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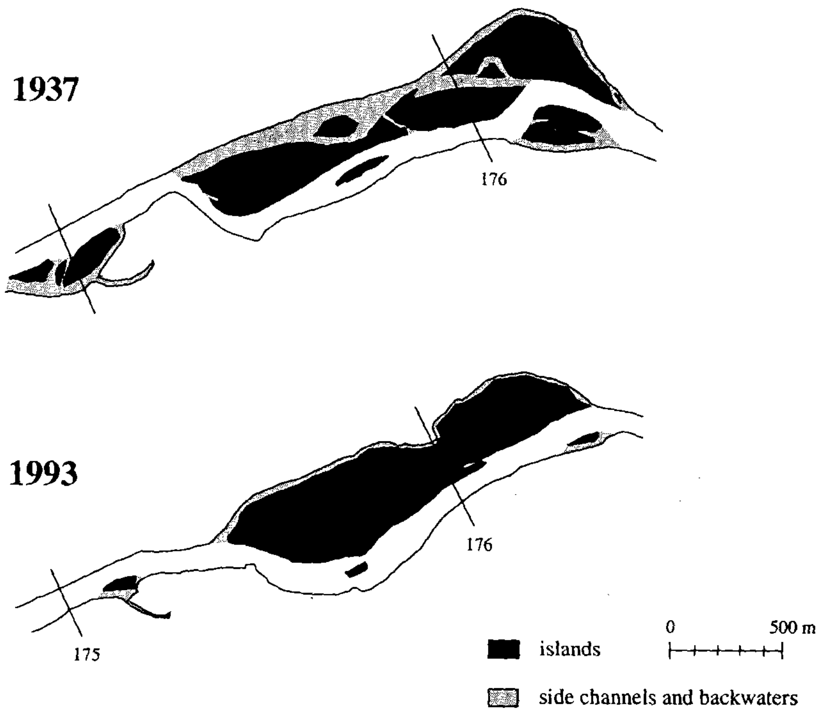

Final Report

Recovery Implementation Program

Project No. 44-B

January 1999

UNIVERSITY OF COLORADO

GEOMORPHOLOGY AND HYDROLOGY OF THE COLORADO AND GUNNISON RIVERS AND IMPLICATIONS FOR HABITATS USED BY ENDANGERED FISHES

FINAL REPORT

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REPORT FOR
RECOVERY IMPLEMENTATION PROGRAM
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EXECUTIVE SUMMARY

Alluvial reaches of the Colorado River near Grand Junction, Colorado, provide important habitat for the endangered Colorado squawfish (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*). Populations of these native fishes have declined dramatically in the past several decades, a situation that is often attributed to the hydrological and ecological effects of upstream reservoir operations. This report summarizes research done over the last five years to evaluate the importance of historical changes in streamflow and sediment loads on alluvial reaches of the Colorado River near Grand Junction. In addition, we describe recent changes in the geomorphology of the Colorado River and address the question of what can be done to improve existing fish habitats.

Our analysis of streamflow data from USGS gauging stations in the upper Colorado River basin shows that peak and mean annual discharges of unregulated rivers have not changed significantly in the last 60 years. In contrast, the Colorado River and its major upper basin tributary, the Gunnison River, have experienced significant decreases in annual peak discharge because of reservoir operations. Since 1950, annual peak discharges of the Colorado River at Glenwood Springs have decreased by more than 40%; annual peak discharges of the Colorado River near Cameo have decreased by 29%; and annual peak discharges on the Gunnison River near Grand Junction have decreased by 38%. In addition, the annual hydrographs of both rivers have changed greatly due to reductions in peak flows and augmentation of base flows.

Annual suspended sediment loads of the Colorado River and Gunnison River have likewise decreased over time. This was particularly apparent during a period from the early 1960s through the late 1970s when annual suspended sediment loads were 30 to 45% less than the long-term average. Analysis of aerial photographs indicates that between 1937 and 1993 the main channel of the Colorado River narrowed by an average of 20 m (~10-15% of its previous width), and about 1/4 of the area formed by side channels and backwaters has been lost.

Observations of channel change during periods of above-average runoff from 1993 through 1995 indicate minor scour and fill of the main channel, but more significant scour and enlargement of side-channel and backwater habitats, and flushing of fine sediment from the bed. Modeled relations between discharge and dimensionless shear stress τ^* for the Colorado River indicate that the threshold for bed load transport ($\tau^* = 0.03$) occurs at about half the bankfull discharge; these flows are exceeded about 30 days per year, on average. The bankfull discharge produces an average τ^* of 0.047 and is exceeded 7 days per year, on average. The width and depth of the main channel thus appear to be set by a discharge that produces an average boundary shear stress that is about ~1.5 times the critical shear stress. A magnitude-frequency analysis of sediment transport indicates that a large proportion of the annual sediment load of the upper Colorado River is carried by moderate to high discharges. Under the present hydrologic regime, 65-78 % of the annual sediment load is carried by flows greater than about 1/2 the bankfull discharge.

INTRODUCTION

The Colorado River is one of many rivers in the United States where populations of native fish are endangered and nearing extinction. Currently four federally listed endangered fishes reside in the upper Colorado River basin: the Colorado squawfish (*Ptychocheilus lucius*), razorback sucker (*Xyrauchen texanus*), humpback chub (*Gila cypha*), and bonytail (*Gila elegans*). The former two species were once abundant in warm-water reaches of the lower Gunnison River and upper Colorado River (we define the "upper" Colorado River as that segment of the river upstream from the Green River confluence; historically this segment was referred to as the "Grand River"). Populations of Colorado squawfish and razorback sucker are now very small, however, and they continue to decline. The reasons for this decline are often cited as (a) competition with non-native species, (b) changes in water quality, and (c) reductions in the amount of in-stream habitat due to reservoir operations, flow diversions and channel modifications (USFWS, 1987; Stanford, 1994). Over 40 species of non-native fish have been introduced into the upper Colorado River basin (Tyus, 1991), and some introduced species, such as channel catfish (*Ictalurus punctatus*), present particular problems for native fishes (Osmundson et al., 1997). Changes in water quality due to agricultural practices and urban development near Grand Junction are an on-going concern. Two decades ago, there was much interest in the problem of diffuse source salinity (Laronne and Shen, 1982), but now attention has turned to the environmental effects of heavy metals, such as selenium (Butler et al., 1993). Finally, there is the issue of reservoirs and diversions: there are 24 reservoirs with a capacity greater than 5,000 acre-feet (6,168,000 m^3) upstream of the Colorado-Utah State line, and almost as many flow diversions (Liebermann et al., 1989). The reservoirs in the upper Colorado River basin are relatively small in comparison to other reservoirs in the Colorado-Green River system, but collectively they alter the annual hydrograph significantly (Liebermann et al., 1989). Flow diversions have less of an impact on peak discharges, but at certain times of the year, especially in late summer, these structures can divert a high proportion (> 50%) of the river's flow. Large diversions have the added impact of blocking fish migration, thereby limiting access to habitats upstream.

It has generally been assumed that reservoirs and diversions have altered stream flows of the upper Colorado River significantly, and that this has caused important changes in the amount, diversity and quality of habitats used by the endangered fishes (USFWS, 1987; Tyus and Karp, 1989; Osmundson and Kaeding, 1991; Stanford, 1994). It has further been assumed that flows can be managed to maintain or improve existing fish habitats, and thereby restore self-sustaining populations of the endangered species. These are reasonable assumptions, given what is known about the downstream geomorphological and ecological effects of dams (Williams and Wolman, 1984; Lignon et al., 1995; Collier et al., 1996; Stanford et al., 1996), but only recently have specific studies been initiated to characterize the hydrological and geomorphological effects of river regulation on fish habitats in the Grand Valley. Osmundson and Kaeding (1991) analyzed changes in streamflow of reaches of the Colorado River near Grand Junction, CO, and concluded that, in the period since the upper basin reservoirs were constructed, peak daily discharges of the Colorado and Gunnison Rivers have been only about half of the long term average. These authors also speculated that without high spring discharges the Colorado River would continue to narrow and become more simplified, a point that was supported in subsequent studies by Osmundson et al. (1995) and Van Steeter (1996). The maintenance of complex, braided-channel reaches is thought to be a key habitat requirement for Colorado squawfish because adult fish are found more often in these reaches than in other, less heterogeneous reaches (Osmundson and Kaeding, 1991).

The present study was undertaken to develop a more thorough understanding of historic and recent changes in the geomorphology of the upper Colorado River and lower Gunnison River, and to develop physically based models for discharges that will improve existing fish habitats. The specific objectives of this study were as follows:

1) Determine how reservoir operations have changed the annual flow hydrograph and sediment-transport capacity of the upper Colorado River;

2) Quantify the effect of these historical changes on channel morphology;

3) Measure existing channel characteristics and responses to snowmelt runoff events; and

4) Provide recommendations for flows that will maintain or improve existing habitats.

The present study focuses on a 90-km segment of the upper Colorado River from Palisade, CO to Westwater, UT. This segment provides important habitat for Colorado squawfish and razorback sucker and marks the upper limit of their range on the main-stem Colorado River. We also include analyses of a 85-km reach of the lower Gunnison River between Delta and Grand Junction, CO. In conducting this work we were fortunate to have abundant flow and sediment load data, high quality aerial photographs, and several years of above-average runoff in which we could observe the effects of high flows on the river. Our results not only provide key information for fisheries biologists and water resource engineers, they also give added insight into questions about rates of channel change, mechanisms of cross section and profile adjustment, and processes of sediment transport in gravel-bed rivers.

RELATION BETWEEN FISH HABITATS AND GEOMORPHOLOGY

The present study focuses on habitats used primarily by Colorado squawfish. Of the four endangered species, Colorado squawfish are perhaps the most studied, and they are certainly the most abundant of the endangered species in the study area (Stanford and Ward, 1986). The population of razorback sucker in the upper Colorado River is very small, and possibly no longer self-sustaining (Osmundson and Kaeding, 1991). Some of the information in this report is applicable to razorback sucker, but this species is considerably different from Colorado squawfish, thus we restrict most of our analysis to processes and conditions that affect the latter species.

Ecology and Habitat Use

The ecology and habitat needs of Colorado squawfish have been described in detail in a number of studies (reviewed by Tyus, 1991 and Stanford, 1994). It is important to note here that much of the present understanding of Colorado squawfish ecology is based on studies of a relatively large population in the Green-Yampa River system. Early studies of this population showed that individual squawfish made long (> 100 km) seasonal migrations to spawn in specific reaches of the Green and Yampa Rivers (Tyus and Karp, 1989; Tyus, 1991). Similar studies of the Colorado-Gunnison River subpopulation of squawfish suggest that, while there is a tendency for adults to congregate near Grand Junction during the spawning season, they migrate relatively short distances (23 km, on average), and they spawn in widely separated reaches (McAda and Kaeding, 1991). For whatever reason, squawfish in the upper Colorado River are not as specific in their selection of spawning sites as their Green-Yampa counterparts are. It does appear, however, that the basic requirements for spawning are similar. Spawning occurs several weeks after the peak in the snowmelt hydrograph between late June and early August when water temperatures reach 18-22°C (McAda and Kaeding, 1991). In the few instances where spawning has been observed in the upper Colorado River, the fish were seen congregating near dissected gravel bars formed by loose, open-framework particles (D. Osmundson, personal communication), similar to what has been observed on the Yampa River (Lamarra et al., 1985; Harvey et al., 1993).

Another behavior pattern of Colorado squawfish that is common to both river systems is their use of backwaters. "Backwaters" are ephemeral, low-velocity embayments that form along the shore, downstream of islands, or at the mouths of secondary (side) channels. In terms of areal extent, backwaters constitute a small amount of the total riverine habitat in the upper Colorado River, but adult squawfish are found relatively often in these low velocity habitats, especially in spring (Osmundson and Kaeding, 1991; Osmundson et al., 1995). Apparently, the fishes seek out these habitats because they provide areas for resting which are close to areas used for foraging.

Rationale Behind This Study

The prevailing thought among biologists is that adult Colorado squawfish prefer "complex" river reaches with a multithread channel pattern (Osmundson and Kaeding, 1991; Osmundson et al., 1995). Complex river reaches offer diverse and heterogeneous habitats, among which fish can select according to their particular needs. Our work is motivated from the point of view that the Colorado River should be managed to improve the widest range of habitats in the widest range of places. The most recent data indicate that while there is a clear tendency for adult squawfish to congregate in the Grand Junction area during the spawning season, they do not use the same sites year in and year out. Thus we suggest that until specific spawning sites are identified, and it is established that these sites are used repeatedly, the most reasonable approach for managing spawning habitats is one that improves the quality of gravel and cobble substrates in many places. The solution to this problem involves specifying a discharge or range of discharges that will initiate gravel transport on a widespread basis, and thereby prevent fine sediment from accumulating on the bed. Fine sediment has probably always been a major constituent of the sediment load of the Colorado River, but there is a tendency for silt and sand to build up on the bed during periods of low flow (c.f. Milhous, 1998). It has been shown in many studies that fine sediment cannot be winnowed from appreciable depths within the bed unless the framework particles themselves are moved (Diplas, 1994; Kondolf and Wilcock, 1996); thus, periodic movement of gravel particles is a key requirement for maintaining spawning substrates.

Another major goal of our work was to specify conditions under which backwater habitats are formed and maintained. The physical characteristics of these features vary widely throughout the study area, however, we do know that they tend to fill in with fine sediment during periods of low flow (Osmundson et al., 1995; Van Steeter, 1996). To prevent this from occurring, a balance must be maintained between the sediment supplied to the reach and the sediment carried out of the reach. Any sediment that is not carried out of a particular reach will be deposited somewhere. It is well established in the sediment-transport literature that material moving in suspension will be deposited on the bed if either (a) the sediment-laden water enters an area of lower flow velocity, such as a backwater, or if (b) the sediment concentration increases. Thus we provide an analysis of sediment concentration data to evaluate historic trends in sediment loads, and determine which flows carry the majority of the annual sediment load through the Grand Valley.

Finally, we consider what discharges would be required to increase channel complexity and form new backwater habitats. To do this, the channel must become wider to create the space for new bars and side channels to form. Using a physically based theory developed by Parker (1979) we show that an approximate threshold for channel widening can be defined in terms of a bed load transport criterion. Parker's results suggest that a channel formed in noncohesive sediment (sand or gravel) will begin to widen once the average boundary shear stress, τ, exceeds the critical shear stress for bed load transport, τ_c, by about 20%. Using field measurements of bankfull depth, and reach-average values of slope and grain size, we show that the bankfull τ is consistently about 1.5 times the τ_c through the entire 90-km study reach.

STUDY AREA

The Colorado River and the Gunnison River have their headwaters in the Rocky Mountains in central Colorado (Fig. 1). The Yampa River and White River, which are both major tributaries of the Green River, likewise have their sources in the Rocky Mountains (Fig. 1). The annual hydrographs of these rivers are dominated by snowmelt runoff which usually begins in late April, reaches a peak in late May or early June, and recedes through July. Late-summer thunderstorms can cause localized flooding on tributaries and increase main-stem discharges by 10 to 20%. These storms can also increase suspended sediment concentrations greatly. Whether the fine sediment delivered by these storms is detrimental to fish and other aquatic organisms is unknown, but there is some overlap between the time when Colorado squawfish spawn (from late-June through July) and the time when these storms normally occur (from mid-July through October).

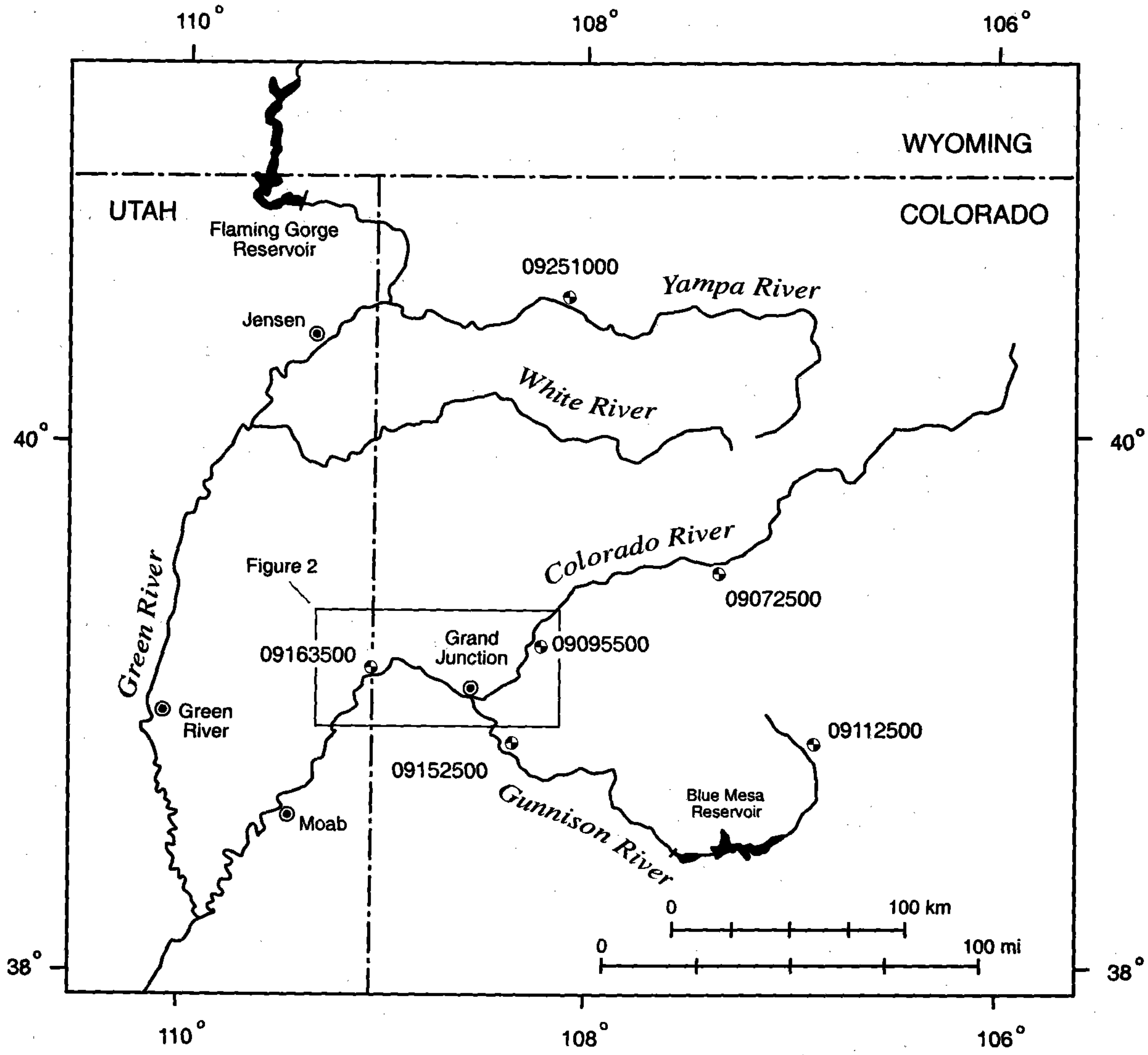

Figure 1. Location of major rivers and selected USGS gauging stations that were used to evaluate long-term trends in streamflow in the upper Colorado River basin. The outlined area near Grand Junction was the focus of more detailed field studies.

Natural streamflows of the Colorado River and Gunnison River are affected by many dams and diversions upstream. The dams in the upper Colorado River basin are not large in comparison to dams such as Glen Canyon or Flaming Gorge- the total volume of water stored in reservoirs in the upper basin is equal to only about half of the average annual streamflow at the Colorado-Utah state line. However, the reservoirs in the upper Colorado River basin are near the source of runoff, and they alter the annual hydrograph significantly (we pursue this point later; see also Liebermann et al., 1989). The Colorado River and Gunnison River carry moderately high sediment loads of 10^5 to 10^7 metric tons per year (Elliot and DeFeyter, 1986). Most of this sediment is derived from the soft shale and sandstone formations that underlie much of western Colorado and eastern Utah (Iorns et al., 1965; Liebermann et al., 1989). This area is drained by a handfull of relatively small, mostly unregulated tributaries which join the main-stem channels downstream from the upper basin reservoirs. The Colorado River and Gunnison River thus both have two separate sources of runoff and sediment: most of the runoff is derived from high elevation basins underlain by resistant crystalline rocks, and most of the sediment is derived from low elevation basins underlain by erodible sedimentary rocks. In typical years the water and sediment are delivered out of phase, resulting in higher suspended sediment concentrations on the rising limb of the hydrograph than on the falling limb. This has probably always been the case, but streamflows are now regulated, whereas sediment inputs are not (we pursue the implications of this in more detail later).

Our detailed studies of channel change and sediment transport focus on a 90-km reach of the upper Colorado River between Palisade, CO and Westwater, UT (Fig. 2). This reach has been important historically to the Colorado squawfish, and it marks the upstream limit of their range in the main stem of the Colorado River. The study area is further subdivided into three contiguous subreaches: The 15-mile reach extends from the eastern end of the Grand Valley, near Palisade, CO, to the confluence with the Gunnison River in Grand Junction; the 18-mile reach covers the next 29 km of river from the confluence with the Gunnison River to the western end of the Grand Valley, near Loma, CO; and the Ruby-Horsethief Canyon reach extends another 39 km downstream from Loma, CO to Westwater, UT (Fig. 2).

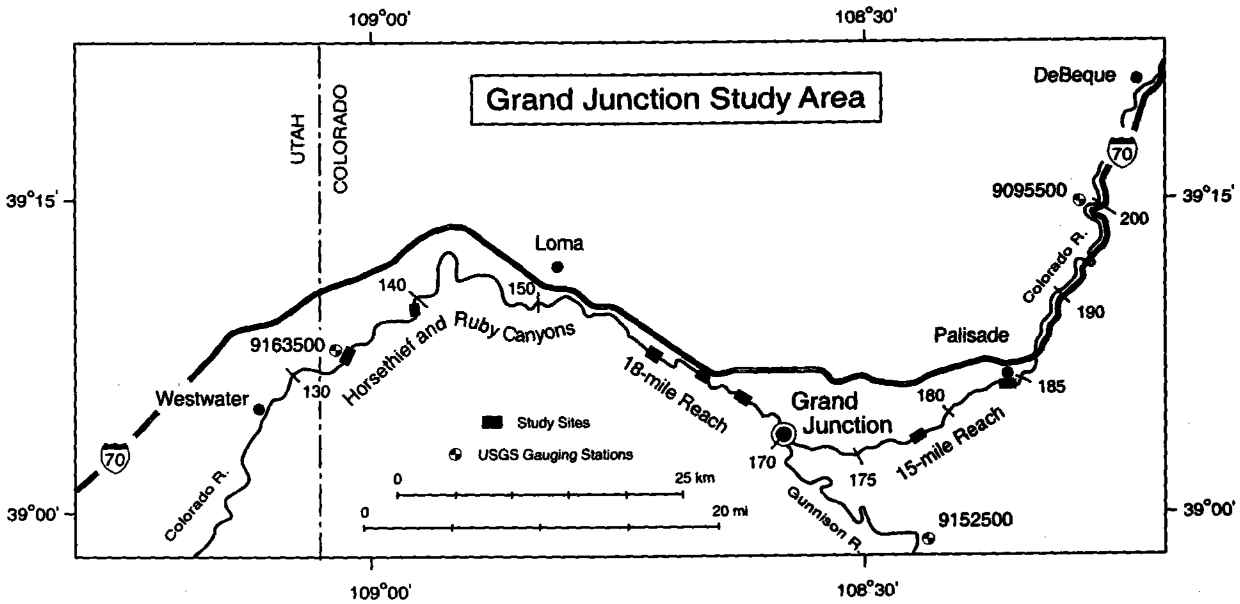

Figure 2. Detailed map showing study reaches near Grand Junction, Colorado.

The bed of the Colorado River is composed of cobble- and gravel-sized particles, except for a short bedrock section in Ruby-Horsethief Canyon known as Black Rocks. The banks and adjacent floodplain are composed of silt and sand covered with thickets of the nonnative tamarisk (*Tamarisk chinensis*) and russian olive (*Elaeagnus angustifolia*), and the native sandbar willow (*Salix exigua*) and cottonwood (*Populus deltoides*). In many places in the Grand Valley the banks have been artificially modified by levees and rip-rap. Otherwise the river is "alluvial", meaning it is free to adjust its width and depth. Average gradients of the 15-mile, 18-mile and Ruby-Horsethief Canyon Reaches are 0.00175, 0.0013, and 0.0010, respectively.

In the Grand Valley, the Colorado River maintains a "wandering" channel pattern formed by single-thread and multi-thread reaches. In multi-thread reaches the channel can split into a series of islands, side channels and backwaters. These reaches contain more diverse and heterogeneous habitats, which may explain the association between channel complexity and squawfish numbers (Osmundson and Kaeding, 1991). Compared to more incised reaches further downstream, side-channels and backwaters are relatively common in the Grand Valley area. Figure 3 shows an aerial photograph of a prominent island and backwater in the 15-mile reach. At high discharge water enters the side channel from upstream at a point not seen in this photograph, and flows out the mouth. As the discharge drops, water no longer enters the side channel, and instead ponds up into the area downstream, forming a backwater. Other features seen in this photograph include an island with traces of the former channel, an active gravel bar, and portions of two runs.

Figure 3. Aerial photograph of a segment of the Colorado River near RM 175.

Also included in this report are descriptions of geomorphic changes and existing conditions along an 85-km reach of the Gunnison River between Delta, CO, and Grand Junction (Fig. 2). The Redlands Diversion dam, located 4 km upstream from the Colorado River confluence, has historically blocked fish from migrating very far up the Gunnison River. However, the recent completion of a fish passage structure at the diversion dam now allows fish to access reaches of the Gunnison River above Grand Junction. The Gunnison River is similar to the Colorado River in many respects, the main difference being that the Gunnison River is more incised than the Colorado, and the channel is less complex overall (see also Milhous, 1998).

DATA SOURCES AND METHODS

Streamflow

The U.S. Geological Survey (USGS), along with other federal and state agencies, has operated gauging stations in the Colorado River basin since the late 1800s. We have examined streamflow records from many gauging stations on the main-stem of the Colorado River, and other gauges on regulated and unregulated tributaries in western Colorado (Van Steeter, 1996). For the purpose of illustration, this report discusses trends from six gauges that have relatively long records and are relevant to our work. These gauges are: East River at Almont, Yampa River at Maybell, Colorado River at Glenwood Springs, Colorado River near Cameo, Gunnison River near Grand Junction, and Colorado River near the Colorado-Utah State Line. The first two sites are representative of rivers with little flow regulation, while the latter four are representative of rivers with significant flow regulation. Table 1 lists information on these gauges and Figure 1 shows their locations.

Table 1. Summary information on gauging stations used to evaluate long-term trends in streamflow of the Colorado River and selected regulated and unregulated tributaries.

Gauge	USGS Number	Period of Record	Q_p (m^3/s)	Q_m (m^3/s)	Stat. Sign.[1] ($p< 0.05$)
East River at Almont	09112500	1911-1949	79	10	
		1935-1949	66	9	
		1950-1995	64	9	N,N
Yampa River at Maybell	09251000	1916-1949	299	46	
		1950-1995	282	42	N,N
Colorado River at Glenwood Springs	09072500	1899-1949	504	82	
		1950-1995	286	61	Y,Y
Colorado River near Cameo	09095500	1934-1949	725	116	
		1950-1995	517	107	Y,N
Gunnison River near Grand Junction	09152500	1902-1949	490	73	
		1950-1995	306	71	Y,N

1. Statistical significance determined using a T-test; Y indicates the difference in peak discharge (Q_p) and mean annual discharge (Q_m) for pre- and post-1950 periods is statistically significant at the $\alpha = 0.05$ level; N indicates the difference is not statistically significant.

Discharge records from these gauging stations were partitioned into "unregulated" and "regulated" time periods on the basis of when there were major changes in the amount of water stored in reservoirs. Plots of cumulative reservoir storage capacity vs. time (Fig. 4) show that the greatest increase in storage capacity in the upper Colorado River basin occurred in 1950, when Granby dam was completed; on the Gunnison River, a large increase in storage occurred in 1966, when Blue Mesa Reservoir was completed. Based on these results, we partitioned the discharge records of the Colorado River and Gunnison River at 1950 and 1966, respectively. One additional reason for splitting the records in mid-century, rather than in the 1930s when the first large reservoirs were built, is that, typically, the regulated portion of the streamflow record is longer than the unregulated portion. By splitting the data as such it increases the number of years indicative of unregulated or slightly regulated conditions, which increases the sample size and strength of our statistical comparisons. Thus for each period prior to and after 1950 (or 1966) the mean annual flood (or average peak discharge, Q_p) and the mean annual flow (average annual discharge, Q_m) were calculated, and the significance of differences between pre- and post-development periods was evaluated using a T-test. Average annual hydrographs for pre- and post-development periods were also constructed by averaging daily values. These hydrographs illustrate differences in the timing and volume of runoff before and after the dams were constructed.

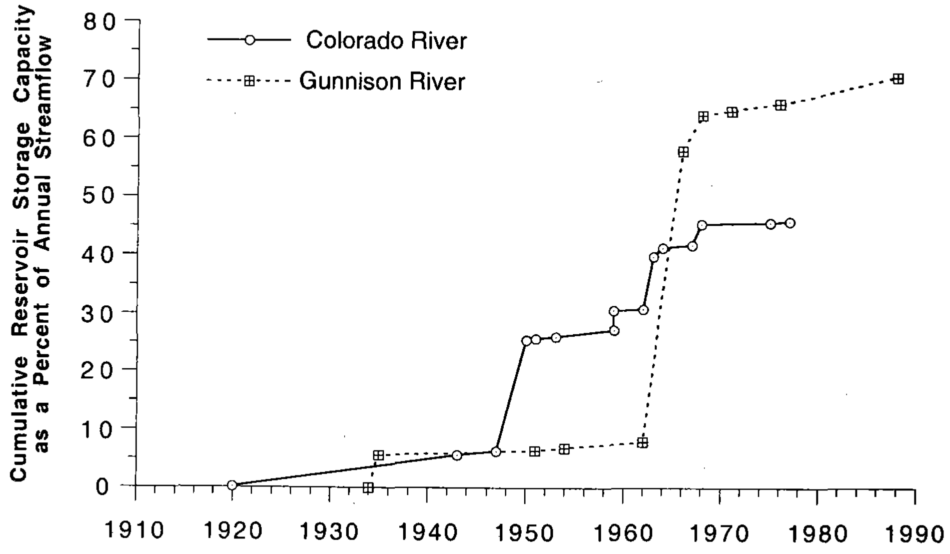

Figure 4. Cumulative reservoir storage capacity as a percentage of annual streamflow for the Colorado River near Cameo, and the Gunnison River near Grand Junction. Data from Liebermann et al. (1989) and USGS Water Supply Papers.

Sediment Loads

Sediment measurements have been made routinely on the upper Colorado River at only a few locations, and then only in the last two decades. The U.S. Bureau of Reclamation (USBR) measured suspended sediment at the Cameo and Gunnison River gauges intermittently in the 1950s (Iorns et al., 1964). The USGS continued measuring suspended sediment at the Gunnison River gauge through 1965. To our knowledge, no further sediment measurements were made at these gauges until the late 1970s, when the USGS again began collecting sediment and water quality data regularly at these sites, and also at the State Line gauge. Nearly all of the sediment measurements that have been made on the Colorado River and Gunnison River are of the suspended load. In 1984, a few bed load samples were taken at a site near the town of DeBeque, CO, approximately 10 km upstream from the Cameo gauge (Butler, 1986). Most of the bed load was finer than 16 mm, which is approximately the median grain size of the subsurface bed material. On the basis of these measurements, Butler (1986) concluded that suspended sediment accounted for more than 98% of the total sediment load of the Colorado River, a point that we support later in this report.

Average Bed Elevations

Changes in average bed elevation were determined by compiling information from the archived field notes of USGS discharge measurements at the Cameo, Gunnison River, and State Line gauges. Among the many hundreds of discharge measurements that are available for these gauges, we selected three measurements in each year corresponding to pre-peak, peak, and post-peak time periods. The average bed elevation for these measurements was then calculated by taking the difference between the observed gauge height and the mean flow depth (Jacobson, 1995), with adjustments for changes in the location and datum of the gauge as necessary.

Aerial Photograph-GIS Analysis

Long-term changes in channel morphology of the Colorado River and Gunnison River were determined from black and white aerial photographs taken in 1937, 1954, 1968, 1993 and 1995. These photographs are of similar scale (1:20,000); however, they cover different parts of the study area, their quality varies, and they were flown with the rivers at different flow levels. The 1954 and 1968 photographs of the Colorado River were taken during periods of relatively low flow; discharges in the 15-mile reach on the days that the photographs were taken were 54 and 60 m^3/s, respectively. The 1937 and 1993 photographs of the Colorado River were taken during periods of moderate flow; discharges in the 15-mile reach on the days that the photographs were taken were 209 and 186 m^3/s, respectively. The 1937 and 1995 photographs covering the Gunnison River were taken at low to moderate discharges of 18 m^3/s and 84 m^3/s, respectively. The differences in photograph quality and flow level introduce several problems which we discuss below.

The steps involved in measuring features on the aerial photographs were to (1) register the photographs to a common scale, (2) digitize the outlines of specific features, and (3) export these images to a Geographic Information System (GIS). The photographs were registered to coordinates by defining four or five common points on the photographs and on 1:24,000 scale topographic maps. The registration points were usually road intersections and bridge crossings. The outlines of banks, islands, bars, side channels, and backwaters were digitized with a computer aided design system (AutoCAD). Figure 5 shows an example of how these features were differen-tiated. Side channels formed where the river splits around an island were distinguished from the main channel on the basis of their smaller size. Backwaters were often associated with side channels, thus, we grouped them as one feature. The digitized images were then exported into ARC INFO, a vector-based GIS, for further analysis. Measurements of instream water area, island area, and side channel-backwater area were made on a mile by mile basis throughout the study reaches.

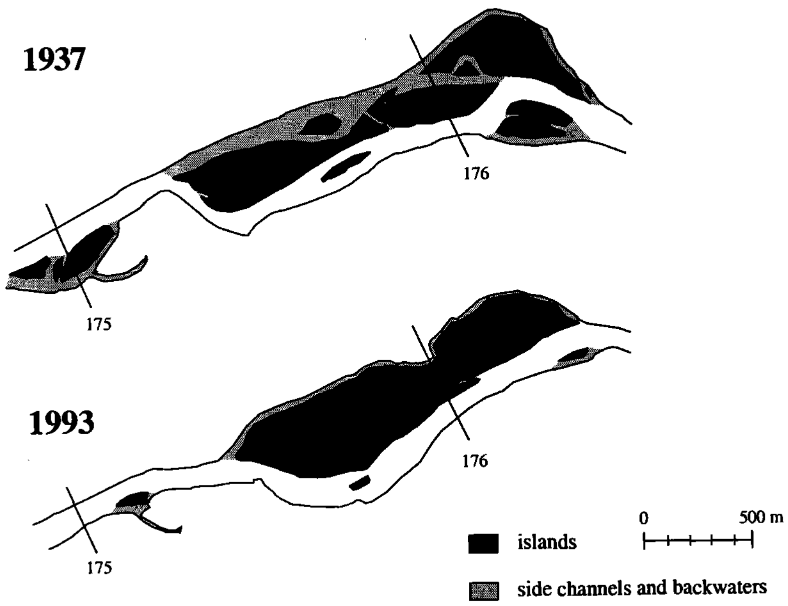

Figure 5. Digitized maps of the Colorado River in 1937 and 1993 showing how specific geomorphic features within the river channel and floodplain were differentiated.

The accuracy of photogrammetric measurements is affected to varying degrees by the clarity of the photographs, differences in flow level, and distortion. Differences in clarity lead to problems in the interpretation of features and the accuracy with which they can be digitized; differences in flow level affect the planform area of the river and associated features; and distortion near the edges of photographs can make objects appear larger or smaller than they really are. For practical reasons, we did not rectify the photographs to correct for distortion. We did, however, evaluate the potential error from these various sources. Errors due to interpretation and tracing of objects on a set of photographs were evaluated by re-digitizing reaches of the river and comparing the results to the original measurements. Errors due to differences in flow level were evaluated from field measurements of channel cross sections at different flows. Finally, errors due to distortion were estimated by measuring the area of 20 islands near the center of the photographs, and comparing this to the area of the same islands when they were near the edges of the adjacent photographs.

The results of these tests indicate that the error associated with interpreting and tracing the main channel boundary is negligible (2%). The error associated with tracing side channels and backwaters is more sizable (10%), because these features are harder to interpret. Differences in discharge have a negligible (~3%) effect on measurements of planform area, as long as the difference in discharge is less than about 30%. Thus, for the Colorado River, we feel confident comparing the photographs from 1954 with those from 1968, and those from 1937 with those from 1993, but not in comparing them all together. For the Gunnison River, the difference in discharges between 1937 and 1995 is relatively large (~80%), but the higher discharge occurs in the more recent set of photographs, which would tend to make the channel appear larger, even if it had not changed. With respect to other sources of error, the average error due to distortion at the edge of photographs is approximately 3%, but since we tried to avoid measuring features near the edge, the error introduced by distortion is certainly much less. Even so, if we assume a worst case scenario where the individual errors are additive, then it is possible that the photogrammetric measurements of main channel area are off by as much as 8%, and that the measurements of side channel and backwater area are off by as much as 16%. If we further assume that every feature was overestimated in one set of photographs, and underestimated in another set, then the maximum potential error could be twice as large. Although it is highly unlikely that the errors are all additive and always in the same direction, we use these values as a basis for saying whether or not the observed changes in channel morphology are significant.

Field Studies

Field studies were conducted from 1993 through 1996 to (1) monitor geomorphic changes; (2) determine the average characteristics of the main channel (width, depth, slope and grain size); and (3) develop flow and sediment transport models. Geomorphic changes in side channels and backwaters were monitored by repeated surveys. Prior to the start of the 1993 snowmelt runoff period, three side channel-backwater sites along the Colorado River were selected for detailed study. USFWS biologists recommended these sites to us because they were typical of habitats used by adult Colorado squawfish. Figure 3 (presented earlier) shows a site that we monitored in the 15-mile reach; the mouth of this side channel is a backwater at most flows. Another site, located near river mile (RM) 162 in the 18-mile reach, is formed by an alternate bar and chute channel. The chute channel conveys water at moderate to high flow but becomes a backwater at low flow. The third site, located near RM 160, is formed by a permanent island and side channel. This side channel conveys water at moderate to high flow but likewise becomes a backwater at low flow. At each site, a series of cross sections were surveyed around the head and mouth of the side channel. These areas were of interest to us because they control the amount of flow into and out of the side channel, which determines whether or not fish can access the site.

The general morphologic characteristics of the Colorado River and the Gunnison River were determined by surveying cross sections of the main channel at evenly spaced, 1-mile intervals. A total of 57 cross sections were surveyed on the Colorado River between Palisade, CO and Westwater, UT, and 53 main cross sections were surveyed on the Gunnison River between Delta, CO and the Redlands diversion dam. These main channel cross sections provide a quasi-continuous view of the downstream hydraulic geometry of each river, which is important if we are to specify the discharges and flow conditions under which the channel is formed and maintained. The main channel cross sections were surveyed with an electronic theodolite (total station) and a motorized rubber raft equipped with a reflecting prism and depth sounder. To measure a section, the total station was set-up over one of the end points, distance readings were taken along the line of the cross section by targeting the prism on the rubber raft, and depth soundings were taken by the person on the raft, who relayed the information by radio to the person on shore. The bankfull width b_b and depth h_b at each cross section were determined in the field by what was usually a clear break in slope between the channel and the floodplain. In September 1995, we re-surveyed 12 of the cross sections (every fifth one) on the Colorado River to determine whether the high flows of that year had caused significant geomorphic changes.

Average slopes of the study reaches were determined two different ways, depending on the contour interval of the available topographic maps. The most recent USGS 1:24,000 topographic maps of the Grand Valley show 10-ft contours along the Colorado River and Gunnison River; we assumed that these data were adequate for determining reach-average slopes. In contrast, the 1:24,000 USGS maps of the Ruby-Horsethief Canyon reach use a 40-ft contour interval, which we did not think was adequate for determining reach-average slopes. To obtain better estimates of the slope through Ruby and Horsethief Canyons we measured water surface elevations at 0.5-mile intervals using a global positioning system (GPS) capable of resolving elevations to less than 1.0 m with differential post-processing. We found that elevations determined with the GPS did not differ appreciably from elevations on the existing topographic maps, but we nonetheless used the GPS data to calculate slopes for this reach.

Sediment samples were taken at many different locations to determine the particle size distribution of the surface and subsurface bed material (gravel-bed rivers often possess a surface layer of sediment- called an "armor" layer or pavement- that is much coarser than the sediment underneath; the surface layer characteristics influence the roughness and mobility of the bed, whereas the subsurface sediment is the primary source of the bed load transported by the river). In this study, bed surface particle size distributions were determined from point counts of 100 or 200 particles on exposed gravel bars. Ideally, we would have sampled according to facies (riffles, runs or pools), but flow depths exceeding 1 meter usually precluded us from taking samples far out into the main channel. Subsurface particle size distributions were determined by taking bulk samples of about 100 kg of sediment, of which the coarse fraction (> 32 mm) was sieved in the field and the fine (< 32 mm) fraction was sieved in the laboratory. Tables A-1 through A-4 give a breakdown of the individual size-fractions for each surface and subsurface sediment sample.

We did not find large variations in the size of the bed material of the Colorado River; most of the surface samples have a median grain size D_{50} between 40 and 60 mm (Fig. 6). The bed material of the Gunnison River is more variable, and slightly finer, than the bed material of the Colorado River (Fig. 7). The subsurface sediment of both rivers is much more variable than the surface sediment; the D_{50} of the subsurface sediment ranges from less than 10 mm to 50 mm (Figs. 6 and 7). On average, the D_{50} of the surface sediment is approximately twice that of the subsurface sediment.

Colorado River

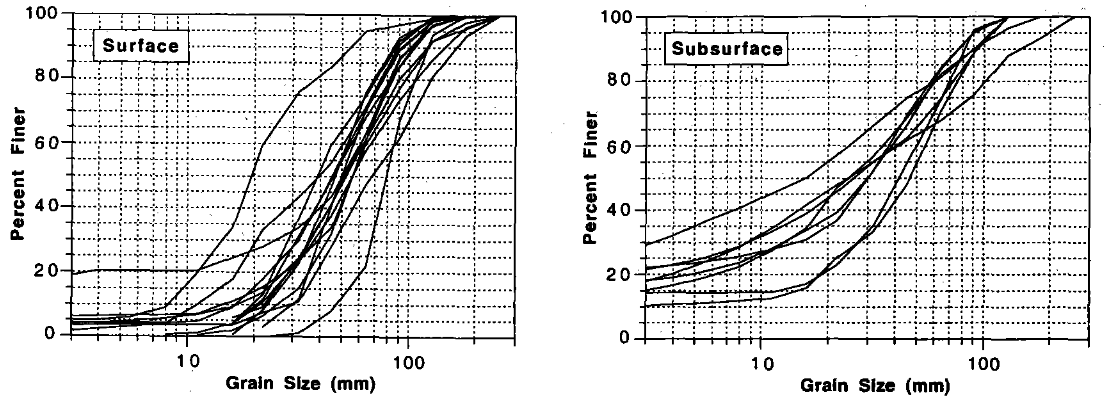

Figure 6. Grain size distributions of surface and subsurface sediment samples from the upper Colorado River. Samples were taken throughout the area (see Tables A-1, A-2).

Gunnison River

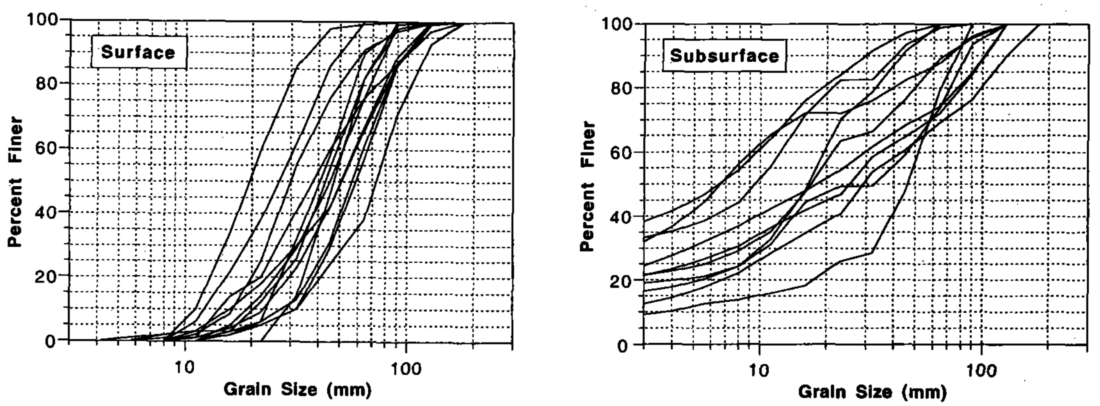

Figure 7. Grain size distributions of surface and subsurface sediment samples from the Gunnison River. Samples were taken throughout the study area (see Tables A-3, A-4).

In addition to these reach-scale measurements, we selected seven additional sites on the Colorado River where we made more detailed measurements of the channel to model the relation between discharge and average boundary shear stress. The locations of these sites are shown in Figure 2 and their average characteristics are summarized in Table 2. These sites are all in single thread reaches approximately 0.5 km long. At each site we surveyed 6 to 8 cross sections spaced about one channel-width apart. Subsequently, we made additional measurements of water surface elevations at different flow levels to calibrate a one-dimensional hydraulic model. Milhous (1998) has done similar work at one site on the Gunnison River. Later in this report we discuss his results, and provide additional estimates of thresholds for gravel transport on the Gunnison River.

Table 2. General characteristics of flow modeling sites

River Mile (RM)	average bankfull conditions width, m	depth, m	slope, m/m	surface (subsurface) sediment D_{84}, mm	D_{50}, mm	D_{16}, mm
184.2	85	2.89	0.0024	140 (120)	75 (26)	32 (1.4)
177.3	75	3.23	0.0020	100 (64)	48 (30)	24 (0.7)
166.0	126	3.27	0.0020	86 (64)	57 (30)	34 (1.4)
162.4	148	3.36	0.0015	105 (72)	55 (16)	27 (0.5)
159.0	148	2.86	0.0017	90 (n/a)	46 (n/a)	25 (n/a)
139.5	106	4.19	0.0012	90 (80)	50 (25)	25 (2.4)
134.0	137	3.22	0.0014	80 (80)	50 (48)	35 (16)

The key problem in estimating discharge thresholds for sediment transport and channel change is to develop appropriate measures of the boundary shear stress, τ, and the critical shear stress, τ_c. The average boundary shear stress is given by

$$\tau = \rho g R S_f \qquad (1)$$

where ρ is the density of water, g is the gravitational acceleration, R is the hydraulic radius (which in wide channels is very nearly equal to the flow depth, h), and S_f is the friction slope or energy gradient. We used a series of observations over a range of flows to calibrate a one-dimensional hydraulic model for each study site (we adapted the step-backwater modeling procedure outlined by Henderson, 1966, to a spreadsheet program). The step-backwater model finds S_f at individual stream channel cross sections using an iterative solution to the energy equation:

$$S_f = \frac{dH}{dx} = \frac{d}{dx}\left(\frac{u^2}{2g} + h + z\right) \qquad (2)$$

where *dH/dx* is the gradient in total energy, *u* is the mean velocity, *z* is the average bed elevation, and *x* is the downstream direction. The model results allow us to evaluate the boundary shear stress and the roughness (Manning's *n*) for a range of discharges.

In the absence of direct observations of particle entrainment from tracer gravels or bed load samples, the only practical means for estimating τ_c is to use the Shields' criterion:

$$\tau_c^* = \frac{\tau_c}{(\rho_s - \rho)\, g\, D} \qquad (3)$$

where τ^*_c is the critical dimensionless shear (Shields) stress, ρ_s is the density of sediment, and D is the particle diameter.

In the last decade there has been much discussion over appropriate values of τ^*_c and the reasons for its variation. It is now well established that τ^*_c varies inversely with the ratio of individual grain size D_i to median grain size D_{50}. However, specific relations between τ^*_c and D_i/D_{50} appear to vary from river to river, as does the criterion for incipient motion, defined for each grain size by some minimum value of τ^*_c (see review by Gomez, 1995). Parker et al. (1982) suggested that the framework gravels begin moving at $\tau^*_c \approx 0.030$; Wilcock et al. (1996) observed gravel transport at values of τ^*_c as low as 0.031; Buffington and Montgomery (1997) report a 3-fold range in τ^*_c with a minimum value of 0.030; Milhous (1998) suggests using an even lower value of 0.021. We have some field evidence that the threshold for bed material transport in the Colorado River is near $\tau^* = 0.030$. In May 1996, while floating through Ruby-Horsethief Canyon, we repeatedly heard a pinging sound caused by bed load moving over riffles. The discharge at the State Line gauge at that time was 600 m^3/s, which according to our modeled discharge-shear stress relations, produces values of τ^* of 0.030 and 0.033 in study reaches near RM 139 and RM 134, respectively. We emphasize, however, that at such low stresses very few framework particles would be moving, and bed load transport rates would be very low. This stage is sometimes referred to as "marginal transport" (Andrews, 1994). A second and much higher transport stage, termed "significant motion" (Andrews, 1994), is characterized by near-continuous movement of framework particles and much higher transport rates. This stage is not well defined in terms of a Shields stress, but data presented by Wilcock and Southard (1989) and Pitlick (1992) suggest that significant motion occurs in the range $0.045 < \tau^* < 0.06$; at stages much above this (say, $\tau^* > 0.09$), transport is so vigorous that gravel bed forms develop.

Finally, we used existing discharge-duration data and sediment-transport relations to determine the "effective discharge", defined as the discharge or range of discharges that transports the majority of the annual sediment load (Wolman and Miller, 1960; Andrews, 1980). Establishing this discharge is very important for defining what flows carry sediment through the study reaches, and thereby prevent further losses in macro-scale habitats. The effective discharge was determined by dividing the series of daily discharges at the Cameo and State Line gauging stations into 34 separate classes, calculating the total load (suspended load + bed load) for each discharge, and multiplying the total load by the frequency of flows in each class. Suspended sediment loads were calculated using separate rising- and falling-limb water discharge-sediment concentration relations for the two gauging stations. Bed load transport rates were calculated using modeled discharge-shear stress relations described above, and the empirical bed load function of Parker et al. (1982):

$$W^* = 0.0025 \exp\left[14.2\left(\phi_{50} - 1\right) - 9.28\left(\phi_{50} - 1\right)^2\right] \qquad (0.95 < \phi_{50} < 1.65) \qquad \text{(4a)}$$

$$W^* = 11.2\left(1 - \frac{0.822}{\phi_{50}}\right)^{4.5} \qquad (\phi_{50} > 1.65) \qquad \text{(4b)}$$

where

$$W^* = \frac{q_b\left(\rho_s/\rho - 1\right)}{\sqrt{g}\,\left(h\,S\right)^{3/2}}$$

and

$$\phi_{50} = \tau^*_{50} / \tau^*_{r50}$$

In the last two equations, q_b is the volumetric bed load transport rate, and ϕ is the transport stage, which is defined in terms of a reference Shields stress τ^*_r that produces a small transport rate of a particular size, in this case the D_{50}. Conceptually, τ^*_r is very similar to τ^*_c. Parker et al. (1982) suggested $\tau^*_r = 0.086$, but this value was with reference to the D_{50} of the subsurface sediment, which is typically much finer than the surface sediment. To account for this difference, and the difference between τ^*_r and τ^*_c (typically approximately 20%), we adjusted the value of τ^*_r down to 0.033. This adjustment gives a relation that is consistent with the earlier assumption about the minimum critical Shields stress for the D_{50}.

This report also includes an appendix with tables containing some of the raw data used in the analyses described above. Spreadsheet or ASCII text-file versions of these tables can be obtained from the lead author upon request (pitlick@spot.colorado.edu, or 303-492-5906).

RESULTS

Long-Term Trends in Streamflow of Unregulated Rivers

The East River, an unregulated tributary of the Gunnison River, has been gauged at Almont, CO, since 1911. There is a gap in the record from 1922 to 1934, but thereafter the record is continuous through the present. The time series of annual peak discharges on the East River at Almont shows several years of high peak flow between 1911 and 1922, and generally lower peaks after 1934 (Fig. 8a). From 1911-1949 annual peak discharges on the East River averaged 79 m^3/s. It is hard to say whether this value is representative of the entire pre-development period because several wet and dry years in the 1920s and 1930s were left out. If we compare the period from 1935 to 1949 with the period from 1950 to 1995, the difference in annual peak discharge is only 3%, which is not statistically significant ($p > 0.05$). Likewise, the difference in mean annual flows for the same time periods is not statistically significant (Fig. 8b). Composite hydrographs for the two periods are very similar (Fig. 8c), the main difference being that flows in the early part of the century were slightly higher and peaked later in the year than in the more recent period.

The Yampa River, located in northern Colorado, is a tributary of the Green River (Fig. 1). The Yampa River has several small reservoirs in its headwaters, but these reservoirs have relatively little effect on flows further downstream. The gauge record for the Yampa River at Maybell, CO, begins in 1917 and runs through the present. The time series of peak and mean annual discharges at this gauge show that streamflows on the Yampa River have changed little this century (Figs. 9a and 9b). Differences in annual peak discharge and mean annual discharge between the two periods 1917-1949 and 1950-1995 are not statistically significant ($p > 0.05$). The composite hydrograph for the early period shows a slightly larger and earlier peak than the more recent period (Fig. 9c), but the difference is small.

The results of the preceding analysis, and our analysis of records from a number of other gauges in the region (Pitlick and Van Steeter, 1994; Van Steeter, 1996), suggest that peak and mean annual discharges of unregulated rivers in the upper Colorado River basin have not changed significantly this century. This finding contrasts with results from previous studies where it has been shown that runoff in the upper Colorado River basin was above-average from 1900 to 1930 (Stockton, 1975; Meko et al., 1991; Dawdy, 1991). The turn-of-the-century period of above-average runoff is clearly evident in the flow records of the large, main-stem rivers (e.g. the Green River at Green River, UT, or the Colorado River at Glenwood Springs; see below), but not so on the smaller tributaries (e.g. the Yampa River at Maybell, the White River at Meeker, or the Dolores River at Dolores, CO). We can conclude only that, while there appears to be some evidence that the early part of this century was wetter than "normal" in the upper Colorado and Green River basins, the phenomena was perhaps not as widespread as is commonly thought.

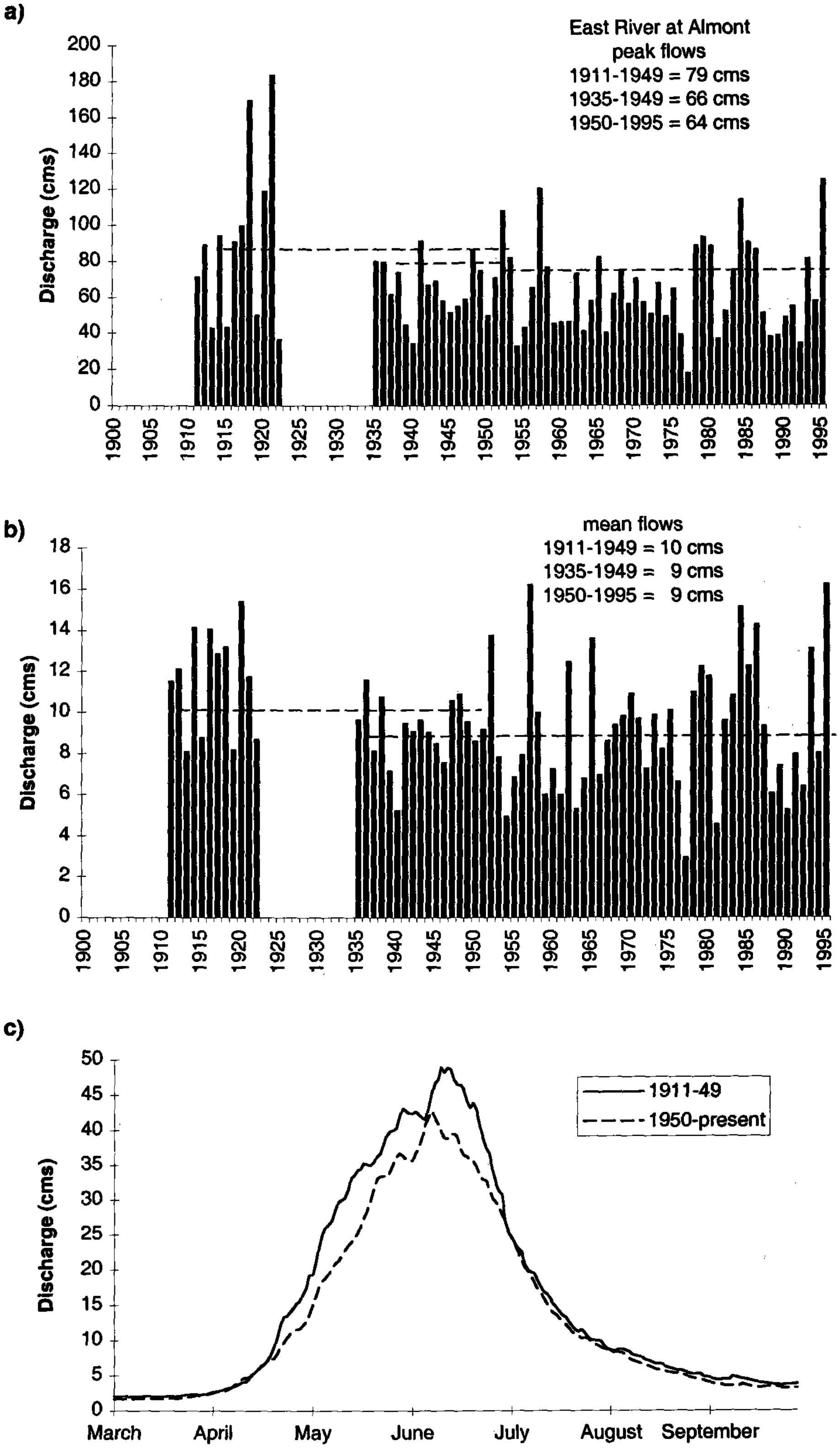

Figure 8. Streamflow data for the East River at Almont, CO (USGS gauge 9112500); (a) instantaneous peak discharges, (b) average annual discharges, and (c) composite annual hydrographs for separate time periods.

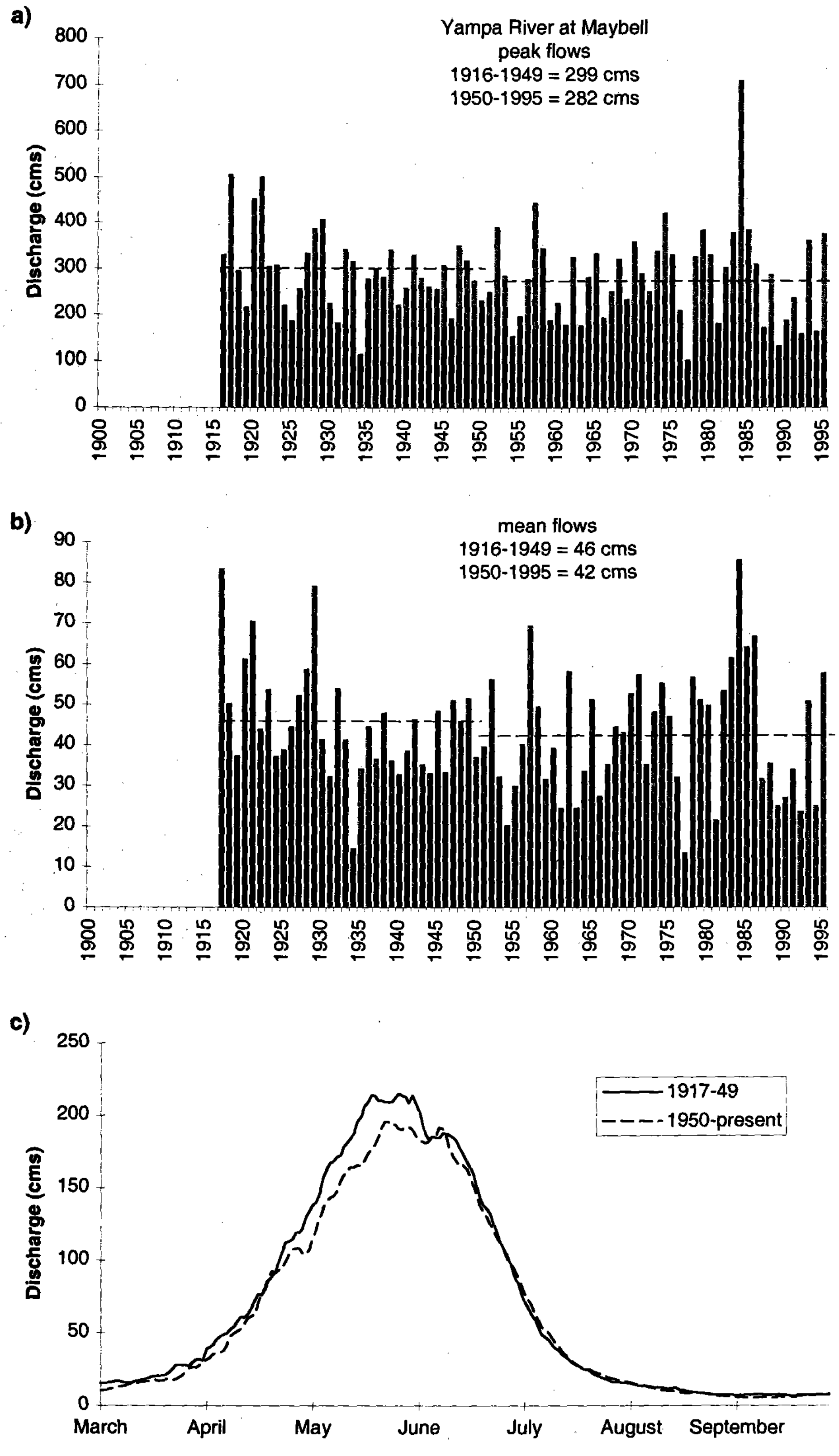

Figure 9. Streamflow data for the Yampa River at Maybell, CO (USGS gauge 9251000); (a) instantaneous peak discharges, (b) average annual discharges, and (c) composite annual hydrographs for separate time periods.

Long-Term Trends in Streamflow of the Colorado and Gunnison Rivers

Dams and diversions begin to affect the streamflow of the Colorado River almost at its source and there are many gauges on the main stem that illustrate the collective effects of flow regulation. The Colorado River has been gauged near Glenwood Springs since the turn of the century. From 1900 through 1965 the gauge was located upstream of Glenwood Springs and upstream of the Roaring Fork River. In 1966 the gauge was moved downstream of the Roaring Fork River. Fortunately, the Roaring Fork River is also gauged at Glenwood Springs, and thus we could extend the older record through the present by subtracting same-day discharges of the Roaring Fork River from those of the Colorado River. The composite record indicates that reservoirs have had significant effects on peak and mean daily flows of the Colorado River (Fig. 10). Annual peak discharges of the Colorado River at Glenwood Springs averaged 504 m^3/s from 1900 to 1949, but only 286 m^3/s from 1950 to 1995 (Fig. 10a); this represents a 43% decrease in average annual peak discharge. Mean annual discharges have decreased by 26% since 1950 (Fig. 10b), which is also a statistically significant change ($p < 0.01$). Annual hydrographs for the two periods are clearly different (Fig. 10c), reflecting the combined effects of the turn-of-the-century period of high runoff, increased export of water by transbasin diversions in the middle part of the century, and the filling of various reservoirs through the late 1960s.

The effects of reservoirs and transbasin diversions in the upper Colorado River basin diminish downstream because of inflow from unregulated tributaries, but the effects are still noticeable at the gauge near Cameo, CO, approximately 18 km upstream of the study area. Figure 11a shows that annual peak discharges of the Colorado River near Cameo have dropped from an average of 725 m^3/s in the period 1934-1949 to an average of 517 m^3/s in the period 1950-1995; this represents a 29% decrease, which is statistically significant ($p < 0.01$). Figure 11b, on the other hand, shows that the difference in mean annual discharges for the two periods is only about 8%. Although this difference is not statistically significant, it would be misleading to conclude that the average annual discharge of the Colorado River have not changed historically. Data presented by Liebermann et al. (1989) and in annual USGS reports indicate that, in any given year, 10-20% of the annual flow at Cameo is diverted out of the basin, with the proportion generally being higher in dry years than in wet years. Our analysis of the Cameo gauge record does not reflect the effect of diversions accurately becauseseveral large diversions lie downstream of gauge, and (b) many of the upper basin diversions were already in place by 1934 when the record begins. A much greater contrast in streamflow patterns is evident in looking at the mean annual hydrographs for separate time periods (Fig. 11c). Spring snowmelt flows are much lower now than they were in the past, and winter base flows are higher (although it is not obvious in this graph, daily discharges in winter and early spring are typically 10 m^3/s higher now than they were before). These changes reflect the normal operation of reservoirs, which is to store runoff in the spring and release it slowly over the rest of the year to generate power or to satisfy irrigation demands.

The simple partitioning of these records into pre- and post-1950 periods obscures more subtle, and we think, important trends in streamflow. We further subdivided the Cameo record into four 15-year intervals and counted the number of days that flows exceeding 316 m^3/s and 631 m^3/s occurred in these intervals (Table 3). We show later that these discharges approximate two sediment transport thresholds, one representing the onset of bed load transport, and the other representing reworking of the bed near bankfull flow. These thresholds pertain to the river in its present form, however, and can be applied to past conditions only in an approximate sense because we know that the channel has become narrower, and the bed material may have changed over time, so that the discharges required to reach these thresholds were perhaps higher or lower in the past.

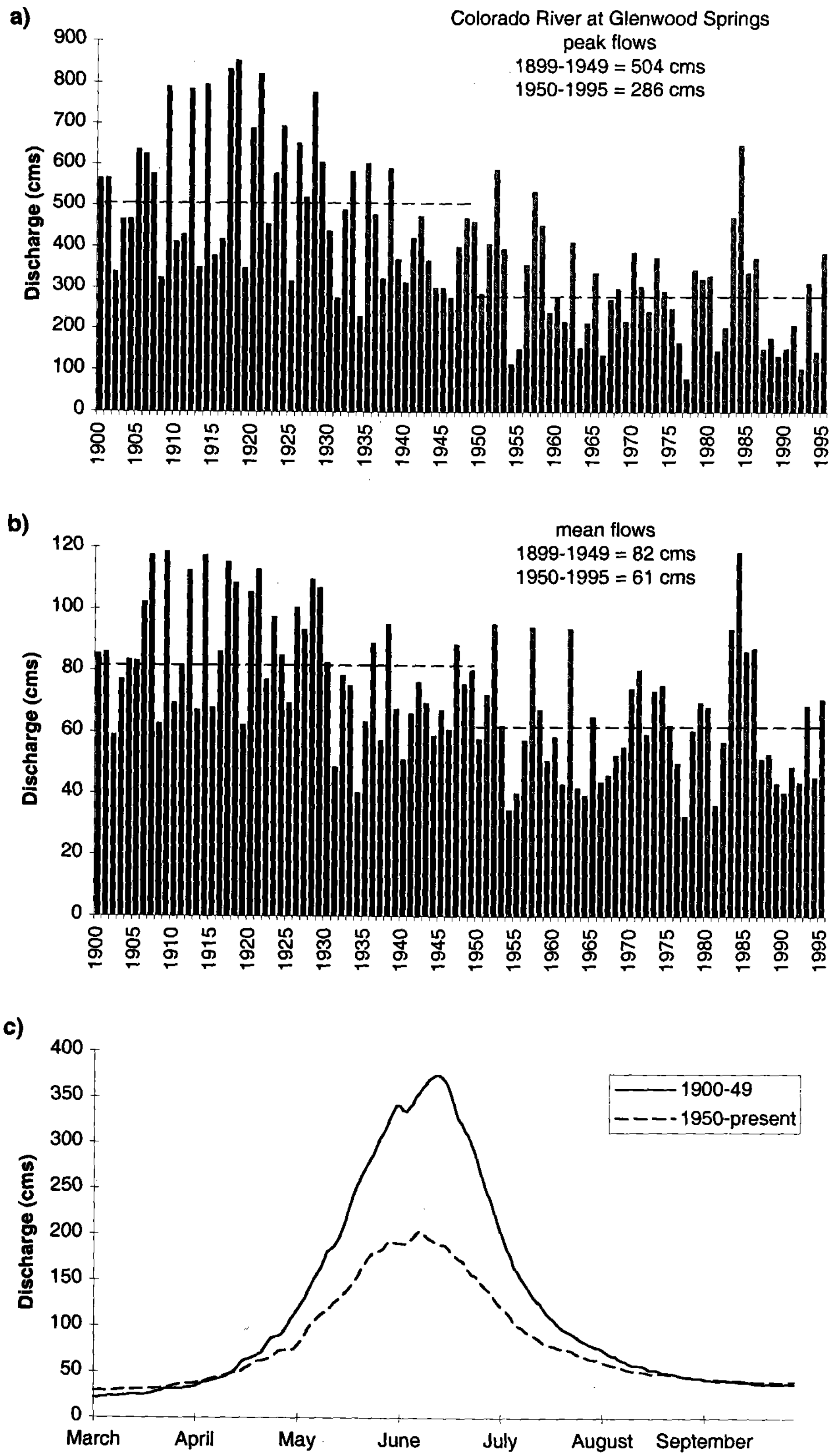

Figure 10. Streamflow data for the Colorado River at Glenwood Springs, CO (USGS gauge 9072500); (a) instantaneous peak discharges, (b) average annual discharges, and (c) composite annual hydrographs for separate time periods.

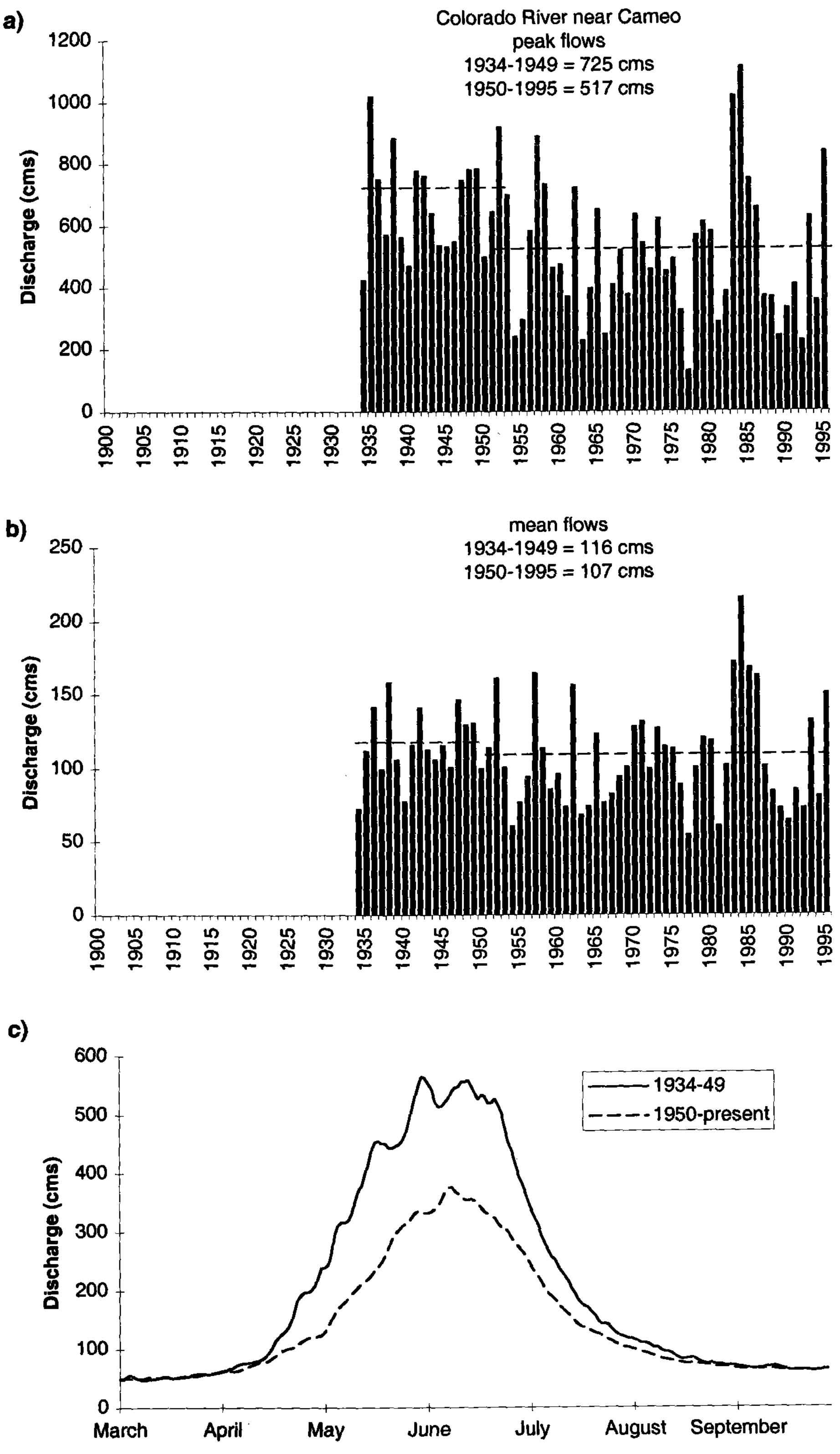

Figure 11. Streamflow data for the Colorado River near Cameo, CO (USGS gauge 9095500); (a) instantaneous peak discharges, (b) average annual discharges, and (c) composite annual hydrographs for separate time periods.

Subdividing the Cameo streamflow record into 15-year intervals shows that the frequency of discharges exceeding 316 m^3/s and 631 m^3/s decreased systematically between 1934 and 1978 (Table 3). The reduction in high flows was particularly significant during the period from 1964 to 1978 when discharges greater than 316 m^3/s occurred, on average, only about 22 days per year and flows exceeding 631 m^3/s didn't occur at all (Table 3). The most recent period from 1979 to 1993 is characterized by more frequent high flows, similar to the period from 1949 to 1963, when flows exceeding 316 m^3/s occurred about 28 days per year, and flows exceeding 631 m^3/s occurred several days per year. These results suggest that flows capable of moving the gravel bed material (and, for that matter, much of the silt and sand also carried by the river) became increasingly less frequent through the late 1970s. Given that a clean loose substrate is a key requirement for spawning, it seems possible that the lack of high flows from the late 1950s through the 1970s may have limited reproductive success and had long-lasting effects on the population of Colorado squawfish (we return to this point later).

Table 3. Number of days that the Colorado River exceeded specific flow thresholds at the Cameo gauging station in each of four separate 15-year periods.

	Number of Days That Specified Discharge Was Exceeded			
Discharge (m^3/s)	1934-1948	1949-1963	1964-1978	1979-1993
316	577	426	328	429
631	86	63	0	69

The Gunnison River, which contributes almost 40% of the annual flow to the lower part of our study area, has gone through similar changes in streamflow hydrology. The Gunnison River is controlled by many dams. The first major dam was completed at Taylor Park in 1935; however, the more significant effects on discharge came after the completion of Blue Mesa Reservoir in 1966. Figure 12a shows that annual peak discharges of the Gunnison River near Grand Junction dropped from an average of 451 m^3/s in the period 1897-1965 to 280 m^3/s in the period 1966-1995; this represents a 38% decrease in annual peak discharge, which is statistically significant. Mean annual discharges of the Gunnison River near Grand Junction have not changed significantly over the period of record (Fig. 12b), but again, the shape of annual hydrograph is now very different compared to unregulated conditions (Fig. 12c).

Our findings on the effects of reservoir operations are qualitatively similar to what has been reported previously by Liebermann et al. (1989) and Osmundson and Kaeding (1991), the main differences being due to how we partitioned the flow records at individual stations. Osmundson and Kaeding (1991) pieced together a 77-year record of peak discharges in the 15-mile reach by combining data from a discontinued gauge near Palisade (after some adjustment) with data from the existing Cameo gauge. Their analysis indicates that peak daily flows in the 15-mile reach are now 56% of the pre-development mean. The discrepancy between their number and ours is large, but explained by the fact that their analysis includes data from 1902-1930, which ours does not, and they reported changes in peak discharge as a "percentage of" the unregulated mean, rather than as a "percent difference" between means, as we have; a value reported as 56% of the pre-development mean equates to a difference in means of 44%. If these differences are accounted for the analyses yield relatively similar results. Our results should be viewed as conservative because the data used to characterize "unregulated" conditions include some years when dams were already in place, and the analysis does not include data from the turn-of-the-century which was possibly anomalous.

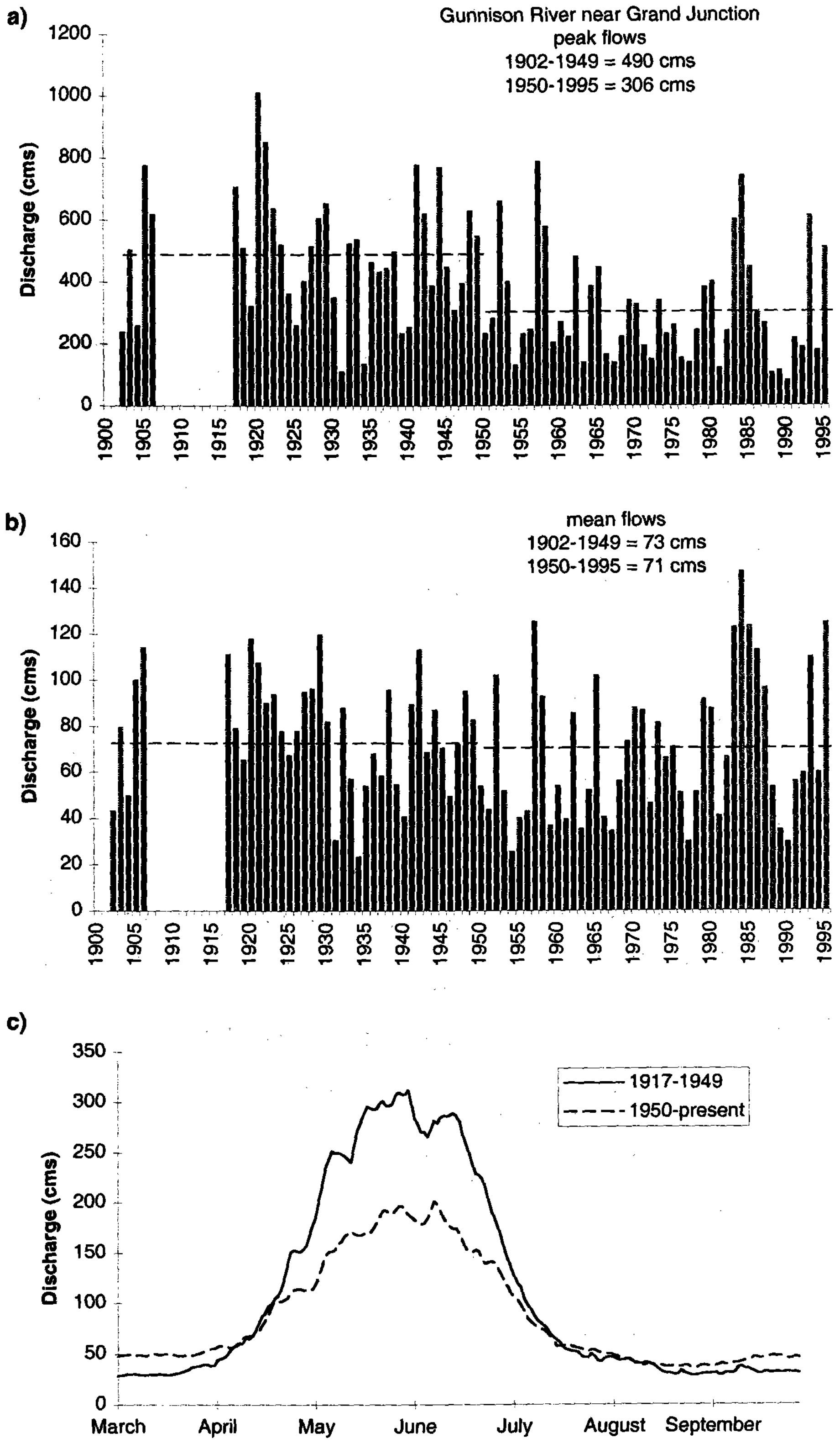

Figure 12. Streamflow data for the Gunnison River near Grand Junction, CO (USGS gauge 9152500); (a) instantaneous peak discharges, (b) average annual discharges, and (c) composite annual hydrographs for separate time periods..

Suspended Sediment Loads

Sediment loads are calculated by taking the product of sediment concentration and water discharge, i.e. $Q_s = k \times C_s \times Q$, where k is a conversion constant. This relation implies that Q_s will change if either Q or C_s change, except in the case where both change by an equal and opposite amount. We know from the preceding analysis that snowmelt discharges of the Colorado River and Gunnison River have decreased over time, thus, without proportionate increases in concentration, sediment loads should also have decreased. To examine this question, we developed a series of rating curves between suspended sediment load and discharge, based on periodic measurements at the USGS gauges. Figure 13 shows pre- and post-peak rating curves for the Colorado River near Cameo (we define "pre-peak" observations as those made between the first day of the water year, Oct. 1, and the day of the peak discharge, and "post-peak" observations as those made from the day after the peak discharge to the last day of the water year, Sept. 30). These data are further subdivided according to whether they were obtained in the 1950s or during the period from 1983-1993. Comparing the two time periods, we note that the samples from the 1950s broadly overlap with the samples from the recent period, indicating that sediment loads carried by given discharges are roughly the same now as before; this is equivalent to saying that sediment concentrations for a given discharge have not changed with time. However, since higher discharges are less likely to occur now because of reservoir operations (Fig. 11 and Table 3), there are fewer days when the Colorado River actually carries high suspended sediment loads (say, $Q_s > 10{,}000$ t/d). In other words, high flows probably carry as much sediment now as they did in the past, but these flows occur less frequently, thus the total load carried annually by the river is often less than before.

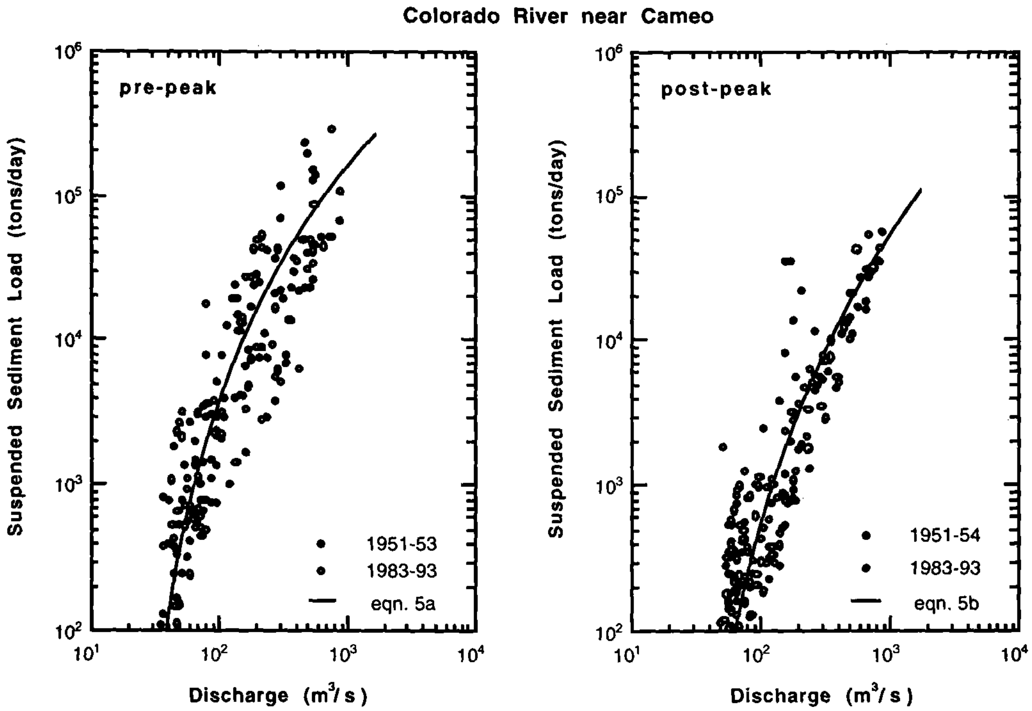

Figure 13. Relation between suspended sediment load and discharge for the Colorado River near Cameo, CO. Data from Iorns et al. (1964) and USGS Water Supply Papers.

Comparison of the two graphs in Figure 13 indicates that suspended sediment loads are typically much higher on the rising limb of the hydrograph than on the falling limb. This hysteresis effect arises because of systematic differences in pre- and post-peak sediment concentrations caused by a lag between the peak in sediment delivery and the peak in snowmelt runoff. Accordingly, we developed separate relations for predicting pre- and post-peak sediment loads:

pre-peak: $$Q_s = 3\,(Q - 25)^{1.6} \qquad (5a)$$

post-peak: $$Q_s = 0.07\,(Q - 20)^{2.0} \qquad (5b)$$

Figure 14 shows corresponding suspended sediment data for the Gunnison River. These data are likewise grouped according to season and sampling interval. Like the Colorado River, the samples from the recent period (1977-1993) overlap with the samples from the earlier period (1949-1965), suggesting that the load carried by the Gunnison River at a given discharge is roughly the same now as it was in the past. Again, this does not mean that the total load has not changed; it means that, for a given discharge, sediment concentrations are similar in comparison to the 1950s. An exception to this generalization occurs with respect to the pre-peak samples taken between 1977 and 1993, many of which fall below the best-fit relation for the earlier period. We presume that this difference is due to the construction of reservoirs on main stem of the Gunnison River and the Uncompaghre River. These reservoirs are located relatively low in the basin, and are therefore capable of trapping proportionally more of the sediment eroded from surrounding areas.

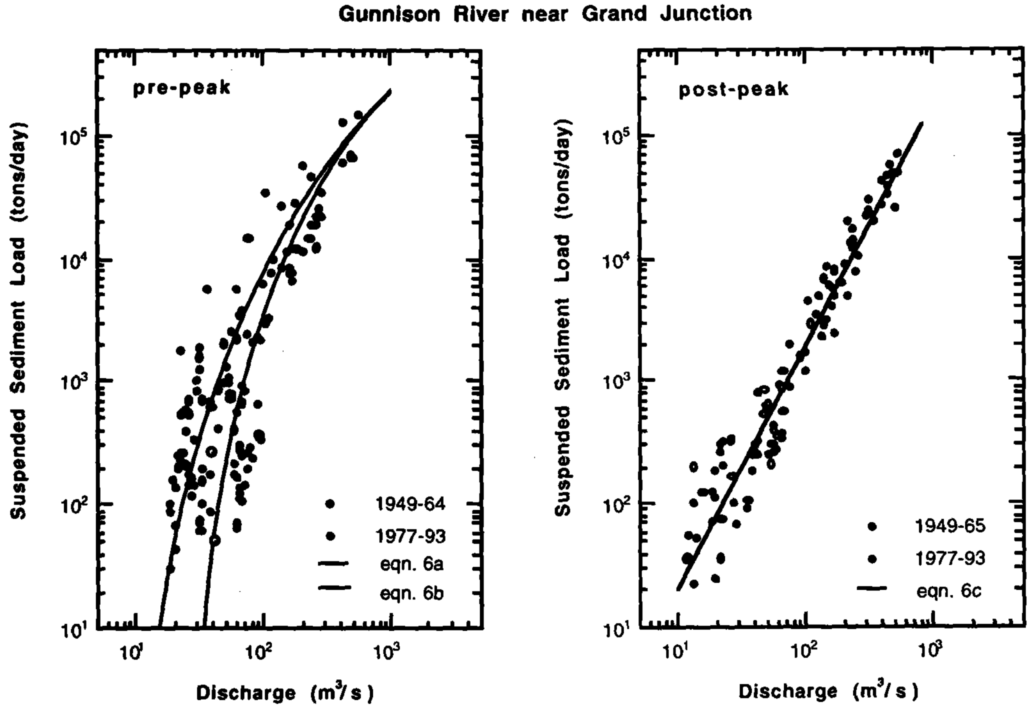

Figure 14. Relation between suspended sediment load and discharge for the Gunnison River near Grand Junction. Data from Iorns et al. (1964) and USGS Water Supply Papers.

Pre-peak sediment loads of the Gunnison River were estimated for separate time periods with the following relations:

pre-peak, 1934-1965: $$Q_s = 16\,(Q - 17)^{1.4} \qquad (6a)$$

pre-peak, 1966-1993: $$Q_s = 16\,(Q - 40)^{1.4} \qquad (6b)$$

Post-peak sediment loads were estimated with a single relation:

post-peak: $$Q_s = 0.2\,(Q)^{2.0} \qquad (6c)$$

Using these relations, and daily discharge values, we calculated suspended sediment loads for the Colorado River and the Gunnison River for each day in the period 1934-1993. The daily values were then summed to estimate the annual suspended sediment load. We should emphasize that this method provides only an approximation of actual values because here, Q_s is estimated from Q, via eqns. 5 and 6, rather than from continuous measurements of sediment concentration.

Time series plots of annual sediment load and annual discharge show that these two variables are moderately well correlated (Fig. 15). However, the range in annual Q_s is much greater than the range in annual Q, indicating that small differences in discharge (and in particular, high discharges) result in large differences in sediment load. Further subdividing these records into separate 15-year periods highlights the interval from 1964 to 1978 when annual sediment loads were very low in comparison to preceding periods (Table 4). As noted earlier, this interval, and several years on either side of it, was characterized by fewer high flow events. From 1964 to 1978 the Colorado River carried an average of about 1.1 x 10^6 metric tons of suspended sediment per year (Table 4); this represents a 30% decrease in load compared to the preceding 15-year period (1949-1963), and a 40% decrease in load compared to the period before that (1934-1948). The Gunnison River experienced similar trends, with annual loads dropping by more than 40% from 1964 to 1978 (Table 4). The net effect of these changes in mass balance would be for sediment to accumulate in the channel, which may in turn have resulted in very rapid losses in the amount of habitat available to fish. It is encouraging to note that from 1979 through 1993 the annual sediment loads of the Colorado and Gunnison Rivers have returned to conditions typical of the earlier periods (Table 4).

Table 4. Comparison of average peak discharge, Q_p, mean annual discharge, Q_m, and suspended sediment load, Q_s, for the Colorado River and the Gunnison River for different time periods.

	Colorado River near Cameo			Gunnison River near Grand Junction		
	Q_p (m^3/s)	Q_m (m^3/s)	Q_s (10^3 t/yr)	Q_p (m^3/s)	Q_m (m^3/s)	Q_s (10^3 t/yr)
1934 - 48	668	116	1.78	453	70	1.68
1949 - 63	570	107	1.57	360	61	1.39
1964 - 78	456	101	1.08	248	62	0.78
1979 - 93	534	116	1.62	321	82	1.41

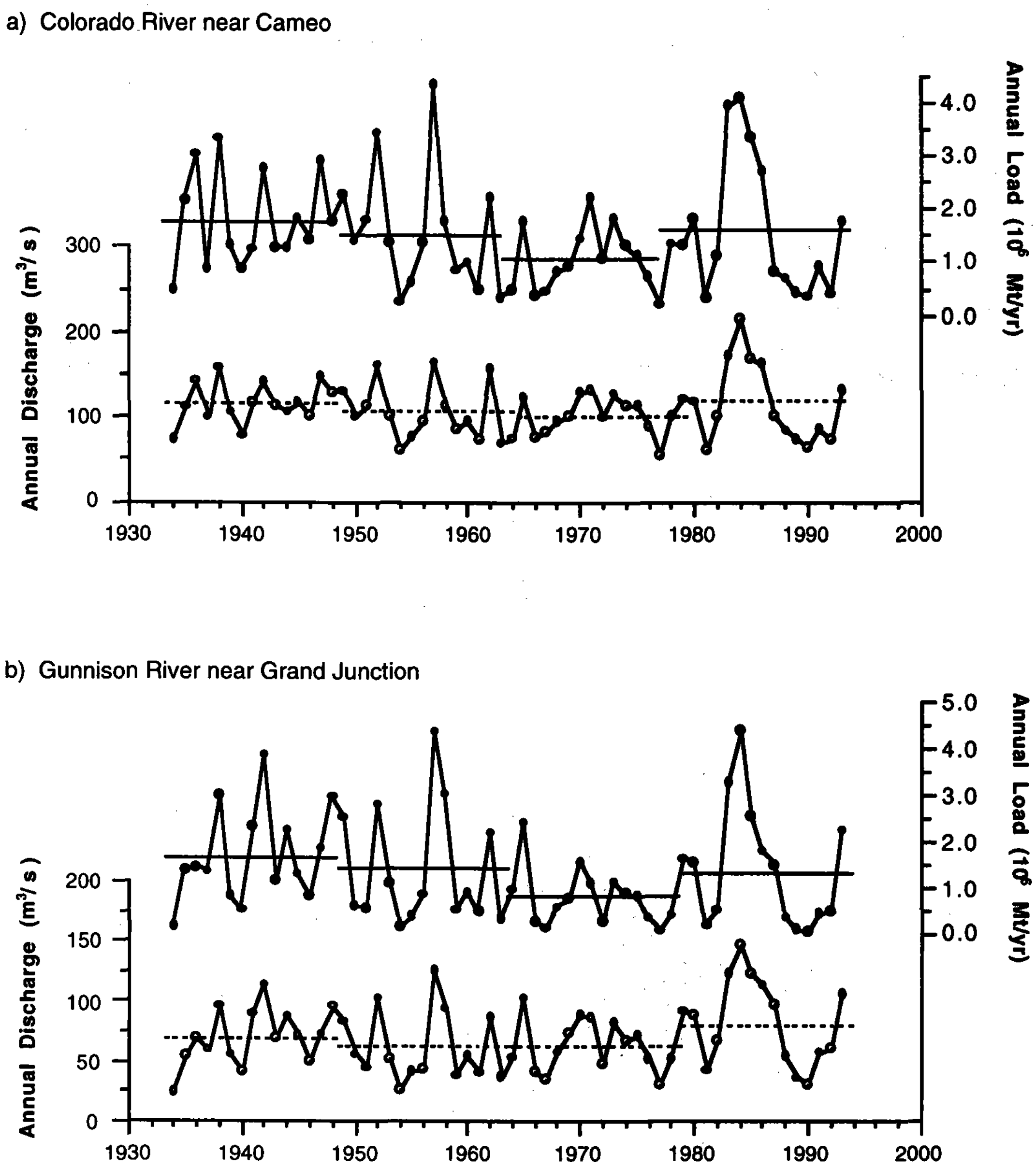

Figure 15. Trends in suspended sediment load and annual discharge of (a) the Colorado River near Cameo and (b) the Gunnison River near Grand Junction. The horizontal lines indicate average suspended sediment loads and discharges for separate 15-year periods.

Changes in Average Bed Elevation

Average bed elevations at the two gauging stations on the Colorado River (Cameo and State Line) have increased by 0.5 to 1.0 m over the last 40 to 60 years (Fig. 16a,b), whereas average bed elevations at the Gunnison River gauge have decreased over time (Fig. 16c). The latter trend is almost certainly due to scour at a road bridge, which lies just downstream of the gauge, thus we do not attach much significance to it. The Colorado River gauges, on the other hand, are located in reaches that are unaffected by such structures, so the persistent aggradation seen at these gauges is due to more natural processes. The question is, is this a local or regional phenomena? If it could be shown that similar amounts of aggradation occurred elsewhere in the Colorado River, then much of the change in sediment transport capacity described above could be accounted for by the storage of sediment in the streambed. However, we see little evidence for widespread aggradation, such as increased braiding and widening, and if anything, the opposite has happened (see below). It seems more likely that the increases in bed elevation observed at these two gauges are the result of local aggradation or the passage of long-wavelength bedforms, and have nothing to do with changes in flow and transport capacity. Either way, the changes in bed elevation observed on the Colorado River are not large in comparison to what has been observed on some other rivers (c.f. James, 1991; Jacobson, 1995). This probably reflects the fact that bed load is a minor constituent of the total load of the Colorado River, and that the bed material is transported only during high flows. If changes in transport capacity are indeed causing aggradation, it is not particularly apparent from these data, or our observations elsewhere.

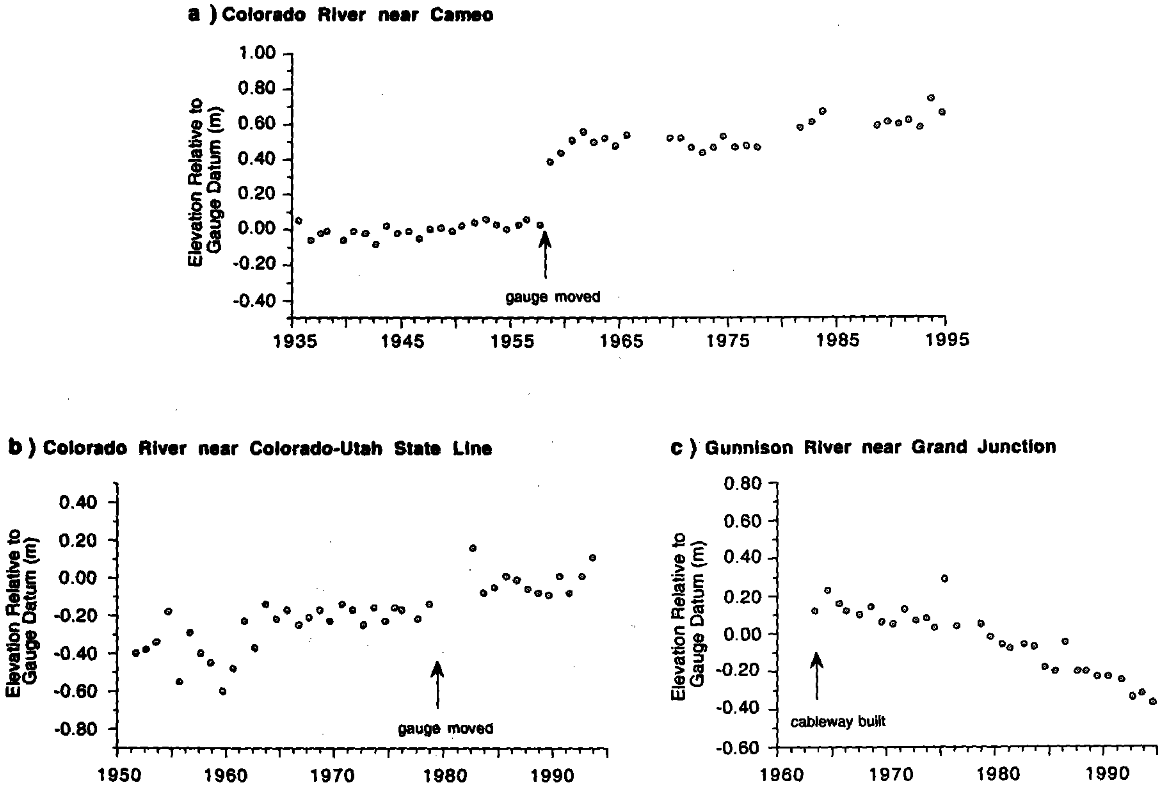

Figure 16. Trends in the average bed elevation derived from data taken during individual discharge measurements on (a) the Colorado River near Cameo, (b) the Colorado River near the Colorado-Utah state line, and (c) the Gunnison River near Grand Junction. Changes in elevation are with respect to the gauge datum.

Historical Changes in Channel Morphology

Our photogrammetric analysis indicates that, in general, the Colorado River and Gunnison River have both become narrower and less complex during the last 50 years. Figure 5, referred to earlier, shows a typical example near RM 176 on the Colorado River where several side channels and small islands present in 1937 had coalesced by 1993 to form one large island and one small side channel. This trend is characteristic of many reaches in the area. In some reaches, however, new side channels and potential habitats were created by major floods in 1983 and 1984. These floods were some of the largest in this century, and they altered the course of the Colorado River in many places, especially where gravel pits were flooded. Thus, although the Colorado and Gunnison Rivers have become narrower and simpler, the period of observation (1937-1993) includes two large floods which created new side channels and restored some channel complexity.

Figure 17 and Table 5 summarize the results of the GIS analysis of geomorphic changes on the Colorado River for the period 1937-1993 (see Table A-5 for a breakdown of the results). In Figure 17, note first the difference in changes between the 15- and 18-mile reaches (RM 185-153) and the Ruby-Horsethief Canyon reach (RM 152-133). The changes in main channel area, island area, and side channel/backwater area are all greater in the 15- and 18-mile reaches where the river is generally less constrained. Note second that the changes in main-channel and side-channel area are consistently negative, indicating decreases in the amount of in-stream water area. When proportioned over the total reach length of 84 km, the reduction in main-channel area amounts to a decrease in average width of about 20 m (-15%, Table 5). The reduction in side-channel area equates to a decrease in average width of about 7 m (-26%, Table 5). However, because side channels are not present within every segment of the river, the change in width, if proportioned only over the length of side channels, is certainly much greater. Side channels are typically 20 to 30 m wide, thus decreases in average width of 7 m or more represent significant losses in potential fish habitat. Changes in island and bar area are negative overall (-9%, Table 5), suggesting these features have gotten smaller, although there are many places where new bars have formed and others have been enlarged. These results suggest that the present-day Colorado River is both a scaled-down and simpler version of the river that existed in 1937.

Table 5. Summary of changes in planform area of the main channel, islands, and side channels of the Colorado River between 1937 and 1993.

	1937 Total Area (ha)	**1993** Total Area (ha)	Change in Total Area (ha)	Change per Unit Length[1] (m)	Change in Area (%)
Main Channel	1125	958	-167	-20	-15
Islands	460	419	-41	-5	-9
Side Channels	225	167	-58	-7	-26

1. The change in area per unit length is computed on the basis of a total reach length of 84 km.

The change in channel area from 1937 to 1993 is much greater than the margin of error, even for the worst case scenario where all objects are measured with the same maximum error, and the error is always in the same direction. The change in side-channel area would be insignificant only in the unlikely case where every polygon in one set of photographs was over-estimated by the maximum, and every polygon in the other set of photographs was underestimated by the maximum.

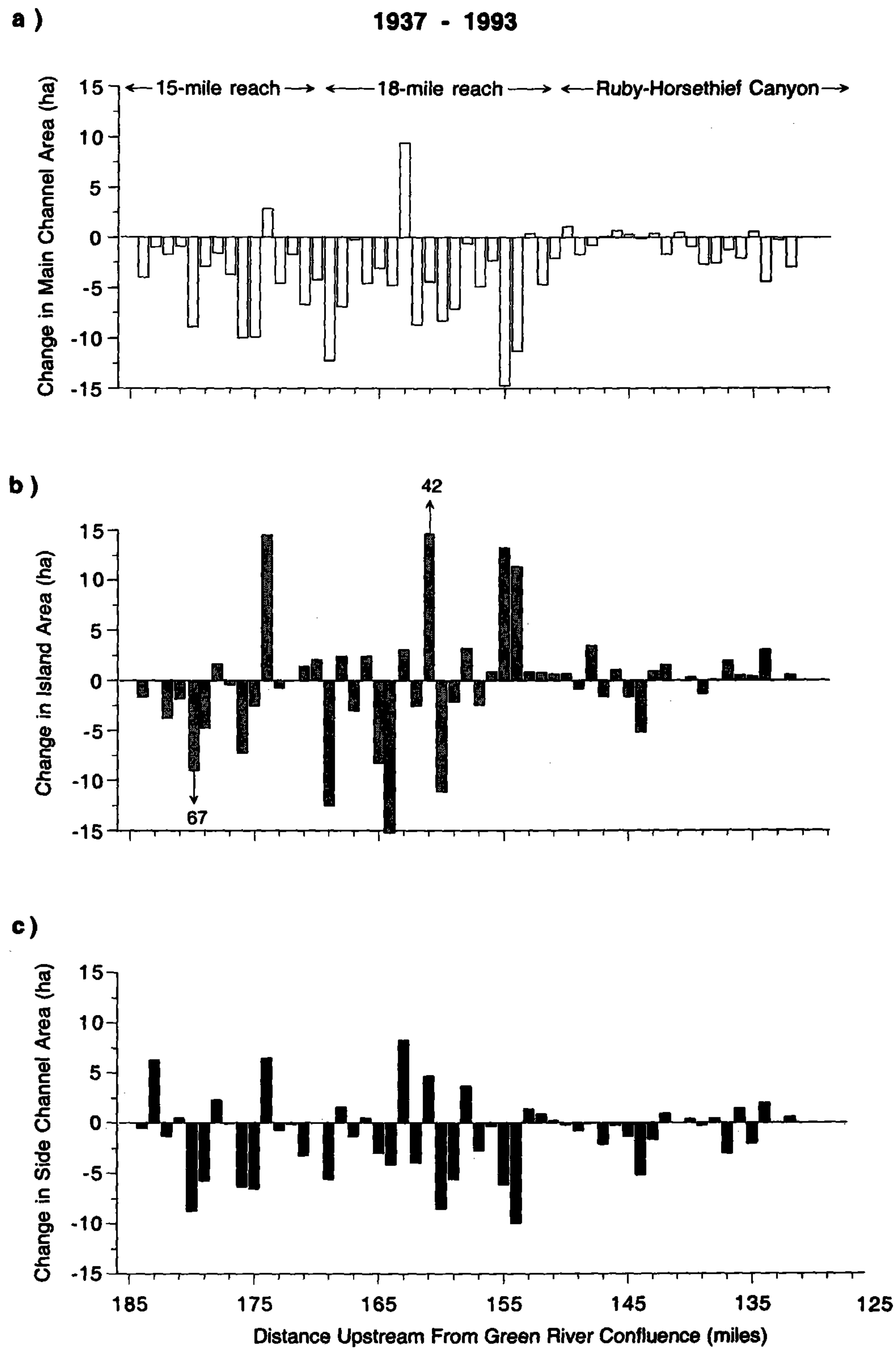

Figure 17. Changes in (a) instream water area, (b) island area, and (c) side channel-backwater area for individual 1-mile segments of the Colorado River from RM 184 to RM 130 between 1937 and 1993 (see Table A-5 for a listing of the basic data).

Changes in main channel area, island area, and side channel area of the Colorado River for the period 1954-1968 are summarized in Figure 18 and Table 6 (see Table A-6 for a breakdown of these results). Similar to the previous comparison, the most significant changes in this period took place in the 15- and 18-miles reaches, and overall, the area of all features decreased. Between 1954 and 1968 the width of the main channel decreased by an average of about 9 m, and the width of side channels decreased by an average of about 4 m (Table 5). The changes observed during this time interval are thus about half as large as those observed between 1937 and 1993, but they occurred in one-fourth of the time. The period between the 1954 and 1968 photographs contains only one major flood (in 1957), many fewer days of high flow (Table 3), and much lower sediment loads (Table 5). These data suggest that the main channel can narrow appreciably, and many side channels and backwaters can be lost altogether, in only a decade or so.

Table 6. Summary of changes in planform area of the main channel, islands, and side channels of the Colorado River between 1954 and 1968.

	1954 Total Area (ha)	**1968** Total Area (ha)	Change in Total Area (ha)	Change per Unit Length[1] (m)	Change in Area (%)
Water	744	670	-74	-9	-10
Island	343	290	-53	-6	-15
Side Channels	139	106	-33	-4	-24

1. The change in area per unit length is computed on the basis of a total reach length of 84 km.

Figure 19 and Table 7 summarize the results of the GIS analysis for the Gunnison River (see Table A-7 for a breakdown of these results). Overall, these results suggest that there has been little change in the planform area of the main channel of the Gunnison River, or in the area of side channels (Fig. 19). However, we should emphasize again that the flow level in the more recent set of aerial photographs was ~80% higher than in the earlier set, which biases the results by an unknown amount. In the field, it is evident from vegetation patterns and the presence of an inset bench along the edge of the present channel that the Gunnison River has narrowed some. Field notes of discharge measurements at the USGS gauge near Grand Junction indicate a decrease in width from about 62 m in 1964 to about 52 m in 1995 for the same discharge of ~50 m^3/s, but it is difficult to say whether the 10 m decrease in width at the gauge is representative of the Gunnison River as a whole, especially since we also know that the bed has scoured at that site.

Table 7. Summary of changes in planform area of the main channel, islands, and side channels of the Gunnison River for the periods shown.

	1937 Total Area (ha)	**1995** Total Area (ha)	Change in Total Area (ha)	Change per Unit Length[1] (m)	Change in Area (%)
Main Channel	502	512	10	1.3	2
Islands	77	67	-10	-1.2	-15
Side Channels	40	39	-1	-0.1	-3

1. The change in area per unit length is computed on the basis of a total reach length of 82 km.

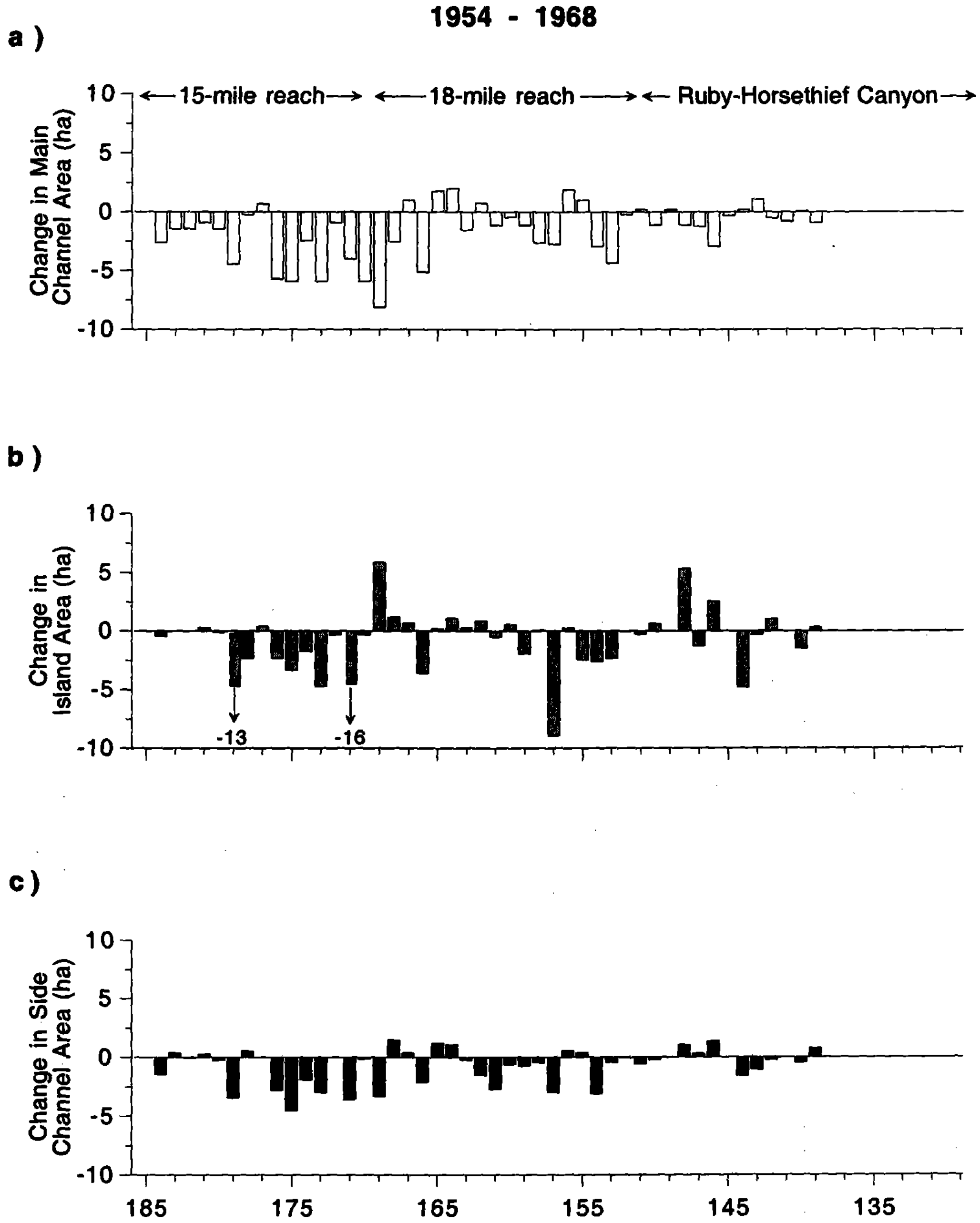

Figure 18. Changes in (a) instream water area, (b) island area, and (c) side channel-backwater area for individual 1-mile segments of the Colorado River from RM 184 to RM 132 between 1954 and 1968 (see Table A-6 for a listing of the basic data).

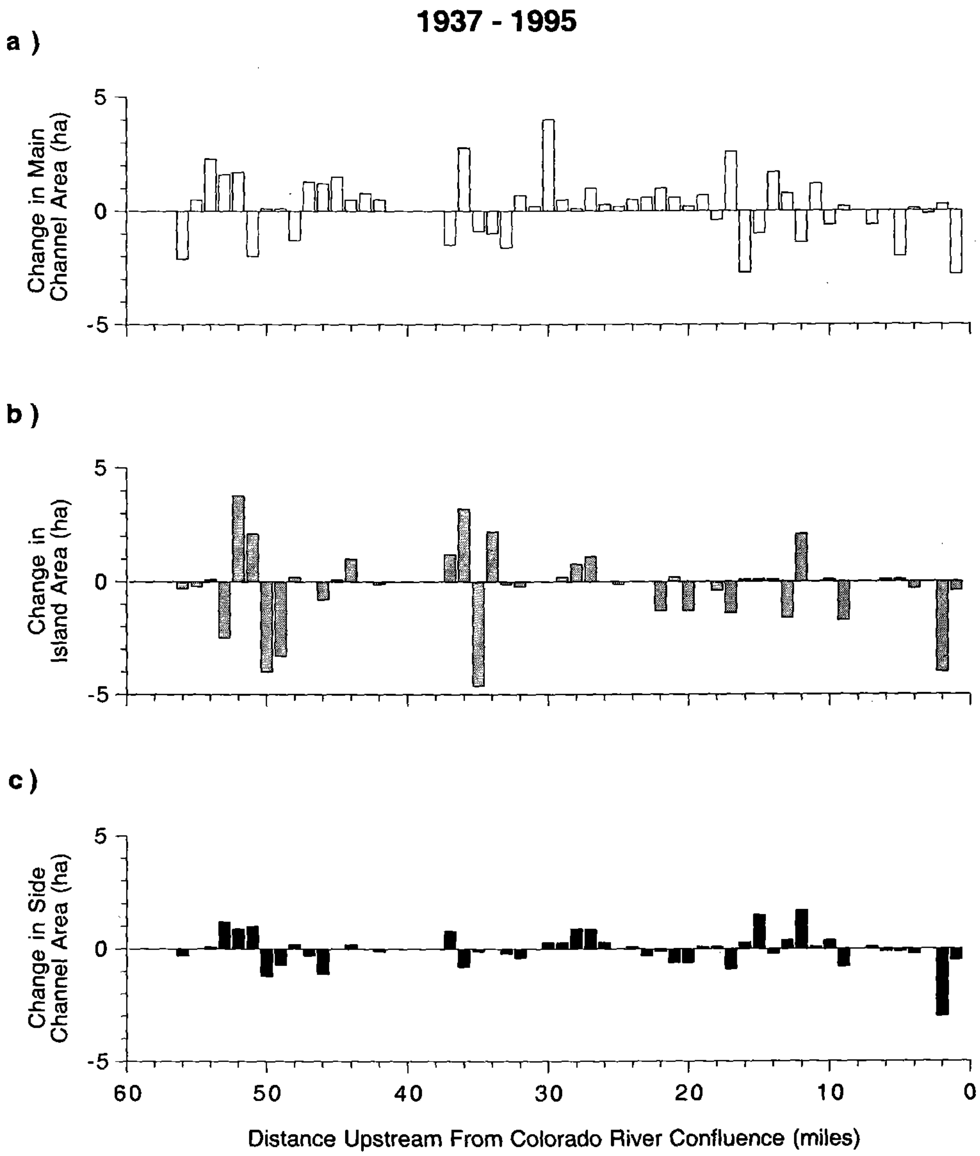

Figure 19. Changes in (a) instream water area, (b) island area, and (c) side channel-backwater area for individual 1-mile segments of the Gunnison River (see Table A-7 for a listing of the basic data). Note the scale of the y-axis in comparison to Figures 17 and 18.

Although we can not say definitively that there have been significant geomorphic changes on the Gunnison River, a comparison of Tables 5 and 7 indicates that, in general, there is much less side-channel and backwater habitat in the Gunnison River than in the Colorado River, and that this has probably always been the case. In 1937 the total area of side channels and backwaters in the Colorado River study reach amounted to about 225 ha (Table 5), whereas in the Gunnison River study reach there was only about 40 ha of side channels and backwaters (Table 7). Analysis of the more recent aerial photographs shows that the Colorado River supports at least 4 times the potential side-channel and backwater habitat as the Gunnison River, and perhaps more if the flow bias in the Gunnison River photographs is removed.

Based on what we have observed in the field, channel narrowing and simplification occur through two processes: lateral accretion along the banks and vertical accretion in side channels. These areas are the most likely sites of fine-sediment deposition because they have lower depths and velocities than the main channel. Side channels also experience more ephemeral flow- some side channels may not experience flow for several years, and then perhaps for only a few days. This allows sediment to build up on the bed, and increases the chance that vegetation will colonize the deposits once they become subaerially exposed. Although this sequence of channel simplification is common to most reaches, it is probably more true of some time periods than others. For example, it appears that the channel narrowed rapidly between 1954 and 1968. Conversely, the channel widened rapidly and significantly in 1983 and 1984. The upper Colorado River has thus evolved to its present state by a complex sequence of events involving both erosion and deposition.

Geomorphic Response to Recent Flow Events

Hydrographs of snowmelt runoff from 1993 to 1995 show that recent flows of the upper Colorado River have ranged from below average to above average (Fig. 20). In 1993 the volume of runoff was above average, and peak discharges were the highest since the record floods of 1984. In 1993 the peak discharge at the Cameo gauge was 660 m^3/s, with a return period of 3.5 years; the peak discharge at the State Line gauge was 1255 m^3/s, with a return period of 6.6 years. In 1993 the average annual peak discharge (Q_p) was exceeded for 11 days at the Cameo gauge, and for 21 days at the State Line gauge.

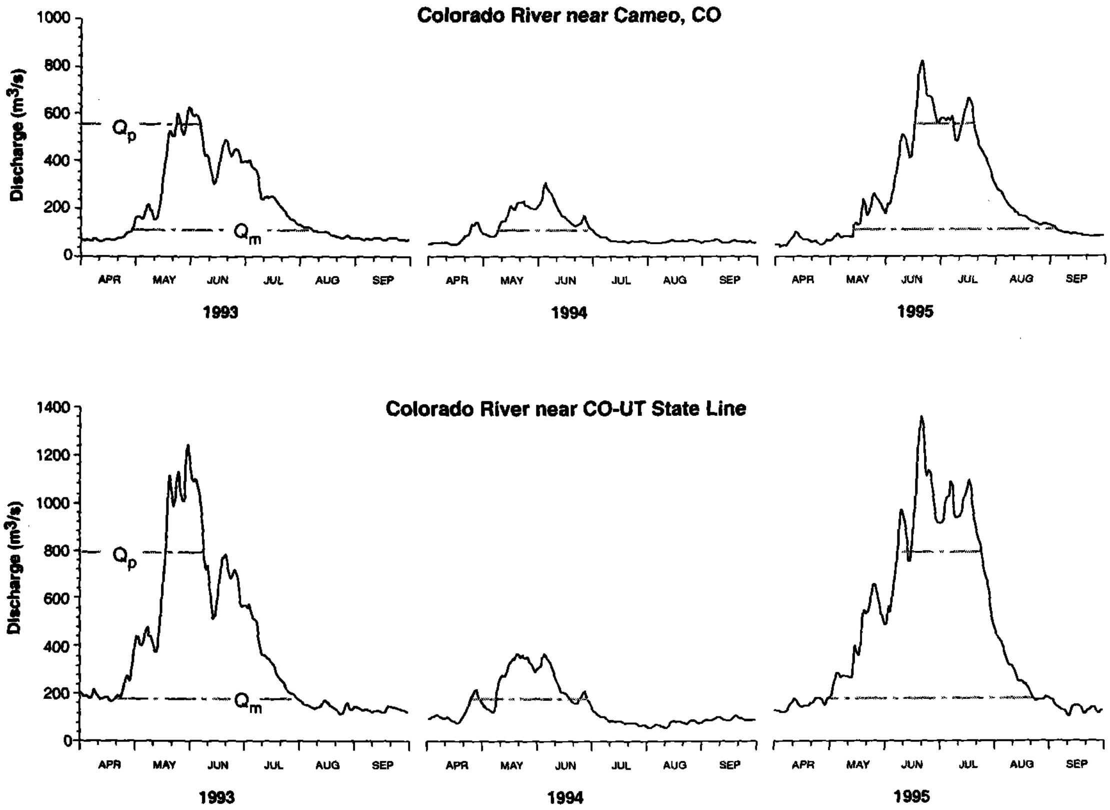

Figure 20. Hydrographs of snowmelt runoff, 1993 through 1995. The line labeled Q_p indicates the average peak discharge. The line labeled Q_m indicates the mean annual discharge.

In 1994 the volume of runoff was below average, as were peak discharges (Fig. 20). The peak discharge at the Cameo gauge in 1994 was 357 m^3/s, with a return period of 1.2 years; the peak discharge at the State Line gauge was 385 m^3/s, also with a return period of 1.2 years. In 1995 the volume of runoff and peak discharges were again above average (Fig. 20). The peak discharge at the Cameo gauge in 1995 was 838 m^3/s, with a return period of 9 years; the peak discharge at the State Line gauge was 1396 m^3/s, also with a return period of 9 years. In 1995 the Q_p was exceeded for 28 days at the Cameo gauge, and for 45 days at the State Line gauge. In the period prior to reservoir construction (1934-1949), the Q_p was exceeded, on average, about 10 days per year at the Cameo gauge. The study period was thus one of above average runoff, not only in comparison to the previous 8 years, but also in comparison to some earlier periods.

Geomorphic changes observed along the main channel during the study period were not particularly striking given this sequence of flow events. Measurements of 12 main channel cross sections prior to and after the period of very high runoff in 1995 show that localized scour and fill occurred at some sections (Fig. 21), but little change occurred at most sections. Data presented by Osmundson et al. (1995) suggest that the river was more active in some places, and there was clear evidence that gravel bars had been extensively re-worked, but sites of widespread bank erosion or scour and fill were not apparent in our surveys.

We observed more noticeable geomorphic changes at our backwater and side channel study sites, particularly at the mouths of the backwaters. Figure 22 shows a series of measurements of cross sections across the mouths of each of the backwaters. In most cases, fine sediment present in April 1993 was scoured from the mouths of the backwaters, and they were enlarged. The pattern of scour was not consistent, however, making it difficult to generalize on the basis of these few observations. The mouth of the backwater near RM 160 scoured ~0.5 m in the first year, but not much thereafter (Fig. 22a); the mouth of the backwater near RM 162 changed little in the first two years, then scoured ~1.0 m in 1995 (Fig. 22b); and the mouth of the backwater near RM 176 scoured some every year, eventually eroding by ~2.5 m (Fig. 22c). Two other backwaters monitored by the USFWS scoured by similar amounts in 1993 (Osmundson et al., 1995). The changes observed during these three years support the view that high flows are necessary for keeping backwaters open, but the effects clearly vary from site to site.

Earlier we showed that about 1/4 of the side channel and backwater habitat in the upper Colorado River has been lost since the late 1930s. We associated these losses with decreases in sediment load that occurred during periods of below-average discharge. The above results indicate that higher-than-average discharges cannot completely reverse the trend of channel simplification, especially if vegetation becomes established and has a chance to mature. Certain species such as tamarisk and willow appear to be very hearty and are not easily disturbed. We have observed that willow and tamarisk seedlings can survive, and continue to grow, in spite of being inundated for many weeks. Vegetation appears to have a pronounced effect on the stability of the channel, and for this reason, it will probably be difficult to create significant amounts of additional new habitat by simply manipulating the hydrograph to produce higher discharges. This is not to say that higher discharges do not serve other important geomorphological purposes. As we show in the next sections, higher discharges are critical for maintaining the quality of existing habitats and for preventing further losses in habitat by carrying the sediment through the reach.

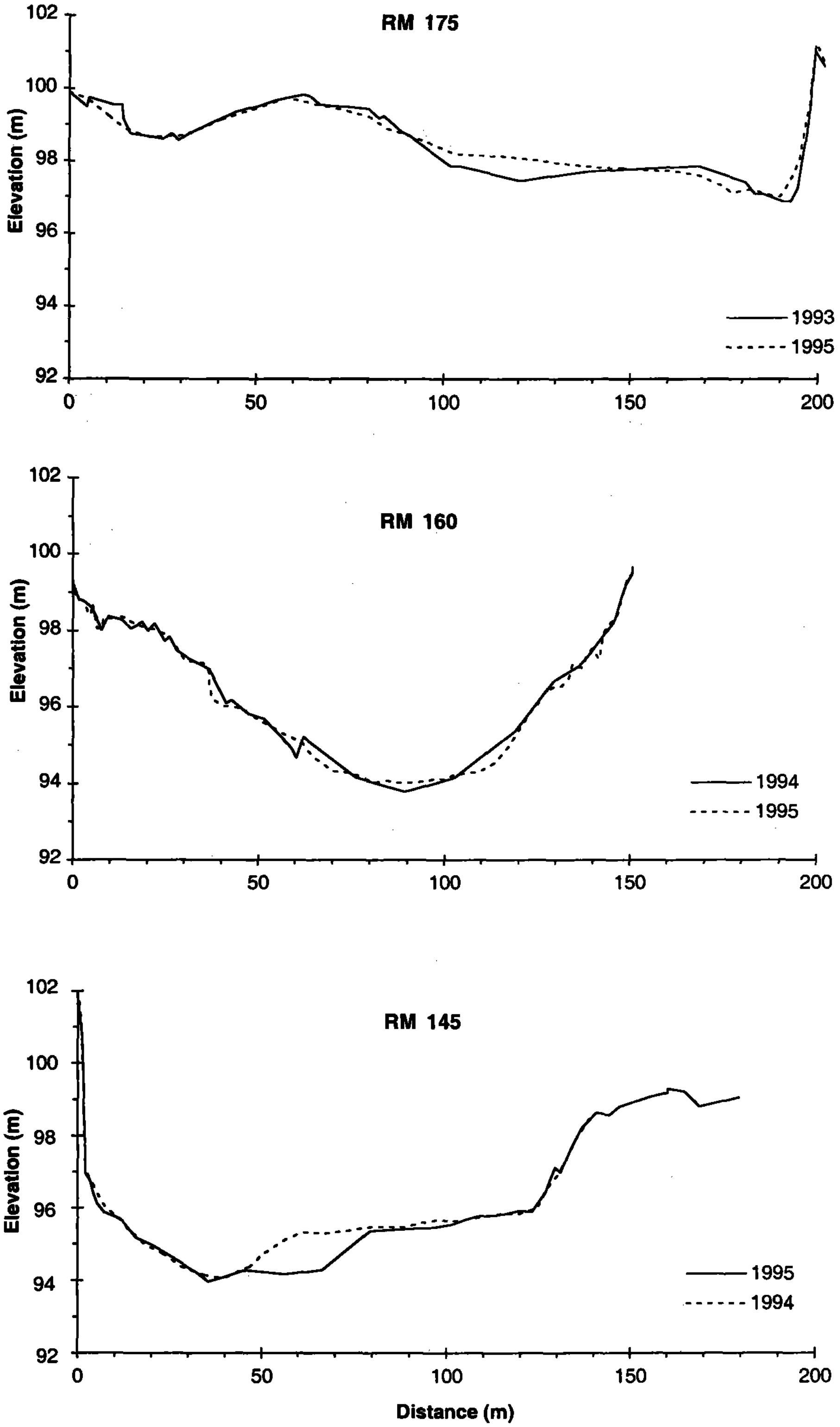

Figure 21. Examples of main channel cross sections surveyed before and after the period of high snowmelt runoff in 1995.

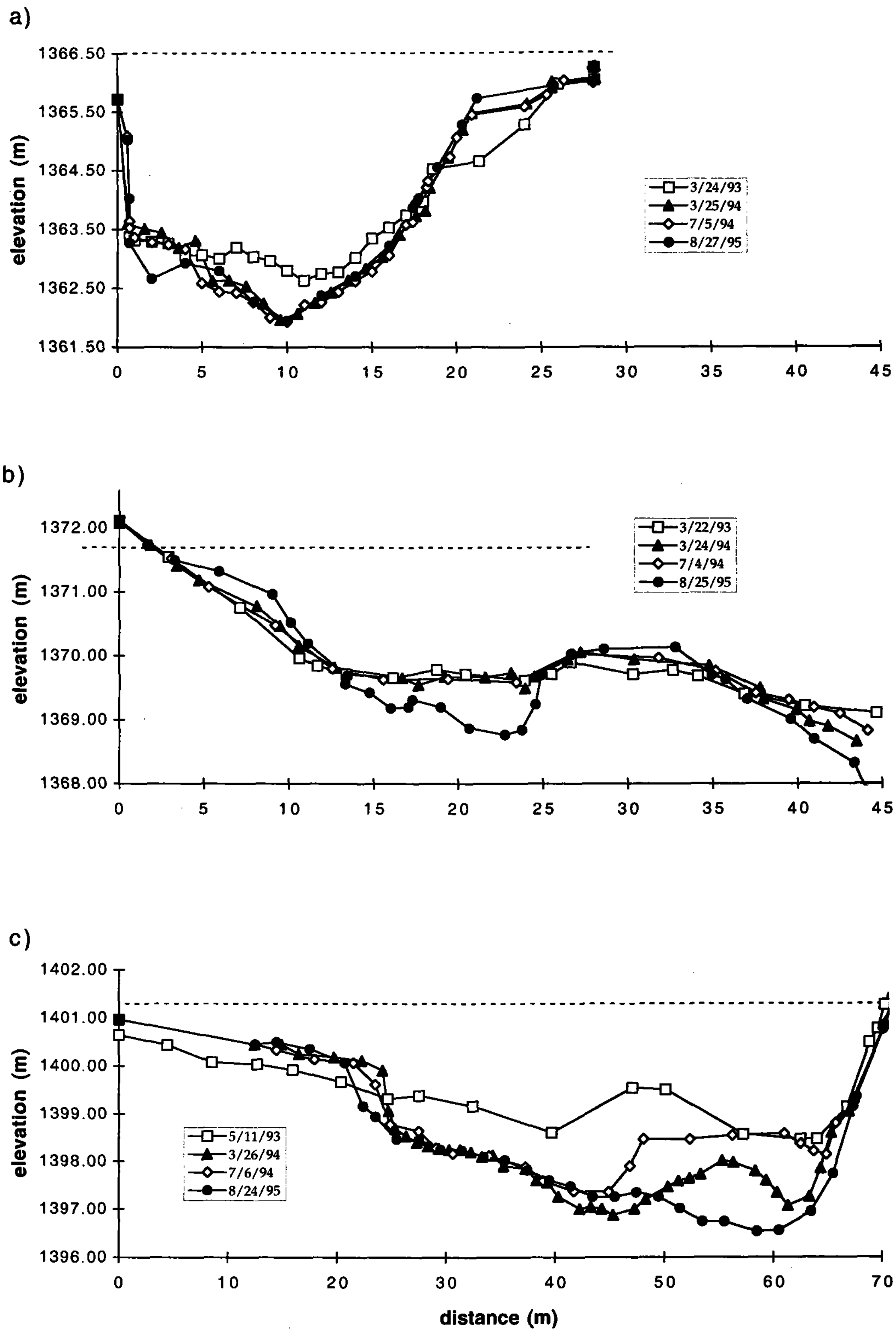

Figure 22. Sequence of cross section measurements taken at the mouths of backwaters in the 15- and 18-mile reaches. Dashed lines indicate approximate bankfull flow levels.

Development of Discharge-Shear Stress Relations

The reaches used to model relations between discharge Q and boundary shear stress τ typically encompass one riffle-pool-run sequence. Runs in the upper Colorado River are generally long in comparison to riffles and pools, thus changes in reach-average hydraulic conditions are governed by what occurs in runs. At low Q the water-surface slope through a run is usually less than the reach-average slope, whereas over a riffle, the local slope may be very steep, differing from the reach-average slope by a factor of 10 or more. As Q increases there is a tendency at most of our sites for the slope to increase over the runs and decrease over the riffles such that the water-surface profile becomes smoother and steeper (Fig. 23a). One exception to this is the site at the State Line gauge (RM 134) where the ponding effect of a downstream bend causes the water-surface slope to decrease as Q increases (Fig. 23b). However, the decrease in slope is not so large that it offsets the increase in depth, such that the shear stress increases across the full range of discharges.

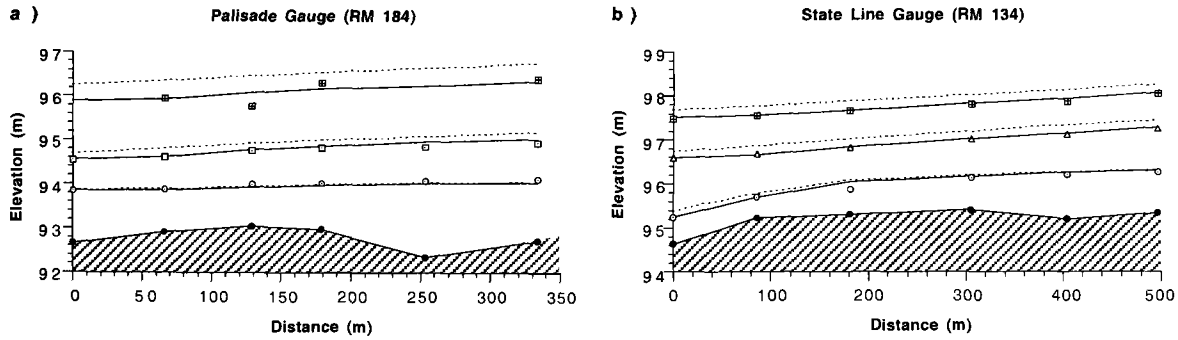

Figure 23. Water-surface profiles at (a) the Palisade gauging station and (b) the State Line gauging station. Lines indicate modeled energy and water-surface profiles, symbols indicate measured water-surface elevations.

Figure 24 shows separate calibrated model relations between discharge Q and dimensionless shear stress τ^* for the State Line and Palisade study reaches. In both plots the closed circles represent reach-average values of τ^*, while the open circles represent values for individual cross sections. The reach-average values are best fit, respectively, by the following equations:

State Line Study reach: $$\tau^* = 0.003Q^{0.37} \quad (7a)$$

Palisade Study Reach: $$\tau^* = 0.0003Q^{0.84} \quad (7b)$$

where the discharge Q is in cubic meters per second. These data show that the relation between Q and τ^* is generally nonlinear and concave-down. However, as the shapes of the curves and the exponents in the above equations indicate, individual Q -τ^* relations can vary from highly non-linear (7a) to nearly linear (7b). The difference in linearity arises because of how geomorphologic conditions within the reaches affect the flow, and the water-surface slope in particular. To clarify the importance of this point, we refer to the base case of "uniform flow", meaning that the mean flow depth and velocity are the same at all sections, and the bed and water-surface slopes are parallel. Under this assumption, it is easy to show that the expected relation between discharge and shear stress is $\tau^* \propto Q^a$, with $a = 0.60$ or 0.67 depending on whether the Manning or Darcy-Weisbach flow resistance equation is used in the formulation. If the water-surface slope or roughness of the reach change significantly with discharge, different values of a can be expected. The results from the State Line reach illustrate a case where the water-surface slope decreases with increasing discharge, producing a concave Q-τ^* relation, with an exponent that is much lower than the uniform-flow values of 0.60 or 0.67. The results from the Palisade study reach illustrate the more typical case of a run-dominated reach where the water-surface slope increases with discharge, producing a steep Q-τ^* relation with an exponent that is higher than the uniform-flow values.

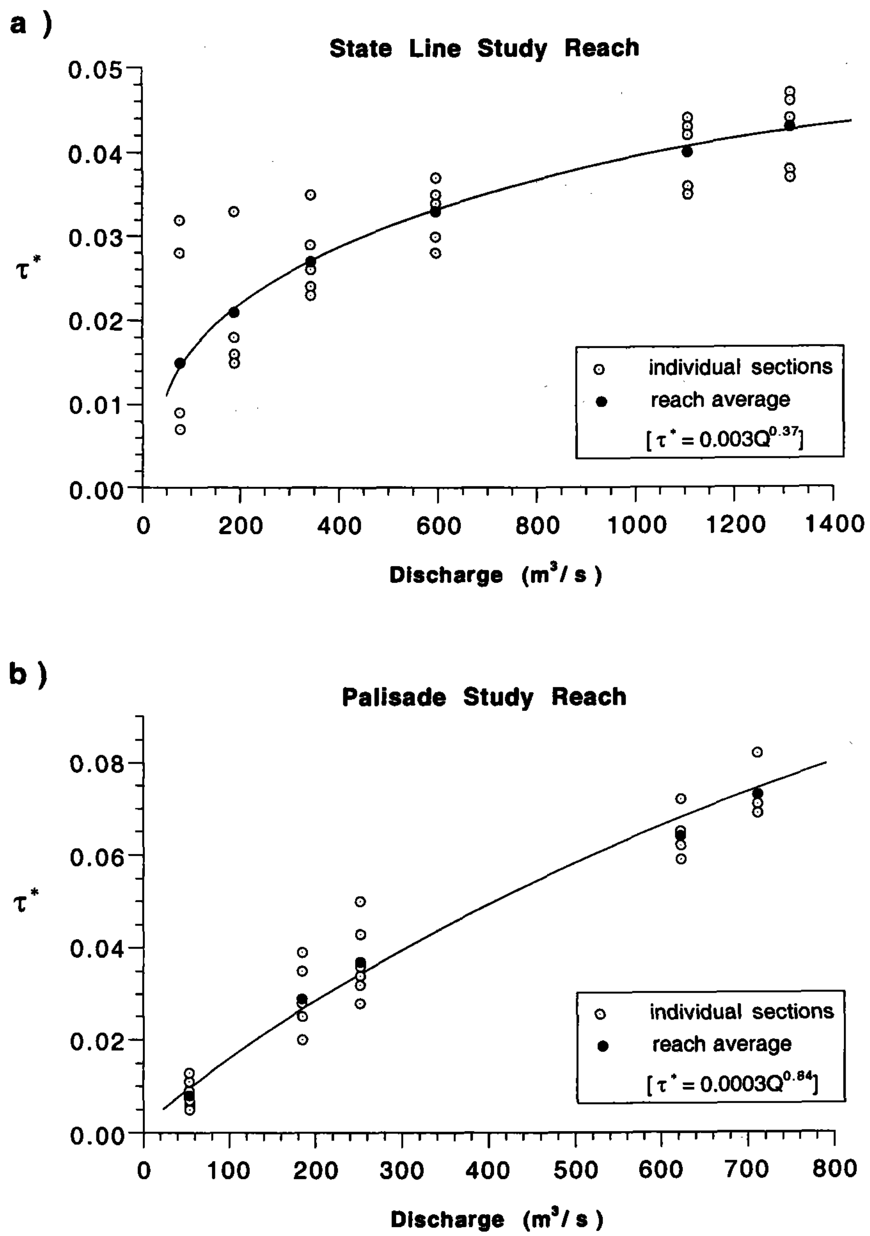

Figure 24. Relations between discharge Q and dimensionless shear stress τ^* for study reaches near (a) the USGS gauge near the CO-UT State Line, and (b) the USGS gauge near Palisade, CO. Open symbols represent values of τ^* at individual cross sections and solid symbols represent the average τ^* for the reach for a given discharge.

Results from five additional flow-modeling sites show that the relations between Q and τ^* can vary from slightly concave to linear, with a ranging from 0.48 to 0.98 (Fig. 25). In several cases, τ^* increases roughly in proportion to Q across the full range of discharges. This is important with respect to the issue of channel maintenance because it is known from basic sediment transport theory that rates of transport usually increase with τ^* to a power greater than 1 (the exponent in several bed load transport relations is 1.5), which means that, for a given increment in Q, higher flows can carry a much larger proportion of the total sediment load than lower flows.

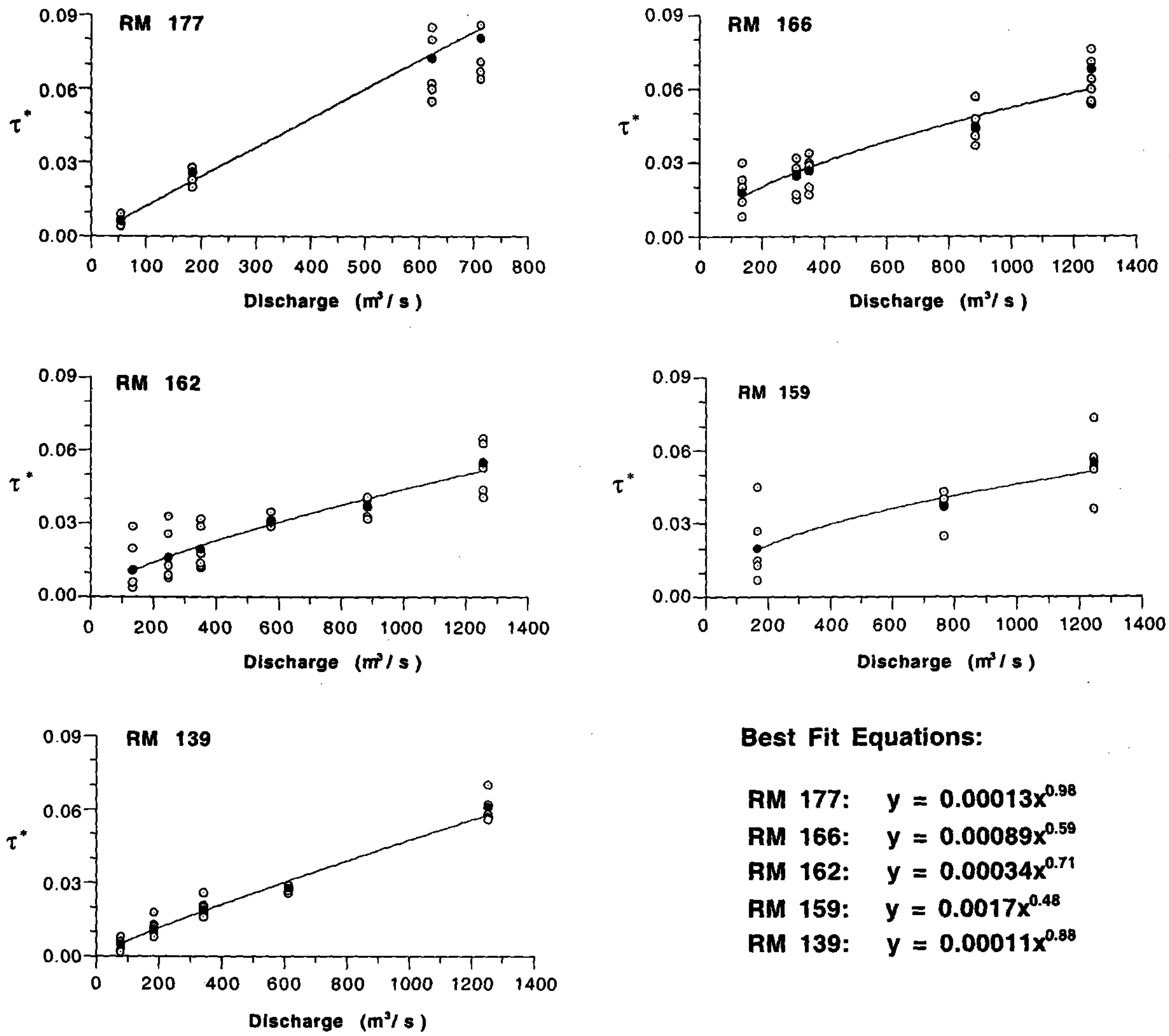

Figure 25. Relations between Q and τ^* for 5 additional study reaches on the Colorado River.

One additional point to make about the results shown in Figures 24 and 25 concerns the significance of data that lie off the reach-average trends. In particular there are several instances where values of τ^* exceed the threshold for bed load transport (0.03) at relatively low flows. This implies that transport is occurring in localized areas at flows less than those that would generate transport through the reach as a whole. Indeed, we have noted in the field that moderate flows can produce values of τ^* which are high enough locally to maintain bed load transport over some riffles and bars. However, we emphasize that this cannot be treated as a steady-state process, as implied by this type of modeling. It is well known from sediment transport theory and field observations that differential erosion and transport will lead to adjustments in the size of the bed material and bed elevation such that a balance between input and output is soon reached. In other words, sediment cannot be transported indefinitely from localized zones of high shear stress without some channel adjustment, and unless bed material is supplied from upstream at an equivalent rate. We raise this point, and the point above about the slope of the Q-τ^* relation, because results presented by Harvey et al. (1993), describing similar work on the Yampa River, suggest that under certain conditions the relation between Q and τ^* is nonmonotonic, with shear stress increasing from low to moderate flow, and then decreasing from moderate to high flow; such a relation predicts that discharges approaching baseflow can generate shear stresses high enough to maintain gravel transport, while discharges exceeding the mean annual flood are not competent to move the bed material. We have not observed these trends at any of our sites, and in general our data do not support this component of the process-response model discussed by Harvey et al. (1993).

The discharges that produce reach-average values of $\tau^* = 0.030$ and $\tau^* = 0.047$ were calculated for each site using the best-fit equations given in Figures 24 and 25; the specific discharges are listed in Table 8, along with the percentage of time that they are equaled or exceeded. On the basis of these results, we estimate that the threshold for gravel transport ($\tau^* = 0.030$) is between 225 and 320 m^3/s in the 15-mile reach, and between 440 and 620 m^3/s in the 18-mile and Ruby-Horsethief Canyon reaches. These flows occur about 7% of the time, or 26 days per year, on average (Table 8); equivalent instantaneous peak discharges occur about 2 out of every 3 years (Van Steeter, 1996). Our field surveys of channel cross sections indicate that this flow is approximately 1/2 of the average bankfull discharge and about 2/3 of the average bankfull depth. Discharges that produce significant motion ($\tau^* = 0.047$) range between 360 and 550 m^3/s in the 15-mile reach, and between 830 and 1060 m^3/s in the 18-mile and Ruby-Horsethief Canyon reaches; these discharges occur about 2% of the time, or 8 days per year, on average (Table 8). Our cross section surveys indicate that this flow coincides almost exactly with the bankfull discharge (see below).

Table 8. Discharges and durations of flows corresponding to specific sediment transport thresholds ($\tau^* = 0.030$ and $\tau^* = 0.047$).

	Discharge, m^3/s		Percent of Time Equaled or Exceeded	
River Mile (RM)	$\tau^* = 0.030$	$\tau^* = 0.047$	$\tau^* = 0.030$	$\tau^* = 0.047$
Sites Upstream of Gunnison River:				
184.2	320	550	7.9	1.6
177.3	225	360	12.6	6.3
average:	273	455	10.3	4.0
Sites Downstream of Gunnison River:				
166.0	440	830	8.2	1.9
162.4	620	1060	4.1	1.1
159.0	500	1025	6.3	1.2
139.5	605	970	4.4	1.4
134.0	505	1050	6.3	1.1
average:	534	987	5.9	1.3

Milhous (1998) made similar measurements along a 2000-meter reach of the lower Gunnison River near Dominguez Flats between Delta and Grand Junction. This reach has an average gradient of 0.0013 and the bed material is gravel with a D_{50} of 70-94 mm. Milhous worked independently of us, but his objectives were very similar and he used many of the same techniques and assumptions that we did; thus his results should be comparable to ours. Milhous (1998) reports that "flushing" of fine sediment, produced by gravel movement at an assumed transport threshold of $\tau^* = 0.021$, occurs at most cross sections at a discharge of 373 m^3/s, which is about 3/4 of the bankfull flow. Discharges that flush sand and silt from riffles, and scour sediment from pools and backwaters, ranged from 210 to 484 m^3/s, or from about half the bankfull discharge up to nearly the bankfull discharge. Milhous provides two separate criteria for maintaining potential spawning habitats (riffles). The first discharge of 355 m^3/s is the flow needed to transport pea gravel (2-4.74 mm) in suspension; the second discharge of 27 m^3/s is the flow needed to transport 0.5 mm sediment as wash load. The difference in terminology and physical significance of these flows is explained as follows: Particles transported in "suspension" exchange with the bed, thus the goal of the former discharge is to prevent sediment finer than 4.74 mm from settling onto the bed and into voids between framework grains; particles transported as "wash load" do not exchange with the bed, thus the goal of the latter discharge is to keep sediment finer than 0.5 mm from being deposited anywhere on the bed, or in other words, to move it completely out of the reach. These are both reasonable ways to view the problem of habitat maintenance, but fundamentally different from the concept of "flushing", which requires movement of the framework grains. Thus, among Milhous' various results, his finding that fines are flushed from the bed at a discharge of 373 m^3/s is most comparable to ours, although the discharge he specifies is higher in a relative sense (~3/4 of bankfull) than what we have found. This discrepancy might be explained by the fact that Milhous (1998) reports a relatively high value for the bed material in this reach compared to what we have found elsewhere in the Gunnison River (see appendix Table A-3); if the "representative" bed material were indeed finer this would lower the value of the discharge required for flushing fines.

Downstream Hydraulic Geometry

Another way to approach the problem of habitat or channel maintenance is to measure the existing hydraulic geometry or bankfull dimensions of the river, and from these dimensions determine the discharge that shapes the channel. To do this, we used data from 53 main-channel cross sections in conjunction with Parker's (1979) theory that the hydraulic geometry of a gravel-bed river is determined by a discharge that produces a boundary shear stress just slightly greater than the critical value for bed load transport.

Figure 26 summarizes downstream trends in the bankfull hydraulic geometry of the Colorado River. The values of bankfull width and bankfull depth shown here are taken directly from field measurements at individual cross sections; the values of bankfull dimensionless shear stress τ^*_b are calculated from eqn. 3, using reach-averaged estimates of S and D_{50}, and the measured bankfull depth. Figure 26a shows that the bankfull width of the Colorado varies by a factor of about three: several sections in the 15-mile reach have bankfull widths of less than 100 m, while one section in the 18-mile reach has a bankfull width of nearly 300 m. Overall, there does not appear to be much of trend in the bankfull width, although the segment of the 15-mile reach from RM 184 to 176 is more narrow than any other segment of the river. Figure 26b, on the other hand, shows that the bankfull depth increases systematically downstream, from an average of about 2.5 m in the 15-mile reach to about 3.5 m in the Ruby-Horsethief Canyon reach. Part of the increase in bankfull depth is due to the effects of the Gunnison River, but the trend in depth is more systematic than step-like. Apparently, it takes many miles for the Colorado River to adjust to tributary inputs. The third plot in this series (Fig. 26c) shows that the calculated values of τ^*_b are very consistent from reach to reach. For the three reaches combined, the average τ^*_b is 0.047, which is ~1.5 times the critical dimensionless shear stress for bed load transport. The consistent trend in τ^*_b occurs because, even though the depth increases downstream, the slope and grain size also decrease (Table A-8).

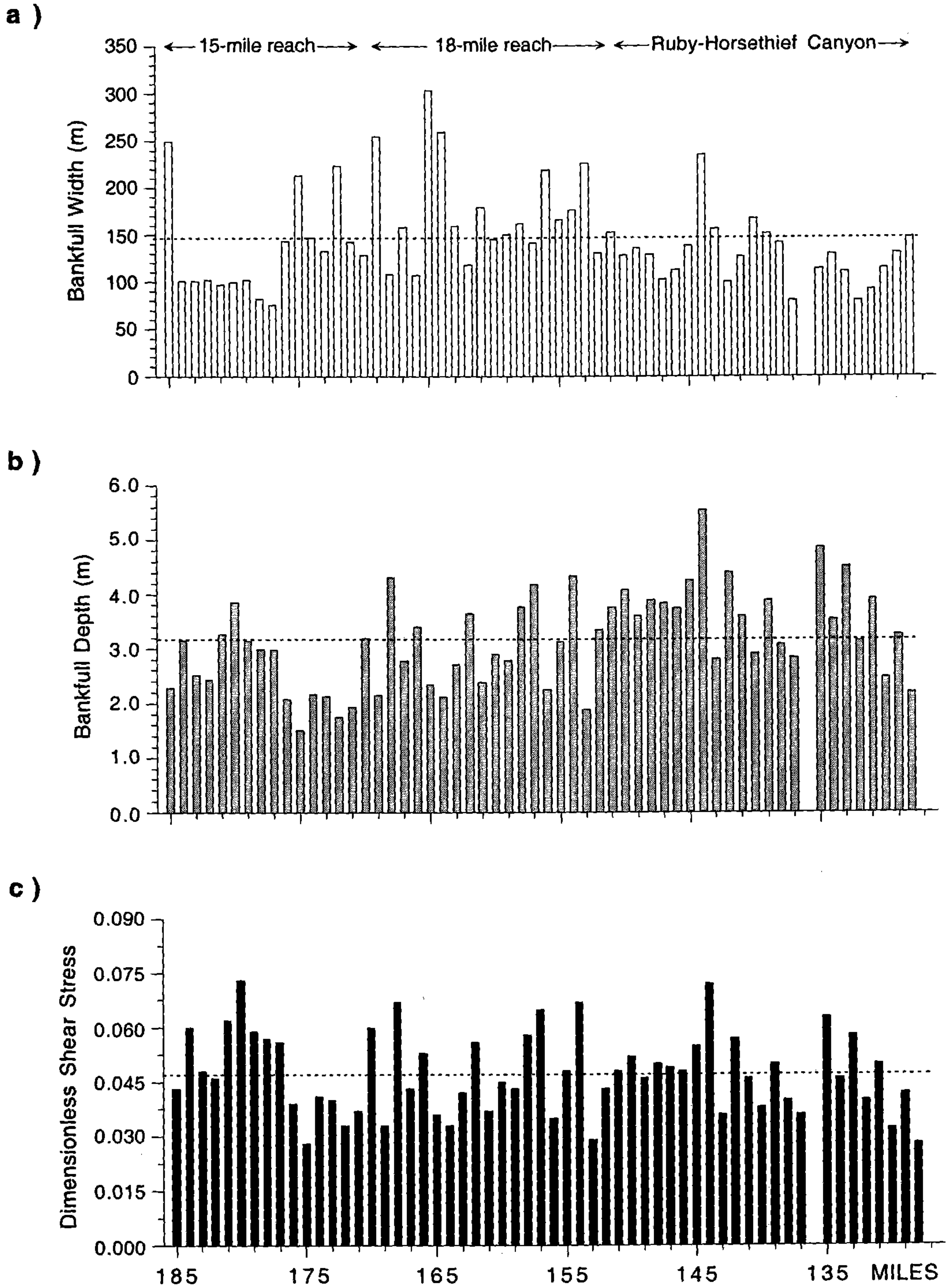

Figure 26. Downstream trends in (a) bankfull width, (b) depth, and (c) dimensionless shear stress of the Colorado River. Dashed lines indicate mean values for the entire reach.

The Gunnison River exhibits similar trends in downstream hydraulic geometry (Figure 27). The bankfull width of the Gunnison River is essentially constant through this 85-km reach (Fig. 27a), however, the variation in width between individual cross sections is notably less than on the Colorado River. Similar to the Colorado River, the bankfull depth increases slightly downstream (Fig. 27b). The increase in depth is again countered by a decrease in slope and grain size (Table A-9) such that τ^*_b stays roughly constant downstream (Fig. 27c).

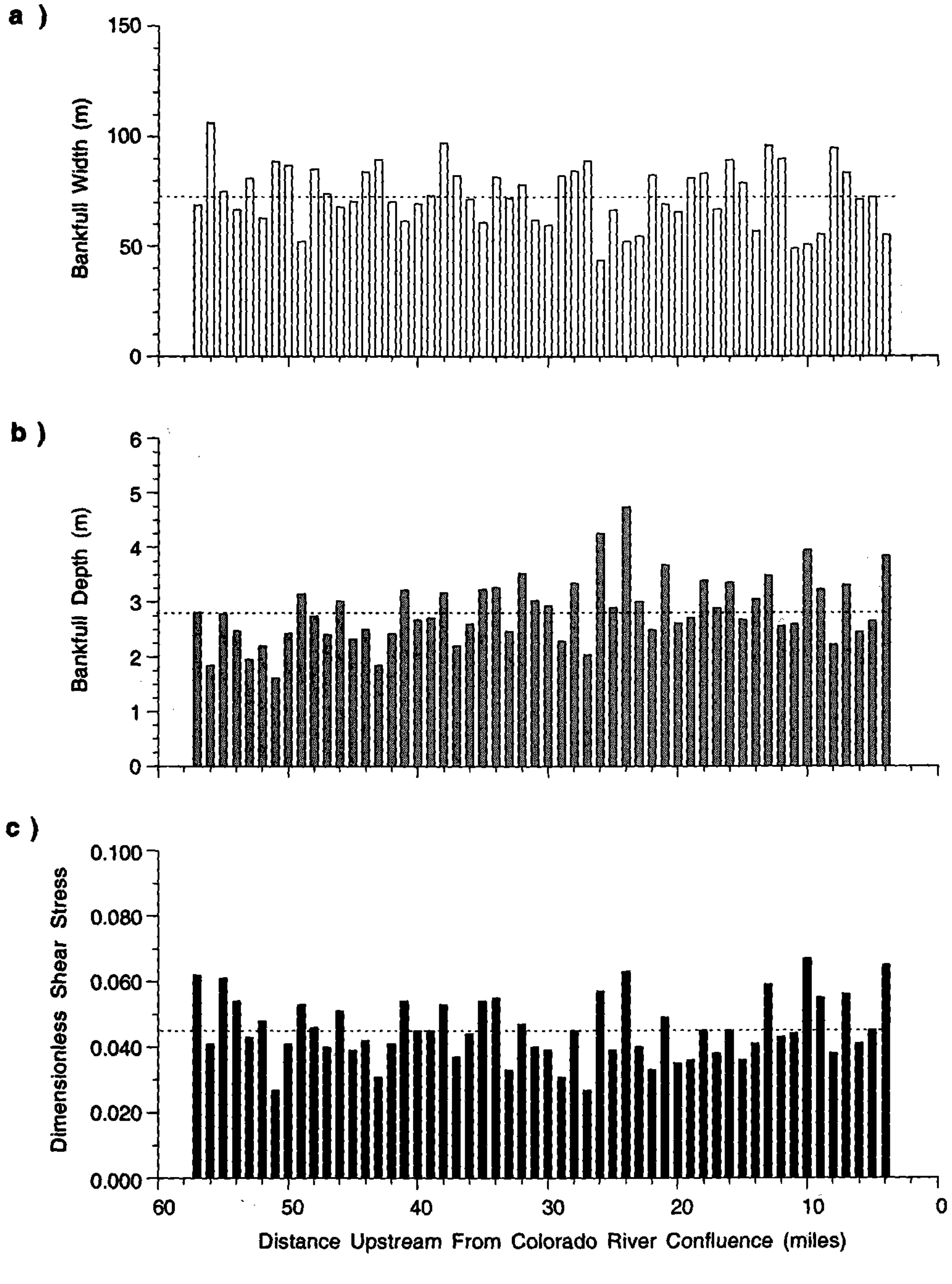

Figure 27. Downstream trends in (a) bankfull width, (b) depth, and (c) dimensionless shear stress of the Gunnison River. Dashed lines indicate mean values for the reach.

The data shown in Figures 26 and 27 have several important implications. First, it appears that both the Colorado River and the Gunnison River become deeper, rather than wider, in the downstream direction. This means that for a given discharge, flow in upstream reaches is generally shallower than in downstream reaches, which may have some influence on habitat availability and biological productivity. Second, the consistent trends in bankfull dimensionless shear stress indicate that the hydraulic geometries of the Colorado River and Gunnison River are related in a consistent and physically meaningful way to a gravel transport threshold, i.e. their bankfull widths and depths are adjusted to discharges that produce an average boundary shear stress that is about 1.5 times the critical shear stress for bed load transport. We interpret these results to mean that the channels of the Colorado River and Gunnison Rivers are more or less in equilibrium with the present flow and sediment transport regimes, altered as they are. The width, depth and slope are adjusted to maintain sediment transport capacity through these reaches, as indicated by the uniform values of b_b and τ^*_b. Furthermore, the reach-average value of $\tau^*_b = 0.047$ defines a threshold for bank erosion and channel widening, which is essential if new bars and additional habitat are to be created. We emphasize, however, that this is a minimum value, and flows that reach this level will probably not cause widespread bank erosion.

Using these same data in combination with equations for continuity, flow resistance and shear stress, we made additional estimates of the discharges required to reach the two transport stages (initial motion and significant motion) referred to earlier. The equation used in making these estimates is derived by assuming uniform flow (a reasonable approximation over long reaches; see Henderson, 1966), and combining the continuity equation with the Manning equation to get

$$Q = \frac{b\, h^{5/3}\, S_o^{1/2}}{n} \qquad (8)$$

where h is the flow depth required to produce a given dimensionless shear stress (found using eqns. 1 and 3), S_o is the reach-average slope, and n is the Manning resistance coefficient. In these calculations we used model-verified n values ranging from 0.030 to 0.035, and assumed values of $\tau^* = 0.030$ for the discharge that initiates bed load transport (termed the critical discharge, Q_c), and $\tau^* = 0.047$ for the discharge that causes significant bed load transport (which we equate with the bankfull discharge, Q_b).

Figure 28 shows the resulting estimates of Q_c and Q_b for individual cross sections, with the median values for specific reaches indicated by horizontal lines. The variation in Q_c is generally less than the variation in Q_b, but both data sets exhibit a considerable range in values. The range in values of Q_c and Q_b arises mostly because of variations in channel width, which are large relative to channel depth (ref. Fig. 26a and 26b). The median values of Q_c and Q_b in the 15-mile reach are 296 m^3/s and 621 m^3/s, respectively (Fig. 28a); these values are in good agreement with our flow modeling results (Table 8). The median values of Q_c and Q_b in the 18-mile and Ruby-Horsethief Canyon reaches are 524 m^3/s and 994 m^3/s, respectively (Fig. 28a); these values are likewise in very good agreement with the flow modeling results (Table 8). In the Gunnison River the median Q_c ranges between 195 and 269 m^3/s and the median Q_b ranges between 377 and 414 m^3/s (Fig. 28b). These values are low in comparison to Milhous' (1998) estimates of a flushing flow discharge (which we equate with Q_c), and the bankfull discharge, but the discrepancy is not large, and probably due to differences in methods and data used in the respective analyses.

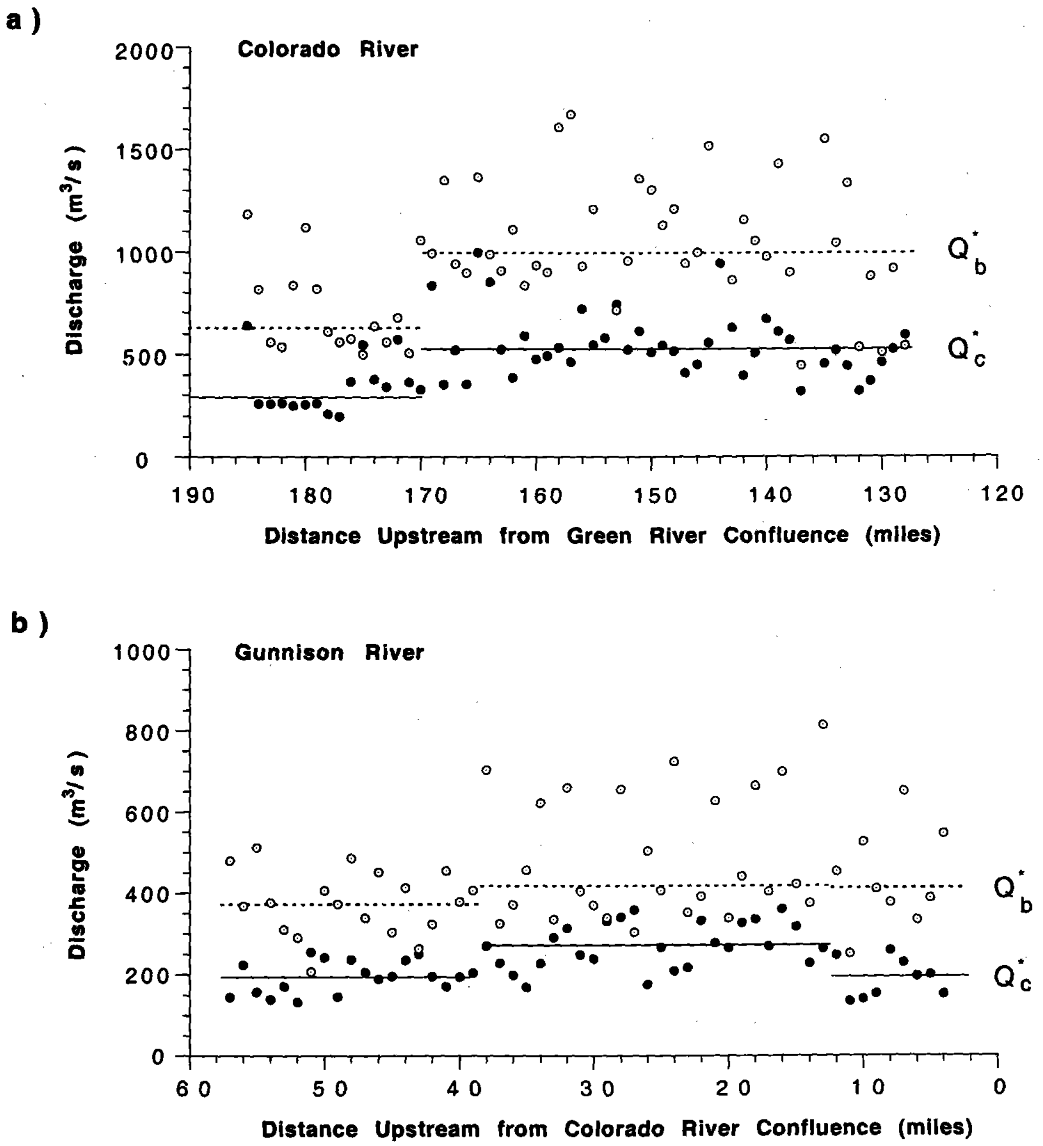

Figure 28. Estimates of the critical discharge, Q_c, and the bankfull discharge, Q_b, at individual cross sections on (a) the Colorado River and (b) the Gunnison River

Annual variations in runoff result in a wide range in the number of days per year that threshold discharges (Q_c and Q_b) are exceeded. In 1994, for example, the Q_c at the State Line gauge was never exceeded, whereas in 1995, it was exceeded for 67 days. Given such large differences in transport frequency, we split the recent flow records from USGS gauges into 5-, 10-, 15- and 20-year intervals to determine the average annual frequency of events exceeding Q_c and Q_b. These data indicate that from 1993-1997 the Q_c was exceeded 39 to 43 days per year, on average, and the Q_b was exceeded 6 to 10 days per year (Table 9). Over longer time intervals, the frequency of particular flows decreases (Table 9), but it appears that an interval of 15 to 20 years is sufficient to define consistent average frequency. For the 20-year period from 1978-1997, the Q_c was exceeded about 30 days per year, on average, and the Q_b was exceeded 5 to 7 days per year (Table 9).

Table 9. Total number of days and average annual frequency of flows that exceeded specific thresholds. The data are listed for separate 5-, 10-, 15-, and 20-year periods to illustrate the effects of using different averaging intervals to evaluate flow frequencies.

Cameo Gauge	days $Q > Q_c$ (296 m^3/s)	days/yr	days $Q > Q_b$ (621 m^3/s)	days/yr
1993-97 :	215	43	29	6
1988-97 :	238	24	29	3
1983-97 :	503	34	103	7
1978-97 :	672	34	103	5
State Line Gauge	days $Q > Q_c$ (524 m^3/s)	days/yr	days $Q > Q_b$ (994 m^3/s)	days/yr
1993-97 :	193	39	43	9
1988-97 :	194	19	43	4
1983-97 :	454	30	138	9
1978-97 :	562	28	140	7
Gunnison R. Gauge	days $Q > Q_c$ (195 m^3/s)	days/yr	days $Q > Q_b$ (377 m^3/s)	days/yr
1993-97 :	199	40	50	10
1988-97 :	201	20	50	5
1983-97 :	460	31	108	7
1978-97 :	548	27	108	5

Magnitude-Frequency Analysis

Magnitude-frequency relations for sediment transport were developed for the Palisade and State Line study reaches (RM 184 and RM 134, respectively) by coupling relations between discharge, sediment transport and flow frequency, as shown in Figure 29. The shaded vertical bars indicate the frequency distribution of daily discharges, and the lines labeled Q_b, Q_s, Q_t, indicate separate magnitude-frequency relations for bed load, suspended load, and total load. In both plots, the abscissa is scaled in logarithmic units to emphasize the highly skewed, bimodal shape of the flow frequency distribution; the sharp mode to the left represents fall and winter base flows, whereas the flatter mode to the right represents spring and summer snowmelt flows. When plotted this way, it is clear that snowmelt flows carry by far the largest proportion of the annual sediment load, as indicated by the area under the curves (Fig. 29). These plots also show that the suspended load Q_s far outweighs the bed load Q_b. We are confident this is not a result of using an empirical equation to estimate Q_b because the calculated bed load transport rates (3-4 kg/m/s at the highest flow) are very reasonable in comparison to rates that have been measured in other active gravel-bed rivers (c.f. Reid et al., 1995; Pitlick, 1992).

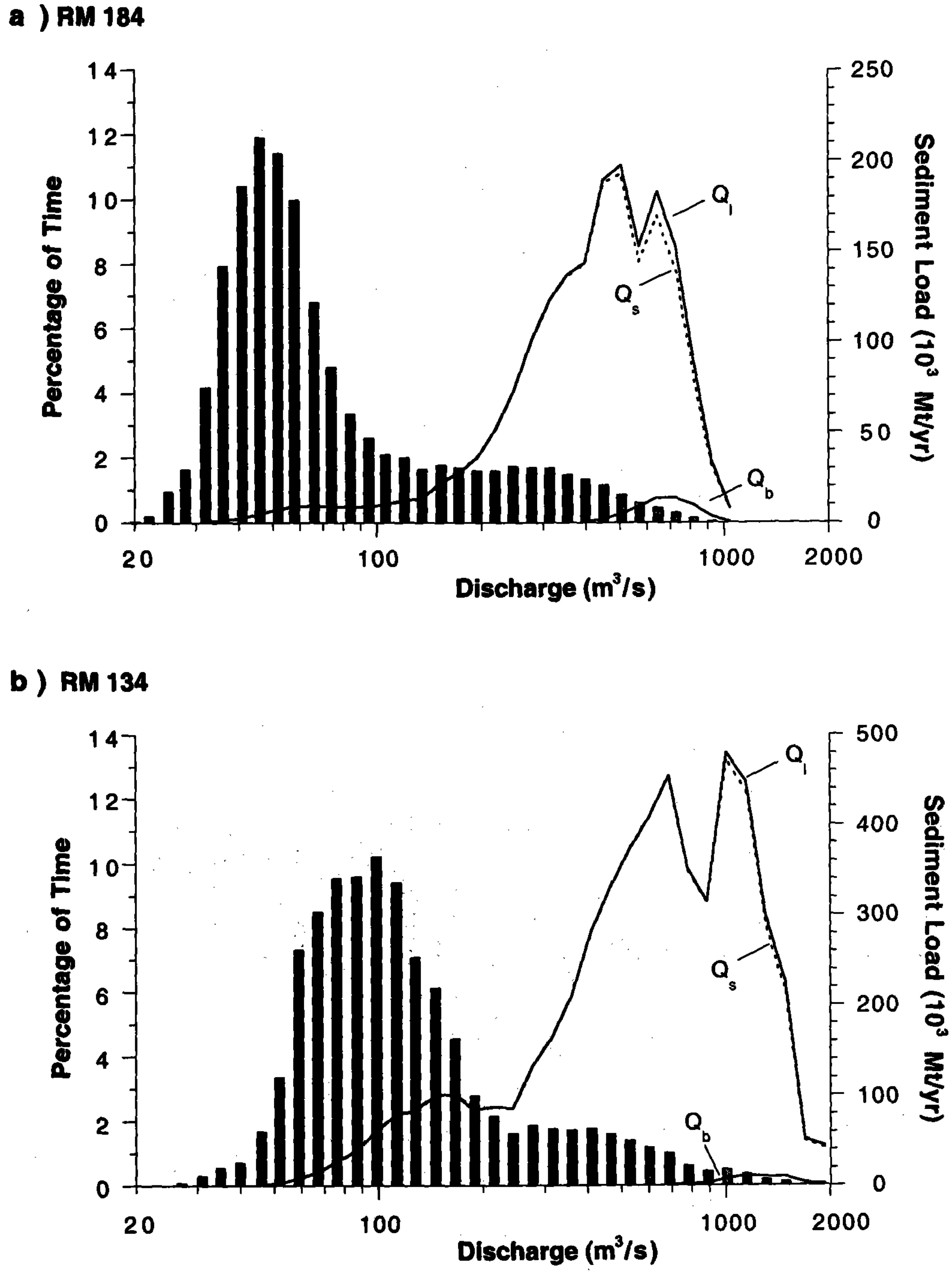

Figure 29. Results of magnitude-frequency analysis for (a) the Palisade gauge (RM 184) and (b) the State Line gauge (RM 134). The vertical bars show the frequency distribution of daily discharges. The lines indicate separate magnitude-frequency relations for suspended load, Q_s, bed load, Q_b, and total load, Q_t.

Referring to the gravel transport thresholds discussed in the preceding section, we note the following points about the magnitude-frequency relations:

1) At the Palisade gauge, 22% of the annual load is carried by discharges less than threshold for bed load transport (Q_c = 296 m^3/s); 26% is carried by discharges greater than the bank-full discharge (Q_b = 621 m^3/s); and 52% is carried by discharges in the range from Q_c to Q_b.

2) At the State Line gauge, 35% of the annual load is carried by discharges less than threshold for bed load transport (Q_c = 524 m^3/s); 20% is carried by discharges greater than the bank-full discharge (Q_b = 994 m^3/s); and 45% is carried by discharges in the range from Q_c to Q_b.

3) Together, these results indicate that 65 to 78% of the average annual sediment load of the upper Colorado River is carried by discharges that exceed the threshold for transporting framework gravels, i.e. $Q_c \approx 1/2Q_b$. The relative importance and efficiency of higher flows is illustrated well by water years 1993 and 1995, which were both above-average. Using data from the State Line gauge, we estimate that the Colorado River carried 40% more sediment in 1993 and 1995 combined than it carried in the previous eight years from 1985 through 1992. In this sense the upper Colorado River acts more like a small upland stream than a large lowland river (see papers by Ashmore and Day, 1988, and Nash, 1994).

4) At both sites, there are two peaks in the magnitude-frequency relation (Fig. 29). As far as we know, there is nothing physically meaningful about the two peaks; they exist only because of particular combinations of flow frequency and sediment transport rate.

The results of the magnitude-frequency analysis have important implications concerning the issue of channel maintenance. If the upper Colorado River is to be maintained in its present condition, then all of the sediment supplied to the reach must be carried through. The effective discharge relations presented above show how the river accomplishes this task under the present hydrologic regime. Another way to use this approach, however, is to consider using reservoir releases to manipulate the hydrograph and optimize sediment transport for a given set of flow conditions. To illustrate what this might achieve, we considered two scenarios: (1) maintain the same annual discharge, meaning no further depletions of water, but change reservoir operating procedures to augment flows on the rising limb of the hydrograph, and (2) allow for a 5% depletion in the total volume of water, but again augment flows on the rising limb of the hydrograph. We focus on the rising limb of the hydrograph because this is when tributaries in the lower part of the basin are delivering sediment to the main stem. Theoretically, rising-limb flows could be augmented by releasing less water in the winter and allowing more water to bypass the reservoirs in the spring.

Figure 30 shows that by augmenting snowmelt discharges in the moderate to high range (300-800 m^3/s), the annual suspended sediment load of the Colorado River near Cameo could be increased by 15% without any loss of water. The benefits of augmenting higher flows (> 800 m^3/s) are even greater, but this opportunity is not likely to present itself often. The greater efficiency of moderate to high discharges is a consequence of the non-linear relation between discharge and sediment load: a given increment of discharge will have a much greater effect on sediment loads at higher discharges than at lower discharges. Because of this nonlinear effect, it is possible to manipulate the hydrograph in ways that increase annual sediment loads yet allow for water depletions. Figure 30 shows that the total sediment load can be increased by 10%, even with a 5% depletion to the annual hydrograph, provided that additional water is delivered near the hydrograph peak.

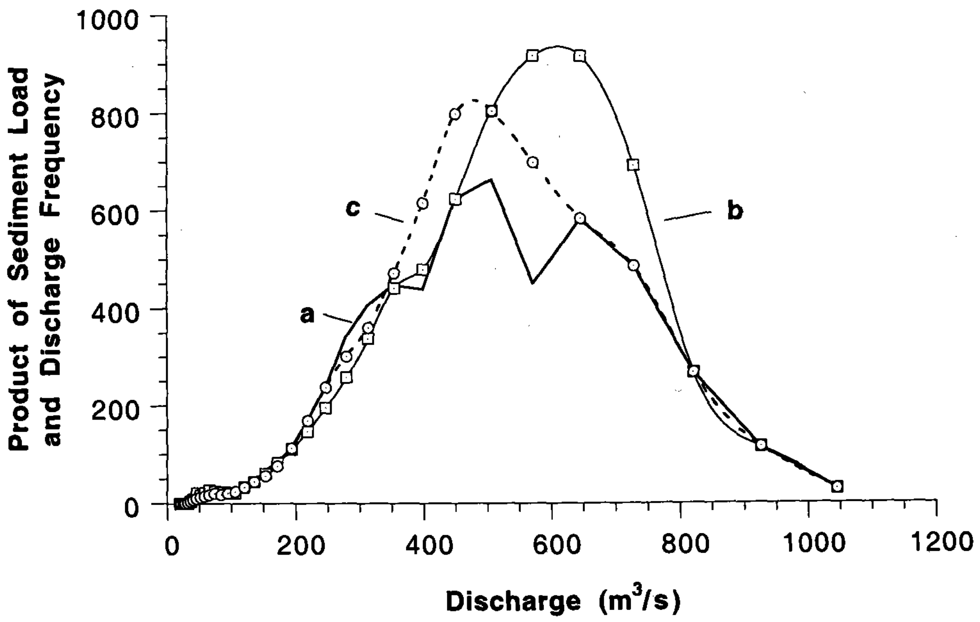

Figure 30. Magnitude-frequency relations for the Colorado River near Cameo under three flow augmentation scenarios. Relation (a) uses the existing pre-peak suspended sediment concentration curve, and the existing flow duration curve; (b) uses a modified flow duration curve with a greater number of days with moderate to high flow (300-800 m^3/s), a reduced number of days with moderately low flow, and no net change in annual runoff; and (c) uses a modified flow duration curve, similar to (b), but with 5% depletion in annual runoff.

DISCUSSION

Among the many results and interpretations presented in this report, there are several points that warrant further discussion. First, although we showed that the annual hydrographs of the Colorado and Gunnison Rivers have been modified significantly because of reservoir operations, there have been certain periods in time when changes in streamflow hydrology were more severe than others. The period from the late 1950s through the 1970s appears to have been particularly important in this regard. Our analysis of streamflow and sediment data from USGS gauging stations indicates that peak discharges and mean annual sediment loads of the Colorado River and Gunnison River were much lower during this period of time than they were before or after. Mass-balance considerations lead us to believe that a substantial amount of sediment would have been deposited in both rivers then, and that this would have affected the quality of various habitats, including spawning bars and backwaters. It also appears that flows capable of moving the gravel bed material, which is a key requirement for flushing fine sediment from the bed, were much less frequent during this time. Add to this the impact of non-native fish which appear to be well adapted to this environment (e.g. channel catfish, *Ictalurus punctatus*), and it is easy to envision how populations of native fish may have declined during this period to the point where they were barely sustainable.

Second, our results indicate that fish habitats in the Colorado and Gunnison River are maintained by flows ranging from about half the bankfull discharge up to the bankfull discharge. We should emphasize, however, that the flows specified here define general, rather than site-specific, criteria for maintaining fish habitat. We have identified discharges that are likely to achieve a certain purpose on a widespread basis, and perhaps not on smaller scales. Studies of spawning bars on the Yampa River, for example, indicate that locally high shear stresses in small chute channels can maintain gravel transport, and keep fine sediment from accumulating on the bed, well after the peak in the hydrograph (Harvey et al., 1993). The results of the Yampa River study imply that high flows may not be necessary for maintaining spawning-bar habitats, contrary to what we have suggested. However, since squawfish in the upper Colorado River do not appear to spawn at the same localities repeatedly it seems most reasonable at this point to recommend discharges that will affect the largest amount of potential spawning habitat, as well as habitats used by native forage fish, benthic invertebrates and other members of the food chain. And, even if there are some ambiguities about spawning habitats, there is no question that discharges in the range from one half bankfull up to bankfull carry the majority of the annual sediment load, and are thus important for maintaining macro-scale habitats such as side channels and backwaters.

Third, although it might be compelling to think that the annual hydrographs of the Colorado River and Gunnison River can be modified with reservoir releases to carry more sediment with potentially less water, there are several practical limitations to consider before this is attempted. The key limitation in the case of the 15-mile reach is the fact that flows are not controlled by a single large dam. Flows entering the 15-mile reach are controlled by a series of relatively small dams, most of which are far upstream. Individually, these reservoirs have neither the storage capacity nor the ability to by-pass water in the way that this was done in the Grand Canyon in 1996. Added to this, the reservoirs in the upper Colorado River basin are managed through complex agreements between federal and state agencies, and water conservancies. Thus, it will require a coordinated effort among the reservoir operators to generate significantly higher flows in the upper Colorado River. Given these limitations, it may not be possible in some years to release enough water to affect sediment transport processes, and it would be a waste of water to attempt this. However, supposing a near-average runoff was expected, it may be possible to augment snowmelt discharges such that the threshold for sediment transport could be exceeded in many places. A goal of future work is to examine these options in more detail and refine flow recommendations for the 15- and 18-mile reaches as necessary.

A second limitation to consider regarding the potential merits of reservoir releases is that the Colorado and Gunnison Rivers have gravel beds, and large-scale changes in the geomorphology of these rivers generally come about only as a result of significant bed load transport. Most gravel-bed rivers do not reach high bed-load transport stages ($\tau \gg 3\tau_c$) except during very large floods. It is unlikely that reservoir releases can produce these conditions in the Colorado or Gunnison River. The potential may exist for generating flows that produce moderate shear stresses ($\tau \approx 1.5\tau_c$), which are important for maintaining certain habitats, but it is unlikely that flows in this range will create significant areas of new habitat. This contrasts with conditions during the experimental flood in the Grand Canyon in 1996, where sand much of the river bed (Andrews, 1991; Collier et al., 1996); this sand was easily put into suspension and transported toward the channel margin where it formed new beaches and created potential new fish habitat (Andrews et al., 1996). We emphasize the differences in the sedimentology of the upper and lower Colorado River because there will undoubtedly continue to be pressure on dam operators to release flows to restore ecological functions, but it can not be assumed that similar methods, applied over short time scales, will produce equivalent benefits on separate reaches of the same river.

CONCLUSIONS

1) Our analysis of streamflow records indicates that peak and mean annual discharges of unregulated streams in the upper Colorado River basin have not changed significantly this century. Peak discharges on regulated portions of the Colorado River and its main tributary, the Gunnison River, however, have decreased significantly in the last 40 years. Since 1950, annual peak discharges of the Colorado River above Glenwood Springs have decreased by more than 40%; annual peak discharges of the Colorado River near Cameo have decreased by 29%; and annual peak discharges on the Gunnison River near Grand Junction have decreased by 38%.

2) To the extent that we can determine, fine sediment from unregulated tributaries continues to be supplied to the Colorado and Gunnison Rivers, more or less as it has since at least 1950. However, since high flows are less frequent now than they were in the past, both rivers have lost some of their capacity to carry sediment. As a result, there has been a tendency over the long term for sediment to build up in the channel, causing both rivers to become narrower and less complex overall. Comparative analysis of aerial photographs of the upper Colorado River indicates that about one quarter of the potential habitat formed by side channels and backwaters in the Grand Valley area has been lost since 1937, and that the main channel has narrowed by an average of about 20 m. Similar analyses of the lower 90 km of the Gunnison River indicate that this reach has likewise become narrower and less heterogeneous, although the losses in potential habitat in this incised reach are small in comparison to the Grand Valley reaches of the upper Colorado River.

3) Our analysis of changes in bed elevations at USGS gauging stations on the Colorado River and Gunnison River indicates that 0.5 to 1.0 m of localized scour or fill are possible over a 40 year period. However, we do not believe that scour or fill are pervasive in the study area because we see little evidence of widespread degradation or aggradation. If aggradation was occurring throughout the area, we would expect to see an increase in channel braiding, when in fact the results of the photogrammetric analysis indicate that just the opposite has occurred.

4) Field studies conducted from 1993 through 1996 show that high flows in 1993 and 1995 mobilized gravel- and cobble-sized sediment almost everywhere and produced clean, loose substrates by flushing fine sediment from the bed. However, we did not observe widespread changes in channel morphology as a result of these flows. Streambanks were eroded locally, and new bars were formed here and there, but the gross morphology of the channel remained essentially the same. We observed more significant changes in side channels and backwaters. Repeated surveys of these features indicated that 0.5 to 2.5 m of fine sediment was scoured from the mouths of the side channels over a 3-year period, supporting the view that macro-scale habitats such as side channels and backwaters are improved by higher-than-average flows.

5) Modeled relations between discharge and shear stress for separate reaches of the Colorado River and Gunnison River indicate that framework gravel and cobble particles begin to move at about 1/2 the bankfull discharge. Threshold discharges for individual reaches are as follows: 296 m^3/s in the 15-mile reach, 524 m^3/s in the 18-mile and Ruby-Horsethief Canyon reaches, and 195-269 m^3/s in the Gunnison River study reach. These discharges were equaled or exceeded an average of 27-34 days per year in the period from 1978-1997, and an average of 39-43 days per year in the period from 1993-1997. A much higher transport stage involving mobilization and reworking of most all particles on the bed (termed significant motion) is associated with the channel forming flow, or bankfull discharge. Bankfull discharges for individual reaches are as follows: 621 m^3/s in the 15-mile reach, 994 m^3/s in the 18-mile and Ruby-Horsethief Canyon reaches, and 377-414 m^3/s in the

Gunnison River study reach. Bankfull discharges in these reaches were equaled or exceeded an average of 5-7 days per year in the period from 1978-1997, and an average of 6-10 days per year in the period from 1993-1997. On both the Colorado River and the Gunnison River, the bankfull discharge produces an average boundary shear stress that is approximately 1.5 times the shear stress required to transport the framework gravel particles. The fact that the hydraulic geometry of these rivers is related in a consistent and physically meaningful way to a gravel transport threshold suggests that prescribed flows are likely to achieve the same result in many places.

6) A magnitude-frequency analysis of sediment transport indicates that a large proportion of the annual sediment load of the upper Colorado River is carried by moderate to high discharges. Under the present hydrologic regime, 22-35% of the average annual sediment load is carried by flows less than about half the bankfull discharge; 45-52% of the average annual sediment load is carried by flows ranging from about half the bankfull discharge up to the bankfull discharge; and an additional 20-26% of the annual load is carried by flows greater than the bankfull discharge.

RECOMMENDATIONS

Some aspects of this study could not have been completed without the availability of high quality historical data. Key among these data were the various sets of aerial photographs taken before, during and after the main period of reservoir construction (1950-1970). Data from USGS gauging stations were likewise necessary for evaluating long-term trends in streamflow and sediment loads.

In the process of conducting field work, we were fortunate to experience a wide range in snowmelt runoff events, from below average to well above average. Nonetheless, four years is a relatively short period of observation, thus continued monitoring of channel change is desirable.

The basic techniques used to model flow and sediment transport in this study are very well established, and straightforward to implement. Our field data and modeling results show that the processes that maintain the physical characteristics of the river are consistent from reach to reach. In specifying discharges that are likely to achieve a certain purpose (e.g. flushing fines) we have relied on a basic geomorphic principle that separate reaches of a river in quasi-equilibrium must operate in a linked fashion to transport the same amount of water and sediment. Thus, while detailed, site-specific studies may provide important data and information about the maintenance of particular habitats, there will always be a need to place this information in a broader context, and to develop recommendations for flows that affect many different habitats in many different places.

Considering the above comments, we offer the following specific recommendations:

1) High quality (1:6000 scale) aerial photographs of the upper Colorado River and lower Gunnison River should be taken at least once every 10 years to document changes in channel morphology; flights should be scheduled during low flows, when features such as bars and backwaters are clearly visible, and to coincide with conditions in earlier photographs;

2) Field studies and observations of the upper Colorado River and Gunnison River should be continued for at least 5 more years to characterize geomorphic responses to natural flow events and coordinated reservoir releases;

3) Flows equal to or greater than 1/2 the bankfull discharge are needed to mobilize gravel and cobble particles on a widespread basis, and to prevent fine sediment from accumulating in the bed. Flows greater than 1/2 the bankfull discharge also transport somewhere between 65 and 78% of the annual sediment load of the Colorado River. Flows greater than 1/2 the bankfull discharge thus provide several important geomorphic functions, assuming they occur with sufficient frequency. In the 20-year period from 1978 to 1997, daily discharges equaled or exceeded 1/2 the bankfull discharge an average of about 30 days per year (c.f. Table 9). Given these results and supporting information about what these discharges accomplish, we recommend that flows equal to or greater than 1/2 the bankfull discharge should occur with an average frequency of at least 30 days per year.

Flows equal to the bankfull discharge produce an average boundary shear stress that is about 1.5 times the critical shear stress for bed load transport; this discharge is sufficient to fully mobilize the bed material and thereby maintain the existing bankfull hydraulic geometry. On the basis of data from the 20-year period from 1978 through 1997, we recommend that flows equal to or greater than the bankfull discharge should occur at least 5 days per year, on average.

Our field observations of processes and rates of change in the Colorado River and Gunnison River indicate that these are reasonable frequencies for flows that will <u>maintain</u> conditions characteristic of the last two decades. To <u>improve</u> conditions within the channel, we suggest mimicking the more recent period of record (1993-1997), in which flows equal to or greater than 1/2 the bankfull discharge occurred with an average frequency of 39-43 days per year, and flows equal to or greater than the bankfull discharge occurred with an average frequency of 6-10 days per year.

4) The single most important thing that can be done to maintain habitats used by the endangered fishes is to assure that the sediment supplied to the critical reaches continues to be carried downstream. Sediment that is not carried through will accumulate preferentially in low velocity areas, resulting in further channel simplification and narrowing.

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GLOSSARY

Annual Flood: Maximum instantaneous peak discharge for the year, usually expressed in cubic feet or cubic meters per second (equivalent to annual peak discharge)

Average Annual Peak Discharge or Mean Annual Flood, Q_p: Arithmetic mean of annual floods; expressed in cubic feet per second or cubic meters per second.

Average Annual Discharge or Mean Annual Flow, Q_m: Arithmetic mean of daily discharges for a year or period of years; expressed in cubic feet per second or cubic meters per second.

Average Boundary Shear Stress, τ: The force per unit area acting on the streambed, as given by equation 1; expressed in kN/m^2.

Backwaters: Permanent or ephemeral embayments that form adjacent to or along the main channel in association with bank protrusions, secondary channels, islands, and bars.

Bankfull Discharge, Q_b: Defined as the flow that fills the channel to the bankfull level, or to the point of incipient flooding. This discharge should not be equated to a flow with any specific return period; expressed in cubic feet per second or cubic meters per second.

Bed Load: That portion of the total sediment load carried in contact with the river bed; expressed as a mass or volume per unit time.

Critical Boundary Shear Stress, τ_c: The shear stress required to initiate bed load transport, expressed in kN/m^2.

Critical Discharge, Q_c: The discharge that initiates bed load transport.

Dimensionless Shear Stress, τ^*, and Critical Dimensionless Shear Stress, τ^*_c: The former variable represents the ratio of the available boundary shear stress, τ_c, to the submerged unit weight of a streambed particle with diameter D; as given by equation 3; the latter variable is similar, except it refers to the specific case of incipient motion, defined by τ_c.

Incipient Motion: The point at which some streambed particles are just beginning to move; characterized by the sporadic movement of a few particles on the bed.

Median Grain Size, D_{50}: The grain size, in millimeters, corresponding to the median or 50th percentile of the particle size distribution; corresponding values for the 84th and 16th percentiles are D_{84} and D_{16}.

Runoff: Volume of water that moves annually past a point; usually expressed as a volume per unit time (e.g. acre-ft per year), or as a depth (inches or cm per year, assuming the volume is distributed uniformly over a given drainage area).

Significant Motion: A condition characterized by frequent movement of most particles on the streambed.

Suspended Sediment Concentration, C_s: The concentration, in milligrams per liter, of sediment carried in suspension at a given discharge.

Suspended Sediment Load, Q_s: That portion of the total sediment load carried in suspension; calculated as $Q_{ss} = c_l \times Q \times C_s$, where c_l is a unit conversion factor (0.0027 for discharges expressed in cubic feet per second, and 0.0864 for discharges expressed in cubic meters per second), Q is the discharge, and the other terms are as defined above; usually expressed in tons per day or tons per year.

Uniform Flow: A state of flow wherein the depth and velocity are constant in the downstream direction; valid only for long (>>100 m) reaches.

Table A-1. Summary of Surface Sediment Data for the Colorado River

LOCATION	percent finer than size indicated, in millimeters: 256	180	128	90	64	45	32	22	16	11	8.0	5.6	4.0	2.8
RM 185.0		100	100	91	72	55	44	33	18	10	4	3	3	2
RM 181.5	100	98	84	62	43	30	15	3	0	0	0	0	0	0
RM 177.3	100	98	92	80	62	42	24	14	9	7	6	5	4	4
RM 176.0	100	97	87	74	58	38	23	16	11	7	0	7	0	6
RM 168.9		100	98	89	71	50	30	18	9	5	4	4	4	4
RM 166.2		100	97	86	62	32	15	6	2	0	0	0	0	0
RM 164.8	100	99	97	83	64	45	22	9	2	0	0	0	0	0
RM 162.4	100	96	92	77	60	34	24	9	6	0	0	0	0	0
RM 159.9		100	97	87	63	44	34	28	24	21	21	21	21	19
RM 159.0	100	100	97	84	69	49	31	12	4	1	1	0	0	0
RM 156.0		100	100	97	87	65	42	22	8	0	0	0	0	0
RM 154.0	100	94	81	62	47	28	11	7	4	4	4	4	4	3
RM 147.0	100	100	99	93	76	47	23	8	1	0	0	0	0	0
RM 144.0		100	99	92	75	60	37	13	4	0	0	0	0	0
RM 142.7		100	94	67	22	8	1	0	0	0	0	0	0	0
RM 139.5		100	99	84	64	42	24	11	4	1	0	0	0	0
RM 134.0		100	99	90	71	41	12	3	0	0	0	0	0	0
RM 130.0		100	99	97	95	84	76	60	34	20	9	6	5	5

Table A-2. Summary of Subsurface Sediment Data for the Colorado River

LOCATION	percent finer than size indicated, in millimeters: 256	180	128	90	64	45	32	22	16	11	8.0	5.6	4.0	2.8	2.0
RM 184.2	100	93	88	76	68	62	55	46	39	33	29	25	23	21	19
RM 177.3			100	95	84	66	52	37	31	28	26	24	23	22	21
RM 168.9			100	96	75	54	35	23	17	14	14	14	14	14	14
RM 166.0			100	95	84	70	52	39	34	28	24	21	19	18	17
RM 162.4		100	96	90	81	75	66	57	50	45	41	37	32	29	25
RM 144.0			100	89	75	63	55	48	42	34	28	24	20	17	15
RM 134.0			100	89	71	48	33	25	16	13	12	11	11	10	10
RM 130.0			100	90	82	69	57	47	34	27	22	19	17	15	13

Table A-3. Summary of Surface Sediment Data for the Gunnison River

LOCATION	percent finer than size indicated, in millimeters													
	256	180	128	90	64	45	32	22	16	11	8.0	5.6	4.0	2.8
RM 56.5		100	99	86	57	29	10	5	2					
RM 44.6		100	97	87	66	42	23	9	4	1				
RM 40.7			100	98	90	58	32	6	2					
RM 37.9			100	87	61	31	13	6	3	3				
RM 35.1		100	100	97	91	76	56	25	9	2				
RM 29.7				100	82	46	14							
RM 28.5		100	93	71	38	24	10	5	3	3	2	1		
RM 26.6			100	99	76	60	41	20	14	1	1			
RM 18.5			100	98	82	54	26	12	3					
RM 13.6				100	99	98	86	60	34	10				
RM 13.0					100	86	62	38	22	6				
RM 9.5			100	89	67	42	30	18	10	3	2			
RM 6.5			100	87	76	50	29	14	5					

Table A-4. Summary of Subsurface Sediment Data for the Gunnison River

LOCATION	percent finer than size indicated, in millimeters														
	256	180	128	90	64	45	32	22	16	11	8.0	5.6	4.0	2.8	2.0
RM 56.5		100	90	76	69	60	54	41	35	28	22	18	14	12	10
RM 51.0			100	85	74	68	62	55	48	43	37	32	28	24	20
RM 44.6			100	84	72	65	58	47	42	37	31	27	23	21	19
RM 40.7				100	99	93	83	83	71	56	44	38	35	33	31
RM 35.1			100	96	88	82	76	72	72	66	56	45	37	31	27
RM 29.7				100	79	48	28	26	18	16	14	13	10	9	8
RM 26.6					100	97	92	84	76	64	54	47	42	38	35
RM 18.5			100	94	74	59	50	50	44	31	24	20	18	16	14
RM 13.6					100	91	79	70	48	33	24	21	20	19	18
RM 6.5			100	95	89	76	66	64	48	35	29	25	23	21	20

Table A-5. Results of GIS Analysis of Channel Change along the Colorado River, 1937-1993.

	Channel Area (ha)			Island Area (ha)			Side Channel Area (ha)		
River Mile	1937	1993	change	1937	1993	change	1937	1993	change
184	17.6	13.6	-4.0	2.6	1.0	-1.6	1.6	1.1	-0.5
183	17.9	16.9	-1.0	9.1	9.1	0.0	1.6	7.9	6.3
182	16.7	15.0	-1.7	3.8	0.1	-3.7	1.5	0.2	-1.3
181	16.0	15.1	-0.9	2.3	0.5	-1.8	0.9	1.4	0.5
180	24.0	15.1	-8.9	67.4	0.4	-67.0	9.7	1.0	-8.7
179	23.0	20.1	-2.9	11.5	6.8	-4.7	8.3	2.6	-5.7
178	17.7	16.1	-1.6	0.5	2.2	1.7	1.0	3.3	2.3
177	13.9	10.2	-3.7	0.4	0.0	-0.4	0.1	0.0	-0.1
176	25.8	15.8	-10.0	20.0	12.8	-7.2	8.1	1.8	-6.3
175	24.8	14.9	-9.9	18.0	15.5	-2.5	9.0	2.5	-6.5
174	17.6	20.5	2.9	1.5	16.1	14.6	3.3	9.8	6.5
173	17.1	12.5	-4.6	1.4	0.7	-0.7	1.3	0.6	-0.7
172	14.6	12.9	-1.7	0.1	0.1	0.0	0.2	0.1	-0.1
171	23.1	16.4	-6.7	17.1	18.5	1.4	7.5	4.3	-3.2
170	30.0	25.8	-4.2	13.0	15.1	2.1	6.0	6.0	0.0
169	29.3	17.1	-12.2	15.0	2.5	-12.5	9.5	3.9	-5.6
168	27.4	20.5	-6.9	17.0	19.4	2.4	7.5	9.1	1.6
167	21.7	21.5	-0.2	4.9	1.9	-3.0	2.8	1.5	-1.3
166	22.7	18.1	-4.6	1.2	3.6	2.4	2.2	2.7	0.5
165	25.8	22.7	-3.1	16.4	8.2	-8.2	7.9	4.9	-3.0
164	22.9	18.1	-4.8	17.7	2.4	-15.3	8.5	4.4	-4.1
163	23.1	32.5	9.4	1.5	4.6	3.1	2.2	10.5	8.3
162	27.5	18.8	-8.7	3.4	0.9	-2.5	6.7	2.8	-3.9
161	26.5	22.1	-4.4	11.5	53.5	42.0	6.5	11.2	4.7
160	27.4	19.1	-8.3	21.4	10.3	-11.1	12.9	4.4	-8.5
159	29.5	22.4	-7.1	19.1	17.0	-2.1	11.1	5.5	-5.6
158	23.5	22.9	-0.6	2.5	5.7	3.2	2.3	6.0	3.7
157	23.9	19.0	-4.9	6.8	4.4	-2.4	5.4	2.7	-2.7
156	18.6	16.3	-2.3	0.7	1.6	0.9	1.1	0.8	-0.3
155	39.4	24.7	-14.7	18.7	32.0	13.3	15.3	9.2	-6.1
154	37.5	26.2	-11.3	72.3	83.7	11.4	19.8	9.9	-9.9
153	21.0	21.4	0.4	0.0	0.9	0.9	0.6	2.0	1.4
152	20.3	15.6	-4.7	2.0	2.9	0.9	0.9	1.8	0.9
151	19.1	17.0	-2.1	0.0	0.7	0.7	0.0	0.3	0.3
150	16.2	17.3	1.1	2.6	3.3	0.7	1.9	1.8	-0.1
149	20.9	19.2	-1.7	0.8	0.0	-0.8	0.8	0.0	-0.8
148	16.3	15.5	-0.8	3.9	7.4	3.5	4.0	3.9	-0.1
147	16.8	16.9	0.1	10.5	8.9	-1.6	3.2	1.1	-2.1
146	17.8	18.5	0.7	0.8	1.9	1.1	1.8	1.6	-0.2
145	17.0	17.3	0.3	1.6	0.0	-1.6	1.4	0.0	-1.4
144	20.6	20.5	-0.1	5.2	0.1	-5.1	5.7	0.5	-5.2
143	16.0	16.4	0.4	2.1	3.0	0.9	3.3	1.6	-1.7
142	20.4	18.7	-1.7	3.7	5.3	1.6	3.1	4.0	0.9
141	16.6	17.1	0.5	0.0	0.0	0.0	0.0	0.0	0.0
140	16.8	15.9	-0.9	3.2	3.5	0.3	5.5	5.9	0.4
139	19.5	16.8	-2.7	1.4	0.1	-1.3	0.9	0.7	-0.2
138	20.1	17.5	-2.6	0.0	0.1	0.1	0.0	0.5	0.5
137	14.6	13.4	-1.2	19.5	21.5	2.0	6.7	3.6	-3.1
136	15.6	13.5	-2.1	0.2	0.7	0.5	0.0	1.4	1.4
135	13.9	14.5	0.6	4.0	4.4	0.4	3.1	1.1	-2.0
134	22.2	17.8	-4.4	0.0	3.1	3.1	0.0	2.0	2.0
133	15.6	15.4	-0.2	0.0	0.0	0.0	0.0	0.0	0.0
132	21.6	18.6	-3.0	0.2	0.7	0.5	0.3	0.9	0.6
total:	1125.4	957.7	-167.7	460.5	419.1	-41.4	225.0	166.8	-58.2

Table A-6. Results of GIS Analysis of Channel Change along the Colorado River, 1954-1968.

	Channel Area (ha)			Island Area (ha)			Side Channel Area (ha)		
River Mile	1954	1968	change	1954	1968	change	1954	1968	change
184	13.1	10.5	-2.6	1.3	0.9	-0.4	1.9	0.5	-1.4
183	10.5	9.1	-1.4	1.8	1.8	0.0	1.1	1.5	0.4
182	12.6	11.2	-1.4	0.0	0.0	0.0	0.0	0.0	0.0
181	11.8	10.9	-0.9	0.1	0.4	0.3	0.4	0.7	0.3
180	10.8	9.4	-1.4	0.1	0.0	-0.1	0.2	0.0	-0.2
179	12.5	8.1	-4.4	13.5	0.6	-12.9	4.5	1.1	-3.4
178	12.4	12.2	-0.2	4.1	1.8	-2.3	2.6	3.2	0.6
177	9.5	10.2	0.7	0.2	0.6	0.4	0.5	0.5	0.0
176	18.2	12.5	-5.7	18.5	16.2	-2.3	7.9	5.1	-2.8
175	18.7	12.8	-5.9	21.3	18.0	-3.3	9.1	4.6	-4.5
174	11.2	8.8	-2.4	3.0	1.3	-1.7	2.6	0.7	-1.9
173	13.6	7.7	-5.9	4.7	0.0	-4.7	3.2	0.2	-3.0
172	11.9	11.0	-0.9	0.3	0.0	-0.3	0.2	0.2	0.0
171	16.2	12.2	-4.0	17.1	0.8	-16.3	5.4	1.8	-3.6
170	24.8	18.9	-5.9	14.1	13.8	-0.3	1.3	1.2	-0.1
169	26.0	17.9	-8.1	16.5	22.4	5.9	11.9	8.6	-3.3
168	17.8	15.3	-2.5	0.8	2.0	1.2	1.1	2.6	1.5
167	18.2	19.2	1.0	1.4	2.1	0.7	1.5	1.9	0.4
166	18.4	13.3	-5.1	4.2	0.6	-3.6	3.6	1.5	-2.1
165	15.8	17.6	1.8	0.0	0.2	0.2	0.3	1.5	1.2
164	13.0	15.0	2.0	0.2	1.3	1.1	0.4	1.5	1.1
163	22.5	21.0	-1.5	5.6	5.9	0.3	5.6	5.4	-0.2
162	19.2	20.0	0.8	6.5	7.4	0.9	5.6	4.1	-1.5
161	20.9	19.8	-1.1	5.6	5.1	-0.5	7.5	4.8	-2.7
160	21.2	20.8	-0.4	18.0	18.6	0.6	8.0	7.4	-0.6
159	18.3	17.2	-1.1	5.4	3.5	-1.9	5.5	4.8	-0.7
158	19.1	16.5	-2.6	3.8	3.9	0.1	3.0	2.6	-0.4
157	17.6	14.9	-2.7	9.5	0.6	-8.9	3.8	0.8	-3.0
156	16.4	18.3	1.9	0.2	0.5	0.3	0.7	1.3	0.6
155	19.3	20.3	1.0	36.5	34.1	-2.4	9.4	9.8	0.4
154	22.7	19.8	-2.9	80.7	78.1	-2.6	12.0	8.9	-3.1
153	17.2	12.9	-4.3	2.3	0.0	-2.3	0.6	0.2	-0.4
152	14.2	14.0	-0.2	0.1	0.0	0.0	0.3	0.3	0.0
151	14.8	15.0	0.2	0.3	0.0	-0.3	0.5	0.0	-0.5
150	14.7	13.6	-1.1	4.6	5.3	0.7	1.2	1.0	-0.2
149	18.1	18.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
148	12.4	11.3	-1.1	5.4	10.7	5.4	1.6	2.7	1.1
147	13.1	11.9	-1.2	12.8	11.6	-1.3	0.9	1.2	0.3
146	16.2	13.3	-2.9	0.7	3.3	2.6	0.2	1.6	1.4
145	15.9	15.6	-0.3	0.0	0.0	0.0	0.0	0.0	0.0
144	17.7	17.9	0.2	5.4	0.7	-4.8	2.0	0.5	-1.6
143	14.2	15.3	1.1	3.8	3.5	-0.3	1.9	0.9	-1.0
142	15.0	14.5	-0.5	6.4	7.5	1.1	3.9	3.6	-0.2
141	15.8	15.0	-0.8	0.0	0.0	0.0	0.0	0.0	0.0
140	13.8	13.9	0.1	5.9	4.4	-1.5	5.2	4.8	-0.4
139	16.3	15.4	-0.9	0.0	0.4	0.4	0.0	0.8	0.8
total:	743.6	670.3	-73.3	342.6	289.7	-52.9	139.2	106.3	-32.8

Table A-7. Results of GIS Analysis of Channel Change along the lower Gunnison River, 1937-1995.

River Mile	Channel Area (ha)			Island Area (ha)			Side Channel Area (ha)		
	1937	1995	change	1937	1995	change	1937	1995	change
56	12.8	10.7	-2.1	0.4	0.1	-0.3	0.4	0.1	-0.3
55	10.0	10.5	0.5	0.3	0.1	-0.2	0.2	0.2	0.0
54	7.0	9.3	2.3	0.0	0.1	0.1	0.1	0.2	0.1
53	9.1	10.7	1.6	5.8	3.3	-2.5	1.6	2.8	1.2
52	8.7	10.4	1.7	0.9	4.7	3.8	1.1	2.0	0.9
51	11.6	9.6	-2.0	0.3	2.4	2.1	0.2	1.2	1.0
50	9.1	9.2	0.1	5.1	1.1	-4.0	2.5	1.3	-1.2
49	8.5	8.6	0.1	4.7	1.4	-3.3	1.3	0.6	-0.7
48	11.8	10.5	-1.3	0.0	0.2	0.2	0.0	0.2	0.2
47	8.7	10.0	1.3	2.5	2.5	0.0	1.1	0.8	-0.3
46	7.5	8.7	1.2	1.8	1.0	-0.8	1.7	0.6	-1.1
45	10.0	11.5	1.5	0.6	0.7	0.1	0.5	0.5	0.0
44	10.2	10.7	0.5	0.2	1.2	1.0	0.5	0.7	0.2
43	8.2	9.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0
42	7.4	7.9	0.5	0.1	0.0	-0.1	0.1	0.0	-0.1
37	12.4	10.9	-1.5	0.2	1.4	1.2	0.4	1.2	0.8
36	8.5	11.3	2.8	3.2	6.4	3.2	1.5	0.7	-0.8
35	9.5	8.6	-0.9	6.3	1.7	-4.6	1.3	1.2	-0.1
34	7.8	6.8	-1.0	5.3	7.5	2.2	2.8	2.8	0.0
33	10.3	8.7	-1.6	0.5	0.4	-0.1	0.6	0.4	-0.2
32	9.3	10.0	0.7	0.2	0.0	-0.2	0.4	0.0	-0.4
31	9.2	9.4	0.2	0.5	0.5	0.0	0.3	0.3	0.0
30	10.0	14.0	4.0	1.9	1.9	0.0	1.0	1.3	0.3
29	9.0	9.5	0.5	0.1	0.3	0.2	0.3	0.6	0.3
28	9.0	9.1	0.1	0.3	1.1	0.8	0.4	1.3	0.9
27	9.0	10.0	1.0	2.3	3.4	1.1	0.9	1.8	0.9
26	6.9	7.2	0.3	0.7	0.7	0.0	0.6	0.9	0.3
25	8.0	8.2	0.2	0.4	0.3	-0.1	0.3	0.3	0.0
24	9.1	9.6	0.5	0.3	0.3	0.0	0.3	0.4	0.1
23	8.7	9.3	0.6	0.9	0.9	0.0	1.2	0.9	-0.3
22	7.8	8.8	1.0	1.4	0.1	-1.3	0.2	0.1	-0.1
21	8.0	8.6	0.6	4.3	4.5	0.2	1.4	0.8	-0.6
20	11.0	11.2	0.2	1.3	0.0	-1.3	0.6	0.0	-0.6
19	9.6	10.3	0.7	0.0	0.0	0.0	0.0	0.1	0.1
18	8.2	7.8	-0.4	2.9	2.5	-0.4	1.5	1.6	0.1
17	8.6	11.2	2.6	1.5	0.1	-1.4	1.1	0.2	-0.9
16	14.7	12.0	-2.7	0.0	0.1	0.1	0.0	0.3	0.3
15	11.3	10.3	-1.0	3.7	3.8	0.1	2.1	3.6	1.5
14	8.3	10.0	1.7	0.3	0.4	0.1	0.6	0.4	-0.2
13	7.7	8.5	0.8	2.5	0.9	-1.6	0.4	0.8	0.4
12	9.3	7.9	-1.4	0.7	2.8	2.1	0.4	2.1	1.7
11	8.7	9.9	1.2	0.8	0.8	0.0	0.4	0.5	0.1
10	9.7	9.1	-0.6	1.1	1.2	0.1	0.8	1.2	0.4
9	9.0	9.2	0.2	1.7	0.0	-1.7	0.8	0.0	-0.8
8	8.8	8.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	13.1	12.5	-0.6	0.1	0.1	0.0	0.2	0.3	0.1
6	12.8	12.8	0.0	0.5	0.6	0.1	0.1	0.0	-0.1
5	11.1	9.1	-2.0	0.2	0.3	0.1	0.3	0.2	-0.1
4	10.8	10.9	0.1	3.3	3.0	-0.3	1.6	1.4	-0.2
3	12.8	12.7	-0.1	0.0	0.0	0.0	0.0	0.0	0.0
2	11.2	11.5	0.3	4.1	0.1	-4.0	3.1	0.1	-3.0
1	11.7	8.9	-2.8	0.4	0.0	-0.4	0.5	0.0	-0.5
total:	501.5	511.9	10.4	76.6	66.9	-9.7	39.7	39.0	-0.7

Table A-8. Hydraulic Geometry Data for the Colorado River

River Mile	River Kilometer	Bankfull Width (m)	Bankfull Depth (m)	Slope	D_{50} (mm)	Bankfull τ (N/m^2)	Bankfull τ^*
185	296	249	2.29	0.00175	56	39.3	0.043
184	294	101	3.15	0.00175	56	54.1	0.060
183	293	101	2.51	0.00175	56	43.1	0.048
182	291	102	2.43	0.00175	56	41.7	0.046
181	290	97	3.27	0.00175	56	56.1	0.062
180	288	99	3.85	0.00175	56	66.1	0.073
179	286	102	3.14	0.00175	56	53.9	0.059
178	285	82	2.99	0.00175	56	51.3	0.057
177	283	76	2.97	0.00175	56	51.0	0.056
176	282	143	2.07	0.00175	56	35.5	0.039
175	280	213	1.50	0.00175	56	25.8	0.028
174	278	147	2.16	0.00175	56	37.1	0.041
173	277	133	2.13	0.00175	56	36.6	0.040
172	275	223	1.75	0.00175	56	30.0	0.033
171	274	142	1.93	0.00175	56	33.1	0.037
170	272	128	3.19	0.00175	56	54.8	0.060
169	270	254	2.15	0.00130	51	27.4	0.033
168	269	108	4.31	0.00130	51	55.0	0.067
167	267	158	2.77	0.00130	51	35.3	0.043
166	266	107	3.40	0.00130	51	43.4	0.053
165	264	303	2.34	0.00130	51	29.8	0.036
164	262	259	2.12	0.00130	51	27.0	0.033
163	261	159	2.70	0.00130	51	34.4	0.042
162	259	118	3.64	0.00130	51	46.4	0.056
161	258	179	2.39	0.00130	51	30.5	0.037
160	256	145	2.90	0.00130	51	37.0	0.045
159	254	150	2.78	0.00130	51	35.5	0.043
158	253	162	3.76	0.00130	51	48.0	0.058
157	251	141	4.18	0.00130	51	53.3	0.065
156	250	219	2.26	0.00130	51	28.8	0.035
155	248	166	3.12	0.00130	51	39.8	0.048
154	246	176	4.33	0.00130	51	55.2	0.067
153	245	226	1.89	0.00130	51	24.1	0.029
152	243	130	3.34	0.00100	47	32.8	0.043
151	242	152	3.75	0.00100	47	36.8	0.048
150	240	127	4.07	0.00100	47	39.9	0.052
149	238	135	3.60	0.00100	47	35.3	0.046
148	237	128	3.88	0.00100	47	38.1	0.050
147	235	102	3.83	0.00100	47	37.6	0.049
146	234	112	3.74	0.00100	47	36.7	0.048
145	232	138	4.25	0.00100	47	41.7	0.055
144	230	235	5.55	0.00100	47	54.4	0.072
143	229	156	2.81	0.00100	47	27.6	0.036
142	227	99	4.40	0.00100	47	43.2	0.057
141	226	126	3.60	0.00100	47	35.3	0.046
140	224	167	2.91	0.00100	47	28.5	0.038
139	222	151	3.88	0.00100	47	38.1	0.050
138	221	141	3.07	0.00100	47	30.1	0.040
137	219	80	2.83	0.00100	47	27.8	0.036
136	218			"Black Rocks"			
135	216	113	4.85	0.00100	47	47.6	0.063
134	214	129	3.53	0.00100	47	34.6	0.046
133	213	110	4.50	0.00100	47	44.1	0.058
132	211	80	3.14	0.00100	47	30.8	0.040
131	210	92	3.91	0.00100	47	38.4	0.050
130	208	114	2.47	0.00100	47	24.2	0.032
129	206	130	3.26	0.00100	47	32.0	0.042
128	205	147	2.20	0.00100	47	21.6	0.028
	average:	145	3.15	0.00130	51	39.0	0.047

Table A-9. Hydraulic Geometry Data for the Gunnison River

River Mile	River Kilometer	Bankfull Width (m)	Bankfull Depth (m)	Slope	D_{50} (mm)	Bankfull τ (N/m^2)	Bankfull τ^*
57	91.2	68.8	2.81	0.0019	53	52.4	0.062
56	89.6	106.3	1.85	0.0019	53	34.5	0.041
55	88.0	75.0	2.78	0.0019	53	51.8	0.061
54	86.4	66.6	2.48	0.0019	53	46.2	0.054
53	84.8	81.1	1.96	0.0019	53	36.5	0.043
52	83.2	62.7	2.20	0.0019	53	41.0	0.048
51	81.6	88.8	1.62	0.0012	44	19.1	0.027
50	80.0	87.0	2.43	0.0012	44	29.3	0.041
49	78.4	52.2	3.14	0.0012	44	37.9	0.053
48	76.8	85.2	2.74	0.0012	44	33.1	0.046
47	75.2	74.0	2.40	0.0012	44	29.0	0.040
46	73.6	67.7	3.01	0.0012	44	36.3	0.051
45	72.0	70.4	2.32	0.0012	44	28.0	0.039
44	70.4	84.3	2.50	0.0012	44	30.2	0.042
43	68.8	89.8	1.84	0.0012	44	22.2	0.031
42	67.2	70.1	2.41	0.0012	44	29.1	0.041
41	65.6	61.2	3.21	0.0012	44	38.7	0.054
40	64.0	69.4	2.67	0.0012	44	32.2	0.045
39	62.4	73.1	2.70	0.0012	44	32.6	0.045
38	60.8	97.3	3.16	0.0012	44	38.1	0.053
37	59.2	82.2	2.20	0.0012	44	26.5	0.037
36	57.6	71.5	2.59	0.0012	44	31.3	0.044
35	56.0	60.8	3.23	0.0012	44	39.0	0.054
34	54.4	81.7	3.26	0.0012	44	39.3	0.055
33	52.8	72.1	2.46	0.0011	50	26.5	0.033
32	51.2	78.1	3.52	0.0011	50	38.0	0.047
31	49.6	62.0	3.02	0.0011	50	32.6	0.040
30	48.0	59.5	2.93	0.0011	50	31.6	0.039
29	46.4	82.3	2.29	0.0011	50	24.7	0.031
28	44.8	84.8	3.34	0.0011	50	36.0	0.045
27	43.2	89.2	2.04	0.0011	50	22.0	0.027
26	41.6	43.6	4.25	0.0011	50	45.9	0.057
25	40.0	66.8	2.89	0.0011	50	31.2	0.039
24	38.4	52.2	4.74	0.0011	50	51.1	0.063
23	36.8	54.4	3.00	0.0011	50	32.4	0.040
22	35.2	82.6	2.49	0.0011	50	26.9	0.033
21	33.6	69.3	3.67	0.0011	50	39.6	0.049
20	32.0	65.9	2.61	0.0011	50	28.2	0.035
19	30.4	81.3	2.70	0.0011	50	29.1	0.036
18	28.8	83.6	3.39	0.0011	50	36.6	0.045
17	27.2	66.9	2.88	0.0011	50	31.1	0.038
16	25.6	89.5	3.36	0.0011	50	36.3	0.045
15	24.0	79.2	2.67	0.0011	50	28.8	0.036
14	22.4	56.7	3.04	0.0011	50	32.8	0.041
13	20.8	96.1	3.49	0.0010	36	34.2	0.059
12	19.2	90.2	2.55	0.0010	36	25.0	0.043
11	17.6	48.9	2.58	0.0010	36	25.3	0.044
10	16.0	50.6	3.94	0.0010	36	38.7	0.067
9	14.4	55.4	3.22	0.0010	36	31.6	0.055
8	12.8	94.7	2.22	0.0010	36	21.8	0.038
7	11.2	83.9	3.31	0.0010	36	32.5	0.056
6	9.6	71.3	2.44	0.0010	36	23.9	0.041
5	8.0	72.6	2.64	0.0010	36	25.9	0.045
4	6.4	55.0	3.84	0.0010	36	37.7	0.065
average =		73.4	2.83	0.0012	46	33.2	0.045

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