

**LONGITUDINAL TRENDS IN CHANNEL CHARACTERISTICS OF THE  
COLORADO RIVER AND IMPLICATIONS FOR FOOD-WEB DYNAMICS**

**John Pitlick**

and

**Robert Cress**

Department of Geography  
Box 260  
University of Colorado  
Boulder, CO 80309-0260

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## EXECUTIVE SUMMARY

The Colorado River basin is home to several endangered warm-water fish, including the Colorado pikeminnow (*Ptychocheilus lucius*, formerly known as the Colorado squawfish). Demographic studies of the age and distribution of Colorado pikeminnow in the main stem of the Colorado River upstream of the Green River confluence indicate that juvenile pikeminnow are located primarily in the lower part of their potential range, while adults are located primarily in the upper part of their potential range. This distribution presumably reflects the availability of food resources and riverine habitats. However, outside of the reaches near Grand Junction, CO, not much is known about the influence of physical channel characteristics on the fish community structure of the Colorado River. The work described in this report is part of a 3-part study to determine how lengthwise variations in the physical characteristics of the Colorado River (width, depth, substrate sediment size, water quality, etc.) influence the production and availability of foods used by benthic invertebrates and native fishes. A better understanding of the links between physical and biological processes is necessary for determining effective strategies for species recovery.

The present study encompasses approximately 300 kilometers of the Colorado River in western Colorado and eastern Utah. Field measurements characterizing the geomorphology of this segment of the river were obtained at closely spaced intervals from approximately Rulison, CO, to Potash, UT. These field measurements were augmented with streamflow and sediment data from four US Geological Survey gauging stations to evaluate temporal and spatial trends in suspended sediment loads. Separate sets of 1937 and 1995 aerial photographs of the reach between Rifle and DeBeque were also analyzed to determine the extent of historical changes in channel characteristics. Finally, detailed measurements were made in several short reaches to calibrate a hydraulic flow model, and derive relations for estimating discharges that mobilize the cobble and gravel bed material of the Colorado River.

The results of the photogrammetric analysis of the Rifle-DeBeque reach indicate that the average width of the main channel of the Colorado River has not changed significantly in this reach in the last 60 years. In contrast, the area of islands has decreased by about 20%, while the area of side channels and backwaters has decreased by about 31%. When proportioned over the total reach length of 58 km, the change in side-channel/backwater area amounts to decrease in average width of about 6 m. Comparison of results from this study with results from a previous study (Pitlick et al., 1999) indicates that the total area of side channels and backwaters present in the Rifle-DeBeque reach is roughly the same as the total area of side channels and backwaters lost historically in the 15- and 18-mile reaches near Grand Junction. It is not clear, however, that the potential habitat in the Rifle-DeBeque reach is as suitable in a biological sense as the reaches downstream. A recent analysis of water temperatures presented by Osmundson (1999) suggests that conditions favoring growth of Colorado pikeminnow are less suitable here than in reaches downstream. Nonetheless, it appears that adult pikeminnow would benefit from having access to the Rifle-DeBeque reach, particularly in low-water years when water temperatures are higher.

The analysis of sediment transport measurements indicates that the annual suspended sediment load of the Colorado River increases markedly through the study area. In downstream order, the long-term average annual suspended sediment loads of the Colorado River are:  $0.4 \times 10^6$  tons/yr at Glenwood Springs;  $1.5 \times 10^6$  tons/yr at Cameo;  $3.4 \times 10^6$  tons/yr at the Colorado-Utah state line; and  $5.4 \times 10^6$  tons/yr at Cisco, UT. The available data indicate that there has been no appreciable change in the concentration or the grain size of suspended sediment carried by the Colorado River, however, average annual sediment loads have decreased significantly because the frequency of higher discharges has been reduced by reservoir operations.

The geomorphology of the study reach was characterized using closely spaced measurements of channel gradient, bed material and cross section morphology. These measurements indicate that the characteristics of the Colorado River change systematically downstream, but not in the manner expected from geomorphological studies of other rivers. Specifically, we observe that the grain size of the substrate sediment decreases rather slowly in comparison to the average gradient. This observation contrasts with the common assumption that substrate sediment size and slope are highly correlated. In addition, we observe that the average bankfull depth increases downstream more rapidly than the average bankfull width. Over the 300-km length of the study area, the bankfull depth increases by roughly 100% (doubles) while the bankfull width increases by only about 30%. This result contrasts with results from many other studies showing that the bankfull width of an alluvial river typically increases downstream faster than the bankfull depth.

Thresholds for coarse-sediment transport were estimated on the basis of flow modeling at 10 sites, and measurements of channel characteristics throughout the study area. These results indicate that the framework gravels of the Colorado begin moving at flows somewhere between 35 and 55% of the bankfull discharge; flows higher than this occur on average about 30 days per year. Flows equal to the bankfull discharge are assumed to rework most of the bed material; the frequency of these flows varies from several (5-7) days per year in upper reaches to a few (1-2) days per year in lower reaches. The magnitudes of these threshold flows are shown to be similar when individual reaches are grouped according to the two major tributaries in the area. For the three reaches above the Gunnison River, we estimate that discharges of 211 to 278 m<sup>3</sup>/s (7500-9800 ft<sup>3</sup>/s) will initiate motion, while discharges of 580 to 623 m<sup>3</sup>/s (20,500-22,000 ft<sup>3</sup>/s) will reach the bankfull level; for the reaches between the Gunnison River and the Dolores River, discharges of 497 to 548 m<sup>3</sup>/s (17,500-19,300 ft<sup>3</sup>/s) will initiate motion, and discharges of 979 to 1320 m<sup>3</sup>/s (34,600-46,600 ft<sup>3</sup>/s) will reach the bankfull level; and for the reaches below the Dolores River, initial motion occurs at discharges ranging from 561 to 659 m<sup>3</sup>/s (19,800-23,300 ft<sup>3</sup>/s), and bankfull flow occurs at discharges ranging from about 1500 to 2000 m<sup>3</sup>/s (54,500-71,000 ft<sup>3</sup>/s).

The biological implications of our results can be summarized as follows: Mobile gravel substrates exist throughout the study area, as do off-channel habitats such as backwaters. However, these features vary in their relative abundance and potential suitability as habitat, depending on location within the study area. Alluvial reaches above Westwater Canyon are characterized by lower flow depths and somewhat coarser substrates than the reaches downstream. However, because of the influence of channel slope, substrate mobility is roughly the same in all reaches, with framework gravels moving at flows equal to about half the bankfull discharge and higher. These flows are an important prerequisite for maintaining mobile bed features and in-channel habitats such as riffles and gravel bars. Perhaps just as important are the conditions favoring primary and secondary productivity. Biological processes at these lower trophic levels are affected by a variety of factors, including nutrient availability, water temperature, turbidity and interstitial void space. Our results indicate that suspended sediment concentrations (turbidity) are typically higher in the lower reaches of the study area than they are in the upper reaches. In addition, our cross section data show that the channel becomes considerably deeper downstream without getting much wider. The net effect of the changes in sediment concentration and cross-section shape is a more box-like channel where proportionally less and less of the bed receives sufficient sunlight to allow primary production. As a result, factors that enhance primary and secondary productivity (clear, shallow water) are optimized in the upper reaches whereas factors that might limit these processes (turbid, deep water) become important in the lower reaches (see related reports by Lamarra, 1999 and Osmundson, 1999 for complete descriptions of the aquatic community structure in the Colorado River).

## INTRODUCTION

The native fish community of the Colorado River is adapted to a dynamic riverine environment characterized by pronounced seasonal fluctuations in water discharge, temperature and sediment load, and significant longitudinal variations in channel morphology, gradient and substrate sediment size. Many aspects of this environment have now been altered either directly or indirectly by human activities. Reservoir operations and flow diversions in the Colorado and Gunnison River basins have reduced peak discharges by 29-38% (Van Steeter and Pitlick, 1998). As a result, both rivers have lost some of their capacity to transport sediment, causing an overall narrowing of the main channel and a loss of associated side channels and backwaters. These changes, along with the introduction of non-native fish species, appear to have adversely affected several native fish species, including the Colorado pikeminnow (*Ptychocheilus lucius*), formerly known as the Colorado squawfish. The Colorado pikeminnow is one of four federally listed endangered species in the upper Colorado River basin and its population remains quite small (Osmundson and Burnham, 1998).

Recent studies of native fish abundance by Osmundson et al. (1998) indicate that juvenile and adult pikeminnow are located in distinctly different reaches of the Colorado River (defined here as that portion of the Colorado River upstream of the Green River confluence). Most of the juvenile and subadult pikeminnow (fish less than about 7 years in age and 550 mm in length) are found in canyon-bound reaches below Westwater Canyon, UT, whereas most of the adults (fish greater than 550 mm in length) are found in alluvial reaches near Grand Junction, CO. The difference in location of adults and juveniles presumably reflects a transition in the need for certain resources and habitats, which are governed in turn by differences in physical conditions within the upper and lower reaches. The upper reach near Grand Junction is characterized by coarse bed materials, and simple to complex channel patterns that provide a wide variety of habitats, including pools, riffles, runs and backwaters (Osmundson et al., 1995; Lamarra, 1999). In contrast, the reach below Moab, UT, is characterized by lower habitat heterogeneity (Lamarra, 1999), and sandy-silty bed materials that are mobile over a wide range of flows. The overall channel pattern in this reach is less complex than it is in gravel-bed reaches upstream, but the mobility of the substrate results in the formation of numerous sand bars and shallow embayments (backwaters) that provide important nursery habitat for young-of-the-year fish.

The physical characteristics of river channels typically change downstream, and the shape of the channel (hydraulic geometry) continually evolves to carry the water and sediment supplied from the drainage basin (Gilbert, 1877; Mackin, 1948; Rubey, 1952). In one of the first attempts to quantify and explain the longitudinal trends in river channel characteristics, Leopold and Maddock (1953) presented a set of empirical equations showing that the width, depth, velocity, slope, and sediment load of rivers varied downstream as power functions of discharge; these equations were referred to collectively as “hydraulic geometry” relations. Data presented in subsequent studies showed that rivers in many different environments are characterized by broadly similar hydraulic geometry relations, meaning the bankfull width, depth and velocity vary downstream in roughly the same way. Specifically, it has been noted in many studies that the bankfull width increases downstream to about the 0.5 power of discharge, while the bankfull depth increases to about the 0.4 power of discharge, and the velocity changes little if at all (Simons and Albertson, 1960; Leopold et al., 1964; Church, 1992; Knighton, 1998). Recent attempts to predict the hydraulic geometry of self-formed alluvial channels focus more on physical processes of sediment transport through a cross section (e.g. Parker, 1979; Ikeda et al., 1988; Pizzuto, 1990). Parker’s theory for the formation of a stable gravel-bed channel predicts that the bankfull width and depth are set by a discharge that produces

an average boundary shear stress that is about 20% higher than the critical shear stress for bed load transport. Pitlick et al. (1999) provided support for Parker's theory by showing that the bankfull hydraulic geometry of the Colorado River and the Gunnison River were adjusted to a flow that produces an average shear stress that is about 1.5 times the critical shear stress. This result, coupled with findings from other sediment transport analyses, formed the basis for their conclusion that flows greater than about 1/2 the bankfull discharge play a primary role in maintaining habitats used by native fishes.

The work described in the present report was undertaken to assess how lengthwise variations in the physical characteristics of the Colorado River influence micro- and meso-scale habitats used by benthic invertebrates and native fishes. As discussed above, the upper and lower reaches of the Colorado River appear to provide different types of habitats for adult and juvenile fishes, and presumably these differences affect the food base upon which they rely. Recent studies of channel change and geomorphic processes in the reach near Grand Junction (Pitlick et al., 1999) have clarified certain questions regarding the impacts of flow regulation, rates of channel change, and processes of habitat formation and maintenance, but large parts of the Colorado River that could serve as potential habitat for native fishes were left unstudied. The present study extends this earlier work by examining fluvial processes and geomorphic characteristics of the reaches upstream and downstream of the area near Grand Junction, from approximately Rifle, CO to Moab, UT. The specific objectives of the study are as follows:

- 1) To determine from separate sets of aerial photographs whether there have been significant changes in the geomorphology of the Colorado River in the reach between Rifle and DeBeque Canyon. Historical accounts indicate that Colorado pikeminnow occupied this reach prior to the construction of three diversion dams in DeBeque Canyon (Quarterone, 1993). One of these structures has been modified to allow fish passage, and the other two are under consideration, thus information on the suitability of habitats within this reach is desirable.
- 2) To evaluate long-term trends in sediment loads at points both upstream and downstream of Grand Junction. Annual sediment loads were estimated using discharge and sediment data from existing US Geological Survey (USGS) gauging stations below Glenwood Springs, CO, near Cameo, CO, near Colorado-Utah State Line, and near Cisco, UT. When combined with information from the previous study (Pitlick et al., 1999), these data show how sediment loads and turbidity levels change moving downstream through the Colorado River system.
- 3) To characterize the existing geomorphology of the river. Additional cross sections of the river were surveyed at 1.6-km intervals from Rulison, CO to Potash, UT. These cross sections provide a semi-continuous view of the hydraulic geometry of the Colorado River, and allow testing of ecologically based models of food web dynamics.
- 4) To provide estimates of discharges that transport coarse sediment (gravels and cobbles) in specific reaches of the Colorado River. Periodic movement of the gravel substrate is required to prevent fine sediment from accumulating in the bed (Kondolf and Wilcock, 1996), which, if allowed to persist, limits primary productivity and reduces the amount of interstitial void space available to benthic invertebrates (Waters, 1995). Assessment of the frequency of coarse-sediment transport provides one indication of the suitability of potential habitats in individual reaches.

## STUDY AREA

This study encompasses approximately 300 km of the Colorado River in western Colorado and eastern Utah (Fig. 1) (distances are given here in river kilometers, RKM, measured upstream of the green River confluence). Field measurements characterizing this segment of the Colorado River were obtained at closely spaced intervals from Rulison, CO (RKM 363), to Potash, UT (RKM 77), with the exception of two short reaches in DeBeque Canyon and Westwater Canyon that were difficult to access. These field measurements have been augmented with streamflow and sediment data from USGS gauging stations below Glenwood Springs, CO; near Cameo, CO; near the Colorado-Utah state line; and near Cisco, UT.

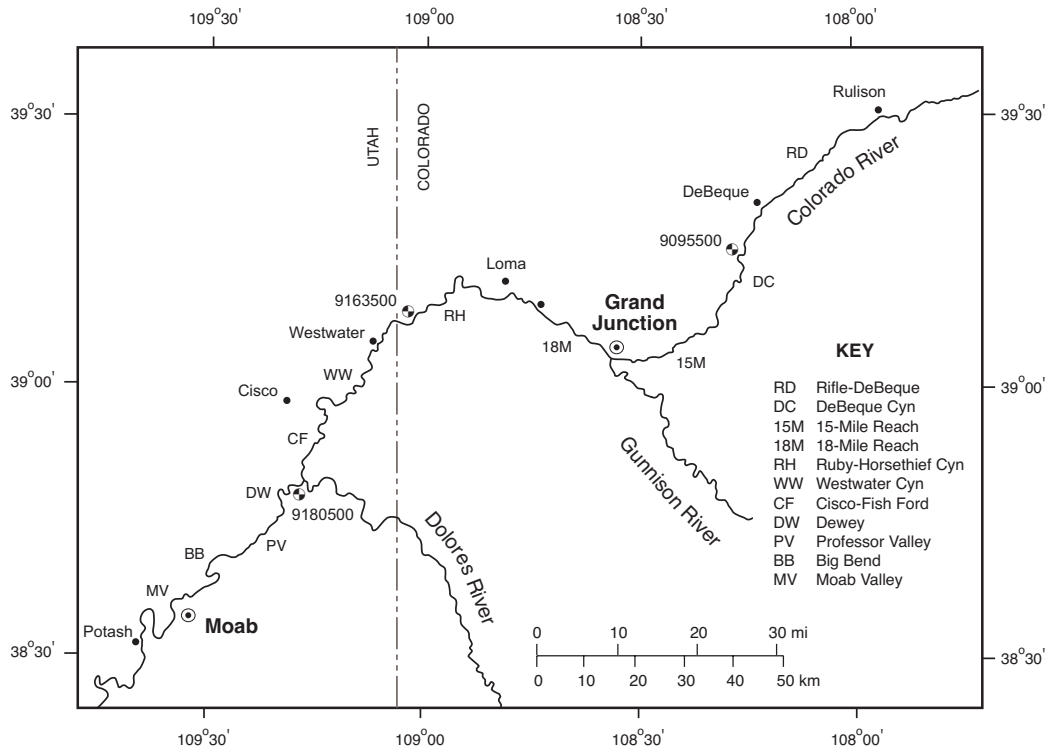


Figure 1. Location map of study area and subreach boundaries.

### *Hydrology*

The majority of runoff carried by the Colorado River is derived from spring snowmelt in alpine and sub-alpine basins in the Rocky Mountains of central Colorado. As the river flows west, it gradually drops in elevation and begins flowing across the Colorado Plateau, a region of sparse vegetation and little rainfall. This region contributes little additional runoff, but a high proportion of the river's annual sediment load (Iorns et al., 1965; Liebermann et al., 1989). Most of this sediment is derived from surface erosion of sedimentary rocks (shale and sandstone) that are found throughout western Colorado and eastern Utah. The Colorado River thus receives its supply of water and sediment from two distinctly different sources, which contrasts with conditions in the typical dendritic drainage basin where water and sediment are supplied more or less evenly along the length of the trunk stream or river. We believe this has been an important influence on the geomorphology of the Colorado River.

Snowmelt runoff in the Colorado River basin follows a predictable annual pattern, with flows typically rising in April and May, reaching a peak in early- to mid-June, and receding through July and August (Fig. 2). Localized thunderstorms and moderately intense rainfalls associated with the southwest monsoon (a regional weather pattern produced by the flow of moist air from the Gulf of California and Pacific Ocean) occur sporadically through late summer and early fall. Fleener's (1997) analysis of precipitation and streamflow records from various stations in the region shows that the hydrologic influence of the monsoon clearly diminishes from southwest to northeast, with the most noticeable effects occurring in San Juan and Dolores River basins near the Four Corners area. Several such storms in the 1940s and 1950s produced moderately large floods with high suspended sediment concentrations (Iorns et al., 1964). Our analysis of streamflow and sediment records from USGS gauges further upstream indicates that these events are not nearly as common in the Grand Junction area as they are further south.

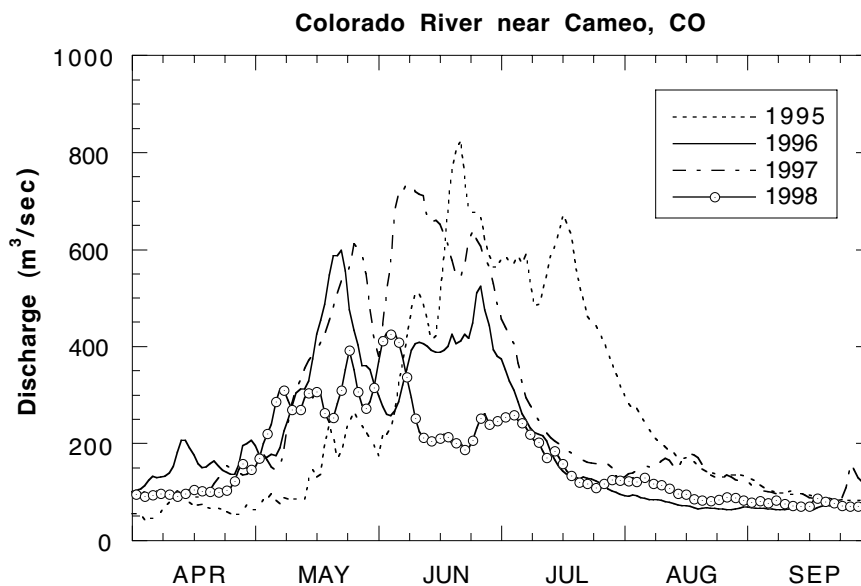


Figure 2. Hydrographs of the Colorado River for 4 recent periods of snowmelt runoff.

Natural streamflows of the Colorado River, and its two major tributaries, the Gunnison River and the Dolores River, are affected by many dams and water diversions upstream. Liebermann et al. (1989) report that there are 24 reservoirs with a storage capacity of more than  $6.2 \times 10^6 \text{ m}^3$  (5000 acre-feet) upstream of the Colorado-Utah state line. Collectively, these reservoirs store the equivalent of about half the annual streamflow of the Colorado River (Pitlick et al., 1999). Most of the dams and reservoirs in the upper basin were constructed between 1950 and 1980, making this a potentially important period with respect to changes in streamflow, sediment loads and habitat characteristics. Diversion structures and canals are likewise located throughout the upper basin. The amount of water diverted out of the Colorado River basin varies from 10 to 20% of the annual natural flow (Pitlick et al., 1999). Large diversions, including several near Grand Junction, have the added effect of blocking upstream fish migrations.

Average annual hydrographs of the Colorado River constructed for separate periods before and after 1950 illustrate the changes in streamflow patterns caused by reservoir operations and flow diversions (Fig. 3). Compared to the period prior to 1950, peak discharges in spring and early summer are now much lower than they were before, and base flows in fall and winter are higher. Our analysis of streamflow records from the Cameo and Cisco gauging stations indicates that, since 1950, instantaneous peak discharges of the Colorado River have decreased by 29 and 33%, respectively, at these two sites (Cress, 1997).

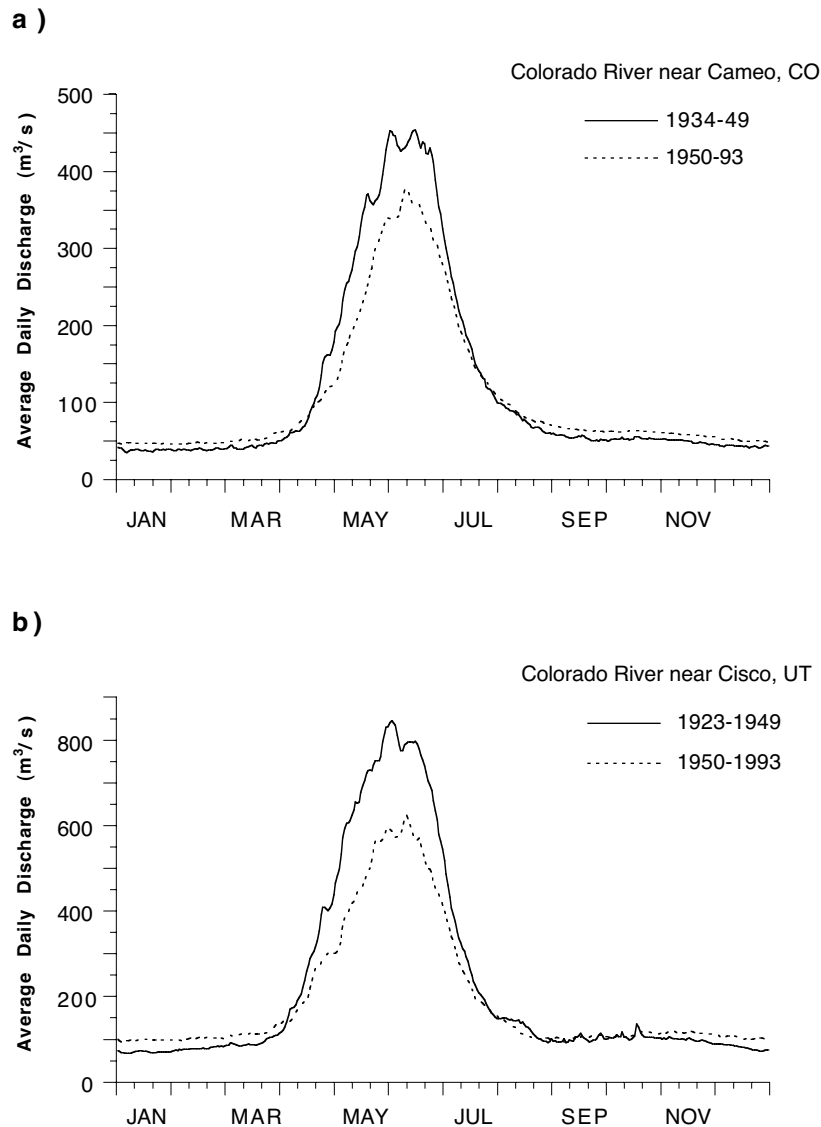


Figure 3. Average annual hydrographs of the Colorado River for separate periods; (a) Colorado River near Cameo, CO and (b) Colorado River near Cisco, UT. Note the September and October spikes in flow in the pre-1950 Cisco hydrograph; these correspond to individual monsoon storms. The same spikes do not appear in the Cameo record because this gauge is located near the northern edge of the monsoon's influence (Fleener, 1997), and they are not as evident in the recent portion of the Cisco record because of the influence of McPhee Reservoir on the Dolores River.

### *Physical Characteristics of Study Reaches*

In the study area the Colorado River flows in a southwest direction, bisecting the Roan Mesa and Paradox Basin physiographic provinces of the Colorado Plateau (Liebermann *et al.*, 1989). As the river traverses this area, it flows through a series of Permian- to Tertiary-age bedrock formations that vary in their resistance to erosion. Where the bedrock consists of shale, such as the Mancos or Morrison Formations, the river flows within very broad alluvial valleys (e.g. near Parachute and Grand Junction, CO, or between Cisco landing and Dewey, UT); where the bedrock consists of sandstones, such as the Wingate, Navaho or Entrada Formations, the river is more confined (e.g. Ruby-Horsethief Canyon, Dewey Canyon, and Big Bend). These differences in bedrock lithology and valley morphology are the basis for subdividing the 300-km study area into 11 separate strata or subreaches that we designate as “fully alluvial” and “quasi-alluvial” reaches. Fully alluvial reaches are those where the river is generally free to migrate laterally, and where a wide floodplain is present; examples include the Rifle-DeBeque reach near Parachute, the 15- and 18-mile reaches near Grand Junction, and the Cisco-Fish Ford Reach near Cisco, UT. Quasi-alluvial reaches are more confined by bedrock, yet still have a floodplain; examples include DeBeque Canyon, Ruby-Horsethief Canyon and Dewey Canyon.

Although there are some clear visual and morphologic differences between fully alluvial and quasi-alluvial reaches, the Colorado River generally does not exhibit abrupt changes in channel gradient, bed material size or bankfull channel width as it flows through these different reaches; exceptions to this generalization are the Westwater Canyon and Big Bend reaches, which are both bounded by resistant bedrock, and the reaches through and below Moab UT, which are sand-bed. Specific attributes of the 11 study subreaches (not including Westwater Canyon) are discussed below, and reach-average characteristics are summarized in Table 1.

Table 1. Average slope, bankfull width ( $w$ ), depth ( $h$ ), and median surface grain size ( $D_{50}$ ) of the Colorado River in specific subreaches.

Subreach Name and Location	Reach Type <sup>1</sup>	slope	w (m)	h (m)	$D_{50}$ (mm)
Rulison-DeBeque (RKM 365-328)	A	0.00196	114	2.45	57
DeBeque Cyn. (RKM 327-316)	QA	0.00150	77	3.12	52
15-mile reach (RKM 298-275)	A	0.00175	134	2.54	58
18-mile reach (RKM 274-246)	A	0.00130	175	3.01	52
Ruby-Horsethief Cyn. (RKM 245-206)	QA	0.00100	129	3.64	47
Cisco-Fish Ford (RKM 180-153)	A	0.00066	147	4.49	38
Dewey (RKM 151-140)	QA	0.00047	132	5.14	34
Professor Valley (RKM 138-126)	A	0.00149	203	4.61	70
Big Bend (RKM 124-113)	QA	0.00098	106	6.43	63
Moab (RKM 111-105)	A	0.00034	151	5.13	28
Potash (RKM 103-77)	A	0.00028	197	4.51	0.025

1) A indicates alluvial reach; QA indicates quasi-alluvial reach.

*Rulison-DeBeque (Stratum 11)*: The uppermost study reach extends 37 river kilometers (RKM) from Rulison, CO, to the head of DeBeque Canyon (RKM 365-328). In this reach, the Colorado River flows through a wide alluvial valley underlain by shales and sandstones of the Green River Formation (Cashion, 1973). Locally the river channel is bounded by Pleistocene pediments and strath terraces. The active floodplain is up to 1 km wide in many areas. Mature stands of native cottonwood trees (*Populus deltoides*) are common on the floodplain, along with shrubs such as willow and sage. Non-native species such as tamarisk (*Tamarisk chinensis*) and Russian olive (*Elaeagnus angustifolia*), are much less abundant in this reach than in reaches downstream. The average bankfull width of the river is 114 m, the bankfull depth is 2.45 m, the average slope is 0.00196, and the bed material is gravel with a median grain size,  $D_{50}$ , of 57 mm (Table 1).

*DeBeque Canyon (Stratum 10)*: DeBeque Canyon begins at RKM 327, about 10 km downstream of DeBeque, and ends upstream of Palisade at RKM 298. DeBeque Canyon is a relatively shallow canyon cut into interbedded shales and sandstones of the Hunter Canyon Formation (Cashion, 1973). This reach is more influenced by engineering structures than any other reach in the study area. Interstate highway 70 borders much of the left bank, a rail line borders much of the right bank, and there are three diversion dams within the canyon. Nonetheless, a narrow floodplain is present along one or both banks, thus we classify this reach as quasi-alluvial. The average slope through DeBeque Canyon is 0.0015, the bankfull width is 77 m, the bankfull depth is 3.1 m, and the bed material consists of gravels and cobbles with an average  $D_{50}$  of 52 mm (Table 1).

*15-mile reach (Stratum 9)*: The 15-mile reach extends for a distance of 24 km from the town of Palisade (RKM 298) to the confluence of the Gunnison River in Grand Junction (RKM 275). We classify this reach as fully alluvial (Table 1), although in many places the left bank is bounded by Mancos shale. This reach and the adjacent 18-mile reach are in urbanized areas where the channel has been modified to varying degrees by gravel mining operations and bank revetments (levees and rip-rap); however, our field mapping of these reaches indicates that levees and rip-rap form much less of the channel boundary than is commonly thought. Floodplain characteristics and vegetation vary widely in this reach. Dense thickets of tamarisk, Russian olive and willow are common, as are open stands of cottonwood. The average slope of the 15-mile reach is 0.00175, the bankfull width is 134 m, the bankfull depth is 2.5 m, and the bed material consists of gravels and cobbles with an average  $D_{50}$  of 58 mm (Table 1).

*18-mile reach (Stratum 8)*: The 18-mile reach extends for 35 km between the confluence of the Gunnison River and the head of Horsethief Canyon, near Loma, CO (RKM 246). This reach possesses many of the same characteristics as the 15-mile reach described above. The average slope of the 18-mile reach is 0.0013, the average bankfull width is 175 m, the average bankfull depth is 3.0 m, and the bed material is gravel and cobbles with a  $D_{50}$  of 52 mm (Table 1).

*Ruby-Horsethief Canyon (Stratum 7)*: Horsethief and Ruby Canyons form a continuous quasi-alluvial reach extending from the western edge of the Grand Valley, near RKM 245, to the entrance to Westwater Canyon, near RKM 201. This reach is bounded by resistant sandstones of the Wingate and Entrada formations, and is more incised than the two reaches immediately upstream. However, a small floodplain covered with dense tamarisk shrubs interspersed with mature cottonwood trees is present along most of the reach, even in areas with steep sandstone walls. The average slope of the reach is 0.0010, the bankfull width is 129 m, the bankfull depth is 3.64 m, and the bed material is gravel with a  $D_{50}$  of 47 mm (Table 1).

*Cisco-Fish Ford (Stratum 6)*: The Cisco-Fish Ford reach begins below Westwater Canyon, near RKM 180, and terminates at RKM 153, about 2 km below the confluence with the Dolores River. The upper portion of this reach is bounded by shales of the Morrison Formation, while the lower portion is bounded by sandstones of the Dakota Group (Williams, 1964). Both units are easily eroded, allowing the river to form a broad alluvial valley with a distinct floodplain. Floodplain vegetation is similar to reaches upstream. The average slope is 0.00066, the bankfull width is 147 m, the bankfull depth is 4.49, and the bed material is gravel with a  $D_{50}$  of 38 mm (Table 1).

*Dewey (Stratum 5)*: The Dewey reach begins at RKM 151 and ends near the head of Professor Valley at RKM 140 (Fig. 1). The first few kilometers of this reach are bounded by Navaho Sandstone and Wingate Sandstone; further downstream, shales of the Cutler Formation appear at river level. Steep-walled cliffs border the river in several places, but a small, discontinuous floodplain is generally present along much of the channel, thus we classify this reach as quasi-alluvial. The average slope of the reach is 0.00047, the bankfull width is 132 m, the bankfull depth is 5.14 m, and the bed material is sand and gravel with a  $D_{50}$  of 34 mm (Table 1).

*Professor Valley (Stratum 4)*: Professor Valley (Fig. 1) is part of the Richardson Amphitheater, a broad valley formed as a result of uplift and differential erosion of a series of northwest-trending salt anticlines. Colman (1983) reports that uplift has been occurring in this area for at least the last 2.5 MY. A sharp inflection in the river's profile occurs just below Hittle Bottom, and the average gradient here increases to 0.00149. Professor Valley also contains several alluvial fans deposited by floods from the La Sal Mountains. Boulders from these fans now form a series of rapids. The river is bounded by shales and thinly bedded sandstones of the Cutler Formation, and Pleistocene terraces. The average bankfull width in this reach is 203 m, the bankfull depth is 4.61 m, and the bed material is gravel and cobbles with a  $D_{50}$  of 70 mm (Table 1).

*Big Bend (Stratum 3)*: The Big Bend reach starts below White's Rapid at RKM 124, and ends at RKM 113 (Fig. 1). The upper portion of the reach is a deeply incised canyon bounded by Wingate sandstone, a resistant bedrock unit that weathers to produce steep hillslopes mantled with talus and large boulders; a floodplain is generally absent here. The lower 6 km of the reach is bounded by the less resistant Navajo Sandstone; the canyon is somewhat wider here and a floodplain is present along one or both banks. Thick tamarisk covers the floodplain in this lower segment. The average slope of the reach is 0.00098, the bankfull width is 106 m, the bankfull depth is 6.43 m, and the average  $D_{50}$  is 63 mm (Table 1).

*Moab (Stratum 2)*: This reach encompasses the area upstream of Moab, UT, through the Moab Valley, from RKM 111 to RKM 105. Although this reach is short, it is unique because, here, the Colorado River goes through an abrupt transition from gravel- to sand-bed, with a corresponding decrease in channel gradient. Near Moab, the river has cut a wide alluvial valley directly across the Moab Anticline. A wide floodplain covered with dense tamarisk is present through much of the reach. The average channel gradient is 0.00034. The average bankfull width is 151 m, the bankfull depth is 5.13 m, and the bed material is gravel and sand with a  $D_{50}$  of 28 mm (Table 1).

*Potash (Stratum 1)*: The reach from Moab to Potash, UT marks the downstream end of the study area. This reach begins at RKM 103 and ends below the Potash plant at RKM 77 (Figure 1). The floodplain is discontinuous here, but well-developed where present. Dense thickets of tamarisk cover the floodplain in this reach. The channel is considerably wider here than upstream, with an average bankfull width of 197 m; the bankfull depth is 4.51 m, and the bed material is sand with a  $D_{50}$  of 0.025 mm (Table 1).

## METHODS

Many of the methods and analytical techniques used in the previous study by Pitlick et al. (1999) have been repeated here, with less of an emphasis on evaluating historical trends, and more of an emphasis on measuring existing conditions within the Colorado River. Accordingly, we have shortened the discussion of techniques involved in analyzing aerial photographs, and lengthened the discussion of the methods and assumptions involved in modeling flow and sediment transport.

### *GIS Analysis of Channel Change in the Rifle-DeBeque Reach*

In order to provide a more complete view of the geomorphology of the Colorado River, and to complement results from our previous studies (Pitlick et al., 1999), we analyzed two sets of black and white aerial photographs covering the reach between Rifle and DeBeque Canyon. Historically, this reach supported populations of Colorado pikeminnow and razorback sucker (Kidd, 1977; Burdick, 1992; Quarterone, 1993), but a series of diversion dams now prevent fish from migrating upstream. The idea of modifying these structures to allow fish passage has been discussed, but the physical characteristics of the reach have not been studied in detail until now.

Changes in channel morphology were determined by digitizing specific features (e.g. channel banks, islands, secondary channels) on black and white stereo photographs taken in 1937 and 1995. Figure 4 shows how these features were differentiated. Secondary channels that form where the flow splits around an island were distinguished from the main channel on the basis of their smaller size. Backwaters and other areas of slow moving water were often associated with side channels, thus we grouped them as one feature.

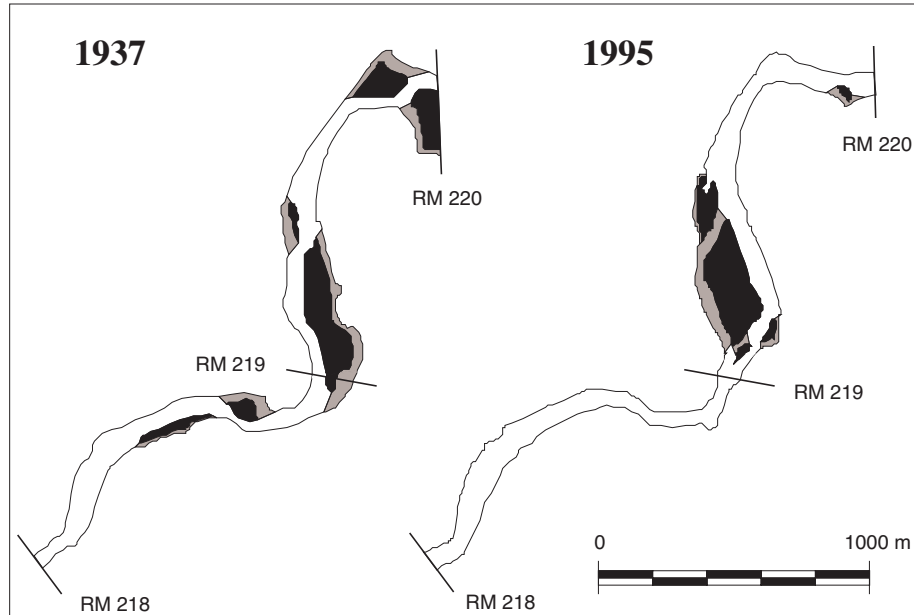


Figure 4. Digitized channel maps of a section of the Colorado River near Parachute, CO.

The 1937 and 1995 aerial photographs are slightly different in scale (1:32,000 and 1:20,000, respectively), and were taken when the river was flowing at different discharges (55 m<sup>3</sup>/s in 1937 and 79 m<sup>3</sup>/s in 1995). The higher discharge in the more recent photographs complicates the analysis slightly because, at higher flows, the channel would appear larger than it would for an equivalent or lower flow. However, the error introduced by different flow levels is very small in this case- probably much less than 5% (Van Steeter, 1996)- and even so, the higher discharge occurs in the more recent set of photographs. This means that changes in planform area since 1937 are probably underestimated by a small amount. Further details of the procedures involved in developing similar GIS data bases are discussed in detail by Pitlick et al. (1999).

### *Sediment Loads*

Annual suspended sediment loads were estimated for various time periods using streamflow and sediment data from the following USGS gauging stations: Colorado River at Glenwood Springs, CO (station 9072500), Colorado River near Cameo, CO (station 9095500), Colorado River near CO-UT state line (station 9163500), and Colorado River near Cisco, UT (station 9180500). We recognize that Glenwood Springs is well upstream of the study area, but we include this station in the analysis because it illustrates how abruptly the sediment load of the Colorado River increases downstream. The hydrologic data from these four gauging stations are of high quality, with record lengths varying from 45 to 100 years. The streamflow record from the Glenwood Springs gauge is the longest, beginning in 1898, but complicated by the fact that in 1966 the gauge was moved to a point downstream of the Roaring Fork River. The records for these two gauges were combined by subtracting daily discharges of the Roaring Fork River, which is also gauged, from the same-day discharges of the Colorado River. The flow record at the Cameo gauge (at RKM 322) begins in 1934 and is continuous through the present. There is another gauge near the town of DeBeque (station 9093700, at RKM 343); however, since this gauge is only 20 km away from the Cameo gauge, and there are few tributaries in between, we have not used these data. The State Line gauge has been in operation since 1951; this gauge was initially located at RKM 224 in Ruby Canyon, but in 1979 it was moved to its present location at RKM 216. The Cisco gauge was established near the Dewy Bridge (RKM 152) in 1914; the record from this gauge is continuous from 1922 through the present.

Suspended sediment samples have been taken at each of these gauging stations, however, reliable data are available only since about 1950, and the amount of data collected at individual stations varies considerably. Approximately 80 suspended sediment samples were taken at the Glenwood Springs gauge from 1951-1965 (Iorns et al., 1964). To our knowledge no additional samples have been taken since then. About 50 suspended sediment samples were taken at the Cameo gauge between 1951 and 1954 (Iorns et al., 1964), and several hundred more samples have been taken since 1983 (USGS Water Supply Papers). Over 100 suspended sediment samples have been taken at the State Line gauge since 1977 (USGS Water Supply Papers). Sediment sampling began at the Cisco gauge in 1930 (Iorns et al., 1964), however, there is some question about the representativeness of samples taken prior to 1950, when a different type of suspended sediment sampler was in use (Topping et al., 1996). Given this concern, we limited our analysis of the Cisco sediment data to samples taken after 1950; since then, several hundred suspended sediment samples have been taken at the Cisco gauge.

Suspended sediment loads were estimated for each of these gauging stations by developing a series of sediment rating curves, or empirical relations between water discharge and suspended sediment load. Such curves allow us to estimate daily suspended sediment loads (which are measured only intermittently) from daily discharges (which are measured continuously). The rating curves were

formulated by calculating instantaneous suspended sediment loads,  $Q_s$ , from point measurements of discharge,  $Q$ , and suspended sediment concentration,  $C_s$ , using the following equation:

$$Q_s = c C_s Q \quad (1)$$

where  $c = 0.0864$  if  $C_s$  is expressed in mg/l and  $Q$  is expressed in  $m^3/s$ . Values of  $Q_s$  are thus given here in metric tons per day or metric tons per year. A relation between  $Q$  and  $Q_s$  was then fit by eye to these individual values (Fig. 5a), with the line chosen empirically to minimize the difference between observed and predicted sediment loads (Fig. 5b). In this case, the fit was straightforward because the data follow a simple log-linear trend.

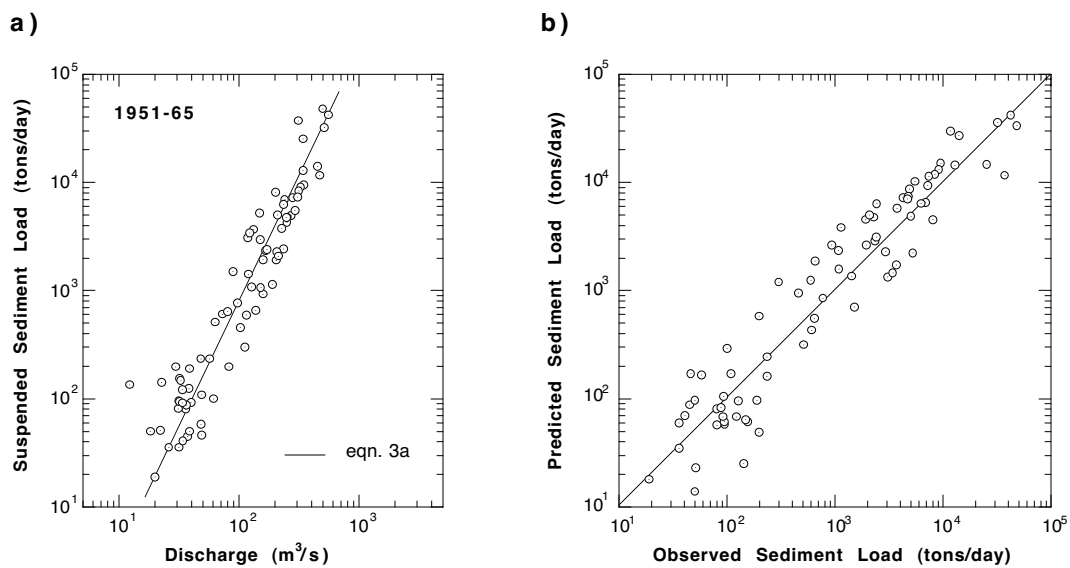


Figure 5. Suspended sediment data for the Colorado River at Glenwood Springs (USGS station 9072500); (a) discharge and suspended sediment load, (b) comparison between observed sediment loads, and loads predicted from equation 3a. Data from Iorns, et al. (1964).

Individual values of  $Q$  and  $Q_s$  were plotted for each of the other gauging stations to produce a series of sediment-load relations (Figs. 6-8). These data were further subdivided according to whether the samples were obtained before or after the peak in the annual hydrograph. Typically, the Colorado River carries much higher suspended sediment loads on the rising limb of the hydrograph than it does on the falling limb. This trend is caused by a rise and fall in suspended sediment concentration that precedes the rise and fall in water discharge. Another smaller subset of the data includes samples taken in late summer and early fall that also have high sediment concentrations. These late-season samples reflect brief but large increases in concentration caused by runoff from localized thunderstorms or regional monsoon storms. Based on the number of such observations at individual stations it appears that these events become more common towards the southwest (downstream) part of the study area.

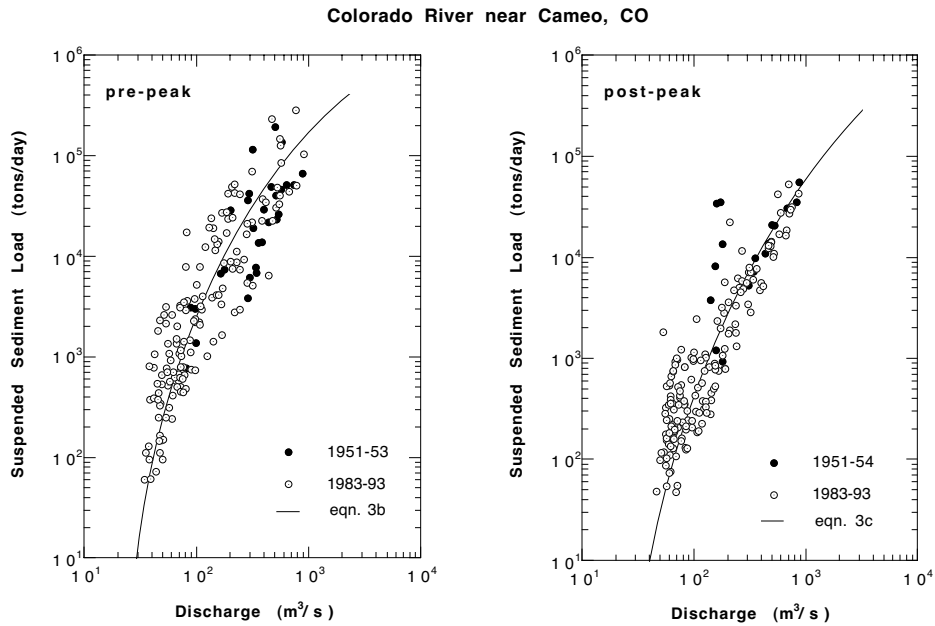


Figure 6. Relations between discharge and suspended sediment load, Colorado River near Cameo (USGS station 9095500). Closed circles indicate samples taken in the early 1950s, open circles indicate samples taken since 1983. Data from Iorns, et al. (1964) and USGS Reports of Water Resources in Colorado (published annually).

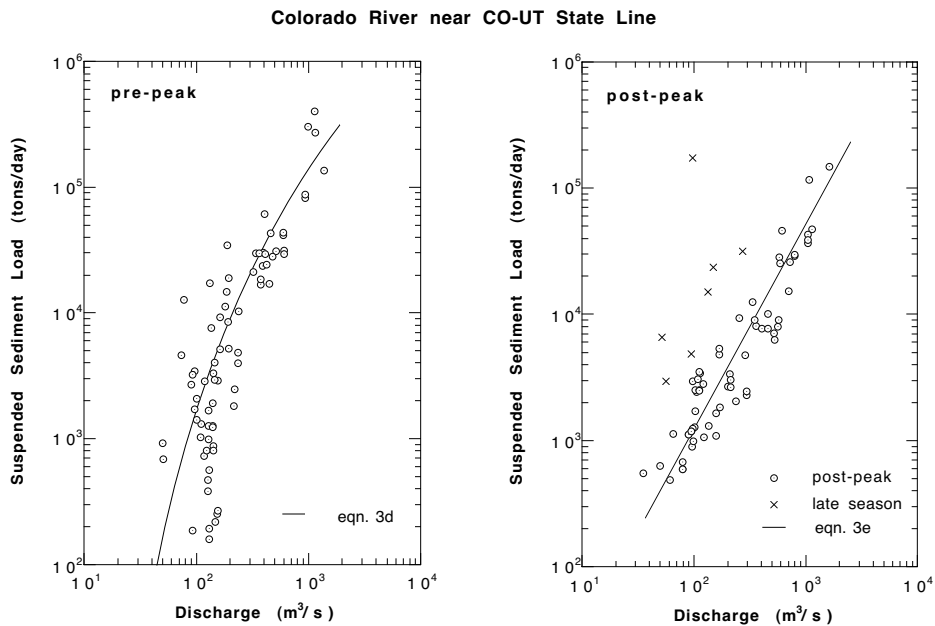


Figure 7. Relations between discharge and suspended sediment load, Colorado River near Colorado-Utah State Line (USGS station 9163500). Data from USGS Reports of Water Resources in Colorado (published annually).

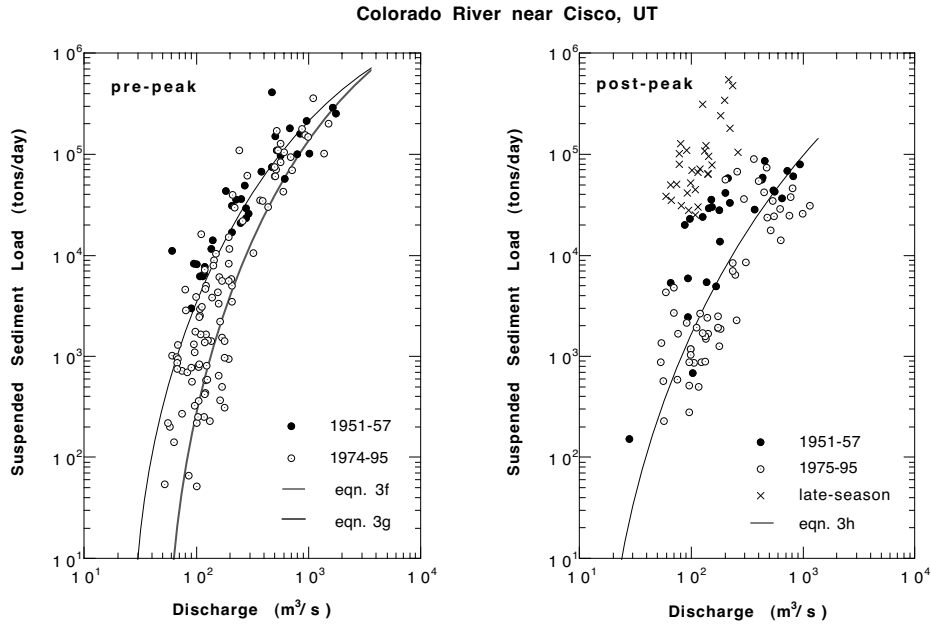


Figure 8. Relations between discharge and suspended sediment load, Colorado River near Cisco, UT (USGS station 9180500). Symbols are the same as in Figure 6. Data from Iorns, et al. (1964) and annual USGS Reports of Water Resources in Utah (published annually).

The scatter exhibited by the data in Figures 6-8 is relatively large, but in our experience, not out of the ordinary. In most cases the data follow trends defined by a curve of the general form

$$\hat{Q}_s = k(Q - Q_o)^a \quad (2)$$

where  $\hat{Q}_s$  is the estimated suspended sediment load, and  $k$ ,  $a$  and  $Q_o$  are coefficients;  $k$  and  $a$  determine, respectively, the position and slope of the sediment rating curve, while  $Q_o$  determines the shape; the larger the value of  $Q_o$ , the more concave the rating curve. Specific values of  $k$ ,  $a$  and  $Q_o$  are listed for each gauging station in Table 2. These values were chosen by trial and error to minimize the difference between observed and predicted suspended sediment loads, as shown in Figures 9-11. For the Glenwood Springs gauge and the Cameo gauge, the selection of specific parameter values was straightforward, resulting in good correspondence between observed and predicted suspended sediment loads over the entire range of discharges (Fig. 9). For the State Line and Cisco gauges the selection of parameter values proved to be more difficult, partly because the data from these gauges follow more irregular trends, and because in the case of the Cisco gauge, the data do not appear to be stationary over the period of record. The equations for these two stations (Table 2) were formulated so that the curves gave positive values of  $Q_s$  over most of the range of  $Q$ ; this meant that the curve did not necessarily pass through the lowest values. As a result, the correspondence between observed and predicted suspended sediment loads at the State Line and Cisco gauges is poor at low discharges, but moderately good at high discharges (Figs. 10 and 11). Fortunately low flows carry relatively little of the total annual sediment load, so the potential error associated with estimates in this range of discharges is not of great concern.

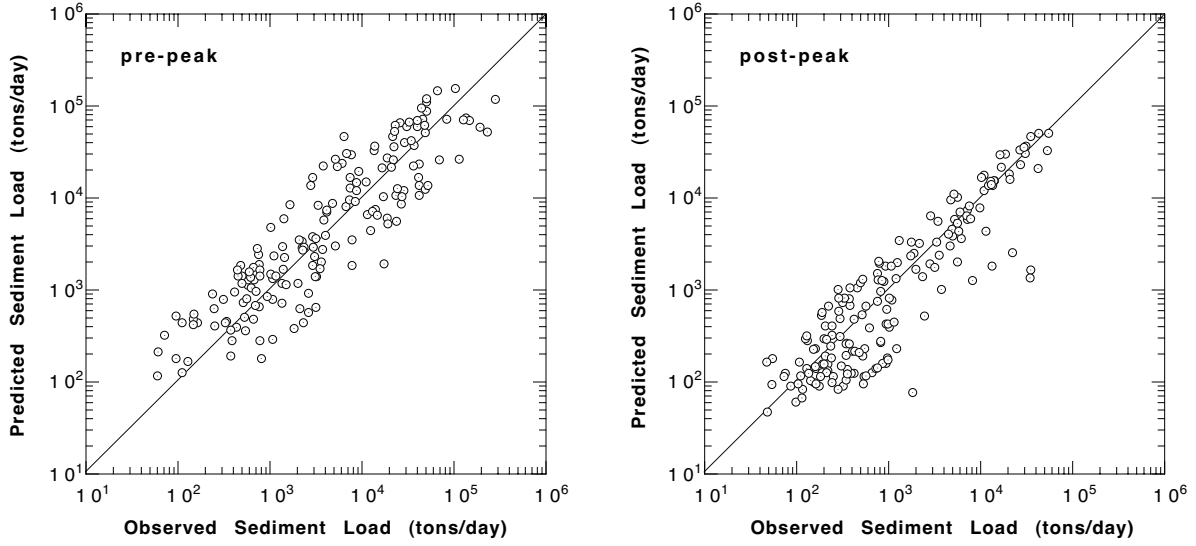


Figure 9. Comparison between observed and predicted suspended sediment loads for pre- and post-peak phases of the annual hydrograph, Colorado River near Cameo.

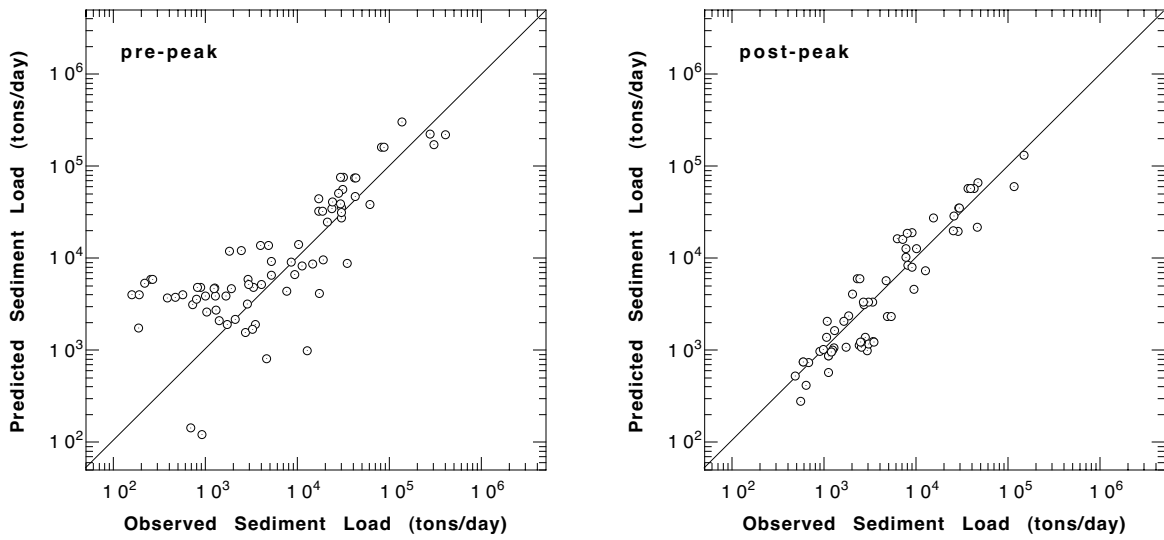


Figure 10. Comparison between observed and predicted suspended sediment loads for pre- and post-peak phases of the annual hydrograph, Colorado River near Colorado-Utah State Line.

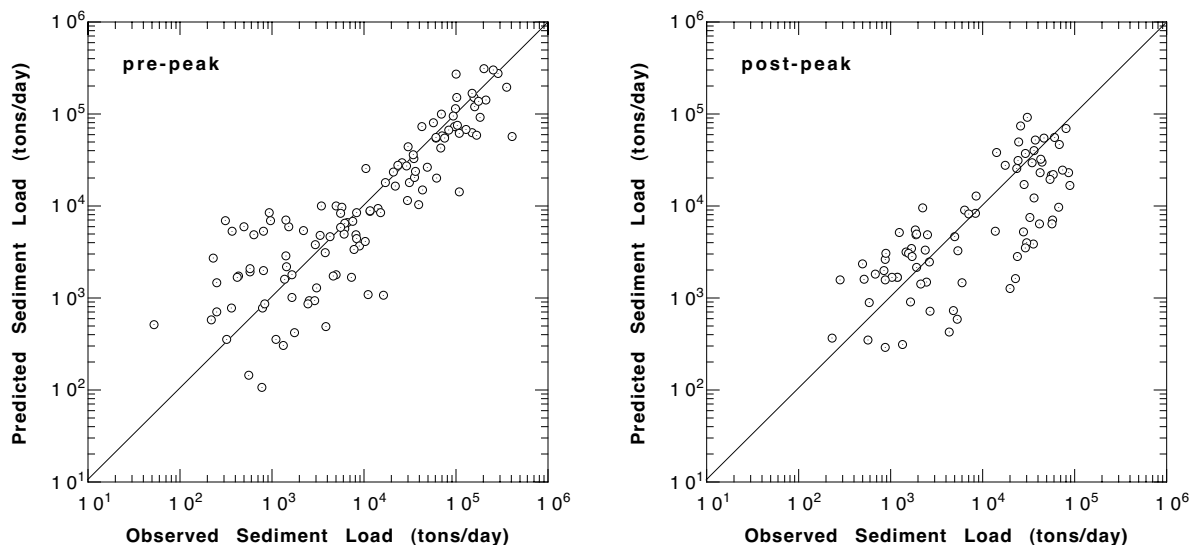


Figure 11. Comparison between observed and predicted suspended sediment loads for pre- and post-peak phases of the annual hydrograph, Colorado River near Cisco, Utah.

Daily suspended sediment loads were calculated for each gauging station using the appropriate equation from Table 2 and the recorded daily discharge. The calculations were repeated for each day of the water year for each year in the period 1934 through 1997. The individual daily values were then summed to give the annual suspended sediment load (see appendix Table A-1).

Table 2. Coefficients and exponents used in the rating curve equation (2) to fit sediment load-discharge data from various USGS gauging stations on the Colorado River.

Location	k	$Q_0$	a	Eqn. No.
Glenwood Springs	0.04	4	2.2	3a
Cameo				
pre-peak	3.0	25	1.6	3b
post-peak	0.07	20	2.0	3c
State Line				
pre-peak	3.0	40	1.6	3d
post-peak	0.1	-30	1.9	3e
Cisco				
pre-peak, 1934-66	40	45	1.2	3f
pre-peak, 1967-97	12	85	1.4	3g
post-peak, all years	5	35	1.4	3h
late season, all years	30	40	1.8	3i

In publishing suspended sediment data, the USGS also often reports the percentage of sediment finer than 0.063 mm (the sand-silt break), and sometimes reports the full particle size distribution of the suspended sediment. These data are useful for evaluating long-term trends in sediment load because the sediment concentration usually increases as the percentage of sand increases. The measurements from the Cisco gauge are by far the most complete in this regard; this data set includes sand-fraction analyses for nearly 300 samples, dating back to 1951. Some sediment-size analyses are available for measurements at the Cameo and State Line gauges, but we have not evaluated these data in detail because they are all from the more recent time period (1979-present).

### *Field Studies*

Field studies were conducted from 1995 through 1998 to characterize the geomorphology of the study reach, and to obtain the data necessary to model sediment transport in individual subreaches.

*Cross Section Surveys:* Cross sections of the main channel were surveyed at evenly spaced, 1.6-km intervals from RKM 366 to RKM 77, with the exception of the two reaches that were difficult to access, and a few sites that could not be surveyed for logistical reasons. Cross sections were surveyed using an electronic theodolite (total station) and a motorized rubber raft outfitted with a depth sounder. To survey a cross section, the total station was set up over one of the endpoints. Distance and depth readings were then taken along the line of the section by targeting a prism on the raft, while at the same time, the person operating the raft would read the depth off the chart recorder and relay the data by radio to the person on shore.

*Bed Material Samples:* Point counts of the surface bed material (pavement or armor layer), and bulk samples of the subsurface sediment were used to characterize the bed materials throughout the study reach. Samples were taken from exposed gravel bars at low flow (in most places, the water was too deep, even at base flow, to allow us to sample across the entire bed, therefore, we could not sample consistently from the same morphologic features, e.g. riffles). In our experience, textural variations from bar to bar are often relatively large, thus for purposes of sediment transport calculations, we grouped the data from individual sites to obtain composite samples for the various subreaches. The average values of  $D_{50}$  listed in Table 1 are, therefore, based on anywhere from 3 to 10 samples in a reach. Surface sediment samples were taken by randomly selecting 100 or 200 particles (the so-called Wolman method) and determining their sizes using a metal template with openings equal to standard sieve sizes. The subsurface samples were taken by first removing the surface layer of particles, then collecting 100-150 kg of the sediment underneath. The coarse fraction of this sample was sieved in the field, and the fine fraction was sieved in the laboratory. A total of 56 surface samples and 27 subsurface samples were taken in the 300-km study reach.

*Bed-Material Transport Thresholds:* Estimates of discharges required to transport the bed material of the Colorado River were made by combining several conventional flow and sediment transport equations, solved and calibrated with the aid of the field data described above. The most important and fundamental equation in this analysis is the Shields' parameter:

$$\tau^* = \frac{\tau}{(\rho_s - \rho) g D} \quad (4)$$

where  $\tau^*$  is the dimensionless shear stress,  $\tau$  is the near-bed shear stress,  $\rho_s$  and  $\rho$  are the densities of sediment and water, respectively,  $g$  is the gravitational acceleration, and  $D$  is the particle size. Equation 4 is essentially a balance between the fluid force causing motion and the weight force (or friction) resisting motion. The variable  $\tau^*$  is continuous, but discrete values defined on the basis of

flume experiments and field observations are used to infer two different phases of transport: *initial* motion and *significant* motion. The initial motion phase denotes the onset of bed load transport at the critical dimensionless shear stress  $\tau_c^*$ . In this phase, very few particles on the bed are moving and bed load transport rates are very low (Wilcock and MacArdell, 1993; Andrews, 1994). This phase is nonetheless important for maintaining micro-scale habitats because it marks the point at which coarse particles start moving and fine sediment begins to be flushed from the bed (Kondolf and Wilcock, 1996; Wilcock et al., 1996). The lower limit for this phase is a matter of some debate. Data compiled by Buffington and Montgomery (1997) suggest that particles equal to the median grain size,  $D_{50}$ , begin moving at a value of  $\tau_c^* = 0.030$ . Milhous (1998) proposes a lower value of 0.021, while flume experiments by Wilcock (1998) indicate that the  $\tau_c^*$  for gravel particles varies from 0.01 to 0.045, depending on the amount of sand on the bed. In the present study, we varied  $\tau_c^*$  from 0.030 in strata 7-11, to 0.025 in strata 6-3, and 0.020 in strata 2. Our reasons for adjusting the value of  $\tau_c^*$  are discussed later, in the section on transport thresholds.

The second transport phase, significant motion, is characterized by continuous movement of most all particles on the bed. A lower limit for this phase is not well established. In a previous study, Pitlick et al. (1999) reasoned that significant motion should occur at flows approaching bankfull, since these flows shape the channel. Using data from reaches near Grand Junction, they found that bankfull flows produced an average  $\tau^*$  of 0.047, which is about 1.5 times the assumed value of  $\tau_c^*$  (Pitlick et al., 1999). We followed a similar convention in this study, although our field data from the reaches below Westwater Canyon (strata 6-2) suggest that that bed-load transport stages corresponding to  $1.5\tau_c^*$  may occur at flows less than bankfull.

There are two other important points to note about (4) and its application. The first point concerns whether the  $D_{50}$  is representative of the bed as a whole, and the implication that if the  $D_{50}$  begins to move, all sizes begin to move (a condition termed *equal mobility*). We will not review this debate here, except to note that in most gravel-bed rivers, framework grains of most all sizes are entrained by flows ranging from about 1/2 to 2/3 of the bankfull discharge. The debate over equal mobility has been resolved by the experiments of Wilcock and McArdell (1993), who showed that, at low shear stresses ( $0.030 < \tau^* < 0.045$ ), the number of coarse particles entrained from the bed is very low in comparison to the number of fine particles entrained, resulting in a bed load that consists of mostly fine particles. At higher shear stresses ( $\tau^* > 0.060$ ), fine and coarse particles are entrained at about the same rate, resulting in nearly equal proportions of fine and coarse bed load. The range in shear stress over which this transition occurs is roughly the same as that defined by our initial motion and significant motion transport stages.

The second point to note about eqn. (4) is that the shear stress  $\tau$  should be formulated in a way that is appropriate for the particular problem. In the general case, the near-bed shear stress is

$$\tau = \rho g R S_f \quad (5)$$

where  $R$  is the hydraulic radius and  $S_f$  is the friction slope. In channels with high width-to-depth ratios,  $R$  is nearly equal to the mean depth,  $h$ , hence these variables are substituted for each other.

An important practical issue with respect to eqn. 5 concerns the formulation of the term  $S_f$ . At the scale of individual features such as pools, riffles and runs (distances of, say, less than 1000 m), natural undulations in bed topography and channel width cause the flow to accelerate or decelerate, which increases or decreases the shear stress produced solely by the downstream component of the

weight of the water ( $\rho g h S$ ). In this case,  $S_f$  is estimated by solving the one-dimensional equation for gradually varied flow:

$$S_f = \frac{dH}{dx} = - \frac{d}{dx} \left( z + h + \frac{u^2}{2g} \right) \quad (6)$$

where  $H$  is the total energy,  $z$  is the bed elevation,  $u$  is the mean velocity in the downstream ( $x$ ) direction. Equation 6 is solved using the step-backwater method, a trial-and-error procedure that is described in many hydraulics texts (e.g. Henderson, 1966; Dingman, 1984), and can be easily programmed on spreadsheets. In this study, the step-backwater method was used with cross section and water-surface elevation data from short ( $\sim 500$  m) reaches to develop relations between  $\tau^*$  and  $Q$ , which were then used to estimate discharges for initial motion and bankfull flow.

At scales much greater than individual pools and riffles ( $> 1000$  m), the variations in channel form have much less of an effect on the boundary shear stress. In this case, the flow can be considered uniform, and the water-surface slope  $S_s$  can be used in place of  $S_f$  in (6). This assumption was adopted herein to calculate reach-average values of  $\tau^*$ .

To estimate the discharge required to initiate bed load transport (termed the critical discharge,  $Q_c$ ) we assume uniform flow, and combine the continuity equation ( $Q = w h u$ , where  $w$  is the flow width), with the Manning equation ( $u = h^{2/3} S_f^{1/2} / n$ , where  $n$  is a resistance coefficient), to get

$$Q = \frac{w h_c^{5/3} S_f^{1/2}}{n} \quad (7)$$

Here,  $h_c$  is the depth required to produce the assumed critical dimensionless shear stress at each cross section, calculated from (4) and (5) using the reach-average  $D_{50}$ . To estimate the bankfull discharge  $Q_b$ , we used the same equation (7) with the bankfull depth  $h_b$  and slightly lower values of Manning's  $n$ . On the basis of the results obtained in calibrating the step-backwater model, we selected values of  $n$  ranging from 0.035 in upstream reaches to 0.025 in downstream reaches.

Equation (7), after some algebraic manipulation involving the term  $S$ , can be rearranged to give a uniform-flow equation for the average boundary shear stress as a function of discharge:

$$\tau = \rho g h S = \rho g \left( \frac{Q n}{w} \right)^{0.6} S^{0.7} \quad (8)$$

The above equation indicates that for constant  $n$  and  $w$ ,  $\tau$  increases to the 0.6 power of  $Q$  and the 0.7 power of  $S$ ; graphically, eqn. 8 plots as a concave-down curve, with a slope that gradually decreases as  $Q$  increases. However, if any of the variables in (8) change with discharge, then the relation between  $\tau$  and  $Q$  may differ from the uniform-flow case. For example, if  $S$  increases with  $Q$ , the relation formed by (8) will be steeper and more nearly linear; conversely, if  $S$  or  $n$  decrease with  $Q$ , or if  $w$  increases, the relation will be flatter and more concave. Reach characteristics determine whether  $S$ ,  $n$  or  $w$  change much with discharge, but whatever the case, the shape of the  $Q$ - $\tau$  relation gives an indication of the potential change in shear stress for a given increment of water discharge: a near-linear relation indicates that  $\tau$  increases in proportion to  $Q$ , whereas a concave relation indicates that  $\tau$  increases more slowly as  $Q$  increases. Equation 8 thus represents a base case against which we can compare modeled discharge-shear stress relations in short reaches where the assumptions of uniform flow, or constant  $w$ ,  $n$  and  $S$ , generally do not hold.

## RESULTS

The results of our analyses are split into four sections. The first two sections focus on historical changes in channel morphology in the uppermost study reach (Rifle-DeBeque), and long-term trends in suspended sediment loads at the four mainstem gauging stations. The last two sections focus on existing channel characteristics and bed load sediment transport relations. All of these results have implications for habitats used by native fishes and other organisms, but the last two sets of results are perhaps most important for providing information and data on contemporary processes of habitat formation and maintenance.

### *Historical Changes in the Geomorphology of the Rifle-DeBeque Reach*

Comparison of aerial photographs of the alluvial reach between Rifle and DeBeque indicates that many portions of this reach have undergone significant geomorphic change since 1937. Figure 12 shows relative differences in main channel area, island area and side channel-backwater area for individual 1.6-km segments of the river. Figure 12a shows that the main channel has experienced relatively small changes in planform area overall, with individual segments of the river equally divided between those where channel area increased and those where channel area decreased. In contrast, Figures 12b and 12c show that there have been significant changes in the area of islands and side channels/backwaters. The change in island area is due mostly to the loss of several large islands between RKM 352 and RKM 376 which appear to have been used as gravel pits during the construction of the interstate highway. The change in side-channel/backwater area (Fig. 12c) is very systematic, with 25 out of 39 subreaches showing a decrease in area.

Table 3 provides a summary of these data. When the difference in area is proportioned over the total reach length of 58 km, the decrease in main channel area of -14 ha amounts to a reduction in average channel width of about 3 m; such a change (-3%) is probably too small to be considered significant. The changes in island area (-75 ha) and side channel area (-33 ha), on the other hand, are clearly significant, and would probably be greater if we could remove the bias introduced by the difference in flow levels in 1937 and 1995. Overall, the total area of islands in the study reach has decreased by 20%, while the total area of side channels and backwaters has decreased by 31% (Table 3). When the difference in area is proportioned over the total reach length, the total change amounts to a 6 m decrease in the average width of side channels. Given that these features are typically 10 to 20 m wide, a decrease in average width of 6 m represents a significant loss in potential fish habitat.

Table 3. Summary of channel changes within the Rifle-DeBeque reach of the Colorado River.

	<b>1937</b>	<b>1995</b>	Change in	Change per	Change
	Total Area	Total Area	Total Area	Unit Length <sup>1</sup>	in Area
	(ha)	(ha)	(ha)	(m)	(%)
Main Channel	469	455	-14	-3	-3
Islands	386	311	-75	-13	-20
Side Channels	105	72	-33	-6	-31

1. The change in area per unit length is computed on the basis of a total reach length of 58 km. Islands and side channels are not continuous over this length.

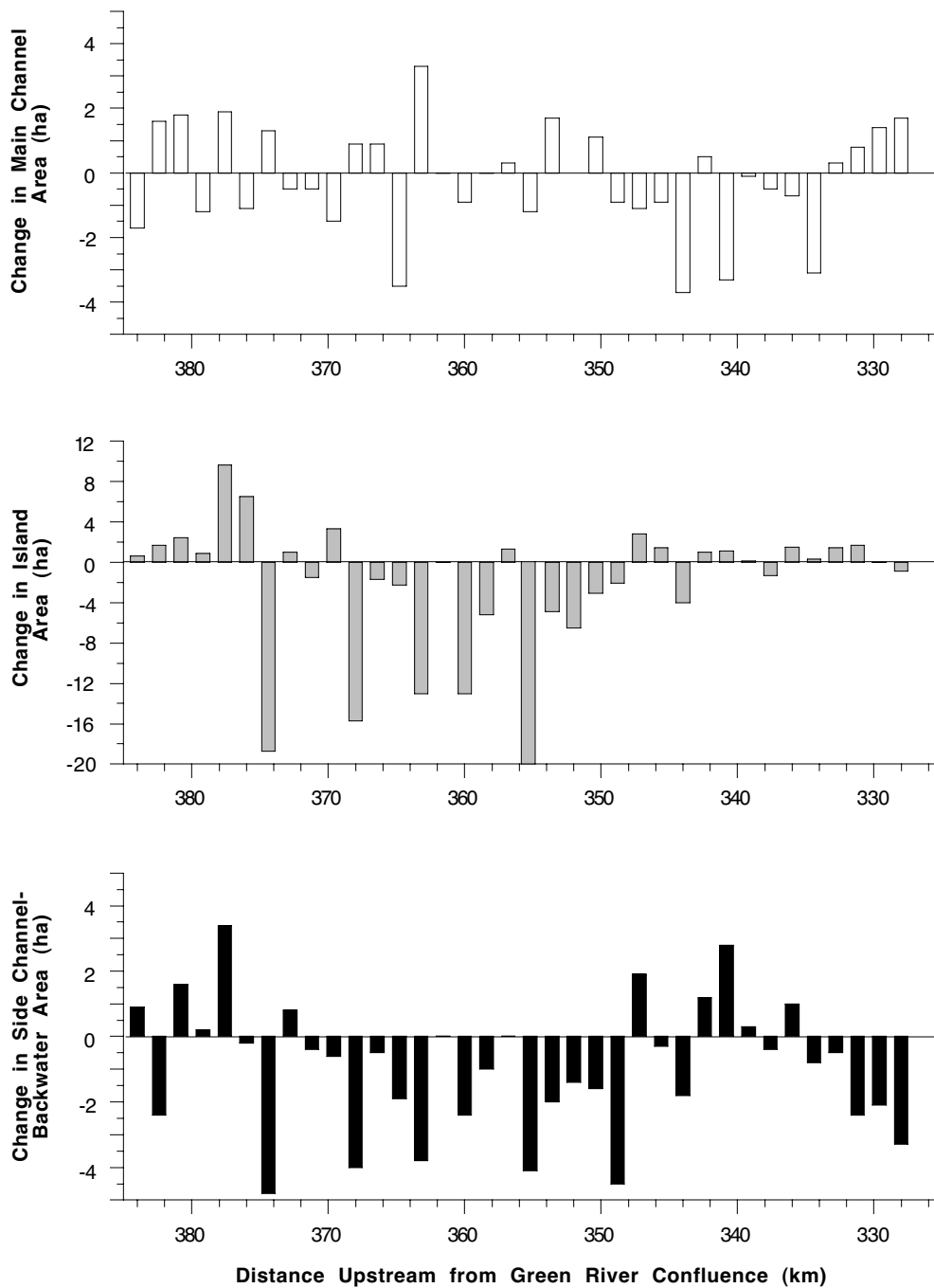


Figure 12. Changes in planform area of in-channel features within individual 1.6-km segments of the Colorado River between Rifle, CO, and DeBeque Canyon; (a) main channel area, (b) island area, (c) side-channel/backwater area.

These results indicate that the principal historical change in the Rifle-DeBeque reach has been for the channel to become less complex as a result of side channels filling in. The process by which this occurs is envisioned as follows. Side channels are characterized by lower flow depths and lower flow velocities than the main channel, thus even under natural conditions their sediment transport capacity is less than the main channel. If, as we have indicated in earlier work (Pitlick et al., 1999), the amount of sediment delivered to these reaches has not changed appreciably, but the river has lost some of its ability to carry this sediment, then whatever it cannot carry will be stored somewhere in the channel. Side channels are the likely sites of storage because they have a lower sediment transport capacity. It is also true that flows through side channels are more ephemeral. Side channels are topographically higher than the main channel, and so are not inundated as often—some side channels may experience flow every year, while others may not experience flow for several years, and then perhaps for only a few days. This allows sediment to build up on the bed, and increases the chance that vegetation will colonize the deposits and stabilize them. Vegetation promotes further deposition until, eventually, the side channel fills to the level of the floodplain. It is hard to say whether a 20-40% reduction in side-channel habitats is significant as far as the native fishes are concerned, or whether this would limit their reintroduction, but it seems clear that these features have been lost over time and the channel is less complex now than it was in the past.

In previous studies, Pitlick et al. (1999) found that between 1937 and 1993 the total area of the main channel of the Colorado River decreased by 15%, and the total area of side channels and backwaters decreased by 26% (Table 4). When proportioned over a total reach length of 84 km, the changes in main-channel and side-channel area equated to decreases in average width of about 20 m and 7 m, respectively. The present study yields similar results for the Rifle-DeBeque reach, although the change in main channel width appears to be negligible. In comparing the two reaches (Tables 3 and 4), we note that the total area of side channels remaining in the Rifle-DeBeque reach (~70 ha) is about the same as the total area of side channels lost in the Grand Junction reach (~60 ha). This result has important management implications because it suggests that a considerable amount of potential habitat for the Colorado pikeminnow is available upstream, and that access to this additional habitat can be provided by outfitting the diversion dams in DeBeque Canyon with fish-passage structures. However, Osmundson's (1999) analysis of water temperatures in these upper reaches suggests that conditions favoring growth of Colorado pikeminnow may be sub-optimal much of the time. It is not really clear, therefore, that the additional habitat in the Rifle-DeBeque reach is as suitable in a biological sense as the reaches downstream. This question probably warrants further study, but our results suggest that adult pikeminnow may benefit from having access to the reach, particularly in low-water years when water temperatures are higher.

Table 4. Summary of previous analyses of geomorphic changes within the 15-mile, 18-mile and Ruby-Horsethief Canyon reaches of the Colorado River (from Pitlick et al., 1999).

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

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

### *Trends in Suspended Sediment Loads*

The suspended sediment load of the Colorado River increases systematically downstream as sediment from erosive areas in western Colorado and eastern Utah enters the main stem. At Glenwood Springs, near the eastern edge of the Colorado Plateau, the annual suspended sediment load averages about  $0.4 \times 10^6$  tons/yr (Table 5). Between there and the Cameo gauge, the annual load increases by a factor of four to about  $1.5 \times 10^6$  tons/yr. The annual load at the State Line gauge is about  $3.4 \times 10^6$  tons/yr, with most of this increase being due to the Gunnison River. At the Cisco gauge the load is about  $5.4 \times 10^6$  tons/yr (Table 5). This increase is relatively large considering the Cisco and State Line gauges are only 55 km apart. However, the difference is not unreasonable given the characteristics of the Dolores River basin (sparse vegetation, widespread exposures of shale bedrock) and the influence of the late season storms. The annual suspended sediment load at Cisco, while high ( $\sim 87$  t/km<sup>2</sup>/yr), is typical of large rivers in semi-arid regions.

Table 5. Summary statistics of average annual discharge and annual sediment load for 4 gauging stations on the main stem of the Colorado River.

USGS Station No.	Drainage Area (km <sup>2</sup> )	Period of Record <sup>1</sup>	Annual Discharge <sup>2</sup>			Annual Sediment Load <sup>2</sup>		
			$\bar{Q}$	SD	$C_v$	$\bar{Q}_s$	SD	$C_v$
9072500	11,800	1934-1997	64	19	0.29	0.37	0.30	0.82
9095500	20,800	1934-1997	111	33	0.30	1.53	1.02	0.66
9163500	46,200	1952-1997	180	72	0.40	3.43	2.67	0.78
9180500	62,400	1934-1997	200	76	0.38	5.43	3.67	0.68

1. Periods of record for the Glenwood Springs gauge (9072500) and the Cisco gauge (9180500) were arbitrarily truncated at 1934 to coincide with the period of record for the Cameo gauge (9095500); the record for the State Line gauge (9163500) begins in 1952, thus no adjustment was made.
2. The mean ( $\bar{Q}$ ) and standard deviation (SD) are expressed in the same units as the data themselves, e.g., in m<sup>3</sup>/s or millions of tons/yr; the coefficient of variation ( $C_v = SD/\bar{Q}$ ) is dimensionless.

The large increase in sediment load between the Cameo and Cisco gauges reflects both an increase in average sediment concentration and an increase in discharge. Referring back to eqn. 1, note that  $Q_s$  is a function of both  $C_s$  and  $Q$ . The difference in  $Q$  between the Cameo and Cisco gauges is not large enough by itself to account for the difference in  $Q_s$ , thus the downstream increase in sediment load must be due to differences in suspended sediment concentration. To evaluate the importance of this difference, we analyzed suspended sediment data from the Cameo and Cisco gauges further by counting the number of observations in which suspended sediment concentrations fell within specified ranges (excluding late-season events which produce concentrations  $>10,000$  mg/l). The results of this analysis (Fig. 13) show that, first, the frequency distributions of pre- and post-peak suspended sediment concentrations are roughly log-normal at both gauges. Second, it is apparent in comparing the data that sediment concentrations are generally higher at the Cisco gauge than they are at the Cameo gauge. This is particularly true of the post-peak samples, in which concentrations commonly exceed 500 mg/l at Cisco, but rarely reach these values at Cameo. In practical terms, these results indicate that summer-time sediment concentrations and turbidity are typically higher in downstream reaches than in upstream reaches. These differences are likely to have some effect on ecological processes because, in general, primary productivity decreases as turbidity increases.

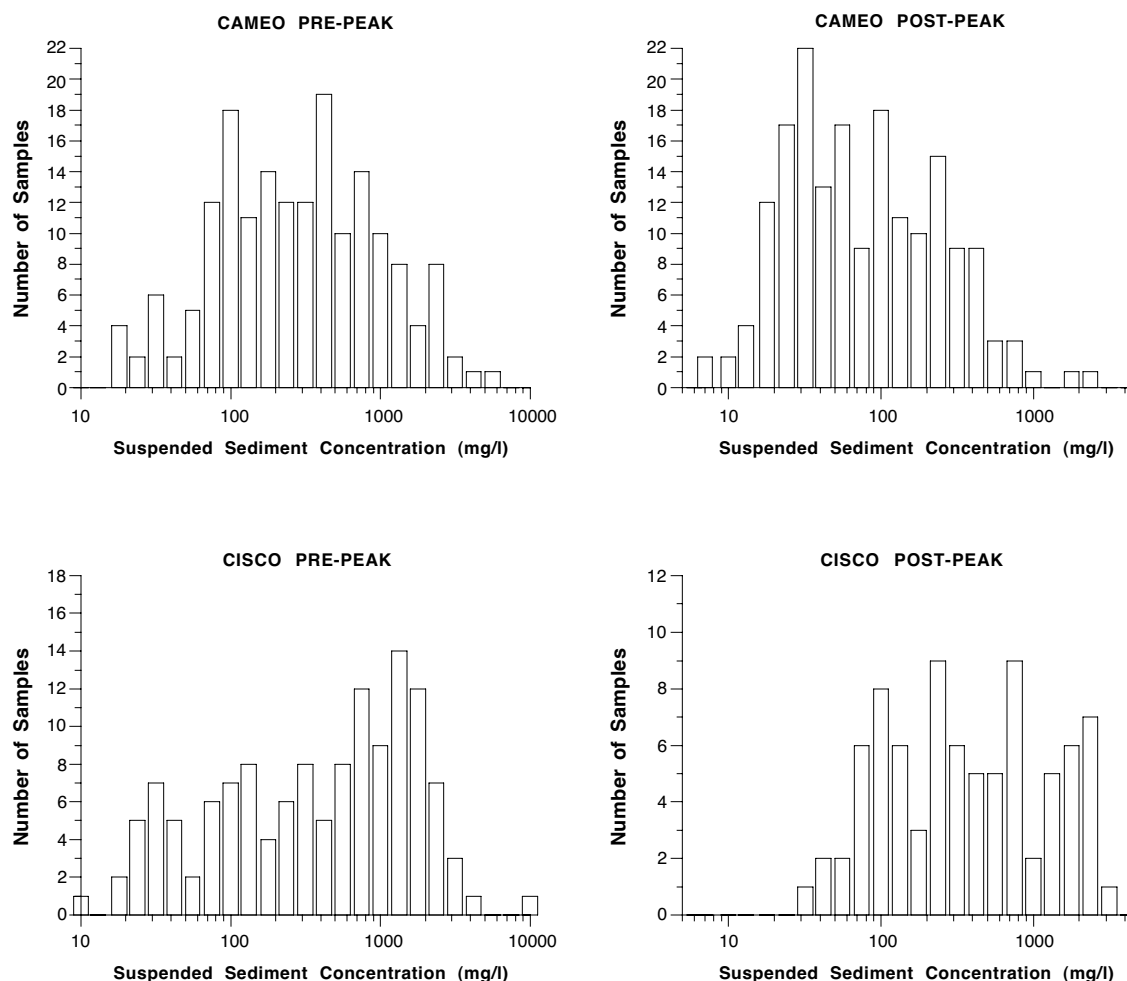


Figure 13. Comparison between suspended sediment concentrations of pre- and post-peak samples from the Colorado River near Cameo, CO, and the Colorado River near Cisco, UT.

The second part of this analysis focused on the long-term effects of flow regulation on sediment loads. The results indicate that reservoirs and flow diversions have had system-wide impacts on the streamflow and sediment-transport regimes of the Colorado River. Figure 14 shows long-term trends in the average annual discharge and suspended sediment load of the Colorado River at these four gauges (see Appendix Table A-1 for a listing of the annual values). The trends at each site are similar, with the annual variations in suspended sediment load generally mimicking the annual variations in discharge. However, at all sites the variability in annual sediment load is greater than the variability in annual discharge. This is a consequence of the nonlinear relation between water discharge and sediment load (eqn. 2), which can result in large differences in load for small differences in flow. In statistical terms, the differences in streamflow and sediment-load are reflected by the respective values of the coefficient of variation,  $C_v$  (Table 5). Note that the  $C_v$  of the annual sediment loads ranges from 0.66 to 0.82, whereas the  $C_v$  of the annual discharges ranges from 0.29 to 0.40. Stating this another way we can say that the deviation in average annual suspended sediment loads is roughly twice the deviation in average annual discharge.

A second, system-wide trend revealed by these data is the distinct period from the late 1950s through the late 1970s when annual sediment loads were much lower than the period before or after. Pitlick et al. (1999) have previously suggested that significant amounts of sediment would have been deposited in the channel during this time, which may have had long-lasting effects on native fish populations. The statistical significance of these differences was evaluated here using the Mann-Whitney test, a nonparametric procedure that is appropriate for situations in which the assumptions of standard parametric procedures are not satisfied (e.g. if the data are not normally distributed). The Mann-Whitney test is essentially a test of differences in means (similar to the t-test), but rather than comparing the data themselves, the test examines differences in the ranks of individual values (Berenson et al., 1988). Two samples are considered to be statistically different if they contain disproportionate numbers of highly or lowly ranked values. Comparisons were made between two periods, 1934-58 and 1959-97; the State Line gauge was excluded from the analysis because the record includes only five years prior to 1958.

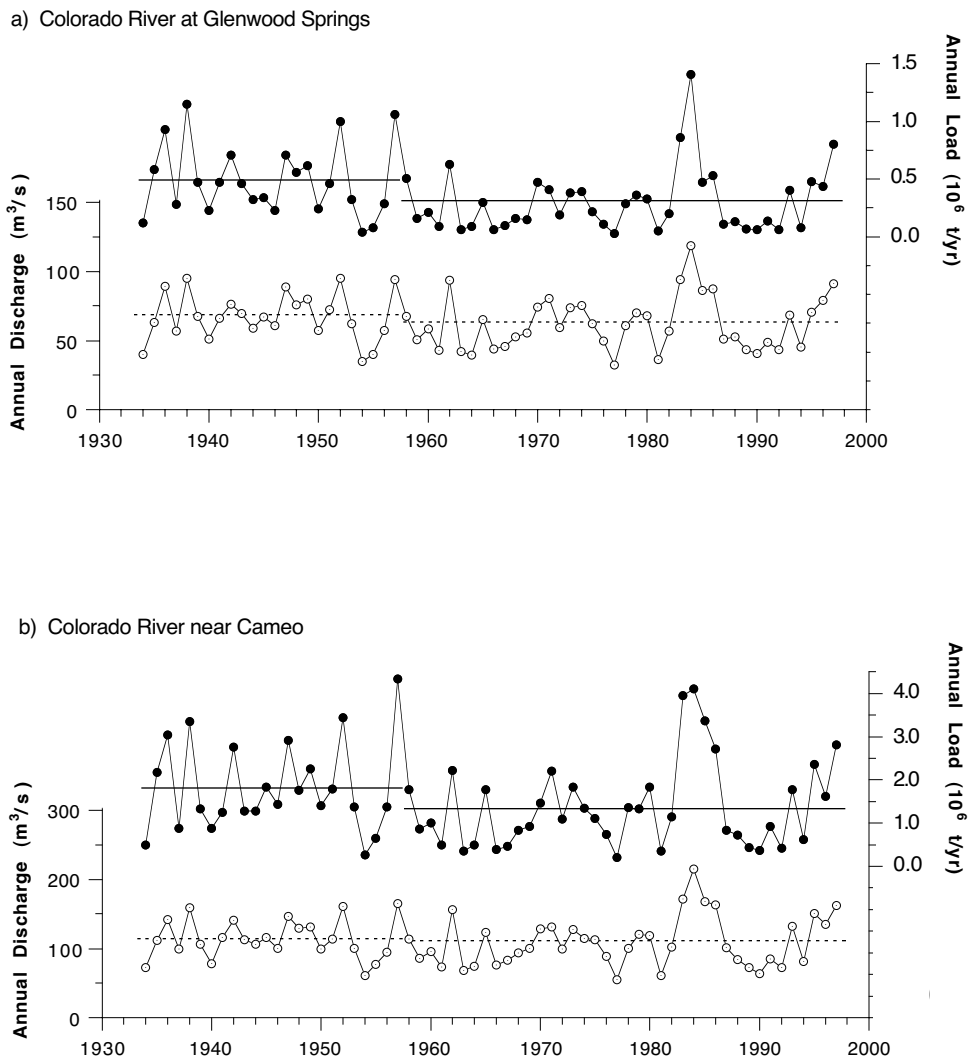


Figure 14. Trends in annual discharge and suspended sediment load at (a) Glenwood Springs and (b) Cameo. Horizontal lines indicate means for the periods 1934-1958 and 1959-1997.

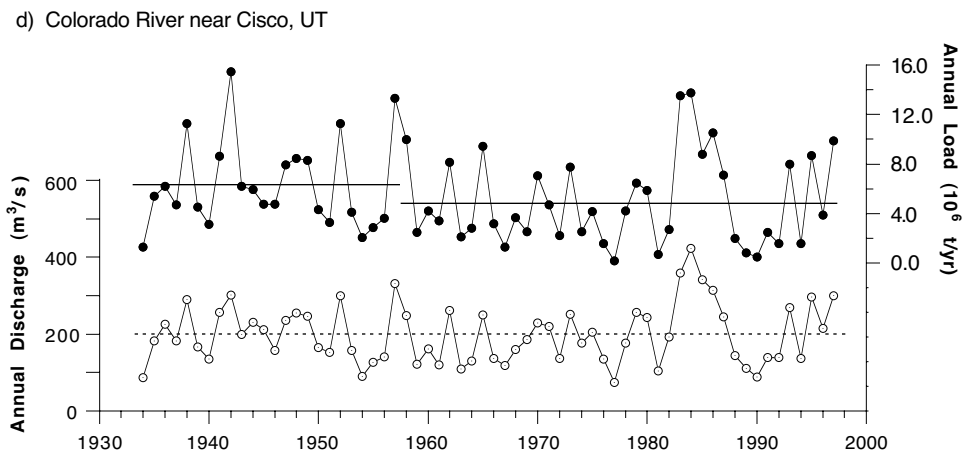
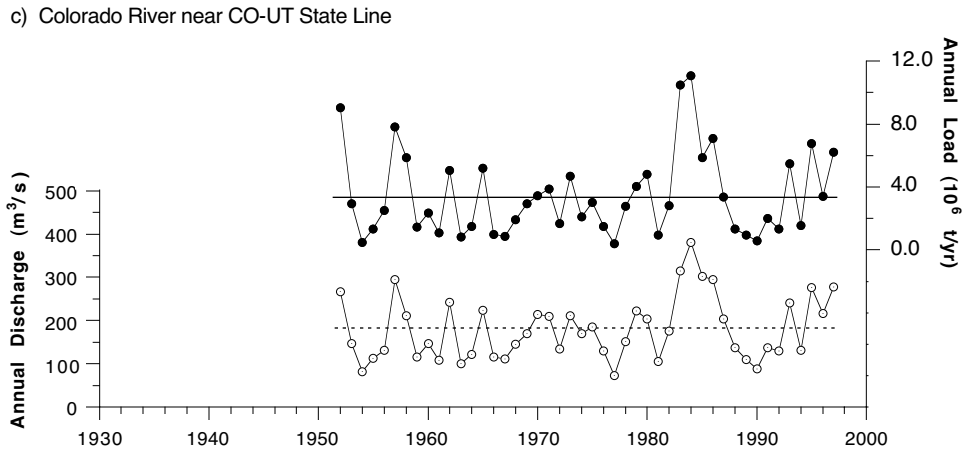


Figure 14 (cont.). Trends in annual discharge and suspended sediment load at the (c) State Line and (d) Cisco gauges. Horizontal lines indicate means for the periods 1934-1958 and 1959-1997.

The results of the Mann-Whitney tests (Table 6) show that since 1934 there has been no significant change in the mean annual discharge of the Colorado River; this is indicated by the low values of the test statistic,  $z$ , and the high values of the significance probability,  $p$ . This result is potentially misleading, however, because it does not take into account the effects of transbasin diversions, many of which were in place prior to 1934.

Turning to the comparisons of sediment loads, the test results indicate that there have been significant changes in the average annual suspended sediment load of the upper Colorado River since the late 1950s ( $p$  values ranging from 0.002 to 0.02; Table 6). Interestingly, the difference between pre- and post-1958 sediment loads decreases downstream, from 40% at the Glenwood Springs gauge to about 25% at the Cisco gauge. This trend likely reflects a combination of the

downstream-diminishing effects of reservoir regulation, and the added input of sediment from unregulated tributaries. Thus, while the hydrologic and geomorphic effects of reservoir operations are very apparent in these and other data (c.f. Pitlick et al., 1999), the results presented in Table 6 suggest that these effects tend to diminish downstream.

Table 6. Summary statistics and results of Mann-Whitney tests for differences in annual discharge and sediment load. The test statistic,  $z$ , is the standard normal variate and  $p$  is the significance probability associated with particular values of  $z$ .

USGS Station No.	Period of Record	Annual Discharge			Annual Sediment Load		
		$\bar{Q}$	$z$	$p$	$\bar{Q}_s$	$z$	$p$
9072500	1934-1958	68			0.49		
	1959-1997	62	1.45	0.073	0.29	2.84	0.002
9095500	1934-1958	114			1.81		
	1959-1997	109	0.93	0.176	1.35	2.07	0.019
9180500	1934-1958	203			6.46		
	1959-1997	197	0.67	0.252	4.77	2.15	0.016

Although the above results show that the quantity of suspended sediment carried by the Colorado River has in general decreased, there does not appear to be any long-term trend in the grain size of the suspended sediment load (Fig. 15). A time-series plot of sand-fraction data from the Cisco gauge shows that, while there is a very wide range in the percentage of sand carried in suspension (0-70%), the amount of sand versus silt and clay have remained essentially the same since the early 1950s (Fig. 15). This result does not imply that the river is carrying the same amount of sand now as it was in the past, rather that the proportions of sand, silt and clay have stayed roughly the same over time. Overall, the suspended sediment load of the Colorado River has decreased because the construction and operation of reservoirs has reduced the magnitude and duration of peak flows.



Figure 15. Percentage of sand in suspended sediment samples, Colorado River near Cisco, UT.

### *Longitudinal Trends in Channel Characteristics*

Our description of downstream trends in the channel characteristics of the Colorado River begins here with a discussion of the relation between channel gradient and particle size. These two variables are closely related, and it has been shown in previous studies that, in the absence of bedrock or structural controls, grain size and bed elevation decrease exponentially downstream (e.g. Bradley et al., 1972). Figure 16 shows a plot of the longitudinal profile of the Colorado River from approximately Rulison, CO to Moab, UT. When plotted at this scale the profile appears to be relatively smooth, except for a steep section through Westwater Canyon (RKM 180-190). Although it is not particularly obvious, the y-axis is scaled in logarithmic units. Plotting the data this way illustrates the fact that the longitudinal profile deviates slightly from the expected exponential trend. A straight line exponential fit through all data points gives an average gradient of 0.0010, but the profile clearly deviates from the average slope at the upper and lower ends.

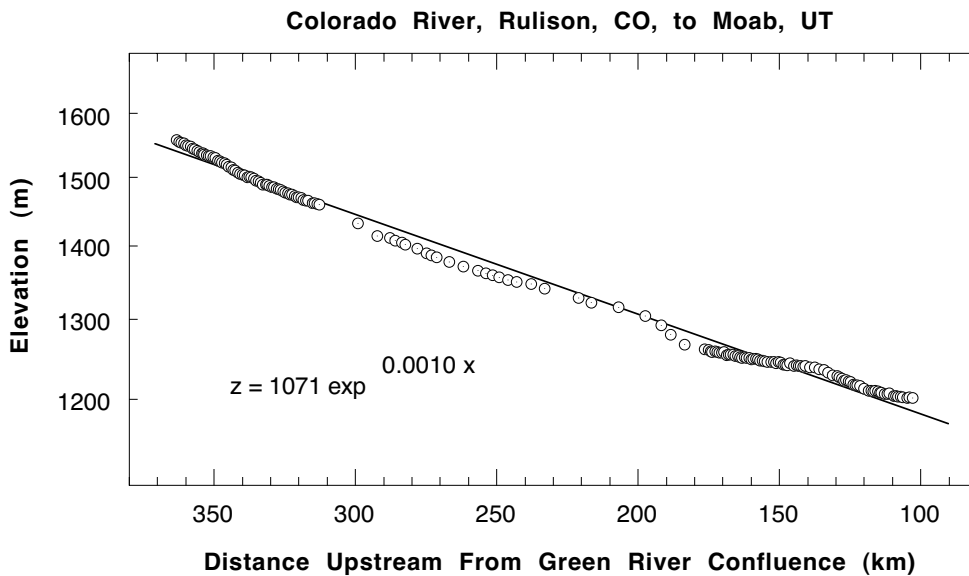


Figure 16. Longitudinal profile of the Colorado River from Rulison, CO, to Moab, UT. The y-axis is scale in logarithmic units to show that the profile deviates from an exponential trend given by the inset equation. The inflections in the profile at RKM 200 and RKM 140 correspond to reaches through Westwater Canyon and Professor Valley, respectively.

Detailed plots of channel gradient derived from GPS measurements in specific subreaches show that there can be subtle inflections in the river's profile (Fig. 17). These inflections are not always caused by transitions in bedrock lithology, as might be expected. In the reach between Rifle and DeBeque Canyon, for example, there is a slight decrease in slope at about RKM 340 (Fig. 17a). This point is 10 km upstream of the nearest tributary, Roan Creek, and more than 15 km upstream of DeBeque Canyon, so it is unlikely that these features have any influence on the profile at that point. In contrast, there is no change in channel gradient where the Colorado River enters DeBeque Canyon and encounters more resistant bedrock (Fig. 17a). Likewise, there is no change in gradient in the transition between the 18-mile reach and the Ruby-Horsethief Canyon reach. In contrast, measurements between Cisco landing and Moab, UT show that the profile becomes much steeper through Professor Valley (Fig. 17b). As mentioned earlier, the inflection in the profile at this point is due to neogene uplift and deformation caused by vertical movement of salt.

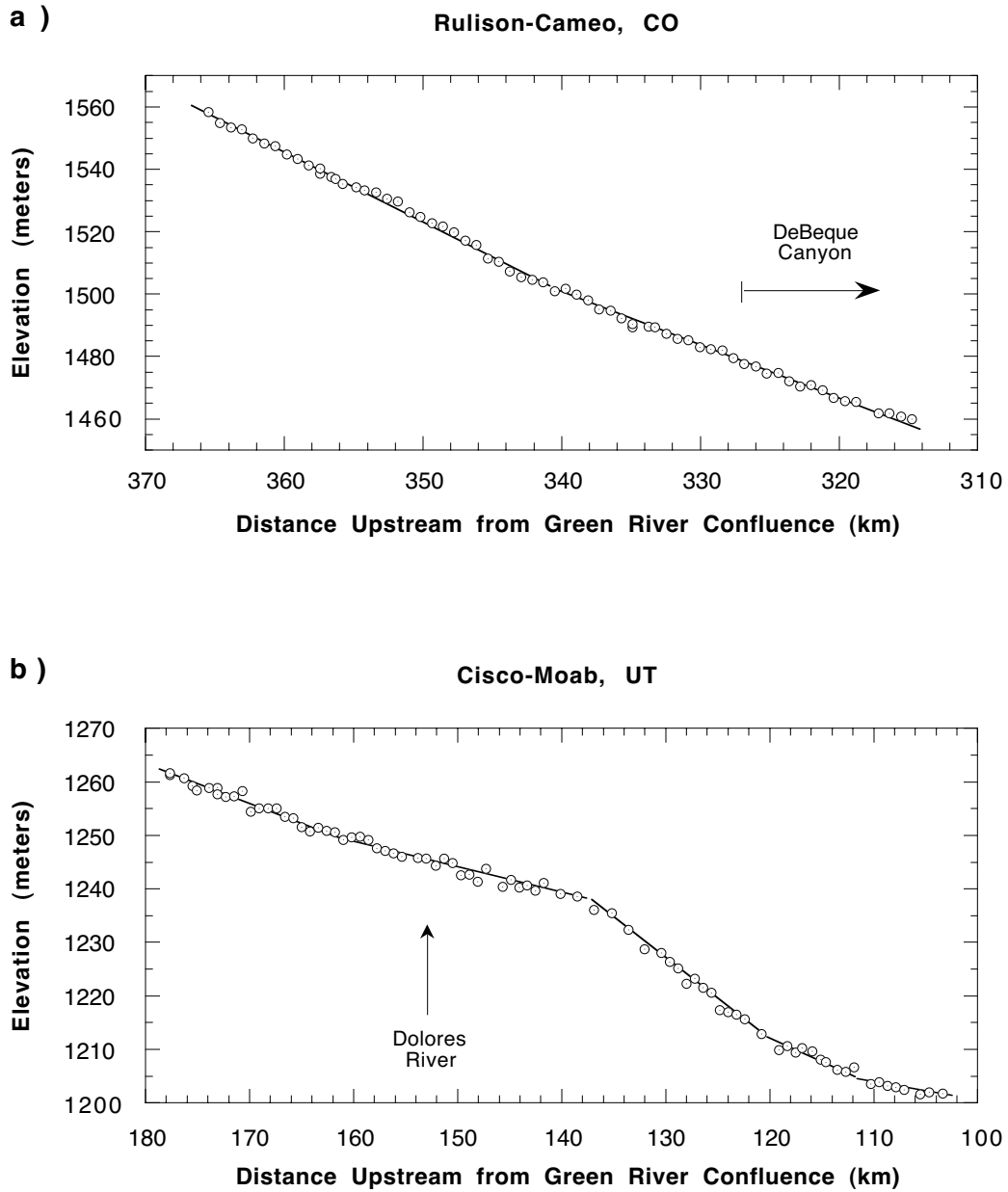


Figure 17. Plots of channel gradient in selected subreaches of the Colorado River between (a) Rulison and Cameo, CO, and (b) Cisco Landing and Moab, UT.

The bed sediment texture of the Colorado River can vary significantly from place to place (see appendix Tables A-2 and A-3). Nonetheless, plots of specific percentiles of the grain size distribution ( $D_{84}$ ,  $D_{50}$ , and  $D_{16}$ ) show that the sizes of both the surface and subsurface bed material decrease systematically downstream (Fig. 18). Exponential fits of the surface-sediment data (Fig. 18a) give a series of subparallel lines with slopes ranging from 0.0009 to 0.0011. Percentiles of the subsurface sediment size distributions are also well fit by exponential functions (Fig. 18b), although the exponents in these relations are somewhat higher (0.0021-0.0034) than in the surface-sediment relations.

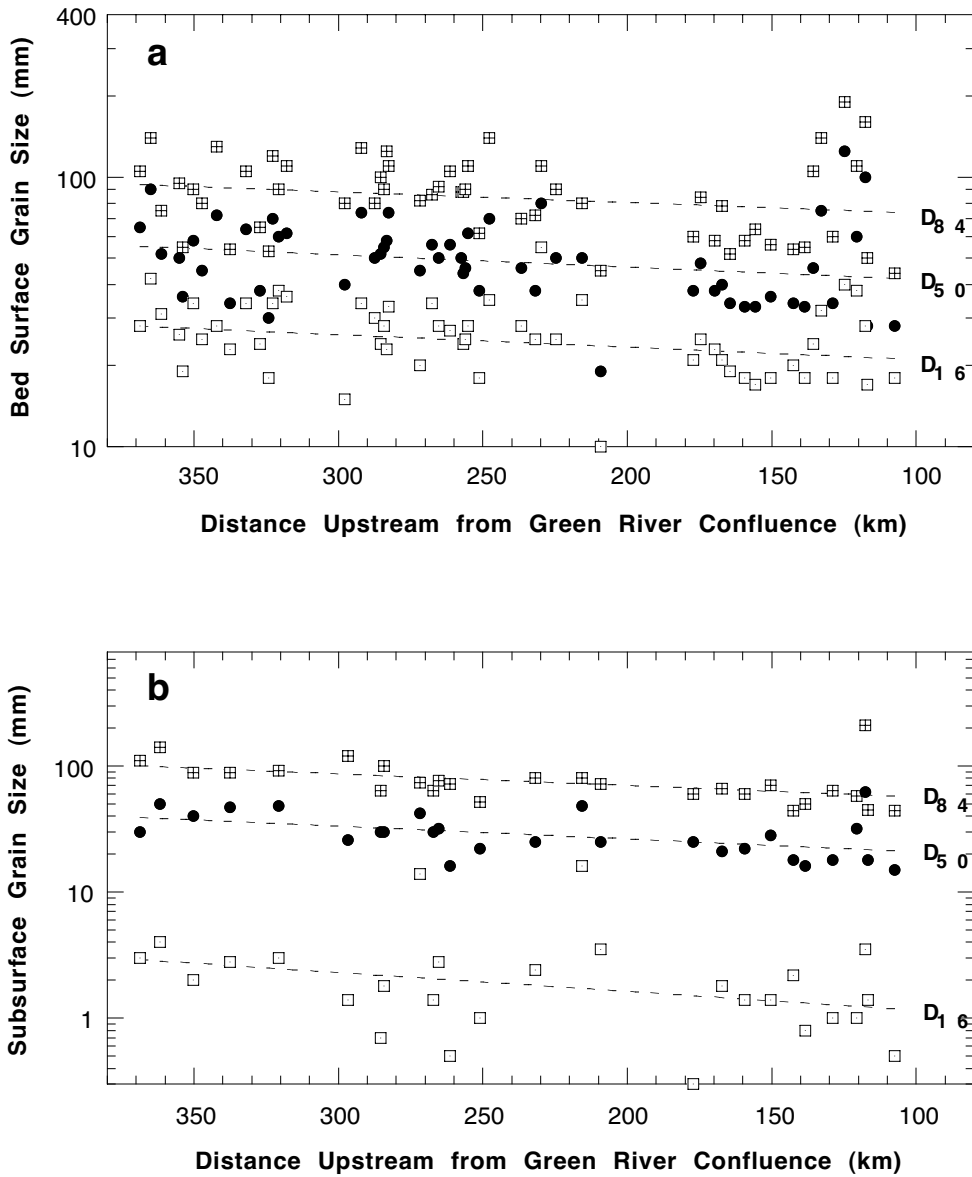


Figure 18. Downstream trends in grain size of the Colorado River; (a) percentiles of the surface sediment size distribution; (b) percentiles of the subsurface sediment size distribution.

Our cross section measurements indicate that the bankfull width and depth of the Colorado River increase systematically downstream, although not in proportion to each other. The general trends in cross section morphology (or hydraulic geometry) are illustrated in Figure 19, which shows a series of main-channel cross sections arrayed from upstream to downstream. These sections are all located in runs, thus they can be considered representative of individual reaches. Note the average bankfull depth increases from about 2.5 m at RKM 345 (stratum 11) to about 5 m at RKM 106 (stratum 2), whereas over the same distance, the average bankfull width increases from 114 m to 151 m (see Table 1).

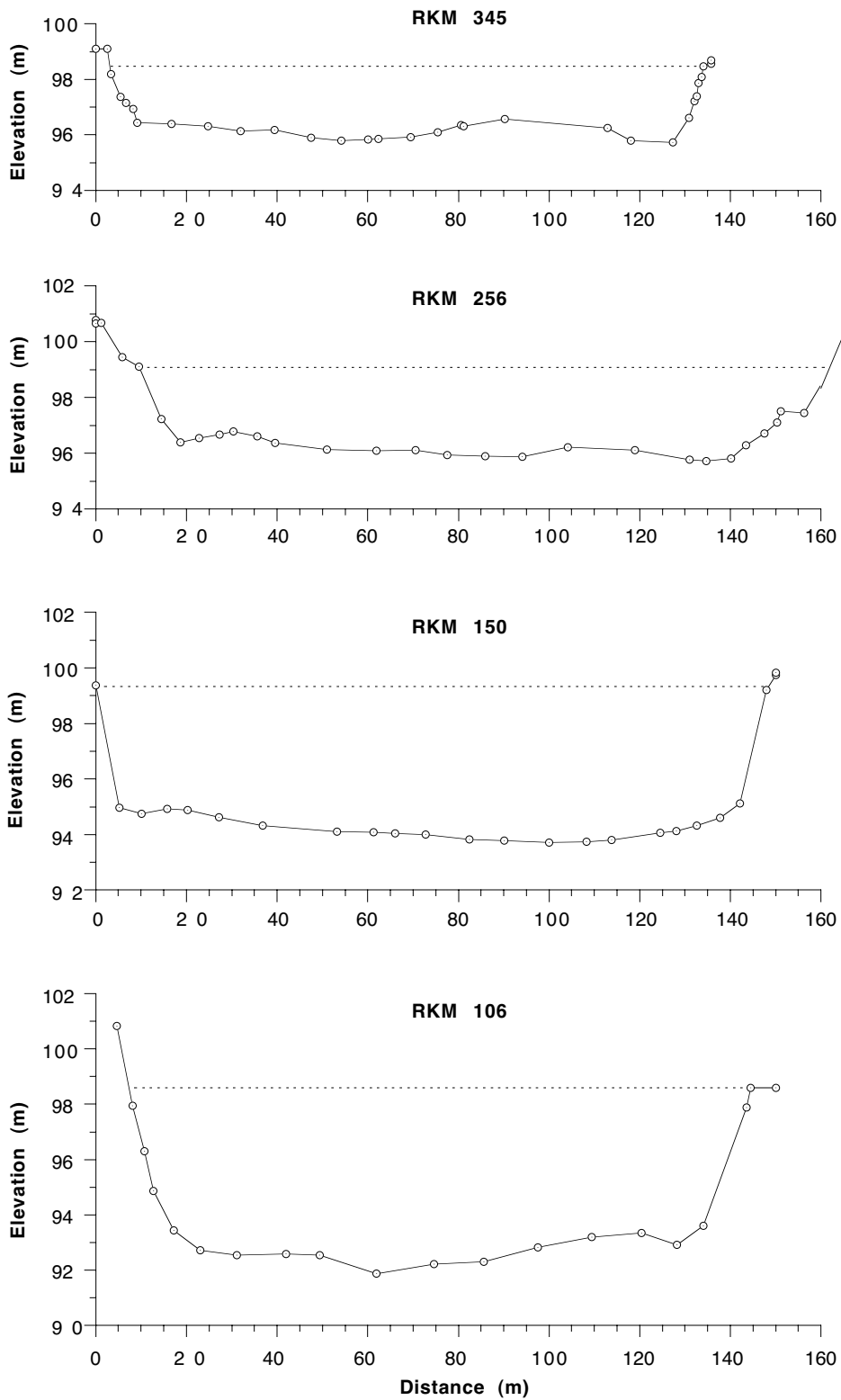


Figure 19. Selected cross sections of the Colorado River. Dashed lines indicate bankfull flow.

The individual measurements of bankfull width and depth are plotted on mile-by-mile basis in Figures 20a and 20b (the complete data set, numbering 149 cross section measurements, is given Table A-4). These data are further subdivided according to whether the cross section is located in an alluvial or quasi-alluvial reach. In comparing adjacent reaches we note some differences in the bankfull width and depth, but these differences are generally small and not statistically significant (Cress, 1997). Note that the y-axes are again scaled in logarithmic units to facilitate comparison with the previous data on slope and grain size. An exponential fit of the trend in bankfull width gives a weak straight-line relation ( $R^2 = 0.14$ ) with a slope of 0.0016. A fit of the bankfull depth data yields a moderately strong exponential relation ( $R^2 = 0.50$ ) with a slope of 0.0030. The difference in exponents indicates that the bankfull depth increases downstream at about twice the rate of the bankfull width.

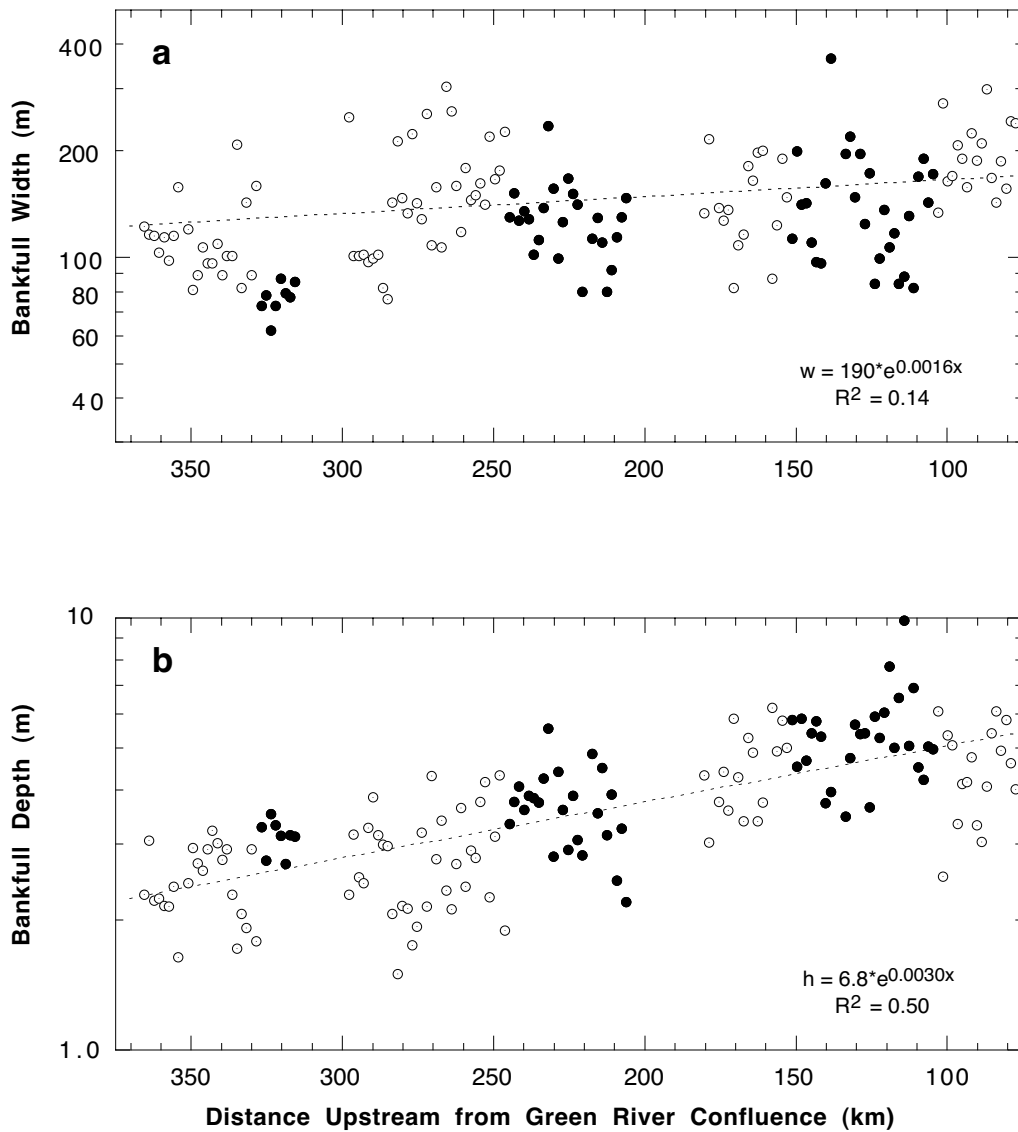


Figure 20. Trends in (a) bankfull width and (b) depth of the Colorado River. Open circles indicate cross sections in alluvial reaches; closed circles indicate cross sections in quasi-alluvial reaches.

Combining the cross-section measurements of bankfull depth with reach-average values of slope and grain size, we get corresponding estimates of the bankfull shear stress,  $\tau_b$ , and the bankfull dimensionless shear stress,  $\tau_b^*$  (Fig. 21). Over the full length of the study area, the  $\tau_b$  decreases by a factor of 3, from an average of 47 N/m<sup>2</sup> in the uppermost reach to an average of 17 N/m<sup>2</sup> in the lowermost reach (Fig. 21a). The high values of  $\tau_b$  clustered around RKM 125 coincide with Professor Valley. A least-squares fit of the full data set gives a weak exponential relation ( $R^2=0.16$ ) with a slope of -0.0032. Over the same distance the median grain size decreases by a factor of 2 (Table 1), resulting in a slight decrease in the  $\tau_b$  (Fig. 21b). This trend is subtle, however, and the slope of the best-fit regression line is not significantly different from zero. For the reach as a whole, the  $\tau_b^*$  averages 0.049. We emphasize the trend in  $\tau_b^*$  because of its importance in sediment transport relations. The consistency in  $\tau_b^*$  indicates that specific sediment transport thresholds are likely to be exceeded in many places, providing some assurance that prescribed discharges will achieve the desired effects on a widespread basis.

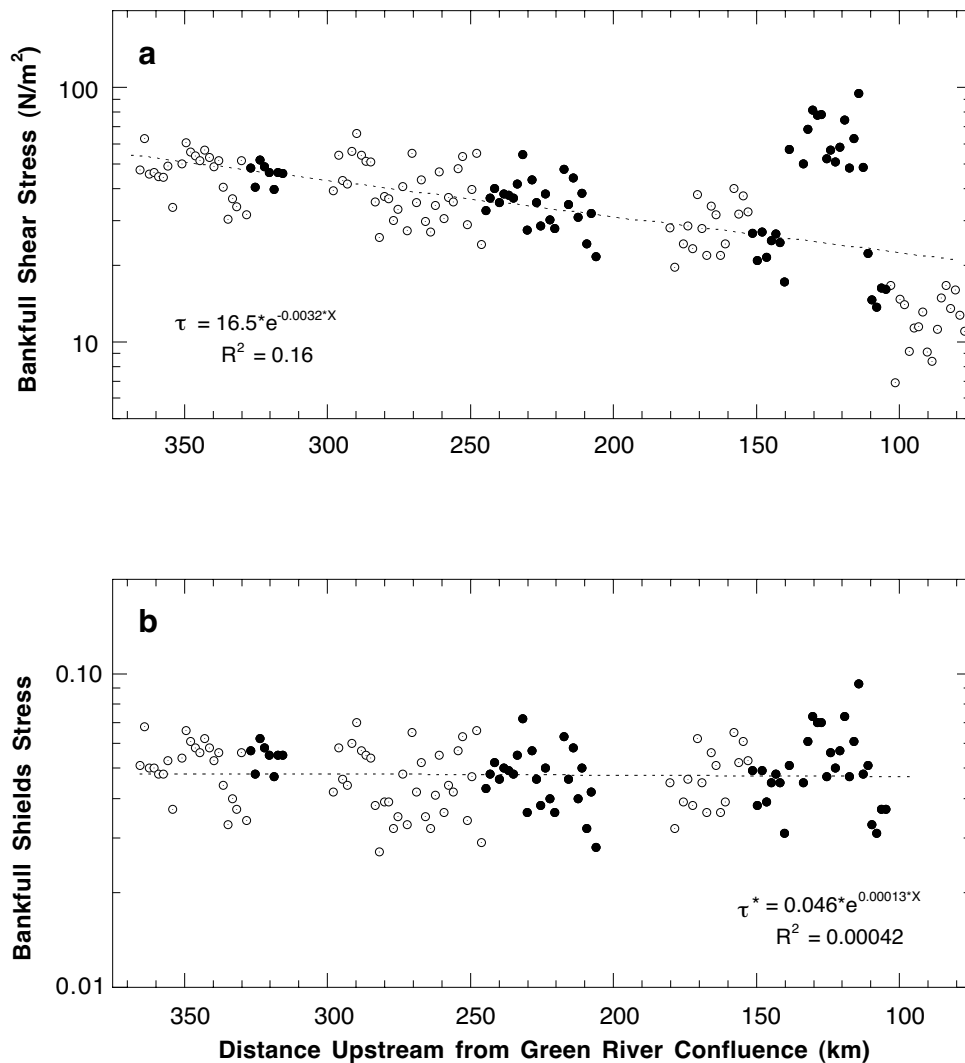


Figure 21. Downstream trends in (a) bankfull shear stress and (b) bankfull dimensionless shear stress of the Colorado River. Symbols are the same as in Figure 20.

### Thresholds for Coarse Sediment Transport

Our estimates of discharges required to move framework gravel particles are arrived at through a two-step process. The first step involves calibrating the hydraulic flow model in short reaches where we have measurements of the channel geometry and corresponding water surface elevations for a series of known discharges. These calculations provide verified values of the roughness coefficient (Manning's  $n$ ), and site-specific relations between discharge and dimensionless shear stress. Counting the three sites discussed below, and the seven sites studied by Pitlick et al. (1999), we have now developed discharge-shear stress relations for ten sites. The second step of the process involves extrapolation of the results from individual sites to longer reaches. This is done by using eqn. (7) along with field-verified values of  $n$  and measured values of width and depth at each of the 149 main-channel cross sections.

To illustrate the basic elements and results of the modeling procedure, Figure 22 shows data from a series of measurements in a 450-m reach near RKM 345. The lower line connecting the average bed elevations shows that the reach is predominantly a run. The closely spaced lines at the top of the figure show calculated water surface profiles for discharges of 300 and 282  $\text{m}^3/\text{s}$ ; an additional set of points corresponding to the latter discharge shows observed water surface elevations. The agreement between observed and calculated water surface elevations for this flow is excellent, with a maximum difference of only 6 cm. This fit was achieved using a Manning's  $n$  of 0.035. The same value was used in modeling the water surface profile for 300  $\text{m}^3/\text{s}$  (about half of the bankfull discharge), with the downstream water surface elevation estimated from a uniform-flow equation (see Bailey and Ray, 1966), and upstream elevations obtained through the trial and error procedure of the step-backwater method. The same steps were repeated for other discharges to give a series of modeled water surface profiles. In the absence of field measurements, the one constraint that can be used to check these results is that, at high flows, the modeled water surface slope should be roughly the same as the reach average slope, which we estimate is 0.0021 on the basis of the GPS measurements.

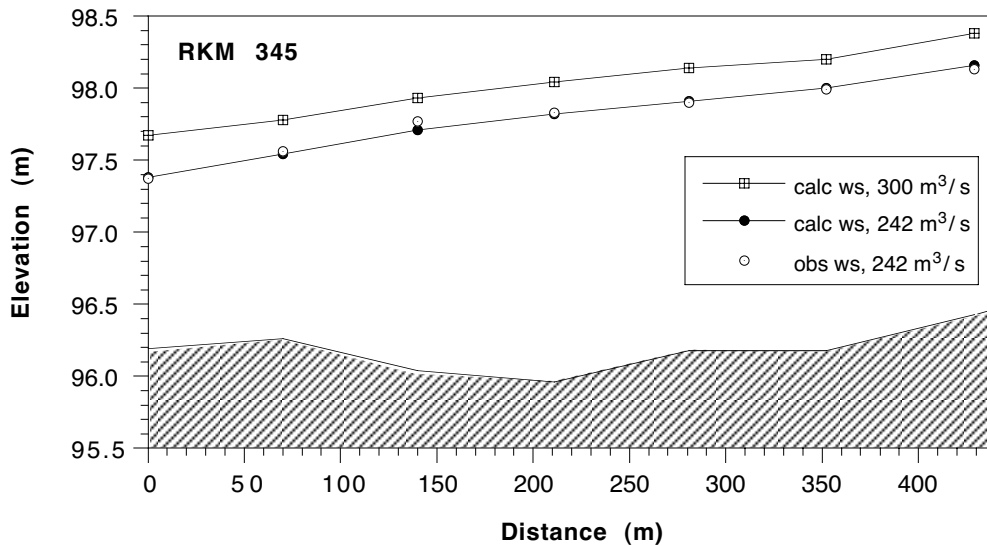


Figure 22. Bed and water surface elevations in a reach near RKM 345.

The model runs provide, among other things, estimates of the flow depth  $h$  and energy slope  $S_f$  at each cross section. This information is used with (4) and (5) to calculate the dimensionless shear stress at each cross section, and to formulate an empirical relation between  $Q$  and  $\tau^*$ , as shown in Figure 23. A power-law fit of the average values of  $\tau^*$  for this site gives a curvilinear relation with an exponent of 0.73. The value of the exponent is slightly higher than the uniform-flow value (0.60) because, here, the  $S_f$  increases from 0.0018 to 0.0021 over the range of flows considered.

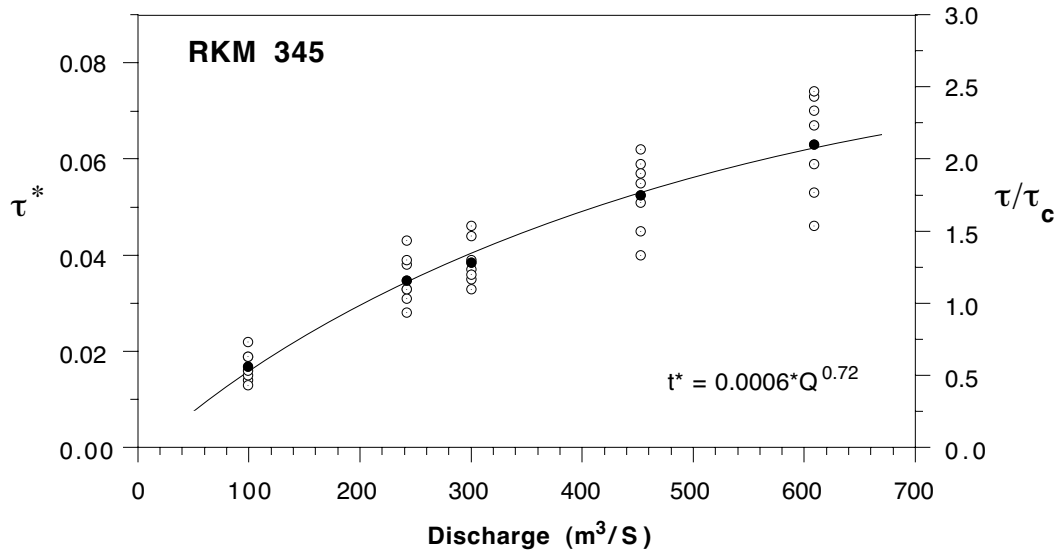


Figure 23. Relation between discharge and dimensionless shear stress, RKM 345.

From the above relation, we estimate that the threshold for *initial* motion in this reach is exceeded at a discharge of  $\sim 210$  m<sup>3</sup>/s (recall that initial motion is the flow corresponding to  $\tau^* = 0.030$ , which is the point where a few framework particles are just beginning to move). The bankfull flow (or the point where most all of the framework particles are moving) is reached at a discharge of about 390 m<sup>3</sup>/s. These discharges are somewhat low in comparison to our reach-average estimates (see below) because the grain size measured at this site (48 mm) is small in comparison to the reach-average value for this segment of the Colorado River (57 mm; Table 1).

Similar measurements and calculations were done at two additional sites in the lower part of the study area. One site is located at RKM 150, about 4 km downstream of the Cisco gauge; the other site is located at RKM 106, about 4 km upstream of the Moab bridge. Water surface elevations were measured at site RKM 150 on three different occasions, and at RKM 106 on four different occasions. These measurements allow us to verify model results over a broad range of discharges, rather than relying on a single set of observations as was done at the site discussed above. We obtained excellent agreement between the observed and calculated water surface elevations at the upper site (RKM 150) by choosing  $n$  values of 0.027-0.029 (Fig. 24a). Similar results were obtained at the lower site (RKM 106) choosing  $n$  values of 0.025-0.026 (Fig. 24b).

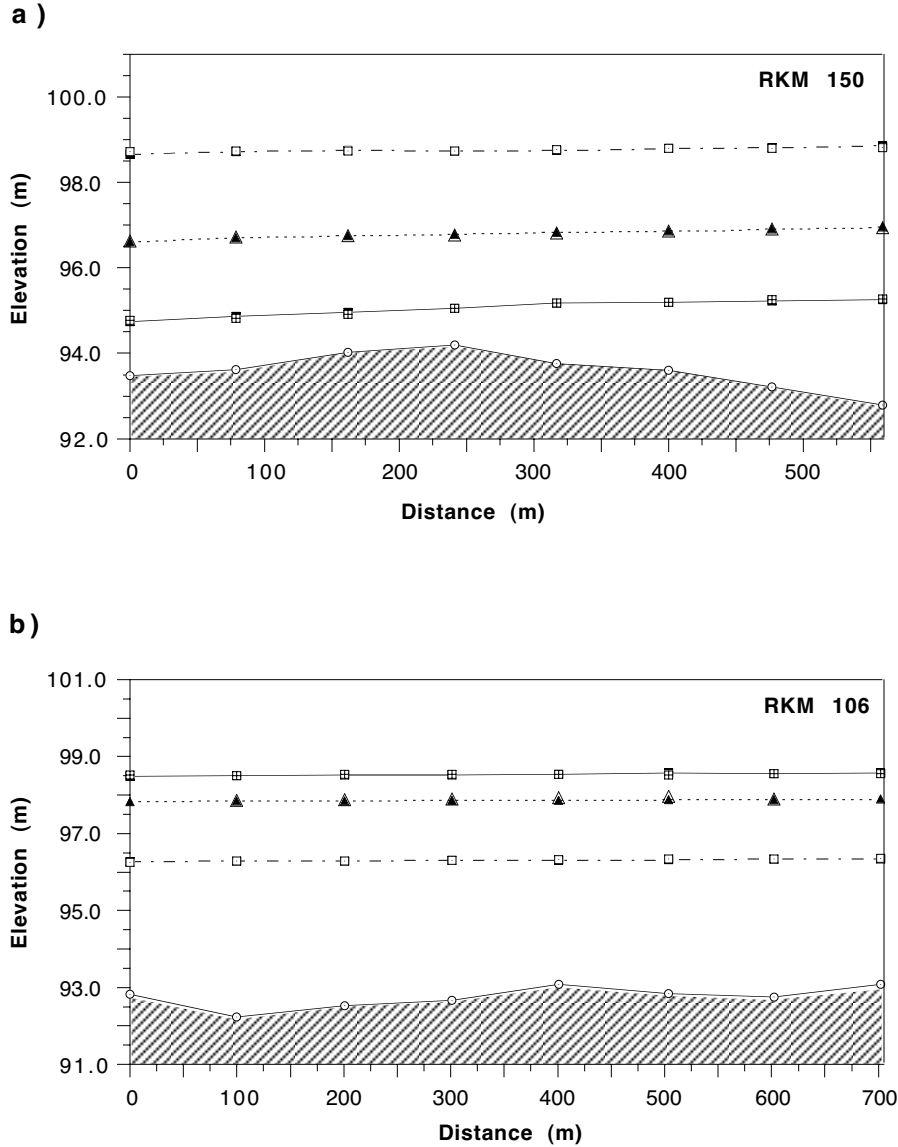


Figure 24. Bed and water surface elevations in reaches near (a) RKM 150 and (b) RKM 106.

In deriving the relations between  $Q$  and  $\tau^*$  for these sites, we obtained some unexpected results. If we formulate the dimensionless shear stress using the observed depth, slope and  $D_{50}$ , we obtain values of  $\tau^*$  that are low in comparison to what might be expected for the conditions. For example, measurements at RKM 150 during a near-bankfull discharge of  $1229 \text{ m}^3/\text{s}$  give a reach-average  $\tau^*$  of 0.031 (Fig. 25a), which is only slightly above the assumed threshold for initial motion (0.030), and well below the value expected for bankfull flow. Similarly, observations at RKM 106 during an overbank discharge of  $1456 \text{ m}^3/\text{s}$  give a reach-average  $\tau^*$  of 0.029 (Fig. 25b). These results imply that bankfull flows in the lower reaches are barely capable of transporting coarse sediment, assuming a threshold for motion of  $\tau^* = 0.030$ . That situation seems very unlikely, and it is clearly not supported by field evidence. There are three possible explanations for this discrepancy: (i) these two sites are not representative of the river as a whole; (ii) the measured grain sizes are not representative of the reach; or (iii) the assumed value of 0.030 for the critical  $\tau^*$  is not appropriate

here. It is not possible to rule out (i) without making similar measurements at other sites; however there is nothing in the modeling results to indicate that these sites are unusual, e.g. the modeled water-surface slopes are similar to the measured reach-average slopes. Likewise, it is difficult to evaluate (ii) and (iii) without additional field measurements. However, we have several reasons for believing that either (ii) or (iii) are true. First, we know from talking to USGS personnel who have made sediment measurements at the Cisco gauge that large sand dunes can be present on the bed at certain flows (D. Topping, personal communication). Furthermore, we know that the sand forming the channel below Moab, UT, must come from somewhere, and a very large percentage of it must pass through the reach between Cisco and Moab. Thus, we suspect that much of the bed is covered with sand, however, we rarely see it because it is resting in the runs and pools where we cannot sample. If this were the case, then the true size of the bed material might be over-estimated from a surface sample of particles exposed on a bar.

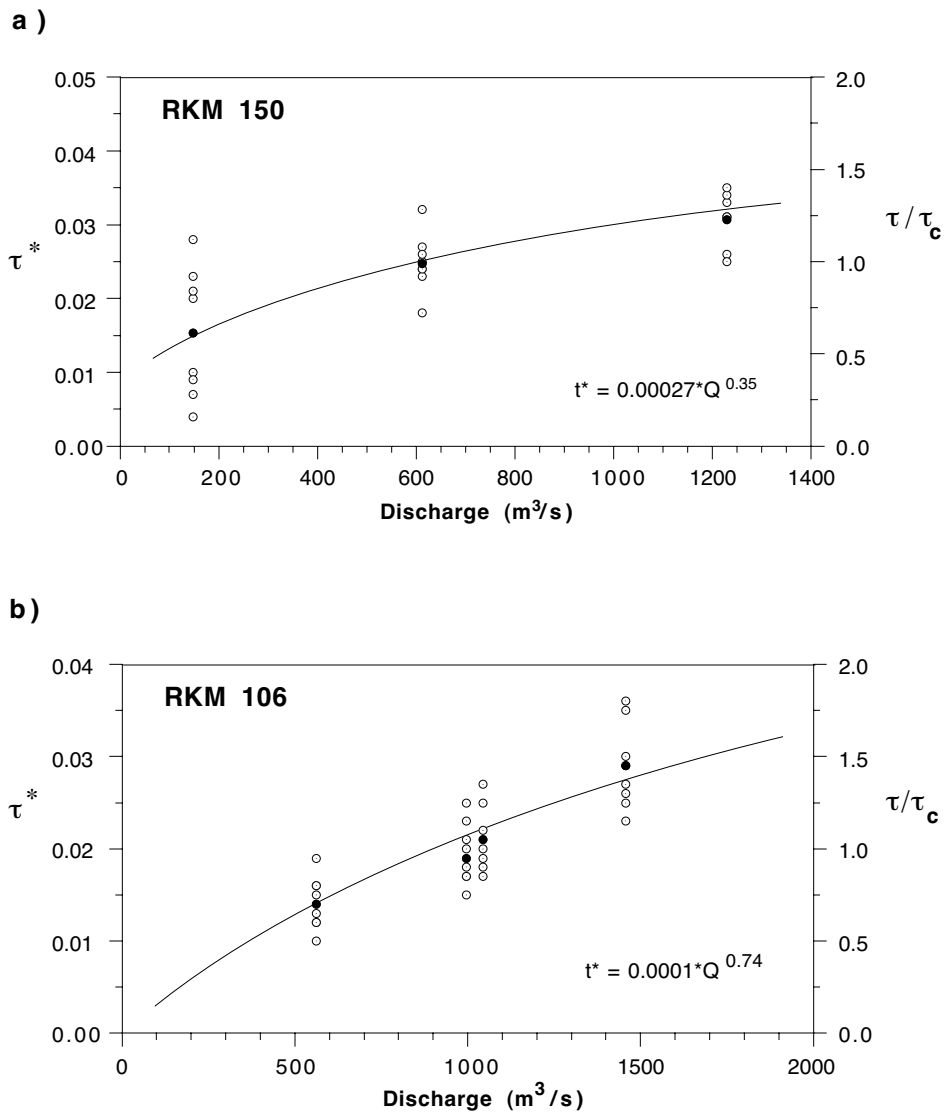


Figure 25. Relations between discharge and shear stress at (a) RKM 150 and (b) RKM 106

A second effect of having more sand on the bed is to reduce the value of the critical dimensionless shear stress,  $\tau_c^*$ . Recent flume experiments by Wilcock (1998) indicate that as the percentage of sand on the bed increases the  $\tau_c^*$  of coarse particles decreases, and their overall mobility increases. Wilcock's data show that with 25% sand in the bed the  $\tau_c^*$  is about 0.025, and with 30% sand, the  $\tau_c^*$  is about 0.020. To account for the potential effect of an increase in sand, we adjusted the value of  $\tau_c^*$  downward to 0.025 for the reaches between Westwater Canyon and Big Bend (strata 6-3), and downward further to 0.020 for the reach near Moab (strata 2). These values were chosen on the basis of an increase in the proportion of sand in the subsurface sediment (see Fig. 18b), and because they produce results consistent with our observations in the 15-mile and 18-mile reaches, where flows equal to about half the bankfull discharge begin moving the framework gravel (Pitlick et al., 1999). This adjustment has an important added effect of potentially lowering the threshold for significant motion (or widespread bed mobilization), since that value is keyed to  $\tau_c^*$ . Data from the lower reaches of the study area (below Westwater Canyon) indicate that the cross-sectional area of the channel increases markedly here, resulting in much higher bankfull discharges. These high flows undoubtedly rework most of the bed material, but it seems possible that transport stages corresponding to  $1.5\tau_c^*$  may occur at flows less than bankfull. Additional field work is needed to test this hypothesis and to verify the geomorphic effects of specific flows in these reaches.

Equations (4), (5) and (7) were used with the measured values of  $w$ ,  $h$  and  $S$ , and appropriate values of  $\tau_c^*$  and  $n$ , to estimate discharges corresponding to initial motion ( $Q_c$ ) and bankfull flow ( $Q_b$ ). The  $n$  values are based on results from step-backwater calculations at 10 different sites (the three discussed above, plus the seven others discussed by Pitlick et al., 1999). Table 7 lists our estimates of  $Q_c$  and  $Q_b$  for each reach (individual values for each cross section are listed in Table A-5). To facilitate comparisons between strata, the results in Table 7 are grouped with respect to the two major tributaries in the area, the Gunnison River and the Dolores River. Grouping the results as such shows that the estimated discharges are similar within strata bounded by these tributaries. For the reaches above the Gunnison River (strata 9-11), we estimate that discharges of 211 to 278 m<sup>3</sup>/s will begin moving framework gravels, while discharges of 580 to 623 m<sup>3</sup>/s reach the bankfull level (Table 7). For the reaches between the Gunnison River and the Dolores River (strata 6-8), we estimate that discharges of 497 to 548 m<sup>3</sup>/s are required for initial motion, and discharges of 979 to 1320 m<sup>3</sup>/s are required to reach the bankfull level. For the reaches below the Dolores River (strata 2-5), we estimate that discharges of 561 to 659 m<sup>3</sup>/s will initiate motion, and discharges of 1500 to 2000 m<sup>3</sup>/s will reach the bankfull level (the median bankfull discharge of 2929 m<sup>3</sup>/s in strata 4 is not particularly meaningful because flows of this magnitude have not occurred in historic time). We do not list a discharge for initial motion in the lowermost reach (strata 1) because the bed material in this reach is predominantly sand that moves essentially all year long.

To get a sense for the range in these estimates, Figure 26 and 27 show box plots of the distribution of individual values of  $Q_c$  and  $Q_b$  within each reach (for those not familiar with box plots, the line across the middle of the box indicates the median; the ends of the box represent upper and lower quartiles; the whiskers represent the range in data, excluding outliers, which are indicated by open circles). These plots indicate that the estimated values of  $Q_c$  and  $Q_b$  can vary by a factor of 3 to 4 within any given reach. The large range in  $Q_c$  and  $Q_b$  is not unexpected and can be explained by the fact that local variations in channel width and depth occasionally result in anomalous values of  $Q_c$  and  $Q_b$ . The true variation in  $Q_c$  and  $Q_b$  within individual subreaches is likely to be much less, otherwise the basic geomorphic requirement of sediment continuity would not be satisfied, i.e. the river would be transporting large amounts of sediment at some locations and not at others. If this was occurring on a widespread basis, we would expect to see systematic aggradation and degradation, when in fact the channel appears relatively stable overall.

Table 7. Summary of parameter values used to calculate the threshold discharge for initial motion ( $Q_c$ ) and the bankfull discharge ( $Q_b$ ). The reaches are grouped by their location relative to the two major tributaries in the study area, the Gunnison River and the Dolores River.

	Strata	$\tau_c^*$	n	$Q_c$	$Q_b$	$Q_c/Q_b$
RKM 365-328	11	0.030	0.035	246	623	0.38
RKM 327-316	10	0.030	0.035	211	580	0.36
RKM 298-275	9	0.030	0.035	278	608	0.46
RKM 274-246	8	0.030	0.033	548	979	0.56
RKM 245-206	7	0.030	0.032	519	1021	0.51
RKM 180-153	6	0.025	0.030	497	1320	0.38
RKM 151-140	5	0.025	0.028	609	1429	0.43
RKM 138-126	4	0.025	0.035	650	2929	0.22
RKM 124-113	3	0.025	0.030	561	2012	0.28
RKM 111-105	2	0.020	0.025	659	1543	0.43
RKM 103-77	1	0.020	0.025	n/a	1788	n/a

Note: Values of discharge are listed in cubic meters per second; to convert these values to cubic feet per second, multiply by 35.3.

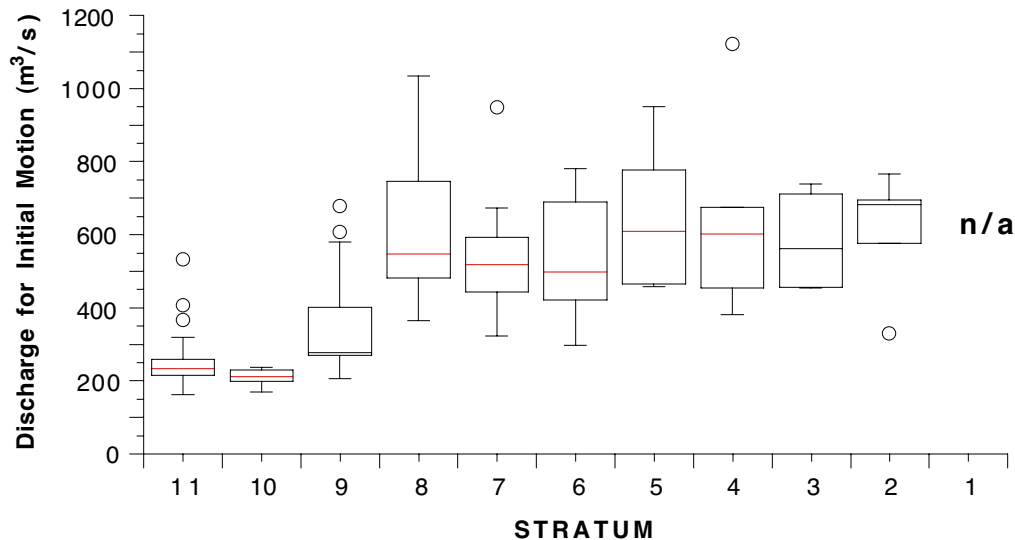


Figure 26. Box plots showing the range in discharges that produce initial motion in specific subreaches of the Colorado River. The line across the middle of the box indicates the median; the ends of the box represent upper and lower quartiles; the whiskers represent the range in data, excluding outliers, which are indicated by open circles.

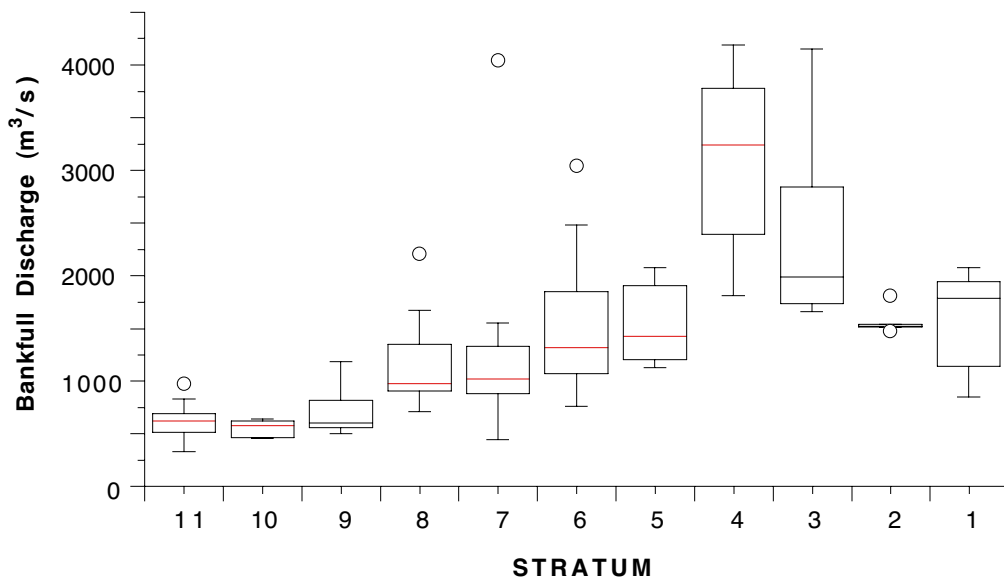


Figure 27. Box plots showing the range in bankfull flow in specific reaches of the Colorado River.

## DISCUSSION

Most contemporary models of fluvial systems describe the longitudinal changes in rivers as an orderly progression in which the channel characteristics adjust smoothly downstream to carry increasing amounts of water and sediment. Empirical and theoretical relations for hydraulic geometry indicate that the bankfull width and depth increase downstream as power functions of discharge (Church, 1992; Hey and Thorne, 1986; Parker, 1979; Simons and Albertson, 1960; Leopold and Maddock, 1953), while the slope and grain size are observed or assumed to decrease as exponential functions of distance (Pizzuto, 1992; Snow and Slingerland, 1987; Brierly and Hickin, 1985; Bradley et al., 1972). These changes in width, depth, slope and sediment size are sometimes accompanied by changes in planform and sinuosity (Schumm, 1985). The ecological implications of downstream transitions in channel characteristics have been discussed in many papers, notably those by Vannote et al. (1980) and Stanford et al. (1996).

The results of this study show that, while the physical characteristics of the Colorado River do indeed change systematically downstream, the changes do not occur in the manner that is often described in the geomorphological literature. Specifically, we observe that the bankfull depth of the Colorado River increases faster downstream than the bankfull width, resulting in a nearly constant width-depth ratio. This observation contrasts with results from many other studies (summarized by Knighton, 1998) showing that an increase in width-depth ratio is typical of most alluvial rivers. In addition, our sediment data show that the bed material of the Colorado River changes slowly downstream- the  $D_{50}$  of the surface sediment decreases by a factor of only 2 over a distance of more than 250 km. Such slow changes in grain size are not expected, and are explained in this case by the influence of ephemeral tributaries and hillslopes which deliver coarse sediment to the main stem without supplying much additional water. In order to satisfy the basic requirement of carrying this sediment, the Colorado River has developed a deep, narrow channel that provides sufficient shear stress to carry the imposed load without much additional flow.

One of the main objectives of this study was to examine the relation between physical channel characteristics and the productivity of aquatic organisms that support the food base for native fishes. Primary productivity is influenced by several factors, including nutrient availability, water temperature and sunlight intensity. In turbid rivers, light intensity attenuates rapidly with depth, thus conditions favorable for primary productivity may exist only where the flow is relatively shallow, such as along the edge of the channel or over riffles. Our observation that the width of the Colorado River changes little downstream, while the depth changes considerably means that, at a given discharge, the wetted perimeter of the channel is roughly the same upstream as it is downstream. However, because the flow is deeper downstream than it is upstream, proportionally less of the bed receives sufficient sunlight to allow primary production, which in turn would affect the amount of food available for benthic invertebrates (see Lamarra, 1999).

Our field observations and modeling results indicate that mobile gravel substrates are present throughout the study area. Clean gravel substrates can potentially provide habitat for periphyton and benthic invertebrates, and spawning sites for adult Colorado pikeminnow. However, our analysis of suspended sediment trends suggests that it may be more difficult to maintain clean gravel substrates in the lower reaches of the study area (especially below the Dolores River) because, on average, suspended sediment concentrations are higher here than they are upstream. This observation, coupled with the disproportionate increase in channel depth and higher sand loads, suggests that there is a relatively abrupt transition in the physical condition of micro-scale habitats in the lower reaches. Samples obtained by Lamarra (1999) indicate that the unit biomass of periphyton and macro-invertebrates decreases rapidly from upper to lower parts of the study area, reaching asymptotically low levels in strata 1 through 5. Similarly, data presented by Osmundson (1999) show that fish that could serve as forage for Colorado pikeminnow are much less abundant in the reaches below Westwater Canyon than they are in the reaches above. Thus, in a broad sense, there appears to be a clear link between the physical habitat characteristics of the Colorado River and the structure of the aquatic community.

Although human activities have influenced many aspects of the Colorado River, it is unlikely that the basic geomorphic characteristics of these reaches were radically different prior to human occupation. For example, given the climate and geology of the region, it is likely that the Colorado River has carried high suspended sediment loads for much of the Holocene. We can also reason that over shorter time scales (say, several hundred years) the average slope of the river has changed little, because a large amount of net deposition is required to change the average slope of a river by even a few percent. Whether the size of the sediment supplied to the river has changed appreciably in historic time is very hard to say, however, exposures in the numerous gravel pits and terraces in the area provide abundant evidence that the Colorado River has always carried a coarse sediment load. Thus, the characteristics of the river that we see today have probably existed for some time, as have the differences in geomorphology.

The contrast between upper reaches, characterized by a laterally active shallow channel, versus lower reaches, characterized by a stable, more-incised channel, has likely been an important influence on the fish community structure of the Colorado River (Osmundson, 1999). Adult Colorado pikeminnow appear to favor habitats in the upper reaches, while other fish such as humpback chub (*Gila cypha*) favor habitats in the canyon-bound reaches. Although these segments of the river are different in character, they are linked by the flow of water, sediment and nutrients, thus the recovery program should continue to take a system-wide approach of improving environmental conditions that benefit the aquatic community as a whole, rather than one species.

## CONCLUSIONS

- 1) Comparative analysis of 1937 and 1995 aerial photographs of the segment of the Colorado River between Rifle and DeBeque, CO, indicates that the average width of the main channel has not changed significantly in this reach in the last 60 years. In contrast, there have been relatively major changes in the area of islands and side channels. We estimate that between 1937 and 1995, the area of islands decreased by 20%, while the area of side channels and backwaters decreased by 31%. When proportioned over a reach length of 58 km, the change in side-channel and backwater area amounts to a decrease in average width of about 6 m.
- 2) Although there has been a reduction in the amount of in-channel habitat in the Rifle-DeBeque reach, a significant amount of potential habitat still exists. Comparison of results from the present study with results from a previous study (Pitlick et al., 1999) indicates that the total area of side channels and backwaters remaining in the Rifle-DeBeque reach is roughly the same as the total area of side channels and backwaters lost historically in the 15- and 18-miles reaches. However, it is not clear that the potential habitat in the Rifle-DeBeque reach is as suitable in a biological sense as some reaches downstream; Osmundson's (1999) analysis of water temperatures here suggests that conditions favoring pikeminnow growth are suboptimal ( $< 25^{\circ}\text{C}$ ) much of time. Nonetheless, adult Colorado pikeminnow would probably benefit from having access to the Rifle-DeBeque reach, particularly in low-water years when water temperatures are higher.
- 3) Our analysis of discharge and suspended sediment data from four USGS gauging stations on the main stem of the Colorado River indicates that annual suspended sediment loads increase by a factor of almost four through the study area. In downstream order, the long-term average annual suspended sediment load of the Colorado River increases from  $0.4 \times 10^6$  tons/yr at Glenwood Springs, CO (upstream of the study area), to  $1.5 \times 10^6$  tons/yr at Cameo, to  $3.4 \times 10^6$  tons/yr at the Colorado-Utah state line, to  $5.4 \times 10^6$  tons/yr at Cisco, UT, in the lower part of the study area.
- 4) Reservoirs and flow diversions have had system-wide impacts on the sediment-transport regime of the Colorado River. Major changes in sediment transport capacity appear to have occurred in the late 1950s and early 1960s. Comparison of the periods 1934-1958 with 1959-1997 indicates that annual suspended sediment loads were 25-35% lower in the more recent period than in the earlier period. Changes in the frequency of high flows are largely responsible for the reduction in annual sediment loads in the latter period.
- 5) Field measurements of the existing characteristics of the Colorado River indicate that the channel gradient, substrate sediment size, bankfull width and bankfull depth change systematically downstream. The channel gradient decreases rapidly in comparison to the grain size, and the bankfull depth increases downstream more rapidly than the bankfull width. Over the 300-km length of the study area the bankfull depth increases by 100% (approximately doubling) while the bankfull width increases by only 30%. These trends have important implications for primary productivity because, in downstream reaches, conditions favorable for primary productivity may exist only where the flow is relatively shallow, i.e. along the very edge of the channel or over riffles.
- 6) The longitudinal changes in channel depth, slope and grain size occur in such a way that the bankfull dimensionless shear stress,  $\tau^*$ , is roughly constant through the gravel-bedded portions of the study area from Rulison, CO, to Professor Valley, UT. This result has important implications for sediment transport because it indicates that the width and depth of Colorado River are adjusted such that the threshold for coarse-sediment transport is roughly the same from reach to reach.

7) Taking the results from the three flow-modeling sites studied here, the seven sites studied by Pitlick et al. (1999), and data from 149 cross sections, we estimate that the framework gravel particles of the Colorado River begin moving at flows ranging from about 35 to 55% of the bankfull discharge (Table 7). Discharges that reach initial-motion and bankfull stages are very similar when the data are grouped with respect to the two major tributaries in the study area, the Gunnison River and the Dolores River. For the reaches above the Gunnison River (strata 9-11), we estimate that discharges of 211 to 278 m<sup>3</sup>/s (7500-9800 ft<sup>3</sup>/s) will initiate motion and discharges of 580 to 623 m<sup>3</sup>/s (20,500-22,000 ft<sup>3</sup>/s) will reach the bankfull level (see Table 7). For the reaches between the Gunnison River and the Dolores River (strata 6-8), we estimate that discharges of 497 to 548 m<sup>3</sup>/s (17,500-19,300 ft<sup>3</sup>/s) will initiate motion, and discharges of 979 to 1320 m<sup>3</sup>/s (34,600-46,600 ft<sup>3</sup>/s) will reach the bankfull level. For the reaches below the Dolores River (strata 2-5), we estimate that discharges of 561 to 659 m<sup>3</sup>/s (19,800-23,300 ft<sup>3</sup>/s) are required to initiate motion and discharges of 1500 to 2000 m<sup>3</sup>/s (54,500-71,000 ft<sup>3</sup>/s) are required to reach the bankfull level.

## RECOMMENDATIONS

- 1) The diversion dams in DeBeque Canyon are being modified to allow fish passage, thus we recommend further geomorphic studies to assess patterns of sediment transport and channel change in the reaches above Palisade. More detailed studies are needed to evaluate the mobility of gravel substrates that might serve as spawning habitat for pikeminnow. Additional studies are needed to evaluate the importance of fine sediment deposition and to assess whether normal snowmelt flows and coordinated reservoir releases are effective in flushing fine sediment from the bed.
- 2) We recommend initiating additional field studies in the Rifle-DeBeque reach to monitor scour and fill in side channels and backwaters. Previous studies have shown that fine sediment is preferentially deposited in these off-channel habitats during periods of low flow (Osmundson et al., 1995; Pitlick et al., 1999); periodic monitoring of scour and fill in side channels provides a useful measure or index of the overall mass balance of sediment moving through the reach.
- 3) Continued monitoring of suspended sediment at the USGS gauging stations is essential for evaluating short- and long-term trends in the sediment load carried by the Colorado River. Thus we recommend continuation of the existing sediment-sampling programs at the USGS gauges.
- 4) The data presented in this report indicate that suspended sediment concentrations during the summer months are typically higher at the Cisco gauge than they are at the Cameo gauge. Some of the difference in sediment concentration is due to natural causes, and some of it is due to irrigation return flow. Given that turbidity levels affect primary productivity, we recommend that additional efforts be made to limit sediment input from agricultural areas in the vicinity of Grand Junction.
- 5) As in the previous study (Pitlick et al., 1999), we emphasize that the single most important thing that can be done to maintain fish habitats in the Colorado River is ensure that the sediment supplied to the critical reaches is carried downstream, otherwise further channel simplification will occur. We have previously shown that flows ranging from 1/2 the bankfull discharge up to the bankfull discharge carry about 50% of the annual load, thus it is important that flows in this range continue to occur regularly (at least 30 days per year). An additional possibility, that has not been studied in any detail, is to consider implementing better land-use practices to reduce erosion and sediment supply from the Roan Plateau and nearby areas. We recommend initiating a pilot study to examine the relation between climate, vegetation, runoff and sediment yield in this region.

## REFERENCES

- Andrews, E.D., 1994. Marginal bed load transport in a gravel-bed stream, Sagehen Creek, California, *Water Resources Research*, v. 30, p. 2241-2250.
- Bailey, J.F. and H.A. Ray, 1966. Definition of a stage-discharge relation in natural channels by step-backwater analysis, *U.S. Geological Survey Water Supply Paper 1869-A*.
- Berenson, M.L., D.M. Levine, and D. Rindskopf, 1988. *Applied Statistics*, Prentice-Hall, Englewood Cliffs, 557 pp.
- Bradley, W.C., R.K. Fahenstock and E.T. Rowekamp, 1972. Coarse sediment transport by flood flows on the Knik River, Alaska, *Geological Society of America Bulletin*, v. 83, p. 1261-1284.
- Brierly, G.J. and E.J. Hickin, 1985. The downstream gradation in particle sizes of the Squamish River, British Columbia, *Earth Surface Processes and Landforms*, v. 10, p. 597-696.
- Buffington, J.M and D.R. Montgomery, 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers, *Water Resources Research*, v. 33, p. 1993-2029.
- Burdick, B. D. 1992. A plan to evaluate stocking to augment or restore razorback sucker in the upper Colorado River, *Final Report to the Recovery Program for the Endangered Fishes of the Upper Colorado River*, U. S. Fish and Wildlife Service, Colorado River Fishery Project, Grand Junction, Colorado.
- Cashion, W.B., 1973. Geologic and structure map of the Grand Junction quadrangle, Colorado and Utah, *US Geological Survey Miscellaneous Investigations Series Map I-736*.
- Church, M., 1992. Channel morphology and typology, in *The Rivers Handbook: Hydrological and Ecological Principles*, P. Calow and G. Petts (eds), Blackwell, Oxford, p. 126-143
- Colman, S.M., 1983. Influence of the Onion Creek salt diapir on the late-Cenozoic history of Fisher Valley, southeastern Utah, *Geology*, v. 11, p. 240-243.
- Cress, R. 1997. Processes of channel adjustment and downstream hydraulic geometry of the upper Colorado River, unpublished MS thesis, University of Colorado, Boulder.
- Dingman, S. L., 1984. *Fluvial Hydrology*, W.H. Freeman, New York.
- Gilbert, G. K., 1877. Report on the geology of the Henry Mountains, *US Geographical and Geological Survey Rocky Mountain Region*, 170 pp.
- Fleener, G.B., 1997. Hydrologic and geomorphic aspects of riparian forest ecology on the lower San Miguel River, Colorado, unpublished PhD thesis, University of Colorado, Boulder.
- Henderson, F.M., 1966. *Open Channel Flow*, MacMillan, New York.
- Hey, R.D. and C.R. Thorne, 1986, Stable channels with mobile gravel beds, *ASCE Journal of Hydraulic Engineering*, v. 112, p. 671-689
- Ikeda, S., G. Parker, and Y. Kimura. Stable width and depth of straight gravel rivers with heterogeneous bed materials, *Water Resources Research*, v. 24, p. 713-722.
- Iorns, W. V., C. H. Hembree, D. A. Phoenix, and G. L. Oakland, 1964. Water resources of the upper Colorado River basin- Basic Data, *US Geological Survey Professional Paper 442*.
- Kidd, G., 1977. An investigation of endangered and threatened fish species in the upper Colorado River as related to Bureau of Reclamation projects, *Final Report, U. S. Bureau of Reclamation*, Northwest Fisheries Research, Clifton, Colorado.
- Kondolf, G.M. and P.R. Wilcock, 1996, The flushing flow problem: Defining and evaluating objectives, *Water Resources Research*, v. 32, p. 2589-2599
- Knighton, D., 1998. *Fluvial forms and processes- a new perspective*, Arnold, London, 383 pp.
- Lamarra, V, 1999. Longitudinal variation in the trophic structure of the upper Colorado River, *Final Report, U.S. Fish and Wildlife Service*, Grand Junction.
- Leopold, L.B. and T. Maddock, 1953. The hydraulic geometry of stream channels and some physiographic implications, *US Geological Survey Professional Paper 252*, 57 pp.

- Leopold, L.B., M.G. Wolman, and J.P. Miller, 1964. *Fluvial Processes in Geomorphology*, W.H. Freeman, San Francisco, 522 pp.
- Liebermann, T. D., D. K. Mueller, J. E. Kircher, and A. F. Choquette, 1989. Characteristics and trends of streamflow and dissolved solids in the upper Colorado River basin, Arizona, New Mexico, Utah, and Wyoming, *US Geological Survey Water Supply Paper 2358*.
- Mackin, J.H., 1948. Concept of the graded river, *Geological Society of America Bulletin*, v. 59, p. 463-512.
- Milhous, R., 1998. Modelling of instream flow needs; the link between sediment and aquatic habitat, *Regulated Rivers*, v. 14, p. 79-94.
- Osmundson, D.B., P. Nelson, K. Fenton, and D.W. Ryden, Relationships between flow and rare fish habitat in the 15-mile reach of the upper Colorado River, *Final Report, U.S. Fish and Wildlife Serv.*, Grand Junction, 1995.
- Osmundson, D.B., and K.P. Burnham, 1998. Status and trends of the endangered Colorado squawfish in the upper Colorado River, *Transactions of the American Fisheries Society*, v. 127, p. 957-970.
- Osmundson, D.B., R.J. Ryel, M.E. Tucker, B.D. Burdick, W.R. Elmlblad, and T.E. Chart, 1998. Dispersal patterns of subadult and adult Colorado squawfish in the upper Colorado River, *Transactions of the American Fisheries Society*, v. 127, p. 943-956.
- Osmundson, D.B., 1999. Longitudinal variation in fish community structure and water temperature in the upper Colorado River: Implications for Colorado pikeminnow habitat suitability, *Final Report, US Fish and Wildlife Service*, Grand Junction, 70 pp.
- Parker, G., 1979. Hydraulic geometry of active gravel rivers, *Journal of the Hydraulics Division*, American Society of Civil Engineers, v. 105, p. 1185-1201.
- Pitlick J. and M.M. Van Steeter, 1998. Geomorphology and endangered fish habitats of the upper Colorado River 2. Linking sediment transport to habitat maintenance, *Water Resources Research*, v. 34, p. 303-316.
- Pitlick, J., M.M. Van Steeter, B. Barkett, R. Cress and M.A. Franseen, 1999. Geomorphology and Hydrology of the Colorado and Gunnison Rivers and Implications for Habitats Used by Endangered Fishes, *Final Report, US Fish and Wildlife Service*, Grand Junction.
- Pizzuto, J.E., 1990. Numerical simulation of gravel river widening, *Water Resources Research*, v. 26, p. 1971-1980.
- Pizzuto, J.E., 1992. The morphology of graded gravel rivers: A network perspective, *Geomorphology*, v. 5, p. 457-474.
- Quarterone, F., 1993. Historical accounts of upper basin endangered fish, Upper Colorado River Fishery Project. U.S. Fish and Wildlife Service, Denver.
- Rubey, W.W., 1952. Geology and mineral resources of the Hardin and Brussels quadrangles (in Illinois), *US Geological Survey Professional Paper 218*, 179 pp.
- Schumm, S.A., 1985. Patterns of alluvial rivers, *Annual Reviews of Earth and Planetary Sciences*, v. 13, p. 5-27.
- Simons, D.B. and M.L. Albertson, 1960. Uniform water conveyance channel in alluvial material, *Journal of the Hydraulics Division*, American Society of Civil Engineers, v. 86, p. 33-71.
- Snow, R.S. and R.L. Slingerland, 1987. Mathematical modeling of graded river profiles, *Journal of Geology*, v. 95, p. 15-33.
- Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, J.A. Lichatowich, and C.C. Coutant, 1996. A general protocol for restoration of regulated rivers, *Regulated Rivers: Research and Management*, v. 12, p. 391-413.
- Topping, D.J., R.S. Parker, J.M. Nelson, and J.P. Bennett, 1996. The apparent mid-20th century sediment load decrease in the Colorado River: investigation of the mechanics of the Colorado River sampler, *Geological Society of America Abstracts with Programs*, v. 28, p. 261.

- Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing, 1980. The river continuum concept, *Canadian Journal of Fisheries and Aquatic Science*, v. 37, p. 137
- Van Steeter, M. M., 1996. Historic and current processes affecting channel change and endangered fish habitats of the Colorado River near Grand Junction, Colorado. Unpublished Ph.D. Thesis, University of Colorado, Boulder.
- Van Steeter and Pitlick, 1998, Geomorphology and endangered fish habitats of the upper Colorado River 1. Historic changes in streamflow, sediment load and channel morphology, *Water Resources Research*, v. 34, p. 287-302.
- Waters, T.F., 1995. *Sediment in Streams*, Monograph 7, American Fisheries Society, Bethesda.
- Wilcock, P.R., 1998. Two-fraction model of initial sediment motion in gravel-bed rivers, *Science*, v. 280, p. 410-412.
- Wilcock, P.R. and B.W. McArdell, 1993. Surface-based fractional transport rates: Mobilization thresholds and partial transport of a sand-gravel sediment, *Water Resources Research*, v. 29, p. 1297-1312.
- Wilcock, P. R., A. F. Barta, C. C. Shea, G. M. Kondolf, W. V. G. Matthews, and J. Pitlick, 1996. Observations of flow and sediment entrainment on a large gravel-bed river, *Water Resources Research*, v. 32, p. 2897-2909.
- Williams, P.L., 1964. Geology, structure, and uranium deposits of the Moab quadrangle, Colorado and Utah, *US Geological Survey Miscellaneous Investigations Series Map I-360*.