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Equilibrium or indeterminate? Where sediment budgets fail: Sediment mass balance and adjustment of channel form, Green River downstream from Flaming Gorge Dam, Utah and Colorado

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Abstract

This study examines bed and bank adjustment in the 105-km reach of the Green River immediately downstream from Flaming Gorge Dam by the use of historical aerial and oblique photographs, analysis of current and abandoned stream-gaging records, and field observations. Although this segment has been previously characterized as sediment deficient, these data show that sediment is accumulating in all reaches and that the bed has not degraded at any location where historical data are available. Adjustment is occurring through a combination of deposition of post-dam sediment and stabilization of pre-dam deposits, resulting in a 10–30% reduction in average width of the channel. All post-dam surfaces are colonized by woody riparian vegetation. The style of channel adjustment varies between geomorphically defined reaches. In canyons dominated by debris fans and gravel-bedded restricted meandering reaches, gravel bars have become inactive and accumulated fine sediment. In the sand-bedded meandering reaches, existing islands have increased in size and new mid-channel islands have formed. In all of these types of reaches, post-dam deposits line the banks and sediment has accumulated in side-channels that previously separated islands from the bank.

These findings demonstrate that sediment budgets that show a balance between inputs and outputs cannot necessarily be interpreted to indicate channel equilibrium. A sediment mass balance for 150-km reach between the dam and the first long-term gage indicates approximate balance of inputs and outputs for the pre- and post-dam periods. When uncertainty in budget components is considered, the mass balance is indeterminate. Although the Green River may have been in approximate equilibrium in the pre-dam period, we have shown that channel width is decreasing in the post-dam period. The post-dam deposits constitute a small but a significant component of the sediment budget upstream from the first major tributary. Sediment is supplied to this reach by small tributaries and, to a lesser extent, erosion of pre-dam alluvium. Downstream from the study area, the volume of the post-dam deposits is tiny relative to the volume of sediment input from the first major tributary.

Keywords: Channel adjustment; Floodplains; Channel narrowing; Degradation; Dams; Sediment budget

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1. Introduction

Channel form reflects the complex adjustment, over time, among water discharge and the quantity and size of sediment supplied to the channel. Perturbations in the water or sediment regimes, such as those caused by large dams, have the potential to result in adjustment of downstream channel morphology. Changes in channel morphology may adversely affect critical fish habitat, riparian vegetation communities, and other aquatic and riparian resources. A fundamental problem in geomorphology is the prediction of these changes. Channel adjustment is accommodated by changes in cross-section form, bed material size and organization, channel planform, and slope. The proportional changes in each component are indeterminate (Leopold and Langbein, 1963) or, at the least, difficult to quantitatively predict (Schumm, 1969). Yet, the need remains to anticipate styles of channel adjustment in response to imposed alterations in the hydrologic and sediment regimes. Thus, case studies remain a critical part of geomorphology's contribution to the study of dams and their management.

This paper addresses two issues within the context of a case study. The first issue concerns uncertainty in sediment budget calculations, and the inevitable loss in predictive capability when that uncertainty is considered. The second issue concerns the need to measure changes in channel form accurately and in a spatially robust manner. The style and magnitude of channel change is largely determined by factors that change downstream, such as the degree of streamflow alteration, tributary sediment supply, and local channel organization. Measurements made over short reaches cannot, therefore, be assumed to apply throughout a long river segment.

Regarding the first issue, the initial step in predicting channel change is typically an assessment of sediment mass balance, which can be computed for suspended, bed, or total load. Mass balance calculations lead to characterization of a river segment as in sediment surplus, deficit, or equilibrium. Where the decrease in sediment transport capacity is large and the sediment supply is relatively unchanged, surplus exists and aggradation may occur, resulting in increased bed elevation, bank narrowing, and/or bed fining. Where transport capacity is not significantly decreased but the total sediment supply is greatly reduced, deficit exists and degradation may occur by bed incision, bank widening, and/or bed coarsening. Widespread channel aggradation in response to sediment surplus, the former condition, has been described on the Rio Grande (Everitt, 1993) and the Platte River (Williams, 1978). Widespread channel degradation, the latter condition, has been described by Komura and Simmons (1967) and Pemberton (1976), among others.

Whether a channel is in sediment surplus or sediment deficit is not necessarily easy to determine, because some perturbations to flow and sediment transport may be less extreme than the examples cited, and the errors associated with estimating sediment loads may be larger than the real differences between influx and efflux. Topping et al. (2000) demonstrated that computed sediment budgets based on measurements of sediment transport might not be statistically different from zero when the uncertainties in sediment sampling are considered. Many mass balance calculations ignore these uncertainties, however, and result in erroneous predictions of river response, as was the case with sediment budgets estimated for Grand Canyon (Schmidt et al., 1999; Schmidt, 1999). The uncertainty in sediment budget calculations is especially great when the influx of tributary sediment causes the mainstem budget to change at each tributary confluence, because detailed transport data are rarely available for each river segment. This situation commonly arises in arid and semi-arid landscapes where tributary input may be episodic, but nonetheless comprise a substantial proportion of the mainstem sediment load. This highly variable sediment influx may be crucial in determining system-wide balance between supply and transport capacity. In these cases, one is forced to integrate data of varying precision and accuracy.

Large uncertainty in sediment mass balance components may result in an indeterminate sediment budget, which leaves the direction and magnitude of channel adjustment unknown. Changes in channel form may be subtle and difficult to detect. Thus, meaningful segment-scale conclusions about channel change can only be gained from accurate and spatially robust measures of channel change. These are the second set of issues addressed by this paper.

Downstream changes in bed and bank material and geomorphic organization may cause large differences in the style and magnitude of change in channel form. Some parts of a channel may be more, or less, susceptible to adjustment in channel width or bed elevation, for example. Exposure of underlying coarse-grained deposits has been shown to halt degradation in sand-bedded rivers (Xu, 1996). Riparian vegetation influences the rates and magnitude of channel adjustment by increasing bank stability, inhibiting erosion, and enhancing sedimentation and floodplain formation (Friedman et al., 1996). The net result is that the magnitude of channel change measured at one place is not necessarily representative of the magnitude of change elsewhere.

In this paper, we present a description of channel adjustment based on historical data and field measurements coupled with a sediment budget that recognizes uncertainty in budget components. The study area is a 104-km segment of the Green River downstream from Flaming Gorge Dam, where the style of channel adjustment was previously characterized as degrading, based on a sediment budget that did not incorporate uncertainty (Andrews, 1986). We show that the sediment budget is indeterminate and that this river segment is not degrading, but is, in fact, accumulating sediment. We also show that robust measures of channel change over long reaches better characterize the style and magnitude of channel adjustment than limited measures over short reaches. This analysis presents a new perspective on the relationship between sediment mass balance, channel-form adjustment, and reach-scale geomorphic organization.

2. Study area description

2.1. Geomorphology of the Green River

The study area extends from Flaming Gorge Dam downstream to the Yampa River confluence in Echo Park (Fig. 1). In these 104 km, the Green River flows through a variety of bedrock lithologies and geologic structures that strongly influence channel and floodplain morphology. Three fundamentally different channel planform and floodplain settings exist within the study area: (1) canyons dominated by debris fans, (2) fixed meanders, and (3) restricted meanders. The sequence in which these settings occur is determined by the surrounding topography and the sequence of rock units encountered by the river. The amount of fine-grained sediment along the channel banks and the depositional environments differ among these reach types, and these differences have the potential for different magnitudes and styles of channel adjustment in response to the same perturbations in flow and sediment transport.

Canyons dominated by debris fans, hereafter referred to as canyons, (Schmidt and Rubin, 1995; Grams and Schmidt, 1999) occur where the alluvial valley is narrow and where tributary debris fans influence channel morphology and hydraulics. Debris fans constrict the main channel, cause rapids and riffles, and control the hydraulics upstream and downstream from each fan. These conditions result in a repeating suite of alluvial deposits described by Schmidt and Rubin (1995) as a fan–eddy complex. Deposits comprising a fan–eddy complex include (1) fine-grained channel-margin deposits adjacent to the ponded flow upstream from each constriction, (2) fine-grained eddy deposits downstream from every constriction and upstream from some constrictions, and (3) gravel or cobble bars further downstream from the constrictions. Different parts of fan–eddy complexes respond differently to changes in the sediment budget for fine- or coarse-grained sediment.

In reaches that do not have tributary debris fans, the Green River meanders in a channel that is partially confined by bedrock. Fixed meanders (Ikeda, 1989) are low-gradient reaches, with a high degree of bedrock confinement, but few or no channel constrictions. The alluvial valley is narrow, the ratio of valley width to channel width is <2, and the channel and alluvial valley meander in parallel. Restricted meanders (Ikeda, 1989) are also low-gradient reaches, but with a lesser degree of bedrock confinement; the active meander belt is constrained at the outside of some meander bends. The alluvial valley tends to be wide, the ratio of valley width to channel width is >2, and the paths of the channel and the alluvial valley frequently diverge. The

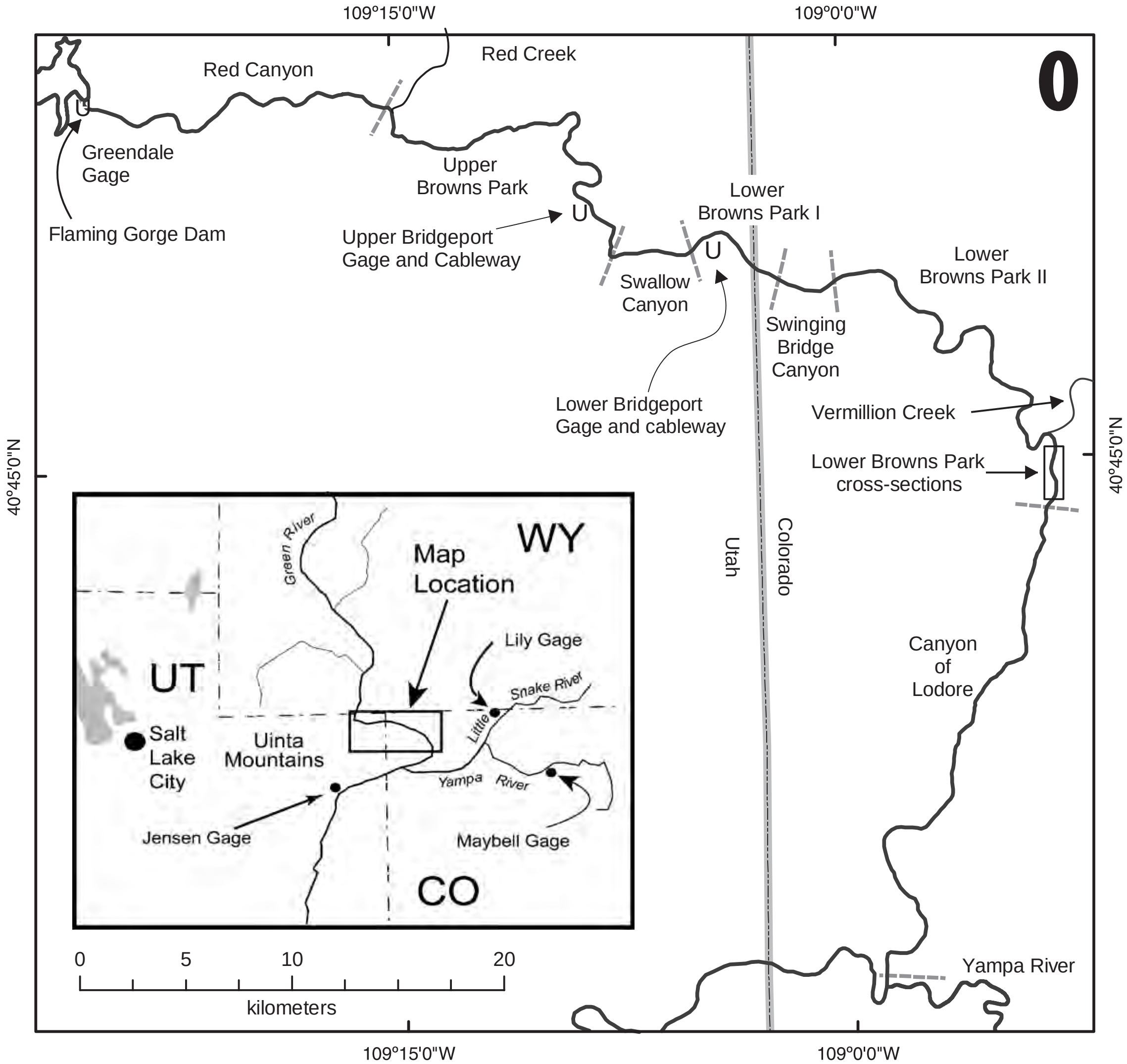

Fig. 1. Map of study area showing reach divisions, U.S. Geological Survey gage stations, and major tributaries. The study site containing the Lower Browns Park cross-sections is also shown.

occurrence of each of these reach types within the study area is listed in Table 1.

2.2. Hydrology

Construction of Flaming Gorge Dam began when the cofferdam began diverting the Green River around the project site on August 17, 1959. Storage of water behind the completed dam began on December 10, 1962. The impact of the dam on streamflow is recorded by the Greendale gage (station 09234500), located 0.6 km downstream from the dam (Fig. 1). Daily streamflow and annual peaks have been measured at Greendale since October 1951. The record for annual peak flows was extended to 1895 by correlation with upstream gages (Grams and Schmidt, 2002). Dam operations have not affected the mean annual flow of the Green River, but have greatly reduced the magnitude of floods. The mean annual discharge at Greendale was 59 m^3/s for the

Table 1
Summary of geomorphic characteristics in the study area

Characteristic	Red Canyon	Upper Browns Park	Swallow Canyon	Lower Browns Park			Canyon of Lodore
				Lower Browns Park I	Swinging Bridge Canyon	Lower Browns Park II	
Reach extent (km)[a]	0–18.1	18.1–39.0	39.0–42.7	42.7–48.3	48.3–51.0	51.0–76.0	76.0–104.2
Reach type[b]	DF	DF/RM	FM	RM	FM	RM	DF
Reach length (km)	18.1	20.9	3.8	5.6	2.8	25.0	28.2
Average gradient	0.0021	0.0015	0.0005	0.0004	0.0002	0.0003	0.0029
Bedrock[c]	pCu	pCu and Tbp	pCu	Tbp	pCu	Tbp	pCu and Paleo.
Bed material	cobble/gravel	gravel/sand	sand/gravel	sand	sand	sand	sand/gravel/cobble
Number of eddy deposits	23	4	0	0	0	0	46
Eddy deposits per kilometer	1.3	0.2	0	0	0	0	2
Number of debris fans	31	9	3	0	1	3	81
Debris fans per kilometer	1.7	0.4	0.8	0.0	0.4	0.1	2.8
Alluvial valley width (m)	65	266	56	617	111	906	88
Channel width (m)	54	65	53	98	98	141	56
Valley width : Channel width	1.20	4.11	1.06	6.27	1.14	6.43	1.57
Gravel bars (ha)	9.09	7.47	0.02	0.00	0.00	0.00	21.18
Gravel bar area per kilometer (m)	5.0	3.6	0.0	0.0	0.0	0.0	0.8

[a] Distance downstream from Flaming Gorge Dam.
[b] Reach type designations: DF is canyon dominated by debris fans, RM is restricted meanders, FM is fixed meanders. Upper Browns Park is transitional from debris fan-dominated canyon to restricted meander.
[c] pCu is highly resistant pre-Cambrian quartzite of the Uinta Mountain Group of formations. Tbp is highly erodible Tertiary Browns Park Formation. Paleo. is an assemblange of highly resistant and resistant Paleozoic sedimentary formations.

period between 1951 and 1962 and 58 m^3/s for the post-dam period between 1963 and 1996. The pre-dam (1895–1962) 2-year recurrence flood was 339 m^3/s, and the post-dam 2-year flood is 147 m^3/s, a reduction of 57% (Fig. 2). This reduction in flood magnitude greatly exceeds reductions that resulted from early twentieth-century climate change (Allred and Schmidt, 1999; Grams and Schmidt, 2002).

2.3. Studies of channel adjustment on the Green River

Channel adjustments following the closure of Flaming Gorge Dam have been described for various segments of the Green River between the dam and the Colorado River confluence, 675 km downstream (Graf, 1978; Andrews, 1986; Lyons et al., 1992; Allred and Schmidt, 1999; Merritt and Cooper, 2000; Grams and Schmidt, 2002). These studies employed a variety of methods in diverse study areas, and consistently documented that channel width decreased from 10% to 20%. Determination of the time frame of adjustment is limited by the available data, and some studies have much greater detail, but all indicate that channel narrowing occurred sometime between the 1930s and the present (1980s or 1990s). Because regional climate variations, reservoir construction, and the introduction and spread of exotic vegetation all impacted the Green River during this period, the relative role of each of these factors is difficult to determine.

The precise timing of the onset of channel narrowing is best constrained in the record of bed elevation and channel width near Green River, Utah, 475 km downstream from Flaming Gorge Dam (Allred and Schmidt, 1999). This record indicates two distinct episodes of channel narrowing during the twentieth century. The first episode occurred between 1930 and 1940, during a period of below average annual peak flows that coincided with the introduction and spread of tamarisk (*Tamarix ramosissima*) in the southern Colorado Plateau (Clover and Jotter, 1944; Christensen, 1962; Graf, 1978). The second episode of narrowing began in 1959 and continued until after the closure of Flaming Gorge Dam. This was a period of naturally low peak flows, immediately followed by

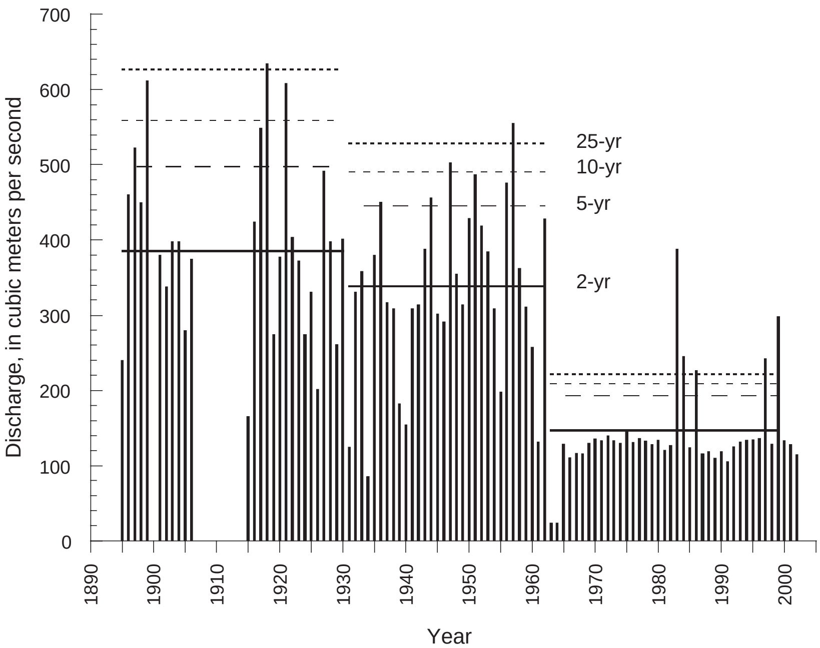

Fig. 2. Annual maximum discharge of the Green River near Greendale, UT. The horizontal lines indicate the magnitudes of the 2-year, 5-year, 10-year, and 25-year recurrence flows for the pre-dam post-Flaming Gorge Dam periods of record. Recurrence intervals were determined using the Log-Pearson Type III distribution. The first post-dam water year is 1963, beginning October 1, 1962. The maximum capacity of the power plant is 130 m^3/s.

artificially low flows during the period of reservoir filling, demonstrating that a sustained period of low peak flows and vegetation establishment are both requisite for channel narrowing.

Channel narrowing in meandering portions of Browns Park was reported by Andrews (1986) and Merritt and Cooper (2000). Andrews (1986) measured channel width from aerial photographs at approximately 1.6-km intervals in Lower Browns Park and reported a 13% decrease in channel width between 1951 and 1980. Merritt and Cooper (2000) reported a 9% decrease in average width between 1954 and 1994 for a study site within Lower Browns Park II (Fig. 1). Andrews (1986) attributed narrowing to bed incision and decreased channel capacity, rather than in-channel deposition. As described below, however, there is no evidence of bed incision in any reach downstream from Flaming Gorge Dam.

Processes of channel narrowing have been described for restricted meandering reaches (Andrews, 1986; Allred and Schmidt, 1999; Merritt and Cooper, 2000; Grams and Schmidt, 2002), fixed meanders (Grams and Schmidt, 2002), and canyons dominated by debris fans (Grams and Schmidt, 2002). Most studies in meandering reaches report that channel width decreases by vertical accretion of fine-grained sediment on the channel margins and in formerly active side-channels (Andrews, 1986; Allred and Schmidt, 1999; Grams and Schmidt, 2002). Merritt and Cooper (2000) described (1) channel narrowing by the establishment of new floodplains on the channel margins, (2) erosion of the pre-dam floodplain (now a terrace) at vertical cutbanks, and (3) additional channel narrowing by the emergence and growth of mid-channel sand deposits. They suggested that the eroding banks are the primary sediment source of the post-dam in-channel deposits and argue that the formation of the mid-channel islands represents a transition from meandering to braiding processes within Browns Park. Although these findings were implied to be representative of Browns Park, their analyses were limited to a 1.5 km site within Lower Browns Park II near the mouth of Vermillion Creek.

3. Computation of sediment budget

Computation of sediment budgets invariably demands compromise between the desire to gain insight about associated channel response and the need to faithfully describe the inherent uncertainty of measurements and calculations. In the case of budgets for regulated rivers, the range in precision and accuracy of available data is typically wide. Some mainstem stations may have detailed data making it possible to calculate annual sediment loads confidently and evaluate shifts in transport relations. However, tributaries and other mainstem stations may have far less data and shifts in transport relations may not be detected. Important tributaries may have no records at all. Thus, one must employ different methods in analyzing various budget components in order to produce one integrated budget, and the different components necessarily have different uncertainties.

The sediment budget for the study area illustrates these issues and problems. We calculated the sand mass balance for the Green River in the study area using all available measurements of bed-material load (including measurements of transport on the bed and in suspension). Because fine-grained deposits that comprise the alluvial deposits of management interest are primarily sand, we calculated the budget for the sand fraction of the bed material load. This mass balance may be expressed as:

$$I_{\mathrm{GRG}} + I_{\mathrm{RC}} + I_{\mathrm{VC}} + I_{\mathrm{YR}} + I_{\mathrm{ugt}} = \Delta S + E_{\mathrm{GRJ}} \qquad (1)$$

where the terms on the left are influx at Greendale (I_{GRG}), Red Creek (I_{RC}), Vermillion Creek (I_{VC}), the Yampa River (I_{YR}), and ungaged tributaries (I_{ugt}). The efflux from the study area is measured at Jensen (E_{GRJ}). Differences between influx and efflux are changes in storage (ΔS).

Each term in the budget represents a station for which sediment records are available or a stream that is a significant sediment source. Good records of suspended sediment concentration and bedload transport are available for a few stations in the study area, but large contributing drainage areas are unmeasured and the temporal record for some measurement stations is very short. The Greendale gage is the measurement station immediately downstream from Flaming Gorge Dam for which some pre- and post-dam sediment records are available. Red Creek and Vermillion Creek are the two largest tributaries that flow into the Green River within the study area, located 18 km and 70 km downstream from the dam, respectively. They each have streamflow gaging stations that were operated for short periods in the 1970s (Red Creek near Dutch John [station 09234700] and Vermillion Creek near Ink Springs Ranch [station 09235450]). A limited number of suspended sediment samples were collected on Red Creek, none are available for Vermillion Creek. For the Yampa River, streamflow and sediment records are available for a gage located about 120 km upstream from the confluence with the Green River (Yampa River near Maybell [station 09251000] and a major tributary to the Yampa River that is downstream from that gage (Little Snake River near Lily [station 09260000]). The Jensen gage (station 09261000) on the Green River is 45 km downstream from the study area (Fig. 1) and has long-term pre- and post-Flaming Gorge Dam streamflow and sediment records. This network of measurement stations leaves an ungaged contributing area of approximately 5700 km^2 upstream from the gage on the Green River at Jensen.

The uncertainty in the sediment flux for each component of the budget varies greatly, and is significant in all cases. Our estimates of mean annual sand load may be divided into three categories: (1) loads estimated based on published daily loads for an extended period of record, (2) loads estimated from rating relations derived from abundant measurements, and (3) loads approximated from very few or no measurements.

For stations with daily measurements for a long period of record, the mean annual load may be calculated either from a transport relation or as the sequential summation of daily loads. Topping et al. (2000) described the sources of error in estimates of sediment load for stations on the Colorado River and showed that sequential summation of short-term loads led to a different sediment budget than extrapolation of a sediment transport relation that was erroneously assumed to be stationary. We applied this method to the data from the Jensen and Red Creek gages. The Jensen gage has published daily loads for 14 pre-dam years and 16 post-dam years, and the Red Creek gage has published daily loads for 5 years. Daily loads were summed to determine the total load for each year. These were averaged to calculate the mean annual load (Table 2). Annual loads were averaged separately for the pre- and post-dam periods at Jensen. We applied a 5% uncertainty to the estimates for the Jensen gage and a 10% uncertainty to the estimates for the Red Creek gage. Topping et al. (2000) argued these to be reasonable error estimates for mainstem and tributary stations with daily data for long and short periods of record, respectively.

For stations that do not have published daily loads, but do have a large number of good quality measurements, we developed sediment rating relations and estimated daily loads based on these relations. Each of these stations has stable sediment rating relations for the period presented in Table 2. Thus, the relations for the Yampa River stations can be considered representative for the period of record (1950s to present), while the relation for the Greendale station represents two pre-dam years with average and above average runoff (Fig. 2). Uncertainty in the mean annual load was estimated as the standard error of the mean from the rating relation regressions (Table 2). These uncertainties range from 11% to 34% of the calculated mean annual loads.

For two stations that have poor or no data, we approximated the annual loads. The record for the Greendale gage in the post-dam period consists of 127 measurements that, because of wide scatter, are not useful for developing a rating relation. These data do, however, indicate that post-dam loads at Greendale are greater than zero, and should not be ignored. The post-dam load at Greendale likely originates from a small ungaged tributary that is immediately downstream from the dam or from delta deposits of a larger tributary that flows into the reservoir just upstream from the dam. To determine a reasonable approximation of this post-dam supply, we calculated daily loads for the measurements, averaged these to determine a mean daily load, and then converted these to mean annual loads. Vermillion Creek is a tributary with a large contributing drainage area but no measurements of sediment transport. We approximated its load to be equal to that of Red Creek, because they have similar mean annual flow. The error in the Greendale estimate is assumed to be 100%, and the error in the Vermillion Creek estimate is assumed to be 50%.

Table 2
Mean annual suspended sediment loads and estimates of error

Station	Period of streamflow record	Period of sediment record	Number of measurements	Regression for total load (log Qs)	R^2	Percent sand	Mean annual loads[a]		
							Suspended (Mg × 1000)	Bed (Mg × 1000)	Sand (Mg × 1000)
Green River in study area									
Green at Greendale (pre-dam)	1950–1962	1957–1958	247	$2.277 * \log Q - 1.101$	0.86	40	1158	–	463 ± 115
Green at Greendale (post-dam)	1963–2001	1975–1988	127	–	–	44	18	–	8 ± 8
Red Creek	1971–1976	1971–1976	69	–	–	29	75	–	22 ± 2
Yampa River basin[b]									
Yampa near Maybell	1916–2001	1951–1993	599	$1.908 * \log Q - 0.553$	0.87	29.9	443	–	132 ± 23
Little Snake at Lily	1922–2001	1958–2001	684	$1.340 * \log Q + 1.639$	0.64	36	1012	291	654 ± 71
Green River downstream from Yampa River confluence									
Green at Jensen (pre–dam)	1952–1962	1948–1962	4525[c]	–	–	22	7160	–	1575 ± 79
Green at Jensen (post–dam)	1963–2001	1963–1979	5639[c]	–	–	30	2920	–	876 ± 44

[a] See text for explanation of load and error estimates.
[b] These stations have intermittent records with large gaps. The total load for the Yampa River is calculated as the sum of the loads of the Yampa River near Maybell (station 9251000) and the Little Snake River at Lily (station 9260000).
[c] Number of actual concentration measurements, daily loads estimated by the USGS are available for every day of the record.

The pre- and post-dam mass balances calculated from the annual load estimates in Table 2 are presented graphically in Fig. 3. For the pre-dam period, the sum of the loads contributed by the Yampa and Green rivers upstream from the confluence agrees with the pre-dam load measured downstream from the confluence at Jensen, within uncertainty in the load estimates. Part of the difference between the load at Jensen and the sum of the upstream inputs likely results from unmeasured input to the reach from ungaged tributaries. The post-dam budget shows a similar result. The load delivered by the Yampa River is unchanged, but the sum of the Yampa and Green river loads is consistent with the load measured at Jensen within measurement uncertainty. Thus, this budget illustrates the relative magnitudes of pre- and post-dam sand loads on the Green River. This budget cannot, however, be used to predict channel adjustment for the study area, because the direction of changes in the budget is indeterminate. For the pre- and post-dam cases, the load estimates for adjacent reaches are relatively close and the uncertainty comparatively large. Any given reach could be in surplus, deficit, or equilibrium. The only way to assess channel adjustment is by direct measurement, and because the indeterminacy of the budget suggests that changes may not be dramatic, robust measurements of channel adjustment are required.

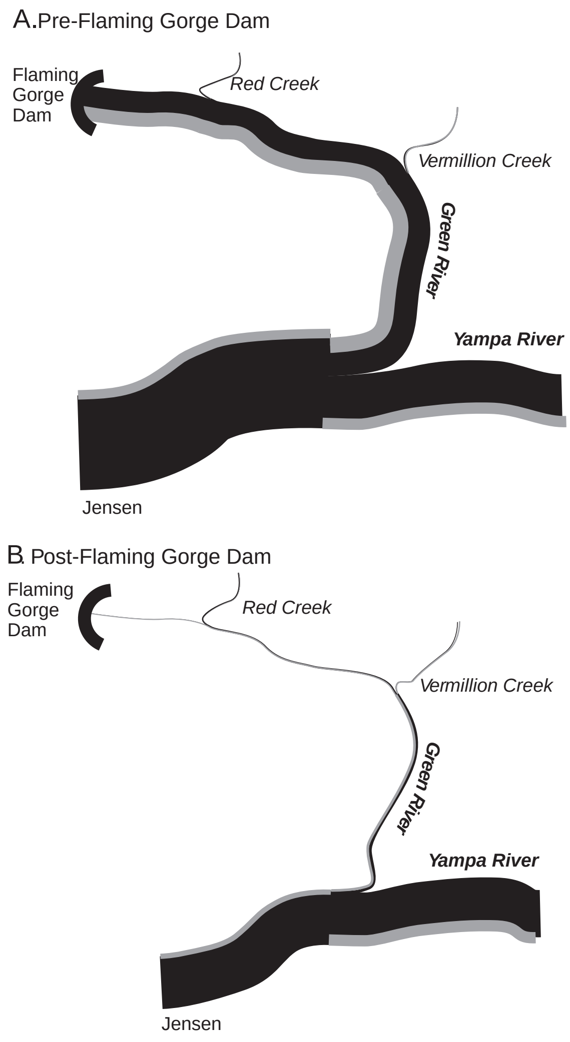

Fig. 3. Estimated pre- and post-Flaming Gorge Dam sediment mass balance for the Green River between the dam and the gage near Jensen, Utah. Line thickness is proportional to calculated sand load for each river segment. The gray portion of each line represents the magnitude of uncertainty, such that the width of the black line is the minimum estimated load and the width of the sum of the black and gray lines is the maximum estimated load. The mismatch between the sum of the upper Green and the Yampa loads compared with the load of the Green downstream from the Yampa indicates an apparent sediment deficit, that in both the pre- and post-dam cases is within the uncertainty of the sediment flux estimates (Table 2).

4. Adjustments of the bed

Change in bed elevation can be detected accurately only by repeat topographic or bathymetric measurements of the channel bed. Such measurement programs are sometimes initiated at the time of dam construction for design and monitoring purposes (e.g. Pemberton, 1976). Downstream from Flaming Gorge Dam, channel cross-sections were surveyed only in the immediate vicinity of the dam and these were not monumented and never repeated. The only other pre-dam measurements of bed elevation within the study area are contained in the discharge measurement records from USGS gage stations. These stations are the Greendale gage in Red Canyon and two separate gage and cableway locations of the abandoned Bridgeport gage (station 9235000) in Browns Park.

4.1. Methods

We obtained historical descriptions, measurement notes, and photographs for the USGS stations within the study area and analyzed the records of channel width, mean bed elevation, and minimum bed elevation. Smelser and Schmidt (1998) provide a comprehensive review of methods for gage station analysis. Details pertinent to the Greendale and Bridgeport gages are discussed below.

The record for the Greendale gage includes measurements from the pre- and post-dam periods. The original Greendale gage and cableway are now submerged under Flaming Gorge Reservoir. The station was relocated to its current position 0.7 km downstream from Flaming Gorge Dam in September 1959, retaining the same name and station number. The pre-dam record includes 100 measurements made at the original cableway and 42 measurements made at the present location. The post-dam record consists of 390 measurements made between October 1962 and March 2001, all made from the same cableway.

The Bridgeport gage was operated from 1911 to 1917. The original gage was installed on October 13, 1911, by E.C. LaRue in the sand-bedded portion of Lower Browns Park (Fig. 1). Six discharge measurements were made at this location before the station was moved in 1914 to a location 9 km upstream, where an additional 11 discharge measurements were made. We refer to the original gage location as the lower Bridgeport gage and cableway and the second location as the upper Bridgeport gage and cableway. The cableway used to make the discharge measurements at the upper Bridgeport site remains suspended across the river, although it is no longer in use. Remnants of the original gage house and a brass marker establishing the gage datum are also present. We surveyed the channel bed under the cableway in October 1999 and compared these measurements with the measurements made between 1914 and 1916, using the original gage datum as a stable reference elevation. At the site of the lower Bridgeport gage, we were unable to find any remnants of the actual gage or the local arbitrary reference datum, which precludes precise correlation between modern measurements of bed elevation and the historical measurements.

In addition to the measurements that can be used to compare pre- and post-dam bed elevations, we have a 10-year record of post-dam bed elevation for a study site at the downstream end of Lower Browns Park (Fig. 1). These data consist of bed topography measured at monumented channel cross-sections established in 1994 and resurveyed at irregular intervals between 1995 and 2004.

4.2. Results

The record of minimum bed, or thalweg, elevation for the Greendale gage shows that the bed has been remarkably stable (Fig. 4). The measurements do indicate annual scour and fill in some years that is associated with high peak flows. The average magnitude of this scour is about 0.18 m, which is on the order of the median bed material size and, therefore, probably within measurement error. The magnitude of scour has not progressively increased or decreased

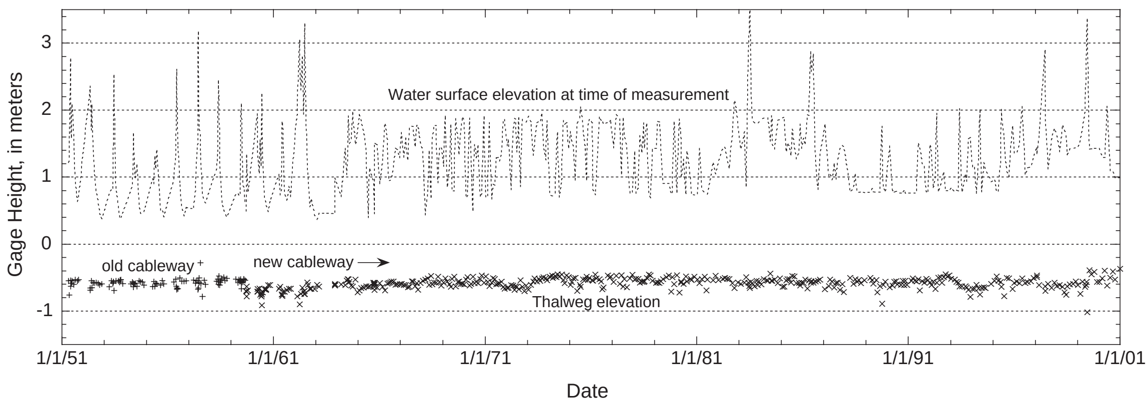

Fig. 4. Time series of thalweg elevation of the Green River at the Greendale gage. Elevation is relative to gage datum. Thalweg elevation is taken from the maximum depth measurements recorded on the discharge measurement notes. Annual changes in thalweg elevation are on the order of the median size of the bed material.

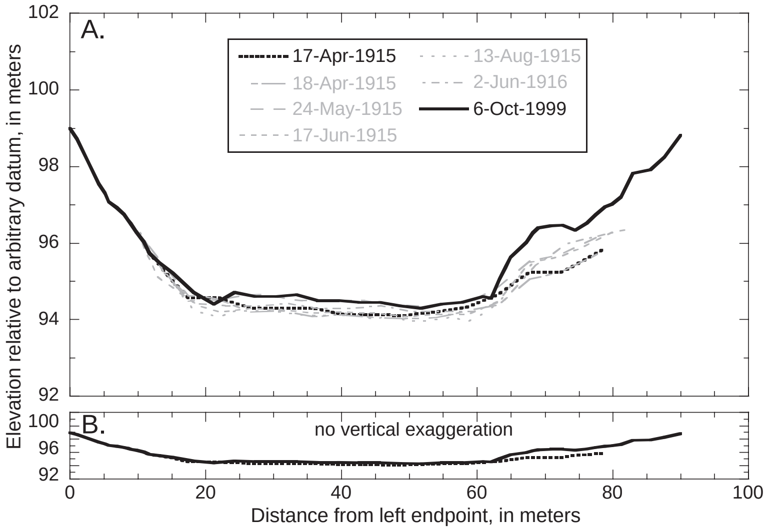

Fig. 5. Plot of bed elevation derived from discharge measurements at the upper Bridgeport cableway that were made in 1915, 1916, and 1999. No measurements were made between 1916 and 1999. These measurements show that there has been aggradation of the bed since 1916, but that this aggradation is only slightly above the range of bed elevations measured in 1915 and 1916.

during the period of record, consistent with the observation of a stable thalweg elevation.

The 1915 and 1916 discharge measurements made at the upper Bridgeport gage show minimum bed elevations that span a range of approximately 0.5 m (Fig. 5). The 1999 measurement of the same cross-section shows the bed near the upper end of that range. While these data do not provide a rich record of annual scour and fill, they do demonstrate that current streambed elevations in Browns Park are not significantly different from those measured almost a century ago.

The repeat measurements of channel cross-sections at the downstream end of Browns Park show the range of bed elevation adjustments that occur in the sand-bedded portion of the study area in the post-dam period. Some of these measurements were made during peak power plant releases and show the bed in a scoured condition (Fig. 6). Subsequent measurements show that the bed refilled to pre-flood

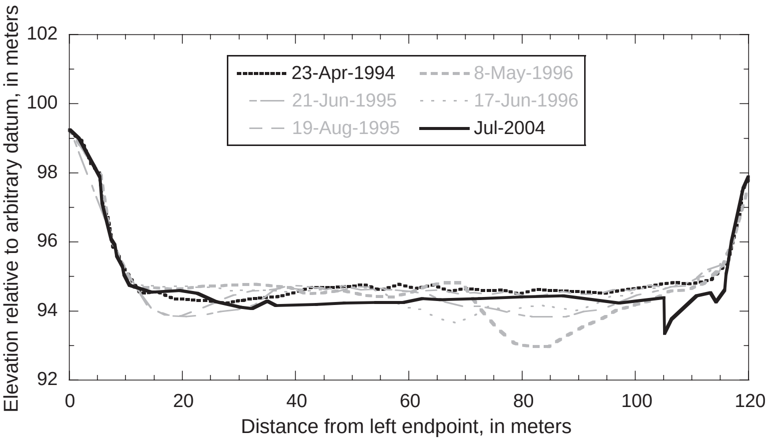

Fig. 6. Plot of bed elevations measured between 1994 and 2004 for a cross-section near the downstream end of Lower Browns Park II. These measurements show scour during maximum power plant releases (May 1996), and subsequent fill (June 1996 and July 2004).

elevations or higher (June 1996). Presumably, the bed also scoured during events in excess of peak power plant capacity that occurred in 1997 and 1999 (Fig. 2). The 2004 measurement shows that the bed recovered from those events and that there has not been net change in bed elevation since 1994.

5. Adjustments of the active channel and floodplain

Changes in channel width and planform are documented by repeat mapping from aerial photographs, analysis of historical oblique photographs, and analysis of gage station records. The records from gage stations and oblique photographs provide detailed site-specific information. Aerial photographs provide comprehensive data for the study area and allow spatially robust quantification of the magnitude of channel adjustment.

5.1. Methods

5.1.1. Mapping from aerial photographs

We mapped all alluvial deposits in the study area to measure pre- to post-dam changes in channel morphology and to evaluate differential response among the reach types. The maps were compiled in a geographic information system (GIS), which includes surface texture, depositional environment, and formative flow regime as descriptors of each deposit. The reaches from Red Canyon to Lower Browns Park were mapped from aerial photographs taken in September 1938 and August 1999 (Table 3). Portions of the study area were also mapped from photographs taken in 1954. The Canyon of Lodore was mapped by Grams (1997), using aerial photographs taken in August 1993.

Table 3
Dates of aerial photographs used in study and discharge at time of photograph

Date	Distance downstream from dam (km)	Discharge (m^3/s)	Source of discharge measurement[a]
9/18/1938	0–27.4	34.5	Linwood, UT
9/19/1938	27.4–50.4	31.7	Linwood, UT
9/21/1938	50.4–75.2	28.6	Linwood, UT
8/23/1954	47.3–75.2	31.1	Greendale, UT
1954 (date unknown)	0–19.3	–	–
8/28/1999	0–75.2	36.8	Greendale, UT

[a] No major tributaries join the Green River between the Linwood (station 9225500) and Greendale gages.

The maps were drawn on overlays on the aerial photographs, which were digitized into a GIS using control points identified on digital orthophotographs for geo-referencing. The root-mean square (RMS) error between the digitized reference points and the known coordinates of those reference points provides a measure of digitizing accuracy. The average RMS errors were 1.0 m for the mapping from the 1999 photographs, 1.3 m for the 1938 photographs, and 10.3 m for the 1954 photographs. The error in 1938 and 1999 mapping is on the order of pencil-line thickness and is acceptable for evaluating change between those years. Because the error associated with the 1954 photographs is much larger, those maps were used mainly for qualitative analyses.

Classification of surface texture as fine- or coarse-grained alluvium provides an approximate characterization of the mobility and adjustability of each deposit. Fine-grained alluvium includes all sand, silt, and clay deposits. Coarse-grained alluvium, or "gravel," includes all gravel- and cobble-size material. The surface texture of channel-side and in-stream deposits was determined in the field.

Depositional environment is used to identify differences in patterns of alluvial deposition and styles of channel adjustment among the reaches. Channel-margin deposits consist of fluvial sediments deposited by downstream-directed flow and are typically horizontally bedded, vertical-accretion deposits. In the canyons and fixed-meander reaches, channel-margin deposits typically occur as 1- to 10-m wide bands on either side of the channel. In restricted meandering reaches, channel-margin deposits may be 100s of meters wide. Scroll topography on channel-margin deposits in the meandering reaches indicates lateral migration of the channel. Eddy deposits within fan–eddy complexes are characterized by sedimentary features that indicate deposition by flow that is directed upstream relative to the main current (Rubin et al., 1990). Because current directions cannot be directly interpreted on aerial photographs, deposit form and location were used to identify eddy deposits. Eddy deposits are abundant in the canyons and rare in the restricted and fixed meanders. Deposits separated from either bank were mapped as islands, and the regions between islands and banks were mapped as side channels. Islands and side channels are common in the canyons and the restricted meander reaches, but rare in the fixed meander reaches. Islands in the canyons and in Upper Browns Park are typically gravel bars partially covered by a veneer of fine sediment. Most islands in the restricted meander reaches are mid-channel sand bars.

The classification of formative flow regime provides a basis for assessing erosion and deposition in the channel and on the floodplain. Formative flow regime was interpreted based on the relative elevation of each deposit, identified in the field and by inspection of the aerial photographs in stereo. Four elevation categories and corresponding formative flow regimes were identified. Deposits that are bare sand and gravel or are sparsely covered with annual vegetation are *active* alluvial deposits. These deposits are formed by flows lower in magnitude than the post-dam average flood (see Table 3 for discharge shown in the aerial photographs). The *post-dam floodplain* is the portion the floodplain inundated every year by the peak power plant discharge of 130 m^3/s, which is also the magnitude of the post-dam average flood (Fig. 7). The *intermediate bench* is higher in elevation and inundated in the post-dam era only by flows greater than power plant capacity, between 130 and 340 m^3/s. Flows of this magnitude occurred in the 1980s, in 1997, and in 1999. The intermediate bench ranges from 0.5 to 1.0 m above the post-dam floodplain, depending on reach characteristics. Both of these surfaces are at least partially covered by perennial woody vegetation including tamarisk, willow (*Salix* sp.), or cottonwood (*Populus deltoides*). The post-dam floodplain and intermediate bench deposits are referred to collectively as *post-dam deposits*. The fourth deposit level category is the *cottonwood–boxelder terrace* (c–b terrace), which was mapped as a terrace because it has not been inundated in the post-dam flow regime. The surface of the c–b terrace is 1.5 to 2.0 m above the elevation of the post-dam floodplain and is inundated by flows on the order of the pre-dam average flood or greater (>340 m^3/s). Cottonwood trees are the dominant riparian vegetation on the c–b terrace in the meandering reaches and boxelder (*Acer negundo*) are most abundant in the canyons.

The map units used for the pre-dam photographs are more generalized than those described above, because field verification of historical deposits is not possible. All mapping was done while viewing the photographs in stereo. The elevation category of each deposit was determined relative to the c–b terrace, which has not aggraded or degraded significantly since the time of the pre-dam photographs. Deposits covered with vegetation and topographically below the terrace were mapped as floodplain and deposits with no vegetation were mapped as active channel.

5.1.2. Measurement of channel change

Comprehensive maps of river segments that can be made from aerial photographs provide robust measures of channel adjustment and eliminate uncertainty that results from sample measurements derived from short reaches or individual cross-sections. However, errors in map registration and digitizing that arise from the limits of the resolution of the photographs, distortion in the photographs, and the quality of the reference base map all introduce error. The level of

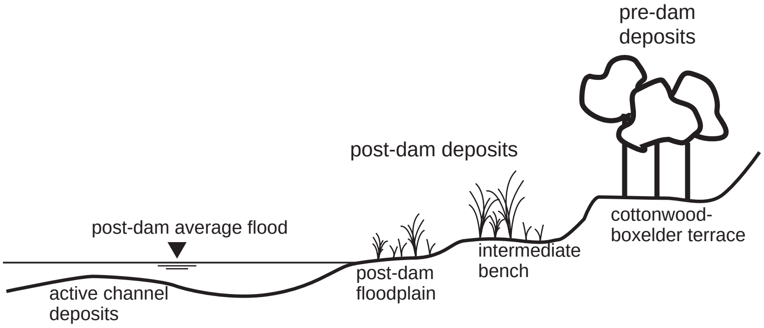

Fig. 7. Sketch showing mapped geomorphic levels and the stage of the post-dam average flood (~120 m^3/s).

uncertainty may multiply when maps derived from different years of photography are compared. Although RMS errors provide a measure of spatial accuracy, they do not describe the accuracy of areal measurements derived from the maps. We constrained the uncertainty in measurements of channel change by performing three redundant analyses. While each method has error, we show that some methods are better suited than others for certain reach types and that by using multiple methods of analysis, error can be reduced.

In the first two methods, the maps derived from the 1938 and 1999 aerial photographs were compared to calculate changes between those dates. In method I, the maps were overlain in a GIS and the elevation category, or formative discharge, of each deposit was compared (Fig. 8A–C). Where active channel deposits were replaced by post-dam floodplain or intermediate bench deposits, "new" floodplain deposits were identified. Where open water was replaced by post-dam floodplain or intermediate bench deposits, "aggraded" floodplain deposits were identified. Where pre-existing terrace or floodplain deposits were replaced by active channel or open water, erosion was identified. This method requires the highest level of accuracy in mapping, because the two maps must overlay precisely to determine changes correctly.

In method II, changes were measured without performing a direct overlay of the maps (Fig. 8D–E). The area of the active channel was measured separately in each the 1938 and 1999 maps, and the net change in channel area was calculated as the difference between these measures. This method does not provide detail about how the deposits changed and the spatial pattern of those changes. The advantage of this method is that it does not require that the two maps overlay precisely, but only that each data set is internally consistent such that the area of each deposit is calculated accurately.

The third method for measuring channel adjustment utilizes our interpretation of the formative events for each deposit depicted in the 1999 maps (Fig. 8F). Based on analysis of pre-dam aerial photographs and over 70 pre-dam oblique photographs, Grams and Schmidt (2002) determined that the post-dam floodplain and intermediate bench map units identified in the field and on the most recent aerial photographs did not exist in the pre-dam period. Our analysis of aerial and oblique photographs in the current study area support that conclusion. Using only the maps made from the 1999 aerial photographs, the area of "new" floodplain was calculated as the sum of the areas of post-dam floodplain and intermediate bench deposits. The advantage of this method is that the calculations rely only on the most recent aerial photographs, which are the highest quality and most detailed. The ability to quantify the area of channel adjustment independent of the historical aerial photographs is especially critical in the narrow canyon reaches. In the canyons, shadows obscure much of the channel on the pre-dam photographs, which limits the detail that may be mapped. Because the deposits in canyons tend to be narrower and smaller than deposits in meandering reaches, small errors in map registration can affect a larger proportion of the total deposit area. Thus, the reaches that have the poorest quality data require the greatest accuracy.

The three methods for calculating channel adjustment agree well in most of the reaches (Table 4). The methods disagree most in Swallow Canyon, because the 1938 photographs have large areas obscured by deep shadows. Thus, methods I and II have the largest uncertainty in this reach. In the Lower Browns Park reaches, 5–8% less narrowing is indicated by method I than by method III. This is because method III only tracks the formation of new floodplain deposits and does not explicitly identify erosion of pre-dam deposits, while method I does. Therefore, method I is the most accurate in meandering reaches where cutbank erosion is a significant process. Method III, based only on the 1999 photographs, is the most accurate in the canyons and fixed meanders where shadows limit the use of old photographs.

5.2. Results

Throughout the study area, open sand bars and bare gravel deposits were abundant in the pre-dam photographs of the river channel and less common in the post-dam photographs. The c–b terrace was present in all photographs, but eroded significantly in parts of some reaches between the pre-dam and post-dam periods. The decline of active channel deposits has resulted from stabilization by woody riparian vegetation and the formation of new inset deposits, the post-dam floodplain and the intermediate bench. This

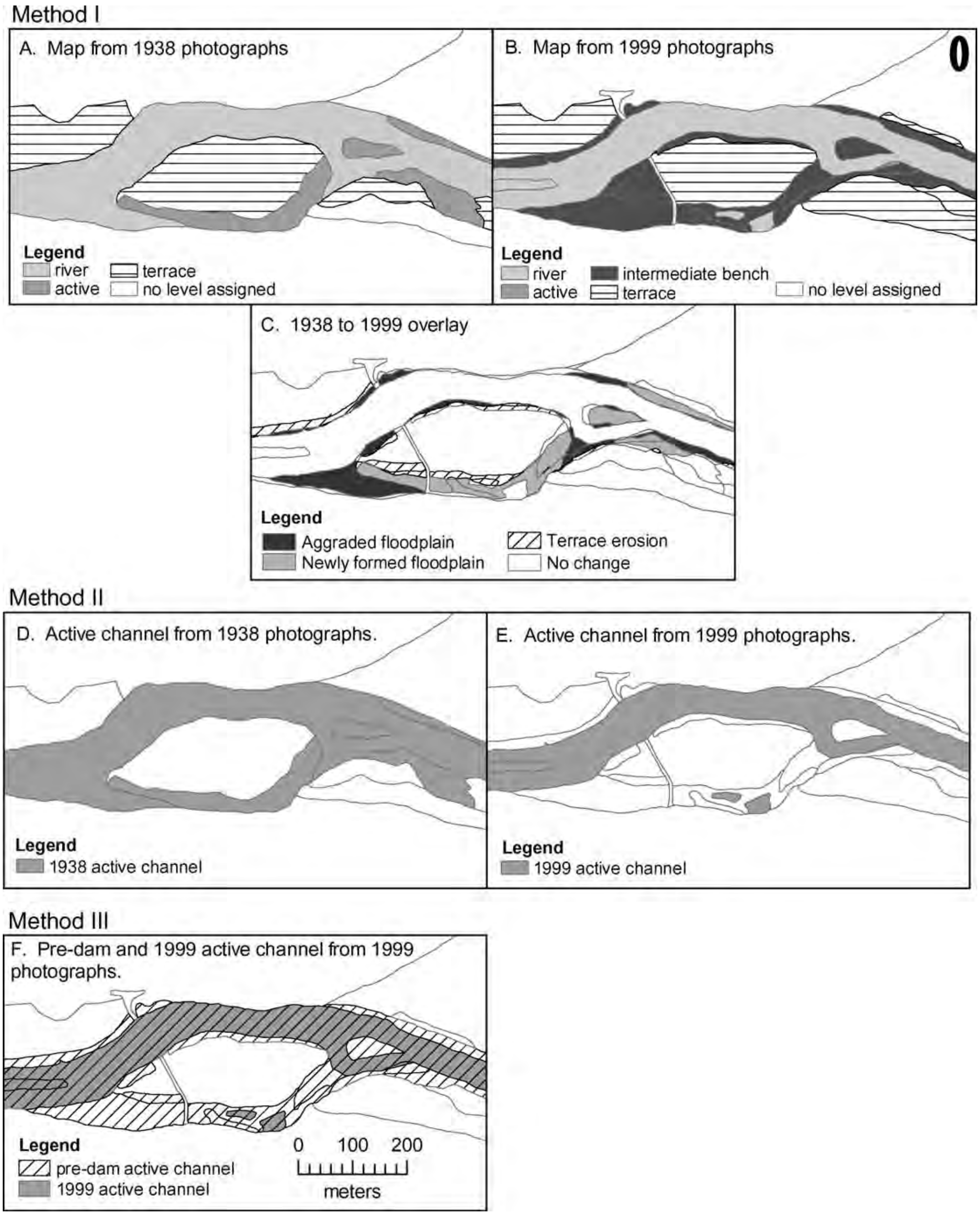

Fig. 8. Comparison of the three methods used to calculate channel narrowing. In method I, the 1938 map (A) and the 1999 map (B) are overlain in the GIS, where the formative discharge of each deposit is compared and used to calculate change in deposit level (C). In method II, the change in active channel area is calculated as the difference in active channel area between that shown on the 1938 aerial photographs (D) and that shown on the 1999 aerial photographs (E). In method III (F) the 1999 active channel area is the same as shown in (E) and the pre-dam active channel area is the 1999 active channel area plus the intermediate bench and post-dam floodplain map units.

Table 4
Change in area of active channel for each reach

Characteristic	Red Canyon	Upper Browns Park	Swallow Canyon[a]	Lower Browns Park I	Swinging Bridge Canyon	Lower Browns Park II	Canyon of Lodore
Active channel width (*m*)							
1938 active channel	59	89	44	149	97	162	na
1954 active channel	62				91	158	na
Pre-dam active channel (from 1999 map)	60	89	55	152	98	173	72
1999 active channel	54	65	53	99	98	141	56
Channel narrowing, m (*percent*)							
Method I - 1938 to 1999 narrowing[b]	4.2 (7%)	22.8 (26%)	0.6 (1%)	44.7 (30%)	–0.7 (–1%)	18.4 (11%)	na
Method II - 1938 to 1999 narrowing by active channel difference[b]	4.8 (8%)	24.4 (27%)	–8.6 (–19%)	50.1 (34%)	–1.0 (–1%)	21.3 (13%)	na
Method III - pre-dam to 1999 narrowing by 1999 map[b]	6.1 (10%)	23.9 (27%)	2.6 (5%)	52.9 (35%)	0.4 (0%)	32.1 (19%)	11.2 (22%)
Proportion of channel narrowing with mapped aggradation							
Aggrading deposits	47%	39%	59%	70%	20%	36%	na

[a]Large areas of shadow on the 1938 photographs in Swallow Canyon skew the 1938 active channel area, 1938 to 1999 narrowing by active channel difference, and the 1938 active channel width.
[b]Shaded boxes are the values most representative of the respective reach. Both method I and method III are shaded for Lower Browns Park II; method I indicates the net change in active channel width, and method III is a measure of total post-dam deposition, which includes post-dam deposits that replace pre-dam active channel and post-dam deposits that replace eroded c–b terrace.

contemporaneous aggradation of alluvial surfaces at multiple elevations is consistent with the observations of Grams and Schmidt (2002) and has been observed on other regulated river systems (Pizzuto, 1994; Schmidt and Rubin, 1995).

Measurable aggradation of fine sediment occurred over about 49% the post-dam floodplain and intermediate bench. Although aggradation may have occurred on a greater proportion of the inset floodplain, it was not detected by our analysis, which is sensitive only to changes in elevation that could be identified on aerial photographs. The aggraded deposits range from a few centimeters to more than 30 cm thick, based on excavations made throughout the study area. Formation of the post-dam floodplain and intermediate bench inset floodplains resulted in some degree of channel narrowing in nearly all of the reaches and up to 50 m Lower Browns Park I (Table 4).

The inset floodplain is composed of different deposit types in different reaches, but consists partly of channel-margin deposits in every reach. In Red Canyon, aggradation of post-dam floodplain deposits on the channel margins caused channel width at the Greendale gage to decrease by about 4 m between 1960 and 2000 (Fig. 9). In Upper Browns Park, the formation of a post-dam inset floodplain as a channel-margin deposit at the upper Bridgeport gage is consistent with repeat measurements of the channel cross-section and excavations of the deposit underneath the cableway. The aerial photographs show that an inset floodplain 12-m wide established between 1938 and 1999 (Fig. 10), consistent with the width of the deposit that repeat cross-section measurements indicate formed between 1916 and 1999 (Fig. 5).

The age of the post-dam floodplain and intermediate bench deposits was determined by dating tamarisk germination events within these deposits near the upper Bridgeport cableway. The upper 1 m of the deposits include up to 9 depositional units. Each depositional unit has internally continuous grain size and bedding, and is distinguished from adjacent units by abrupt changes these characteristics (Fig. 11). The thickest units are fine sands (median diameter between 0.1 and 0.2 mm). Thin interbeds include very fine sand, silt, and clay. Two depositional units are continuous throughout the trench and underlie tamarisk germination horizons. Two tamarisk plants excavated in the trench germinated in or on the clay-rich horizon shown on Fig. 11. The age of these plants at

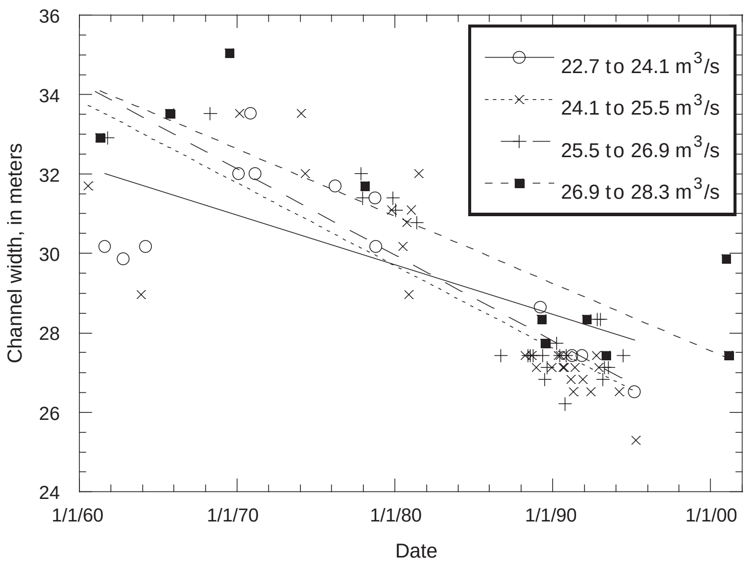

Fig. 9. Time series of channel width at the Greendale cableway from USGS discharge measurement notes. Only measurements made between 22.7 and 28.3 m^3/s were used. These data were divided into increments of 1.4 m^3/s and show that the trend of decreasing width is similar for each increment. Correlation coefficients for the trendlines are between 0.70 and 0.91.

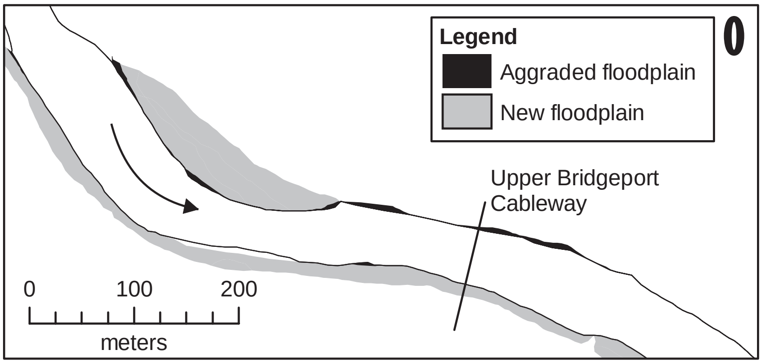

Fig. 10. Map showing aggradation on channel-margin deposits in the restricted meander reach of Upper Browns Park.

the germination surface was between 34 and 38 years, indicating germination between 1962 and 1966. Four additional tamarisk for which the germination point could not be positively identified had minimum ages of between 36 and 40 years. Because the 1962 flood of 428 m^3/s (Fig. 2) was the only event in this period that inundated the elevation of the germination horizon, that is the most likely year of germination. The 0.5 m of deposition that occurred since germination most likely occurred in 1983, during the only other flood that inundated that elevation of the deposit. These data show that this deposit was initially formed by the last large flood prior to dam closure and stabilized by vegetation that became established following that event. Continued aggradation occurred during the one post-dam flood that inundated the deposit. Both the pre- and post-1962 deposits identified in the trench overlie the 1916 bed (Fig. 11B),

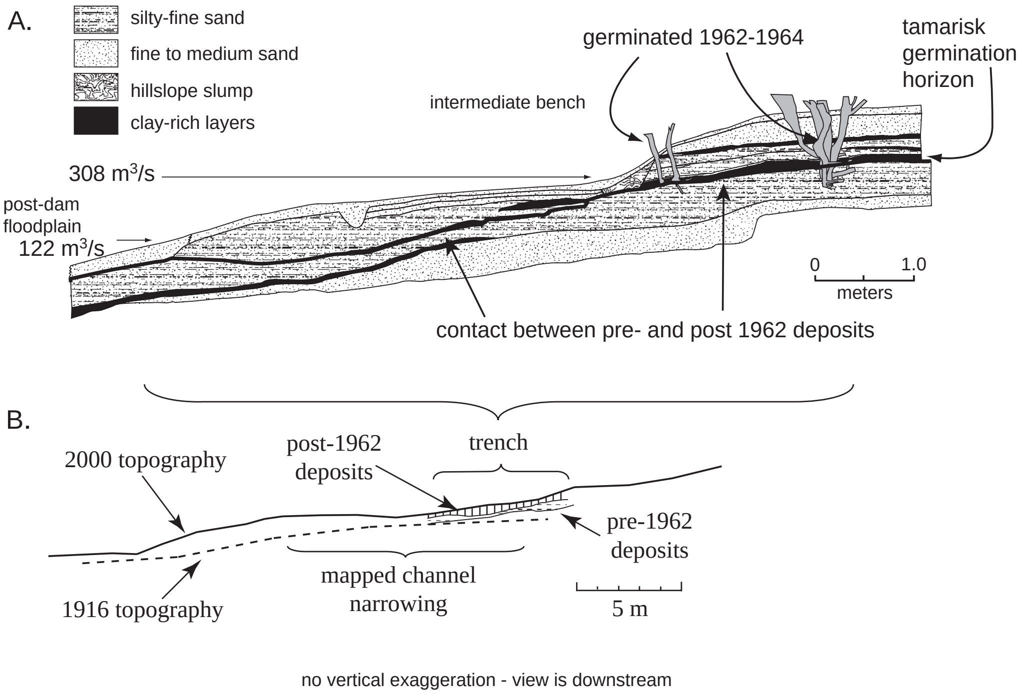

Fig. 11. Stratigraphic cross-section of excavation at upper Bridgeport cableway. Tamarisk germination horizons identify contact between pre- and post-1962 deposits (A). Deposits identified in excavation shown in relation to topography measured in 1916 and 2000 (B).

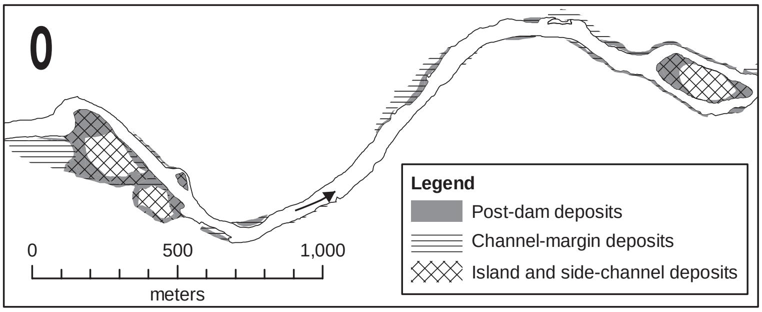

Fig. 12. Map showing channel narrowing caused by aggrading islands and aggradation in side-channels in Red Canyon. The Green River is flowing from left to right.

showing that the post-dam floodplain and intermediate bench are post-dam deposits that cap pre-dam twentieth-century deposits.

Channel narrowing by vegetation establishment and aggradation of inset floodplains occurred throughout the study area, but the magnitude of channel narrowing and the style of channel transformation varied greatly among the reach types. In the fixed meanders, which have the simplest channel morphology, post-dam floodplain formation was limited to channel-margin deposits, and these reaches have the lowest magnitude of channel narrowing (Table 4). The

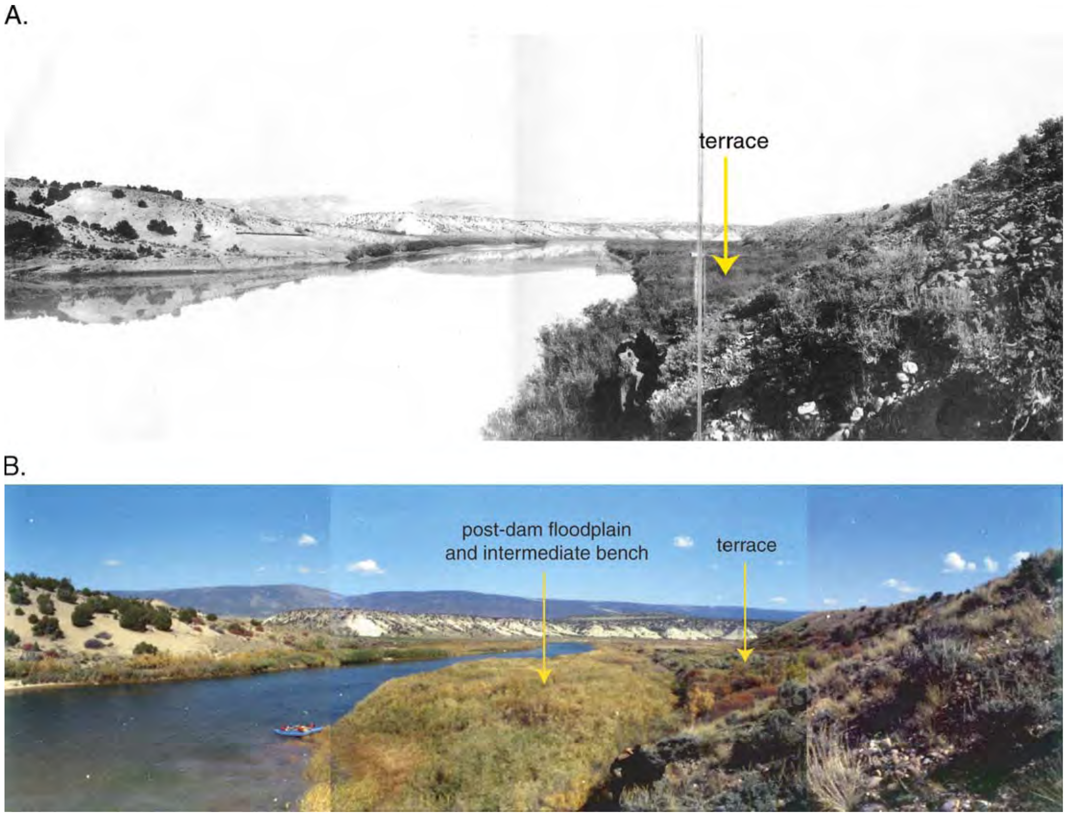

Fig. 13. Photograph looking downstream from the location of the lower Bridgeport gage to the lower Bridgeport Cableway. The original photograph was taken October 13, 1911 by E.C. LaRue (A), and the repeat was taken on October 7, 1999 (B).

canyons and the restricted meanders have more complicated channel morphology, and exhibited different styles and greater magnitudes of channel narrowing.

In the canyons dominated by debris fans, much of the channel narrowing occurred by the transformation of large parts of formerly active gravel bars into post-dam floodplain and intermediate bench surfaces (Fig. 12). Fine-grained deposits accreted on bar surfaces and along bar margins, which caused channel narrowing and in some cases resulted in the attachment of gravel islands to the adjacent bank. Narrowing by this mechanism accounted for 43% and 29% of the total area of channel narrowing in Red Canyon and the Canyon of Lodore, respectively.

The deposits of the restricted meander portions of Upper Browns Park and Lower Browns Park include mid-channel islands, point bars, and broad floodplains. The pre-dam photographs of these reaches show that there were large gravel bars in Upper Browns Park and large sand bars in Lower Browns Park. In Upper Browns Park, where gravel bars are common, aggradation on these deposits occurred in a pattern similar to that observed in the canyons. Towards the downstream end of Upper Browns Park, where the bed is mixed coarse and fine sediment and gravel bars are less frequent, most of the post-dam surfaces established along the channel margins (Fig. 10).

In Lower Browns Park, channel narrowing occurred by the accretion of large channel-margin deposits on the margins of the c–b terrace, by the aggradation of new mid-channel islands, and accumulation of fine-sediment in side channels. The post-dam channel-margin deposits in Lower Browns Park are large and line most of both banks throughout the reach (Fig. 13). Elsewhere in Lower Browns Park, post-dam deposits completely filled side channels and resulted in the attachment of former islands to deposits on the banks (Fig. 14).

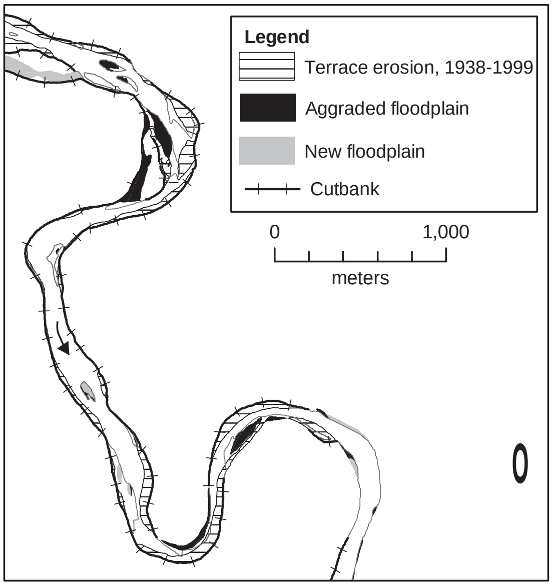

Fig. 15. Map showing meander-bend migration by deposition on point bars and erosion of cutbanks between 1938 and 1999 in Lower Browns Park II.

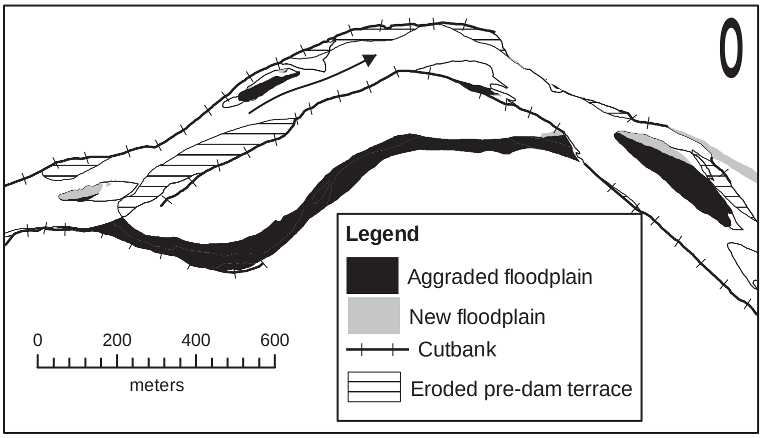

Fig. 14. Map showing aggrading islands and side-channels in Lower Browns Park II. The Green River is flowing from left to right.

New islands composed of post-dam floodplain and intermediate bench deposits have formed in different locations (Fig. 14). The pattern of channel narrowing is most complex in the portions of Lower Browns Park where formation of the inset floodplain was accompanied by erosion of the pre-dam c–b terrace. Much of the post-dam deposition in Lower Browns Park occurred on point bar deposits where the deposition was accompanied by erosion of the c–b terrace on the opposite bank (Fig. 15).

Erosion of the pre-dam c–b terrace, which did not occur in Upper Browns Park or the canyon reaches, was widespread in Lower Browns Park. About 60% of the bank length in the Lower Browns Park reaches is nearly vertical bare soil, and about 60% of those banks eroded measurably between 1938 and 1999 (Table 5). The magnitude of cutbank retreat was greatest in Lower Browns Park II where an average of more than 23 m of terrace was eroded between 1938 and 1999. The rate of terrace erosion was greater in the 1938 to 1954 period (~80 cm/year) than in the 1954 to 1999 period (20 to 40 cm/year). Based on the latter rate, about 13 m of terrace erosion has occurred since dam closure in 1962. The total magnitude of post-dam deposition exceeded this magnitude of erosion by about 19 m, which represents the magnitude of net channel narrowing. Together, erosion of the c–b terrace and deposition on the post-dam floodplain indicates that the post-dam channel, which is fixed in position in the other reaches, is actively meandering in Lower Browns Park.

Table 5
Summary of erosion of terrace deposits and active cutbanks

Parameter	Lower Browns Park I[a]	Swinging Bridge Canyon	Lower Browns Park II
Bank length (km)	12.10	6.22	69.10
Cutbank length (km)	7.49	1.22	40.58
Percent of cutbank that is eroding	62%	60%	62%
Reach-average terrace erosion			
1938 to 1954 (m)	12.5	1.0	12.7
1954 to 1999 (m)	10.3	4.6	16.5
1938 to 1999 (m)	11.0	2.2	23.4

[a] Only 50% of Lower Browns Park I was mapped in 1954. Values reflect averages over the portion of the reach that was mapped.

6. Discussion

6.1. Adjustment of the bed

Widespread or systematic degradation of the bed has not occurred downstream from Flaming Gorge Dam, based on comparison between recent and pre-dam measurements of bed elevation at all locations where such data are available. Studies describing degradation downstream from large dams have shown that erosion of channel controls is typically greatest near the dam and decreases further downstream (Pemberton, 1976; Williams and Wolman, 1984). The record of bed elevation at the Greendale gage demonstrates the long-term stability of the gravel riffle immediately downstream from Flaming Gorge Dam. Stability in this reach is a strong indication that channel controls farther downstream have not degraded. Bed response between channel controls in Red Canyon is, however, not known. Pool segments contain small patches of fine-grained sediment among larger gravels, cobbles, and boulders, and the possibility remains that dam closure and operations have resulted in the evacuation of sediment from these areas. The bed in Upper Browns Park, dominated by long gravel riffles but lacking coarse-grained debris fans, is more adjustable than the bed in Red Canyon. This adjustability is shown by measurements of scour and fill at the upper Bridgeport gage made from 1914 to 1916. These measurements also show that, despite variability, mean bed elevation did not decrease between 1914 and 1999. The cableway traverses mixed sand and gravel bed material between coarser-grained riffles and is probably representative of the parts of upper Browns Park where the bed is most adjustable. The absence of long-term net degradation at this section suggests that the bed has not degraded in Upper Browns Park.

Although repeatable pre-dam measurements of bed elevation in Lower Browns Park do not exist, the available evidence indicates that there has not been net degradation since dam closure. Repeated post-dam measurements of the bed at the downstream end of Lower Browns Park demonstrate a highly adjustable bed with no net degradation, indicating that sand scoured during floods must be approximately balanced by upstream supply.

6.2. Adjustment of the active channel and floodplain

The channel of the Green River narrowed from 10% to 22% in the canyons dominated by debris fans and between 19% and 34% in the restricted meanders. Similar magnitudes of channel narrowing were measured in reaches farther downstream (Andrews, 1986; Lyons et al., 1992; Allred and Schmidt, 1999; Grams and Schmidt, 2002). Only in the short fixed meander reaches have the decreases in channel width been less than 5%. Channel narrowing was accomplished partly by deposition of fine-grained sediment forming inset floodplains and partly by abandonment of pre-dam deposits that are now stabilized by vegetation.

The very different magnitudes of channel adjustment between adjacent reaches result partly from reach geomorphic characteristics and partly from reach position relative to tributary sediment supply locations. For reaches with similar degrees of streamflow regulation and sediment supply, decreases in channel width proportional to pre-dam channel width were greatest in the restricted meanders, somewhat less in the canyons, and least in the fixed meanders (Grams and Schmidt, 2002). The different magnitudes of adjustment between the two canyon reaches within the study area illustrate the effect of tributary sediment contributions. Channel width decreased by an average of 10% in Red Canyon, which is upstream from the mouth of Red Creek. Channel width in the Canyon of Lodore, downstream from Red Creek and Vermillion Creek, decreased by more than 20%. This suggests that sediment contributions from small tributaries can have a large impact on channel morphology in a regulated river.

The style of channel narrowing varied greatly among the canyons, fixed meanders, and restricted meanders (Fig. 16). In all cases, channel width decreased where strips of post-dam deposits accreted along the channel margins, with wider depositional bands in the restricted meanders and the narrowest bands in the fixed meanders. In the canyons, channel narrowing also occurred where fine sediment aggraded on formerly active gravel bars and accumulated in side channels and eddies. In the restricted meanders, channel narrowing occurred by aggradation on broad channel-margin deposits, point bars, new mid-channel islands, and in side channels.

The processes of channel narrowing that we describe for Lower Browns Park are consistent with the observations of Merritt and Cooper (2000), who also reported decreases in active channel area resulting from the stabilization of deposits on the channel margins and the emergence of mid-channel islands. Our results confirm that eroding pre-dam deposits (c–b terrace) are a sediment source, which Merritt and Cooper (2000) speculated. Furthermore, we estimate that the mass of sediment eroded from the c–b terrace is equivalent to approximately 70% of the estimated sand input from Red Creek (Table 6).

Merritt and Cooper (2000) suggested that bank erosion, lack of point bar deposition, and mid-channel island formation indicated transition from meandering to braiding processes. Our analysis of channel adjustment throughout Browns Park indicates, however, that c–b terrace erosion is more than balanced by the formation of inset floodplains, which includes deposition in multiple channel settings, including point bars. Channel meandering remains the dominant channel-forming process in Lower Browns Park, but the actively forming floodplains are much lower in elevation than the pre-dam floodplain that is being replaced. Essentially, the pre-dam floodplain (c–b terrace), which is disconnected from the river by post-dam hydrology, is being replaced by a post-dam floodplain that is connected to the river. This fundamental change in floodplain dynamics seriously affects the establishment and recruitment of native and non-native riparian vegetation species. Decreased water tables place drought stress on the mature cottonwood forest that occupies the c–b terrace while conditions on the post-dam floodplain and intermediate bench favor the establishment of non-native tamarisk (Merritt and Cooper, 2000).

6.3. Sediment mass balance

The sum of measured and estimated inputs of sand to the Green River upstream from Jensen

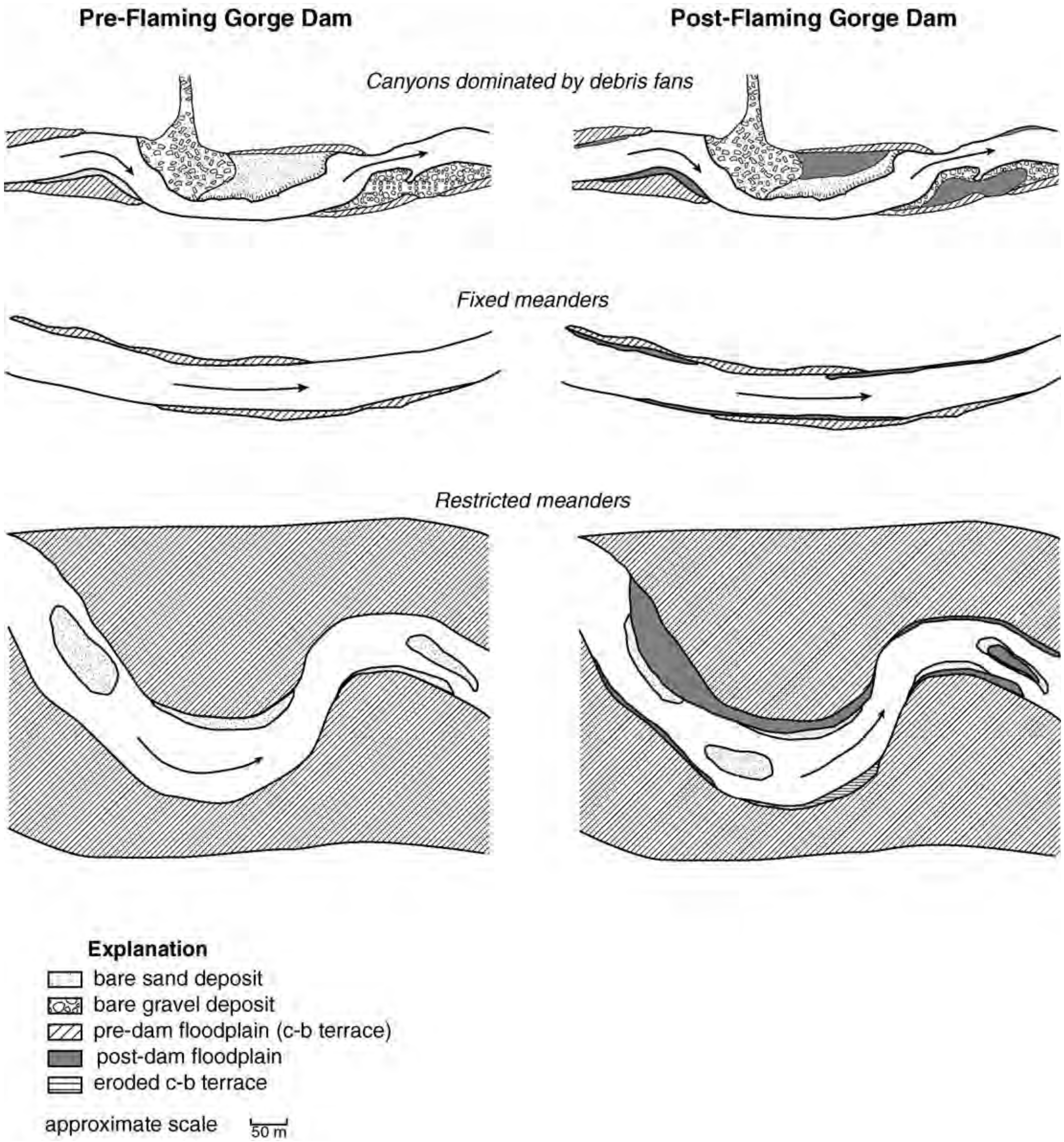

Fig. 16. Illustration showing the patterns of channel narrowing observed in each reach type. In the debris fan-dominated canyons post-dam fine sediment deposits occur along the channel margins, over gravel bars, and stabilize portions of eddy bars. In the fixed meander reaches, post-dam deposits are limited to narrow strips inset within the pre-dam channel. In the restricted meander reaches, the post-dam deposits fill pre-existing side channels, build point bars, and also line the banks as inset flood-plain features. Erosion of the c–b terrace also occurs in the restricted meander reaches.

balance the measured export at the Jensen gage within measurement uncertainty. This result has been interpreted to indicate equilibrium with respect to channel morphology downstream from the Yampa River confluence and sediment deficit upstream from that major sediment source (Andrews, 1986). Full consideration of the uncertainty in the sediment budget indicates that the budget is better described as indeterminate, which is not equivalent to an equilibrium condition. Our measurements of channel adjustment indicate that the Green River is still accumulating sediment in all reaches between the

Table 6
Estimated annual sediment budget for the Green River from flaming Gorge Dam to Jensen, Utah

Reach	Length (km)	Post-dam deposits[a] (Mg) × 1000	Terrace erosion (Mg) × 1000	Input to reach (Mg) × 1000	Source of input	Influx[b] (Mg) × 1000	Efflux[c] (Mg) × 1000	Flux at gage[d] (Mg) × 1000
Red Canyon	18	1 ± 1	– ± –	8 ± 8	Greendale gage	8 ± 8	7 ± 9	– –
Upper Browns Park	22	7 ± 5	2 ± 1	22 ± 2	Red Creek	29 ± 11	24 ± 17	– –
Swallow Canyon to Gates of Lodore	37	17 ± 12	15 ± 8	22 ± 11	Vermillion Creek	46 ± 28	44 ± 48	– –
Canyon of Lodore	29	4 ± 3	– –	– –	none measured	44 ± 48	40 ± 51	– –
Echo Park to Jensen Gage	45	10 ± 7	– –	786 ± 94	Yampa River	826 ± 145	816 ± 152	876 ± 44

[a] Data for Red Canyon through Browns Park from this study. Data for downstream reaches from Grams and Schmidt (2002).
[b] Sum of efflux from previous reach and tributary input.
[c] Difference between influx and change in storage (post-dam deposits−terrace erosion) for indicated reach.
[d] Transport measurements from Jensen gage.

dam and the Yampa River confluence and that an equilibrium reach does not yet exist.

The relationship between channel adjustment and the post-dam sediment load of the Green River can be examined by integrating measured changes in sediment storage with the post-dam sediment budget. The volume of post-dam deposits was approximated as the product of the estimated deposit thickness (0.3 ± 0.2 m) and the area of aggraded post-dam floodplain and intermediate bench deposits. The large error margin on our estimate of deposit thickness provides minimum and maximum values on the most likely magnitude of post-dam deposition. The volume of sediment loss associated with c–b terrace erosion was estimated using an average cutbank height of 2.4 ± 1.2 m and approximating the eroded volume as a triangular wedge. The difference between the volume deposited and the volume eroded is the change in storage for each reach (Table 6). In reaches where terrace erosion and post-dam deposition occurred, erosion was less than deposition, but of the same order of magnitude. Considering uncertainty, c–b terrace erosion in Lower Browns Park is approximately balanced by deposition on inset floodplains.

The magnitude of c–b terrace erosion and post-dam deposition are tiny relative to all input and flux terms downstream from the Yampa River and increase in relative magnitude nearer the dam. Downstream from the Yampa River, changes in sand storage are less than 1% of the total sand flux (Table 6). The magnitude of erosion and deposition is easily within the error of the load estimate. In this case, it is impossible to predict equilibrium with respect to channel form based on the sediment budget. Channel form has changed significantly (Grams and Schmidt, 2002), yet the mass of accumulated sediment is an insignificant fraction of the sediment flux. As the magnitude of the changes in storage relative to mainstem sediment flux increase, the inputs from small tributaries become increasingly important. In Browns Park, the changes in sand storage are as large as 20% of the sand load delivered by Red Creek. Now changes in storage are significant relative to mainstem transport and tributary supply, but tributary supply is so poorly constrained that it is still impossible to calculate a mass balance that will reliably predict channel adjustment.

These findings are similar to those of Topping et al. (2000) who demonstrated that uncertainties in the sediment budget of the Colorado River downstream from Glen Canyon Dam precluded any conclusions regarding long-term net sediment accumulation. The results we have presented for the Green River demonstrate that significant channel adjustments can occur in reaches where indeterminate sediment budgets suggest equilibrium, even when those budgets are constructed from the best available data. Thus, while it may be reasonable to use sediment budgets to demonstrate aggrading or degrading conditions based on large sediment imbalances, sediment budgets may often be too imprecise to interpret as an indication of channel equilibrium. In situations where sediment budgets indicate balance between supply and export, those results may be best interpreted as inconclusive.

7. Conclusions

Flaming Gorge Dam has strongly impacted the water and sediment regimes of the Green River. Despite severely reduced post-dam sediment supplies, the bed of the Green River has not degraded in Red Canyon or in Browns Park and post-dam deposits have caused channel narrowing in nearly all reaches within the first 104 km downstream from the dam. The magnitude of channel narrowing does not correlate linearly with distance downstream from the dam, but is related to (1) the degree to which peak flows have been reduced by the dam, (2) the magnitude of post-dam sediment supply relative to pre-dam sediment supply, and (3) local geomorphic characteristics. In Lower Browns Park, the pre-dam flood deposits (c–b terrace) that are no longer inundated are eroding and being replaced by inset floodplains that are connected to the post-dam hydrologic regime.

These findings illustrate some of the limitations in the use of sediment budgets for predicting and interpreting channel adjustment on river systems. Using the best available data, it is impossible to construct a sediment budget for the Green River that shows either a sediment deficit or surplus condition greater than the uncertainty in the estimate. This, however, should not be interpreted to indicate the river is in equilibrium. Our measurements of channel narrowing demonstrate that significant channel adjustment has occurred in a reach for which the sediment budget is inconclusive, and that the volume of sediment contained in post-dam deposits is within the error of the sediment budget.

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