Changes in Morphology and Endangered Fish Habitat of the Colorado River

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ABSTRACT

The present study investigates changes in channel morphology and potential losses of fish habitat in reaches of the Colorado River near Grand Junction, Colorado. We have used aerial photographs, discharge records, and field studies to evaluate the significance of historical changes in flow regime and the effects of more recent flow events. Our analysis of aerial photographs indicates there have been measurable decreases in the amount of backwater habitat, although this varies with the specific time period. A preliminary analysis of peak flow data from several gaging stations in the region indicates that in the last 30 years there has been a 19% decrease in the average peak discharge of the Colorado River in the study area. This coincides with the time when most of the major reservoirs in the upper basin were constructed. Peak flows on unregulated tributary streams have remained stationary over the last 60 years. Field studies conducted in 1993 during a period of higher than average runoff reveal minor changes in channel morphology. Results from flow modeling are consistent with this observation: model results indicate that the peak flow in 1993 was just sufficient to cause significant movement of cobble and gravel bed material.

INTRODUCTION

There are currently four species of fish in the upper Colorado River which are listed as endangered. These fish are the bonytail chub, the humpback chub, the Colorado squawfish, and the razorback sucker. The latter two species were once plentiful in the reaches of the Colorado River near Grand Junction, Colorado. Several factors appear to have contributed to the decline of these fish, including competition with non-native species, deterioration in water quality, and a loss of habitat due to river channelization and flow regulation. The present study focuses on the issue of habitat loss. Biologists have suggested that *backwaters* are an important habitat for these fish (Tyus and Karp, 1989), and that these habitats have been lost over time because of changes in the flow regime of the Colorado River (Osmundson and Kaeding, 1991; Kaeding and Osmundson, 1989). It is reasonable to assume that a reduction in peak flows will result in changes in channel morphology (Andrews, 1986; Williams and Wolman, 1984; Schumm, 1969), and thus, the U.S. Fish and Wildlife Service has recommended that more water be released from upstream reservoirs to improve in-channel habitat and enhance the recovery of these fish (Osmundson and Kaeding, 1991). However, it is not clear exactly how high these flows should be or how long they should last. The present study was undertaken to determine the extent of historical changes in riverine habitat and to improve our understanding of the processes of habitat formation.

Specifically, the objectives of this study were to:

(1) quantify historic changes in the morphology of the Colorado River near Grand Junction, Colorado;

(2) evaluate these changes in light of what is known about the history of water-resource development in the upper basin; and

(3) examine the processes of in-channel habitat formation and evolution.

Surprising little was known about the history of the Colorado River in this area until the present study was begun. And although the issue of habitat loss will remain a complex issue, the present study represents an important first step towards identifying past trends and future prospects for habitat improvement. Objective solutions to these problems are all the more necessary now because demands for water in the Colorado River are high and any attempts to alter the flow regime of the river to improve habitat for endangered fish must be weighed against the needs of various other water users.

STUDY AREA

This study covers approximately 32 miles of the Colorado River near Grand Junction, Colorado (Fig. 1). This segment of the river includes what are commonly referred to as the 15-mile and 18-mile reaches; these reaches are located, respectively, upstream and downstream of the confluence with the Gunnison River (Fig. 1). In this area, the Colorado River alternates between single-thread and multi-thread reaches, suggesting it is very close to a threshold between braiding and meandering. The riverbed is formed by cobble- and gravel-sized sediment while the banks and floodplain are made up mostly of fine sand and silt. In many places, a dense thicket of tamarisk and willow vegetation lines the banks. In other places, particularly in the 15-mile reach, the banks have been artificially modified by levees and rip-rap.

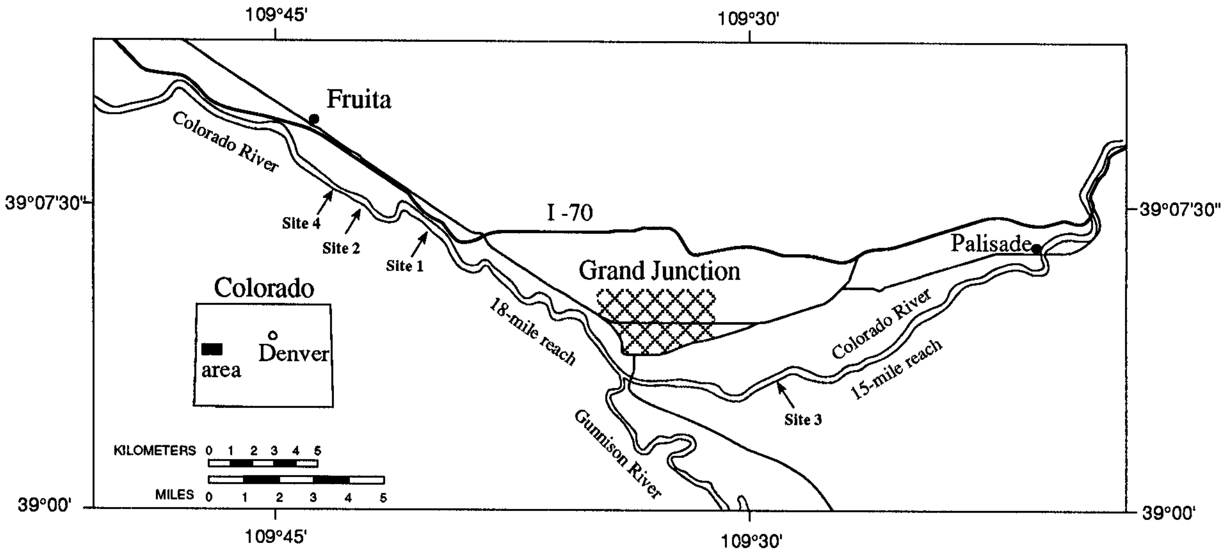


Figure 1. Location map of area encompassed in this study.

The annual discharge of the Colorado River in this area is dominated by a spring snowmelt that usually peaks in late May or early June (Fig. 2). The natural flow regime of the river is affected by storage in upstream reservoirs and by irrigation withdrawals, particularly in the late summer. The USGS operates stream-flow gaging stations on the Colorado River at sites near De Beque (9093700), near Cameo (9095500), and near the Colorado-Utah state line (9163500).

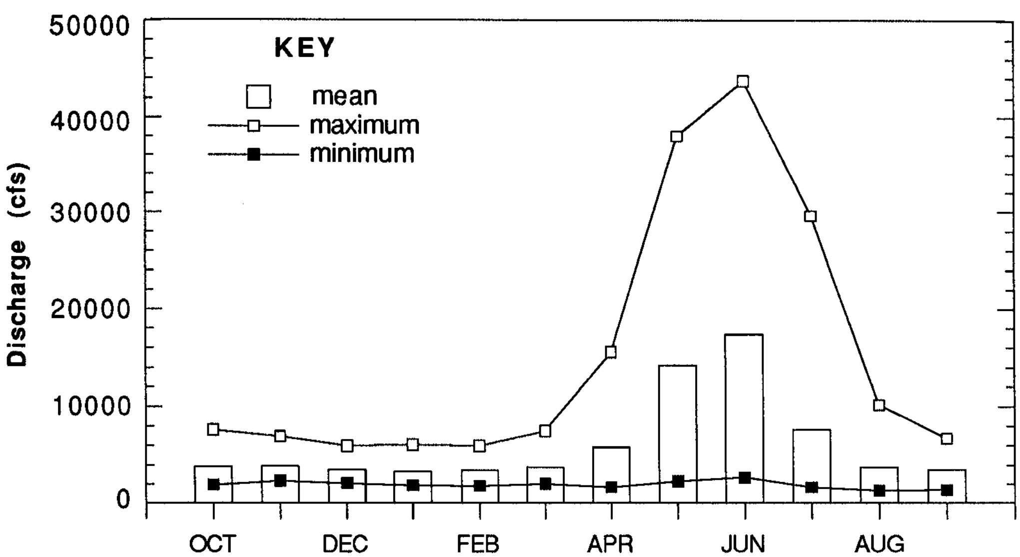


Figure 2. Maximum, minimum and mean monthly discharges for the Colorado River near the Colorado-Utah state line. Data are based on the period of record from 1951 to 1993.

Sediment data have been collected at these gages intermittently. Sediment measurements made at the Cameo gaging station from 1982 to 1984 indicate that the total sediment load of the Colorado River is dominated by suspended sediment (Butler, 1986). In typical years, the rating curve of water discharge versus sediment concentration shows a pronounced hysteresis with concentrations of suspended load being significantly higher on the rising limb of the hydrograph than on the falling limb (Fig. 3). Presumably this trend is related to differences in the sources of water and sediment within the Colorado River basin. In early spring, much of the runoff in the main stem of the Colorado River is derived from lower elevation tributaries that drain erodible shale and sandstone formations. In late spring, more runoff is derived from higher elevation tributaries that drain the resistant crystalline rocks of the Front Range and the Sawatch Range.

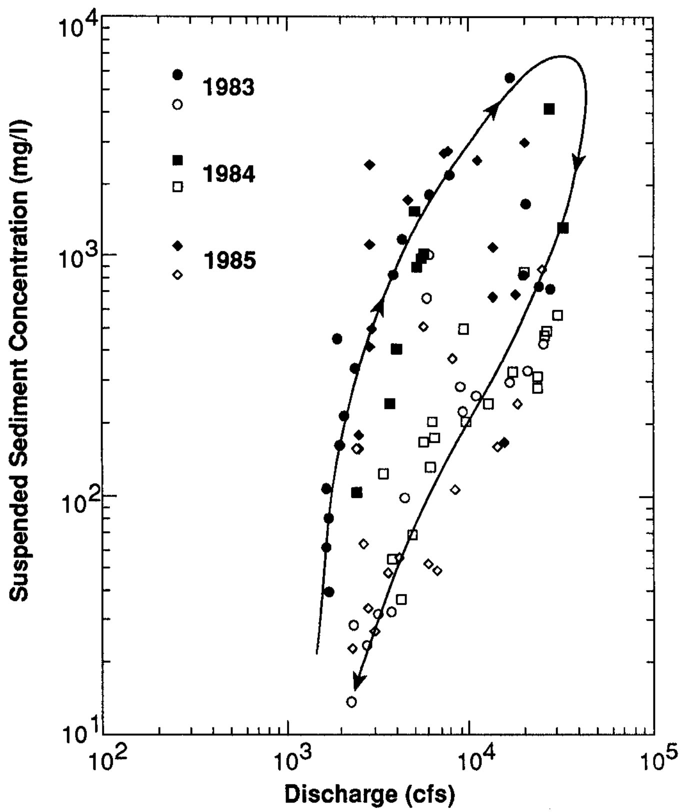


Figure 3. Suspended sediment data and rating curve for the Colorado River near Cameo, CO. Closed symbols indicate measurements taken prior to the annual peak discharge and open symbols indicate measurements taken after the annual peak discharge.

METHODS

Historical Changes in Channel Morphology

Changes in the morphology of the river channel within the study reaches were analyzed using aerial photographs flown in 1937, 1954, 1968, and 1986. The photographs are similar in scale (1:20,000 to 1:24,000) but they were taken at different times of the year and thus the river discharge varies. The 1937 and 1986 photographs were taken with the river flowing at a moderate discharge; respective discharges at the Cameo gage were 7,400 and 6,900 cfs. The 1954 and 1968 photographs were taken with the river at low flow; respective discharges at the Cameo gage were 1,900 and 2,100 cfs. The outlines of specific features such as channel banks, islands, emergent bars, and side channels were digitized on the photographs using a computer aided design system (ACAD). Figure 4 shows an example of how these features were differentiated.

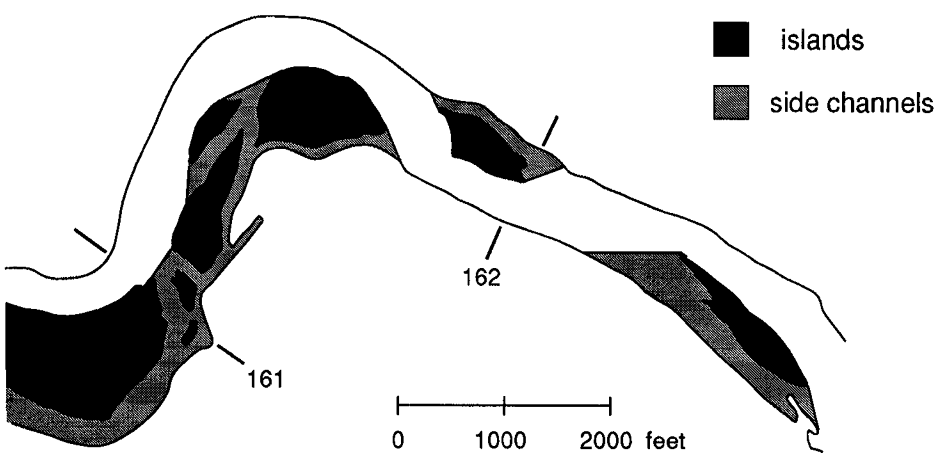


Figure 4. Differentiation of channel features.

The different sets of photographs were adjusted to a common scale by first finding four or five common points on each photograph and on a USGS 1:24,000 topographic map; these points were typically road intersections. The UTM coordinates of these points were then determined from the topographic map. The ACAD files were exported to ARC INFO, a vector-based Geographic Information System (GIS). Subroutines within ARC INFO were used to calculate the area of the main channel, islands and side channels and to compare changes over time. Our estimates of error are ± 2% for the water and island areas and ± 10% for the side channel areas.

Evaluation of Flow Records

Streamflow data were obtained from USGS Water Supply Papers and from a commercially available CD-ROM and software package that contains peak- and daily-flow data from the USGS WATSTORE files. These data were used to quantify changes in flow regime due to reservoir regulation and water withdrawals. We have made no attempt at this point to evaluate the quality of these records, particularly the peak flow data from early in the century. We raise this point because it appears that peak flows on the Colorado River were anomalously high in the early 1900s (Graf, 1985) and because other researchers have questioned estimates of peak discharge made early in the century on streams elsewhere in Colorado (Jarrett et al., 1993). In any event, it was not until the middle of this century that water development in the upper basin began to have much of an effect on streamflows of the upper Colorado River (Liebermann et al., 1989), and thus our analysis focuses on the changes in flow regime that occurred after 1930.

Field Studies

Field measurements were made at four sites in spring and summer 1993; three of these sites were chosen to study changes in backwater habitats (Sites 1-3, Fig. 1) and the fourth site (Site 4, Fig. 1) was chosen to evaluate thresholds for bed-material transport. The backwater study sites are all formed by a lateral bar or island that forces flow down a side channel. These side channels are in all cases much smaller than the main channel. Field work at these sites consisted of repeated topographic surveys to determine the extent of erosion and deposition in the side channels. A series of cross-sections were established across each of the channels prior to the 1993 spring runoff, and they were surveyed subsequently throughout the summer. Measurements of the bed material substrate were also made at each site.

The site chosen for studying bed-material transport is located in a single thread alluvial reach of the Colorado River near Fruita (Site 4, Fig. 1). In this reach, the river has an average slope of 0.0015 and the bed material consists of cobbles and gravel. Survey measurements of channel cross sections and water surface slopes were taken through the reach at several different flows in the summer of 1993. These data were subsequently used to calibrate and run a standard 1-dimensional flow model (the step-backwater method; Henderson, 1966) to calculate changes in the average boundary shear stress (τ) over a range of discharge. The critical shear stress (τ_c) for the bed material was determined from the Shields' parameter:

$$\tau^*_{c_i} = \frac{\tau_c}{(\rho_s - \rho)\, g\, D_i} \tag{1}$$

where $\tau^*_{c_i}$ is the critical dimensionless shear stress, ρ_s and ρ are the density of sediment and water, respectively, g is the gravitational acceleration, and D_i is the particle size. For this analysis, we used D_{50} as the representative grain size and chose $\tau^*_{c_{50}} = 0.03$ as the criterion for incipient motion. At this level of τ^*, most of the particles on the stream bed are immobile, and it is the sporadic movement of a few individual particles that produces low but measurable bed load transport (Parker et al., 1982). Andrews (1994) refers to this condition as "marginal transport". With an increase in shear stress, more of the bed becomes mobile, until at $\tau^*_{c_{50}} = 0.06$, many particles are in transport, and there is "significant motion" of the bed material (Andrews, 1994; Wilcock and Southard, 1989). We believe this condition is most relevant to the problem of maintaining fish habitat. The result of our hydraulic analysis is a relation that shows how the average boundary shear stress changes with discharge. We are interested in defining not only the discharge required for incipient motion ($\tau/\tau_c = 1$), but also the discharge required to produce general motion ($\tau/\tau_c = 2$) of the bed material.

RESULTS

Historical Changes in Channel Morphology

Our analysis of the 1937 and 1986 aerial photographs showed that overall there was a negligible (+ 1%) change in the area of the main channel, but a 20% decrease in the area of islands and an 18% decrease in the area of side channels and backwaters (Table 1). However, these changes were not uniform throughout the entire 32 mile reach. Figure 5 shows that although the area of side channels and backwaters on average decreased between 1937 and 1986, there were many reaches where side-channel area increased. Some of these reaches include sections of the river that were changed dramatically in 1983 and 1984 when high flows flooded abandoned gravel pits. Thus, the 1937-1986 comparison reflects both episodic changes due to recent high flow events as well as long-term and potentially systematic changes in channel morphology.

The analysis and comparison of the 1954 and 1968 aerial photographs produced results similar those described above. For the 1954-1968 time period, there was a 12% decrease in the area of the main channel, a 16% decrease in the area of islands, and a 27% decrease in the area of side channels and backwaters (Table 2). Compared to results for the 1937-1986 time period, results for the 1954-1968 time period indicate that nearly all of the 32 reaches experienced a reduction in main channel area and side channel/backwater area (Fig. 6). These results provide perhaps a clearer answer to the question of whether reductions in peak discharge have caused significant changes in channel morphology because they are not complicated by the effects of high flows (as in the earlier analysis, which includes changes resulting from the 1983 and 1984 floods). From 1954 to 1968, the mean annual flood was exceeded at the Cameo gage a total of 5 times, and then only twice in the last 10 years of the period. This would suggest that when peak flows are lower than average, i.e. when droughts occur several years in succession, the channel will become narrower and there will be a loss of side channel and backwater habitat. We note however that changes in channel morphology were not always systematic nor were they permanent; some places within the study reach showed significant change in the absence of high flows, and other places showed no discernible change even after very high flows.

Table 1. Changes in instream water area, island area, and side channel/backwater area, 1937-86.

Mile	Instream Water Area (10^3 ft^2) 1986	Instream Water Area (10^3 ft^2) 1937	Island Area (10^3 ft^2) 1986	Island Area (10^3 ft^2) 1937	Side Channel Area (10^3 ft^2) 1986	Side Channel Area (10^3 ft^2) 1937
184	1,474	1,894	32	280	32	172
183	2,174	1,926	506	979	527	172
182	1,592	1,797	0	409	0	161
181	1,948	1,722	161	247	22	97
180	1,560	2,582	0	7,252	0	1,044
179	2,260	2,475	560	1,237	323	893
178	1,625	1,905	129	54	9	108
177	1,216	1,496	0	43	8	6
176	1,991	2,776	1,119	2,152	204	872
175	2,550	2,668	1,485	1,937	936	968
174	2,905	1,894	1,270	161	1,205	355
173	1,496	1,840	32	151	75	140
172	1,474	1,571	3	8	0	22
171	2,184	2,486	1,636	1,840	527	807
170	3,131	3,228	1,162	1,399	377	646
169	2,873	3,153	1,377	1,614	581	1,022
168	3,594	2,948	1,517	1,829	1,603	807
167	3,067	2,335	161	527	301	301
166	2,851	2,443	226	129	129	237
165	3,013	2,776	603	1,765	603	850
164	2,496	2,464	452	1,905	581	915
163	5,165	2,486	1,668	161	861	237
162	2,679	2,959	603	366	549	721
161	3,389	2,851	5,294	1,237	1,517	699
160	2,346	2,948	1,108	2,303	646	1,388
159	3,056	3,174	1,453	2,055	829	1,194
158	3,400	2,529	334	269	1,108	247
157	2,539	2,572	75	732	269	581
156	2,087	2,001	43	75	43	118
155	3,400	4,239	3,034	2,012	1,022	1,646
154	3,228	4,035	8,016	7,779	1,194	2,130
153	2,410	2,260	172	0	86	65
Total:	81,173	80,433	34,231	42,907	16,167	19,621
Percent Change:	**+ 1%**		**-20%**		**-18%**	

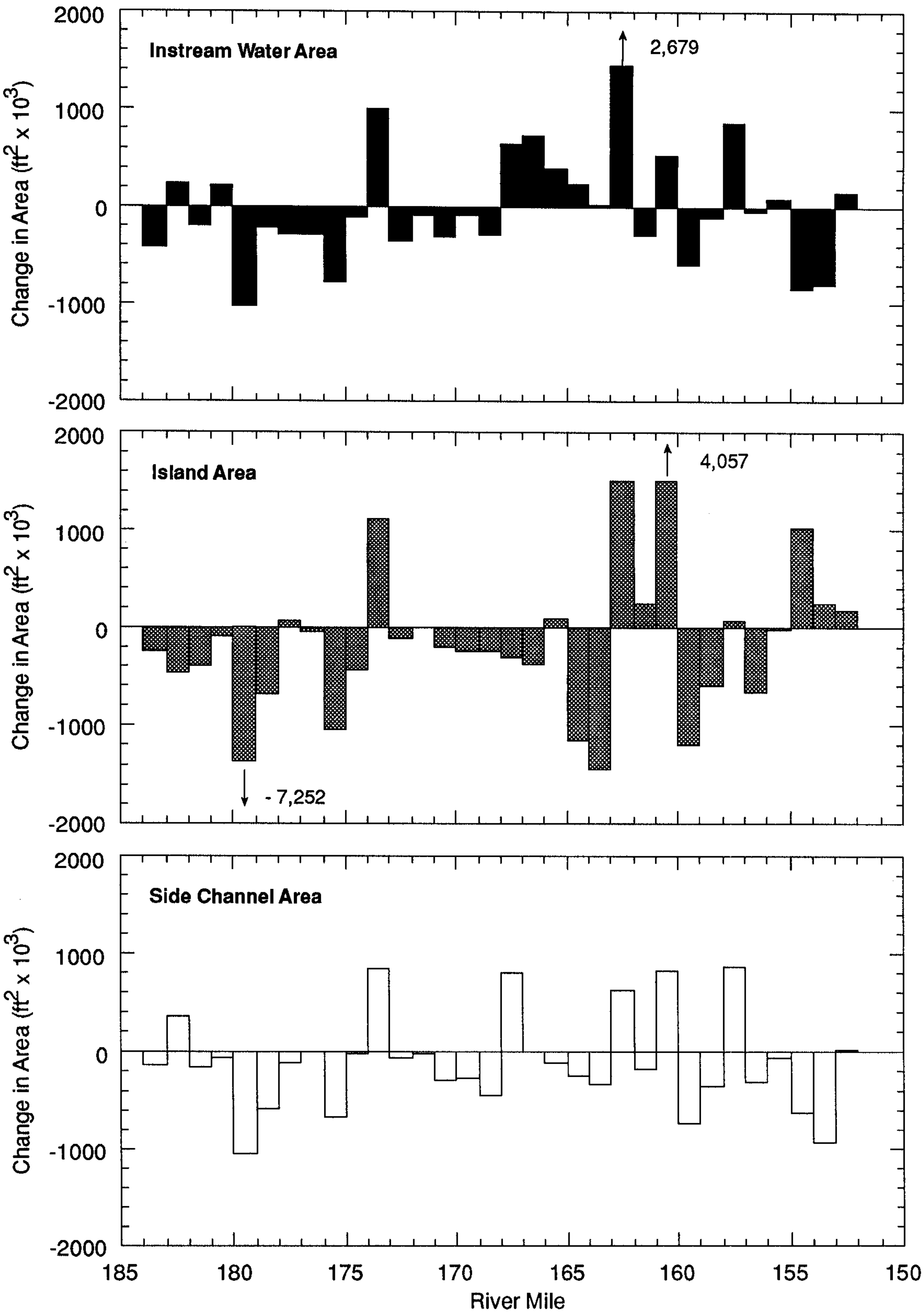


Figure 5. Mile-by-mile summary of changes in specific channel features, 1937-86.

Table 2. Changes in instream water area, island area, and side channel/backwater area, 1954-68.

Mile	Instream Water Area (10^3 ft^2) 1968	Instream Water Area (10^3 ft^2) 1954	Island Area (10^3 ft^2) 1968	Island Area (10^3 ft^2) 1954	Side Channel Area (10^3 ft^2) 1968	Side Channel Area (10^3 ft^2) 1954
184	1,130	1,410	97	140	54	204
183	979	1,130	194	194	161	118
182	1,205	1,356	0	0	0	1
181	1,173	1,270	43	11	75	43
180	1,011	1,162	0	11	0	22
179	872	1,345	65	1,453	118	484
178	1,313	1,334	194	441	344	280
177	1,098	1,022	65	22	54	54
176	1,345	1,958	1,743	1,991	549	850
175	1,377	2,012	1,937	2,292	495	979
174	947	1,205	140	323	75	280
173	829	1,463	0	506	22	344
172	1,184	1,280	0	32	22	22
171	1,313	1,743	86	1,840	194	581
170	2,034	2,668	1,485	1,517	129	140
169	1,926	2,798	2,410	1,775	925	1,280
168	1,646	1,915	215	86	280	118
167	2,066	1,958	226	151	204	161
166	1,431	1,980	65	452	161	387
165	1,894	1,700	22	0	161	32
164	1,614	1,399	140	22	161	43
163	2,260	2,421	635	603	581	603
162	2,152	2,066	796	699	441	603
161	2,130	2,249	549	603	516	807
160	2,238	2,281	2,001	1,937	796	861
159	1,851	1,969	377	581	516	592
158	1,775	2,055	420	409	280	323
157	1,603	1,894	65	1,022	86	409
156	1,969	1,765	54	22	140	75
155	2,184	2,077	3,669	3,927	1,054	1,011
154	2,130	2,443	8,404	8,683	958	1,291
153	1,388	1,851	0	247	22	65
Total:	50,067	57,179	26,097	31,992	9,574	13,063
Percent Change:	**-12%**		**-16%**		**-27%**	

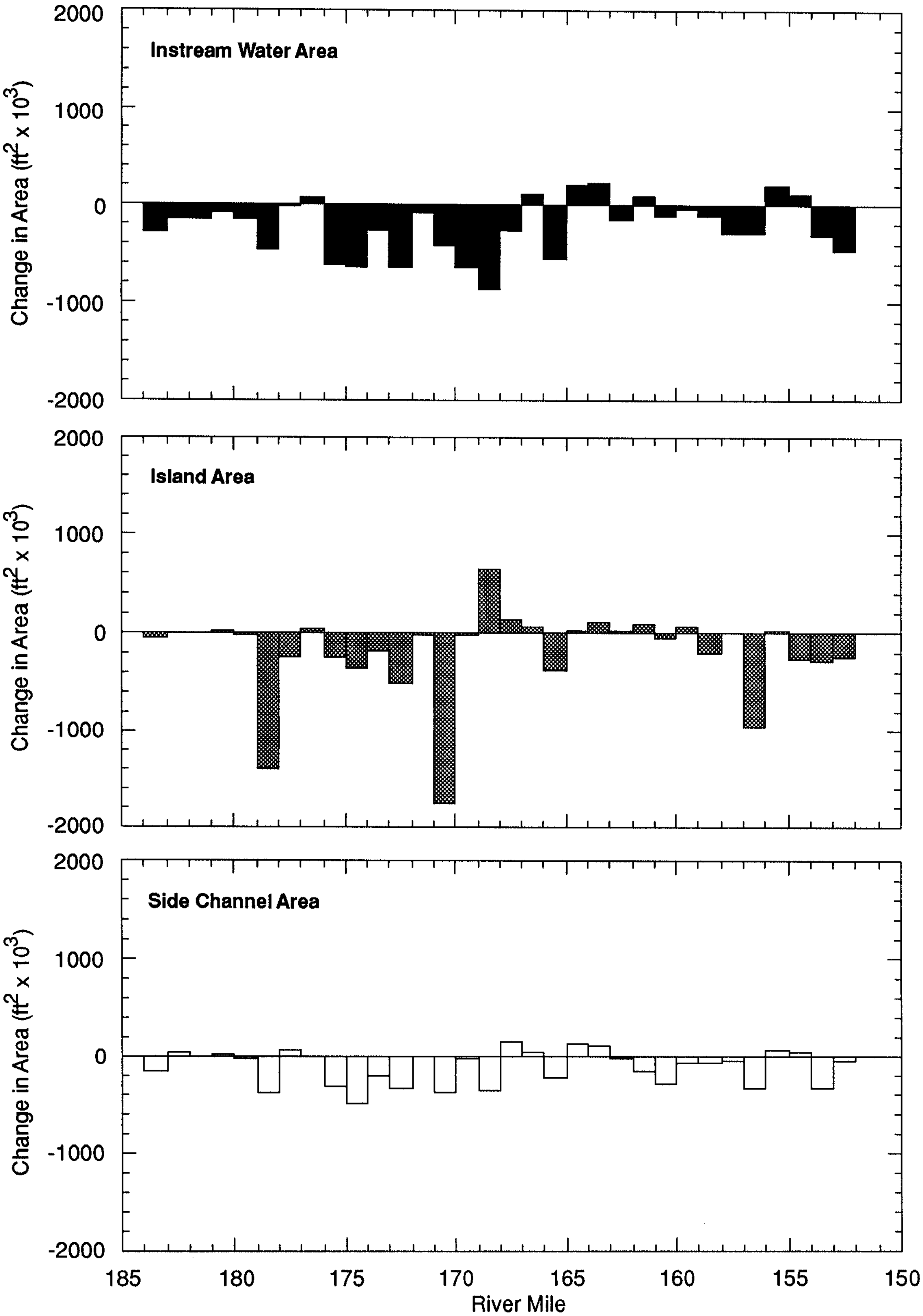


Figure 6. Mile-by-mile summary of changes in specific channel features, 1954-68.

Evaluation of Flow Records

We have not yet completed a full analysis of the effects of transbasin diversions and reservoir regulation on the flow regime of the upper Colorado River. However, it is possible using data presented by Liebermann et al. (1989) and compilation of data from selected gaging stations to make some preliminary conclusions about the impacts of water resource development.

Liebermann et al. (1989) summarize pertinent information on diversions and reservoirs that affect flow in the upper Colorado River basin. Their report includes a listing of all the major diversions and reservoirs, including when they were emplaced and estimates of the amount of water exported annually, or for reservoirs, the normal operating capacity. Figure 7 shows that there was very little water exported from the Colorado River basin until about 1950; after this, there was a sharp increase in transbasin diversions (these data are for the Colorado River above Lees Ferry, AZ). Compared to peak discharges, however, the amount of water diverted at present is small. For example, in May 1993, exports through the Alva B. Adams tunnel, the largest diversion in the basin, amounted to less than 3% of the discharge at Cameo. Thus, we feel that transbasin diversions have probably had much less of an effect on peak flows than reservoirs.

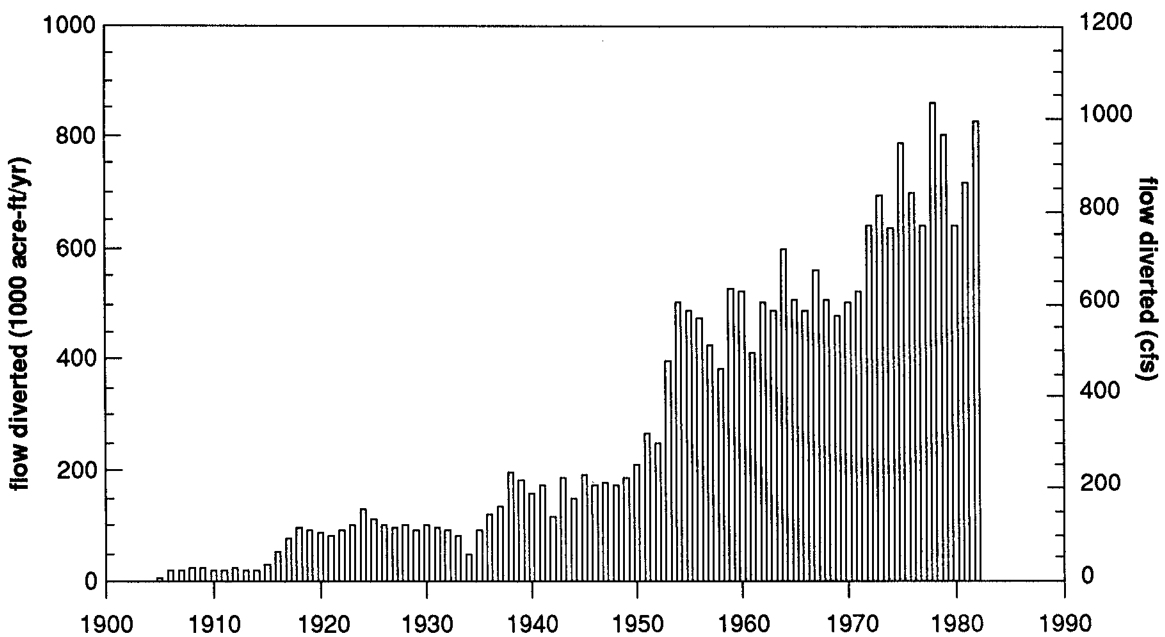
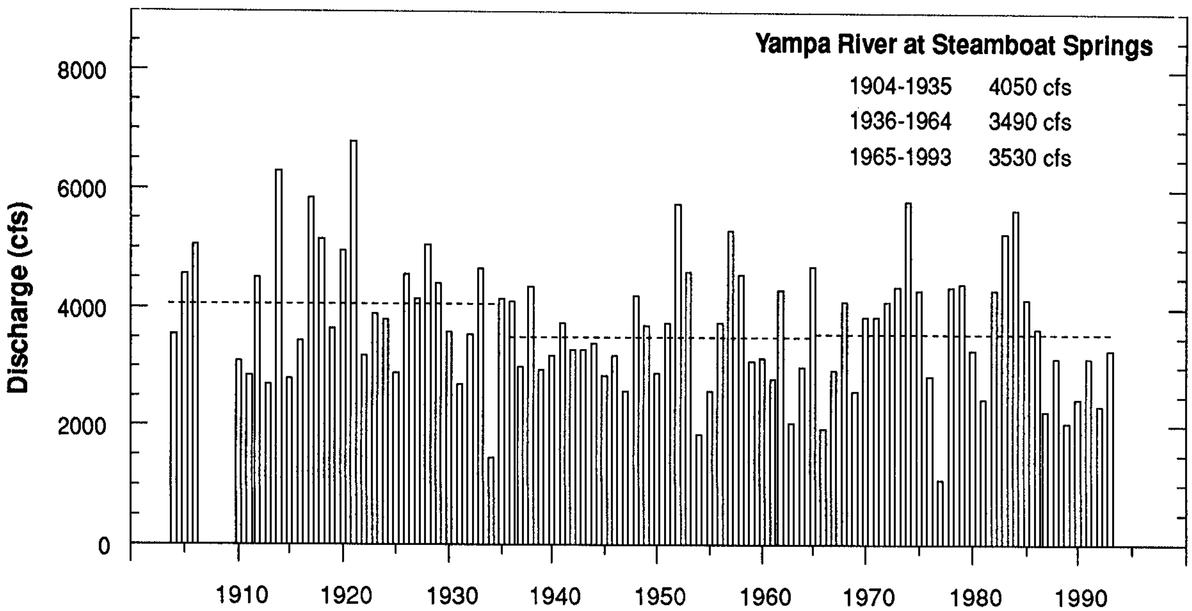


Figure 7. Annual export of water from the upper Colorado River basin above Lee's Ferry, Arizona (data from Liebermann et al., 1989).

A separate problem that somewhat complicates our hydrologic analysis is the observation that peak flows of the Colorado River were much higher early in this century than on average (Graf, 1985; Stockton and Jacoby, 1976). This is quite evident when looking at the long-term records from several gaging stations in the region (Fig. 8). For example, peak flows of the Yampa River at Steamboat Springs averaged 4050 cfs from 1904 to 1935. From 1936 to 1993, the average peak discharge was much less, about 3500 cfs. Peak flows of the Yampa River at Steamboat Springs have been affected very little by regulation, so the decrease in average peak discharge must be largely the result of a return to conditions of lower precipitation and runoff. Peak flow data from the East River at Almont, an unregulated tributary of the Gunnison River, are less complete, but they show very similar trends of higher-than-average flows early in the century followed by an essentially stationary average for the last 60 years (Fig. 8).

The early-century period of anomalously high flows is also seen in the long-term record of peak discharge of the Colorado River near Glenwood Springs (Fig. 9). From 1900 to 1930, the peak discharge at Glenwood Springs averaged about 20,000 cfs. Although there were several transbasin diversions in the upper basin at this time, these would have had little effect on peak flows. From 1931 to 1961, the peak discharge averaged only 13,400 cfs; some of the decrease in peak discharge in this time period is related to the construction of reservoirs in the upper basin but some of the decrease is undoubtedly the result of a shift toward conditions of lower precipitation and runoff. The more recent part of the record shows that peak flows on the main stem of the Colorado River have continued to decrease (Fig. 9). From 1962 to 1993, the average peak discharge of the Colorado River at Glenwood Springs was 9,700 cfs; compared to the previous 30-yr period, this represent a 28% decrease in average annual peak discharge. For roughly the same time period (1965 to 1993), the average peak discharge of the Colorado River at Cameo (located in De Beque Canyon, just upstream of the 15-mile reach) decreased by 19% (Fig. 9). These data indicate rather clearly that reservoirs constructed in the last 30 years have had significant impacts on the natural flow regime of the Colorado River.



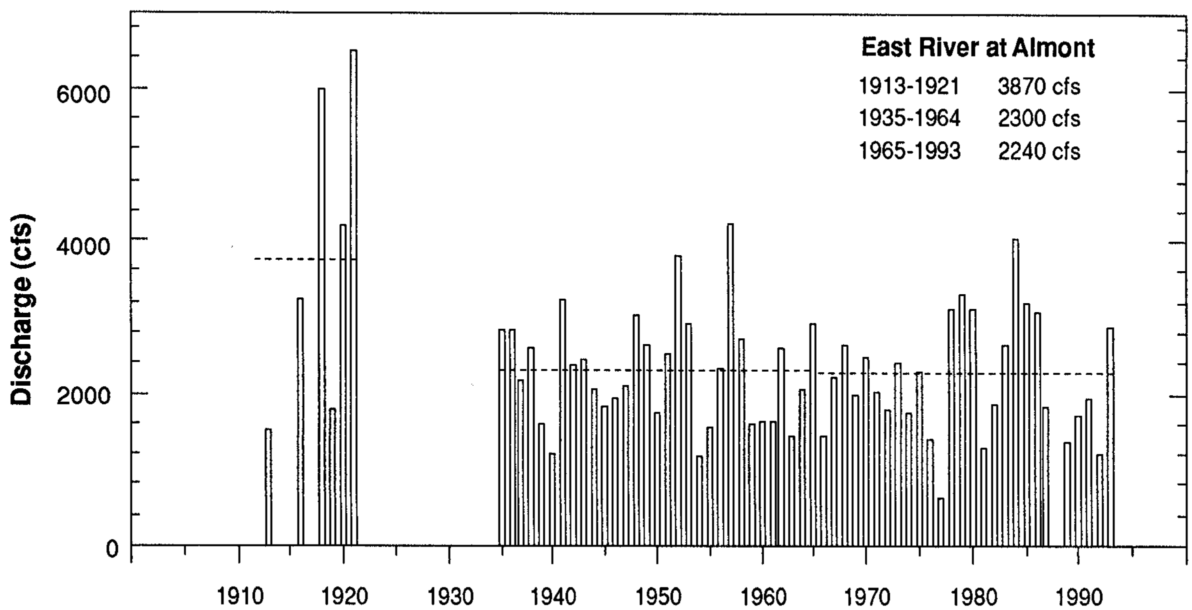


Figure 8. Annual peak discharge for 2 streams in the headwaters of the upper Colorado River.

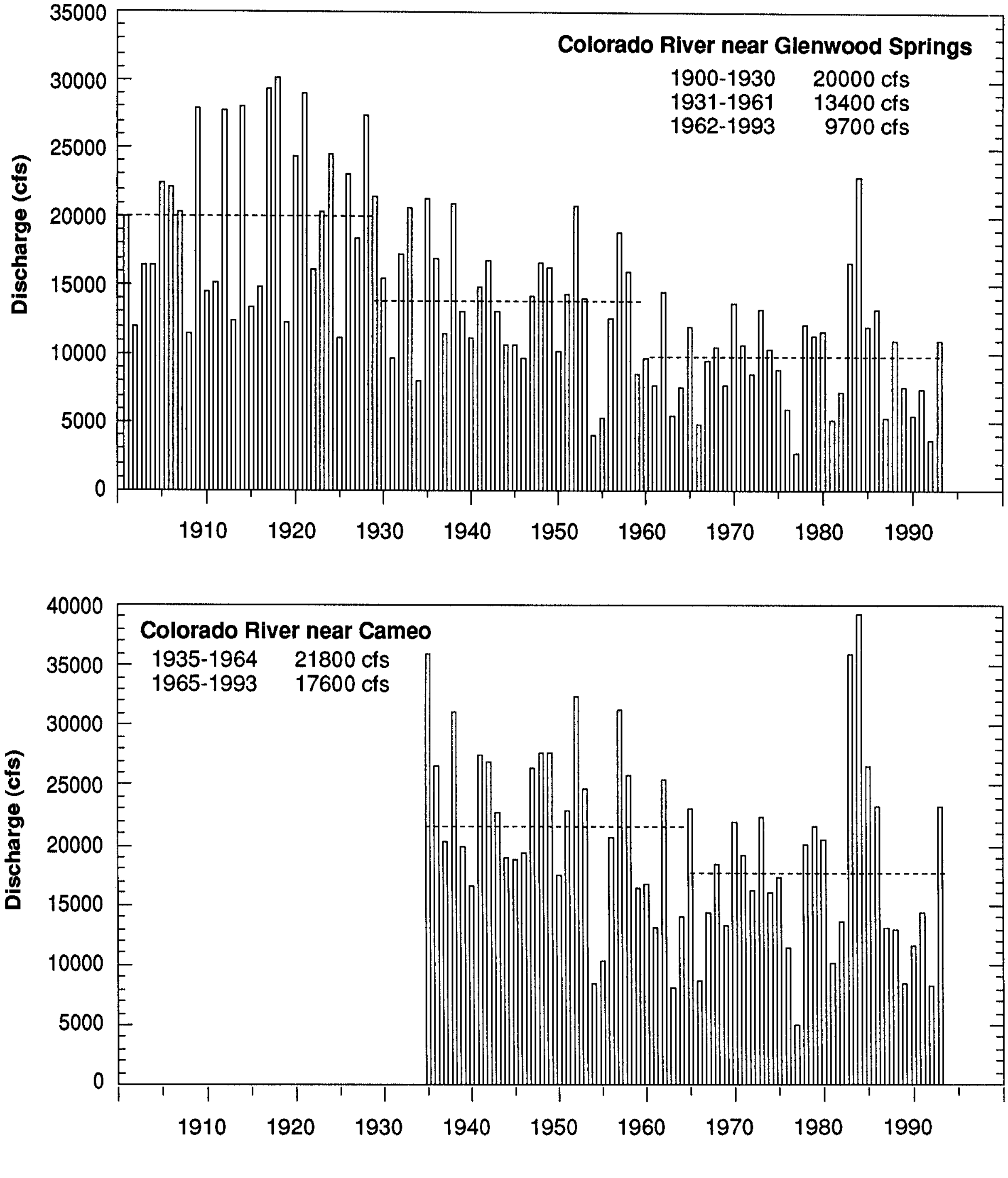


Figure 9. Annual peak discharges on the main stem of the upper Colorado River.

Field Studies

The volume and peak discharge of runoff in the upper Colorado River were higher in 1993 than they have been in almost a decade. The peak discharge of the Colorado River at the Colorado-Utah state line gage was 44,300 cfs (Fig. 10). This discharge ranks as the 6th highest in 43 years of record and corresponds to an 8-year flood on the annual series. Equally significant was the fact that these high flows persisted for some time: the mean annual flood of 27,700 cfs was exceeded for 22 days and the mean annual flow of 6,200 cfs was exceeded for 126 days.

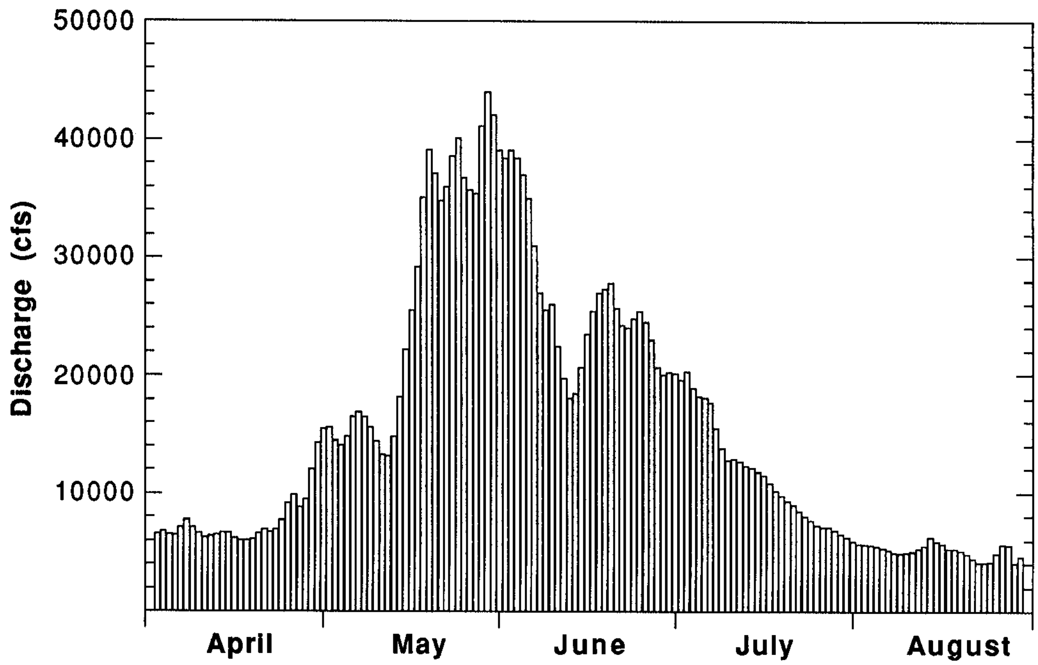
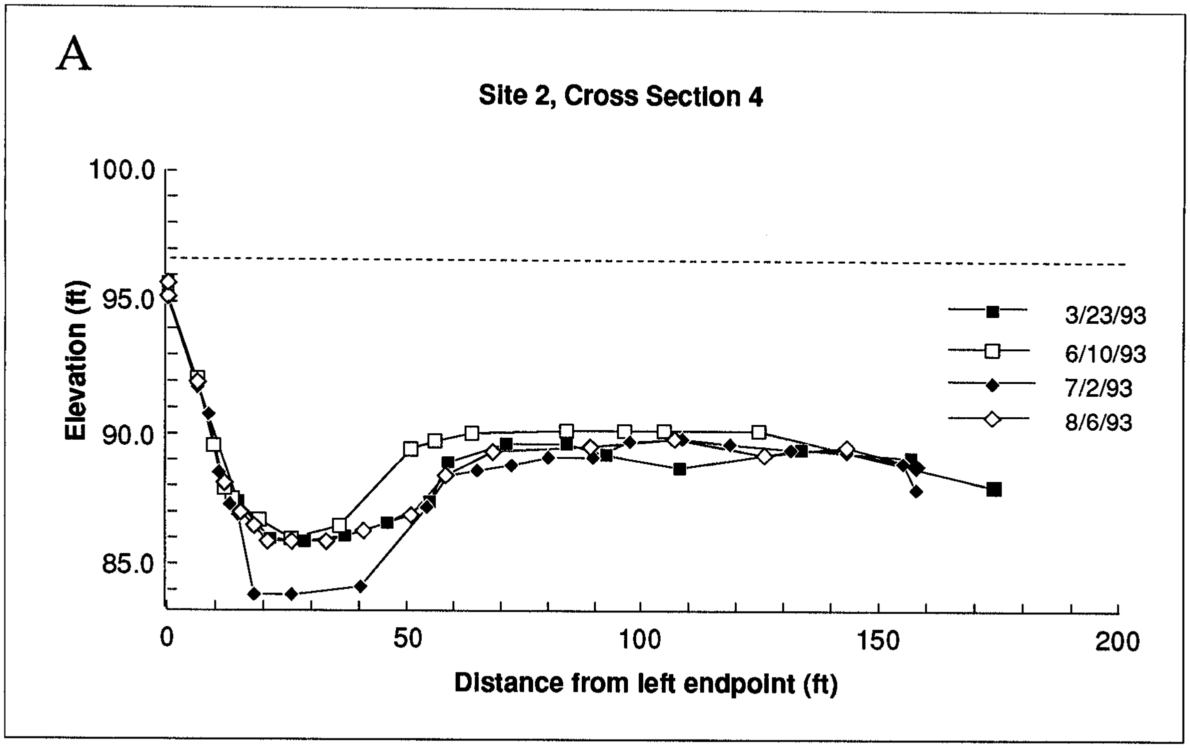


Figure 10. Mean daily discharge of the Colorado River near the Colorado-Utah state line during the 1993 snowmelt runoff period.

Although runoff in 1993 was well above average, we did not observe widespread changes in channel morphology in either the 15-mile reach or the 18-mile reach. Field measurements at the 3 backwater study sites indicate that fine sediment (silt) was scoured from the mouths of the side channels and there was some movement of coarse bed material, both in side channels and in the main channel. Figure 11-A shows the left-bank portion of a main channel cross section that spans



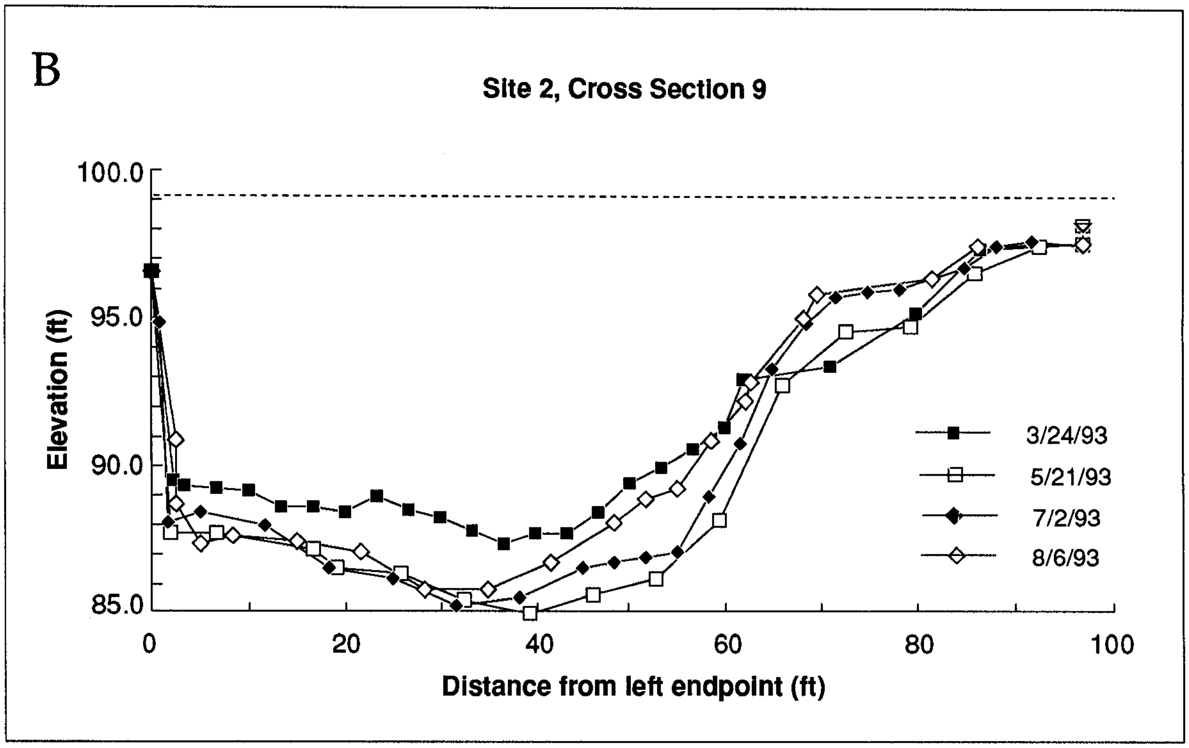


Figure 11. Cross sections spanning a side channel in the 18 mile reach; (A) shows a cross section at the entrance of the side channel; (B) shows a cross section at the mouth of the side channel. Dashed line indicates high water during snowmelt runoff in 1993

a lateral bar and the side channel at Site 2 in the 18-mile reach. At peak discharge, flow in the main channel was about 10 ft deep. The bed material at this particular cross section consists of cobbles. These measurements indicate that there was some scour (< 2 ft) of the coarse bed material, but by the end of the summer (8/6), the channel had ref-filled and changes overall were not pronounced. Figure 11-B shows a cross section spanning the lower portion of the same side channel. At the time of our first survey in March, 1993, the bed was covered with silt. Subsequent high flows scoured 2 to 3 ft of silt to expose a cobble bed. As much as 3 ft of silt was deposited on the channel banks (Fig. 11-B). We noted this in many other places, and also observed that tamarisk and willow seedlings became established on these silty deposits very quickly.

Our analyses of changes in boundary shear stress and thresholds for sediment motion were done for a single-thread reach about 0.5 mi downstream from the site discussed above. Results from 3 model runs with different discharges are summarized in Table 3. A plot of the ratio of average boundary shear stress to critical shear stress (τ/τ_c or transport stage) versus discharge indicates the threshold for transport of D_{50}, corresponding to $\tau/\tau_c = 1.0$, occurs at a discharge of 20,000 ft^3/s (Fig. 12). This discharge is about 3.5 times the mean annual flow, and equivalent to a 1.67-year flood. Significant motion of bed material, corresponding to $\tau/\tau_c = 2.0$, occurs at a discharge of 41,000 ft^3/s. This discharge is at least a 5-year flood. Thus, at this particular site, discharges well in excess of the mean annual flow are required to initiate motion of the bed material, and discharges approaching the bankfull condition are required for complete mobility.

Table 3. Summary of results from flow modeling

discharge (cfs)	depth (ft)	velocity (fps)	Manning's n	friction slope, S_f	τ^*
5,820	3.64	4.36	0.029	0.0017	0.021
27,000	8.10	7.00	0.028	0.0011	0.036
42,400	9.38	9.51	0.028	0.0017	0.064

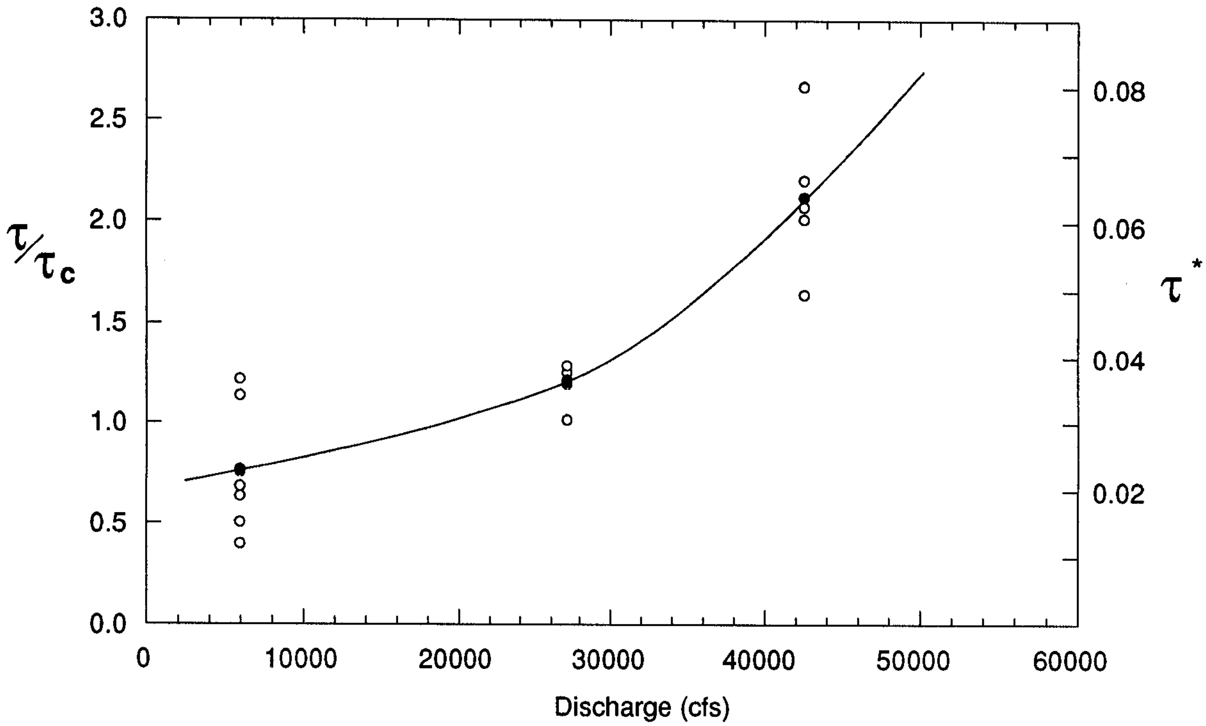


Figure 12. Changes in the ratio of shear stress to critical shear stress with increasing discharge.

We stress that these results are relevant to only one site. Nonetheless, later in the summer, we observed that there had been movement of gravel- and cobble-sized bed material in many other areas. In addition, the amount of fine sediment present in the bed was noticeably less than in previous years. The prevailing thought among biologists is that "clean" substrates are a desired habitat for the endangered fish (Tyus and Karp, 1989). We cannot say whether the high flows in 1993 improved fish habitat because we do not have fish census data indicating whether or not populations increased. However, it was clear on many of the exposed gravel bars that much fine sediment had been winnowed from the bed. Assuming that most of the fine sediment is removed only after the framework particles had begun to move (Kondolf et al., 1987), then the results from this analysis indicate that flows well in excess of the mean annual flow are needed to maintain clean substrates. A goal of future work is to expand this analysis to additional sites to develop more specific criteria for maintaining habitat for endangered fish in the upper Colorado River.

SUMMARY

The results of our study of changes in channel morphology and fish habitat in the upper Colorado River can be summarized as follows:

1. Based on an analysis of two separate sets of aerial photographs, we conclude that there have been measurable changes in the morphology of the Colorado River but these changes have not necessarily been systematic over time. Comparing photographs flown in 1937 and 1986, we observed that there was a negligible (+ 1%) change in the area of the main channel, but a 20% decrease in the area of islands and an 18% decrease in the area of side channels and backwaters. Although the decrease in side-channel area appears to be significant we are not sure at this point how much of the change was a direct result of the record floods that occurred in 1983 and 1984 and how much was systematic over the entire time period. Comparing photographs flown in 1954 and 1968, there was a 12% decrease in the area of the main channel, a 16% decrease in the area of islands, and a 27% decrease in the area of side channels and backwaters. The results of this comparison are perhaps more indicative of what to expect during an extended period of low to moderate annual peak discharge.

2. A preliminary review and analysis of peak flow data from several gaging stations in the upper Colorado River basin indicates there has been a systematic reduction in the average peak discharge, particularly in the last 30 years. This coincides with the time when most of the major reservoirs in the basin were constructed. In comparing the 30-yr periods prior to and after 1965, we note that the average peak discharge of the Colorado River near Cameo has decreased by 19%. Peak flows on unregulated tributary streams have remained stationary over the same 60-yr period.

3. Field studies conducted in the 15- and 18-mile reach during snowmelt runoff in 1993 reveal relatively minor changes in channel morphology even though the 1993 peak flow was the highest in almost a decade. Field measurements at the 3 backwater study sites indicate that a few feet of fine sediment (silt) were scoured from the mouths of the side channels and there was some movement of coarse bed material in side channels and in the main channel. Results derived from modeling flow in a single thread reach indicate the threshold for transport of cobble bed material

(incipient motion) occurs at a discharge of about 20,000 cfs; this discharge is 3 times the mean annual flow. Significant motion of bed material, corresponding to a shear stress of twice the critical shear stress, occurs at a discharge of about 41,000 ft^3/s. This discharge is equivalent to at least a 5-year flood, and during the high flow period in 1993, this discharge was exceeded for 3 days.

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