Prepared in cooperation with the National Park Service

Resurvey of Cross Sections on the Green River in Browns Park, Colorado and Utah

Open-File Report 2026–1013

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

Cover: Green River looking downstream towards the Gates of Lodore, taken at the Green River above Gates of Lodore streamgage (U.S. Geological Survey streamgage 404417108524900). Photograph by David Topping, U.S. Geological Survey.

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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.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
metric ton (t)	1.102	ton, short [2,000 lb]
metric ton (t)	0.9842	ton, long [2,240 lb]
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)

Datums

Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88) orthometric elevation modeled from GEOID12b.

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83) (2011).

Supplemental Information

A water year is the 12-month period from October 1 through September 30 of the following year and is designated by the calendar year in which it ends.

Abbreviations

~	about
D_{50}	average median grain size
GPS	Global Positioning System
GNSS	global navigation satellite system
LRE	local relative elevation
NGSPID	National Geodetic Survey Permanent Identifier
NSRS	National Spatial Reference System
p	limit of significance
r	correlation coefficient
RTK	real-time kinematic
USGS	U.S. Geological Survey

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Abstract

This study resurveyed 10 previously established cross sections and established 8 new cross sections on the Green River in Browns Park, Colorado and Utah, to document changes in channel width, depth, and area since earlier surveys conducted in 1994 and 1999. The measured area of the channel cross sections on the Green River in Browns Park generally increased between the 1994 surveys and 2019. This increase in cross-sectional area was observed in 9 of the 10 resurveyed cross sections and is indicative of net sediment erosion. The increase in cross-sectional area occurred through channel widening (bank retreat) and increases in depth (bed incision). An analysis of the contribution of bank versus bed changes to the overall area change indicates that the erosion is mostly from the bed of the channel. In addition, weak longitudinal trends in the bed-sand grain-size distribution are consistent with progressive depletion of the sand stored on the bed of the Green River in Browns Park. The findings from our cross-section resurvey support the conclusion that the Green River in Browns Park is experiencing progressive sediment loss and is in a state of sediment deficit.

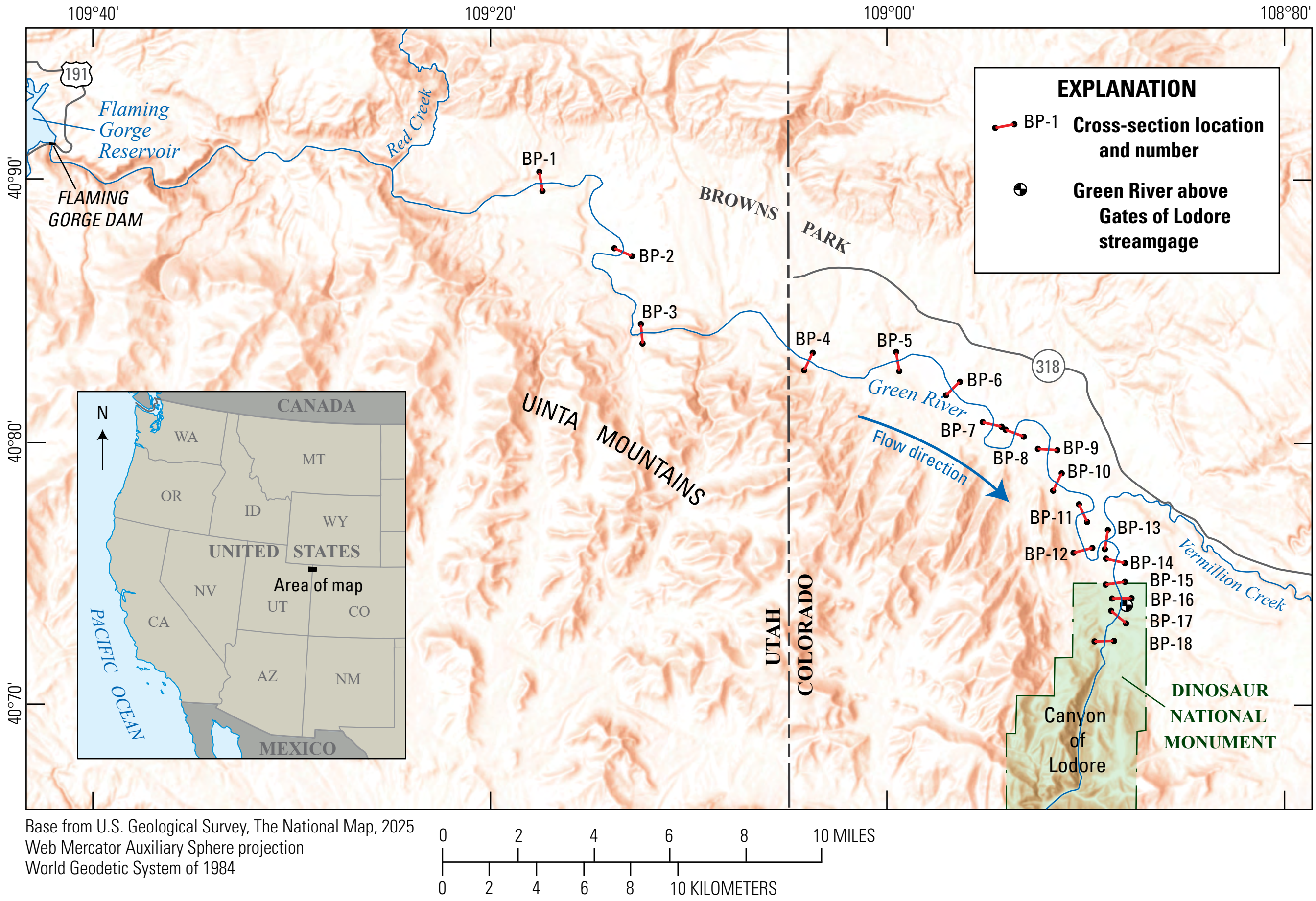
Introduction

Since its gates closed in December 1962, Flaming Gorge Dam has considerably altered the flow and sediment regime of the Green River downstream from the dam. Although the dam did not substantially affect the mean annual discharge, it reduced the magnitude and frequency of peak flows that had historically maintained a wider channel while increasing the magnitude of base flows (Andrews, 1986; Merritt and Cooper, 2000). The dampened flood regime enabled rapid establishment of riparian vegetation within the formerly active channel, contributing to channel narrowing (Merritt and Cooper, 2000; Grams and Schmidt, 2005). By trapping all sediment supplied from upstream within the reservoir, Flaming Gorge Dam has also greatly reduced the sediment supplied to the Green River downstream from the dam (Andrews, 1986; Grams and Schmidt, 2005; Topping and others, 2018).

After construction of Flaming Gorge Dam, the only sediment available for transport by the Green River downstream from the dam is the sediment supplied by tributaries and that stored in alluvial reaches of the Green River. Red Creek enters the Green River about (~) 15 kilometers (km) downstream from Flaming Gorge Dam and is the first source of sediment downstream from the dam (fig. 1). Approximately 3 km downstream from Red Creek, the Green River enters Browns Park, a predominantly alluvial broad valley that is the first source of stored alluvial sediment downstream from Flaming Gorge Dam (fig. 1). Browns Park and the tributaries of Red Creek and Vermillion Creek are the only major sources of sediment for the Green River farther downstream in the Canyon of Lodore within Dinosaur National Monument. Vermillion Creek enters the Green River in the lower section of Browns Park ~72.5 km below Flaming Gorge Dam (fig. 1).

The status of the sediment budget in Browns Park, whether in surplus or deficit, has been the subject of a number of studies and is a component of an ongoing U.S. Geological Survey (USGS) sediment monitoring project. Although researchers agree that Flaming Gorge Dam greatly altered the Green River's sediment regime by severely reducing sediment supply, they have reached differing conclusions on whether the reach is experiencing sediment surplus or deficit in the postdam era. Several researchers have concluded that the Browns Park reach is in sediment deficit. Andrews (1986) concluded that the Green River upstream from the Yampa River confluence was in sediment deficit. From aerial photographs, Andrews (1986) determined that the bankfull channel narrowed by ~10 percent between 1951 and 1980. Channel narrowing typically indicates sediment deposition and surplus; however, Andrews (1986) estimated the bankfull channel depth decreased by 2.4 feet postdam on the basis of stage-discharge relations computed using bankfull channel width measured from aerial photos predam and postdam and hydraulic geometry relations. Using the 35.4 km of alluvial channel in Browns Park, this channel bed erosion would equate to ~8.6 million metric tons of sand eroded, most likely between 1962 and 1980 (Andrews 1986). Schmidt and Wilcock (2008) also determined the reach was in sediment deficit on the basis of predam and postdam changes in flow and sediment supply; however, Schmidt and Wilcock (2008) did not indicate that incision was likely in the Browns Park reach.

Other research has not provided evidence of sediment deficit for the Green River in Browns Park. Merritt and Cooper (2000), studying a ~2 km long reach in lower Browns Park using aerial photographs, documented a complex sequence of channel changes in Browns Park, including channel narrowing followed by bank erosion and the emergence of mid-channel sand deposits. Merritt and Cooper (2000) proposed that these changes were driven by the interplay of reduced peak flows, bank erosion supplying



Base from U.S. Geological Survey, The National Map, 2025
Web Mercator Auxiliary Sphere projection
World Geodetic System of 1984

Figure 1. Schematic map showing the study site and locations of the surveyed cross sections on the Green River in Utah and Colorado. Cross-section data from Griffiths and others (2026).

sediment, and the establishment of vegetation influencing channel morphology. Merritt and Cooper (2000) predicted further bank erosion, with the sand supplied by future bank retreat not being transported out of Browns Park but supplying additional mid-channel sand deposits. The predicted net result was a reduction in the active channel area. Grams and Schmidt (2005) observed from aerial photographs and analysis of channel change at two former U.S. Geological Survey (USGS) streamgages and discovered channel narrowing in nearly all reaches within the first 104 km downstream from Flaming Gorge Dam. This channel narrowing was attributed to sediment accumulation of postdam sediment inputs, erosion and redeposition of sediment from predam terraces, an increase in size of existing vegetated islands, and formation of new islands. On the basis of bed-elevation comparisons with predam elevations, Grams and Schmidt (2005) found no evidence of widespread channel incision and concluded that the sediment budget was “indeterminate” rather than in deficit. This conclusion was based on their finding that the mass of accumulated sediment in the reach was within the margin of error of their sediment-budget calculations.

More recently, the USGS Grand Canyon Monitoring and Research Center began continuous 15-minute sediment-transport monitoring at the USGS Green River above Gates of Lodore, Colorado, streamgage 404417108524900 (USGS streamgage 404417108524900; also referred to as the Lodore streamgage) on the Green River near the downstream terminus of Browns Park. The monitoring equipment was tested at this streamgage in July 2012 and installed in October 2012. This streamgage is part of a continuous sediment-transport monitoring network on the Little Snake, Yampa, and Green Rivers to study sediment transport and inform National Park Service resource managers (Topping and others, 2018). Data from this network are available at https://www.gcmrc.gov/discharge_qw_sediment/. Topping and others (2018), using sand loads from the Lodore streamgage as the export from the Browns Park sediment budget and estimates from the historical USGS sediment records of Red and Vermillion Creeks as the inputs to the Browns Park sediment budget, determined that mean-annual sand export from Browns Park exceeded the estimated inputs during water years 2013–16 by between a factor of 1.2 and 4.4, leading them to conclude that the long-term mean-annual sand budget for Browns Park is negative.

Most previous studies relied on aerial photographs to determine the channel widths and, from that, infer the state of the Browns Park sediment budget. Although this approach allows for a much greater spatial resolution because changes can be measured along the entire channel length, the aerial photography method poses problems when inferring sediment budgets. Most importantly, sediment budgets calculated from these methods only include changes in floodplain sediment storage that result from the conversion of floodplain to active channel or active channel to floodplain. Erosion or deposition from the channel bed cannot be measured by repeat aerial images. In addition, there could be a bias towards floodplain deposition that arises because large regions of deposition are more easily detected than thinner slivers of potentially much thicker regions of bank erosion (fig. 2). Hence, a region of floodplain deposition can be easily identified in an aerial photograph, especially after colonization by vegetation, whereas a region of cut-bank erosion may not be detected unless bank retreat exceeds the spatial resolution of the image. Another fundamental problem of the aerial photography method is that the area of floodplain erosion or deposition measured by repeat images must be converted to a volume by estimating the thickness of floodplain deposition and bank retreat. For example, figure 2*A* depicts a stable channel (no lateral migration or vertical change) in a reach in sediment equilibrium. The lateral migration of the channel in figure 2*A* will result in cut-bank erosion and an equal cross-sectional area of bar or floodplain deposition, shown in figure 2*B*. Under equilibrium conditions, the thickness of the cross-sectional area of cut-bank erosion will exceed that of bar or floodplain deposition, but the width of the cross-sectional area of cut-bank erosion will be much smaller than that of deposition.

The common use of vegetation to delineate the edges of active river channels in aerial photographs can cause problems interpreting sediment budgets because changes in the active

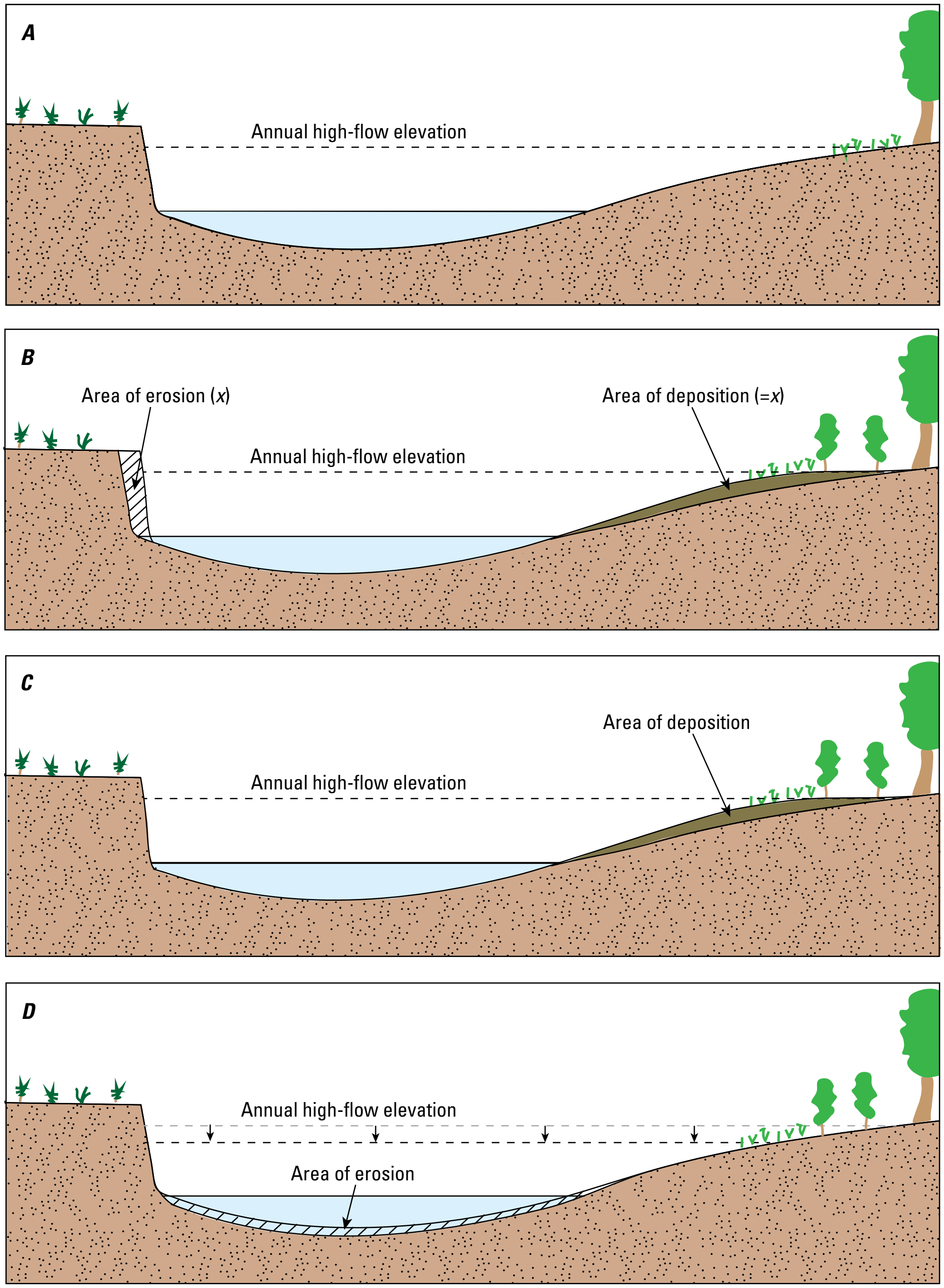


Figure 2. Idealized cross sections showing (*A*) a stable channel with no change in sediment storage; (*B*) channel change in a reach with the sediment budget in equilibrium, such that the quantity of sediment eroded from the cut bank on the left (*x*) is equal to the quantity of sediment deposited on the accreting floodplain; (*C*) potential channel change in a reach in sediment surplus; and (*D*) possible channel change in a reach in sediment deficit.

channel width may not correlate to changes in the cross-sectional area of the channel. Additionally, changes in the active channel bed elevation cannot be detected using traditional aerial photograph analysis. These channel bed elevation changes may occur when the annual flood stage decreases from reduced flood peaks, channel bed incision, or, as is likely in the case of Browns Park, a combination of these two processes. In the case of channel bed incision with no change in annual flood stage, vegetation can expand into the higher abandoned regions of the channel, even without sediment deposition, thereby creating an appearance in aerial photographs identical to that in figure 2*C*. In the case of bed incision combined with reduced annual flood stage, this effect is exacerbated (fig. 2*D*). Although the example depicted in figure 2*D* would be correctly interpreted in an analysis of aerial photographs as active channel narrowing, it would then mistakenly be classified as a reach in sediment surplus when the quantity of sediment stored in the cross section has actually decreased. To help determine the state of the sediment budget of the Green River in Browns Park and to determine where in the channel sediment is being deposited or eroded, we resurveyed 10 cross sections first surveyed in 1994. This report includes the results of our cross-section resurvey and provides an update to the Browns Park sediment budget described in Topping and others (2018).

Purpose and Scope

The purpose of this report is to document the changes in width, depth, and cross-sectional area of previously established cross sections on the Green River in Browns Park. Additionally, new cross sections were surveyed in reaches of the Green River in Browns Park that lacked cross sections and can serve as a benchmark condition for future repeat surveys. All cross-section endpoints were documented using modern Global Positioning System (GPS) measurements so that future researchers may easily replicate these surveys. The scope of this report is limited to changes in width, depth, cross-sectional area, and resulting sediment budget of the Green River in Browns Park.

Previous Surveys of Cross Sections in Browns Park

The cross sections in Browns Park were established to characterize the channel geometry and establish long-term monitoring sites (table 1). The cross sections were established and first surveyed in April (Grams, 1997) and October (Grams and others, 2002) of 1994. Endpoints of these cross sections were monumented with rebar (Grams and others, 2002) and (or) with T-posts (Grams, 1997) and documented with photographs. The endpoint monuments served as local elevation control during the initial and subsequent surveys completed prior to our study. The cross sections were surveyed using a Kevlar tag line suspended between the two endpoints, and a total station and survey rod were used to survey position and surface elevation along the tag line. In areas that were too deep to be waded, a depth-recording echo sounder (fathometer) was used in place of the survey rod to determine the depth to the channel bed.

The Grams and others (2002) study established eight cross sections on the segments of the Green River in Red Canyon and what they termed “Upper Browns Park,” “Lower Browns Park I,” and “Lower Browns Park II;” they resurveyed the seven upstreammost cross sections in October 1999. Our study resurveyed the downstream four cross sections from the Grams and others (2002) study and named these cross sections BP-1 through BP-4, for Browns Park (table 1). Grams (1997) measured 67 cross sections spaced ~1 km apart farther downstream on the Green River, beginning near Vermillion Creek in lower Browns Park, extending through lowermost Browns Park and the Canyon of Lodore (fig. 1), and ending farther downstream. Our study resurveyed the six upstream cross sections of the Grams (1997) study and named these cross sections BP-13 through BP-18 (table 1). Three of the six cross sections we resurveyed from Grams (1997) had been previously resurveyed several times: BP-13 had no resurveys; BP-14 was resurveyed in June 1995, August 1995, and May 1997; BP-15 had no resurveys; BP-16 was resurveyed in August 1995; BP-17 had no resurveys; and BP-18 was resurveyed in June 1994, June 1995, August 1995, May 1996, August 1996, June 1997, and July 1997. Additionally, BP-18 was resurveyed in July 2004 (Grams and Schmidt, 2005).

Methods

We determined the approximate locations of previously surveyed cross-section endpoints using photographs, field notes, and locations marked on topographic maps. The exact locations of the endpoint monuments were determined using photographs and a magnetic detector; all monuments were located (table 1). The 2019 resurvey (Griffiths and others, 2026) was conducted from October 9–13, 2019, using the real-time kinematic (RTK) GPS with one permanent base station deployed at the Browns Park National Wildlife Refuge headquarters, one local base station moved between each cross section, and one rover. Local base-station control was established on a temporary benchmark, and the position of the base station was established using a National Geodetic Survey Online Positioning User Service solution. The monuments were surveyed, and the cross sections were then surveyed using the same RTK unit along the line defined by the monuments on each bank; a survey point was collected at the top and at the ground surface of each monument. The density of the survey points was dependent on the complexity of the terrain surveyed; points were surveyed at each break in slope and every 2–5 meters (m) in areas with no substantial topographic or bathymetric variability. Three of the cross sections had an additional center monument in line with the endpoints (table 1), which were likely established during the initial surveys in channel cross sections too wide for the tagline used to cross. During our 2019 resurvey, points greater than ~2 m in depth below the water

Table 1. Locations, top elevations, and descriptions of endpoint monuments for cross sections studied along the Green River in Browns Park in Utah and Colorado.

[L and R in cross-section endpoint names (BP-#) indicate left and right bank as seen by an observer in the middle of the river channel facing downstream. Locations are Global Positioning System (GPS) coordinates. Latitudes and longitudes reported in degrees north and west, respectively. m, meter]

Cross-section endpoint name	2019 Survey			Endpoint monument	Original study
	Latitude*	Longitude*	Top elevation (m)**		
BP-1L	40.899225	–109.176429	1,660.98	Wooden post with crossbar	Grams and others, 2002
BP-1R	40.898380	–109.176399	1,661.28	Rebar, possibly disturbed	Grams and others, 2002
BP-2L	40.872271	–109.133603	1,649.55	Rebar	Grams and others, 2002
BP-2R	40.872968	–109.134727	1,648.65	Rebar	Grams and others, 2002
BP-3L	40.841942	–109.123269	1,639.33	Rebar	Grams and others, 2002
BP-3R	40.841416	–109.123126	1,641.55	Rebar	Grams and others, 2002
BP-4L	40.830170	–109.036782	1,636.42	Rebar	Grams and others, 2002
BP-4R	40.829458	–109.037587	1,638.57	Rebar	Grams and others, 2002
BP-5L	40.832747	–108.991295	1,636.50	Rebar	Griffiths and others, 2026
BP-5R	40.829435	–108.989625	1,636.51	None	Griffiths and others, 2026
BP-6L	40.823851	–108.969029	1,635.03	Rebar	Griffiths and others, 2026
BP-6R	40.823033	–108.970661	1,635.27	None	Griffiths and others, 2026
BP-7L	40.807065	–108.945697	1,635.02	Rebar	Griffiths and others, 2026
BP-7R	40.807615	–108.948541	1,634.53	None	Griffiths and others, 2026
BP-8L	40.804309	–108.936557	1,633.85	Rebar	Griffiths and others, 2026
BP-8R	40.803362	–108.933984	1,633.85	None	Griffiths and others, 2026
BP-9L	40.798061	–108.916892	1,633.61	Rebar	Griffiths and others, 2026
BP-9R	40.798071	–108.919407	1,633.53	None	Griffiths and others, 2026
BP-10L	40.784545	–108.911462	1,632.97	Rebar	Griffiths and others, 2026
BP-10R	40.782273	–108.912349	1,633.04	None	Griffiths and others, 2026
BP-11L	40.772308	–108.899840	1,633.32	Rebar	Griffiths and others, 2026
BP-11R	40.773869	–108.900411	1,632.77	None	Griffiths and others, 2026
BP-12L	40.759490	–108.897069	1,632.32	Rebar	Griffiths and others, 2026
BP-12R	40.758320	–108.900421	1,632.01	None	Griffiths and others, 2026
BP-13L	40.762904	–108.888380	1,632.25	T-post	Grams, 1997
BP-13C	40.761830	–108.888539	1,631.68	Rebar	Grams, 1997
BP-13R	40.761112	–108.888640	1,632.38	T-post	Grams, 1997
BP-14L	40.754271	–108.883425	1,632.08	T-post, bad precision	Grams, 1997
BP-14C	40.754718	–108.885044	1,631.78	Rebar	Grams, 1997
BP-14R	40.755041	–108.886241	1,631.18	Rebar	Grams, 1997
BP-15L	40.746985	–108.882191	1,637.72	Rebar	Grams, 1997
BP-15C	40.746740	–108.883922	1,631.76	T-post	Grams, 1997
BP-15R	40.746359	–108.886596	1,632.67	T-post	Grams, 1997
BP-16L	40.740224	–108.880647	1,633.52	Rebar	Grams, 1997
BP-16R	40.740127	–108.882696	1,633.97	T-post	Grams, 1997
BP-17L	40.731694	–108.883477	1,630.47	T-post, damaged	Grams, 1997
BP-17R	40.732862	–108.885826	1,631.36	Rebar	Grams, 1997
BP-18L	40.724728	–108.888287	1,631.81	T-post	Grams, 1997
BP-18R	40.724669	–108.889711	1,630.50	T-post	Grams, 1997

*Decimal degree is referenced to the North American Datum of 1983 (NAD 83) (2011).

**Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), using the Geoid12B model.

surface were collected by adding the depth of water measured with an echo sounder to the rod height of the GPS receiver; the GPS receiver was positioned directly above the echo sounder transducer. The density of survey points for all cross sections surveyed in 2019 exceeded those collected in the initial surveys of 1994. In addition to resurveying previously established cross sections, eight new cross sections, BP-5 through BP-12 (table 1), were established on the Green River in Browns Park between the river segments surveyed by Grams and others (2002) and Grams (1997). These new cross sections were established to provide future researchers the ability to monitor channel changes in this reach that is sand-bedded at time of study and to better link possible changes in the previously established upstream and downstream cross sections (Griffiths and others, 2026).

During our RTK survey, static global navigation satellite system (GNSS) observables averaging 44 minutes in duration were collected at 18 RTK base-station locations near each of the cross sections. GNSS vectors were post-processed from concurrent observables at both a passive National Spatial Reference System (NSRS) station HOPE (National Geodetic Survey Permanent Identifier [NGSPID] LN0701), and an active continuously operating reference station CNC1 (NGSPID DL3583). The resulting vectors were constrained to published NSRS positions in a least squares adjustment. North American Datum of 1983 (NAD 83) accuracy of the 18 adjusted RTK base positions were determined to be 0.032 m horizontal and 0.061 m vertical (95th percentile of stations reporting 2-sigma uncertainties). The GNSS data were collected using Trimble R8s receivers with Trimble Access Ver2017.24 and processed with Trimble Business Center Ver5.32 (Trimble, 2017, 2020).

During the 2019 survey, we also collected three bed-sediment samples at each cross section if the bed sediment was fine enough to permit sampling; these bed-sediment measurements are available under the Dinosaur Ancillary Sediment Data link at https://www.gcmrc.gov/discharge_qw_sediment/. These bed-sediment samples were attempted at all cross sections, including at the new cross sections established during our study. The bed-sediment samples were collected at stations located approximately at the left quarter, center, and right quarter of the active channel width. Because the bed sediment was cobble or boulders, no bed-sediment samples were collected from BP-1 through BP-3. Only two samples were collected at BP-4 because cobbles comprised the bed at the left quarter station. Three bed-sediment samples were collected at all other cross sections.

For our analyses of change, we converted our NAD 83 cross-section coordinates into the horizontal coordinate systems of each cross section used in the original surveys (Grams, 1997; Grams and others, 2002). Where the left-bank monument was undisturbed and we obtained accurate GPS precision, we converted our North American Vertical Datum of 1988 (NAVD 88) elevations into the original survey vertical coordinate system using their reported elevation of the top of the left-bank monument. Where the right-bank monument was used (BP-2, BP-14, and BP-17), we converted our NAVD 88 elevations into the original vertical coordinate system using their reported elevation of the top of the right-bank monument. Where we obtained accurate GPS coverage and monuments were undamaged, the relative distance between the two endpoints and the relative elevation change between the two endpoints were compared between our resurvey and the original survey. For the eight comparisons between monuments, the width difference ranged from −0.058 m to 0.152 m (mean of 0.034 m) and the elevation difference ranged from −0.025 m to 0.169 m (mean of 0.013 m).

The width and cross-sectional area were measured along and relative to a horizontal line between the two endpoints at the elevation of the lower of the two endpoints, referred to as the local reference elevation (LRE). The width was measured as the distance between two points where the cross-section topography intersected the LRE. The mean depth below the LRE was calculated by dividing the cross-sectional area below the LRE by width at the LRE. Changes in the net cross-sectional area between surveys were calculated to include changes in the total cross-sectional area (that is, the combined change in cross-sectional area above and below the LRE) over the full extent of the 2019 cross sections.

To determine the amount of change occurring in the active channel bed, we used the water surface elevation from the initial 1994 surveys when the Green River discharge averaged ~1,400–1,600 cubic feet per second (ft^3/s). The 1994 surveys typically recorded water surface elevations on both banks; for simplicity we used the left bank elevation. Where the 1994 water surface elevation intersected the 1994 surveyed topography was the width of the active channel bed, the change in area in this active channel bed width indicates whether the active channel bed has aggraded or eroded. Subtracting the area of change associated with the active channel bed from the net change below the LRE results in the area of bank change. The area of bank change combines erosion of predam terrace material with, if present, small inset floodplain deposits.

Changes in the Browns Park Cross Sections

The measured cross-sectional area of the Green River channel cross sections in Browns Park generally increased between the initial 1994 survey and our 2019 resurvey (figs. 3, 4, 5; table 2), which indicates net erosion of sediment from these cross sections. Of the 10 cross-sections resurveyed, 9 increased in area; only the uppermost cross section, BP-1, decreased in area. Cross-sectional area increases occurred through a combination of widening (bank retreat) and increases in depth; in the nine cross sections that increased in area two, BP-3 and BP-4, had net bank deposition and only one, BP-13, had aggradation of the active channel bed (table 3). The increases in depth were manifest through an increase in the area of active channel bed (table 3), the maximum depth below the LRE (table 2), or both. The area of active channel bed increased in 8 of the 10 cross sections (the area of active channel bed decreased in BP-1 and BP-13), and the maximum depth increased in 7 of the 10 cross sections (tables 2, 3). The

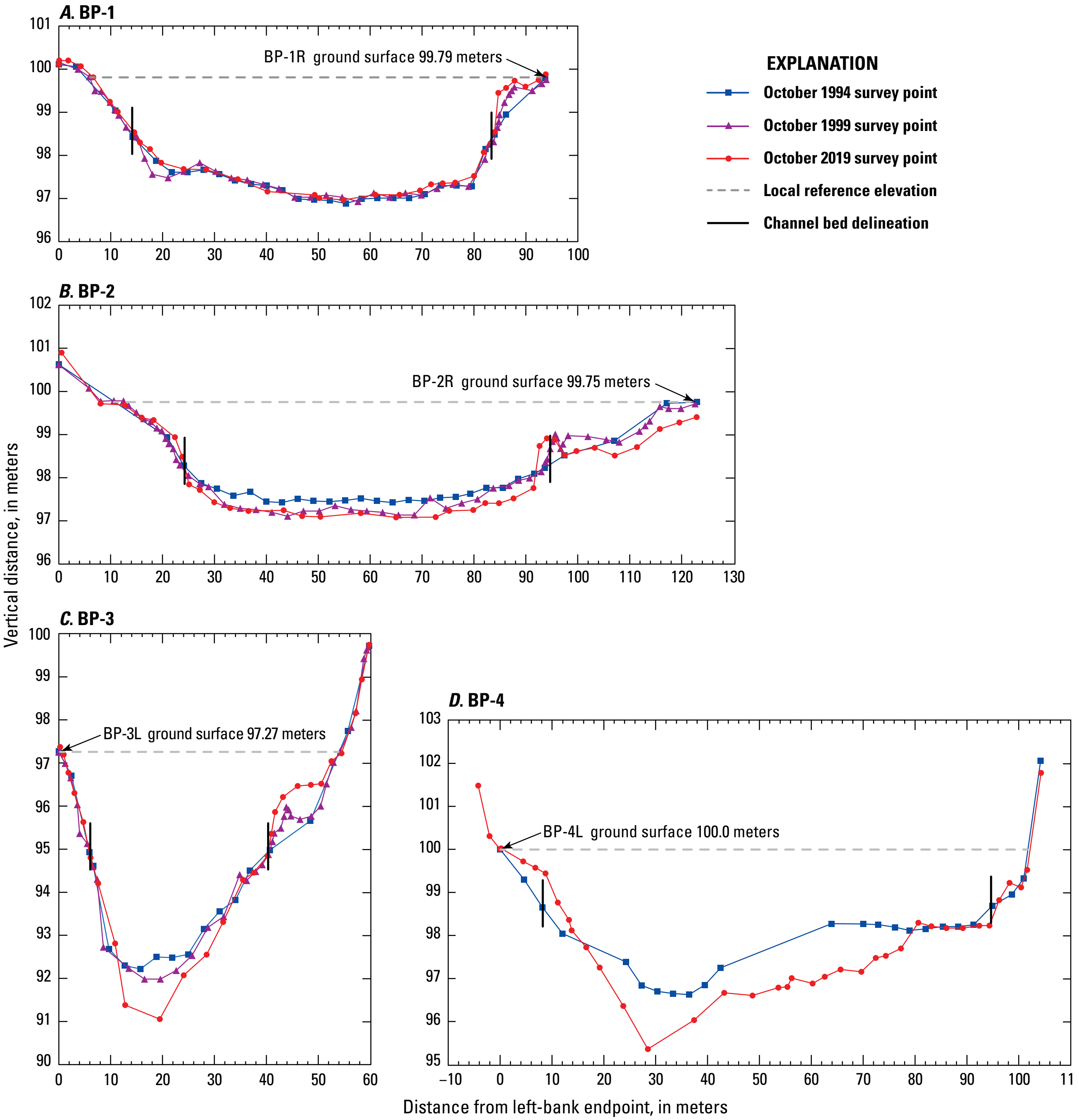


Figure 3. Plots showing cross-section survey data from 1994, 1999, and 2019 on the Green River in Browns Park in Utah and Colorado. *A*, BP-1; *B*, BP-2; *C*, BP-3; and *D*, BP-4. The lower of the two cross-section endpoints, indicated with its elevation on each cross-section plot, was used to determine the local reference elevation used to calculate channel width and depth. Cross sections are depicted as they would be seen by an observer facing downstream. The vertical distance is local to each cross section.

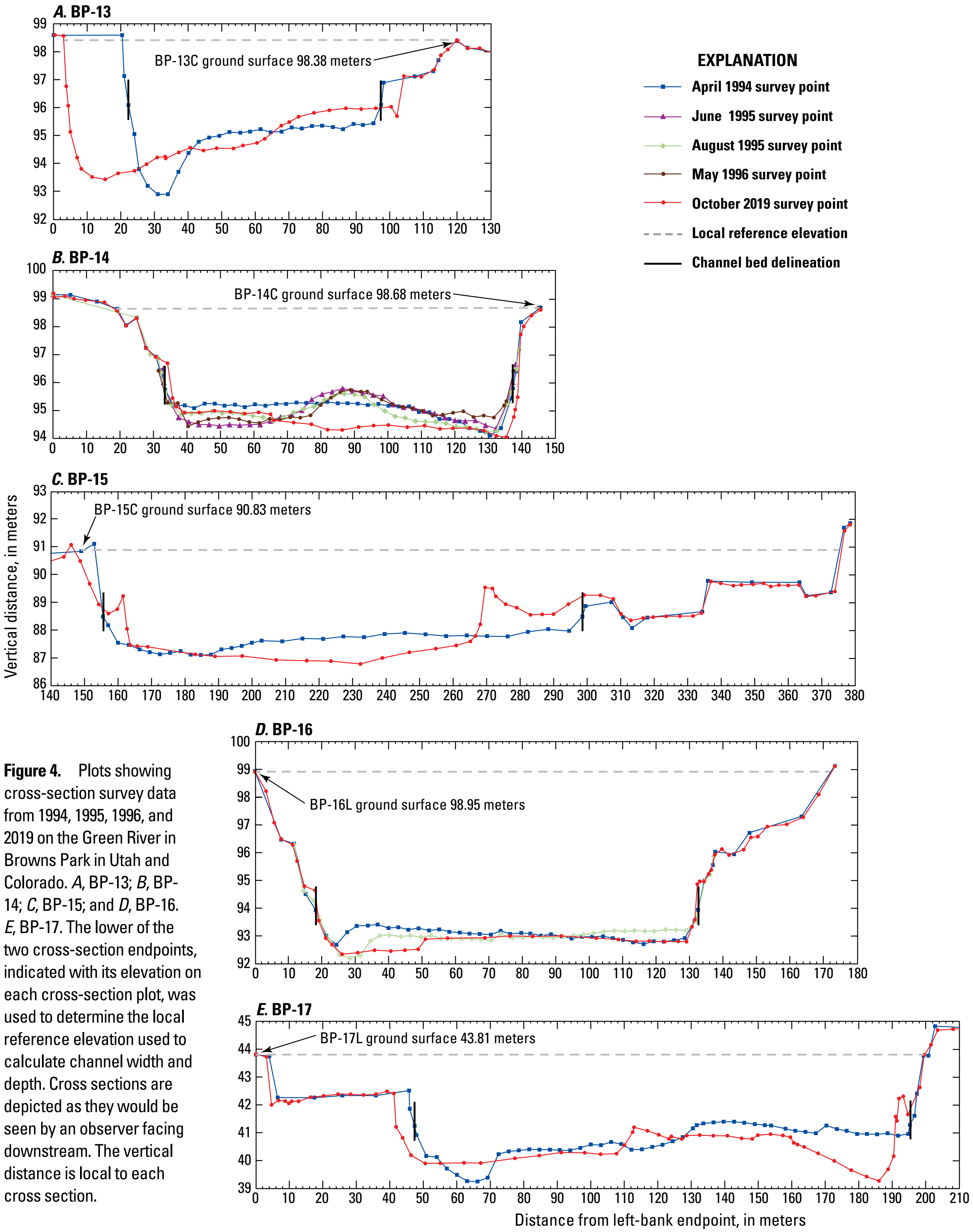


Figure 4. Plots showing cross-section survey data from 1994, 1995, 1996, and 2019 on the Green River in Browns Park in Utah and Colorado. *A*, BP-13; *B*, BP-14; *C*, BP-15; and *D*, BP-16. *E*, BP-17. The lower of the two cross-section endpoints, indicated with its elevation on each cross-section plot, was used to determine the local reference elevation used to calculate channel width and depth. Cross sections are depicted as they would be seen by an observer facing downstream. The vertical distance is local to each cross section.

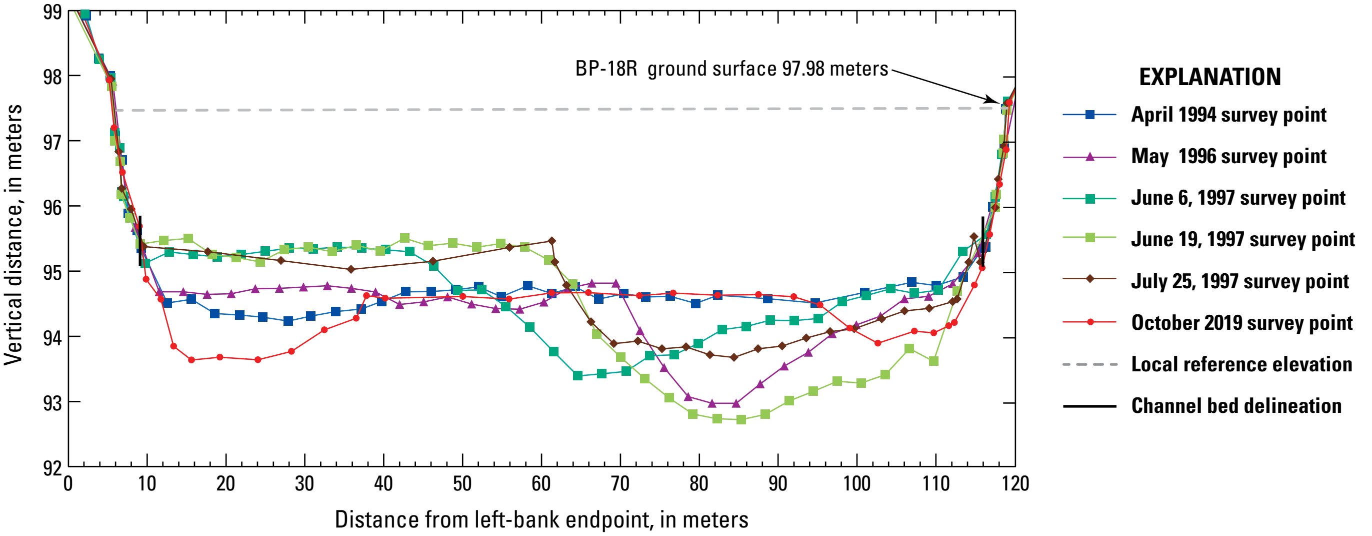


Figure 5. Plots showing cross-section BP-18 survey data from 1994, 1995, June 6, 1996, June 19, 1996, July 25, 1996, and 2019 on the Green River in Browns Park in Utah and Colorado. Surveys from June 1994, June 1995, August 1995, June 1996, and July 2004 are not shown. The lower of the two cross-section endpoints, indicated with its elevation on each cross-section plot, was used to determine the local reference elevation used to calculate channel width and depth. Cross sections are depicted as they would be seen by an observer facing downstream. The vertical distance is local to the cross section.

LRE width increased in 7 of the 10 cross sections, with 2 cross sections, BP-13 and BP-15, having more than 5 m of bank retreat between the 1994 and 2019 surveys (fig. 4; table 2). The area of bank change (the total area of change below the LRE minus the area of active channel bed change) also increased in 7 of the 10 cross sections (table 3).

To determine whether the primary driver of channel area change between the 1994 and 2019 surveys was the change in width or change in depth, the area associated with lateral bank change and the area associated with active channel bed change were calculated, and the ratio of bank to bed change was computed (table 3). The ratio of the area of bank change to the area of bed change provides an estimation of the importance of each type of channel change to the overall change in cross section area. Ratios greater than 1 indicate that most changes in cross-sectional area are from changes in the bank, whereas ratios less than 1 indicate that bed-elevation changes dominate the changes in cross-sectional area. Two cross sections (BP-1 and BP-13) were dominated by changes in bank area, one cross section (BP-15) had about equal contributions to cross-sectional area change from bank-position and bed-elevation changes, and the other seven cross sections had channel cross-sectional area changes dominated by bed-elevation changes (table 3). This analysis is biased by the elevation of the 1994 water surface but does provide insights into where most of the channel cross-sectional area changes occurred; in the cross sections resurveyed in Browns Park, most channel change is from the bed and shows incision. Hence, the channel of the Green River in Browns Park is most similar to the idealized channel in figure 2*D*, where a river in sediment deficit is undergoing channel bed incision.

There are two disparate discharge regimes on the Green River in Browns Park. The dominant flows that occur over most of the year are Flaming Gorge Dam releases through the powerplant that range from ~800 to ~2,700 ft^3/s. Superimposed on these flows are spring peak dam releases, designed to advantage native fish species, with peaks ranging from ~4,500 to ~9,000 ft^3/s that last from days to weeks (U.S. Fish and Wildlife Service, 1992; Muth and others, 2000; Bureau of Reclamation, 2005, 2006; Bestgen and others, 2011; LaGory and others, 2019; USGS, 2025b). Because the dunes and bars in sand-bedded parts of a river typically increase in amplitude as discharge increases (for example, Cant and Walker, 1978; Rijn, 1984; Andrews and Nelson, 1989; Fujita, 1989; Julien and Klaassen, 1995), cross-section surveys conducted during and immediately after spring peak-flow releases could have higher, or lower, bed elevations than observed during surveys conducted during the rest of the year. This effect is likely seen at BP-14 (fig. 4*B*) during the surveys of June 1995, August 1995 and May 1996, which were conducted immediately after, two and a half months after, and during peak flows, respectively. It is possible that the higher mid-channel bar in the central part of BP-14 in August 1995 persisted for several months after recession of the 1995 spring peak flow because the subsequent low discharges (~800 ft^3/s; USGS, 2025b) were too low to quickly rework the bed.

In addition to peak flows causing temporary increases in dune amplitude and changes in bar configuration, peak flows can also cause large amounts of scour or fill that can radically change cross-section shape during and immediately after high discharge events (for example, Colby, 1964; Topping and others, 2000). This effect is likely seen at BP-18 (fig. 5) during the surveys of June

Table 2. Cross-section channel width, mean depth below the local reference elevation (LRE), maximum depth below the LRE, and total cross-sectional area from each survey on the Green River in Browns Park in Utah and Colorado.

[Data from Grams (1997), Grams and others (2002), and Griffiths and others (2026). Locations and names of cross sections (BP-#) are given in table 1. Channel cross-sectional areas are reported below the LRE and above the LRE. Net changes in cross-sectional area include changes both below and above the LRE. m, meter; m^2, square meter, — no net change calculated]

Survey date	Width at LRE (m)	Maximum depth below LRE (m)	Channel cross-sectional area below LRE (m^2)	Channel cross-sectional area above LRE (m^2)	Net change in cross-sectional area (m^2)
			BP-1		
10/14/1994	88.4	2.9	181.8	1.2	—
10/6/1999	88.0	2.9	178.7	1.3	–3.1
10/9/2019	86.6	2.8	172.9	2.0	–6.5
			BP-2		
10/15/1994	112.1	2.3	175.6	4.7	—
10/6/1999	110.2	2.6	186.3	4.0	11.4
10/9/2019	115.1	2.7	202.3	4.2	15.7
			BP-3		
10/16/1994	54.1	5.1	166.9	6.3	—
10/7/1999	54.2	5.3	170.5	5.8	4.1
10/9/2019	54.4	6.2	173.4	5.5	3.2
			BP-4		
10/16/1994	101.8	3.4	206.4	3.4	—
10/10/2019	101.7	4.6	254.9	1.9	50.0
			BP-13		
4/22/1994	99.5	5.5	293.7	4.4	—
10/12/2019	116.7	5.0	366.6	0.6	76.7
			BP-14		
4/22/1994	127.4	4.6	399.3	5.6	—
6/2/1995	127.4	4.3	413.3	5.6	14.0
8/19/1995	127.4	4.4	416.3	5.6	3.0
5/7/1996	127.4	4.3	406.7	5.6	–9.6
10/12/2019	127.9	4.6	448.8	5.2	42.5
			BP-15		
4/23/1994	222.3	4.7	812.2	0.0	—
10/12/2019	229.4	5.1	833.6	0.0	21.4
			BP-16		
4/23/1994	172.4	6.3	803.0	0.9	—
8/19/1995	172.4	6.8	810.6	0.1	8.4
10/13/2019	172.7	6.6	831.3	0.1	20.7
			BP-17		
4/23/1994	200.9	4.6	534.8	26.0	—
10/13/2019	199.6	4.8	586.8	25.1	52.9
			BP-18		
4/23/1994	115.3	3.7	372.2	3.7	—
6/21/1994	115.3	4.1	384.3	3.7	12.1
6/2/1995	115.3	4.1	399.7	3.5	15.6
8/19/1995	115.5	4.1	377.8	3.3	–21.7

Table 2. Cross-section channel width, mean depth below the local reference elevation (LRE), maximum depth below the LRE, and total cross-sectional area from each survey on the Green River in Browns Park in Utah and Colorado.—Continued

[Data from Grams (1997), Grams and others (2002), and Griffiths and others (2026). Locations and names of cross sections (BP-#) are given in table 1. Channel cross-sectional areas are reported below the LRE and above the LRE. Net changes in cross-sectional area include changes both below and above the LRE. m, meter; m^2, square meter, — no net change calculated]

Survey date	Width at LRE (m)	Maximum depth below LRE (m)	Channel cross-sectional area below LRE (m^2)	Channel cross-sectional area above LRE (m^2)	Net change in cross-sectional area (m^2)
			BP-18—Continued		
5/8/1996	115.3	5.0	400.2	3.4	22.3
6/17/1996	115.3	4.3	387.9	3.5	–12.4
6/6/1997	115.4	4.6	371.0	3.7	–17
6/19/1997	115.3	5.3	392.8	3.2	22.2
7/25/1997	115.3	4.3	365.6	3.4	–27.4
7/2004	115.3	4.6	401.5	3.9	35.4
10/13/2019	115.6	4.3	399.1	3.6	–2.1

Table 3. Changes in cross-section bed and bank areas between the original 1994 surveys and this 2019 survey on the Green River in Browns Park in Utah and Colorado.

[Data from Grams (1997), Grams and others (2002), and Griffiths and others (2026). Reported changes in bed and bank areas are the difference between the original 1994 surveys and our surveys. Ratios in bold and followed by an asterisk (*) are cross sections that decreased in total area (net deposition), nonbold ratios are cross sections that increased in total area, and ratios in italic and followed by two asterisks (**) are cross sections that had either area of increase in bank area with decrease in active channel bed area or decrease in bank area and increase in bed area. m, meter; m^2, square meter]

Cross section	Total area of change (m^2)	Area of active channel bed change (m^2)	Area of bank change (m^2)	Ratio of bank change to bed change	Width of active channel bed from 1994 surveys water's edge (m)	Mean bed elevation change (m)
BP-1	–9.6	–1.3	–8.3	**6.31***	69.5	0.019
BP-2	27.2	21.3	5.9	0.28	70.2	–0.30
BP-3	7.3	15.2	–7.9	*0.52***	34.4	–0.44
BP-4	50.0	51.8	–1.8	*0.03***	86.4	–0.60
BP-13	79.4	–3.3	82.7	*24.74***	75.2	0.04
BP-14	49.9	46.7	3.2	0.07	103.7	–0.45
BP-15	21.4	12.1	9.3	0.77	143.0	–0.08
BP-16	29.2	27.6	1.6	0.06	114.3	–0.24
BP-17	52.9	40.7	12.2	0.30	147.9	–0.28
BP-18	27.0	26.3	0.6	0.02	106.7	–0.25

and July 1996 conducted during and after a spring peak flow: the mean discharge at the USGS Green River near Greendale, Utah, streamgage (USGS streamgage 09234500) was 4,660 ft^3/s on June 6; 8,290 ft^3/s on June 19; and 1,420 ft^3/s on July 25 (USGS, 2025b). Because short periods of high discharge can cause large temporary changes in cross-section geometry, it is important to avoid using surveys conducted during and immediately after peak flows when analyzing cross sections for long-term change in sediment storage. Accordingly, as the discharges preceding the 1994 and 2019 surveys were similar, with daily mean Flaming Gorge Dam releases between ~1,300 and ~1,600 ft^3/s (USGS, 2025b), and because the 1994 and 2019 surveys were conducted many months after any peak flows, we are confident that the observed cross-section changes between these surveys were not the result of discharge-dependent bed-elevation changes.

The bed sediment observed in the three upstream cross sections during the 2019 resurvey was primarily composed of cobbles and boulders. The bed sediment measured in 2019, as well as the lack of bed elevation change at BP-1 since 1994, indicate that the bed of this cross section has likely been dominated by the same larger gravel clasts since at least 1994 and is largely immobile during modern flows (fig. 3*A*).

Downstream at BP-2, about half of the bed width had already degraded to the 2019 elevation between the 1994 and 1999 surveys, indicating that bed armoring was ongoing during that 5-year interval. Although additional future surveys would be needed to determine whether the bed-armoring process is ongoing or was completed between the 1999 and 2019 surveys, the downstream progression of bed armoring indicates that this reach is in sediment deficit and experiencing net sediment loss. Despite 9 of the 10 cross sections having an increase in cross-sectional area, thus indicating net erosion, local deposition occurred near the active channel margins in all the upstream cross sections (fig. 3). These channel-margin deposits are inset floodplain deposits forming at the elevation of the common ~4,500 ft^3/s powerplant-capacity releases from Flaming Gorge Dam during parts of May and (or) June (Bureau of Reclamation, 2005, 2006).

Sediment Mass Balance for the Green River in Browns Park

From the resurveyed cross sections, we calculated the total change in the quantity of sediment stored in the Green River channel in Browns Park between 1994 and 2019 and estimated the annual rate of change. This analysis rests on the critical assumptions that the cross sections are representative of channel changes in Browns Park and that the rate of change has been constant over time. In addition, to simplify the rate-of-change estimate, we ignore that the downstream cross sections were first surveyed in April 1994, whereas the upstream cross sections were first surveyed in October 1994 (table 2), and instead approximate that all the changes occurred between October 1994 and October 2019. To ensure that we could directly compare our resurvey results with the sediment-transport-based erosion rates from Topping and others (2018), we only used the results from the eight cross sections above the Lodore streamgage used by Topping and others (2018) (fig. 1). The net change in the cross-sectional area of sediment between 1994 and 2019 at each cross section was used to estimate the changes in sediment storage between the cross sections; for example, the average change in the cross-sectional area of sediment at BP-1 and BP-2 was applied to the channel length between cross sections BP-1 and BP-2. We assume that the change in sediment volume is entirely a change in the volume of sand, which is justified by the analysis indicating that most of the change occurred on the channel bed and because our bed-sediment samples were mostly composed of sand-size sediment. Using a quartz density of 2,650 kilograms per cubic meter (kg/m^3) and ~40-percent porosity (Curry and others, 2004), the dry bulk density of riverbed sand used to convert volume to mass is ~1,590 kg/m^3. By this approach, the total quantity of sand eroded from the 30.5 km length of Browns Park above the Lodore streamgage was ~2,650,000 metric tons, at an annual erosion rate of ~106,000 metric tons per year. Because almost half of the total channel length occurs between BP-4 and BP-13, we checked that the weighting of these two cross sections did not bias the results by also calculating the average change in cross-sectional sediment area among the eight cross sections above the Lodore streamgage and applying that average to the entire reach. This second method yielded a result (~2,630,000 metric tons) consistent with the first.

The erosion rates for Browns Park calculated from our cross-section resurvey were in reasonable agreement with the sand budget for Browns Park in Topping and others (2018). For water years 2013–16, Topping and others (2018) reported that the measured mean-annual sand export past the Lodore streamgage was 79,000±26,000 metric tons, and the assumed mean-annual sand input to Browns Park from Red and Vermillion Creeks based on historical USGS measurements was 34,000±10,000 metric tons. Differencing these numbers, with propagation of uncertainty, yields a mean-annual erosion rate for Browns Park of between ~9,000 and ~81,000 metric tons per year. Given the uncertainties in the measured loads at the Lodore streamgage, between ~20 and ~60 percent of the sand export from Browns Park during water years 2013–16 occurred during the four peak flows released from Flaming Gorge Dam during these years (Topping and others, 2018). Updating these results to include data that post-dated Topping and others (2018) but preceded our 2019 resurvey[1] yields a mean-annual sand export of 100,000±31,000 metric tons past the Lodore streamgage for water years 2013–19 (USGS, 2025a). Subtracting this updated sand export rate from the historical sand input rate from Topping and others (2018), with propagation of uncertainty, yields a mean-annual erosion rate for Browns Park of between ~25,000 and ~107,000 metric tons per year, a value consistent with our survey-estimated annual erosion rate of ~106,000 metric tons per year.

Longitudinal Bed Grain-Size Trends in the Green River in Browns Park

Two grain-size measures were used to detect longitudinal trends in the bed-sand grain distribution measured during our 2019 resurvey: the cross-sectional average median grain size (D_{50}) and the cross-sectional average percentage of very fine sand (0.0625–0.125 millimeter [mm] sand) in the bed. These cross-sectional averages were calculated among the bed sediment samples collected across each cross section. The amount of very fine sand in the bed was used as a measure of the bed-sand grain-size distribution in addition to D_{50} because changes in the fine tail of the bed-sand grain size are more sensitive to changes in the upstream sand supply than is the median grain size (Topping and others, 2018, 2021). The correlation coefficient (r) and level of significance (p)

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[1] This update included a stage-discharge rating-curve revision, a slight change to the calibration for the acoustical suspended-sand measurements, and additional bedload measurements that together caused a ~9 percent increase in the sand loads at the Lodore streamgage relative to those reported by Topping and others (2018) for water years 2013–16 (Topping and others, 2025).

associated with least-squares linear regressions fit to these to bed-sand metrics were used to detect longitudinal trends in the bed-sand grain-size distribution during the 2019 resurvey; *p* was determined using *F*-tests. Although the bed-sand grain size distribution fined slightly downstream in 2019 (fig. 6) and is therefore consistent with the winnowing expected by the progressive depletion of the upstream sand supply in a river segment in sediment deficit (Rubin and others, 1998; Topping and others, 2018, 2021), the longitudinal trends in D_{50} and the percentage of very fine sand on the bed are both weak (that is, $0.2<|r|<0.4$) and insignificant (that is, $p>0.05$).

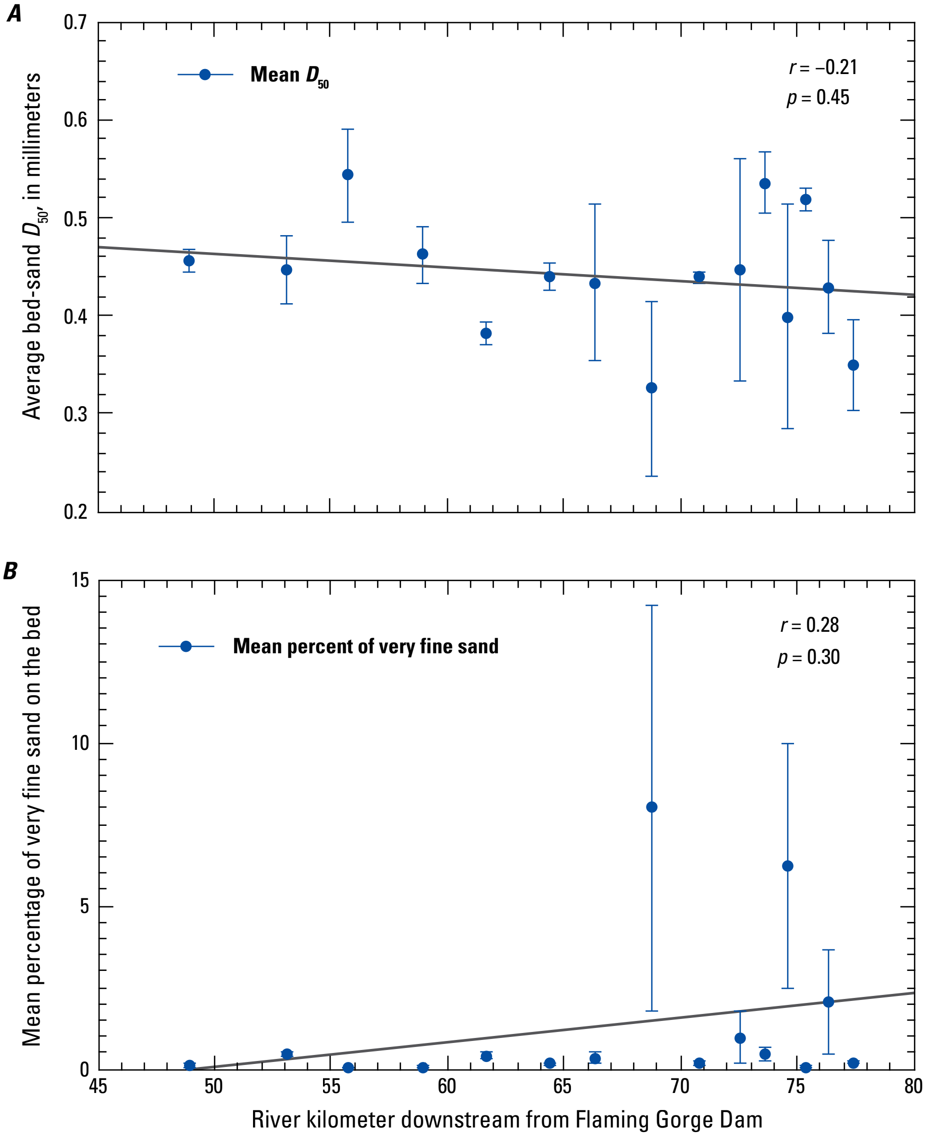

Figure 6. Plots showing *A*, the cross-sectional average median grain size (D_{50}) of the bed sand and *B*, the cross-sectional mean percentage of very fine sand on the bed, plotted as a function of the river kilometer downstream from Flaming Gorge Dam on the Green River in Utah. Error bars are one standard error calculated among the two to three bed-sediment samples in each cross section. Solid lines are best-fit least-squares linear regressions; correlation coefficients (*r*) and levels of significance (*p*) associated with these regressions are shown.

Conclusions

The 2019 U.S. Geological Survey resurvey of cross sections on the Green River in Browns Park indicates changes in channel morphology and sediment storage since the initial surveys in 1994. Most previous studies of channel changes in Browns Park relied on aerial photographs to calculate changes in the active channel width and determined that the channel was narrowing, implying deposition of sediment. In this study, we document a net increase in the cross-sectional area, or erosion, with some relatively minor inset floodplain deposition. Nine out of 10 resurveyed cross sections showed an increase in cross-sectional area (and thus a net decrease in the cross-sectional area of sediment), indicating net erosion from this river segment. Net erosion occurred through both widening (bank retreat) and increases in depth (bed incision), with bed incision dominating over bank retreat in most cross sections. The observed channel changes, particularly bed incision, strongly indicate that the postdam Green River in Browns Park is in a long-term state of sediment deficit. Furthermore, the likely downstream progression of bed armoring and possible coarsening of the upstream part of Browns Park together are consistent with this river segment being in sediment deficit. Based on the eight cross-sections resurveyed above the Green River above Gates of Lodore, Colorado, streamgage, approximately 106,000 metric tons of sand per year were exported from Browns Park. This agrees with water years 2013–19 sediment-transport measurements indicating mean-annual sand export exceeding the estimated sand input. The widespread channel incision among the cross sections provides strong evidence that this segment of the Green River continues to adjust to the altered flow and sediment regimes imposed by Flaming Gorge Dam. Long-term monitoring of the Browns Park cross sections, including resurvey of the new cross sections established during our study, could be valuable for tracking future channel evolution and informing river management decisions.

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