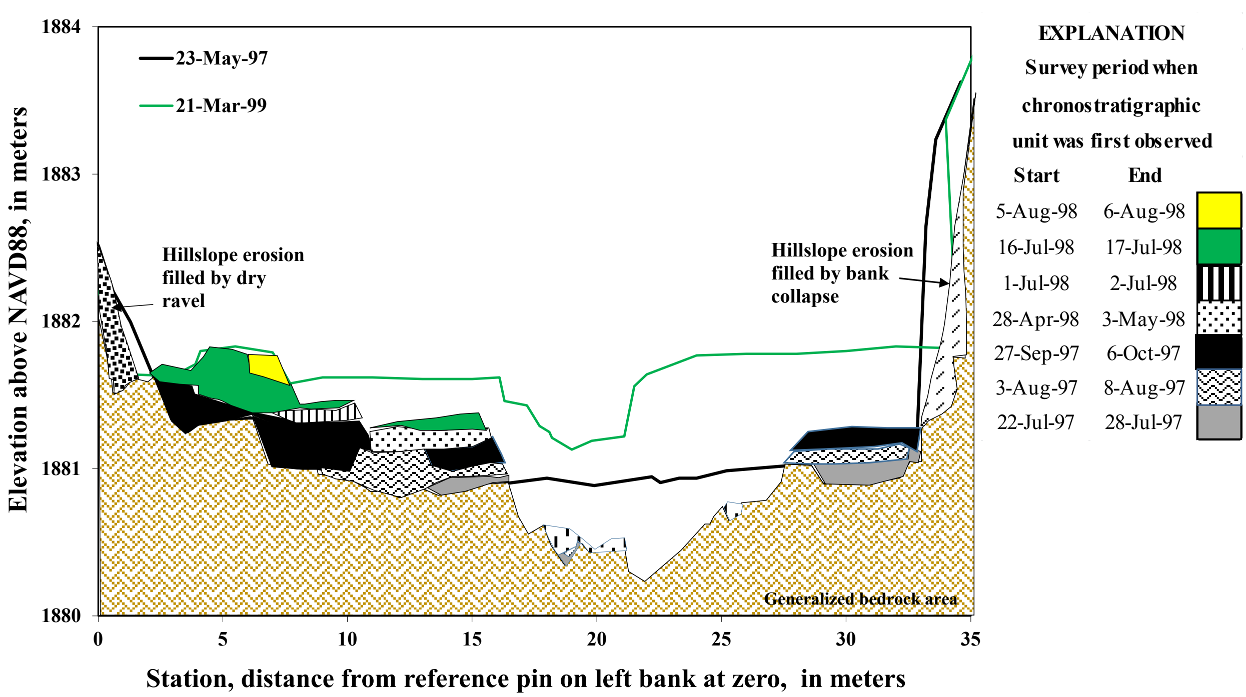

Figure 12. Preservation plot for cross section 187 (XS0187). Vertical exaggeration is 5.9×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0187_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

Another process was the steady erosion by dry ravel (Anderson and others, 1959; Gabet, 2003; Roering and Gerber, 2005) from the equatorially-facing hillslope along the left bank of the creek. This process continuously buried the zero reference pin. Much of the dry ravel was observed in the winter as a consequence of the freeze-thaw process on these hillslopes, which thawed in the morning light, releasing sand and gravel that then rolled downslope. Much of the hillslope erosion along the right bank took place during the high waters in 1997, 1998, and 1999. The net effect of deposition and erosion has been to create a series of four small terraces with different elevations. Thalweg elevation in June 2014 (1880.3 m) was 0.5 m lower than the thalweg measured in 1997 after the extreme flood on July 12, 1996 (fig. 12).

Figure 13. Winter aggradation process near the location of cross section 187 (XS0187), 1998. Photograph was taken on January 20, 1998, looking upstream. During the winter, the sediment composing the channel banks was frozen and, thus, cohesive. Flowing water was then only able to erode a narrow, slot-like channel, and at times, some winter and early spring flows exceeded the capacity of the small, incised channel, spread onto the adjacent surface, and deposited sediment, which refroze. Sediment particles in the photograph are typically 2–4 millimeters in diameter and are derived from the weathered granite that underlies most of the Spring Creek basin. The channel is about 0.3 meters wide.

XS0250 Narrative

Cross section 250 was measured within a relatively narrow reach of Spring Creek at the beginning of the expanding reach leading to the mouth. Since the extreme flood on July 12, 1996 (about 510 m^3/s), the net change in cross-sectional area from 1996 through 2014 has been the net deposition of about 8 m^2 of sediment (fig. 5). The thalweg elevation in June 2014 (1,882.9 m) was 0.3 m lower than in 1997.

Aggradation reached a maximum in July 1999. The winter aggradation process happened when the sediment composing the channel banks was frozen and, thus, cohesive. Flowing water was then only able to erode a narrow, slot-like channel, and at times, some winter and early spring flows exceeded the capacity of the small, incised channel, spread onto the adjacent surface, and deposited sediment, which refroze (white densely and sparsely stippled polygons in figure 14; see also figs. 13, 41, 45). Numerous units associated with major floods (>1 m^3/s) also have been preserved at the location of this cross section, where the valley is constricted and floods deposited units at greater heights (for example, unit with black and wavy symbols on upper terrace on right bank in figure 14).

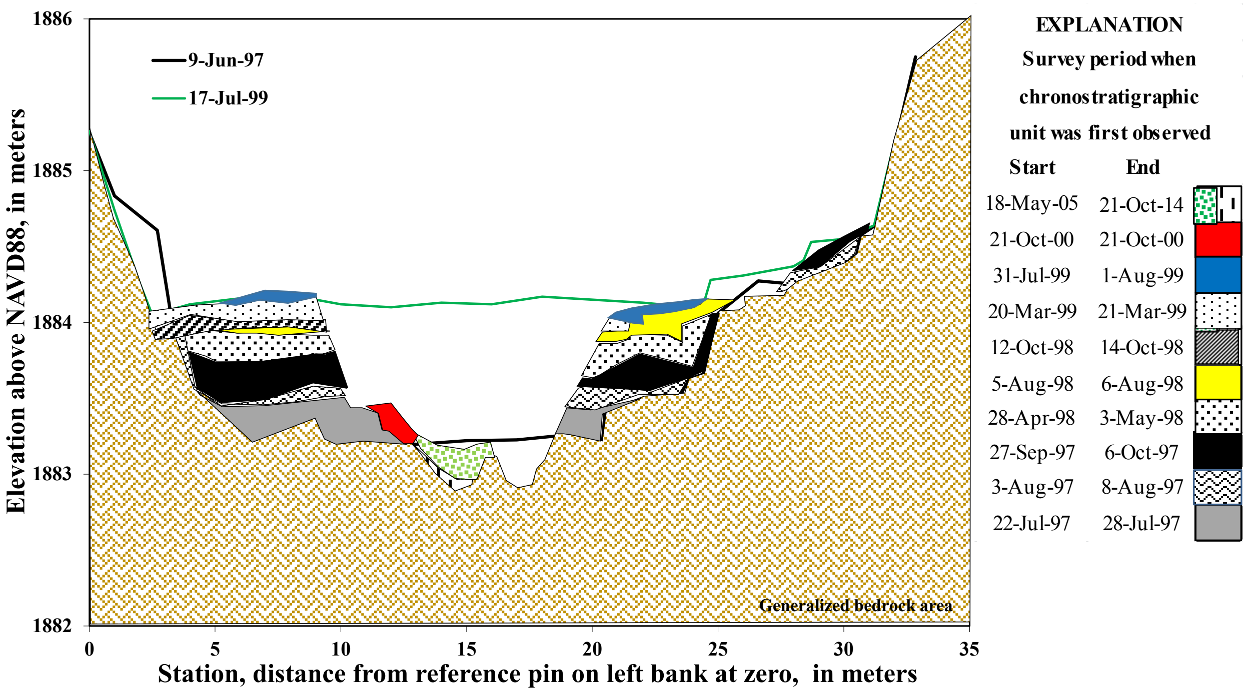

Figure 14. Preservation plot for cross section 250 (XS0250). Vertical exaggeration is 6.1×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0250_SciBase.xlsx) for survey data. (Green stippling indicates channel-bank dry-ravel deposits. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

Five chronostratigraphic units (deposited by one extreme and four major floods) compose terraces on the left and right banks and are nearly horizontal and relatively uniform. These units resemble similar laminar stratigraphy at XS0679 and XS0815. No unit corresponding to the major flood on July 9, 1998, is preserved at this cross-section location.

The unit corresponding to the flood on July 16, 2000, (red polygon in figure 14) was not deposited on top of the left-bank terrace but at the base and after incision had begun. Units of the same age in both terraces are similar in thickness, and the top elevation of each terrace is similar (about 1,884.2 m). Though these units were deposited by different floods, they do not necessarily differ in lithology.

XS0341 Narrative

Cross section 341 was the first one to be surveyed (December 14, 1996) at the downstream end of a long, broad, braided reach (about 40–50 m wide) that starts near XS0567 (fig. 15). Since the extreme flood on July 12, 1996 (about 510 m^3/s), the net area of deposition has been slightly greater than the net area of erosion from 1996 through 2014 such that the cross-sectional area has increased only 3 m^2 since 1996 (fig. 5).

Figure 15. Repeated views of the Spring Creek channel that include the location of cross section 341 (XS0341), 1998–2009. All views are looking downstream. The yellow dashed line in each photograph indicates the approximate location of XS0341. *A*, May 3, 1998. Yellow-and-orange tripod and level are near XS0555. B. Barkett (about 1.8 meters [m] tall) is standing near XS0470. *B*, Photograph was taken on July 11, 1998, after the flood on July 9, 1998 (48–58 cubic meters per second). D. Kinner (about 1.8 m tall) is standing at XS0555 on cobble-and-boulder bar left by the flood. *C*, May 30, 2000. D. Martin (1.7 m tall) is standing near XS0520. *D*, May 18, 2005. *E*, June 2009.

One chronostratigraphic unit from the major and extreme floods on August 26 and 31, 1997, (black polygons in figure 16) dominates the sediment preserved at this section, and the unit from the earlier floods on July 28, 29, and 31, 1997, (wavy-line polygon in figure 16) occupies the lowest level of the cross section. Winter aggradation happened when the sediment composing the channel banks was frozen and, thus, cohesive. Flowing water was then only able to erode a narrow, slot-like channel, and at times, some winter and early spring flows exceeded the capacity of the small incised channel, spread onto the adjacent surface, and deposited sediment, which refroze (white densely stippled polygon in figures 12, 14, 16).

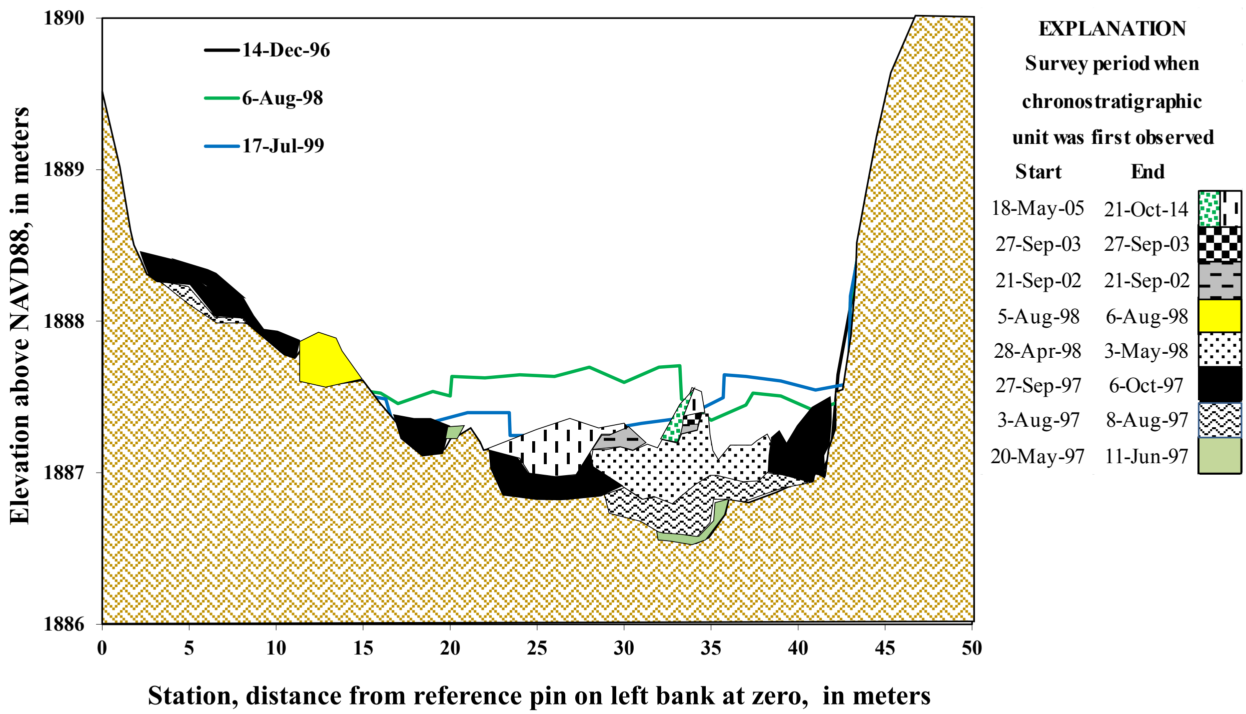

Figure 16. Preservation plot for cross section 341 (XS0341). Vertical exaggeration is 4.7×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0341_SciBase.xlsx) for survey data. (Green stippling indicates channel-bank dry-ravel deposits. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

Willows did not recolonize the cross-section location until about 2005 (fig. 15*C*–*E*). The mound of sediment near station 34 on top of the large winter deposit (fig. 16) has been trapped by a willow clump growing on the left bank of the channel (fig. 17). In 2014, the clump was 3–4 m tall and about 2 m in diameter at chest height. The 2014 channel thalweg was essentially at the same elevation (1,887.0 m) as the channel thalweg was in December 1996. Original willow clumps that survived the extreme flood on July 12, 1996, (between stations 0 and 10) have died, and new willows have colonized the area from about station 10 to the left edge of the water near station 35 (figs. 15E, 17).

Figure 17. Photograph showing willows approximately 1.5 meters (m) tall at the location of cross section 341 (XS0341), 2005. Photograph was taken on May 18, 2005, looking upstream, and the willows are about 3 m downstream from station 34 on XS0341. D. Martin is 1.7 m tall from head to toe.

XS0393 Narrative

Cross section 343 was measured near the downstream end of a long, broad reach (about 40–50 m wide) that starts near XS0567 (fig. 18). Since the extreme flood on July 12, 1996 (about 510 m^3/s), the net change in cross-sectional area from 1996 through 2014 has been an increase of about 8 m^2 (fig. 5). The right bank impinges on a steep hillslope with an outcrop of bedrock at the base, whereas the left bank slopes gently upward.

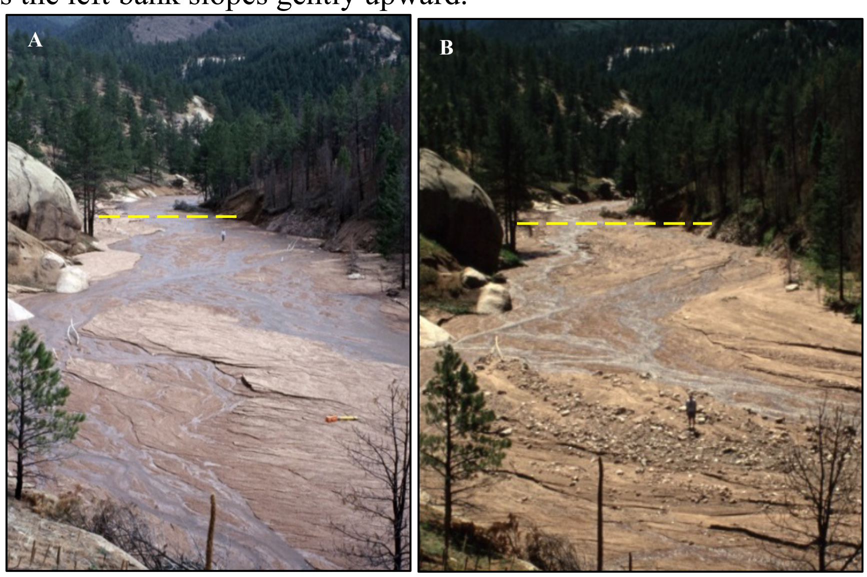

Figure 18. Repeated views of the Spring Creek channel that include the location of cross section 393 (XS0393), 1998–2005. All views are looking downstream. The yellow dashed line in each photograph indicates the approximate location of XS0393. *A*, May 3, 1998. Yellow-and-orange tripod and level are near XS0555. B. Barkett (about 1.8 meters [m] tall) is standing near XS0470. *B*, Photograph was taken on July 11, 1998, after the flood on July 9, 1998 (48–58 cubic meters per second). D. Kinner (about 1.8 m tall) is standing at XS0555 on cobble-and-boulder bar left by the flood.

Figure 18. Repeated views of the Spring Creek channel that include the location of cross section 393 (XS0393), 1998–2005. All views are looking downstream. The yellow dashed line in each photograph indicates the approximate location of XS0393. *C*, May 30, 2000. D. Martin (1.7 m tall) is standing near XS0520. *D*, May 18, 2005. *E*, June 2009.—Continued

The largest chronostratigraphic unit was deposited by the major and extreme floods on August 26 and 31, 1997 (>1 m^3/s, black polygon in figure 19), which moved boulders and cobble-sized particles, creating a bar at the surface of the flood deposit (fig. 19). This bar was buried by chronostratigraphic units deposited by smaller floods on July 9, 1998, (green polygon in figure 19) and July 31, 1998 (yellow polygon in figure 19). The chronostratigraphic unit associated with the July 9, 1998, flood (green polygon in figure 19) is preserved at only five other cross-section locations (XS0100, XS0187, XS755, XS0815, and XS1006), whereas sediments from the larger floods on August 26 and 31, 1997, (black polygons) and July 31, 1998, (yellow polygons) are preserved at all 14 cross-section locations between XS1200 and XS-2.7, except at XS0815.

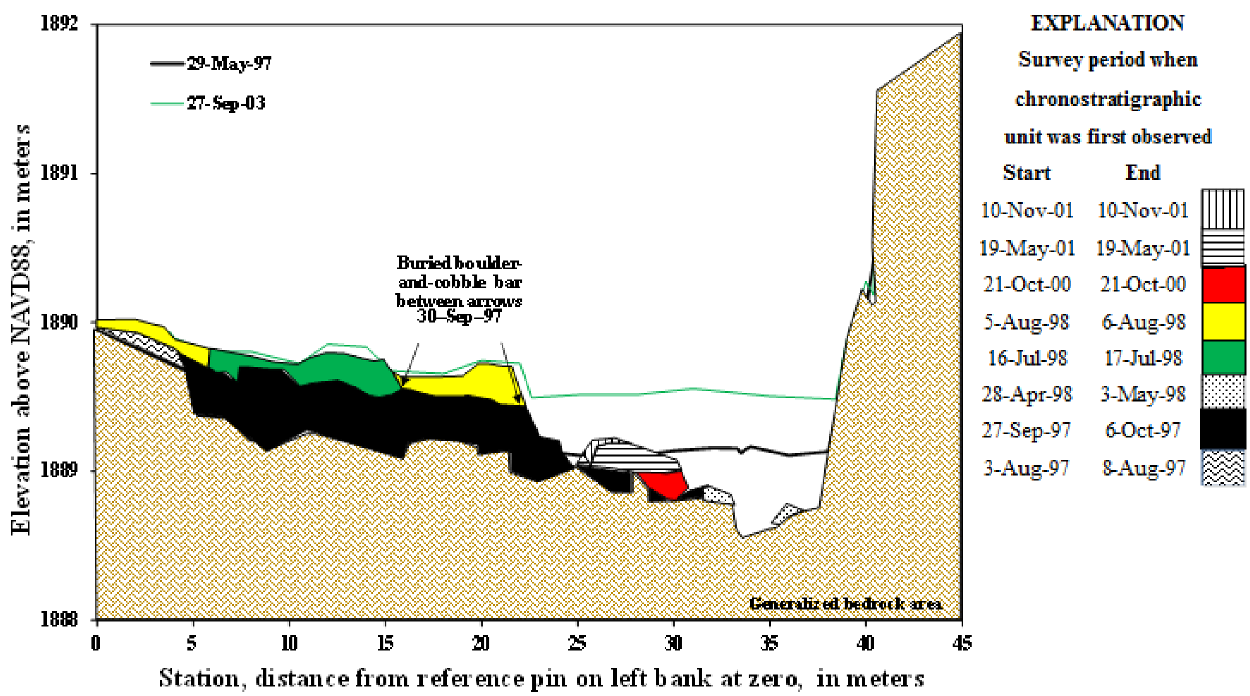

Figure 19. Preservation plot for cross section 393 (XS0393). Vertical exaggeration is 7.7×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0393_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

Aggradation continued through September 2003 (fig. 18 *C–D*). Subsequently, Spring Creek cut down to a thalweg elevation in 2014 that is about 0.5 m below the thalweg elevation in 1996 (1,888.6 m) (fig. 19). The location of this cross section was bare sand and gravel in 1996 after the extreme flood and has remained sparsely vegetated through 2014 except along the channel (fig. 20).

Figure 20. Photograph showing the reach of Spring Creek where cross section 393 (XS0393) was measured, 2008. Photograph was taken on May 5, 2008, looking upstream. The yellow dashed line indicates the approximate location of XS0393. Tripod in the center right of the photograph is about 1.4 meters tall.

XS0483 Narrative

Cross section 483 was measured at the upstream end of a long, broad reach (about 40–50 m wide) ending near XS0567 (fig. 21). Since the extreme flood on July 12, 1996 (about 510 m^3/s), the net deposition was almost balanced by the net erosion such that the change in cross-sectional area from 1996 through 2014 has been the addition of only 2 m^2 (fig. 5) (the total cross-sectional area is about 40 m^2 if the maximum elevation of the black dashed line in figure 22 is used).

Figure 21. Repeated views of the Spring Creek channel that include the location of cross section 483 (XS0483), 1998–2009. All views are looking downstream. The yellow dashed line in each photograph indicates the approximate location of XS0483. *A*, May 3, 1998. Yellow-and-orange tripod and level are near XS0555. B. Barkett (about 1.8 meters [m] tall) is standing near XS0470. *B*, Photograph was taken on July 11, 1998, after the flood on July 9, 1998 (48–58 cubic meters per second). D. Kinner (about 1.8 m tall)

is standing at XS0555 on a cobble-and-boulder bar left by the flood. *C*, May 30, 2000. D. Martin (1.7 m tall) is standing near XS0520. *D*, June 2009.

The top of the chronostratigraphic unit on the right bank (black polygon in figure 22) does not correspond to the level of the extreme flood on August 31, 1997 (about 140–180 m^3/s) because the cross section ends at the mouth of a tributary. This sediment originated within the tributary basin and was deposited as an alluvial fan at the mouth of the tributary. The lower deposits (grey and yellow polygons in figure 22) were deposited by floods on June 21, 1997, (1.35 m^3/s) and on July 31, 1998 (82 m^3/s). A similar deposit (black polygon in figure 22) is preserved on the left bank but much lower down, near the bottom of the sequence.

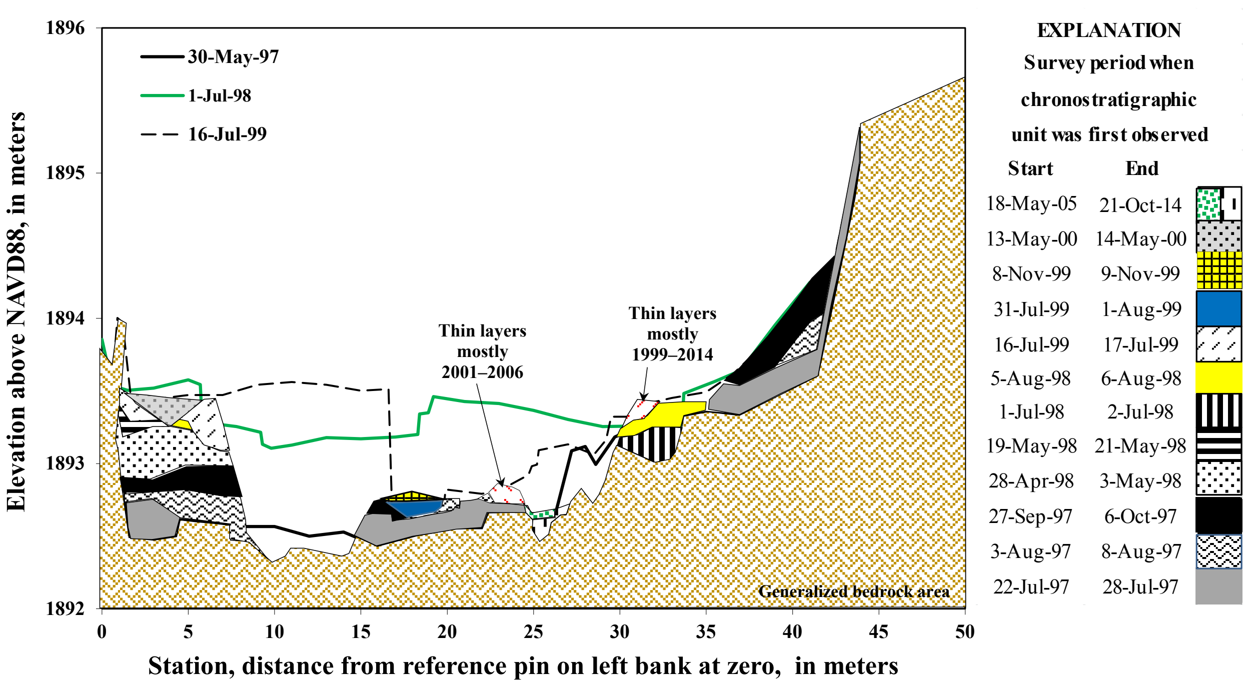

Figure 22. Preservation plot for cross section 483 (XS0483). Vertical exaggeration is 8.5×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. The vertical relief shown on the plot is a boulder near station 1 on the line of section (see also fig. 23). See Moody and Martin (2017, XSEC0483_SciBase.xlsx) for survey data. Green stippling indicates channel-bank dry-ravel deposits. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

The chronostratigraphic unit within the terrace on the left bank (white densely stippled polygon in figure 22) represents winter aggradation. Winter aggradation happened when the sediment composing the channel banks was frozen and, thus, cohesive. Flowing water was then only able to erode a narrow, slot-like channel, and at times, some winter and early spring flows exceeded the capacity of the small, incised channel, spread onto the adjacent surface, and deposited sediment, which refroze (see also figs. 12, 14, 16). A similar winter aggradation deposit is shown in figure 22 as a grey densely stippled polygon.

A chronostratigraphic unit (yellow checkered polygon in figure 22 between stations 15 and 20) formed while Spring Creek was braided. Braided-stream deposits were observed to form when multiple threads of shallow water (fig. 21*A*–*C*) deposited bedload as levees. These levees caused flow paths to alter directions leaving the deposits to accumulate. This chronostratigraphic unit is small in area at the location of this cross section but much larger at other cross-section locations (for example, downstream at XS0100, and upstream at XS0567 through XS1200). This deposit and an earlier deposit left by a major flood on July 29, 1999, (6.4 m^3/s) (blue polygon in figure 22) are only preserved within the flood plain sediments and not in the terraces on the left and right banks or in the alluvial fan deposits from the tributary. The channel thalweg in 2014 was only about 0.1 m lower than the elevation of the thalweg after the extreme flood in 1996 (1,892.4 m) (fig. 22).

The location of cross section 483 was initially characterized by bare sand and gravel forming a braided-stream channel (fig. 21*A*, *B*). There has been little revegetation on the flood plain adjacent to the channel (figs. 21*C*, *D*, 23). Most of the vegetation consists of willows along the channel margin.

Figure 23. Photograph showing the reach of Spring Creek where cross section 483 (XS0483) was measured, 2008. Photograph was taken on May 5, 2008, looking upstream. The yellow dashed line indicates the approximate line of section. The right end of the yellow dashed line is on a 1-meter-diameter boulder. The edge of the large bedrock outcrop seen in figure 21 is on the right edge of the photograph. The tripod is on the left-bank terrace. No willows are growing along the channel margin in this photograph, but by 2009 (fig. 21*D*) willows had colonized both edges of the water and were about 1.5 meters tall.

XS0567 Narrative

Cross section 567 (about 32 m wide) was measured midway in an expanding reach (fig. 24) that starts at XS0679 (about 25 m wide) and ends at XS0483 (about 42 m wide), just downstream from the large bedrock outcrop on the left side of figure 24*A*, *B*, *D*. Since 1996, small terraces have formed on each side of the channel, and as a result the cross-sectional area of net deposition exceeds that of the net erosion from 1996 through 2014 by about 12 m^2 (fig. 5).

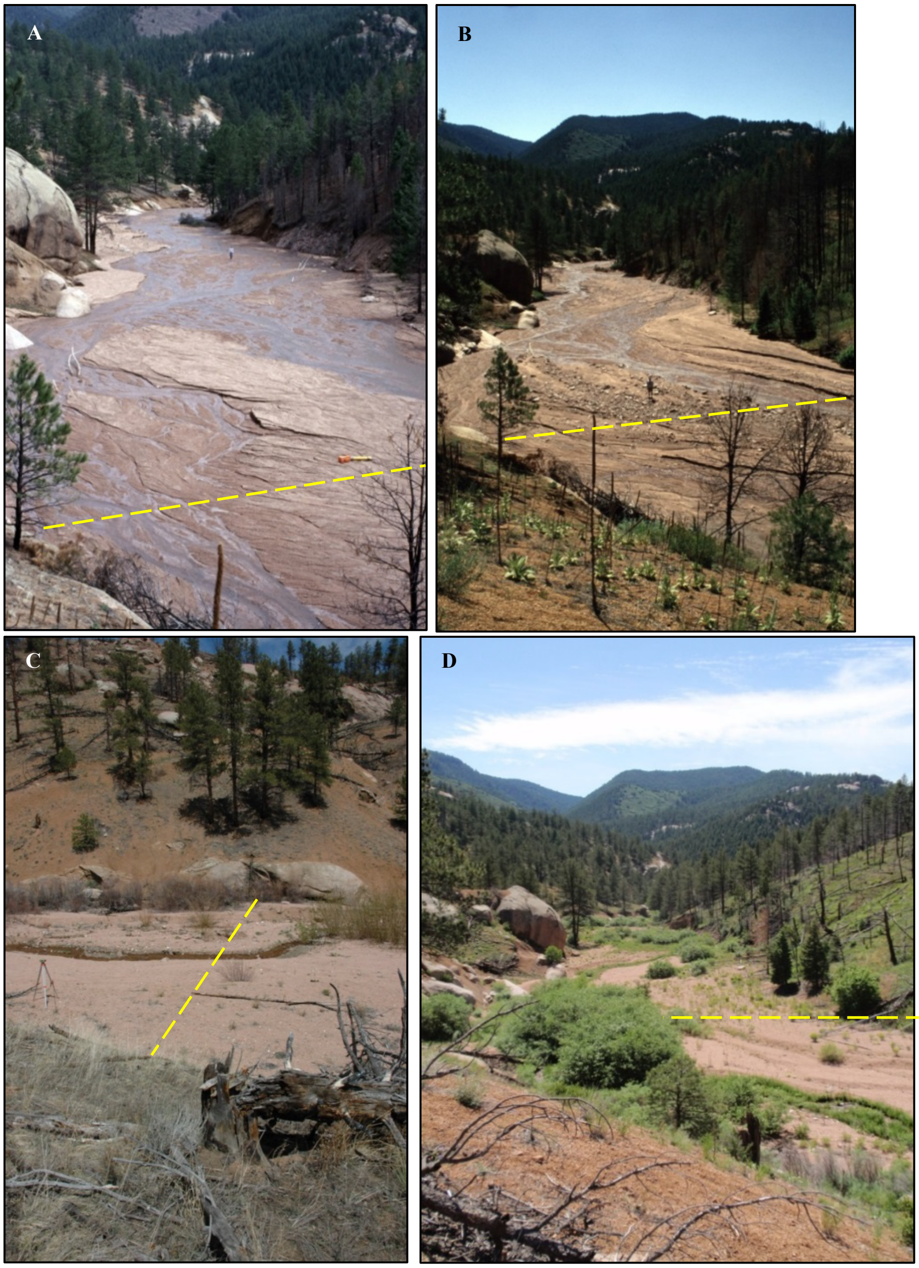

Figure 24. Repeated views of the Spring Creek channel that include the location of cross section 567 (XS0567), 1998–2009. The yellow dashed line in each photograph indicates the approximate location of XS0567. *A*, May 3, 1998. View is looking downstream from the hillslope above XS0567. Yellow-and-orange tripod and level are near XS0555. B. Barkett (about 1.8 meters [m] tall) is standing near XS0470. *B*, Photograph was taken on July 11, 1998, after the flood on July 9, 1998 (48–58 cubic meters per second). View is looking downstream from the hillslope above XS0567. D. Kinner (about 1.8 m tall) is standing near XS0555 on a cobble-and-boulder bar left by the flood. *C*, May 5, 2008. View is from right bank looking toward the left bank. Tripod is about 1.5 m tall. *D,* June 2009. View is looking downstream from the hillslope above XS0567.

Numerous chronostratigraphic units associated with several major (>1 m^3/s) and an extreme flood (>10 m^3/s) have been preserved at the location of this cross section. They are those deposited by the flood on June 21, 1997, at the base of the left bank (grey polygon in figure 25); by the floods on July 28, 29, and 31, 1997, at the base of the right bank (wavy-line polygon); and by the floods on August 26 and 31, 1997 (black polygon). The flood sequence is then interrupted by a relatively large chronostratigraphic unit within both terraces (white densely stippled polygon in figure 25), which represents winter aggradation (1997–1998). Winter aggradation happened when the sediment composing the channel banks was frozen and, thus, cohesive. Flowing water was then only able to erode a narrow, slot-like channel, and at times, some winter and early spring flows exceeded the capacity of the small, incised channel, spread onto the adjacent surface, and deposited sediment, which refroze (see also figs. 13, 41, 45). A similar chronostratigraphic unit was deposited during the winter of 1999–2000 (grey densely stippled polygon in figure 25).

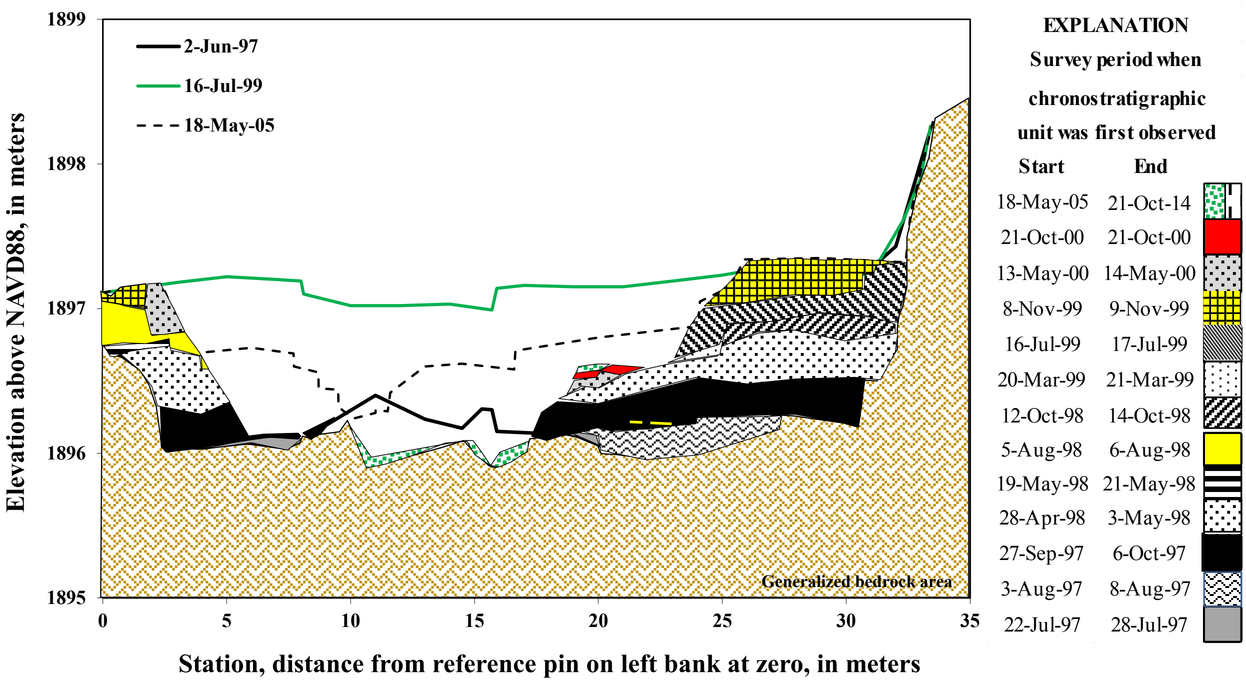

Figure 25. Preservation plot for cross section 567 (XS0567). Vertical exaggeration is 5.9×. Each labeled sediment deposit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0567_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

The chronostratigraphic unit deposited by the flood on July 31, 1998, (about 82 m^3/s) appears only on the left bank (yellow polygon in figure 25). Water discharge was elevated and steady for several periods from April 30 through June 22, 1999 (May 2–8, about 0.15 m^3/s; May 25–27, about 0.15 m^3/s; and June 9–22, about 0.12 m^3/s). During this interval between the survey on March 20–21, 1999, and the survey on July 16–17, 1999, with no minor floods (0.1–1 m^3/s) or major floods (1–10 m^3/s), a large amount of sediment was eroded from upstream at XS0679 (loss of 11.00 m^2), creating an incised channel, while a new chronostratigraphic unit was deposited downstream at the location of cross section 567 (14.69 m^2, see descending diagonal polygon in figure 25).

The layer atop the terrace (yellow-checkered polygon in figure 25) is the combination of units formed by a major flood on August 4, 1999, (1.2 m^3/s) and a series of eight minor floods from August 9 through September 10, 1999. This combined unit is relatively large. It does not appear as large at the locations of other cross sections downstream except at XS0100, but it is mostly preserved in upstream deposits from XS0755 to XS1100. It does not appear to be a continuous depositional layer along the length of Spring Creek. The thalweg at the location of this cross section in 2014 was about 0.1 m lower than the thalweg elevation in 1996 (1,896.0 m), after the extreme flood on July 12, 1996.

XS0679 Narrative

Cross section 679 was measured in a relatively narrow part of the valley of Spring Creek that was characterized by a net deposition of about 16 m^2 from 1996 through 2014 (fig. 5). The area where this cross section was measured was unusual in that it showed continual aggradation after the extreme flood on July 12, 1996, (about 510 m^3/s) until about 2001, whereas the locations of many of the other cross sections went through cycles of incision between major floods and aggradation during major floods, which releveled the surface from valley wall to valley wall.

This section was observed to aggrade by two depositional processes. In the first process, surface water coming from upstream and transporting bedload flowed out onto the sediment deposit, percolated into the sediment, and left behind stranded bedload particles. This process slowly formed an "in-channel" fan (Moody, 2001) with no water on its surface but with surface water reappearing downstream at the base of the fan (fig. 26).

Figure 26. Photograph of the downstream end of an in-channel fan, May 1997. Photograph was taken in May 1997 looking upstream. Surface flow from upstream completely disappears into the fan and reappears downstream at approximately the location where D. Wolf (about 1.8 meters tall) is standing.

In the second depositional process, the fan aggraded during the winter when the sand-and-gravel sediment was frozen, making it cohesive. Any water from upstream that was transporting sediment spread out over the broad fan and deposited sediment; frequently the water and sediment froze on the surface, making it impossible to walk up the fan (fig. 27). This winter aggradation process (white densely and sparsely stippled and grey densely stippled polygons in figure 28) was comparable to deposition after major floods.

Figure 27. Summer and winter photographs of the in-channel fan at the location of cross section 679 (XS0679), 1998–1999. Views are looking upstream at the downstream face of the fan. The yellow dashed line in each photograph indicates the approximate location of XS0679. *A*, July 11, 1998. D. Kinner (about 1.8 meters [m] tall) is standing near XS0640. The cobbles and boulders were left by the flood on July 9, 1998 (48–58 cubic meters per second). *B*, January 12, 1999. Person (about 1.9 m tall) is standing near XS0660. Note that the elevation of the frozen surface of the in-channel fan is higher than in figure 27*A*; it has risen to the base of the twin trees on the right bank.

The chronostratigraphic unit corresponding to deposition during the winter of 1998–1999 (sparsely stippled polygon in figure 28) was originally much larger, but erosion during snowmelt runoff in 1999 (see XS0567 Narrative) eroded a large amount of sediment (11.00 m^2), which lowered the elevation of the fan. However, the fan continued to aggrade until May 2001, when a channel was eroded along the left bank at the cross-section location (fig. 29*A*) abandoning the fill terrace along the right bank. The channel continued to deepen. It was about 1.5 m deep on October 14, 2006, (fig. 28) and by 2010 was about 2.5 m lower than its highest elevation (figs. 28, 29*C*).

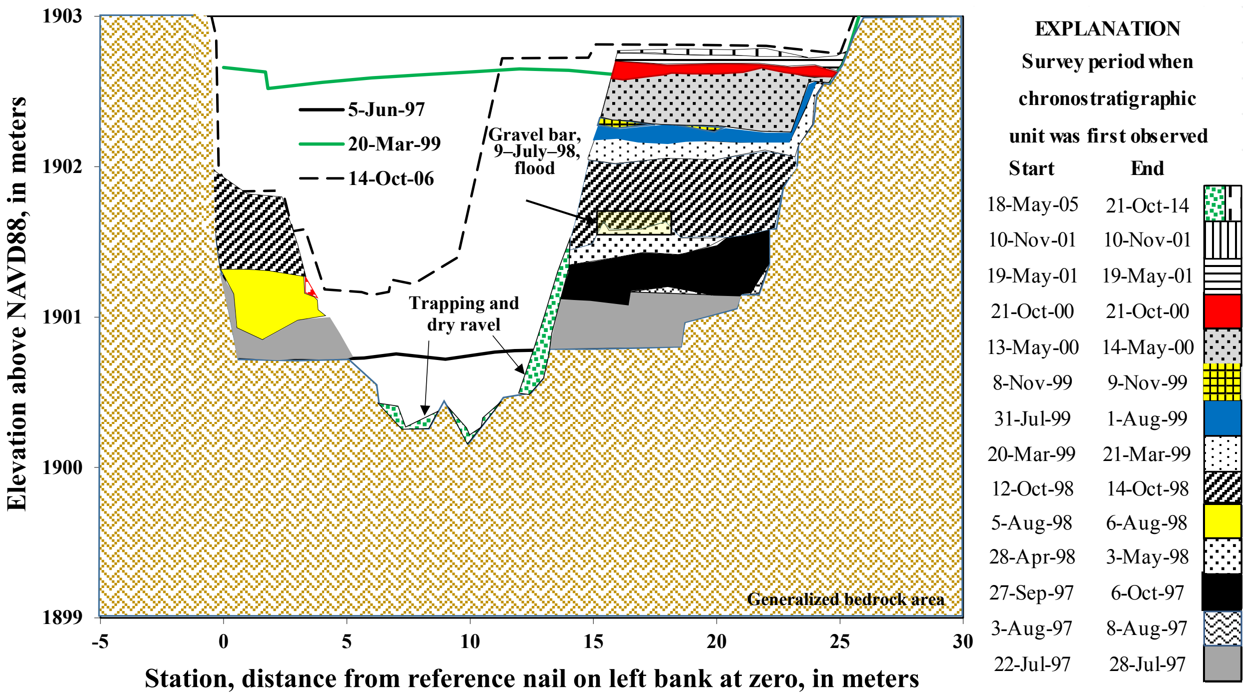

Figure 28. Preservation plot for cross section 679 (XS0679). Vertical exaggeration is 6.2×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0679_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

As Spring Creek cut down, starting after 2001 (fig. 29), it abandoned the in-channel fan, leaving a cut terrace and preserving most of the chronostratigraphic units corresponding to major flood deposits (fig. 28). The sequence of depositional floods and their associated chronostratigraphic units from oldest to youngest is June 21, 1997 (grey polygon); July 28, 29, and 31, 1997 (wavy-line polygon); August 26 and 31, 1997 (black polygon); July 31, 1998 (yellow polygon); July 29, 1999 (blue polygon); and July 16, 2000 (red polygon). Units corresponding to different floods do not necessarily differ in lithology. They appear as relatively uniform, or laminar, layers (fig. 30) compared to those observed in some of the other cross sections with more irregularly shaped units (for example, XS0187, XS0393, XS0755, and XS0905). This laminar appearance most resembles the stratigraphy at XS0250 and XS0815. After 2008, willows quickly recolonized the channel (fig. 29*B*, *C*), and by 2010, the creek had developed anabranching channels (fig. 31; see also Nansen and Huang, 1999).

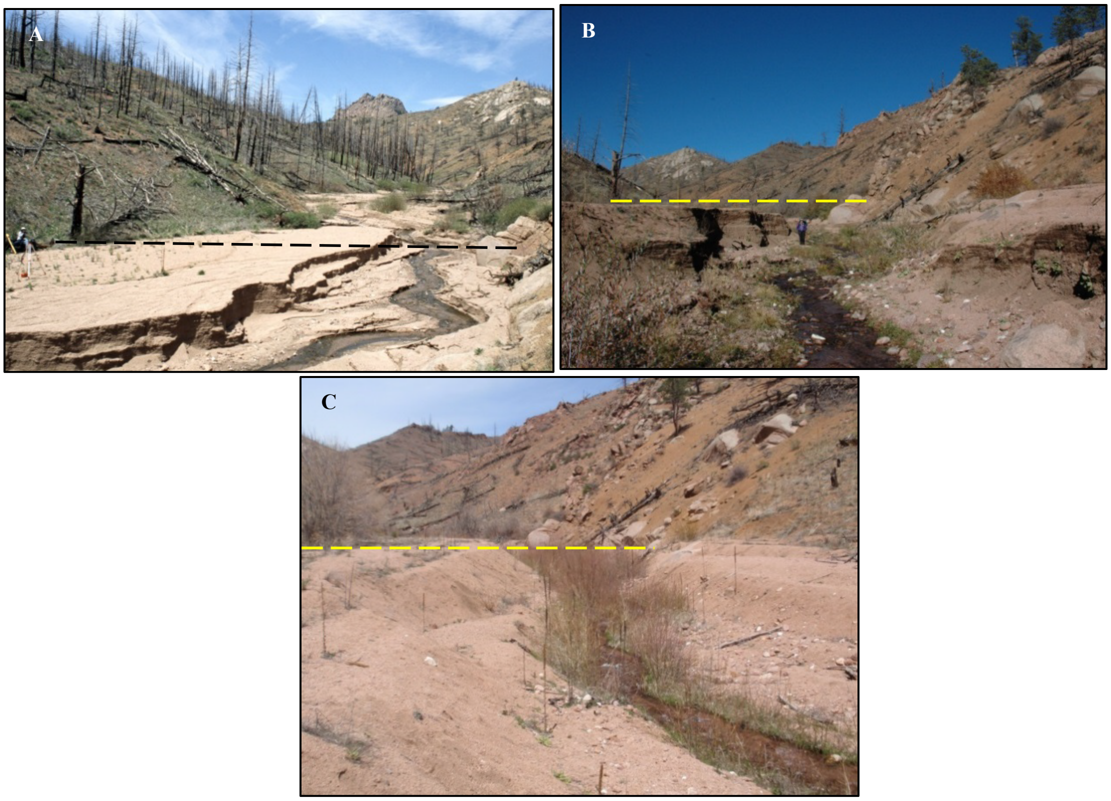

Figure 29. Repeated views of the Spring Creek channel that include the location of cross section 679 (XS0679), 2005–2010. All views are looking upstream at the successive stages of incision of the in-channel fan. The black or yellow dashed line in each photograph indicates the approximate location of XS0679. *A*, May 18, 2005. Tripod is about 1.5 meters (m) tall. Note that there is no large, shrubby vegetation along the margins of the channel. *B*, October 25, 2007. D. Martin (about 1.7 m tall) is standing on the line of section. Willows, forbs, and some grass have begun to colonize the channel margins. *C*, May 8, 2010.

Figure 30. Close-up view of the lithology of the right bank at the location of cross section 679 (XS0679), 2007. Photograph was taken on October 25, 2007. Sediment is mostly sand and gravel (2–4-millimeter diameter) deposited by multiple floods. Layers are evident but extend continuously only for short distances, on the order of 2–4 meters (m). Larger numerals on left side of rod are 0.1 m apart. The height of the prominent black bars along the face of the rod is 1 centimeter.

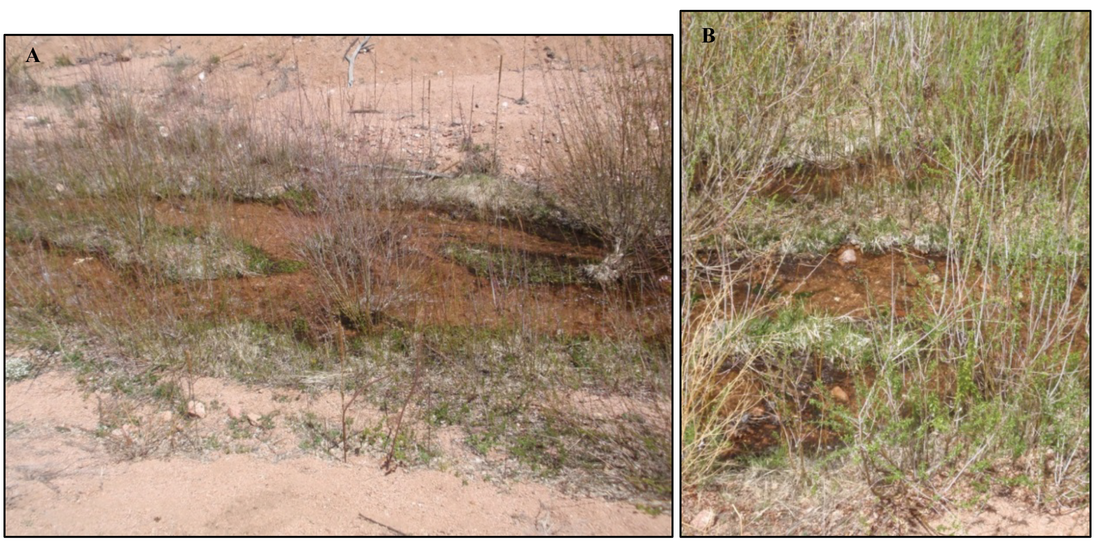

Figure 31. Photographs of an anabranching channel at the location of cross section 679 (XS0679), 2010–2011. *A*, May 8, 2010. *B*, May 7, 2011.

The in-channel fan acted as a dam. Channel slopes upstream from XS0679 ranged from 0.025 to 0.040, whereas downstream from XS0679 they ranged from 0.038 to 0.056. Unlike the reach upstream from XS0250, which expanded into a wide reach (about 40–50 m), the reach upstream from XS0679 was relatively narrow (about 15–30 m). The reach from XS0679 through XS0905 saw a maximum in net deposition from 1996 through 2014 (fig. 5). The thalweg in June 2014 was about 0.6 m lower than the thalweg in 1996 after the extreme flood on July 12, 1996 (fig. 28).

XS0755 Narrative

Cross section 755 was the first section measured upstream from the in-channel fan (Moody, 2001) that developed downstream at XS0679 and acted as a dam, raising the base level of Spring Creek. Cross section 755 was measured within a reach of maximum net deposition, and the cross-sectional area of deposited sediment increased 13 m^2 from 1996 through 2014 (fig. 5). This section continued to aggrade until 2002, and thereafter it incised (fig. 32) (Moody and Martin, 2017).

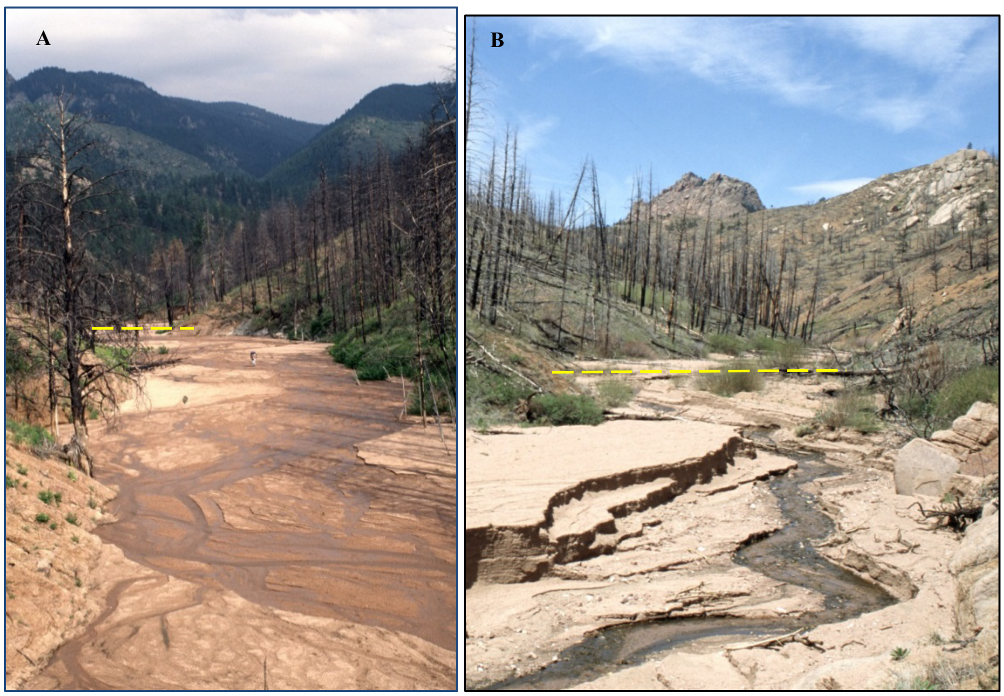

Figure 32. Photographs of the Spring Creek channel that include the location of cross section 755 (XS0755), 2000–2005. The yellow dashed line in each photograph indicates the approximate location of XS0755. *A*, May 30, 2000. View is looking downstream. D. Martin (about 1.7 meters tall) is standing near XS0795 in about the center of the photograph. *B*, May 18, 2005. View is looking upstream from the left bank of XS0679 through the headcut.

Sediments were observed to be deposited at the location of this cross section by floods in response to summer convective storms. Chronostratigraphic units corresponding to major and extreme flood deposition (wavy-line polygon, July 29 and 31, 1997; black polygon, August 26 and 31, 1997; green polygon, July 9, 1998; and yellow polygon, July 31, 1998; fig. 33) do not appear as layers with substantial horizontal extent as they do at XS0250, XS0679, and XS0815, but rather as truncated and irregularly shaped deposits. The unit from the July 9, 1998, flood is preserved only at the locations of five other cross sections (XS0100, XS0187, XS0393, XS0815, and XS1006), whereas the larger floods on August 26 and 31, 1997, (black polygons) and July 31, 1998, (yellow polygons) are preserved at cross-section locations from XS-2.7 through

XS1200 (except at XS0815 and XS1100). The final chronostratigraphic unit in the flood sequence is the combined deposits formed by a major flood on August 4, 1999, (1.2 m^3/s) and a series of eight minor floods from August 9 through September 10, 1999 (yellow checkered polygon in figure 33).

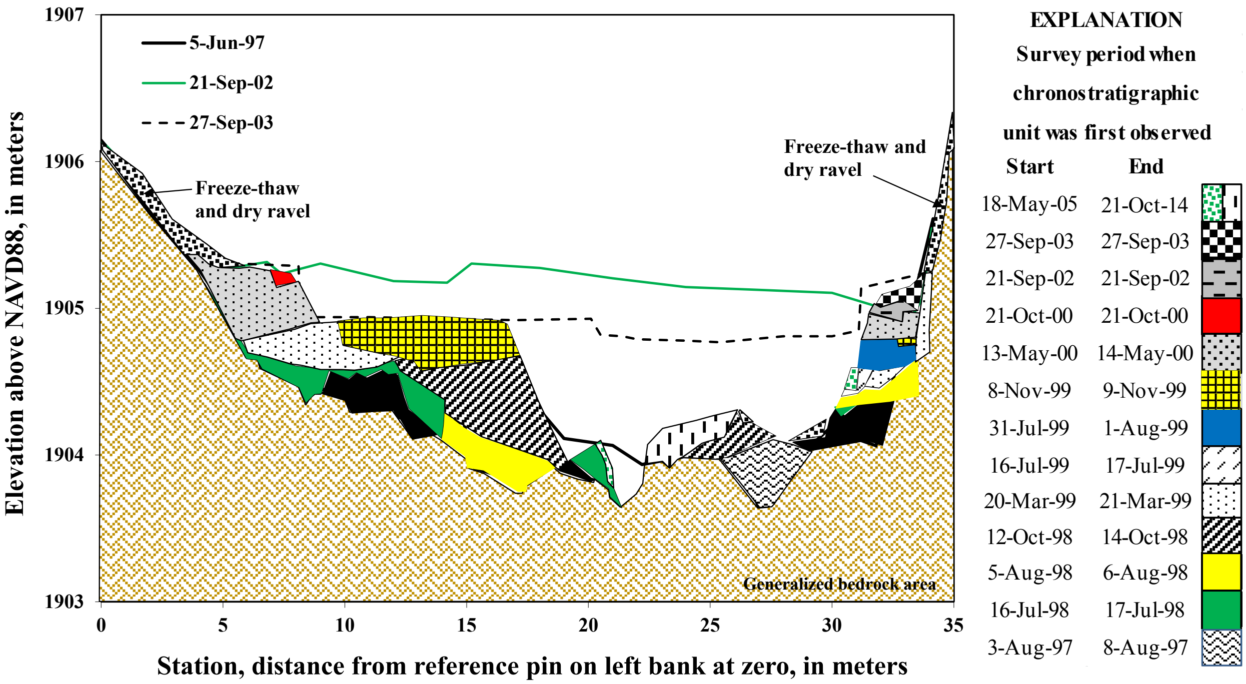

Figure 33. Preservation plot for cross section 755 (XS0755). Vertical exaggeration is 6.0×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0755_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

Other chronostratigraphic units (ascending-diagonal, white sparsely stippled, and grey densely stippled polygons), especially on the left bank, were deposited during braided-stream conditions, by percolation, and during winter conditions when frozen, or cohesive, sediment filled the channel. Braided-stream deposits were observed to form when multiple threads of shallow water deposited bedload as levees. These levees caused flow paths to alter directions, leaving the deposits to accumulate (fig. 32). Percolation deposits formed when surface water, transporting bedload, percolated into the sediment and left behind stranded bedload particles, which with time developed into relatively large deposits (fig. 26). Additionally, any water from upstream that was transporting sediment spread out and lost velocity where the channel slope decreased (0.025–0.040). Frequently during the winter, the sediment filling the braided channel was frozen, or cohesive. Flowing water was then only able to erode narrow, slot-like channels, and, at times, some winter and early spring flows exceeded the capacity of the small, incised channels, spread onto the adjacent surface, and deposited sediment, which refroze (figs. 13, 41, 45).

The headcut at XS0679 that started after 2001 progressed upstream through XS0755 (fig. 32), and by 2007 willows had begun to recolonize the cross section and were about 1–2 m high (fig. 34). Some dry ravel (Anderson and others, 1959; Gabet, 2003; Roering and Gerber, 2005) from the adjacent hillslopes has contributed to the deposit on the left and right banks. In general, bank deposits exposed by erosion appear to have some stratigraphy, but layers are only continuous over 1–5 m (fig. 35). The thalweg in June 2014 was at the same elevation as the thalweg in 1996 after the extreme flood on July 12, 1996 (1,903.6 m elevation) (fig. 33).

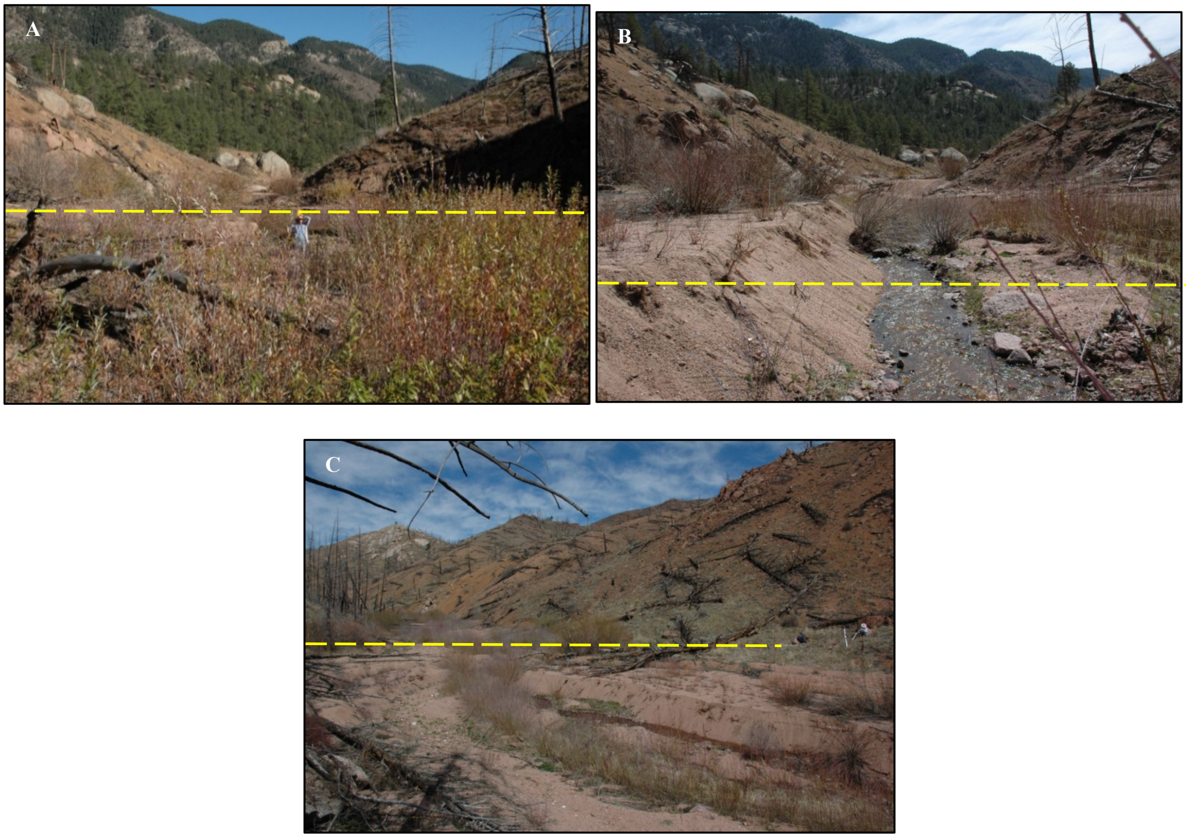

Figure 34. Photographs of the Spring Creek channel that include the location of cross section 755 (XS0755), 2007–2008. The yellow dashed line in each photograph indicates the approximate location of XS0755. *A*, October 25, 2007. View is looking downstream. D. Martin (about 1.7 meters tall) is standing on the line of section for XS0755. Willows have begun to recolonize the cross section. *B*, May 5, 2008. View is looking downstream. The terrace surface on the left bank formed in 2003 as a cut terrace when the 1999–2000 winter deposits were eroded. *C*, May 5, 2008. View is looking upstream.

Figure 35. Photograph of left bank of cross section 755 (XS0755), 2007. Photograph is looking upstream and was taken on October 25, 2007. Recent erosion of young willows has left nearly vertical banks with apparent layers of sediment, but generally these layers are not continuous over tens of meters. The yellow level book is 19 centimeters tall.

XS0815 Narrative

Cross section 815 was the second section measured upstream from the in-channel fan (Moody, 2001) that developed at XS0679 and acted as a dam, raising the base level of Spring Creek upstream from XS0679. Channel slopes upstream from XS0679 ranged from 0.025 to 0.040, whereas downstream from XS0679 they ranged from 0.038 to 0.056. The area where cross section 815 was measured was a braided reach (fig. 36A), and the cross-sectional area of sediment continued to aggrade to a maximum value of 26.8 m^2 in 2002, after which time it began to incise (fig. 37) such that the net change in area from 1996 through 2014 was the addition of 14.8 m^2 (fig. 5).

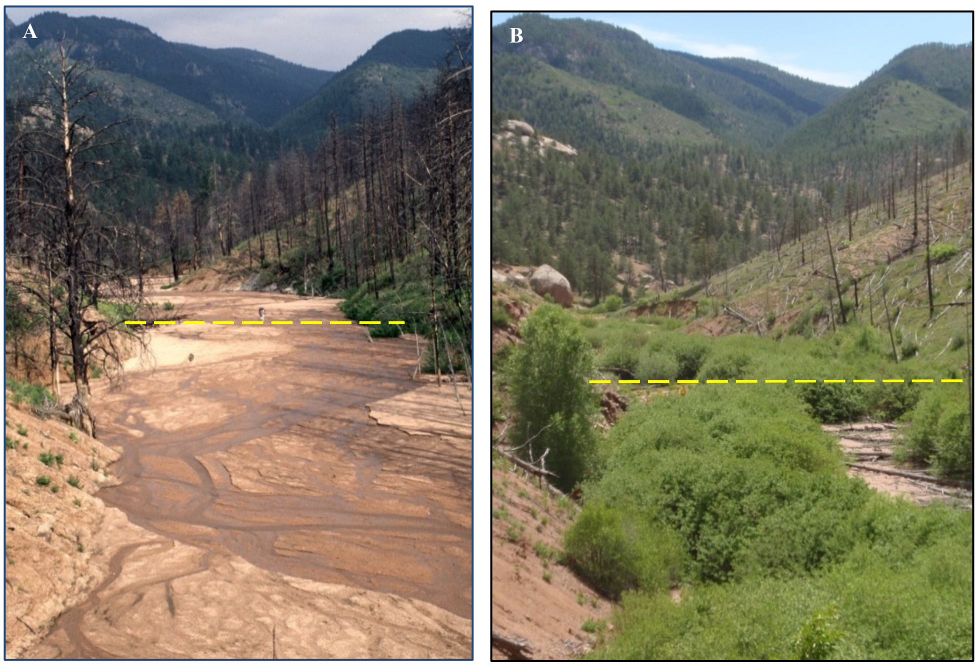

Figure 36. Repeated views of the Spring Creek channel that include the location of cross section 815 (XS0815), 2000–2012. Both views are looking downstream. The yellow dashed line in each photograph indicates the approximate location of XS0815. *A*, May 30, 2000. D. Martin (about 1.7 meters [m] tall) is standing near XS0795 in about the center of the photograph. *B*, June 2, 2012.

Figure 37. Photograph of the Spring Creek channel that includes cross section 0815 (XS0815), 2008. Photograph was taken on May 5, 2008, looking upstream. The yellow dashed line indicates the approximate location of XS0815. Two terraces can be seen along the left bank. One is a fill terrace created around October 2000 (the tripod [about 1.5 meters tall] is on this terrace). The other is a cut terrace formed around 2003 and is composed mostly of sand and gravel with little vegetation.

This section preserved all chronostratigraphic units associated with major floods except the floods on August 26 and 31, 1997 (shown as a black polygon in other preservation plots). These flood deposits form three distinct terrace levels: a cut terrace (1,907.3 m elevation) on the left bank (top of red polygon in figure 38), whose proximal surface was eroded down between September 21, 2002, and September 27, 2003, to form a second cut terrace (1,907.1 m), and a third cut terrace (1,906.3 m) on the right bank. The upper chronostratigraphic units within the terrace on the left bank are essentially horizontal and relatively uniform in thickness, whereas some of the lower sediment deposits are more irregular. The laminar appearance most resembles stratigraphy at XS0679 and XS0250. However, the units represent different flood deposits than those at XS0250 and XS0679, and the sediment deposits corresponding to each flood do not necessarily differ in lithology.

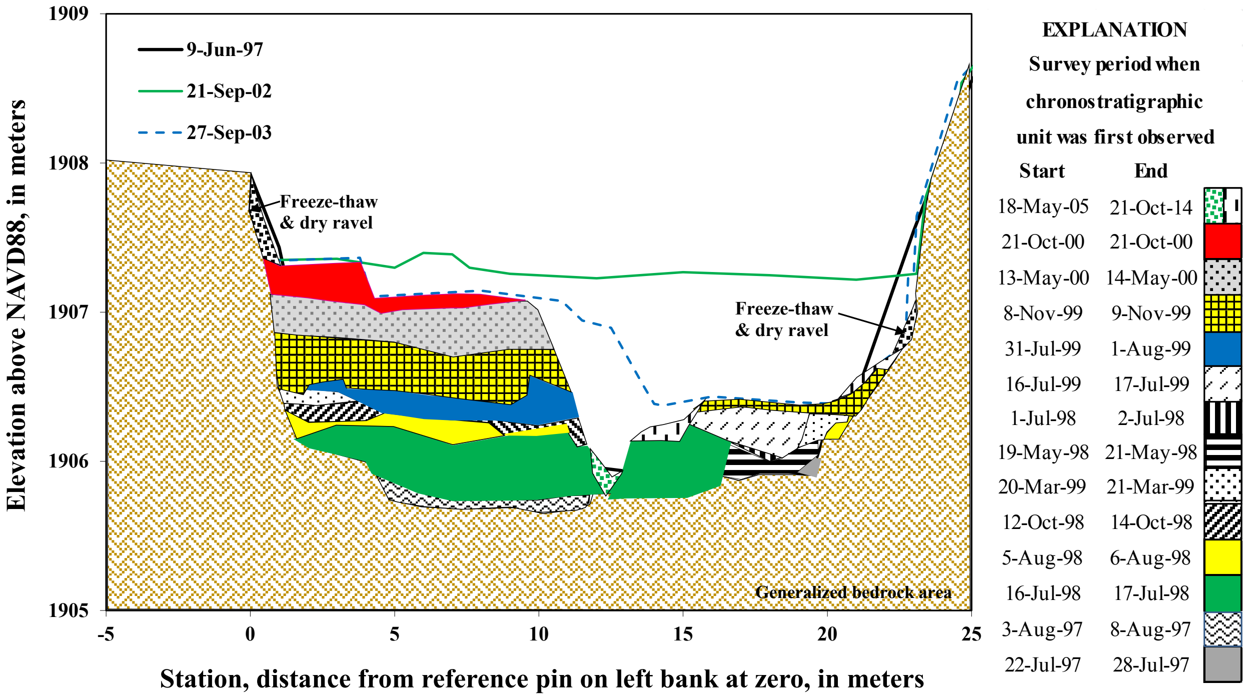

Figure 38. Preservation plot for cross section 815 (XS0815). Vertical exaggeration is 5.2×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0815_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

Interspersed between the flood deposits are braided, percolation, and winter deposits. Braided-stream deposits were observed to form when multiple threads of shallow water deposited bedload as levees. These levees caused flow paths to alter directions, leaving the deposits to accumulate (fig. 36*A*). Percolation deposits formed when surface water, transporting bedload, percolated into the sediment and left behind stranded bedload particles, which with time accumulated to form relatively large deposits (fig. 26). Frequently, during winter, sediment filling the braided channel was frozen and, thus, cohesive. Sometimes during the winter flow exceeded the capacity of small (0.2–1.0 m wide), shallow channels, and sediment-bearing water spread out from the small channels, deposited sediment on the surface, and refroze (figs. 13, 41, 45).

Willows have flourished within the reach from XS0755 to XS0905 and at XS0815 (fig. 36*B*). At the locations of most cross sections measured downstream from XS0815, the thalweg was lower in 2014 than in 1996; however, at XS0815 the thalweg was 0.2 m higher than in 1996 (fig. 38). This highlights the net deposition measured at this cross section, which is the highest measured at any section.

XS0905 Narrative

Cross section 905 was measured at the upper end of a depositional reach that begins at the in-channel fan (Moody, 2001) at XS0679. This fan acted as a natural dam, raising the base level of Spring Creek in the area upstream from XS0679 to XS0905. Channel slopes upstream from XS0679 ranged from 0.025 to 0.040, whereas downstream they ranged from 0.038 to 0.056. Cross section 905 shows a net increase in cross-sectional area of 12 m^2 from 1996 through 2014 (fig. 5). It continued to aggrade until about 2002, then incised, leaving a fill terrace on the left bank and a cut terrace on the right bank (figs. 39, 40).

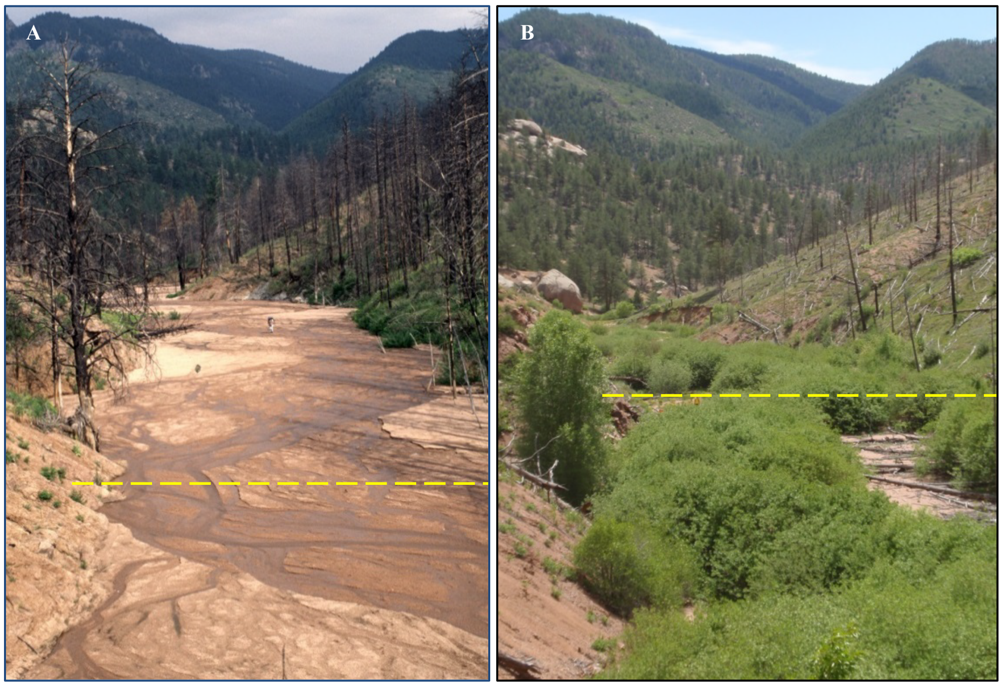

Figure 39. Repeated views of the Spring Creek channel that include the location of cross section 905 (XS0905), 2000–2012. Both views are looking downstream. The yellow dashed line in each photograph indicates the approximate location of XS0905. *A*, May 30, 2000. D. Martin (about 1.7 meters [m] tall) is standing near XS0795 in about the center of the photograph. *B*, June 7, 2012.

In general, chronostratigraphic units associated with major and extreme floods are irregularly shaped because of erosion between surveys. This is especially true for the combined chronostratigraphic units on the left bank associated with the major floods on July 28, 29, and 31, 1997, which are in two separate pieces (wavy-line polygon in figure 40). Sediment deposits from the major and extreme floods on August 26 and 31, 1997, are in four pieces (black polygon in figure 40). Those deposited by the major flood on July 31, 1997, are in three pieces (yellow polygons in figure 40). The shape of the July 29, 1999, flood deposit (blue polygon in figure 40) is the original shape, as it was surveyed only two days after the flood.

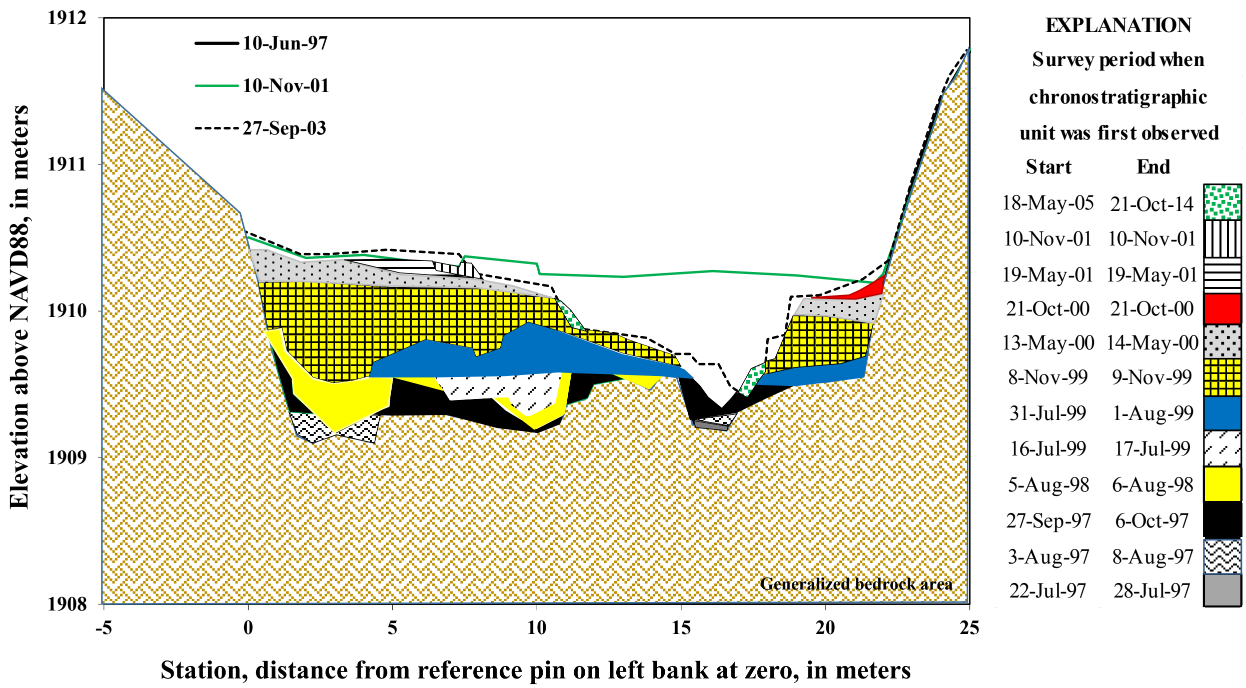

Figure 40. Preservation plot for cross section 905 (XS0905). Vertical exaggeration is 5.1×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC0905_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

The large sediment deposit (yellow checkered polygon in figure 40) consists of braided-stream deposits from a major flood on August 4, 1999, and a series of eight minor floods from August 9 through September 10, 1999, when Spring Creek was still mostly a braided stream (fig. 39*A*). Braided-stream deposits were observed to form when multiple threads of shallow water deposited bedload as levees. These levees caused flow paths to alter directions, leaving the deposits to accumulate. Similar large sediment deposits were found at XS0567, XS0755, XS0815, and XS1200, but they are much smaller or nonexistent at other cross sections. The left bank terrace is capped by chronostratigraphic units deposited in winter (1999–2000 [grey densely stippled polygon] and 2000–2001 [vertical and horizontally striped polygon]. During winter, sediment filling the braided channel was frozen and, thus, cohesive (fig. 41). Sometimes flow during the winter exceeded the capacity of small (0.2–1.0 m wide), shallow channels, and sediment-bearing water spread out from the small channels, deposited sediment on the surface, and refroze (see also figs. 13, 45).

Figure 41. Photograph of the Spring Creek channel that includes the location of cross section 905 (XS0905), 1999. Photograph was taken on January 12, 1999. The yellow dashed line in the photograph indicates the approximate location of XS0905. B. Lange (about 1.8 meters tall) is standing near XS0865.

Incision at XS0905 started between the surveys on September 21, 2002, and September 27, 2003 (dashed line in figure 40). XS905 was not surveyed again until September 23, 2014 (11 years later; table 1), partly because of the dense growth of willows across the section (fig. 39*B*). There was little change in the channel profile between the surveys in 2003 and 2014, with only a net loss of 1.23 m^2 of cross-sectional area over the 11 years. The thalweg elevation in 2003 was 1,909.4 m, similar to the elevation in 2014 (1,909.3 m), which was about 0.2 m higher than the elevation of the thalweg in 1996.

XS1006 Narrative

Cross section 1006 was measured at the upper end of an expanding reach of Spring Creek. At the location of this cross section, there was a net increase of 6 m^2 of cross-sectional area between the time of the extreme flood on July 12, 1996, (about 510 m^3/s) and June 2014 when this study concluded (fig. 5). Cross section 1006 was measured about 100 m downstream from the narrowest cross-section location (XS1100, about 9 m wide), between the mouth and the gage site near XS1470. Most of the chronostratigraphic units associated with major flood deposits are preserved at the location of this cross section (fig. 42). They are, from oldest to youngest, June 21, 1997 (grey polygon at the base of the right and left banks); July 28, 29, and 31, 1997 (wavy-line polygon); August 26 and 31, 1997 (black polygon); July 9, 1998 (green polygon); July 31, 1998 (yellow polygon); and July 29, 1999 (blue polygon).

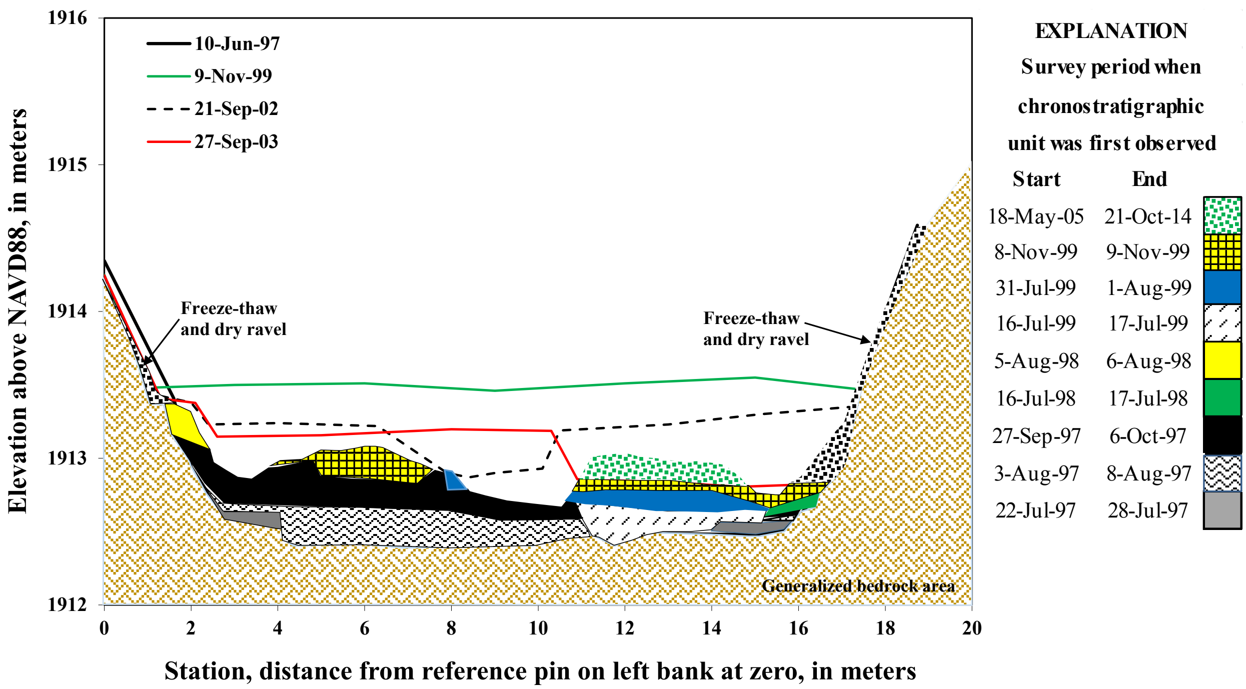

Figure 42. Preservation plot for cross section 1006 (XS1006). Vertical exaggeration is 3.4×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC1006_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

The large chronostratigraphic unit (yellow checkered polygon) consists of braided-stream deposits from a major flood on August 4, 1999, and a series of eight minor floods from August 9 through September 10, 1999. Braided-stream deposits were observed to form when multiple threads of shallow water deposited bedload as levees. These levees caused flow paths to alter directions, leaving the deposits to accumulate (fig. 39*A*). Similar sediment deposits from this time period are found at XS0567, XS0755, XS0815, XS0905, and XS1200.

Winter sediment deposits are notably absent at XS1006. These frequently formed at locations where other cross sections were measured during winter when the sediment filling the braided channel was frozen and, thus, cohesive. At the other locations, sometimes flow during the winter exceeded the capacity of small (0.2–1.0 m wide), shallow channels, and sediment-bearing water spread out from the small channels, deposited sediment on the surface, and refroze (figs. 13, 41, 45).

The maximum thickness of deposition was measured on November 9, 1999 (fig. 42); the thalweg elevation for the braided stream that existed at that time was 1,913.5 m. Incision began sometime after this survey, and the thalweg elevation had lowered to 1,912.8 m by September 27, 2003. This cross section was not surveyed again until June 10, 2014, (11 years later) when the thalweg elevation was 1,912.7 m, 0.3 m higher than the thalweg elevation on June 10, 1997.

XS1100 Narrative

The channel width at the location of cross section 1100 is the narrowest within the primary study reach from the mouth of Spring Creek to the gage 20 m upstream from XS1450. A net erosion of 4 m^2 in cross-sectional area was measured in this cross section after the extreme flood on July 12, 1996 (about 510 m^3/s) to October 21, 2014 (fig. 5). Initially, the cross section aggraded rapidly to a maximum elevation around October 1997. The thalweg elevation then decreased from 1,916.2 m on October 5, 1997, to 1,915.5 m on October 21, 2014 (fig. 43). Erosion left no remnants of sediment deposits from most of the major floods except the flood on July 29, 1999 (blue polygon in figure 43).

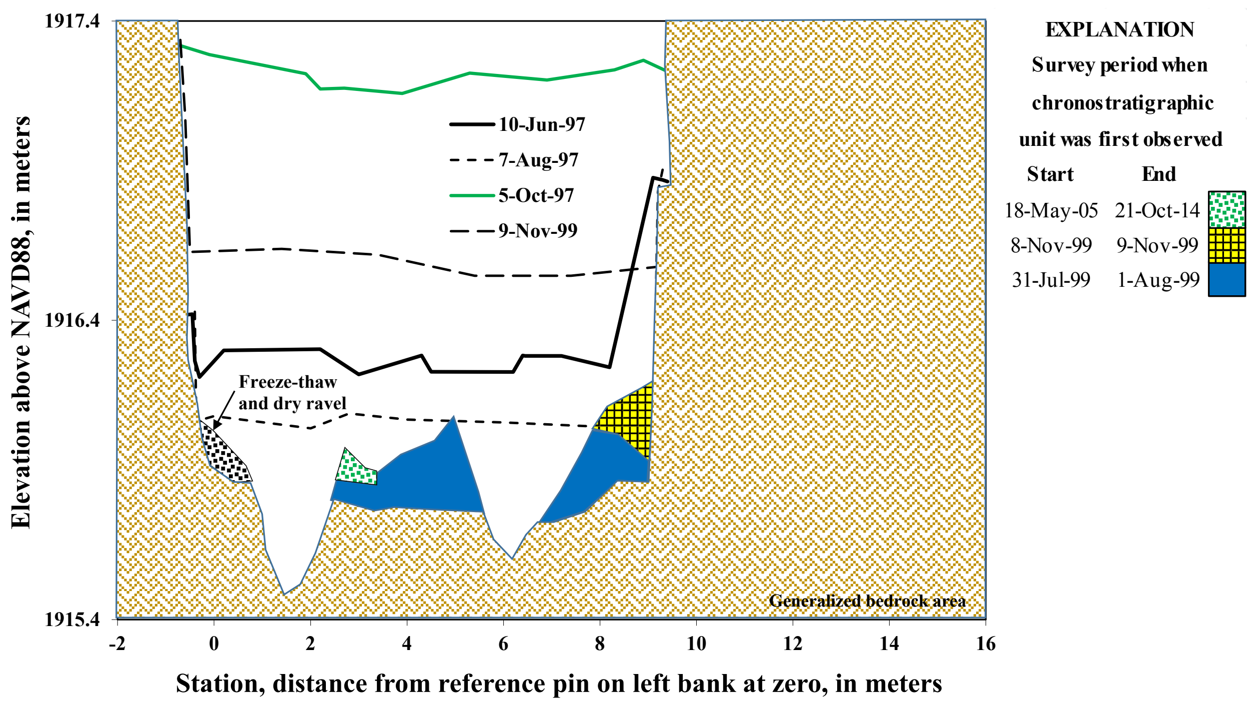

Figure 43. Preservation plot for cross section 1100 (XS1100). Vertical exaggeration is 6.2×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. The original reference pin at station -0.4 meter was buried by sediment. See Moody and Martin (2017, XSEC1100_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

Spring Creek at XS1100 alternated between a braided stream (fig. 44) and a single-thread stream (fig. 45). Major floods often filled the narrow channel with sediment, causing Spring Creek to take on a braided form. Steadier flow after the floods slowly eroded a channel. The chronostratigraphic unit shown as a yellow checkered polygon in figure 43 is a remnant of a braided-stream deposit from a major flood on August 4, 1999, and a series of eight minor floods from August 9 through September 10, 1999. Braided-stream deposits were observed to form when multiple threads of shallow water deposited bedload as levees. These levees caused flow paths to alter directions, leaving the deposits to accumulate (fig. 44). This unit was originally about 0.5 m thick, extended across the entire channel, and the top surface was the survey line dated 9–Nov–99 (long-dashed line in figure 43). As of 2014, the unit was only preserved along the right bank. Similar large units are found at XS0567, XS0755, XS0815, XS0905, and XS1200.

Figure 44. Photograph of the Spring Creek channel that includes the location of cross section 1100 (XS1100), 1997. Photograph was taken on September 15, 1997, looking downstream. The yellow dashed line indicates the approximate location of XS1100. J. Moody (1.9 meters tall) is standing on the truncated alluvial fan from tributary 1165. This photograph was taken by R. Meade when the deposition at XS1100 was at a maximum (green profile labeled 5–Oct–97 in figure 43).

Winter sediment deposits are notably absent at XS1100, as at XS1006 downstream. These frequently formed at other cross-section locations during the winter when the sediment filling the braided channel was frozen and, thus, cohesive (fig. 45). Sometimes, flow during the winter exceeded the capacity of small (0.2–1.0 m wide), shallow channels, and sediment-bearing water spread out from the small channels, deposited sediment on the surface, and refroze (figs. 13, 41,45). Sediment thicknesses were about 0.2–0.5 m. At the location of this cross section, the runoff during the winter incised a channel (fig. 45) sufficient in size to convey any winter discharge, and thus overbank deposition was not common.

Figure 45. Photograph of the Spring Creek channel that includes the location of cross section 1100 (XS1100), 1998. Photograph was taken on February 18, 1998, looking upstream. The yellow dashed line in the photograph indicates the approximate location of XS1100. An equatorially (south) facing hillslope is on the right side of the photograph. The sediment in the channel on the left side of the photograph is frozen (and cohesive) and therefore leaves a vertical bank when eroded by water. The maximum elevation was during October 1997 and the top of the sediment can be seen on the bedrock outcrop at the right edge of the photograph.

As willows recolonized the channel, the stream formed anabranching channels (fig. 46). Similar channels in Australia were described by Nanson and Huang (1999) but were dominated by a eucalyptus species rather than the willows seen here. Anabranching channels are also found at other cross-section locations at the upper end of the study reach (upstream from XS0567, for example at XS0679), and, less commonly, at the lower end of the study reach (from XS0567 downstream to the mouth).

Figure 46. Photograph of the Spring Creek channel that includes the location of cross section 1100 (XS1100), 2010. View is looking downstream and the water surface is about 1 m wide. The yellow dashed line indicates the approximate location of XS1100. The effects of vegetation trapping and armoring have produced an anabranching channel as the willows re-colonized the reach.

XS1200 Narrative

Cross section 1200 was measured about 20 m downstream from a substantial left-bank tributary to Spring Creek (basin area of 0.37 km^2). There was a net increase from 1996 through 2014 of about 8 m^2 in the cross-sectional area of accumulated sediment (fig. 5), some of which originated from the left-bank tributary. The incised alluvial fan from the tributary can be seen on the right edge of figure 47 and on the left side of figure 48*A*. This relatively large net deposition is anomalous to the general pattern of net change for Spring Creek, which showed a decrease in net deposition and some negative values (net erosion) upstream from a reach of maximum net deposition between XS0567 and XS1006 (fig. 5).

Figure 47. Photograph of the Spring Creek channel that includes the location of cross section 1200 (XS1200), 1998. Photograph was taken on May 3, 1998, looking upstream. The yellow dashed line indicates the approximate location of XS1200. B. Barkett (about 1.7 meters tall) is standing near cross section 1230 where a left-bank tributary joins Spring Creek. The upstream end of the narrow terrace on the right bank of XS1200 can be seen abutting the bedrock outcrop at the left center of the photograph.

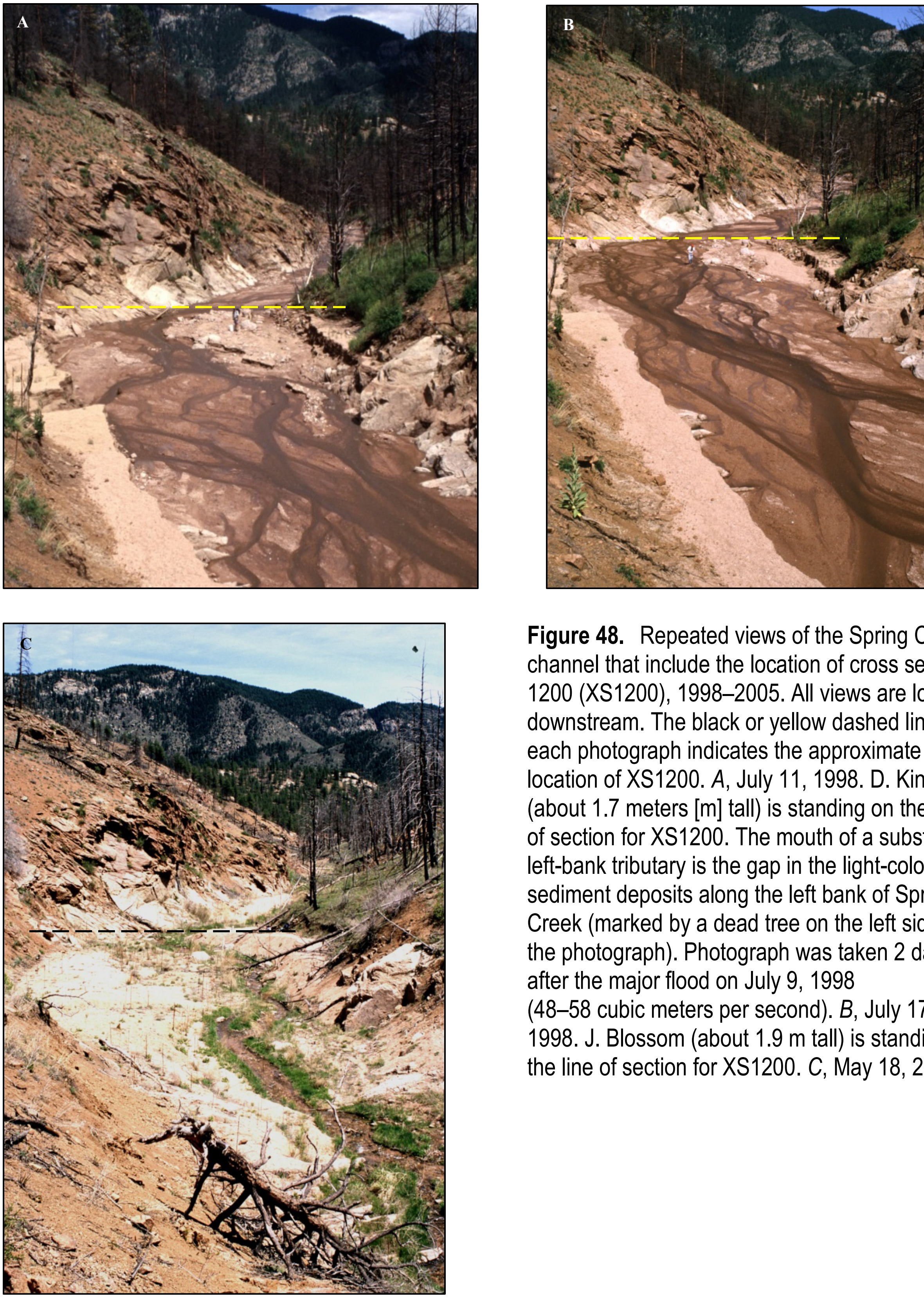

Figure 48. Repeated views of the Spring Creek channel that include the location of cross section 1200 (XS1200), 1998–2005. All views are looking downstream. The black or yellow dashed line in each photograph indicates the approximate location of XS1200. *A*, July 11, 1998. D. Kinner (about 1.7 meters [m] tall) is standing on the line of section for XS1200. The mouth of a substantial left-bank tributary is the gap in the light-colored sediment deposits along the left bank of Spring Creek (marked by a dead tree on the left side of the photograph). Photograph was taken 2 days after the major flood on July 9, 1998 (48–58 cubic meters per second). *B*, July 17, 1998. J. Blossom (about 1.9 m tall) is standing on the line of section for XS1200. *C*, May 18, 2005.

Chronostratigraphic units are generally irregular in shape as a result of erosion of the original deposit. A good visual example is the unit associated with the major floods on July 29 and 31, 1997 (wavy-line polygon in figure 49) and the unit associated with the combined floods on August 26 and 31, 1997 (black polygon in figure 49), both of which have been segmented by channel incision. The channel responsible for this was later filled by a unit from the major flood on July 16, 2000 (red polygon in figure 49). The magnitude of deposition and erosion can be quite large. This is best illustrated by the green survey line labeled 5–Oct–97 in figure 49 that indicates the elevation of the combined flood deposits from the August 26 and 31, 1997, floods, which was about 1.5 m above the previous survey on August 7, 1997. This was subsequently eroded, leaving only the remnant black polygons shown in figure 49 and a left-bank channel near station 4.

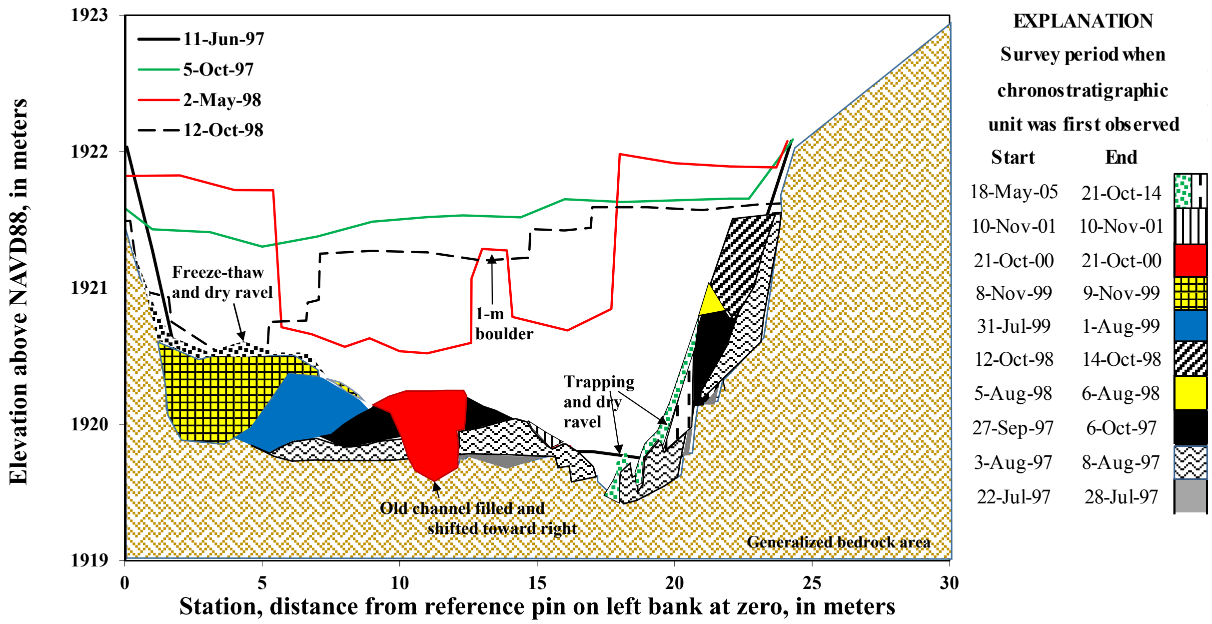

Figure 49. Preservation plot for cross section 1200 (XS1200). Vertical exaggeration is 4.1×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC1200_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

The flood on July 29, 1999, deposited sediment (blue polygon in figure 49) alongside the right margin of the channel that existed near station 4 and formed a secondary channel near station 12. This secondary channel became the main channel when a chronostratigraphic unit filled the channel near station 4 (yellow checkered polygon in figure 49). This unit consists of braided-stream deposits from one of the smaller major floods on August 4, 1999, (1.2 m^3/s) and a series of eight minor floods from August 9 through September 10, 1999. Braided-stream deposits were observed to form when multiple threads of shallow water (fig. 48*A, B*) deposited bedload as levees. These levees caused flow paths to alter directions, leaving the deposits to accumulate. Similar sediment deposits from this time period are preserved at XS0567, XS0755, XS0815, and XS0905, but are absent downstream from XS0567.

The 1-m-diameter boulder (fig. 49) was on the line of section on May 2, 1998, and was transported and deposited by the extreme flood on August 31, 1997 (140–180 m^3/s). It was not present during the survey on August 7, 1997, previous to the flood. It was gone after the flood on July 9, 1998. Although relatively large, a 1-m-diameter boulder can be easily transported by rolling when the bed is relatively smooth (composed of mostly 2–4-mm-diameter gravel, fig. 50) (Wiberg and Smith, 1987). A similar transport of a boulder probably happened at XS-2.7, emplacing the large boulder noted near station -3 in figure 6. Incision at XS1200 revealed apparent stratigraphic layers (fig. 50), but these layers were only continuous for short distances of about 1–5 m.

Figure 50. Photographs of the right-bank flood deposits near the location of cross section 1200 (XS1200), 1998. *A*, April 15, 1998. The layers appear continuous in this photograph over several meters but often are not continuous over distances of tens of meters. These sediment deposits were exposed after the major flood on August 31, 1997 (140–180 cubic meters per second [m^3/s]). *B*, October 21, 1998. View is looking upstream at flood deposits (in the right bank at XS1230) exposed by the major flood on July 31, 1998 (about 82 m^3/s). Yellow, level book is 19 centimeters (cm) tall and 12 cm wide.

Revegetation of the location of cross section 1200 has not been as dramatic as that in the deposition reach between XS567 and XS1100. The braided character (fig. 48*A*, *B*) has evolved into a single-thread channel with primarily grass along the channel margins (fig. 48*C*). The thalweg elevation of this single-thread channel in June 2014 (1,919.5 m) was 0.2 m higher than the thalweg in 1997 after the extreme flood on July 12, 1996 (about 510 m^3/s) (fig. 49).

Figure 51. Photograph of the Spring Creek channel that includes the location of cross section 1200 (XS1200), 1998. Photograph was taken on July 2, 1998, looking upstream. The black dashed line indicates the approximate location of XS1200. Yellow tripod is 1.5 meters tall.

XS1340 Narrative

Cross section 1340 was measured in a narrow, bedrock-dominated reach of Spring Creek extending from 1,240 m to 1,470 m upstream from the confluence of Spring Creek with the South Platte River. Little sediment was preserved within this bedrock reach from June 1997 through June 2014 (fig. 52). Initially, sediment was deposited by the extreme flood on July 12, 1996, (about 510 m^3/s) along the right bank, and by June 2014 there had been a net erosion of about 2.5 m^2 of cross-sectional area (fig. 5).

Figure 52. Photograph of incised bedrock about 10 meters upstream from the location of cross section 1340 (XS1340), 2010. This photograph taken on May 8, 2010, shows the characteristics of a relatively narrow, bedrock-dominated reach of Spring Creek between about XS1240 and XS1450, which is near the streamgage. A small colony of cattails is located at left-center of the photograph.

At XS1340, the deposited sediment volume reached a maximum in the fall of 1997 (red line labeled 5–Oct–97 in figure 53), which is similar to the timing observed at XS1200 and XS1100 downstream. Thereafter, most of the chronostratigraphic units deposited by major floods were eroded and not preserved. The first big incision and removal of sediment was after the flood on July 31, 1998, and later, during the flood on July 29, 1999. By November 9, 1999, the thalweg elevation (1,926.1 m) was at a minimum and remained essentially unchanged until September 23, 2014. Only the flood deposits from the major floods on July 29, 1999, (blue polygon in figure 53) and on July 16, 2000, (red polygon in figure 53) are preserved at the location of this cross section.

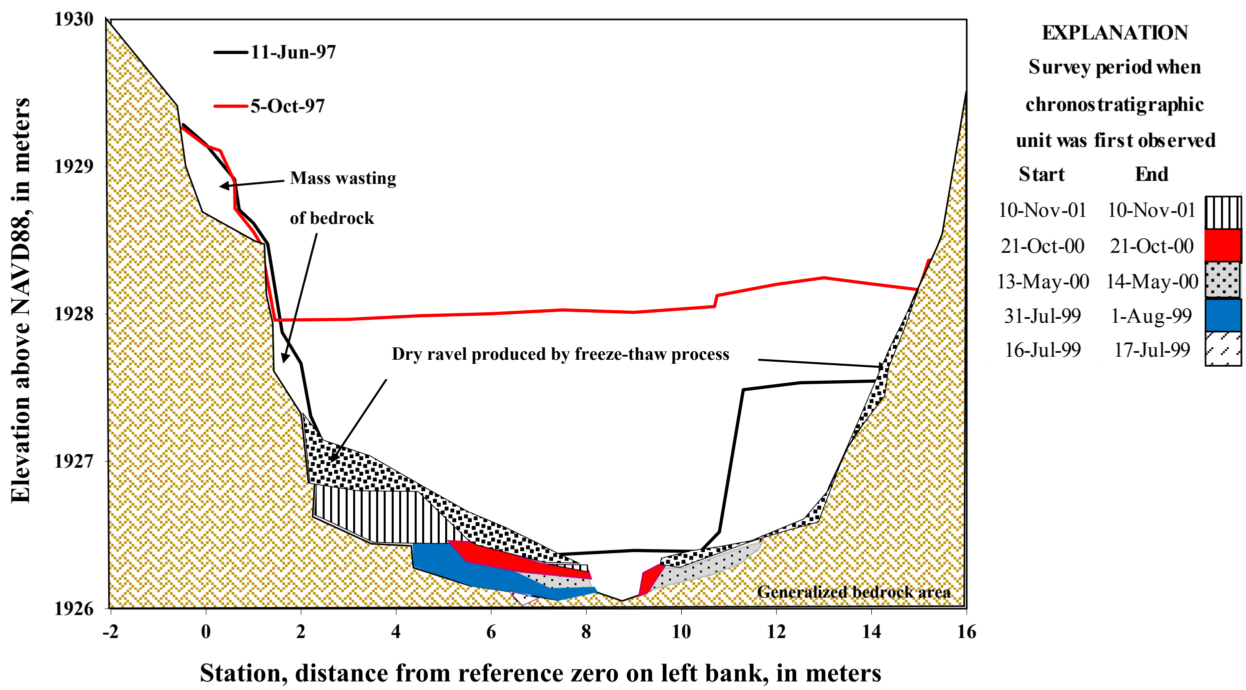

Figure 53. Preservation plot for cross section 1340 (XS1340). Vertical exaggeration is 3.1×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC1340_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

The chronostratigraphic unit represented by grey densely stippled polygons in figure 53 consists of winter and braided-stream deposits left after the earlier survey on November 9, 1999. Frequently during the winter, sediment filling the braided channel became frozen and, thus, cohesive. Sometimes flow during the winter exceeded the capacity of small (0.2–1.0 m wide), shallow channels, and sediment-bearing water spread out from the small channels, deposited sediment on the surface, and refroze (figs. 13, 41, 45). Braided-stream deposits were observed to form when multiple threads of shallow water (fig. 54*A*) deposited bedload as levees. These levees caused flow paths to alter directions, leaving the deposits to accumulate.

Figure 54. Repeated views of the Spring Creek channel that include the location of cross section 1340 (XS1340), 1998–2005. Both views are looking upstream. The red dashed line indicates the approximate location of XS1340. The yellow arrow points to the same boulder in both photographs. *A*, July 17, 1998. Channel contains a braided stream. *B*, May 18, 2005. Channel contains a single-thread stream.

In this narrow reach, the hillslopes adjacent to the channel are steep and some sediment deposits at XS1340 were derived from the hillslope by the processes of dry ravel (Anderson and others, 1959; Gabet, 2003; Roering and Gerber, 2005), freeze-thaw during winter, and some overland flow (fig. 55). This type of chronostratigraphic unit made up a substantial accumulation at XS1340 after about 2000 (black irregularly stippled polygon in figure 53). The freeze-thaw component was observed in the winter when the equatorially (south) facing hillslope thawed in the morning light and sand and gravel was released to roll downslope. The overland flow component was in response to rainfall that caused a minor flood on August 31, 2001 (0.24 m^3/s).

Figure 55. Hillslope fan between the locations of cross section 1340 (XS1340) and XS1450, 2001. The sediment in the fan was deposited in the bedrock channel by dry ravel during the summer, by the freeze-thaw process during the winter, and some hillslope runoff after a rain storm on August 13, 2001. L. Pine is about 1.8 meters (m) tall. This site is about 20 m upstream from XS1340 where similar hillslope processes were observed.

XS1450 Narrative

Cross section 1450 was measured at the upstream end of a narrow, bedrock-dominated reach of Spring Creek extending from 1,240 m to 1,470 m upstream from the confluence of Spring Creek with the South Platte River (fig. 56). Sediment was not preserved within this part of the bedrock reach from May 1998 through June 2014. Deposition during the extreme flood on July 12, 1996, (about 510 m^3/s) was minimal, as shown in the photograph in figure 56, which was taken 4 months after the flood. The first cross-section survey was on May 3, 1998, after seven major floods in 1997 that ranged from 1.15 to 140–180 m^3/s.

Figure 56. Spring Creek gage site, 1996–2001. *A*, November 6, 1996. View is looking upstream. G. O'Neil (about 1.7 meters [m] tall) is standing at the future location of the streamgage that was operational in April 1997. The site is about 20 m upstream from XS1450, which is also within the narrow (about 10 m wide) bedrock reach. The extreme flood (about 510 cubic meters per second) was on July 12, 1996. *B*, April 6, 2001. View is looking downstream at the gage site just beyond the fallen tree where D. Martin (about 1.7 m tall) is standing. The bed and banks through this reach are bedrock. The yellow arrow points to the gage house.

The only chronostratigraphic unit from a major flood that has been preserved is from the flood on July 16, 2000 (red polygon in figure 57). This rests on top of a chronostratigraphic unit deposited during the winter of 1999-2000 (grey densely stippled polygon in figure 57) when sediment filling the braided channel was frozen, that is, cohesive. Sometimes flow during the winter exceeded the capacity of small (0.2–1.0 m wide), shallow channels, and sediment-bearing water spread out from the small channels, deposited sediment on the surface, and refroze (figs. 13, 41, 45).

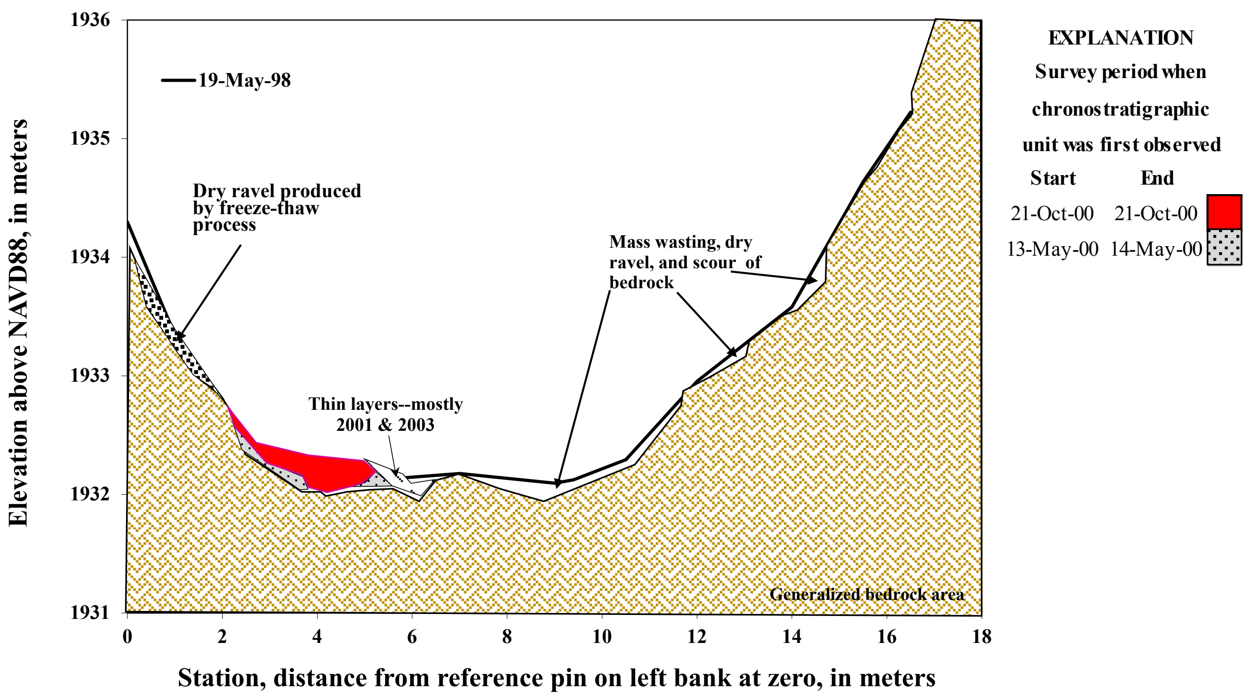

Figure 57. Preservation plot for cross section 1450 (XS1450). Vertical exaggeration is 2.5×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC1450_SciBase.xlsx) for survey data. Thick line indicates the cross-section profile on the given date. NAVD88 is the North American Vertical Datum of 1988.

The thalweg elevation at XS1450 has remained essentially constant (1,932.0 m) varying only 0.1 m over a period of 16 years. This is reflected in the net change, which was essentially zero with only the deposition of <1 m^2 (fig. 5), most of which is from the July 16, 2000, flood mentioned above. This cross section would best be characterized as having been measured in a transport section in which sediment neither eroded nor aggraded (fig. 57).

XS4850 Narrative

Cross section 4850 was measured in the most upstream location of all the cross sections (fig. 1*B*, 58, 59) and was selected to monitor the depletion of the original sediment deposited by the extreme flood on July 12, 1996, (about 510 m^3/s) in the headwater of Spring Creek. It is located about 3,400 m upstream from the streamgage site (near XS1450), The first survey was on July 18, 1998, and this cross section was not resurveyed as frequently as the other cross sections downstream (only 7 times), Thus, the initial profile also includes the deposition from seven major floods in 1997 and one major flood in 1998 as a single chronostratigraphic unit. The discharges of these eight major floods ranged from 1.15 to 140–180 m^3/s at the gage downstream.

Figure 58. Photograph of the Spring Creek channel that includes the location of cross section 4850 (XS4850), 2014. Photograph was taken on June 22, 2014, looking downstream from the top of a bedrock outcrop. This nearly vertical bedrock outcrop extends across the channel (about 20 meters upstream from XS4850) and forms a waterfall when Spring Creek is flowing. The nearly flat surface composed of bare sand and gravel seen in this photograph begins at the base of the bedrock outcrop. Most of the burned trees that were once upright have fallen down.

Figure 59. Photographs of the two ends of cross section 4850 (XS4850), 2014. *A*, View shows the area around the zero reference pin on June 22, 2014. The zero pin is located at the base of the bedrock outcrop to the left center of the photograph. *B*, View shows the location of the right bank reference pin. The reference pin is near the left foot of J. Smith (about 1.6 meters tall).

The chronostratigraphic unit represented by the green crosshatched polygon in figure 60 is the result of four fluvial depositional processes. One process is during major floods on July 31, 1998 (82 m^3/s downstream at the gage) and July 29, 1999 (6.4 m^3/s downstream at the gage). A second is deposition during the winter. Frequently during winter, sediment filling the braided channel was frozen and, thus, cohesive. Sometimes flow during the winter exceeded the capacity of small (0.2–1.0 m wide), shallow channels, and sediment-bearing water spread out from the small channels, deposited sediment on the surface, and refroze (figs. 13, 41, 45). A third process is deposition under braided-stream conditions, which occurred at XS4850 through August 1, 1999 (see nearly horizontal green profile line in figure 60 that shows no incised channel). Braided-stream deposits were observed at the location of other cross sections to form when multiple threads of shallow water deposited bedload as levees. These levees caused flow paths to alter directions leaving the deposits to accumulate (for example, see figs. 21*A*, *B*, 36, 48*A*, *B*). Finally, a fourth process is when surface water, transporting bedload, percolates into the sediment leaving behind stranded bedload particles, which with time can accumulate into relatively large deposits (figs. 26, 27).

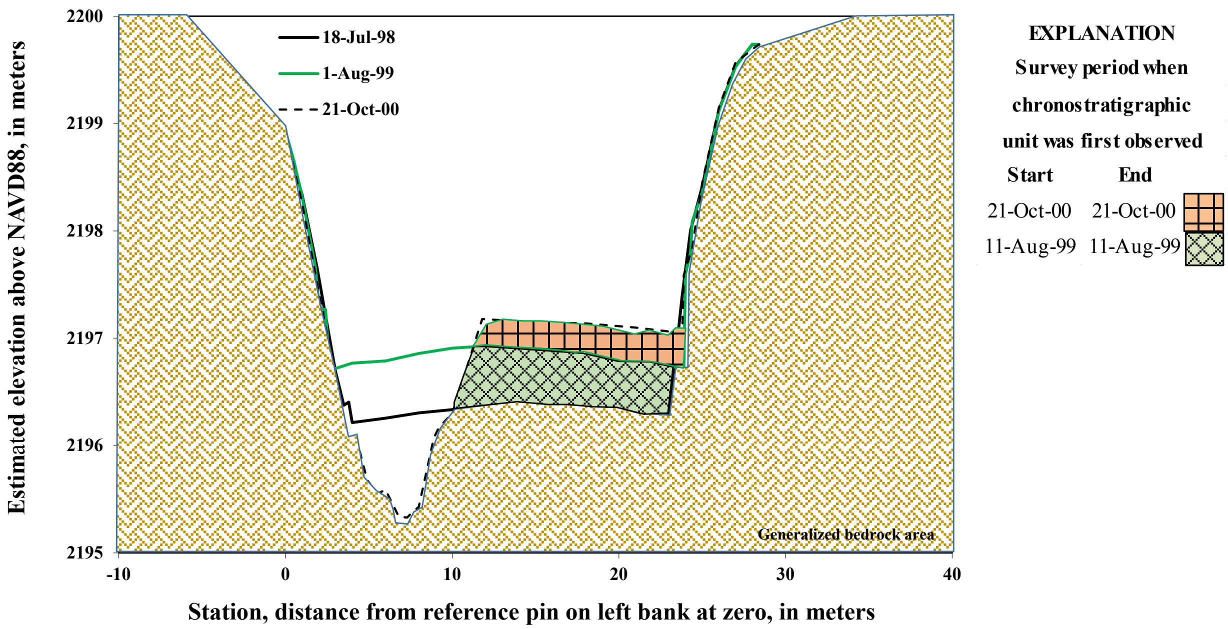

Figure 60. Preservation plot for cross section 4850 (XS4850). Vertical exaggeration is 6.4×. Each chronostratigraphic unit may have originally had a larger cross-sectional area that has since been reduced in size by subsequent erosion. See Moody and Martin (2017, XSEC4850_SciBase.xlsx) for survey data. Thick lines indicate the cross-section profile on the given date.

The chronostratigraphic unit represented by the orange checkered polygon in figure 60 is the result of a similar composite of fluvial depositional process, which created a terrace that is about 2 m above the water level. Two major floods (August 4, 1999, 1.2 m^3/s; and July 16, 2000, 4.6 m^3/s) were recorded downstream at the gage; however, it is not known if there were floods at the location of this cross section. Incision along the left bank at XS4850 began sometime after

August 1, 1999, and is shown by the profile measured on October 21, 2000 (dashed line in figure 60). The cross-sectional profile remained unchanged thereafter for the next four surveys (October 25, 2001; September 21, 2002; June 14, 2005; and June 22, 2014). The estimated thalweg elevation in June 2014 (2,195.2 m) was 1.1 m lower than the original thalweg elevation surveyed in 1998 (fig. 57).

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Appendix 1. Universal Transverse Mercator (UTM) Coordinates for Cross Sections in Spring Creek

[XS, cross section; LB, left bank; RB, right bank; pin, 1/2-inch steel rebar about 1.2 m long; m, meter; NAD83, North American Datum 1983; NAVD88, North American Vertical Datum 1988. Cross section 4850 was not tied into this coordinate system because of its large separation distance from the other 17 cross sections, and therefore data from cross section 4850 are estimates]

Cross-section number	Channel bank	Station (m)	Marker	UTM coordinates (NAD83) North (m)	UTM coordinates (NAD83) East (m)	NAVD88 Elevation (m)
XS-2.7	RB	40.5	pin	4359974.1	485331.1	1876.00
XS0100	LB	0.0	pin	4360104.4	485332.1	1879.45
XS0100	RB	38.7	pin	4360087.2	485297.6	1880.16
XS0187	LB	0.0	pin	4360182.8	485284.9	1882.35
XS0187	RB	35.3	pin	4360158.4	485259.7	1884.31
XS0250	LB	0.0	pin	4360218.0	485237.0	1885.38
XS0250	RB	32.9	pin	4360204.3	485207.2	1885.89
XS0341	LB	0.0	pin	4360302.3	485186.2	1889.23
XS0341	RB	44.9	pin	4360268.4	485157.0	1889.29
XS0393	LB	0.0	pin	4360329.5	485132.8	1890.13
XS0393	RB	40.5	nail	4360292.0	485117.5	1891.55
XS0483	LB	0.0	pin	4360363.5	485055.3	1894.14
XS0483	RB	43.8	pin	4360328.6	485028.8	1895.25
XS0567	LB	0.0	pin	4360406.5	484973.1	1896.94
XS0567	RB	33.4	pin	4360373.3	484969.5	1898.45
XS0679	RB	24.7	pin	4360396.2	484855.6	1902.85
XS0755	LB	0.0	pin	4360438.3	484796.1	1906.35
XS0755	RB	34.0	pin	4360405.2	484787.8	1905.82
XS0815	LB	0.0	pin	4360448.5	484739.5	1908.20
XS0815	RB	25.5	pin	4360424.3	484732.2	1909.09
XS0905	LB	0.0	pin	4360478.1	484649.2	1910.55
XS0905	RB	24.9	pin	4360453.5	484653.3	1911.94
XS1006	LB	0.0	pin	4360472.3	484550.9	1914.67
XS1006	RB	18.9	pin	4360453.8	484549.4	1914.92
XS1100	RB	9.0	nail	4360475.1	484457.2	1916.40
XS1200	LB	0.0	pin	4360516.7	484362.3	1922.09
XS1200	RB	24.2	pin	4360492.6	484361.9	1922.34
XS1340	LB	–0.5	nail	4360481.3	484227.7	1929.32
XS1340	RB	15.5	pin	4360465.5	484229.7	1928.48
XS1450	LB	0.0	pin	4360439.7	484124.1	1934.97
XS1450	RB	14.0	nail	4360424.6	484130.7	1935.90
XS4850	LB	0.0	pin	4359060.7	481413.4	2094
XS4850	RB	28.0	pin	4359039.3	481421.5	2096