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Geomorphology and endangered fish habitats of the upper Colorado River

1. Historic changes in streamflow, sediment load, and channel morphology

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Abstract. The hydrologic, geomorphic, and ecologic effects of reservoir operations are thought to be key factors in the decline of native fishes in the upper Colorado River basin. The present paper examines the extent to which changes in streamflow and sediment loads have affected alluvial reaches of the Colorado River near Grand Junction, Colorado. The analysis shows that since 1950, annual peak discharges of the Colorado River and its major tributary, the Gunnison River, have decreased by 29–38%. The total volume of runoff delivered to the study area has not changed significantly over the period of record, but the annual hydrograph has been modified greatly by reductions in peak flows and augmentation of base flows. Annual suspended sediment loads of the Colorado River and Gunnison River have likewise decreased. This was particularly apparent during the period from 1964 to 1978, when annual sediment loads were 40–65% less than the long-term average. Analysis of aerial photographs indicates that between 1937 and 1993 the main channel of the Colorado River has narrowed by an average of 20 m and about 1/4 of the area formed by side channels and backwaters has been lost.

1. Introduction

The Colorado River is one of many rivers in the western United States where populations of native fish are endangered and nearing extinction. There are currently four federally listed endangered fishes in the upper Colorado River: the Colorado squawfish (*Ptychocheilus lucius*), razorback sucker (*Xyrauchen texanus*), humpback chub (*Gila cypha*), and bonytail (*Gila elegans*). The former two species were once plentiful in reaches of the Colorado River in western Colorado and eastern Utah. More recently, populations of both species have declined, presumably because of competition with nonnative species and/or reductions in the amount or quality of in-stream habitat [*Stanford*, 1994]. Over 40 species of nonnative fish have been introduced into the upper Colorado River basin [*Tyus*, 1991]. Added to this there are 24 reservoirs with a capacity greater than 5000 acre-feet (6,168,000 m^3) upstream from the Colorado-Utah state line that have altered the natural flow regime of the river [*Liebermann et al.*, 1989]. The collective effects of predation, competition, and water resource development appear to be very serious because they are impacting fish species that have survived for more than 2 million years.

Proposed plans to increase populations of the endangered fish species have become major water resource issues in the Colorado River basin. Indeed, one of the goals of the April 1996 artificial flood in Grand Canyon was to improve habitat used by some of these same species [*Collier et al.*, 1996]. However, unlike Grand Canyon, where environmental studies have been underway for some time [*National Research Council*, 1987, 1991], or the Green River, where several studies of channel change have been conducted [*Graf*, 1978; *Andrews*, 1986], very little of this type of research has been done on upper reaches of the Colorado River (by "upper" reaches we mean those reaches upstream of the Green River confluence; this segment of the Colorado River is sometimes referred to as the Grand River, its name prior to 1921). Reports by *Iorns et al*. [1965], *Elliot and DeFeyter* [1986], and *Liebermann et al*. [1989] describe long-term trends in streamflow, sediment load, and water quality in the Colorado River basin, but these reports are now at least 10 years out of date. In more focused studies, *Schmidt* [1985] examined regional denudation patterns, and *Laronne and Shen* [1982] studied erosion and solute transport on shale hillslopes near Grand Junction, Colorado. However, no one has examined how changes in streamflow and sediment load have affected the geomorphology of the upper Colorado River.

The U.S. Fish and Wildlife Service (USFWS), in cooperation with other federal and state agencies, water resource development interests, and environmental organizations, established the Recovery Implementation Program for Endangered Fish Species in the upper Colorado River Basin [*USFWS*, 1987]. The purpose of this program is to increase the populations of the endangered fishes while allowing water resource development to proceed in accordance with interstate compacts. This is a complex issue involving many different interests, but there is clearly a need to understand how physical habitats used by the endangered fishes have changed historically, and to develop criteria for flows that will maintain or improve existing habitats. It has been assumed that reservoirs and transbasin diversions in the upper Colorado River basin have altered streamflows greatly and that this has caused significant changes in the amount, diversity, and quality of habitats used by the endangered fishes [*Stanford*, 1994]. It has further been assumed that under existing conditions, streamflows can be managed to maintain or improve habitats and

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thereby support recovery. The work described in this and the accompanying paper [*Pitlick and Van Steeter*, this issue] was undertaken to see whether these assumptions are tenable. The present paper provides background information on the Colorado squawfish and their use of habitats in reaches near Grand Junction, Colorado, along with analyses of long-term trends in streamflow, sediment load, and channel change. We focus on the Colorado squawfish because the habitat needs of this fish are perhaps the best understood and because they are the most abundant of the endangered fishes in the study area [*Stanford and Ward*, 1986]. In the second paper we present results of field studies conducted from 1993 through 1995 and use these observations to develop criteria for flows that will maintain or improve existing habitat. In conducting this work we were fortunate to have abundant flow and sediment load data, good 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 biologists and water resource engineers, they give added insight into questions about rates of channel change, mechanisms of cross-section adjustment, and processes of sediment transport in gravel-bed rivers.

2. Colorado Squawfish

The Colorado squawfish is a large piscivore which historically grew to more than 1.5 m in length and 40 kg in weight [*Behnke and Benson*, 1983]. At present it is uncommon to find fish greater than 800 mm in length in the upper Colorado River, and there are perhaps only about 600 adult squawfish remaining in the reach between Palisade, Colorado, and the confluence with the Green River in Utah [*Osmundson and Burnham*, 1996]. The majority of adult squawfish are found near Grand Junction, Colorado; some of these fish are estimated to be more than 30 years old [*Osmundson et al*., 1996]. Colorado squawfish can migrate long distances (>300 km [*Miller et al*., 1983]), but adults in the upper Colorado River typically move less than 10 km [*McAda and Kaeding*, 1991; *Osmundson et al*., 1997]. Presumably, these fish do not need to travel such long distances because forage fish are more abundant in the Grand Junction area than elsewhere.

Colorado squawfish spawn when they are 6–7 years old [*Behnke and Benson*, 1983]. Movement patterns of radio-tagged adult Colorado squawfish and sampling of larval fish indicate that spawning sites are widely distributed along the upper Colorado River [*McAda and Kaeding*, 1991]. For whatever reason, squawfish in the upper Colorado River do not appear to exhibit the same type of homing behavior and fidelity to spawning bars that squawfish in the Green River do [*Stanford*, 1994]. Spawning occurs several weeks after the peak in the snowmelt hydrograph between late June and early August, when water temperatures reach 18° to 22°C [*Hamman*, 1981; *Marsh*, 1985; *McAda and Kaeding*, 1991]. The fish spawn in shallow water over gravel bars composed of loose, open-framework particles [*Harvey et al*., 1994]. A clean substrate with deep interstitial voids is important for successful spawning because the eggs are adhesive [*Tyus and Karp*, 1989; *Hamman*, 1981]. The eggs hatch after approximately 5 days, and then the larvae detach from the bed and drift downstream. Larval and young squawfish eat algae, plankton, invertebrates, and other larval fish. When the fish reach approximately 200 mm in length, they prey exclusively on other fishes [*Vanicek and Kramer*, 1969; *Muth and Snyder*, 1995].

Adult Colorado squawfish are found in a variety of habitats, including pools, riffles, runs, and backwaters. These habitats are defined as follows: pools and riffles are, respectively, the deepest and shallowest parts of the channel; runs are sections with relatively uniform width and depth; and backwaters are ephemeral, low-velocity embayments that form along shore or in association with side channels. Two types of backwaters exist in the upper Colorado River. In the sand-bed reaches downstream of Moab, Utah, backwaters form adjacent to emergent sand bars. These backwaters are important nursery habitat for larval squawfish since they provide a warm, nutrient-rich environment [*Tyus and Karp*, 1989]. In the gravel-bed reaches near Grand Junction, Colorado, backwaters are typically associated with midchannel bars or islands. Backwaters are important habitat for adult squawfish because they provide refuge from the main channel and staging areas for spawning. Figure 1 shows an aerial photograph of one of these features. 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, flow no longer enters the side channel, and water ponds into the area from downstream, forming a backwater (Figure 1). Other features seen in this photograph include a stabilized island showing traces of the former channel, an active gravel bar, and portions of two runs. In terms of areal extent, runs constitute by far the majority of habitat in the upper Colorado River. This might explain why squawfish are found relatively often in runs [*Osmundson et al*., 1995], but otherwise runs are not considered to be especially important habitats. The prevailing thought among biologists [*Tyus and Karp*, 1989; *Stanford*, 1994; *Osmundson et al*., 1995] is that adult Colorado squawfish prefer complex, multithread reaches, such as those shown in Figure 1. Multithread reaches provide habitat diversity and greater opportunities for forage, rest, and predator avoidance. Multithread reaches also have backwaters in close proximity to spawning bars, which allows spawning adults to conserve energy and minimizes the distance that larvae drift downstream. This can be critical since larvae must reach suitable feeding areas before their yolk supplies are depleted [*Tyus and Haines*, 1991].

3. Study Area

The upper Colorado River and its principal upper basin tributary, the Gunnison River, have their headwaters in the Rocky Mountains in central Colorado (Figure 2). The Yampa River and White River, major tributaries of the Green River, likewise have their sources in the Rocky Mountains (Figure 2). 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. Summer thunderstorms are common in this area. These storms can cause localized flooding on tributaries and increase turbidity on the larger rivers for several days, but they generally do not have a significant effect on main stem discharges.

Natural streamflows of the Colorado and Gunnison Rivers are affected by many diversions and dams. The dams in the upper Colorado River basin are not large in comparison to other dams in the Colorado-Green River system, such as Flaming Gorge or Glen Canyon Dams; collectively, the reservoirs upstream of the study area store only about 10% of the total volume of water in Lake Powell. However, the reservoirs in the upper Colorado River basin are nearer the source of runoff, and thus they alter the annual hydrograph significantly (we

Figure 1. Aerial photograph of a segment of the Colorado River in the 15-mile reach. This photograph shows a dissected gravel bar, portions of two runs, a stable island, and a relatively long backwater. The trapezoidal pond with the small island is 250 m across. Flow is from right to left.

pursue this point later; see also work by *Liebermann et al.* [1989]). The upper Colorado River carries moderately high sediment loads of 10^5–10^7 t/yr (metric tons per year) [*Elliot and DeFeyter*, 1986]. Much of this sediment is derived from the area in western Colorado and eastern Utah underlain by Cretaceous shales and sandstones [*Iorns et al.*, 1965; *Liebermann et al.*, 1989]. This area is drained by a few small tributaries that join the main stem of the Colorado River downstream from the upper basin reservoirs; most of these tributaries are unregulated. The upper Colorado River thus has two distinct 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 fall limb. This has probably always been the case, but now streamflows are 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 three contiguous reaches near Grand Junction, Colorado, that mark the upstream limit of the range of the Colorado squawfish on the main stem of the Colorado River (Figure 3). The 15-mile reach (as it is referred to by USFWS) extends from Palisade, Colorado, to the confluence of the Gunnison River at Grand Junction; the 18-mile reach (as it is referred to by USFWS) extends 29 km downstream from the Gunnison River to Loma, Colorado; and the Ruby-Horsethief Canyon reach extends another 39 km downstream from Loma to Westwater, Utah (Fig. 3). In the 15- and 18-mile reaches the channel pattern alternates between relatively simple single-thread segments to complex multithread segments with islands, side channels, and backwaters (Figure 1). Studies by *Osmundson and Kaeding* [1991] suggest that Colorado squawfish are found more often in multithread reaches, presumably because habitat heterogeneity is greater in these reaches. The Ruby-Horsethief Canyon reach is more single thread, but a narrow floodplain is present through most of this reach, and backwaters and side channels are found in several areas. The river is gravel bed, while 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, particularly in the 15-mile reach, the banks have been artificially modified by levees and rip-rap. The average slope through all three reaches is 0.0014.

4. Data Sources and Methods

4.1. 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 long-term streamflow records from a number of gauges on the main stem of the Colorado River and nearby regulated and unregulated tributaries [*Van Steeter*, 1996] but discuss only a portion of this work here. The East River at Almont (09112500, Figure 2) and the Yampa River at Maybell (09251000, Figure 2) are representative of rivers with little flow regulation. The Colorado River at Glenwood Springs

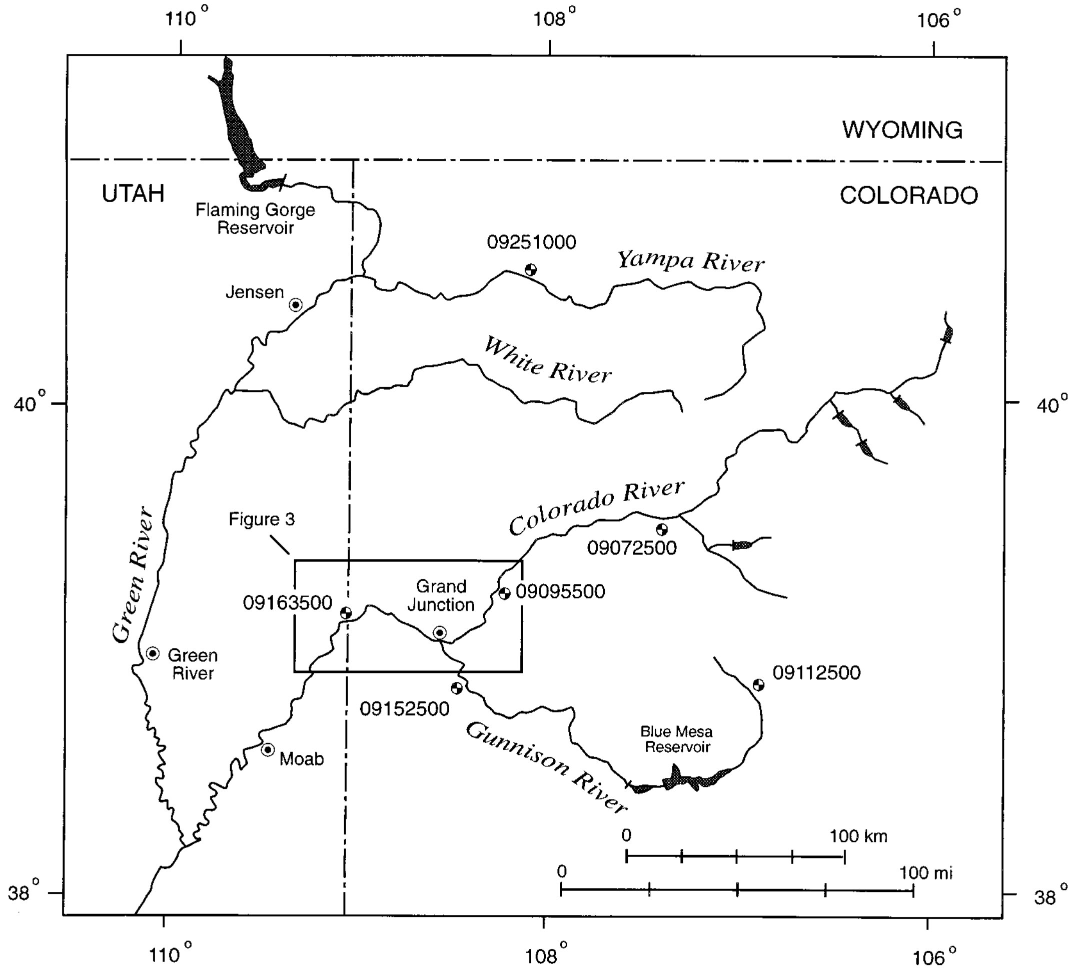

Figure 2. Location of rivers and selected gauging stations in the upper Colorado River basin.

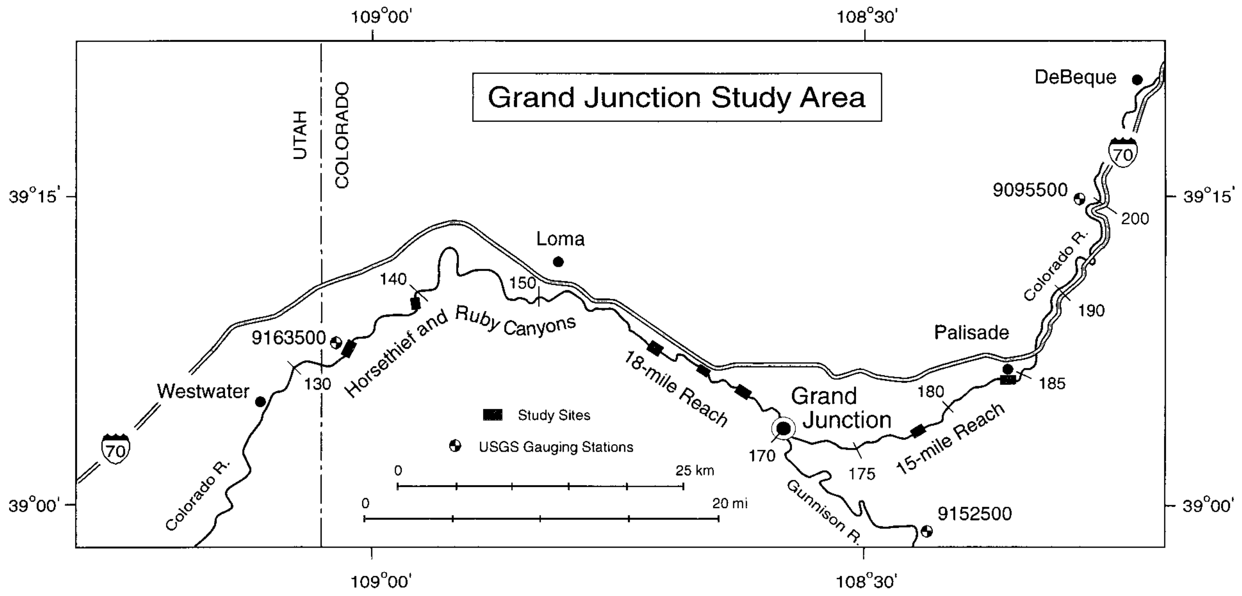

Figure 3. Detailed map showing study reaches near Grand Junction, Colorado.

(09072500, Figure 2) and the Gunnison River near Grand Junction (09152500, Figure 2) are representative of rivers with significant flow regulation. Two other gauges in the vicinity of the study area (Colorado River near Cameo, 09095500, and Colorado River near the Colorado-Utah state line, 09163500, Figure 2), have shorter records than the other gauges but likewise show the effects of flow regulation.

Since 20 of the 24 reservoirs upstream of the study area were built after 1950, the flow records were divided into a predevelopment period (1900–1949) and a postdevelopment (1950–1995) period. For each period the average peak discharge (mean annual flood) and the average annual discharge (mean annual flow) were calculated, and the significance of differences between the two periods was determined using a *t* test. Average annual hydrographs for pre- and postdevelopment periods were constructed by averaging daily flow values. These hydrographs illustrate differences in the timing and volume of runoff between the two periods.

4.2. Sediment Loads

Sediment measurements in the upper Colorado River have been made routinely at only a few places, and then mostly 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 suspended sediment measurements at the Gunnison River gauge through 1965. To our knowledge, no further sediment measurements were made at these gauges until the late 1970s and early 1980s, when the USGS began regularly collecting sediment and water quality data at these sites, and also at the state line gauge. Nearly all of the sediment measurements on the Colorado and Gunnison Rivers are of suspended load. A few bed load samples were taken in 1984 at a site near the town of DeBeque, Colorado, about 10 km upstream from the Cameo gauge [*Butler*, 1986]. Most of the bed load was finer than 16 mm, which is about the median grain size of the subsurface bed material [*Pitlick and Van Steeter*, this issue]. 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 in the accompanying paper [*Pitlick and Van Steeter*, this issue].

4.3. Average Bed Elevations

Changes in average bed elevation were determined by compiling the field notes of discharge measurements at the Cameo, Gunnison River, and state line gauges. Among the many hundreds of discharge measurements, we selected three measurements for each year corresponding to prepeak, high flow, and postpeak time periods. The average bed elevation for individual measurements was calculated by taking the difference between the gauge height and the mean depth [*Jacobson*, 1995], adjusting for changes in the location and datum of the gauge where necessary.

4.4. Aerial Photograph–GIS Analysis

Changes in channel morphology of the 15-mile, 18-mile, and Ruby-Horsethief Canyon reaches were determined from black-and-white aerial photographs taken in 1937, 1954, 1968, and 1993. These photographs are of similar scale (nominally 1:20,000), but their quality varies, and they were flown at different times of the year with the river at different flow levels. The 1954 and 1968 photographs were taken at low flow (discharges in the 15-mile reach were 54 and 60 m^3/s, respectively). The 1937 and 1993 photographs were taken at moderate flow (discharges in the 15-mile reach were 209 and 186 m^3/s, respectively). The differences in photograph quality and flow level introduce several problems, which we discuss below.

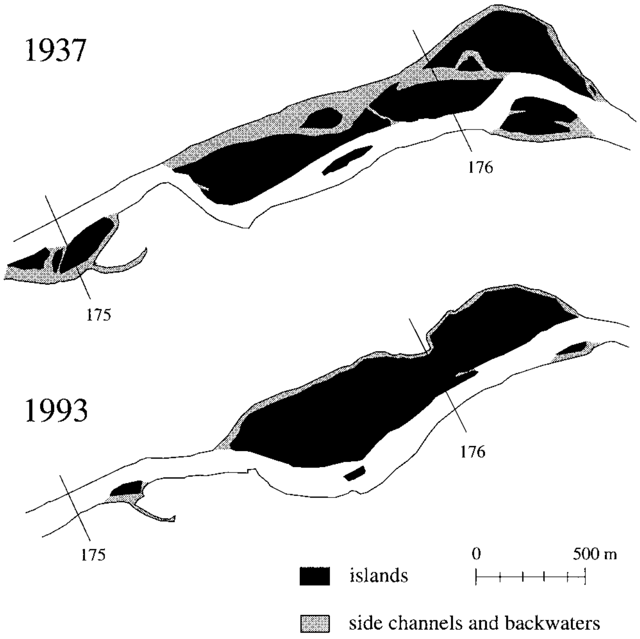

Figure 4. Example showing how geomorphic features within the Colorado River were differentiated and changes that occurred between 1937 and 1993. Compare the digitized 1993 map with the photograph in Figure 1.

The steps involved in measuring channel changes 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 the river banks, islands, bars, side channels, and backwaters were digitized using a computer aided design system (AutoCAD). Figure 4 shows an example of how these features were differentiated. Side channels 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 90-km study reach.

The accuracy of these measurements is affected to varying degrees by the clarity of the photographs, differences in discharge, and the amount of distortion. Differences in clarity can lead to problems in the interpretation of features and the accuracy with which they can be digitized, differences in discharge affect the planform area of the river and associated features, and distortion (including the effects of camera tilt) can make objects appear larger or smaller than they really are, especially near the edges of photographs. For practical reasons we did not rectify the photographs to correct for distortion. We did, however, evaluate the potential error from these various

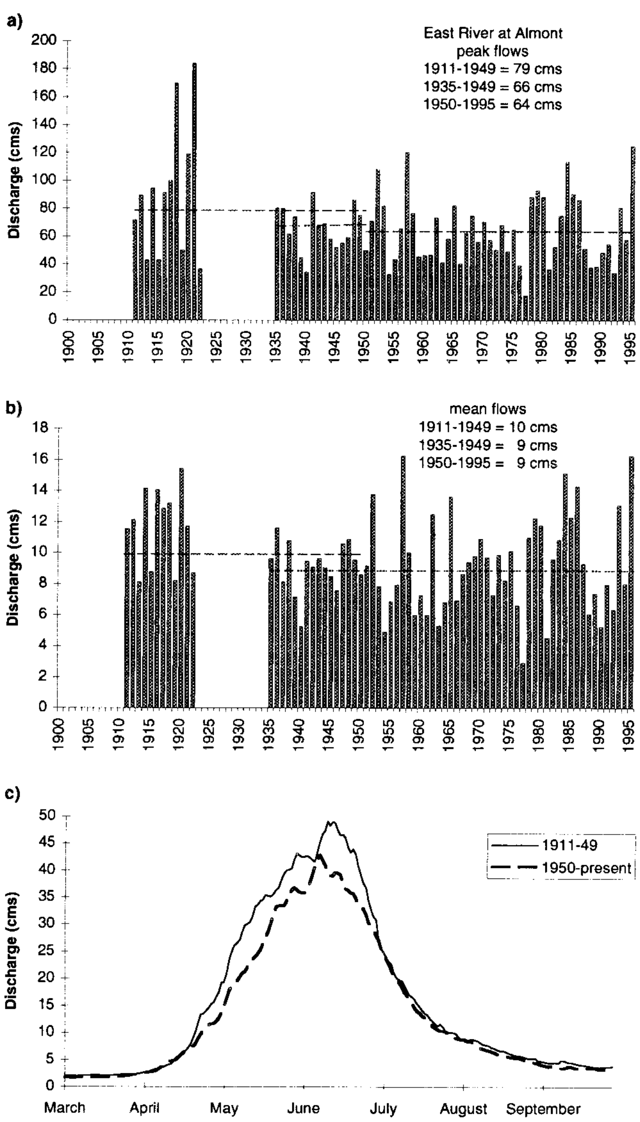

Figure 5. Streamflow data for the East River at Almont (09112500), an unregulated tributary of the Gunnison River: (a) annual peak discharge, (b) average annual discharge, and (c) composite hydrographs for separate periods.

sources. Errors due to interpretation and tracing of objects on a set of photographs were evaluated by redigitizing reaches of the river and comparing the results to the original measurements. Errors due to differences in discharge 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 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 the measurements of planform area as long as the difference in discharge is less than about 30%. Thus we feel confident in comparing the 1954 and 1968 photographs and the 1937 and 1993 photographs but not in comparing them all together. The average error due to distortion at the edge of photographs is about 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–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.

5. Results

5.1. Analysis of Streamflow on Unregulated Rivers

The East River, an unregulated tributary of the Gunnison River, has been gauged at Almont, Colorado, since 1911. There is a gap in the record from 1922 to 1934, but thereafter it is continuous through the present (1997). The time series of annual peak discharges on the East River at Almont shows that peak flows in the early part of this century (around 1920) were high compared to the period after 1934 (Figure 5a). In most of the streamflow records we have examined [*Van Steeter*, 1996], the 1920s stand out as a period of anomalously high flows; this finding is consistent with the previous work of *Stockton and Jacoby* [1976] who showed, using tree-ring reconstructions of runoff, that the early part of this century was one of the wettest periods in the Colorado River basin in the last 400 years. From 1911 to 1949 annual peak discharges on the East River averaged 79 m^3/s. This value is not representative of the entire period, however, because some dry years in the early 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 discharges is 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 (Figure 5b). Composite hydrographs for the two periods are very similar (Figure 5c), the main difference being that flows in the early part of the century are slightly higher and peak later than those in the more recent period.

The Yampa River, located in northern Colorado, is a tributary of the Green River (Figure 2). 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, Colorado, 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 (Figures 6a and 6b). The period of above-average runoff in the early part of the century is not as evident here as it is elsewhere, probably because the record does not begin until 1917. The 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 (Figure 6c), but the difference is small. We conclude on the basis of these data and data from several other gauges [*Van Steeter*, 1996; *Pitlick and Van Steeter*, 1994] that peak discharges and average annual discharges on unregulated rivers in Colorado were slightly higher than average during the early part of the 20th century, but that since then, peak and mean annual streamflows have not changed significantly.

5.2. Analysis of Streamflow on 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 (Figure 2) 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 on the Colorado River. The composite record indicates that reservoirs have clearly had significant effects on peak and mean daily flows of the Colorado River (Figure 7). In the postdevelopment period (1950–1995), annual peak discharges of the Colorado River at Glenwood Springs have averaged 286 m^3/s (Figure 7a); this represents a 43% decrease relative to the predevelopment (1900–1949) average of 504 m^3/s. If we exclude the anomalously wet period prior to 1930 and compare only the years 1931–1961 and 1962–1995, then the decrease in annual peak discharges at Glenwood Springs is not as great (28%) but is still statistically significant ($p < 0.01$). Mean annual discharges have decreased by 26% (Figure 7b), which is also a statistically significant change ($p < 0.01$). Annual hydrographs for the two periods are clearly different (Figure 7c), reflecting the combined effects of the 1920's wet period, the increased export of water by transbasin diversions, and the filling of reservoirs in the 1950s and 1960s.

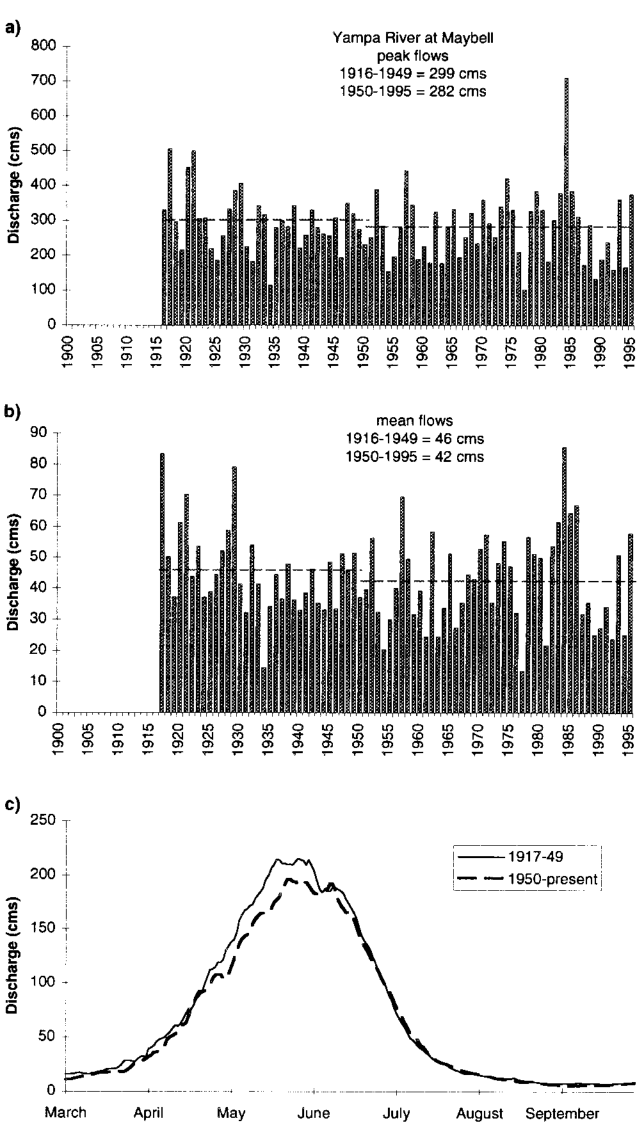

Figure 6. Streamflow data for the Yampa River at Maybell (09251000), a tributary of the Green River with little flow regulation: (a) annual peak discharge, (b) average annual discharge, and (c) composite hydrographs for separate periods.

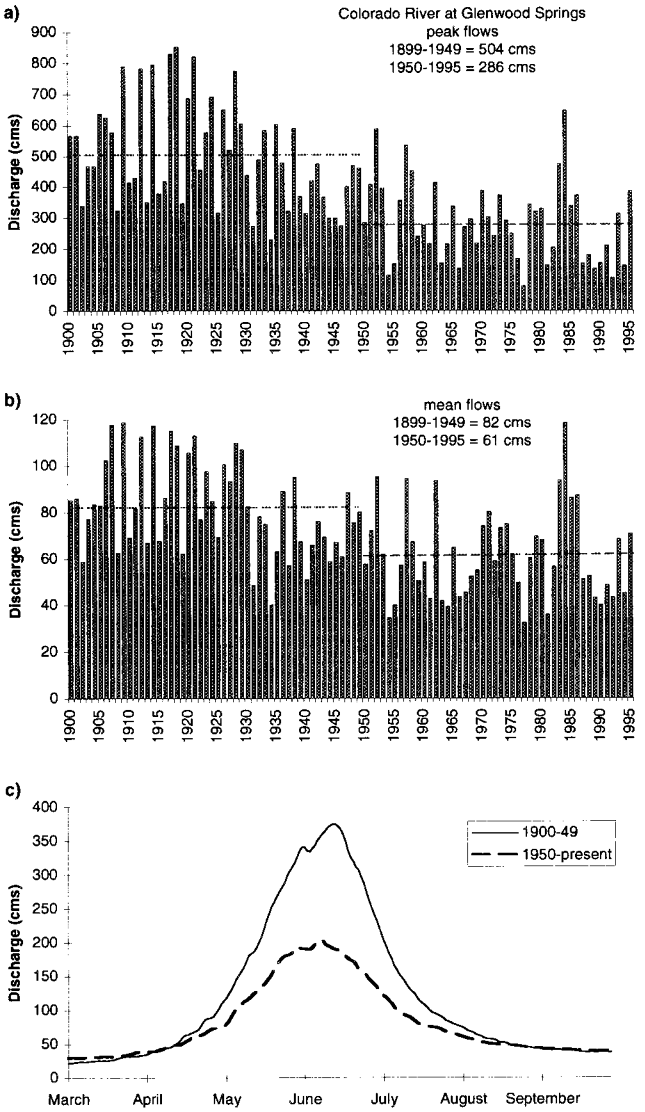

Figure 7. Streamflow data for the Colorado River at Glenwood Springs (09072500), a site influenced by many reservoirs upstream: (a) annual peak discharge, (b) average discharge, and (c) composite hydrographs for separate periods.

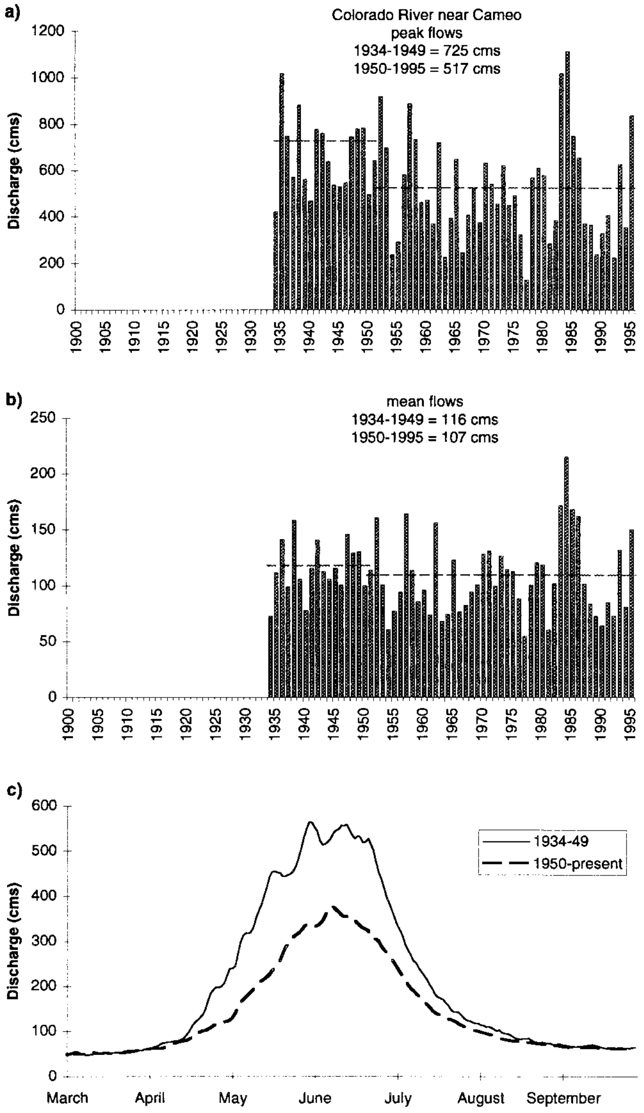

Figure 8. Streamflow data for the Colorado River near Cameo (09095500), a site influenced by many reservoirs upstream: (a) annual peak discharge, (b) average discharge, and (c) composite hydrographs for separate periods.

The effects of reservoirs and transbasin diversions in the upper Colorado River basin diminish downstream because of added flow from unregulated tributaries, but the effects are still noticeable at the gauge near Cameo, approximately 18 km upstream of the study area. Figure 8a shows that annual peak discharges of the Colorado River near Cameo have dropped from an average of 725 m^3/s in the predevelopment (1934–1949) to 517 m^3/s in the postdevelopment period (1950–1995); this represents a 29% decrease in annual peak discharge. If we split the record differently and compare equal-length intervals from 1934 to 1963 and from 1964 to 1995, then the decrease in annual peak discharge is 20%; either way, the difference is statistically significant ($p < 0.01$). In contrast, mean annual discharges at Cameo have not changed significantly over the period of record. From 1934 to 1949 the mean annual discharge was 116 m^3/s, and from 1950 to 1995 the mean annual discharge was 107 m^3/s, which represents a decrease of only 8%. The apparent lack of change in mean annual discharge belies the fact there have been pronounced changes in the annual hydrograph of the Colorado River near Cameo (Figure 8c). The hydrograph for the more recent period is flatter than that for the earlier period: peak flows are lower now, and base flows are higher, 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-development periods somewhat obscures more subtle, and we think, important trends in streamflow. We further subdivided the Cameo record into four 15-year intervals, 1934–1948, 1949–1963, 1964–1978, and 1979–1993, and counted the number of days that flows exceeding 300 and 500 m^3/s occurred in each of these intervals. We show in the accompanying paper [*Pitlick and Van Steeter*, this issue] that these discharges define approximately two sediment transport thresholds, one representing the onset of bed material transport, and the other representing widespread transport and significant reworking of the bed near bank-full flow. These thresholds pertain to the river in its present form and can be applied to past conditions only in an approximate sense because we do not know whether the size of the bed material has changed over time. On the other hand, we know that in general the channel has become narrower (see below), so that the discharges required to reach these thresholds were probably higher in the past. Nonetheless, we can evaluate the frequency that particular discharges were exceeded. Our analysis shows that the frequency of discharges exceeding 300 m^3/s and 500 m^3/s decreased systematically between 1934 and 1978 (Table 1). The reduction in high flows was particularly significant during the period from 1964 to 1978, when discharges greater than 300 m^3/s occurred only about 20 days per year and flows exceeding 500 m^3/s occurred only 2 or 3 days per year (Table 1). 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 300 m^3/s occurred about 1 month per year and flows exceeding 500 m^3/s occurred about 8 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 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).

The Gunnison River, which joins the Colorado River at Grand Junction (Figure 2) and 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 several dams. The largest of these dams (Blue Mesa Reservoir) was completed in 1966, and from

Table 1. Frequency of Daily Discharges Exceeding Specified Values

Discharge, m^3/s	Number of Days That Specified Discharge Was Exceeded			
	1934–1948	1949–1963	1964–1978	1979–1993
300	577	426	328	429
500	195	124	38	177

then on, flows on the Gunnison River have been systematically regulated. Figure 9a shows that annual peak discharges of the Gunnison River near Grand Junction have dropped from an average of 490 m^3/s in the predevelopment period (1902–1949) to 306 m^3/s in the postdevelopment period (1950–1993); this represents a 38% decrease in annual peak discharge. Mean annual discharges of the Gunnison River near Grand Junction have not changed significantly over time (Figure 9b), but the shape of annual hydrograph is now very different. Figure 9c shows the extent to which reservoir operations have modified the snowmelt portion of the annual hydrograph of the Gunnison River, and although it is not particularly apparent in this figure, base flows have nearly doubled such that the total volume of runoff has not changed significantly.

This comparison between unregulated and regulated rivers shows rather clearly that water resource development projects, mainly dams, have significantly altered the natural flow regimes of the upper Colorado River and the Gunnison River. Peak discharges in reaches used by the endangered fishes are 29–38% lower now than they were in the past, and although average annual discharges have remained essentially the same, reservoir operations clearly affect the way that runoff is distributed throughout the year.

5.3. Suspended Sediment

Sediment loads are calculated as the product of the sediment concentration, C_s, and the water discharge, Q, either of which may change with time and watershed conditions. Given that there have been discrete periods when peak flows of the Colorado River were lower than average, an important point to resolve with respect to sediment loads is whether sediment concentrations have changed appreciably over time. Although few sediment data are available for earlier periods, these data provide a key link between changes in streamflow, sediment loads, and channel morphology. Figure 10 shows separate plots of suspended sediment concentration and discharge for samples taken at the Cameo gauge in the early 1950s and for samples taken from 1983 to 1993. These samples are further grouped according to whether they were taken before the peak in the annual discharge hydrograph (rising limb), after the peak (falling limb), or in late summer, when runoff from localized thunderstorms can raise sediment concentrations for several days (we define "prepeak" observations as those made between the first day of the water year, October 1, and the day of the peak discharge, and "postpeak" observations as those made from the day after the peak discharge to the last day of the water year, September 30). The curved lines in Figure 10 are pre- and postpeak relations drawn by eye to follow the nonlinear trends of the data and to minimize any trends in residuals. For comparison the same curves are plotted for both time periods:

$$\text{Prepeak} \qquad C_s = \frac{5(Q-12)^4}{Q^3} \tag{1a}$$

$$\text{Postpeak} \qquad C_s = \frac{(Q-18)^4}{Q^3} \tag{1b}$$

where Q is in cubic meters per second and C_s is in milligrams per liter. It does not appear from these data that sediment concentrations in recent years (1983–1993) were appreciably different than they were in the 1950s, and thus we used the above pair of relations to calculate sediment loads for the entire period of record, 1934–1993.

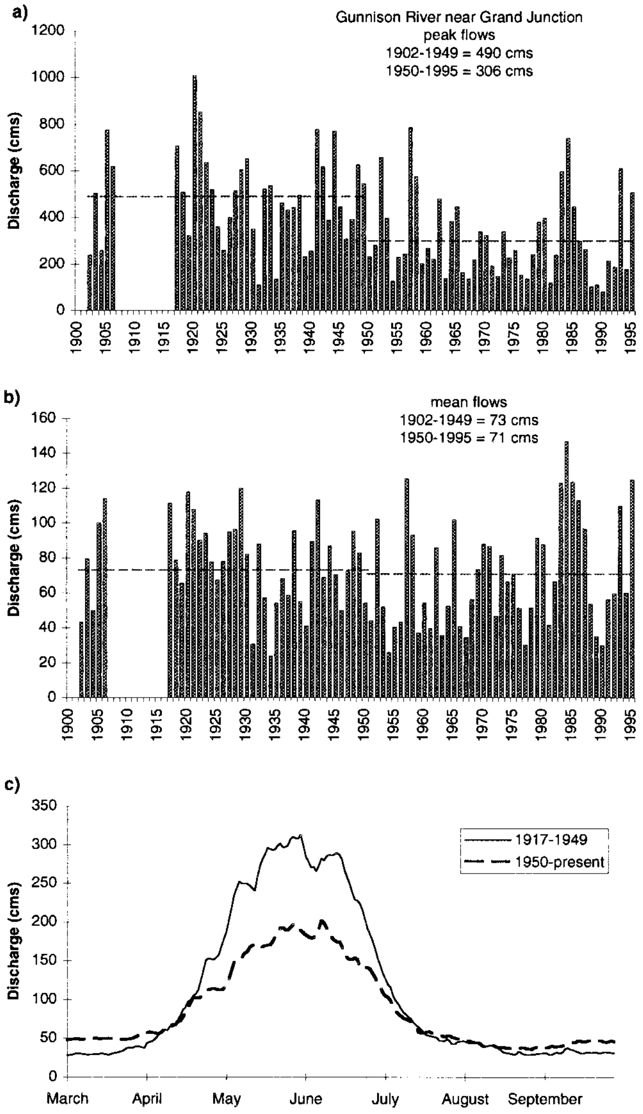

Figure 9. Streamflow data for the Gunnison River near Grand Junction (09152500), a site with several moderate-size reservoirs upstream: (a) annual peak discharge, (b) average discharge, and (c) composite hydrographs for separate periods.

Compared to the Colorado River, suspended sediment concentrations in the Gunnison River follow less consistent trends (Figure 11). During the earlier period (1949–1965) there appears to be some difference between pre- and postpeak sediment concentrations, but this is not as clear as it was on the Colorado River. Very little, if any difference in pre- and postpeak sediment concentrations is evident in the more recent data (Figure 11). This may have to do with how the three dams on the main stem of the Gunnison River are operated, or with the fact that they trap proportionally more of the prepeak sediment load derived from the sandstone and shale bedrock units in the surrounding areas. For the period prior to 1966, sediment concentrations in the Gunnison River were estimated with the following empirical relations:

$$\text{Prepeak} \qquad C_s = \frac{100(Q-10)^{3.6}}{Q^3} \tag{2a}$$

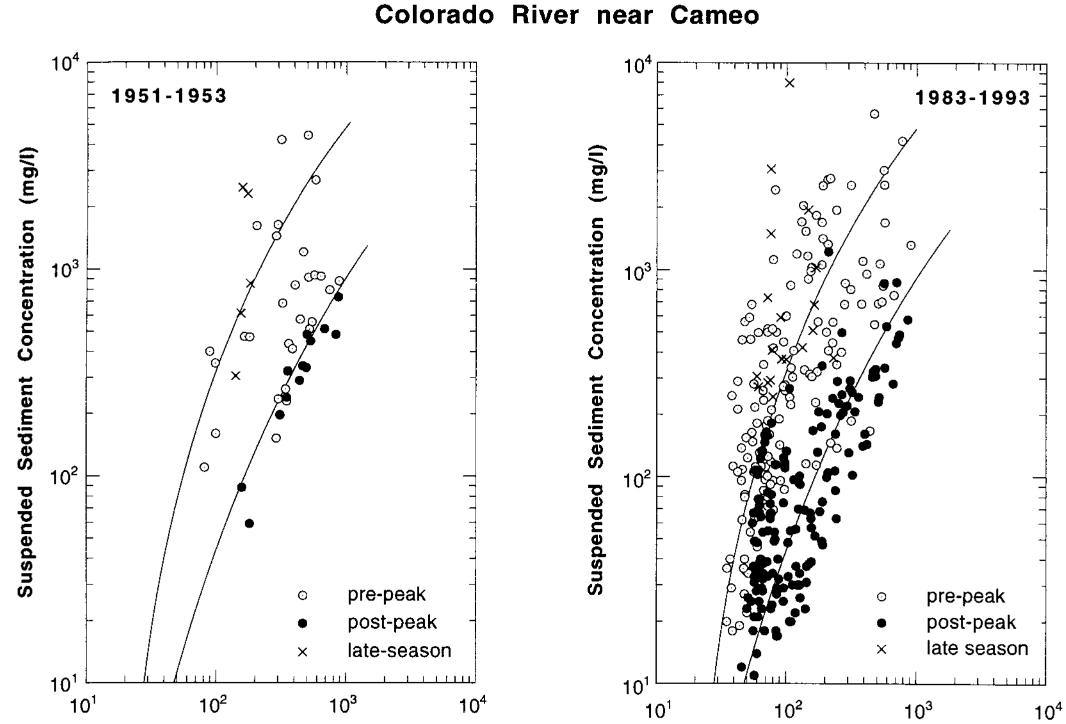

Figure 10. Relation of suspended sediment concentration to discharge in the Colorado River near Cameo for two separate time periods. Data for 1951–1953 are from *Iorns et al.* [1964]; data for 1983–1993 are from USGS Water Supply Papers. Curved lines are the same for both time periods.

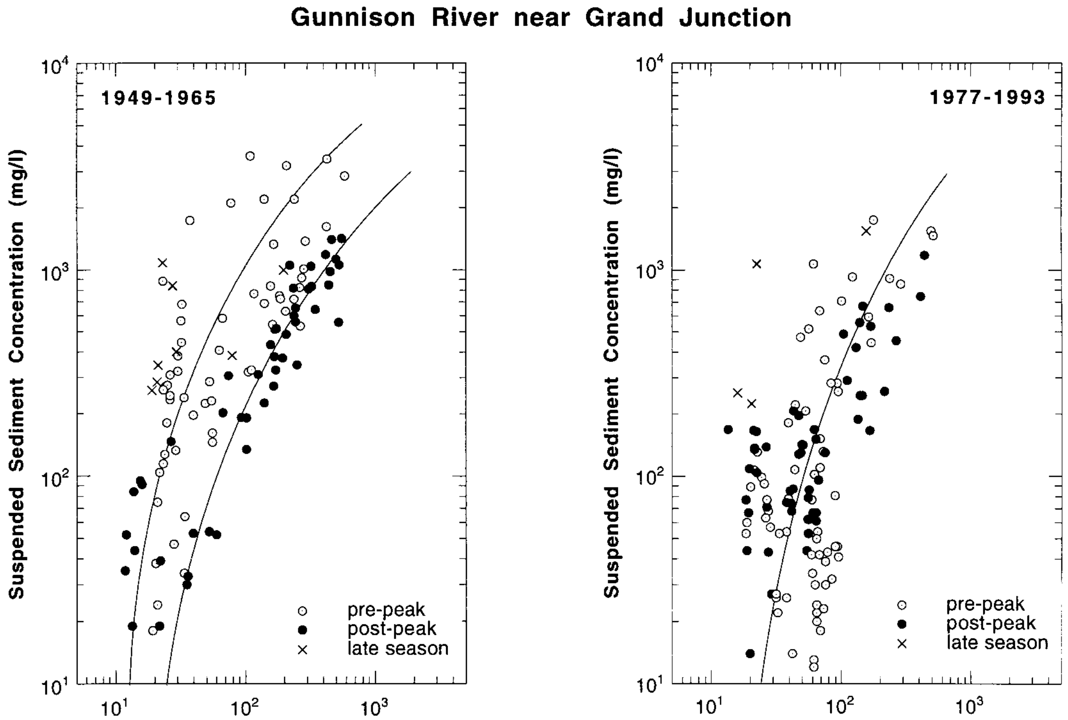

Figure 11. Relation of suspended sediment concentration to discharge in the Gunnison River near Grand Junction for two separate time periods. Data are from *Iorns et al.* [1964] and USGS Water Supply Papers. Curved lines are different for each time period.

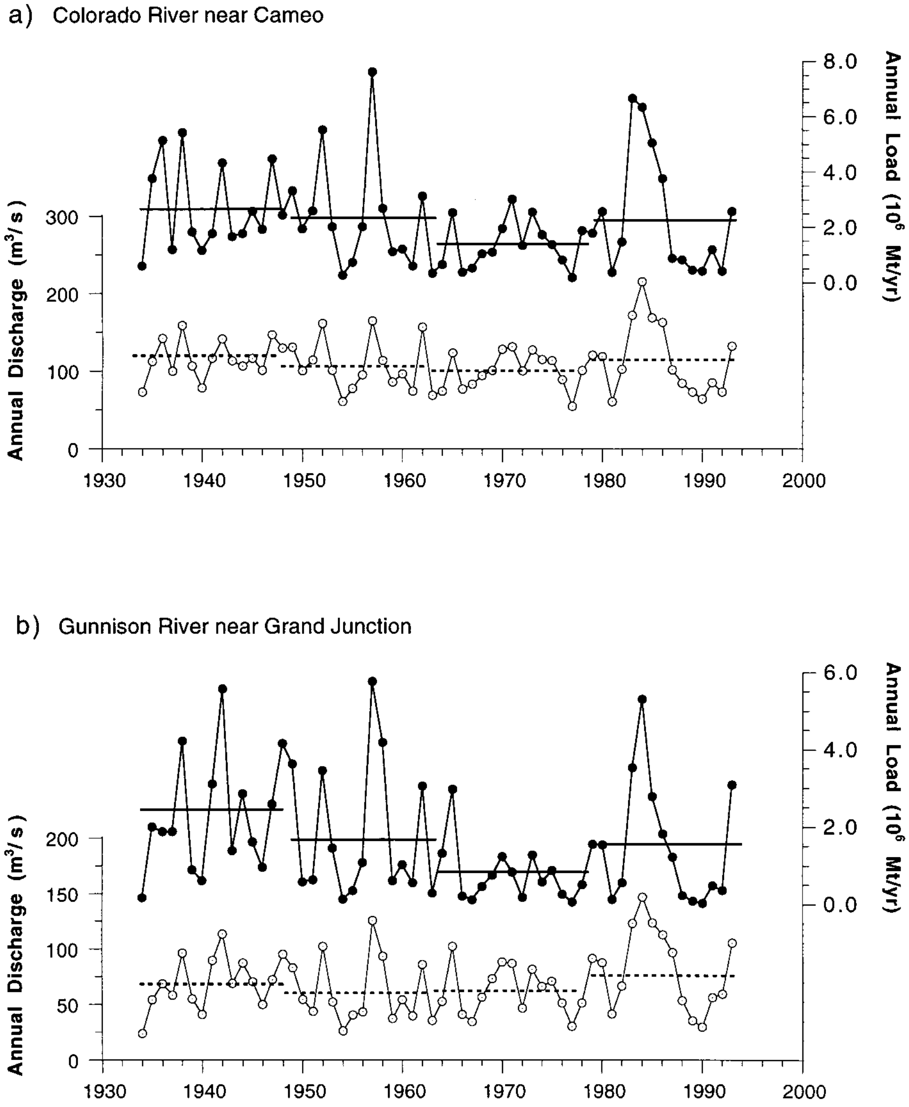

Figure 12. Trends in annual discharge and suspended sediment discharge for (a) the Colorado River near Cameo and (b) the Gunnison River near Grand Junction. The horizontal lines indicate average values of discharge and suspended sediment load for individual 15-year periods.

Postpeak
$$C_s = \frac{2.5(Q - 10)^4}{Q^3} \tag{2b}$$

For the period after 1966, sediment concentrations were estimated with a single relation:

$$C_s = \frac{5(Q - 10)^4}{Q^3} \tag{2c}$$

Using these empirical relations and separate pre- and postpeak values of daily discharge, we calculated annual suspended sediment loads, Q_s, of the Colorado River near Cameo and the Gunnison River near Grand Junction for the period 1934 to 1993. To reiterate, these two sites represent the majority of sediment input to the 15-mile and 18-mile reaches, both of which have historically been important for the Colorado squawfish. Figure 12 shows that annual sediment loads of the Colorado and Gunnison Rivers are highly variable in comparison to average annual discharges. Much of this has to do with the nonlinear relation between sediment concentration and water discharge, and because of this, trends in average discharge are not a good indicator of trends in average sediment load. Further subdividing these records into separate 15-year periods highlights the interval from 1964 to 1978, when annual sediment loads on both rivers were much lower than the long term average even though annual discharges were only slightly less (Table 2). As noted earlier the period from 1964 to 1978, and several years on either side of it, was characterized by fewer high flow events. From 1964 to 1978 the average annual suspended load of the Colorado River near Cameo was about 1.4 million Mt/yr, which was only about half of the annual load from 1934 to 1948 and 40% less than the annual load from 1949 to 1963 (Table 2). In recent years (1979–1993) average annual sediment loads of the Colorado River have been nearly as high as they were earlier (Table 2). From 1964 to 1978 the average annual suspended load of the Gunnison River near Grand Junction was only about a third of what it was from 1934 to 1948 and about half of what it was from 1949 to 1963 (Table 2). As with the Colorado River, average annual sediment loads

Table 2. Comparison of Average Annual Peak Discharge, Q_p; Mean Annual Discharge, Q_m; and Annual Suspended Sediment Load, Q_s, for the Colorado River Near Cameo and the Gunnison River Near Grand Junction for Different Time Periods

	Colorado River			Gunnison River		
	Q_p, m^3/s	Q_m, m^3/s	Q_s, 10^6 Mt/yr	Q_p, m^3/s	Q_m, m^3/s	Q_s, 10^6 Mt/yr
1934–1948	668	116	2.63	453	70	2.26
1949–1963	570	107	2.31	360	61	1.79
1964–1978	456	101	1.38	248	62	0.78
1979–1993	534	116	2.28	321	82	1.52

of the Gunnison River have been as high in recent years (1979–1993) as they were during earlier periods.

5.4. Average Bed Elevations

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 40–60 years (Figures 13a and 13b), whereas average bed elevations at the Gunnison River gauge have decreased over time (Figure 13c). 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 storage in the bed. However, we see little evidence for widespread aggradation, such as increased braiding and widening; 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 bed forms and that they 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 [cf. *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.

5.5. Changes in Channel Morphology

Our photogrammetric analysis indicates that in general, the Colorado River has become narrower and less complex during

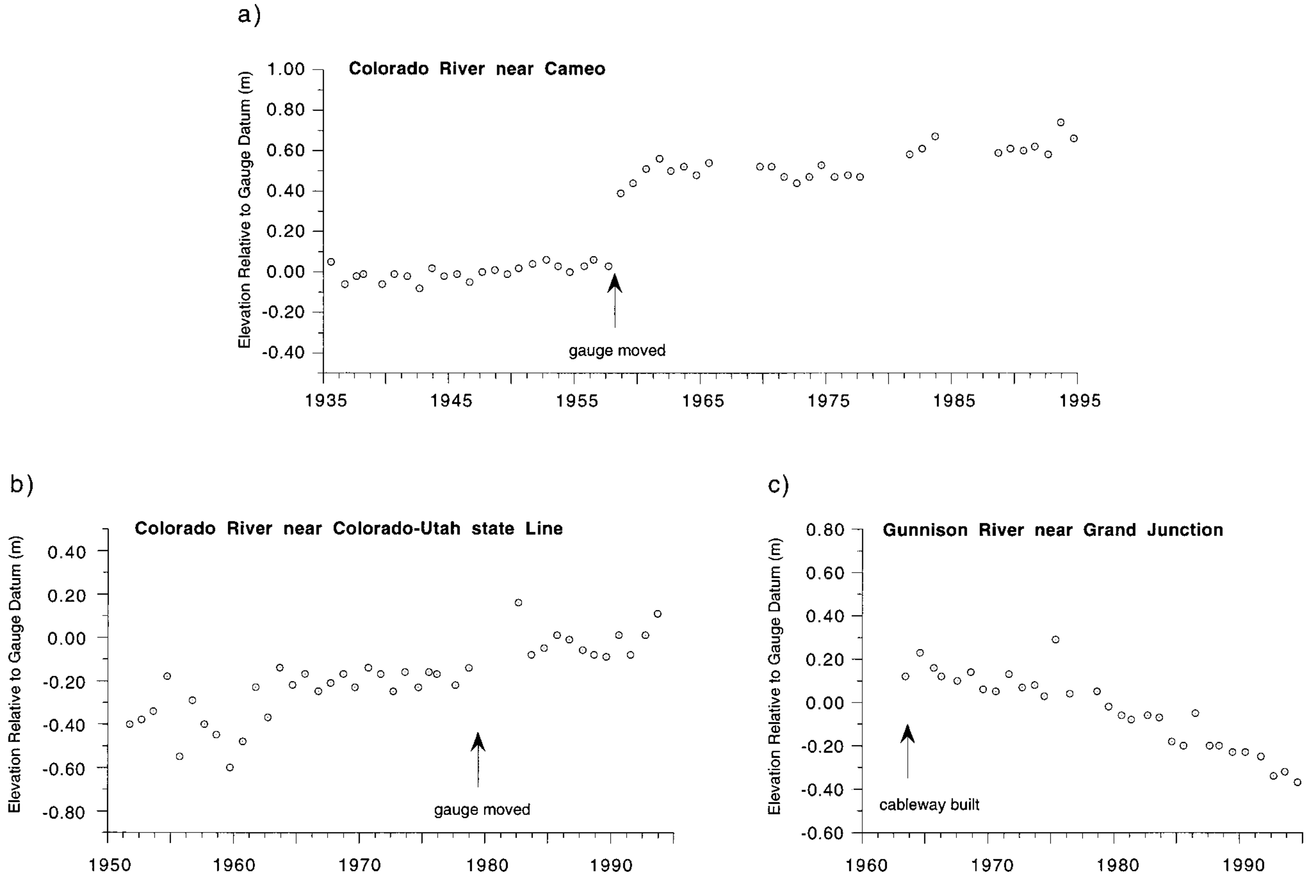

Figure 13. Trends in the average bed elevation derived from low-flow discharge measurements at USGS gauging stations: (a) the Colorado River near Cameo, (b) the Colorado River near the Colorado-Utah state line, and (c) the Gunnison River near Grand Junction. Gaps in the record indicate periods where data were obtained but are missing from USGS archives.

the last 50 years. Referring back to Figure 4, note how the side channels and small islands near river mile 176 coalesced to form one large island and one small side channel. This trend is typical of many, but not all, of the reaches near Grand Junction. In a few reaches the total area of side channels has increased, and potential new habitat has been formed. These reaches are typically in areas that were changed dramatically by the major floods that occured in 1983 and 1984. These floods were some of the largest in this century, and they altered the course of the river in many places, especially where gravel pits were flooded. Thus, although the general trend in the upper Colorado River is toward a less complex channel, the period of observation (1937–1993) includes two very large floods, which created new side channels and restored some channel complexity.

Figure 14 shows changes in planform area between 1937 and 1993 for individual 1-mile (1.6-km) segments of the river. Note first the difference between the 15- and 18-mile reaches (river miles 185–153) and the Ruby-Horsethief Canyon reach (river miles 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 channel is less constrained. Note second that the changes in main-channel and side-channel areas are consistently negative, indicating decreases in 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 3). The reduction in side-channel area equates to a decrease in average width of about 7 m (−26%, Table 3). However, because side channels are discontinuous and 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 20–30 m wide; thus decreases in average width of side channels of 7 m or more represent significant losses in potential fish habitat. Changes in island and bar area are negative overall (−9%, Table 3), suggesting these features have gotten smaller, although there are many places where new islands or bars have formed and other ones have been enlarged (Figure 4). We included islands in this analysis because we were interested in seeing whether the river and its associated features had all become smaller or whether there was a disproportionate loss of some features such as backwaters. 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 3. Summary of Changes in Planform Area of the Main Channel, Islands, and Side Channels of the Colorado River for the Periods Shown

	Total Area, ha		Change in Total Area, ha	Change per Unit Length,* m	Change in Area, %
	1937	1993			
Main channel	1125	958	−167	−20	−15
Islands	460	419	−41	−5	−9
Side channels	225	167	−58	−7	−26
	Total Area, ha		**Change in Total Area, ha**	**Change per Unit Length,* m**	**Change in Area, %**
	1954	1968			
Water	744	670	−74	−9	−10
Island	343	290	−53	−6	−15
Side channels	139	106	−33	−4	−24

*The change in area per unit length is computed on the basis of a total reach length of 84 km. Islands and side channels are not continuous over this length.

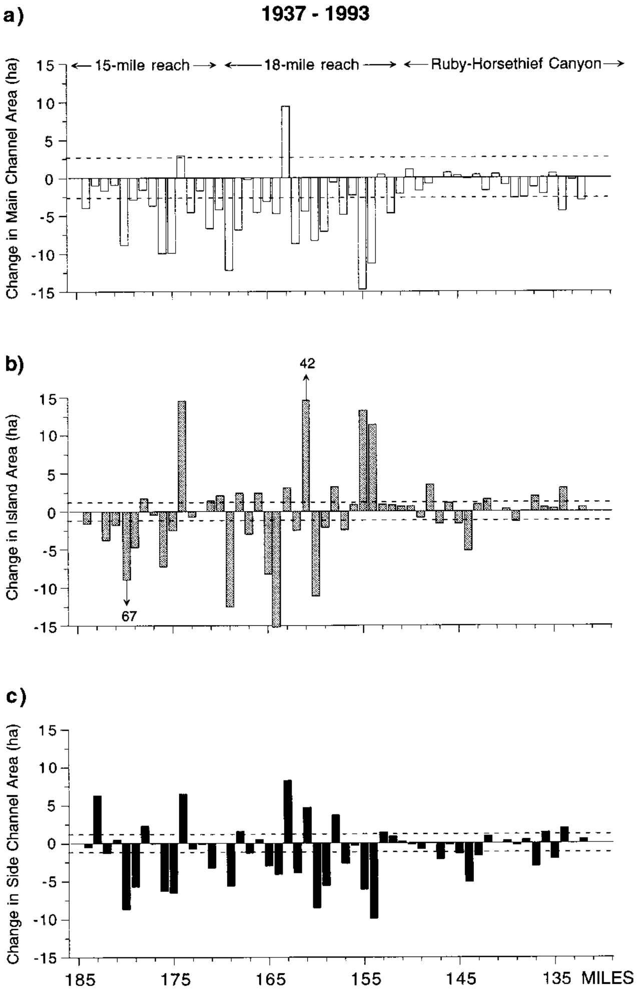

Figure 14. Changes in (a) main channel area, (b) island area, and (c) side-channel–backwater area between 1937 and 1993. Dashed lines represent mean error per mile based upon ±8% for instream water and islands and ±16% for side-channel–backwaters.

The change in in-stream water area for the period 1937–1993 is easily 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. Because of the larger error associated with measuring islands and side channels, the actual changes in these features is perhaps more or less than what we have indicated. The changes would be insignificant only in the unlikely case that every polygon in one set of photographs is overestimated by the maximum, and every polygon in the other set of photographs is underestimated by the maximum.

Changes in main-channel area, island area, and side-channel area for the period from 1954 to 1968 are summarized in Figure 15 and Table 3. Similar to the previous comparison, the most significant changes in this period took place in the 15- and 18-mile reaches (Figure 15), and overall, the area of all fea-

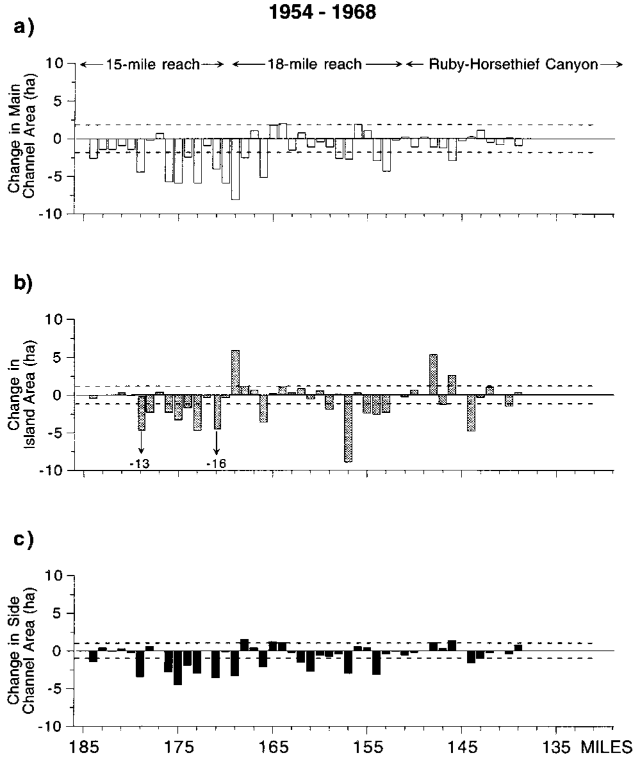

Figure 15. Changes in (a) main channel area, (b) island area, and (c) side channel/backwater area between 1954 and 1968. Dashed lines represent mean error per mile based upon ±8% for instream water and islands and ±16% for side-channel–backwaters.

tures decreased (Table 3). 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 3). 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 1), and much lower sediment loads (Table 2). 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.

On the basis of 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 are characterized by lower depths and velocities than the main channel. Side channels also experience more ephemeral flow; some side channels are inundated every year, but others may not experience flow for several years, and then perhaps only a few days or a week. This allows sediment to build up on the bed and increases the chance that vegetation will colonize and stabilize the deposits once they become subaerially exposed. We suggest in the accompanying paper [*Pitlick and Van Steeter*, this issue] that once this has happened, it is difficult to reverse. Although this sequence of deposition and channel simplification is common to many of our study reaches, it is probably more true of some time periods than others. For example, it appears that the channel narrowed very 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.

6. Discussion

The results presented here indicate that the annual hydrograph of the upper Colorado River has been modified significantly in the last 40 years because of reservoir operations. To the extent that we can determine, sediment from unregulated tributaries downstream of the reservoirs has continued to enter the main stem Colorado River more or less as it has in the past, but since high flows are now regulated, the river has lost some of its capacity to carry this sediment. As a result, there has been a general tendency for sediment to built up in the channel, causing it to become narrower and less complex overall.

These hydrologic and geomorphic changes have likely had some adverse impacts on the native fish community of the upper Colorado River. In particular, it appears that the reaches near Grand Junction that support the largest population of adult squawfish are less heterogeneous now than they were before. Furthermore, it seems likely that the quality of certain habitats was affected by sustained periods of low flow. We showed that there was a period from the late 1950s through the 1970s when peak discharges and annual sediment loads of the upper Colorado River were much lower than the long-term average. Mass balance considerations lead us to believe that a substantial amount of sediment would have been deposited in the channel then and that this would have affected the quality of various habitats, especially spawning bars. It also appears that flows capable of moving gravel and flushing fine sediment from the bed were much less frequent during this time. Add to this the impact of predation by nonnative 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. Thus, even if there is a reasonable amount of spawning-bar and backwater habitat still available in the upper Colorado River, and even if these habitats have been improved by recent high flows (Pitlick and Van Steeter, this issue), the population of Colorado squawfish may be too small at present to take advantage of improvements in environmental conditions.

Although the upper Colorado River has responded in a familiar way to changes in discharge and sediment load [*Schumm*, 1969; *Williams and Wolman*, 1984; *Collier et al.*, 1996], our results show that the channel has evolved to its present condition in a complex way. It appears that the channel narrowed rapidly during the late 1950s and 1960s when high discharges were much less frequent. The effects of low discharges were somewhat reversed by very large floods in 1983 and 1984. These floods caused extensive geomorphic changes and restored some of the preexisting channel complexity, but it is not clear that they benefited the endangered species in other ways [*Stanford*, 1994]. However, it is clear that without these events further simplification and channel narrowing would have occurred.

Finally, although this study was designed to address specific questions regarding changes in fish habitat, there are some parallels between our work and other studies of the geomorphic response to river regulation. Most relevant to our work is

Andrews' [1986] study of the effects of Flaming Gorge Reservoir on the Green River in Utah. *Andrews* [1986] found that mean annual discharges of the Green River had not changed appreciably since the construction of Flaming Gorge Dam, but the hydrograph had been altered considerably and sediment loads had decreased. From 1962 to 1985 the mean annual sediment load of the Green River decreased by 54% at Jensen, Utah, 168 km downstream from the reservoir, and by 48% at Green River, Utah, 460 km downstream from the reservoir. We observed similar decreases in sediment loads over roughly the same time period and the same distance. The interesting point here is that the construction of many reservoirs over a period of several decades has had essentially the same effect on the Colorado River and Gunnison River as a single reservoir has had on the Green River.

7. Summary and Conclusions

Given that there are 20-plus reservoirs and almost as many diversions in the upper Colorado River basin, it should not be surprising that water resource developments have affected the natural flow and sediment-transport regimes of the river. The questions we have attempted to answer in this paper are not if, but, By how much have flows and sediment loads of the upper Colorado River changed? and How have these changes affected habitats used by endangered fish?

Our analysis of streamflow records indicates that peak and mean annual discharges of unregulated tributaries of the upper Colorado River have not changed significantly since about 1930. Peak discharges on regulated portions of the upper 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 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%. The latter two examples are most relevant to our work because they record the changes in the input of water and sediment to the reaches that are critical habitat for the Colorado squawfish.

The total volume of runoff delivered annually to reaches of the Colorado River near Grand Junction has not changed significantly over the period of water resource development, but there are clear differences now in the way that runoff is distributed over the year. Composite annual hydrographs constructed for the last few decades show that spring snowmelt flows are typically much lower and recede quicker now than before and that winter base flows are higher than before.

Another possible factor that may have influenced squawfish populations is the change in sediment loads that occurred in the period from 1964 to 1978 when high flows were much less frequent than they were before or have been since. We estimated that from 1964 to 1978 the average annual suspended load of the Colorado River near Cameo was at least 40% lower than the long-term average. During this same time period, the average annual suspended load of the Gunnison River near Grand Junction was at least 50% lower than the long-term average.

Our analysis of changes in bed elevations at USGS gauging stations on the Colorado River and Gunnison River suggests that 0.5–1.0 m of localized scour or fill is possible over a 40-year period. However, we do not believe that scour or fill are pervasive in our study reaches because we do not see evidence of widespread degradation or aggradation. If the bed was generally aggrading, we would expect to see an increase in channel braiding, when in fact it appears that just the opposite has occurred. The results of our photogrammetric analyses show that there has been a disproportionate decrease in the area of side channels and backwaters relative to the main channel. This indicates that the main channel and associated features (islands and side channels) have not simply decreased in size, but that the river has also become less complex. It remains to be seen whether a 10% or 15% reduction in main channel width or a 25% reduction in side channel and backwater area represents a critical loss of habitat, but the results presented in the accompanying paper indicate that it is difficult to restore habitats through natural processes once they are lost.

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