N.D. Pitlick

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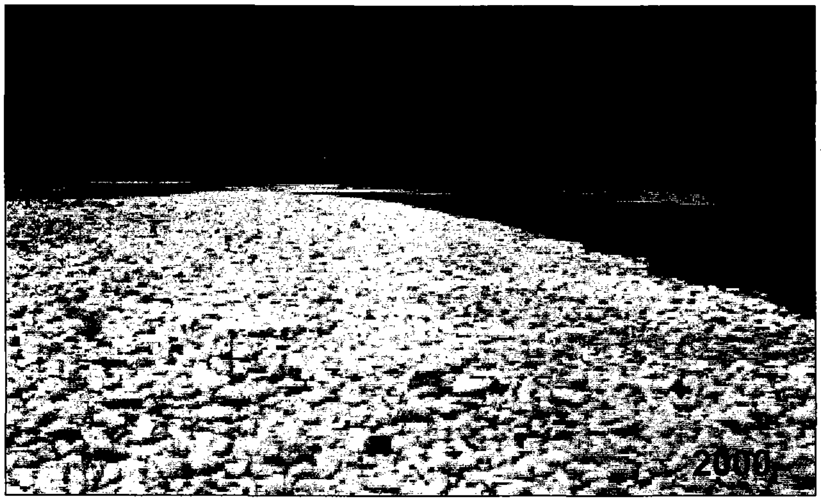
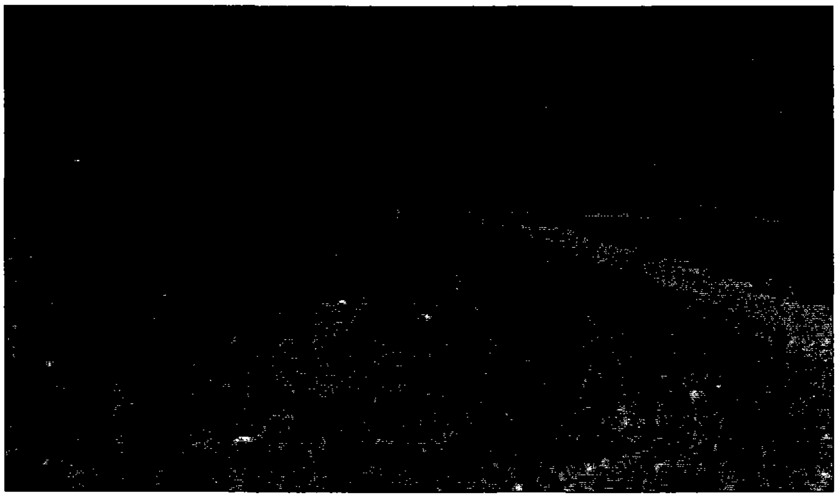
CHANNEL MONITORING TO EVALUATE GEOMORPHIC CHANGES ON THE MAIN STEM OF THE COLORADO RIVER





Final Report
Recovery Program Project Number 85

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EXECUTIVE SUMMARY

The 15-mile and 18-mile reaches of the Colorado River in western Colorado provide important habitat for three endangered fishes: the Colorado pikeminnow (*Ptychocheilus-lucius*), the razorback sucker (*Xyrauchen-texanus*), and the humpback chub (*Gila Cypha*). Success in recovering these fishes will depend in large part on the maintenance and improvement of existing habitats which have been lost or altered as a result of water management activities in the upper Colorado River basin. Under certain conditions reservoir operations can be adjusted to allow a portion of the runoff to bypass reservoirs, boosting peak spring flows in the 15- and 18-mile reaches. The purpose of this study, therefore, was to assess the effects of coordinated reservoir releases and normal snowmelt flows on geomorphic processes in the 15- and 18-mile reaches. Conditions in specific reaches were monitored from 1998-2004 to verify thresholds for sediment transport and to provide additional information on discharges that perform important geomorphic functions. Field measurements focused on geomorphic effects of late spring-early summer flows and seasonal variations in the movement of fine sediment.

The study period included several years of intense drought with very low runoff produced throughout the upper Colorado River basin. U.S. Geological Survey records of streamflow suggest that water years 2002-2004 were perhaps the lowest in the upper Colorado River basin in the last 100 years. Nonetheless, coordinated reservoir operations were implemented for 7 days in 1998 and 10 days in 1999, resulting in increases in discharge of 40-56 m^3/s (1500-2000 ft^3/s), in the 15-mile reach. The bypass flows were successful in boosting background flow levels by 10-15%, which was sufficient to mobilize the bed material in a number of places in the 15- and 18-mile reaches. The limited availability of water in subsequent years prevented further tests of the geomorphic effects of bypass flows. The flows that did occur were well below average, thus the

thresholds for mobilizing the bed material were exceeded very infrequently. Over the 7-year period of the study, the discharge required to produce initial motion (~1/2 the bankfull discharge) was exceeded for a total of 78 days, which is only about 1/3 the frequency recommended in previous reports. The discharge required to completely mobilize the bed (bankfull discharge) did not occur at all.

Geomorphic changes in the 15- and 18-mile reaches were monitored using periodic surveys of main-channel cross sections and backwaters, and comparative analysis of aerial photographs taken in 1993 and 2000. These measurements indicate that, overall, the large-scale morphology of the Colorado River has changed little in the last decade. Vertical and lateral deposition of fine sediment occurred in all of the side channels monitored, however, the changes detected in these features were again relatively minor.

Additional analyses of suspended sediment records from gauging stations in the study area reconfirm the importance of late-spring flows for carrying sediment. The analysis indicates that roughly 80% of the sediment carried in suspension consists of silt- and clay-sized particles. Concentrations of suspended sediment at all gauging stations are consistently higher on the rising limb of the hydrograph than they are on the falling limb, thus the total annual sediment load is dominated by late-spring flows. Both sediment concentration and water discharge are high in the spring, thus the total annual sediment load is dominated by flow conditions during this period of time. About 20% of the total suspended sediment load consists of sand. This sediment reaches a peak 2-3 weeks after the peak in water discharge, and not far in advance of the typical period of time when Colorado pikeminnow are preparing to spawn. It is not clear that the sand moving at this time of the year represents a problem in an ecological sense; however, it is evident that the sand has the potential to move either in suspension or in contact with the bed, with the threshold occurring at flows between 125 and 150 m^3/s (4500-5500 ft^3/s).

Intensive field measurements, coupled with results from one-dimensional hydraulic model, were used to assess variations in flow properties with discharge in a 0.8-km study reach. The field measurements indicate that there is a relatively abrupt transition in the water-surface width and wetted area of the channel between discharges of 125 and 175 m^3/s (4500-6200 ft^3/s). At discharges < 125 m^3/s most of the flow is confined to the baseflow channel, and more than half the channel perimeter is dry. At discharges > 125 m^3/s flow begins to cover low-lying bar surfaces; width increasing steadily from there until ~280 m^3/s when most of the channel bed is inundated. This discharge is consistent with flow-modeling results indicating that the threshold for initial motion of the bed material in this reach is exceeded at a discharge of 286 m^3/s. That value is within 3% of the value recommended in previous reports. Adjusting the model results to account for spatial variations in grain size increases the threshold slightly, indicating there is very little bed load transport within the reach at flows less than 300 m^3/s (~10,600 ft^3/s).

The results discussed in this report are broadly consistent with the results presented in previous reports, therefore, all of the previous recommendations are retained. It is assumed that periodic movement of the gravel bed material of the Colorado River is important for maintaining habitats used by native fishes and other aquatic organisms. It also assumed that periodic movement of the bed material is important for maintaining a channel with some morphologic complexity or heterogeneity. Finally, it is assumed that the mass balance of sediment carried by the Colorado River must be maintained over the long run, otherwise there will be continued narrowing and simplification of the channel, and a loss of associated habitats. The following discharges, including frequency and duration, are recommended to achieve these purposes:

Category A

Discharge: > 621 m^3/s (22,000 cfs)

Purpose: Overtop the floodplain, completely mobilize the bed surface

Duration: 5 days per year, averaged over a period of several years

Frequency: One out of every three years

Category B

Discharge: > 283 m^3/s (10,000 cfs)

Purpose: Initiate bed material transport, inundate low-lying bars

Duration: 30 days per year, averaged over a period of several years

Frequency: Every other year

Category C

Discharge: 115 – 155 m^3/s (4,000 – 5,500 cfs)

Purpose: Maintain sand in suspension over riffles

Duration: 10 days per year, on the receding limb of the annual hydrograph; in typical years, this would occur in the period from late June to early July

Frequency: Every year

INTRODUCTION

Alluvial and canyon-bound reaches of the Colorado River in western Colorado and eastern Utah provide important habitat for three endangered fishes in the upper Colorado River basin- the Colorado pikeminnow (*Ptychocheilus-lucius*), the razorback sucker (*Xyrauchen-texanus*), and the humpback chub (*Gila Cypha*). Success in recovering these fishes will depend in large part on the maintenance and improvement of existing habitats within several key reaches of the Colorado River, including the 15-mile and 18-mile reaches near Grand Junction, Colorado. Along with lower reaches of the Gunnison River, the 15- and 18-mile reaches represent the upper limit of the current range of Colorado pikeminnow and razorback sucker on the mainstem of the Colorado River; humpback chub are found in incised bedrock reaches further downstream (Black Rocks and Weswater Canyon). The 15- and 18-mile reaches are characterized as having a mildly sinuous channel pattern with varying amounts of complexity; bankfull depths average 2.5-3 m and substrate grain sizes vary from granules to cobbles [*Pitlick et al.*, 1999; *Pitlick and Cress*, 2002]. This combination of physical characteristics, together with light and nutrient availability, provides for relatively high levels of primary and secondary production in comparison to reaches further downstream, and a relative abundance of native prey fishes (flannelmouth sucker and bluehead sucker) [*Osmundson et al.*, 2002]. Presumably, it is the availability of habitat in the 15- and 18-mile reaches, and the abundance of potential prey fishes, that draw Colorado pikeminnow upstream as they mature (razorback sucker, which are currently very rare, historically used the 15- and 18-mile reaches for purposes similar to Colorado pikeminnow; however, the resource and habitat requirements of this species is only partly understood). Further migration by either species to habitats upstream of the 15-mile reach is presently limited by a series of low-head diversion dams near Palisade, Colorado, thus management and monitoring of conditions within the 15-mile reach is an important priority.

Streamflows into the 15-mile and 18-mile reaches are regulated by a series of reservoirs and diversions. At present there are 25 reservoirs with a storage capacity greater than 5,000 acre-feet (6.2 x 10^6 m^3) upstream of the Colorado-Utah state line [*Liebermann et al.*, 1989]. These reservoirs are distributed throughout the upper basin; individually, they are not large in comparison to some other dams in the Colorado-Green River system (e.g. Flaming Gorge or Glen Canyon), but collectively they have the capacity to store the equivalent of about half the annual flow volume of the Colorado River at the Colorado-Utah state line [*Pitlick et al.*, 1999]. Reservoir construction and operations have altered the timing and magnitude of peak flows in the 15- and 18-mile reaches significantly. Since 1950, annual peak discharges of the Colorado River, and its major tributary the Gunnison River, have decreased by 30-40% [*Pitlick et al.*, 1999]. In addition to altering peak flows, upper basin reservoirs store spring runoff which is diverted later in the year to municipalities and projects east of the continental divide. Diversions remove an average of about 14% of the native flow of the Colorado River annually, although in some years as much as 30% of the flow is taken out of the basin [*Osmundson* et al., 2002].

The primary geomorphic effect of water-management activity in the Colorado River basin has been to reduce the sediment-transport capacity of the river. Analysis of suspended sediment data from gauging stations operated by the U.S. Geological Survey (USGS) indicates that surface erosion of sedimentary rocks in areas immediately upstream of the key reaches contributes a large proportion of the sediment carried by the Colorado River [*Iorns et al.*, 1965; *Liebermann et al.*, 1989; *Pitlick and Cress*, 2000]. Most of the reservoirs in the upper Colorado River basin are well above these areas, and therefore have little effect on the amount of sediment delivered downstream. However, because of reductions in peak flows, both the Colorado River and the Gunnison River have lost some of their capacity to carry sediment. Changes in transport capacity over the long term have caused sediment to accumulate in the channel, causing it to become narrower and less complex overall. *Van Steeter and Pitlick* [1998] report that between 1937 and 1993 the main channel of the Colorado River narrowed by an average of about 20 m, and one quarter of the area formed by side channels and backwaters had been lost.

Although water-management activities have caused persistent, long-term changes in the hydrology of the Colorado River, the potential exists to coordinate reservoir operations in the upper basin to periodically augment spring snowmelt flows and enhance peak discharges in the 15- and 18-mile reaches. The function and importance of peak flows were summarized in the recommendations given previously by *Pitlick and Cress* [2000]:

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

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

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

The recommendations above emphasize physical processes associated with particular flows, and stress the importance of sediment transport in shaping and maintaining habitats used by the endangered fishes. Use of individual habitats within the 15- and 18-mile reaches varies with fish species and life stage [*Lagory et al.*, 2003], but most all habitats are affected by the movement of sediment. Spawning habitats formed by gravel and cobble substrates (riffles, shoals, or bars) require periodic flushing to remove interstitial fine sediment [*Pitlick and Van Steeter*, 1998; *Osmundson et al.*, 2002]. Low velocity channel-margin habitats, including backwaters and secondary channels, require continued transport of fine sediment to prevent deposition and further channel simplification [*Osmundson et al.*, 1995; *Van Steeter and Pitlick*, 1998]. Disturbance of elevated surfaces by high flows is necessary to limit establishment of vegetation and stabilization of channel bars.

The present study was initiated to assess the geomorphic effects of coordinated reservoir operations, and to develop a better understanding of the timing of sediment supply and sediment transport in key reaches of the upper Colorado River. The specific objectives of this study were to:

1. Monitor rates of channel change and assess the geomorphic effects of coordinated reservoir releases and normal snowmelt flows.
2. Define the window of time of peak sediment delivery from unregulated tributaries.
3. Verifying discharge thresholds for coarse-sediment transport.
4. Examine processes of fine sediment transport and deposition on the falling limb of the hydrograph.
5. Provide data on thresholds and durations of discharges that perform important geomorphic functions so that biologists can integrate this information with biological information and refine flow recommendations as necessary.

Field measurements coinciding with the late spring-early summer period of peak runoff were taken at various locations in the 15- and 18-mile reaches from 1998 through 2004. An array of techniques was used to monitor changes in channel geomorphology and the movement of fine and coarse sediment in response to different flow levels. Results of this work will aid in refining flow recommendations so that, in the future, reservoir operations can be adjusted and releases can be timed to provide the greatest benefit to the endangered fishes.

STUDY AREA

Field studies for this project focused on conditions within specific segments of the 15- and 18-mile reaches of the Colorado River near Grand Junction, Colorado (Fig. 1). The general setting and characteristics of these reaches are described in detail in a number of previous reports [*Osmundson and Kaeding*, 1991; *Pitlick et al.*, 1999; *Pitlick and Cress*, 2000]. The channel pattern in the 15- and 18-mile reaches is mildly sinuous; in a number of places the channel splits into two or more branches, resulting in braided-like pattern. In a long-term sense, however, the channel is relatively stable overall. Floodplains and low lying alluvial surfaces border the river channel through most of the study area. In several reaches, the river flows against vertical bedrock walls underlain by Mancos shale; elsewhere, the channel is confined locally by concrete rip rap and artificial levees. Floodplains and low lying bars are covered with a mix of recent and mature vegetation. Dominant woody species include native sandbar willow (*Salix exigua*) and cottonwood (*Populus deltoides*), and non-native tamarisk (*Tamarisk chinensis*) and russian olive (*Elaeagnus angustifolia*).

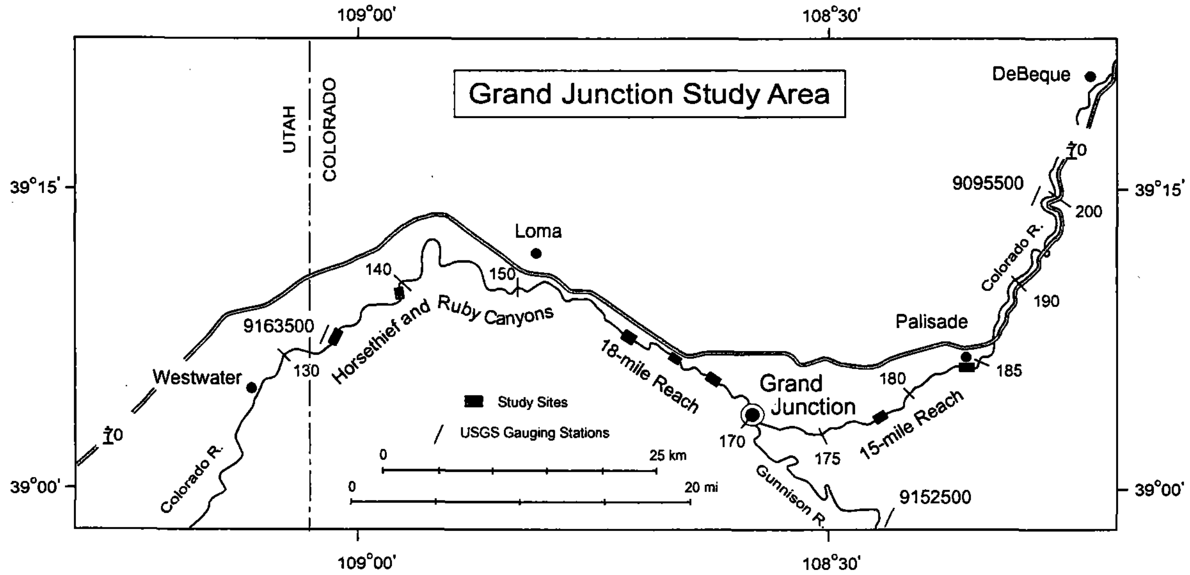


Figure 1. Detailed map showing study reaches near Grand Junction, Colorado.

The channel bed material in the 15- and 18-mile reaches consists of gravel- and cobble-sized sediment. The median grain size, D_{50}, of the bed surface sediment (armor) in the 15-mile reach, as determined from point counts of 100-200 rocks on exposed gravel bars, ranges from 40 to 80 mm, with an average D_{50} of 58 mm (Fig. 2a). The D_{50} of the bed surface sediment in the 18-mile reach ranges from 40 to 70 mm, with an average of 51 mm (Fig. 2b).

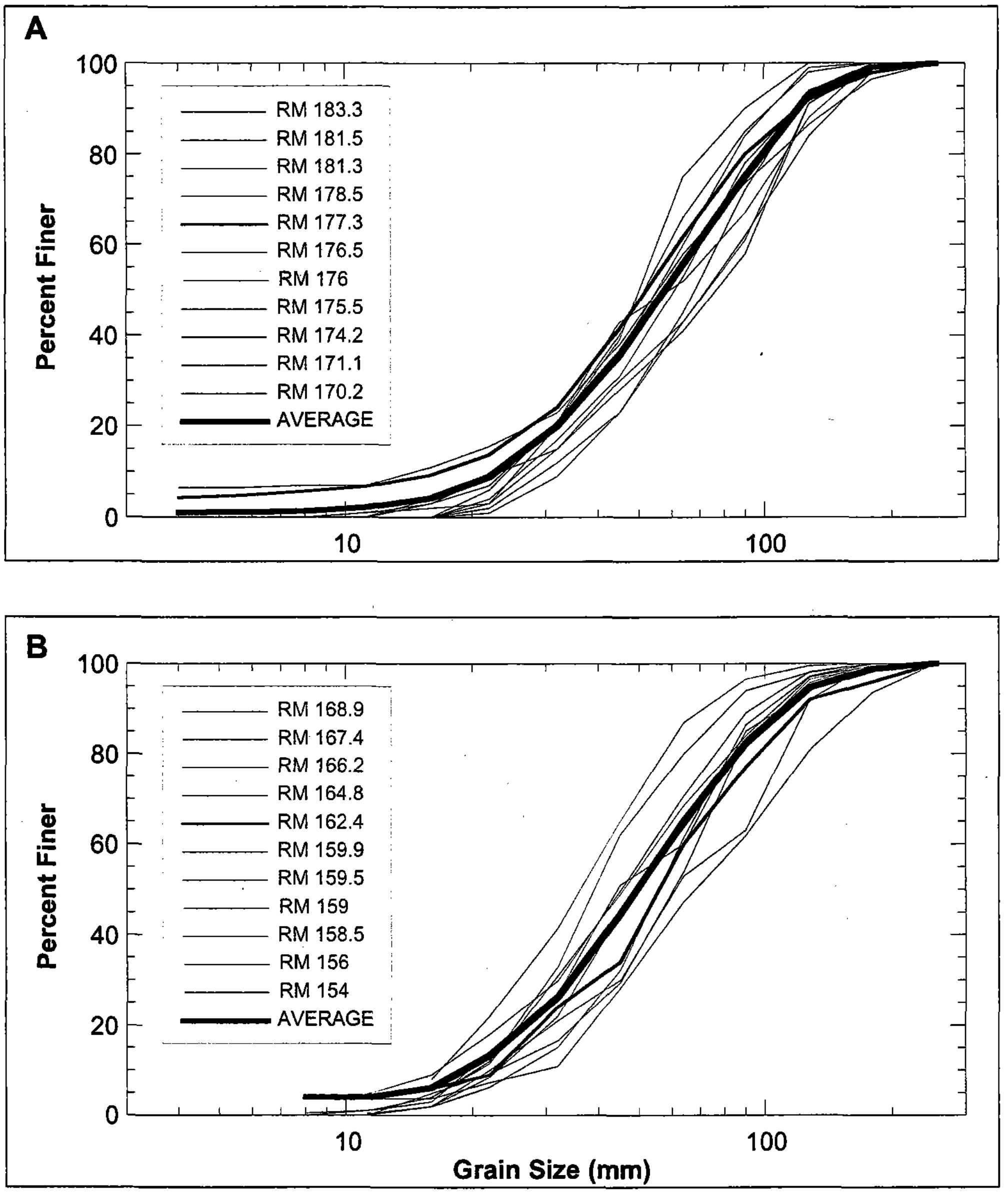


Figure 2. Grain size distributions of the bed surface (armor) layer based on pebble-count samples from (a) the 15 mile reach and (b) the 18 mile reach.

Average channel gradients of the 15-mile and 18-mile reaches were determined with a mapping grade global positioning system (GPS). Readings of the water surface were taken at 0.8-km intervals along the length of the river. Subsequently, the raw data were corrected with differential post-processing techniques and base-station measurements obtained by the Mesa County Public Works Department. Post-processing of the field data reduces the vertical positional error to ± 0.5-0.3 m. These errors tend to be random and are small in comparison to the total drop in elevation through the study reaches (35-45 m). The GPS measurements show that the longitudinal profile of the Colorado River is very smooth between Palisade, CO, and Westwater, UT (Fig. 3). Average channel gradients determined from these measurements are 0.00175 in the 15-mile reach; 0.0013 in the 18-mile reach; and 0.0010 in the Ruby-Horsethief Canyon reach.

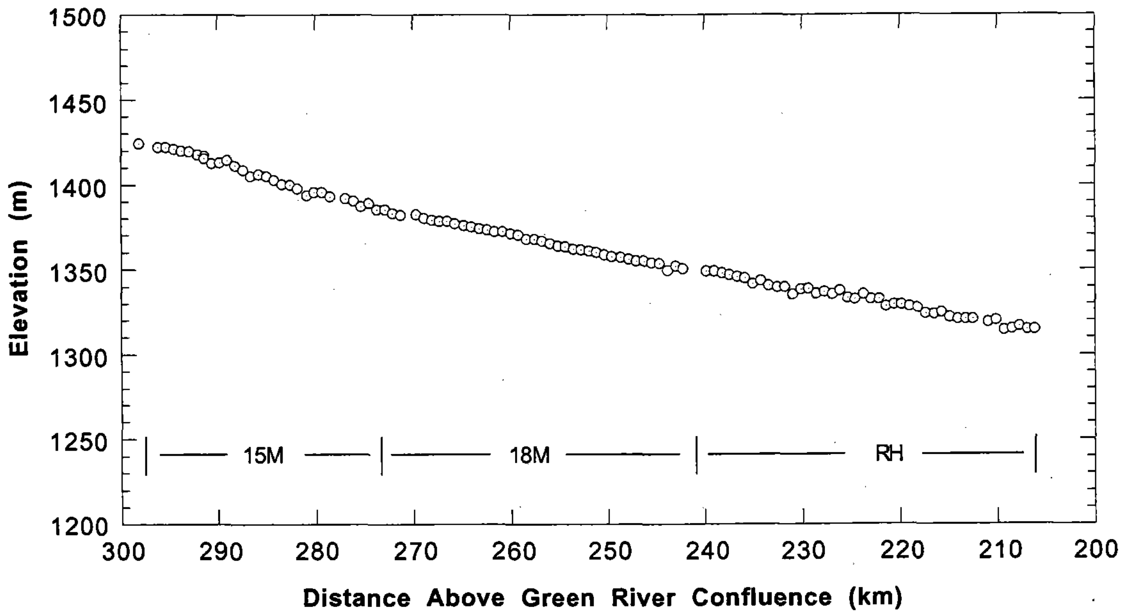


Figure 3. Longitudinal profile of the Colorado River from Palisade, CO, to Westwater, UT. Distances are listed in river kilometers (RKM) above the Green River. Bars below the data indicate the locations of the 15-mile reach (15M), 18-mile reach (18M), and Ruby-Horsethief Canyon reach (RH). The confluence with the Gunnison River is located at RKM 275.

Natural streamflows of the Colorado River are regulated by a series of storage reservoirs and water diversions upstream of the study area. Data reported by *Liebermann et al.* [1989] indicate that there are 24 reservoirs with a capacity greater than 6.2×10^6 m^3 (~5,000 acre-feet) upstream of the Colorado-Utah state line. A number of these reservoirs were built to store and supply water to communities located on the east side of the continental divide, and on average about 14 % of the annual flow of the Colorado River is diverted out of the basin. Most of the storage reservoirs in the upper Colorado River basin were constructed in the period between 1950 and 1966. Reservoir operations have affected both the timing and magnitude of peak snowmelt flows in the study area. Since 1950 instantaneous peak discharges of the Colorado River and its major tributary, the Gunnison River, have decreased by and average of 29-43% [*Van Steeter and Pitlick*, 1998]. However, in most years, runoff from unregulated or moderately regulated tributaries is still sufficient to produce a prominent spring peak in the annual hydrograph. Much smaller peaks associated with late-summer thunderstorms are also common.

The Colorado River carries moderately high sediment loads, increasing downstream from 1.5×10^6 metric tons per year at the US Geological Survey (USGS) gauging station near Cameo, CO, to 3.4×10^6 metric tons per year at the USGS gauging station near the Colorado-Utah state line [*Pitlick and Cress*, 2000]. At least 95% of the total sediment load consists of fine sediment (silt and sand) carried in suspension [*Pitlick and Van Steeter*, 1998]. Much of the fine sediment is derived from surface erosion of friable sedimentary rocks underlying the Roan Mesa. The contribution of fine sediment from this area remains high. Coarse sediment (cobble and gravel) is derived from local as well as distant sources. Although gravel is a minor component of the total sediment load of the Colorado River, this material forms the bed of the channel, and therefore provides habitat for benthic invertebrates as well as native and non-native fishes.

DATA SOURCES and METHODS

Analysis of Streamflow and Suspended Sediment

The USGS operates four streamflow gauging stations within the study area. These stations are used for continuous monitoring of river stage and streamflow, and periodic sampling of water quality. Stations on the main stem of the Colorado River include: the Colorado River near Cameo (station no. 09095500, located in DeBeque Canyon); the Colorado River below Grand Valley Diversion near Palisade (station no. 09106150, located at the head of the 15-mile reach); and the Colorado River near the Colorado-Utah state line (station no. 09163500, located near the downstream end of Ruby-Horsethief Canyon). One station on the Gunnison River is also included in the analysis: Gunnison River near Grand Junction (station number 09152500). Measurements of streamflow begin at the Cameo gauge in 1934; at the Palisade gauge in 1990; at the state line gauge in 1952, and at the Gunnison River gauge in 1902.

Measurements of suspended sediment have been taken periodically at three of these four locations. The record from the Cameo gauge is the most complete; this data set includes 576 measurements of discharge and suspended sediment concentration between 1982 and 1998; 449 of these samples were analyzed to determine the fraction of sediment finer than 0.0625 mm, which is the break between silt and sand. The record from the Gunnison River gauge includes 306 measurements of discharge and suspended sediment concentration between 1959 and 1999; 120 of these samples were analyzed to determine the fraction of sediment finer than 0.0625 mm. The record from the state line gauge includes 281 measurements of discharge and suspended sediment concentration between 1976 and 1999; 150 of these samples were analyzed to determine the fraction of sediment finer than 0.0625 mm.

Coordinated Reservoir Operations

From 1997-2000, representatives from various federal agencies and reservoir operators in the upper Colorado River basin participated in discussions to coordinate and modify reservoir operations to enhance spring peak flows in the 15-Mile Reach. The specific objectives of the coordinated reservoir operations program (CROS) are as follows:

> The objective of CROS is to coordinate bypasses of inflows from various reservoirs resulting in enhancement of habitat in the 15-Mile Reach of the Colorado River without exceeding the National Weather Service flood level of 26,600 cfs at Cameo. These bypasses may have passed through the participating reservoirs during the runoff period. Coordinated reservoir operations moves those bypasses to the peak of the runoff hydrograph to enhance spring peak flows, which are important to spawning and improvement of aquatic food sources. Coordination and modification of operations are voluntary and occur within current authorizations and guidelines and without affecting project yields to either federal or non-federal reservoirs (*source*: Annual Summary of Coordinated Reservoir Operations for 1998 to Benefit the Endangered Fishes of the Upper Colorado River Basin, Colorado Water Conservation Board).

Timetables and procedures for coordinating reservoir operations were developed annually from 1997-2000 through a coordination committee composed of representatives from each of the participating agencies and reservoir operators. Prior to the start of spring snowmelt, hydrologic conditions within the upper Colorado River basin were assessed and the decision whether to modify reservoir operations was discussed. Measurements of the snowpack in 1997, 1998 and 1999 indicated that the snow-water equivalent and runoff in most parts of the basin would be near average, thus operations were adjusted in those years to bypass inputs to reservoirs. Plans were in place to bypass flows in 2000, however, unusually warm weather in early May caused a rapid reduction in snow-water equivalent throughout the basin and coordinated reservoir operations were called off that year.

Channel Geomorphology

Changes in channel geomorphology produced by normal and augmented streamflows were determined from (i) analysis of aerial photographs taken seven years apart and (ii) repeated surveys of channel cross sections in selected reaches.

Aerial Photographs: High quality color aerial photographs of the critical reaches of the Colorado River were taken in August, 2000, for the purposes of comparison with an earlier set of photographs taken in September, 1993. The separate sets of photographs cover the same section of the Colorado River from Palisade to approximately Loma, CO (RKM 300-250), and they were flown at the same scale (1: 6000), in late summer, with the river flowing at approximately the same discharge. Both sets of photographs were georeferenced by Positive Systems, resulting in seventeen total georeferenced mosaics. Eight mosaics from the 1993 data set and 9 mosaics from the 2000 data set were used to delineate channel characteristics. The aerial photographs were not orthorectified to account for flight angle or distortion effects; however, these effects were assumed to be minimal given the relatively low relief of the river and surrounding terrain in the study area. Georeferencing was done in UTM coordinates.

From the aerial photographs, a layer in ArcView was digitized to represent the boundary between river miles. The layer created in ArcView for these river miles stores the UTM coordinates from the mosaic of aerial photographs, thus allowing a single layer for river miles to be utilized on the aerial photographs from both years. This assures the comparison between years will be based on identical sections of channel. These river mile boundaries were verified between topographic maps and the aerial photos.

For each year, in each river mile, a separate layer was digitized to represent the main channel, side channels, and exposed channel bars. Thus each river mile for each year contains three different layers. The area of each channel feature was then computed for each river mile and compared between years. The digitizing of channel features was done by creating shapefiles for each layer (Fig. 4). These shapefiles were digitized by hand by zooming in on important channel features and carefully digitizing the features point by point along the boundary. More points were digitized near irregular boundaries and a typical channel reach contains several hundred digitized points to delineate individual features. All of the resultant shapefiles are in UTM coordinates associated with the aerial photograph mosaics.

Figure 4. Segment of the Colorado River near the Fruita bridge, RKM 251, showing delineation of separate channel features (blue = main channel, green = side channels).

Cross Section Surveys: Detailed measurements of channel properties were taken in a 1-km long reach centered around RKM 283 (RM 176) to provide more detail on channel changes and to model thresholds for bed load transport. This particular segment of the Colorado River was chosen because conditions within the reach are relatively natural; the reach includes a through-flowing secondary channel, alluvial channel margins with a limited amount of rip-rap, and well-defined floodplains along both the north and south sides of the channel (Fig. 5). In addition the study reach includes property on the south bank that was obtained by the USFWS and the Bureau of Reclamation, and is therefore relatively easy to access.

Figure 5. Location of reach used for detailed studies of channel change.

Initial topographic surveys of the study reach were conducted in May, 1998. Eleven cross sections were placed at evenly spaced (~80 m) intervals through the reach, covering a total channel length of 800 m. Measurements of the channel-bed and water-surface elevations were taken with a total station and a rubber raft outfitted with a depth sounder. Survey measurements of the cross sections were repeated in August, 1998; October, 1999; and July, 2001. Separate measurements of the water surface elevations were taken periodically throughout the study for use in calibrating a one dimensional hydrodynamic model for computing roughness coefficients, velocities and boundary shear stresses for various flow levels (discussed below).

Samples of the bed sediment were taken at a number of locations within the study reach. The bed surface (armor layer) was sampled with point counts of 100 or 200 particles following the method described by *Wolman* [1954]. Particles were sampled randomly within specific areas of the channel, and measured at 1/2-phi intervals using a metal template (gravelometer). A separate sample of the subsurface sediment (substrate) was obtained in order to determine the bulk size distribution of the bed material. A total of 135 kg of sediment was collected in this sample, with the largest rock weighing 10 kg, or 7% of the total sample weight. The coarse fraction (>32 mm) of the subsurface sample was sieved in the field and the fine fraction (<32 mm) was sieved in the laboratory, again at 1/2-phi intervals. A graphical plot of the grain size distribution of this sample (Fig. 6) indicates that the substrate has a median grain size, D_{50s}, of 30 mm, and 17% is finer than sand (2 mm). The size distribution of this sample is very similar to two other samples collected previously in the 15-mile reach (*Pitlick et al.*, 1999).

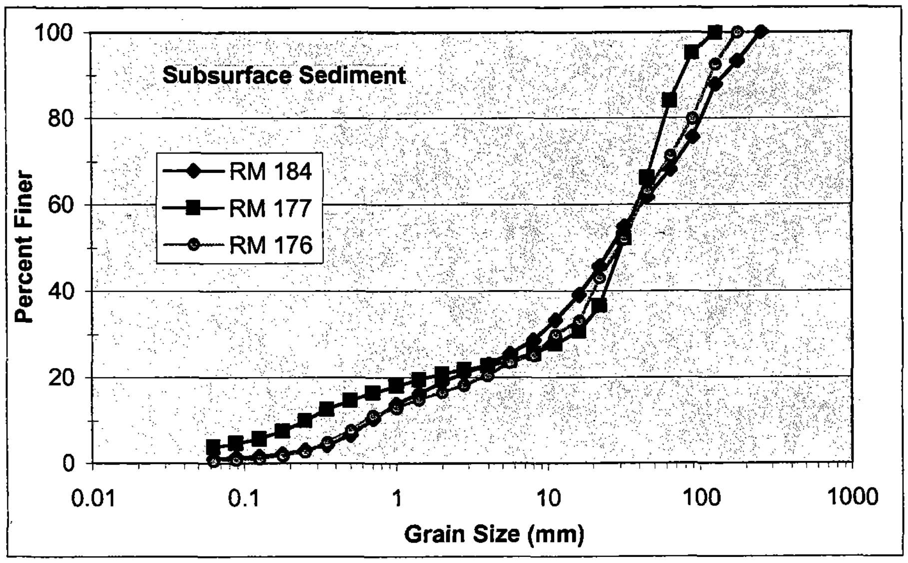


Figure 6. Grain size distributions of subsurface sediment at 3 locations in the 15-mile reach.

Additional characteristics of the study reach are summarized in Table 1. Based on data from the cross section surveys, the channel has an average bankfull width of 127 m, an average bankfull depth of 1.90 m; and an average median grain size of 69 mm (Table 1). These values correspond relatively well to the average characteristics of the 15-mile reach, determined from earlier surveys of channel geometry (*Pitlick et al.*, 1999). In comparison to the 15-mile reach as a whole, the site at RM 176 is characterized by a slightly lower bankfull depth and a slightly higher median grain size (Table 1.). These differences are primarily the result of an increase in channel gradient within the study reach: the study reach has an average slope of 0.0020 m/m, whereas the 15-mile reach has an average slope of 0.00175 m/m.

Table 1. General characteristics of the Colorado River at the RM 176 study site.

	Bankfull Width (m)	Bankfull Depth (m)	Median Grain Size, D_{50} (mm)[1]
XSECT 1	132	1.38	60
XSECT 2	110	2.15	-
XSECT 3	116	1.69	52
XSECT 4	105	1.70	59
XSECT 5	87	2.20	99
XSECT 6	104	2.40	81
XSECT 7	119	1.96	82
XSECT 8	148	1.98	76
XSECT 9	154	1.82	-
XSECT 10	163	1.82	67
XSECT 11	163	1.80	-
Site average	127	1.90	69
15-mile reach average[2]	134	2.54	58

1. Values of D_{50} at cross sections 6, 7, 8, and 10, represent the average of two samples.
2. Averages for the 15 mile reach from *Pitlick et al.* (1999).

Sediment Transport

Sand and Granules: Seasonal transport of sand and granules over gravel bars and riffles was monitored by installing a series of stream-bed traps at various locations. The traps consist of 20-cm coffee cans mounted within a piece of plastic pipe, both placed flush with the bed surface

(Fig. 7). The cans were filled with clean gravel > 32 mm in size. At various times after the peak in the annual hydrograph the cans were retrieved, emptied of fine sediment, and replaced. Conditions limited us from retrieving cans in flows more than ~0.5 m deep. Samples taken from the traps were subsequently sieved at 1/2 phi intervals.

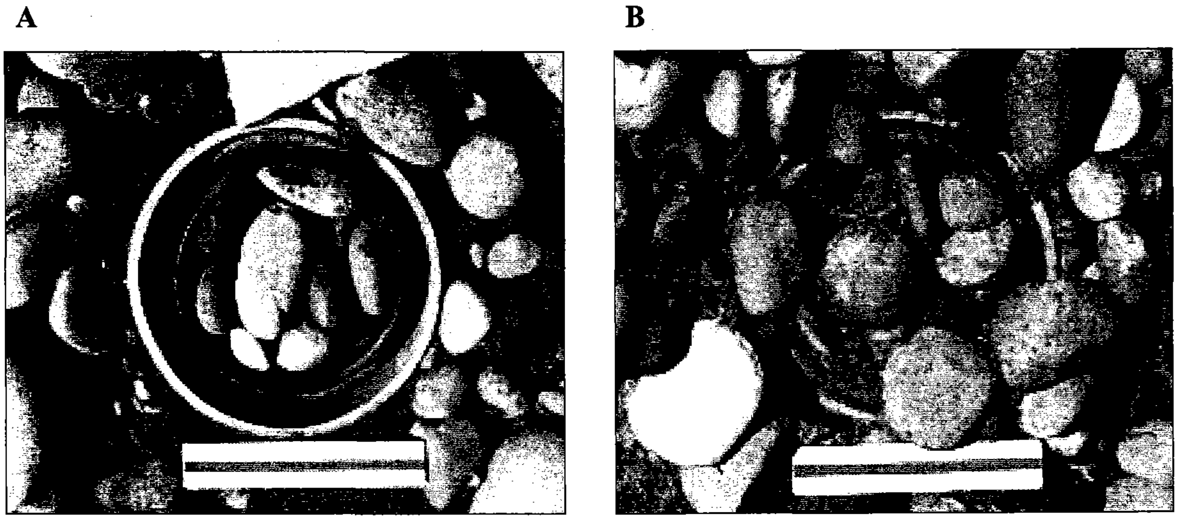


Figure 7. Traps used to monitor the movement of sand. Photo on the left (a) shows a trap prior to runoff; photo on right (b) shows the same trap after runoff. Ruler is 15 cm in length.

Cobble and Gravel: Estimates of discharges required to mobilize cobble- and gravel-sized sediment were made by coupling several equations for flow and sediment transport, calibrated with the aid of field data from the study reach near RM 176. Spot measurements of water-surface elevations were made at each of the cross sections in the study reach at eight different discharges ranging from 37 to 394 m^3/s. The water-surface measurements were used with cross section data to calibrate a one-dimensional hydraulic model to determine variations in flow properties, including channel roughness (Manning's n), mean velocity, U, and average boundary shear stress, τ. Other measures of flow conditions, such as wetted perimeter, P, and water surface area, A_s, were obtained as part of this process.

Thresholds for motion of cobble- and gravel-sized sediment (framework grains) were estimated from the relation for dimensionless shear stress:

$$\tau^* = \frac{\tau}{(\rho_s - \rho)\, g\, D_{50}} \qquad (1)$$

where ρ_s and ρ are the densities of sediment and water, respectively, g is the gravitational acceleration, and D_{50} is the median grain size of the bed surface (armor layer). In a simple physical sense, the variable τ^* represents a balance between the fluid forces acting to move particles on the bed versus the resistance due to their mass. Movement of a small number of framework grains begins when τ^* exceeds a threshold or critical value, τ^*_c. Results from field and laboratory studies suggest that values of τ^*_c may be affected by several factors, including particle shape [*Gomez*, 1995], sand content [*Wilcock*, 1998], spatial variations in bed texture and bed structure [*Lisle et al.*, 2000; *Konrad et al.*, 2002; *Church et al.*, 1998], and average channel gradient [*Mueller et al., 2005*]. In addition, there is a practical problem of defining the degree of bed mobilization, i.e. whether transport involves only a few coarse clasts or many clasts. Finally, some gravel rivers can carry significant amounts of sand-sized sediment; this is potentially a problem because sand moves at flows much lower than those required to move the coarser clasts, and it can move either as bed load or suspended load, depending on the flow. Such is the case in the Colorado River. Thus, it is possible to distinguish three phases of bed load transport: the first phase, involving movement of sand and granules over an otherwise stable bed surface, is termed *overpassing* (*Ashworth and Ferguson*, 1989); this sediment is not the same as 'wash load' (sediment supplied from sources other than the bed itself), and in fact may represent a significant proportion (> 20 %) of the total bed load of a gravel river system (this point is pursued in detail later). The second transport phase, involving sporadic motion of small to moderate percentages of the framework grains, is termed *partial transport* [*Wilcock and McArdell*, 1995]. A recent analysis of bed load transport thresholds by *Mueller et al.* (2005) indicates that the movement of framework grains on the bed surface (partial transport) occurs at flows equal to about 67% of the bankfull discharge. The third bed load transport phase, involving motion of most all particles on the bed is termed *fully mobilized transport*[*Wilcock and McArdell*, 1993]. This transport phase has been equated with the bankfull discharge [*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000; *Pitlick and Wilcock*, 2001], the rationale being that these flows shape the channel and thereby mobilize most all of the sediment on the channel bed.

The flow levels or discharges required to reach the transport phases discussed above are determined by selecting a threshold value of τ^* and solving (1) for the corresponding shear stress, τ. In previous studies of the Colorado River and the Gunnison River, *Pitlick et al.* [1999] set the threshold for initial motion at $\tau^* = 0.03$. Results from field studies elsewhere served as the basis for selecting that value; however, the value of 0.03 is not a hard number, and recent work suggests that there may be substantial variation in the critical τ^*. Indeed, this study was motivated in part by uncertainties associated with the choice of the critical τ^*. For the purposes of the present study, the threshold for initial motion was determined using an empirical relation developed by *Mueller et al.* [2005]. This relation is based on an analysis of flow and bed load transport measurements taken in 45 gravel-bed streams and rivers in the western USA and Canada. The analysis focused on variations in the threshold for bed load transport which arise from changes in flow structure as channel gradient and bed roughness increase. For each data set, *Mueller et al.* [2005] plotted the relation between bed load transport rate and dimensionless shear stress, and, following the procedure of *Parker et al.* [1982], estimated the reference dimensionless shear stress, τ^*_r, associated with a small, non-zero transport rate The resulting estimates of τ^*_r were then correlated to reach-average slope, giving the values shown in Figure8. A least squares fit of the data in this figure gives the equation

$$\tau^*_r = 2.18S + 0.021 \qquad (2)$$

where S is the average channel gradient. This relation is statistically significant ($r^2 = 0.70$ and $p \ll 0.001$), and suggests that τ^*_r increases linearly with increasing channel gradient. This result is counterintuitive, but explained by hydrodynamic effects associated with poorer sorting of the bed material in high gradient channels. The monitoring site near RM 176 has an average gradient of $S = 0.002$, thus the estimated τ^*_c for that location is 0.025.

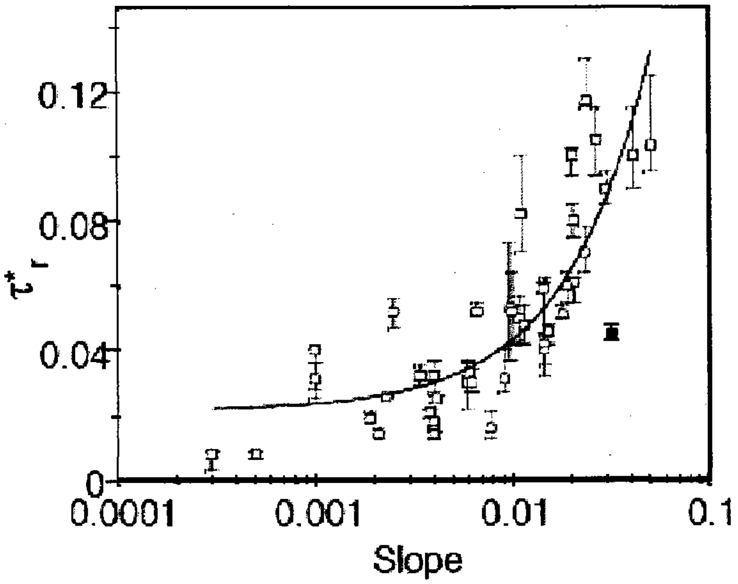


Figure 8. Variation in τ^*_r as function of slope with error bars indicating potential range of τ^*_r values for individual data sets. A logarithmic scale is used for the x-axis to highlight the range in values for moderate-high slopes. One outlier (solid symbol) was excluded (from *Mueller et al.*, 2005).

The shear stress available to move sediment on the channel bed varies temporally as the discharge rises and falls, and spatially as the flow accelerates or decelerates over the topography (pools and riffles). The boundary shear stress, τ, is the force per unit bed area acting in the direction of flow,

$$\tau = \rho\, g\, R\, S_e \tag{3}$$

where ρ is the density of water, g is the gravitational acceleration, R is the hydraulic radius, and S_e is the slope of the energy grade line, also termed the friction slope. In channels with a high width-depth ratio, R is approximately equal to the mean flow depth, h, hence these variables are often used in place of each other. Assuming ρ and g are constant, (3) shows that τ varies with the product of R and S_e. Both R and S_e may vary with discharge, however, not necessarily in the same direction. As discharge increases, R generally increases; however, S_e may increase, decrease, or stay the same, depending on the topography of the channel reach. Undulations in the bed caused by pools and riffles force the water to accelerate (or decelerate), producing a net fluid force in addition to the weight of the water moving downstream. The effects of these flow accelerations are accounted for in the one dimensional equation for gradually varied flow, which can be written as follows,

$$S_e = -\frac{dH}{dx} = -\frac{d}{dx}\left(z + h + \frac{U^2}{2g}\right) \tag{4}$$

where S_e is the energy gradient (also called the friction slope), H is the total energy, z is the average bed elevation, h is the average flow depth (approximately equal to R), and $u^2/2g$ is the velocity head. The first term on the right hand size of (4), dz/dx, is the bed slope, which may be either positive or negative. The second term, dh/dx, is the water surface slope, which also can be positive or negative. These two terms are typically of the same magnitude, thus they are both important, but they can be of opposite sign, in which case their effects on the friction slope and shear stress can offset each other. Together, the first two terms, dz/dx and dh/dx, represent the streamwise gradient in gravitational potential energy. The third term, $d(u^2/2g)/dx$, represents the streamwise gradient in kinetic energy, which is produced by changes in the speed of the flow as it moves over the topography; this term is generally smaller than the other two, however it can add significantly to the total energy loss, particularly in cases where the two other terms are of equal magnitude but opposite sign. Equation 4 thus shows that the flow's ability to do work against the bed friction, dH/dx, depends on the sum of three different terms, which vary in their importance depending on the particular flow level and site characteristics.

Equation 4 was solved using the standard step method, an iterative procedure that balances the total energy, H, along a series of channel cross sections. The model was used to predict the depth and velocity at each cross section for a series of known discharges and assumed values of the roughness coefficient, Manning's n. The model results and assumed values of Manning's n were then verified by comparing the predicted water surface elevations with those measured in the field.

RESULTS

Summary of Streamflows, 1998-2004

This study coincided with a period of sustained and severe drought that affected most of the upper Colorado River basin. Hydrologists continue to discuss the significance and long-term context of this drought, however, it appears that water years 2002-2004 were the lowest in the upper Colorado River basin in at least the last 100 years (*USGS Fact Sheet 2004-3062, August, 2004*). The 7-year period of this study includes two extremely dry years (2002 and 2004) and three other years (2000, 2001, and 2003) which were below average (Table 2). The 2002 water year stands out as the most extreme of these years. In 2002 the Colorado River reached a peak discharge of only 121 m^3/s (Table 2) at the Cameo gauge (USGS station 09095500); this flow ranks as the lowest instantaneous peak discharge in the 71-year period of record for this gauge. The peak discharge of the Gunnison River at the Whitewater gauge (USGS station 09152500) was only 82 m^3/s (Table 2); this flow occurred in September, 2002, thus it was not associated with snowmelt, and it ranks as the second lowest peak discharge in the 96-year period of record for this gauge. Peak flows in 2004 were also very low; peak discharges in that year rank as the third and fourth lowest peak flows at the Cameo and Whitewater gauges, respectively.

The period from 1998-2004 was not only dry overall, but also characterized by an unusual string of years starting in 1998 in which one year after another was followed by lower and lower total runoff. Figure 9 shows trends in annual runoff at the two gauges upstream of the 15-mile reach (Palisade and Cameo, respectively). The record for the Palisade gauge is relatively short (14 yr), however, it shows that prior to 1998 runoff was about equally divided between above-average and below-average years (Fig. 9a). The record for the Cameo gauge is much longer, going back to 1934 (Fig. 9b), and it shows that while the sequence of low-flow

Table 2. Summary of streamflows for the period 1998-2004 and comparisons with longer-term averages at gauging stations on the Colorado River and Gunnison River.

COLORADO RIVER NR CAMEO, CO, USGS 09095500

	Peak Discharge (m^3/s)	Percent of Average	Annual Discharge (m^3/s)	Percent of Average	Annual Runoff (ac-ft)
ave 1950-97	**524**		**109**		
1998	445	85	120	110	3063000
1999	442	84	108	99	2766000
2000	464	89	91	83	2324000
2001	275	52	76	70	1940000
2002	121	23	50	45	1267000
2003	595	113	75	69	1919000
2004	211	40	64	59	1643000

COLORADO RIVER NR PALISADE, CO, USGS 09106150

	Peak Discharge (m^3/s	Percent of Average	Annual Discharge (m^3/s)	Percent of Average	Annual Runoff (ac-ft)
ave 1991-97	**573**		**97**		
1998	419	73	104	107	2664000
1999	377	66	87	89	2215000
2000	408	71	70	72	1788000
2001	227	40	50	52	1289000
2002	128	22	27	27	681000
2003	609	106	56	58	1426000
2004	169	29	42	43	1072000

GUNNISON RIVER NR GRAND JUNCTION, CO, USGS 09152500

	Peak Discharge (m^3/s)	Percent of Average	Annual Discharge (m^3/s)	Percent of Average	Annual Runoff (ac-ft)
ave 1950-97	**306**		**70**		
1998	300	98	82	117	2092000
1999	182	60	66	95	1694000
2000	163	53	57	82	1462000
2001	146	48	46	66	1173000
2002	82	27	31	45	804000
2003	170	55	34	48	862000
2004	107	35	35	49	883000

COLORADO RIVER NR CO-UT STATE LINE, USGS 09163500

	Peak Discharge (m^3/s)	Percent of Average	Annual Discharge (m^3/s)	Percent of Average	Annual Runoff (ac-ft)
ave 1951-97	**797**		**180**		
1998	739	93	209	116	5350000
1999	507	64	170	95	4358000
2000	507	64	137	76	3490000
2001	374	47	110	61	2802000
2002	156	20	69	38	1752000
2003	739	93	103	57	2635000
2004	268	34	95	53	2425000

years from 1998 through 2004 is unusual, it is perhaps not unprecedented. The period from 1987-1992 was likewise characterized by a series of below-average years, with several years of low flow occurring in succession. In the 16-year period from 1954-1969, the average annual discharge was exceeded in only four years, half the expected number. The 2000-2004 drought is notable for its severity, however, strings or three or four low-flow years in a row have occurred several times in the past, and they are very likely to occur in the future.

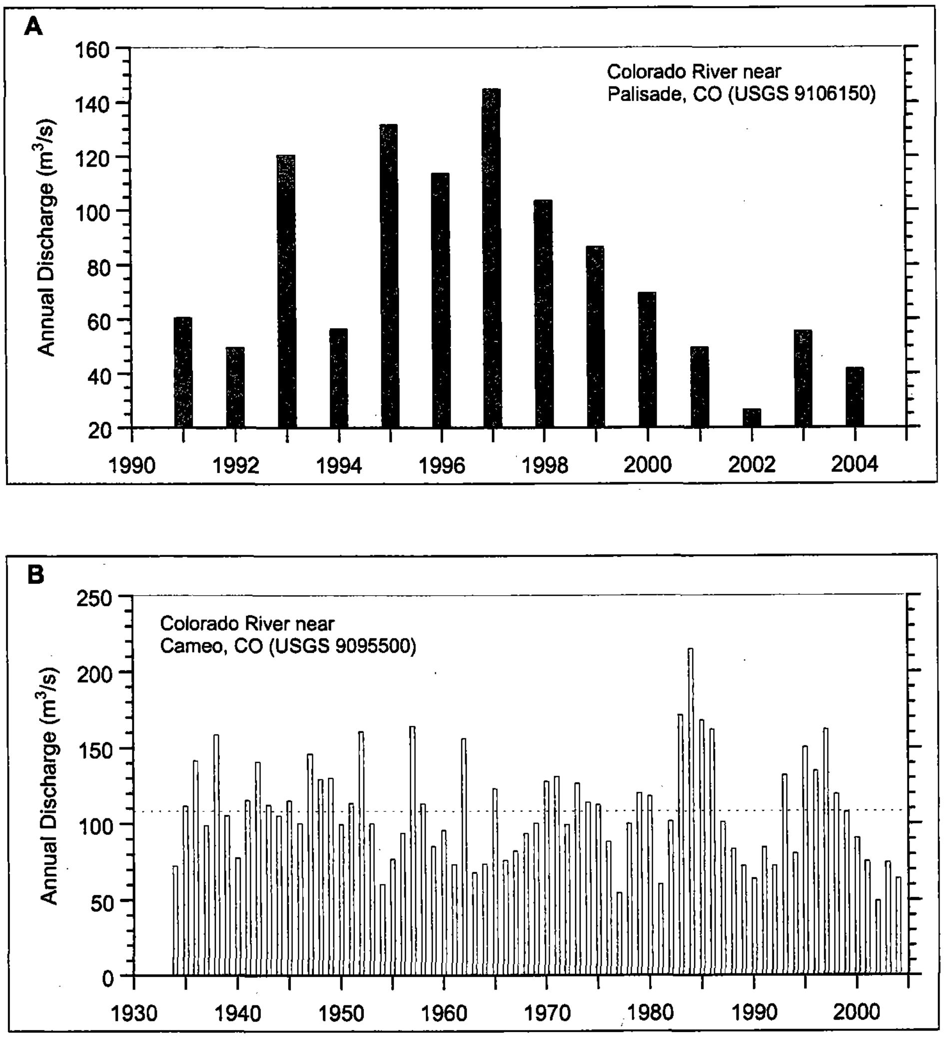


Figure 9. Trends in annual runoff of the Colorado River based on streamflow records from USGS gauging stations (a) near Palisade, CO, and (b) near Cameo, Colorado.

In previous studies supported by the Recovery Program, *Pitlick et al.* (1999), and *Pitlick and Cress* (2000), provided flow recommendations for different reaches of the Colorado River, including the 15-mile and 18-mile reaches. These recommendations focused on discharges that would exceed thresholds for (i) initial mobilization, and (ii) complete mobilization of the bed sediment of the Colorado River, under the assumption that these flows are important for maintaining habitats used by the native fishes and other aquatic organisms. Table 3 lists the threshold discharges, the recommended durations of these discharges (days per year), and the number of days that those discharges were observed during the period 1998-2004. The results provide an indication of the ability of the Recovery Program to meet the flow recommendations given in previous studies and reports. The data listed in Table 3 indicate that the target flows for initial motion (~1/2 the bankfull discharge) were exceeded very infrequently- only about 1/3 of the recommended frequency- and the target flows for complete mobilization of the bed (bankfull discharge) did not occur at all.

Table 3. Comparison between recommended and observed frequencies of sediment-transporting flows in the 15 mile and 18 mile reaches, 1998-2004. Threshold discharges and recommended frequencies are based on results presented in *Pitlick and Cress* (2000).

	15 Mile Reach		18 Mile Reach	
Threshold flows:	$Q_c = 278$ m^3/s	$Q_b = 608$ m^3/s	$Q_c = 548$ m^3/s	$Q_b = 979$ m^3/s
Recommended	30	5	30	5
Observed (days/yr)				
1998	24	0	13	0
1999	31	0	0	0
2000	10	0	0	0
2001	0	0	0	0
2002	0	0	0	0
2003	13	0	6	0
2004	0	0	0	0
Total	78	0	19	0

Coordinated Reservoir Operations

Peak snow-water equivalents and reservoir pool levels in the upper Colorado River basin were sufficient in 1997, 1998 and 1999, thus reservoir operations were coordinated in these three years to deliver higher flows to the 15-mile reach. Plans were also in place to bypass flows in 2000; however, very warm weather in early spring that year rapidly depleted the snowpack, and bypass operations were called off.

Coordinated reservoir operations were implemented for 7 days in 1998, resulting in the release of an additional 24,000 acre-feet from upper basin reservoirs. Figure 10 shows that these releases increased the peak discharge in the 15 Mile Reach by about 1,500 cfs (40 m^3/s) and extended the duration of the peak runoff period by several days. In 1999, coordinated reservoir operations were implemented for 10 days, resulting in the release of an additional 40,000 acre-feet from upper basin reservoirs. Figure 10 shows that these releases increased the peak discharge in the 15 Mile Reach by about 2,000 cfs (56 m^3/s).

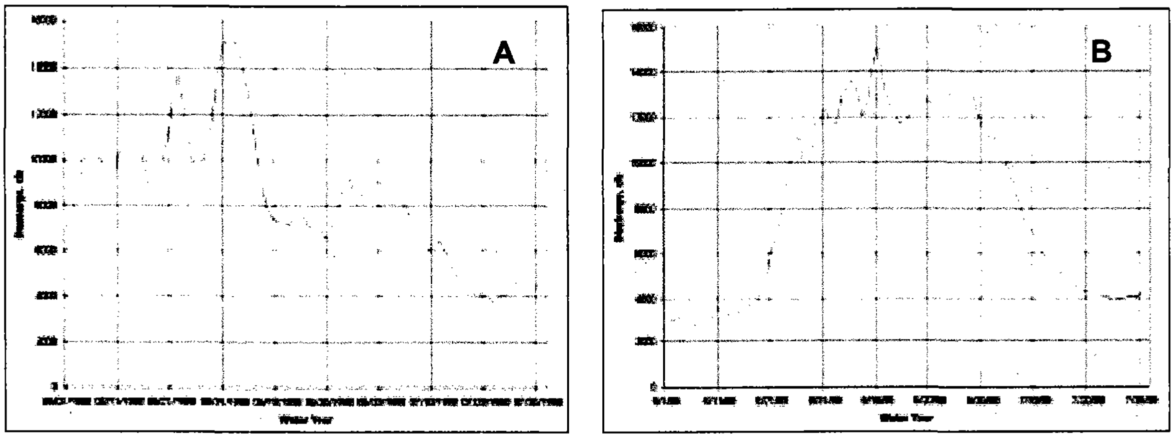

Colorado River near Cameo, CO

Figure 10. Record of discharge at the USGS gauging station on the Colorado River, near Cameo, Colorado for periods of snowmelt runoff in (a) 1998 and (b) 1999. Dotted line indicates the discharge that would have occurred at this location without the added flow produced by coordinated reservoir operations.

The increases in discharge produced by the bypass flows were not particularly large (only 10 to 15% of the discharge in the 15 mile reach), however, two important conclusions can be drawn from these tests: First, the reservoir operators and federal agencies demonstrated that they could coordinate efforts to enhance peak flows to improve habitats used by the endangered fish. They did so voluntarily and without significantly disrupting their ability to supply water for other uses. Some water was "lost" in the process, however, the volumes released were a fraction of the total storage capacity of the upper basin system. Second, the bypass flows were successful in boosting background flow levels within a specific window of time, making it much more likely that the discharges needed to initiate bed load transport were exceeded in a number of places in the 15 mile reach, not just a few isolated spots. Without the bypass flows, transport would have been more limited, and the observed sequence of flows would have fallen well short of the recommendations given in previous reports. Unfortunately, the total storage capacity of the upper basin reservoir system amounts to no more than about half the annual flow of the Colorado River (*Pitlick et al.*, 1999), thus there are clear limits on the potential uses of bypass flows, particularly in a string of dry years such as those experienced from 2002-2004.

Changes in Channel Morphology

Cross-section Measurements: Survey measurements of 11 main-channel cross sections in the reach near RM 176 show that changes in the overall morphology of the Colorado River were relatively minor during the monitoring period (Fig. 11). Minor amounts of bank erosion (< 2 m) occurred at several cross sections, but the topography of the study reach remained essentially unchanged. Enlarged views of measurements across the secondary channel in this reach (Fig. 12) show that minor amounts of sediment were deposited along the right bank, but overall, the topography of the secondary channel at RM 176 changed little during the monitoring period.

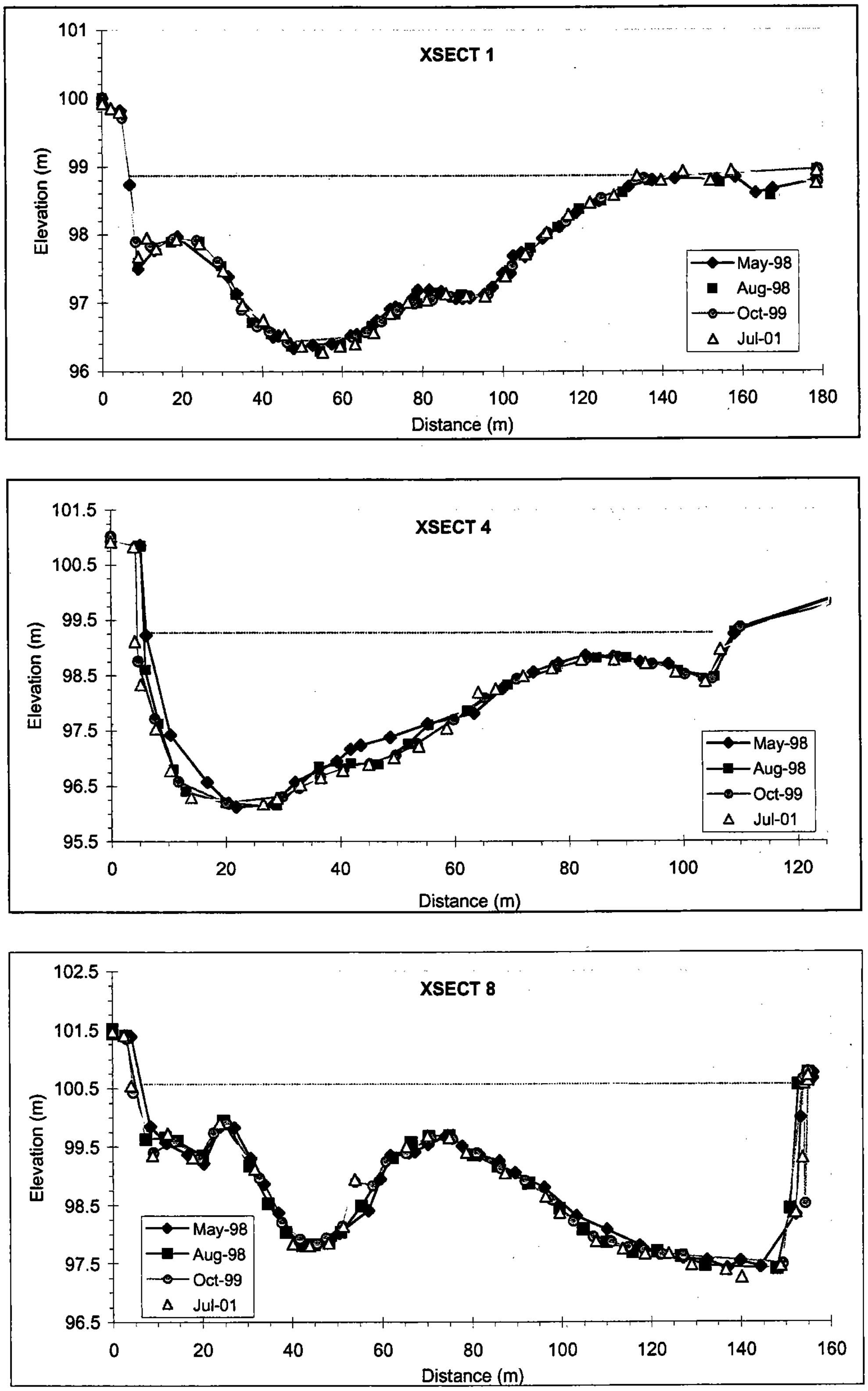


Figure 11. Main channel cross sections within the study reach near RM 176.

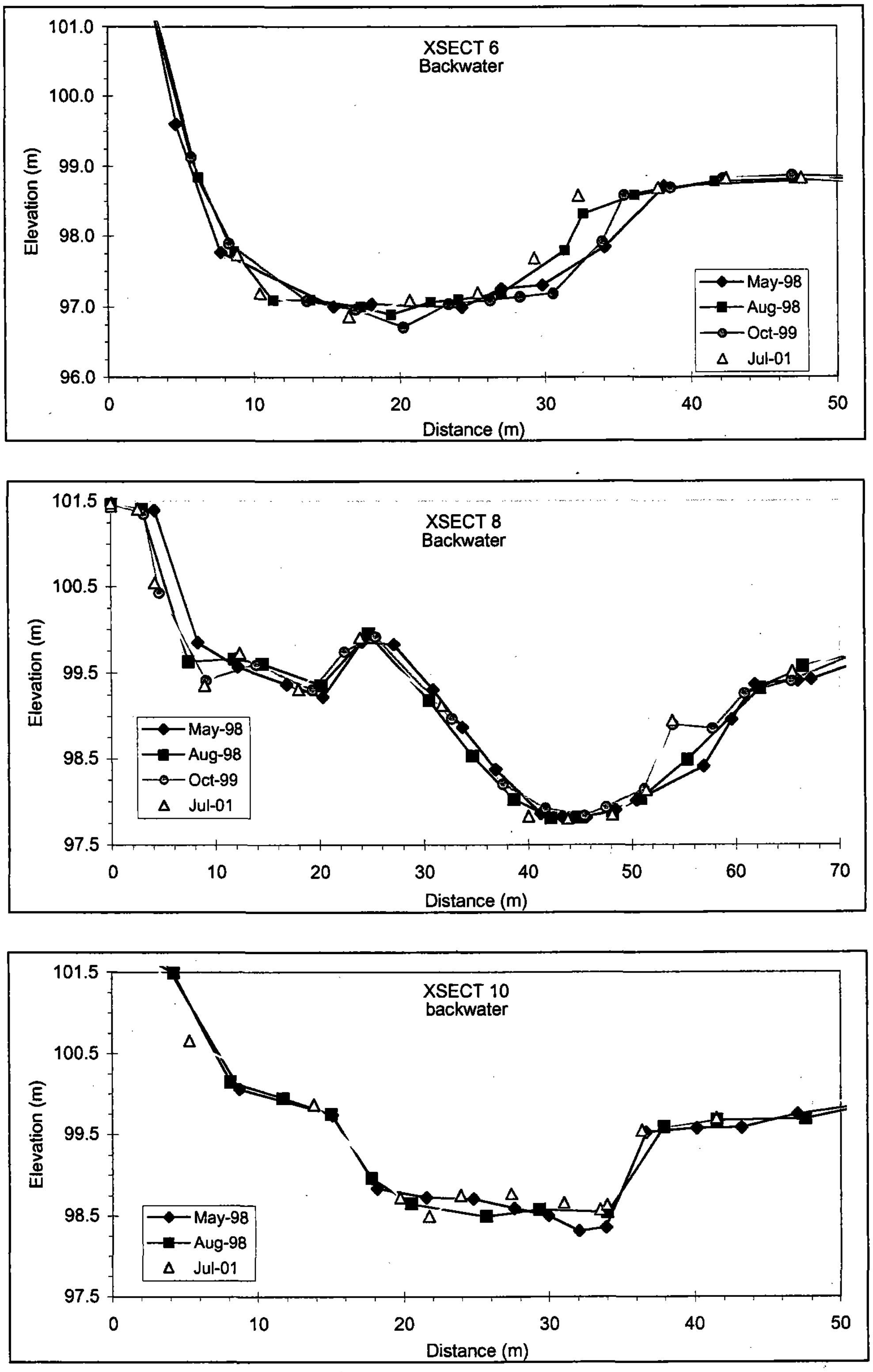


Figure 12. Backwater cross sections within the study reach near RM 176.

Backwater cross sections were monitored at three other sites, one located several hundred meters downstream of the lower end of the RM 176 study reach, and two others located in the 18-mile reach, which were first surveyed in 1993 as part of an earlier study (*Pitlick et al.*, 1999). The backwater at RM 175.5 is short and moderately sinuous, whereas the other backwaters are relatively long and straight. A substantial amount of sediment was deposited in the backwater at RM 175.5 in the first two years of monitoring (Fig. 13a); subsequently, in 2002, the mouth of the RM 175.5 backwater was dammed by beavers, eliminating access to and from the main channel. Sedimentation in the other two backwaters was minor in comparison. The backwater at RM 162 aggraded by 0.2 to 0.5 m between 1995 and 2001 (Fig. 13b), whereas the backwater near RM 160 changed little, except for deposition of a small berm along the right bank (Fig. 13c)

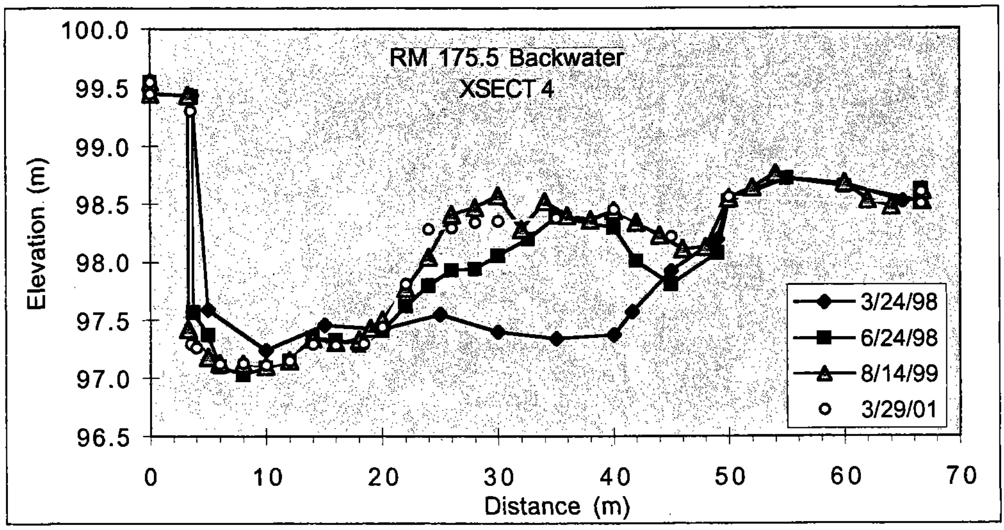
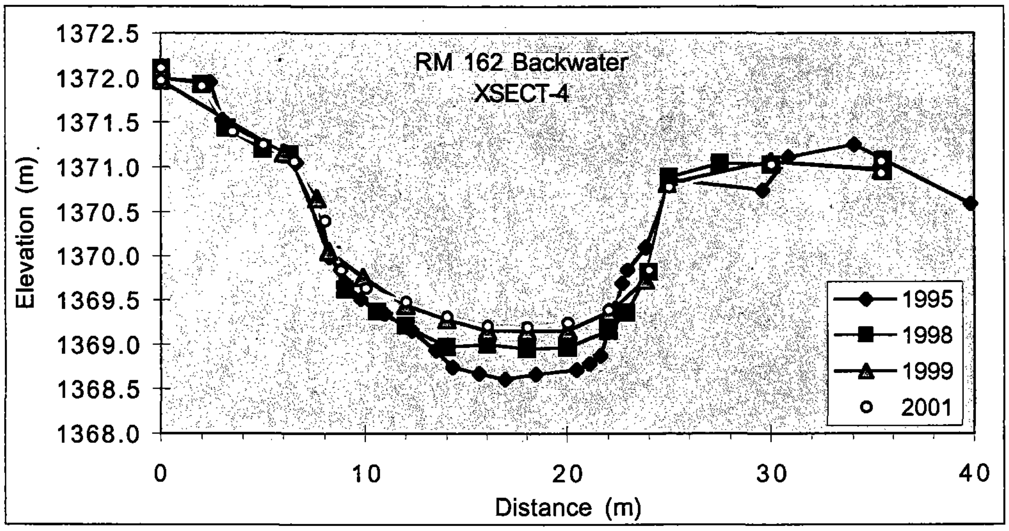
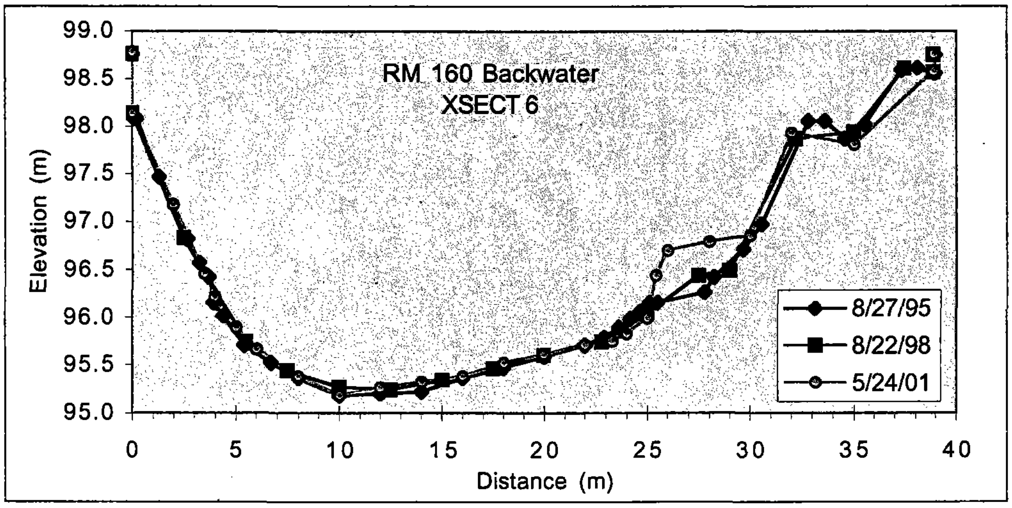


Figure 13. Backwater cross sections in other locations within the 15- and 18-mile reaches.

Figure 13, continued





<u>Comparison of Aerial Photographs</u>: The photogrammetric analysis of channel change suggests that the planimetric area of individual features within the 15-mile and 18-mile reaches decreased slightly between 1993 and 2000. Among the three mapping units, the area of bars and side channels changed the most, while the area of the main channel changed the least (Fig. 14a). However, it is evident that much of the change detected in the analysis occurred in the 18-mile

reach, and that appears to be mostly due to lower flow levels in 2000 as compared to 1993; changes in the 15-mile reach, where flows levels were similar, were generally quite small. Nonetheless, the loss of side channels appears to be real in the vicinity of RM 183 and RM 173, as does the increase in bar area and channel complexity near RM 175. The percentage change in most features is small (< 20 %) and small in comparison to results presented in earlier studies, which were based on photographs taken much further apart in time (*Pitlick et al.*, 1999).

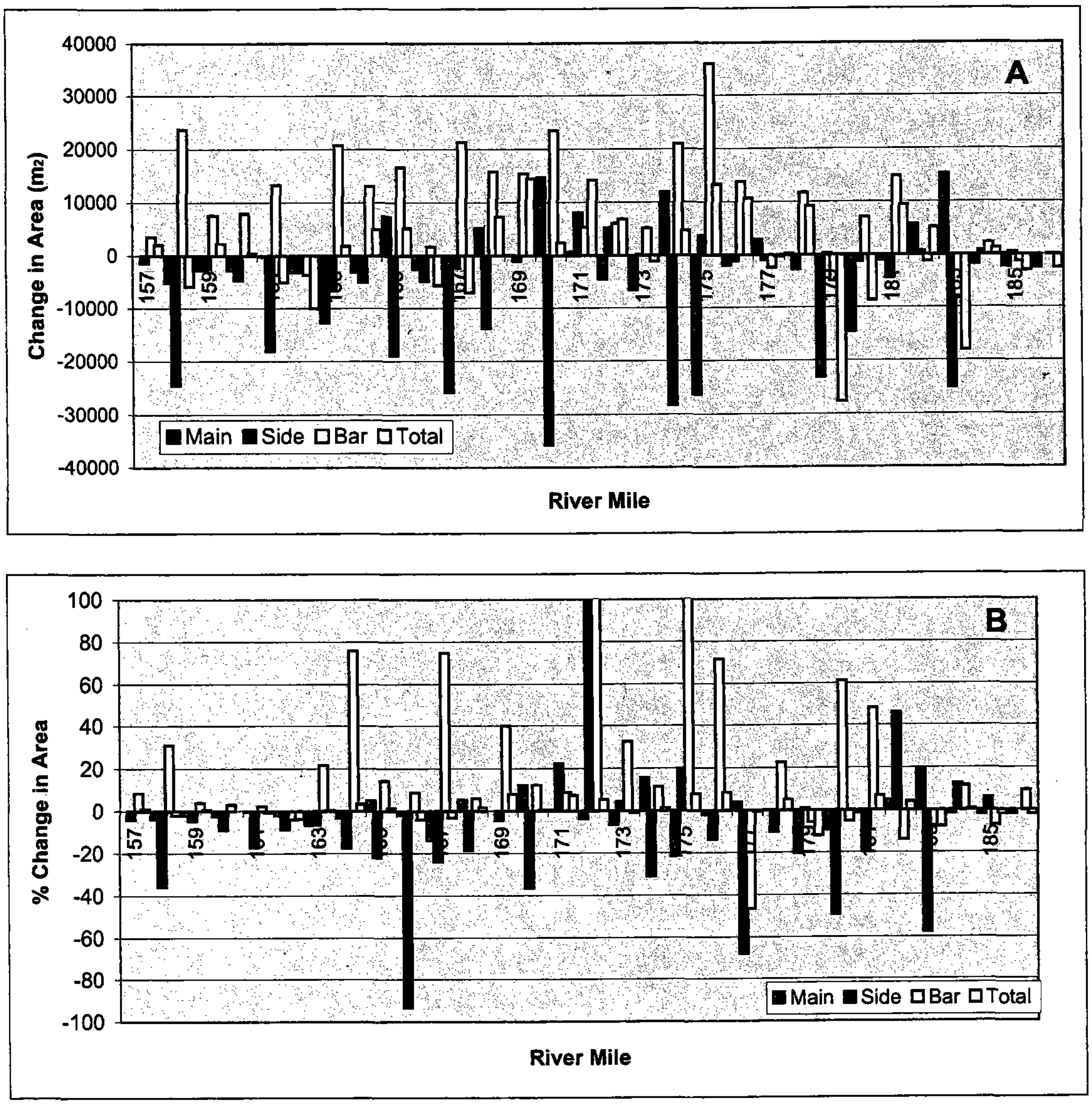


Figure 14. Change in planimetric area of features within the channel of the Colorado River; (a) absolute change in area (b) change expressed as a percentage of the initial area.

Sediment Transport

Seasonal Trends in Suspended Sediment: Measurements of suspended sediment have been made at USGS gauging stations in the study area periodically from 1976-1999. The length of record and number of observations at each stations varies; however, the complete data set contains hundreds of entries listing water discharge, sediment concentration, and percentage of sand measured in suspended sediment samples. These data were retrieved from the USGS data base and are used here to examine seasonal trends in sediment transport more closely.

Figure 15 plots suspended sediment relations for the Colorado River near Cameo, CO. The panel on the left (Fig. 15a) plots the suspended sediment concentration, C_s (*mg/l*), versus the instantaneous water discharge, Q (*m^3/s*), with samples distinguished according to whether they were taken prior to or after the peak in the annual hydrograph (rising limb and falling limb, respectively). The panel on the right (Fig. 15b) plots suspended sediment load, Q_s, (*metric tons per day*) versus instantaneous water discharge. The load is calculated from $Q_s = 0.0864\ C_s\ Q$, where the constant 0.0864 is a factor for converting units.

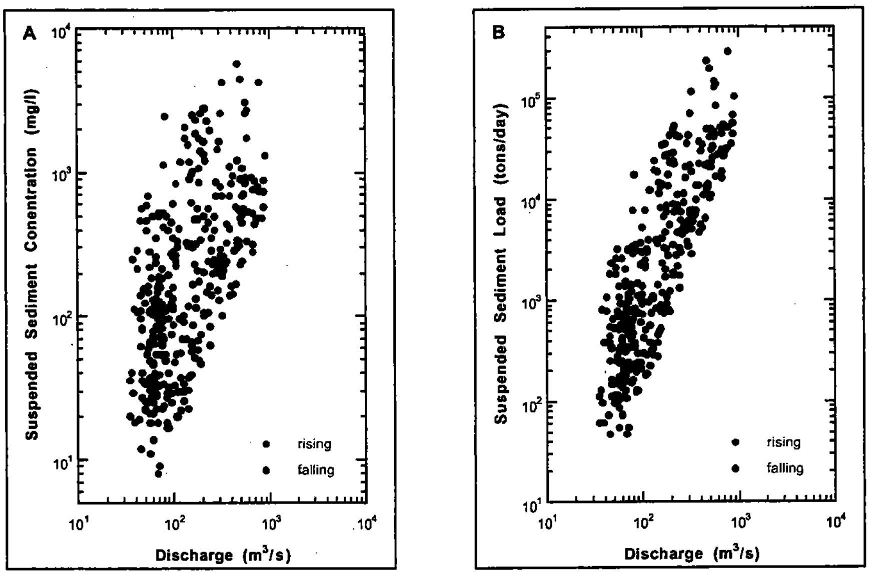


Figure 15. Suspended sediment relations for the Colorado River near Cameo, CO; (a) suspended sediment concentration versus water discharge, and (b) suspended load versus water discharge.

The data in Figure 15a illustrate that suspended sediment concentrations in the Colorado River are generally much higher on the rising limb of the hydrograph than they are on the falling limb. This effect- known as hysteresis- is common to all of the gauges in the study area [*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000]. Suspended sediment loads are likewise consistently higher on the rising limb of the hydrograph than they are on the falling limb (Fig. 15b). The rising-limb flows carry much higher suspended sediment loads because it is during this time (typically in May) when both sediment concentration and water discharge are high. Suspended sediment concentrations can reach moderately high levels at other times of the year, particularly after summer thunderstorms; however, since flows are generally low at that time of year, these events carry a small proportion of the total annual suspended sediment load.

The data set for the Cameo gauge also includes 449 measurements of the percentage of sand in the suspended sediment samples. Sand includes those sediment sizes falling in the range from 0.065-2.0 mm; sediment finer than 0.0625 mm is silt and clay. If the percentage of sand in a sample is known, so too is the percentage of silt and clay, thus the total suspended sediment load can be proportioned between the sand fraction and the silt-clay fraction. Figure 16 shows the same data as in the previous figure, with the suspended sediment load split between silt-clay and sand fractions. The two graphs are plotted at the same scale, thus it is evident that, in general, the silt-clay fraction of the suspended sediment dominates over the sand fraction; on average, 80% of the suspended sediment load of the Colorado River consists of silt and clay. It is also evident in these plots that there is much more scatter in the relation between discharge and silt-clay fraction than there is in the relation between discharge and sand fraction. This observation indicates that amount of silt and clay carried in suspension is driven in part by the supply of fines from sources outside the channel; however, the relation between silt-clay and discharge is not completely random, and it is clear that the amount of fines carried by the Colorado River increases systematically with discharge.

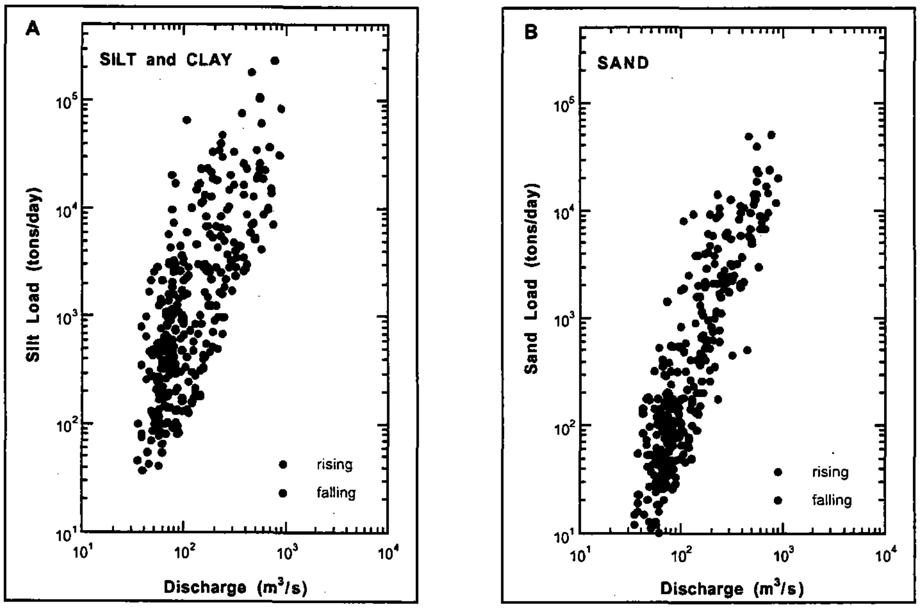


Figure 16. Suspended sediment loads of the Colorado River, near Cameo, CO, weighted by the proportion of (a) silt and clay and (b) sand in suspended sediment samples.

The right panel of Figure 16 shows that there is much less scatter in the relation between discharge and sand load, as well as a clearer separation between rising-and falling-limb samples. This observation suggests that sand transport rates are driven perhaps as much by hydraulics as sediment supply. Least squares regression of the sand data yields the following relations:

Sand load, rising limb: Q_s = 0.007Q^2.35 (r^2 = 0.49)

Sand load, falling limb: Q_s = 0.001Q^2.44 (r^2 = 0.74)

The exponents in the above relations are similar to each other and lie within the range of values typically observed in alluvial rivers [*Leopold and Maddock*, 1953; *Nordin and Beverage*, 1965]. The difference in coefficients and the offset in sample values suggests one of two things: (i) the sand supply is being depleted over time, thus the same discharge carries a lower sand load after the peak in the hydrograph than it did before the peak, or (ii) the grain size of the sand supply is becoming coarser with time, thus not as much sand is being carried in suspension, nor is it being carried as high in the flow; some of the coarser sand could instead be moving as bed load. It is not possible to distinguish between these effects without specific data characterizing the evolution of the grain size distribution of the suspended load over time. Whatever the case, is not uncommon for the size distribution of the suspended load to change over time as finer or coarser sediment becomes available. For example, suspended sediment measurements taken on the Colorado River in Grand Canyon, before the construction of Glen Canyon dam, show that the median grain size of the suspended load generally increased on the receding limb of the annual hydrograph [*Topping et al.*, 2000]. Similarly, measurements of the bed material and suspended bed-material load taken in sand-bed reaches of the Rio Grande in the late 1950s likewise showed that the bed material became coarser over the period of the hydrograph [*Nordin and Beverage*, 1965]. These observations are relevant to the present study because, if there is a natural tendency for the grain size distribution of the suspended sediment load in the Colorado River to coarsen with time, then any further reduction in peak flows could lead to a significant reduction in the total mass of sand carried. It is important to maintain the mass balance of all sediment sizes in order to maintain the existing channel capacity, as well as the existing suite of in-channel habitats. The USGS data indicate that about 20% of the suspended load is sand-sized sediment, which is approximately equal to the proportion of sand found in the substrate (bulk bed material). The similarity in percentages suggests that the sand in transport in the Colorado River exchanges in equal proportions with the sand stored in the bed, consistent with contemporary theories for equilibrium transport in gravel-bed channels [*Parker et al.*, 1982; *Parker and Toro-Escobar*, 2002].

In order to examine seasonal patterns in flow and sediment transport more closely, synthetic annual time series of discharge and sediment concentration were constructed for the three gauges with the most complete records (Cameo, Whitewater and State Line). The time series were formed by arranging all of the flow and sediment measurements in chronological order from January 1 through December 31, regardless of the year in which they were taken. Figure 17 shows the synthetic time series of discharge and suspended sediment concentration for the Colorado River near Cameo, CO. The irregular patterns (noise) reflect the fact that the data are arranged by the day of the year, independent of the year. The smooth curve running through the data is fit using a locally weighted least squares method. The trends in this plot show that in typical years the peak in suspended sediment concentration occurs 2-3 weeks prior to the peak in water discharge (Fig. 17a). The distinct mode of high sediment concentration running from early April to late June illustrates that sediment supply and transport are highest at this time.

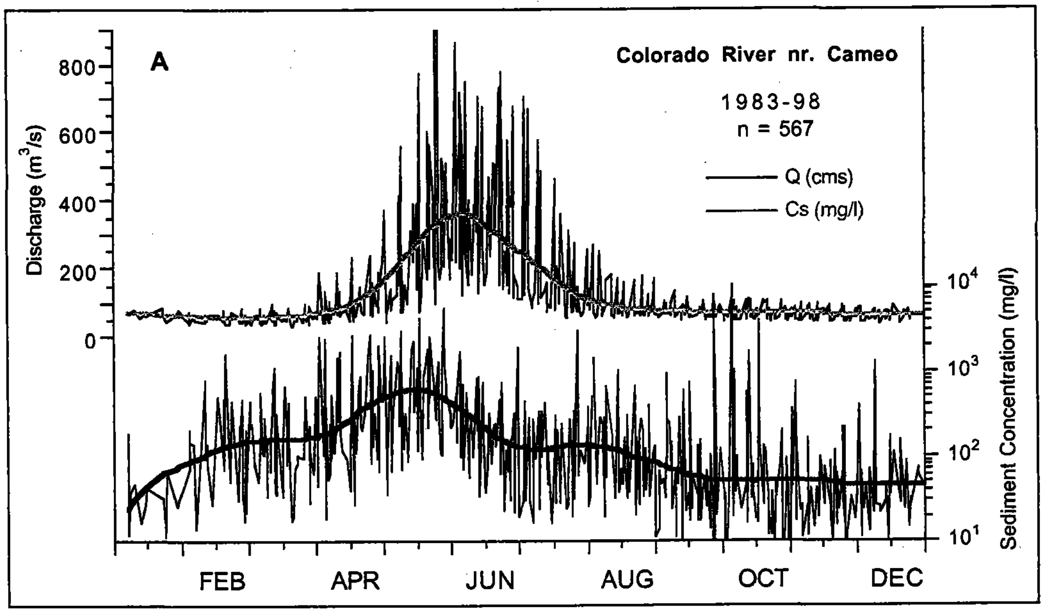
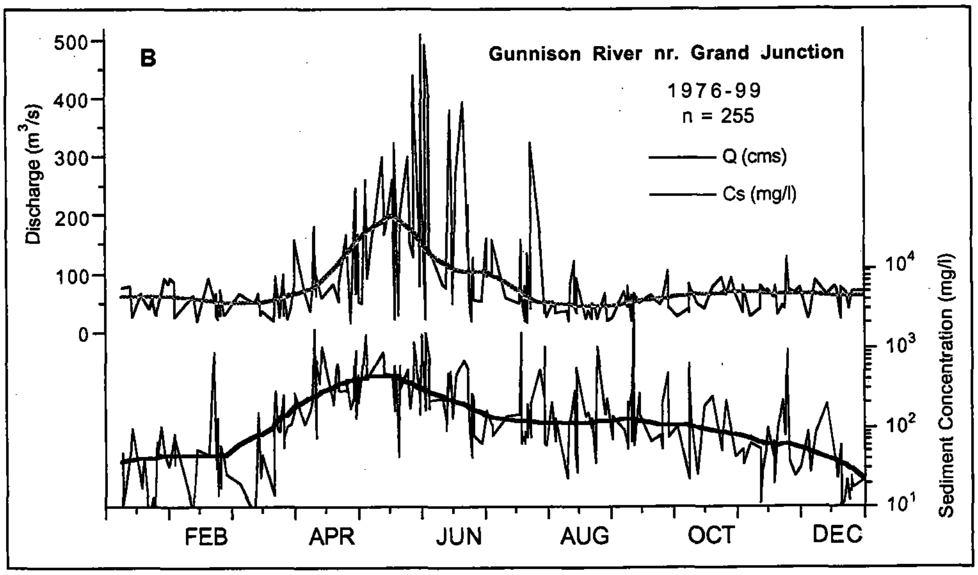


Figure 17. Seasonal trends in discharge and suspended sediment concentration, (a) Colorado River near Cameo, CO, (b) Gunnison River near Grand Junction, and (c) Colorado River near Colorado-Utah state line.

Figures 17b and 17c plot similar relations for the Gunnison River and the Colorado River near the CO-UT state line. The patterns observed at these site are similar to those observed at Cameo, although not as clear because of the fewer observations. In both cases the peak in sediment concentration precedes the peak in water discharge by several weeks, and there is a distinct period from April through June were concentrations are higher overall.



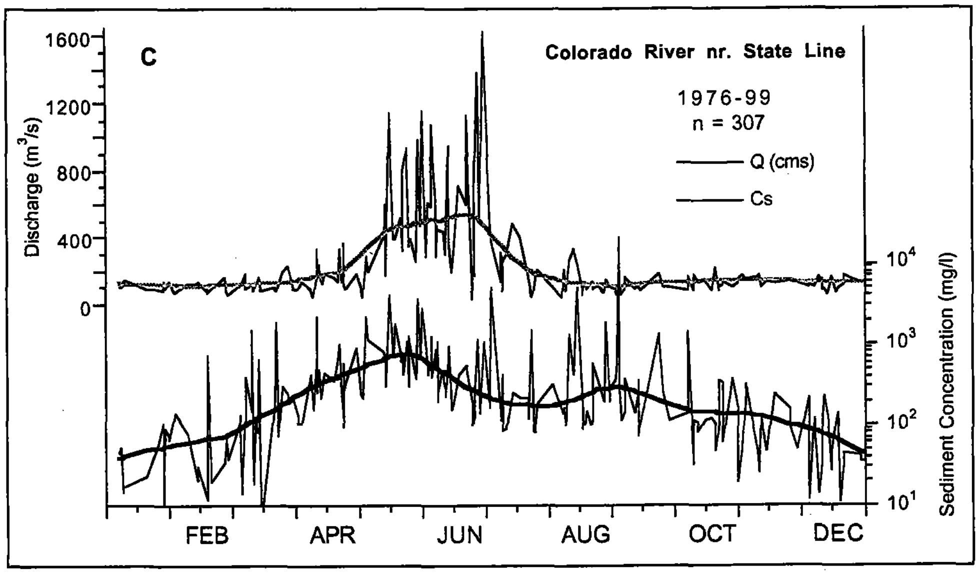
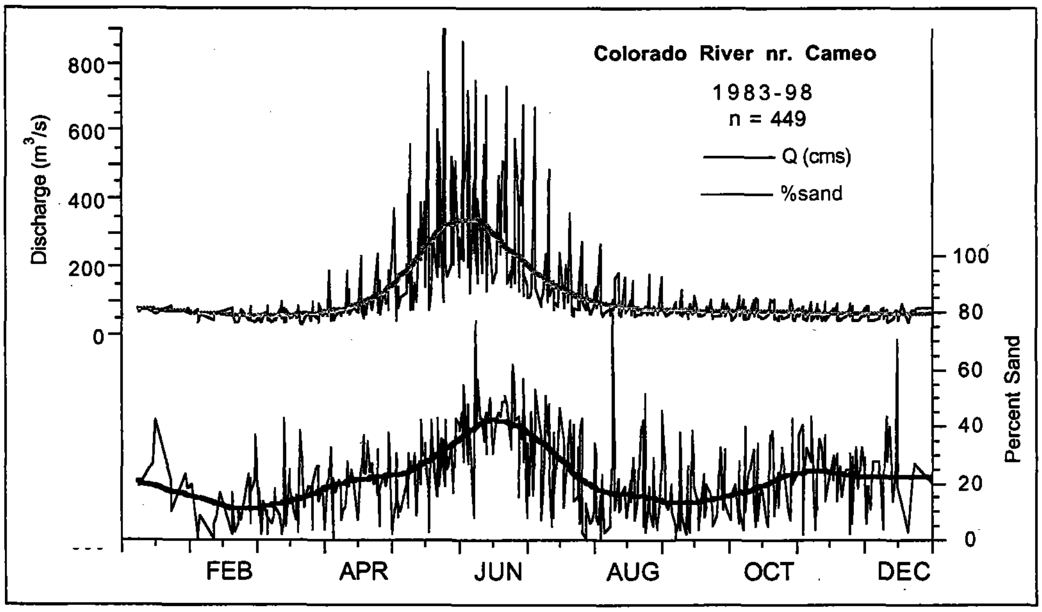
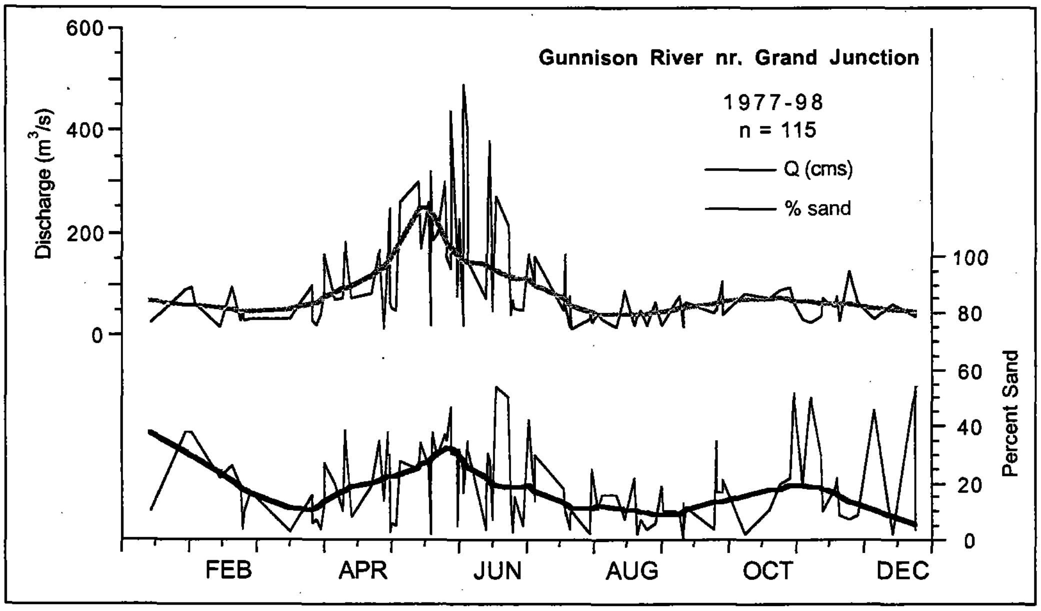


Figure 17, continued

Figure 18 shows three similar plots displaying time-series trends in discharge and the percentage of sand in suspended sediment samples. A consistent, yet somewhat different pattern emerges here: it is evident that the peak in sand concentration occurs 2-3 weeks after the peak in water discharge (Fig. 18). The trends at the Gunnison River gauge and State Line gauge are not as well defined, but consistent with the observations at the Cameo gauge.





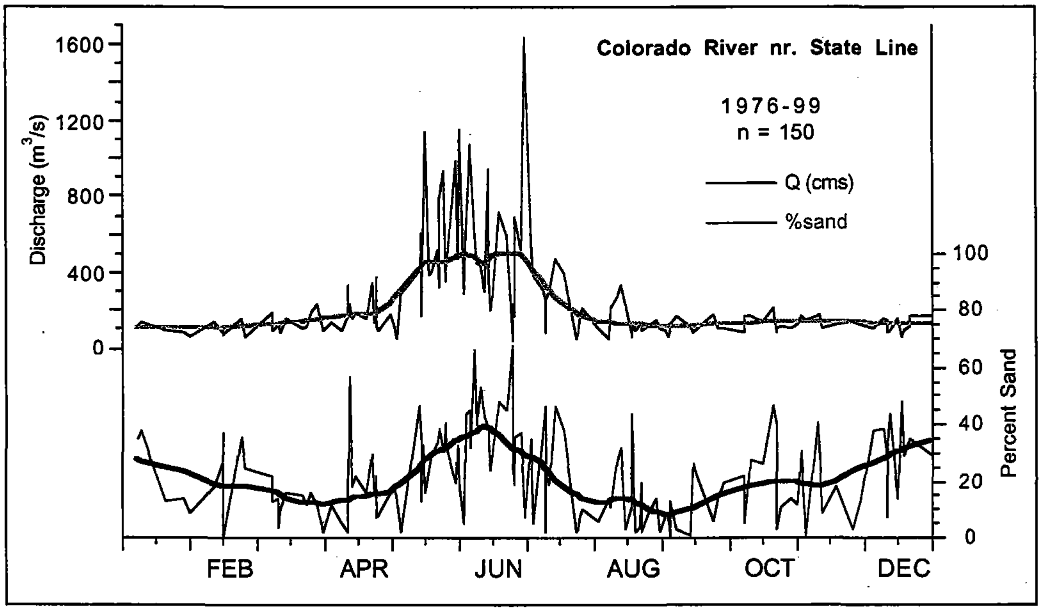


Figure 18. Seasonal trends in discharge and the percentage of sand in suspended sediment samples, Colorado River near Cameo, CO, Gunnison River near Grand Junction, and (c) Colorado River near Colorado-Utah state line.

The trends in sand percentage indicate that in typical years the Colorado River and the Gunnison River continue to transport sand in suspension for several weeks after the peak in the annual hydrograph. Although the trends are somewhat irregular, the timing of the peak in sand concentration at the three gauges occurs at roughly the same time (mid-June). If sand was moving through this river system as a wave or pulse, then there should be a lag in the timing of the peak percentage of sand in the downstream direction. This does not appear to be the case, suggesting again that much of the sand in transport is derived locally, i.e. from the channel bed, rather than discrete sources upstream. The observed patterns are probably not unnatural and it would be reasonable to assume that, if this has always been the case, then the native fishes have evolved to cope with these conditions. The key question is whether the timing of the peak in sand transport has any effect on spawning, or the fishes preferences for spawning in certain areas, and thus is there a reason to be concerned about changes in the timing of the peak?

Sediment Trap Data: Streambed sediment traps were installed in riffle and run habitats to monitor the movement of fine sediment (broadly defined) on the receding limb of the hydrograph when Colorado Pikeminnow normally spawn. The primary objectives of the trap measurements were to determine the sizes of sediment in transport at that time, and to a lesser extent, to provide qualitative information on transport rates. If one of the goals of coordinated reservoir releases is to flush fine sediment from the bed to improve micro-habitats , then it is reasonable to consider how long the benefits of a flushing flow may last.

The figures on the following page summarize the results from the trap measurements. Hydrographs for the period of snowmelt runoff are shown for each of the four years in which the traps were used, 1998-2001. The vertical lines on the hydrographs indicate specific dates that the trap samples were taken. The figures to the right of the hydrographs show the grain size distribution of the sediment taken from the traps; these do not include the first sample of the year, which would include sediment collected any time during the previous 9-10 months. For comparison, these figures also show the grain size distribution of the bed material (red lines), as determined from three bulk samples of the subsurface sediment in the 15 mile reach.

The first point to note in these figures is that the grain size of the sediment caught in the traps is much finer than the sediment sampled from the bed. The median grain size of the subsurface sediment, D_{50s}, is about 30 mm (medium gravel), whereas the median grain size of the trapped sediment is typically between 0.1 and 0.5 mm (fine-medium sand). About 10% of the subsurface sediment falls in that size range. The sediment caught in the traps is found in appreciable quantities in the bed, therefore, it represents a component of what *Einstein* [1950] termed the *bed material load* (the other component– termed *wash load*- is sediment that is not found in appreciable quantities in the bed; silt and clay fall into that category in this case).

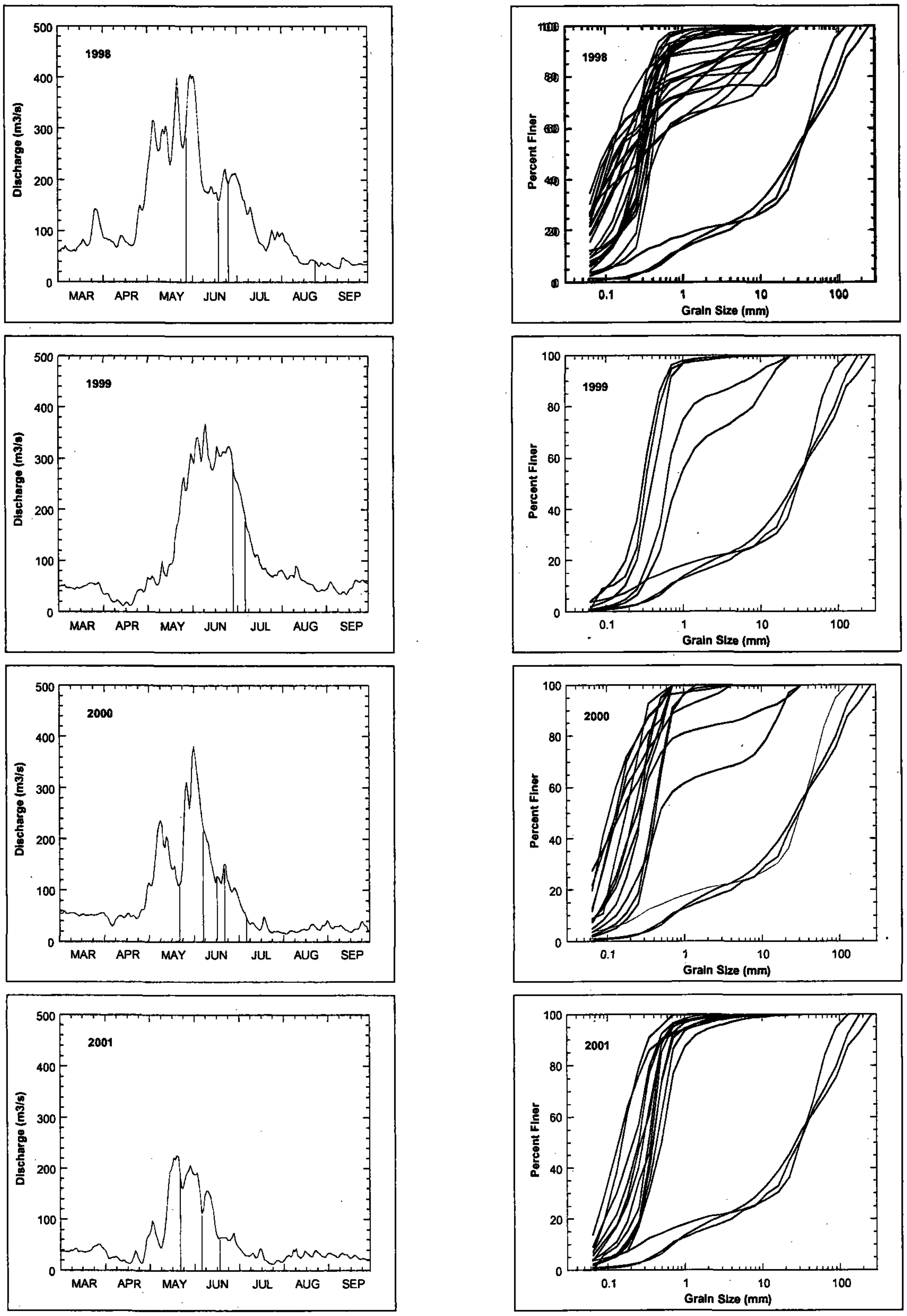


Figure 19. Panel on the left shows hydrographs, 1998-2001, with gray lines indicating dates that bed sediment traps were retrieved. Right, size distributions of sediment collected in traps.

The second thing to note in these figures is that there was very little sediment coarser than sand ($D > 2$ mm) caught in the traps in years when the peak discharge did not exceed ~300 m^3/s. This is approximately the flow level that was recommended for producing initial motion of the bed material [*Pitlick and Cress*, 2000]. The presence of pebbles and fine gravel in samples taken near the peak in 1998 indicates that portions of the bed surface were indeed mobilized during the period of high flow that year. These sizes are not as common in samples collected in subsequent years, suggesting that, at flows less than ~300 m^3/s, most of the bed surface remains immobile, as predicted. However, in addition, the data clearly show that even during periods of low flow, the Colorado River continues to transport fine-medium sand ($0.1 < D < 0.5$ mm). In a general long-term sense, this has probably always been the case; however, with streamflows now regulated, there are concerns that the build up of fine sediment on the bed of Colorado River will impair biological productivity [*Osmundson et al.*, 2002]. Thus, in addition to moving coarse sediment on the bed surface, another management goal might be to augment flows on the recessional limb of the hydrograph to keep fine-medium sand in suspension over the most productive and important habitats (riffles). The criterion for suspension is based on an empirical relation for estimating the settling velocity, w_s, of natural particles in water as a function of grain size and grain shape [*Dietrich*, 1982]. When the local fluid shear velocity, $u_* = (ghS_e)^{1/2}$, exceeds the settling velocity of a given particle size, $u_* > w_s$, then those sizes should be transported in suspension; otherwise they should move as bed load. Using *Dietrich's* [1982] relations for quartz-density sediment with a shape factor or 0.7, the fall velocity for medium sand, $D = 0.5$ mm, is calculated to be $w_s = 7$ cm/s. Based on results from flow modeling in the reach near RM 176 (discussed in the next section), a discharge of 125 m^3/s should be sufficient to keep particles finer than 0.5 mm in suspension over riffles.

Hydraulic Response to Changes in Discharge: The reach selected to evaluate thresholds for coarse sediment transport in the 15 mile reach is located about 2 km downstream of the Corn Lake State Wildlife Area and the highway 141 bridge. The reach is relatively straight (Fig. 20) with a prominent bar along the left (south) side of the main channel (also shown in the cover photo). The majority of the study reach would be characterized as run habitat; there is a short section of riffle habitat in the middle of the reach, and a relatively deep pool at the lower end of the reach (Fig. 20). A secondary channel/backwater occurs along the south bank. The average bankfull channel width is 127 m and the average gradient is 0.0020 m/m.

Water-surface elevations were surveyed through the study reach at eight different discharges ranging from 37 to 396 m^3/s. These measurements were used with data from the cross sections surveys to determine changes in wetted area of the channel and to calibrate the roughness coefficient in the gradually varied flow model. Table 4 summarizes some of the basic data from measurements at various discharges.

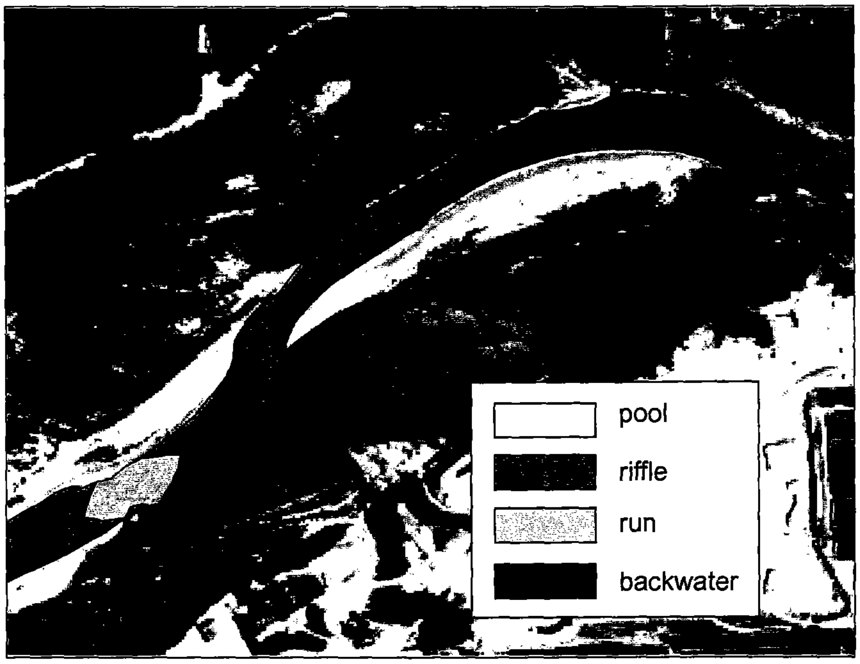


Figure 20. Delineation of in-channel habitats within the RM 176 study reach.

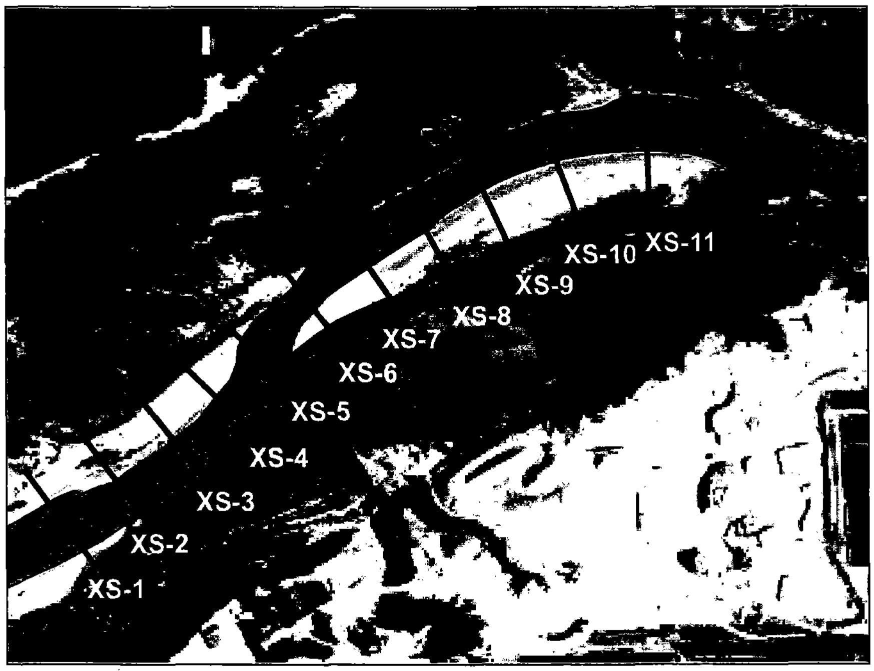


Figure 21. Locations of channel cross sections within the RM 176 study reach.

Table 4. Summary of flow conditions for the range of modeled flows.

Q (cfs)	Q (cms)	Q/Q_c[1]	Q/Q_b[2]	H (m)	U (m/s)	n
1300	36.8	0.13	0.06	0.85	0.89	0.037
4400	124.6	0.45	0.20	1.25	1.61	0.029
6200	175.6	0.63	0.29	1.30	1.54	0.032
7910	224.0	0.81	0.37	1.43	1.69	0.032
9820	278.1	1.00	0.46	1.41	1.80	0.030
12200	345.5	1.24	0.57	1.57	1.99	0.030
12800	362.5	1.30	0.60	1.57	2.10	0.028
13900	393.6	1.42	0.65	1.63	2.14	0.028

1. Ratio of observed discharge to initial motion discharge.
2. Ratio of observed discharge to bankfull discharge.

Flow levels within the study reach were observed at discharges ranging from baseflow up to about 2/3 of the bankfull discharge. Hydraulic conditions within the reach vary in a somewhat irregular way as discharge increases over this range. At baseflow the water-surface width averages 54 m (Fig. 22a), which is less than half the average bankfull width. At this flow the wetted area of the channel is ~40,000 m^2 (Fig. 22b) and more than half of the channel perimeter is dry. Flow stays within the baseflow channel until the discharge reaches approximately 140 m^3/s (~5000 cfs), at which point, the flow begins to inundate bar surfaces, causing a rapid increase in the water surface width and wetted area of the channel (Fig. 22a, b). The width and wetted area increase slowly thereafter; most of the channel is inundated once the flow reaches

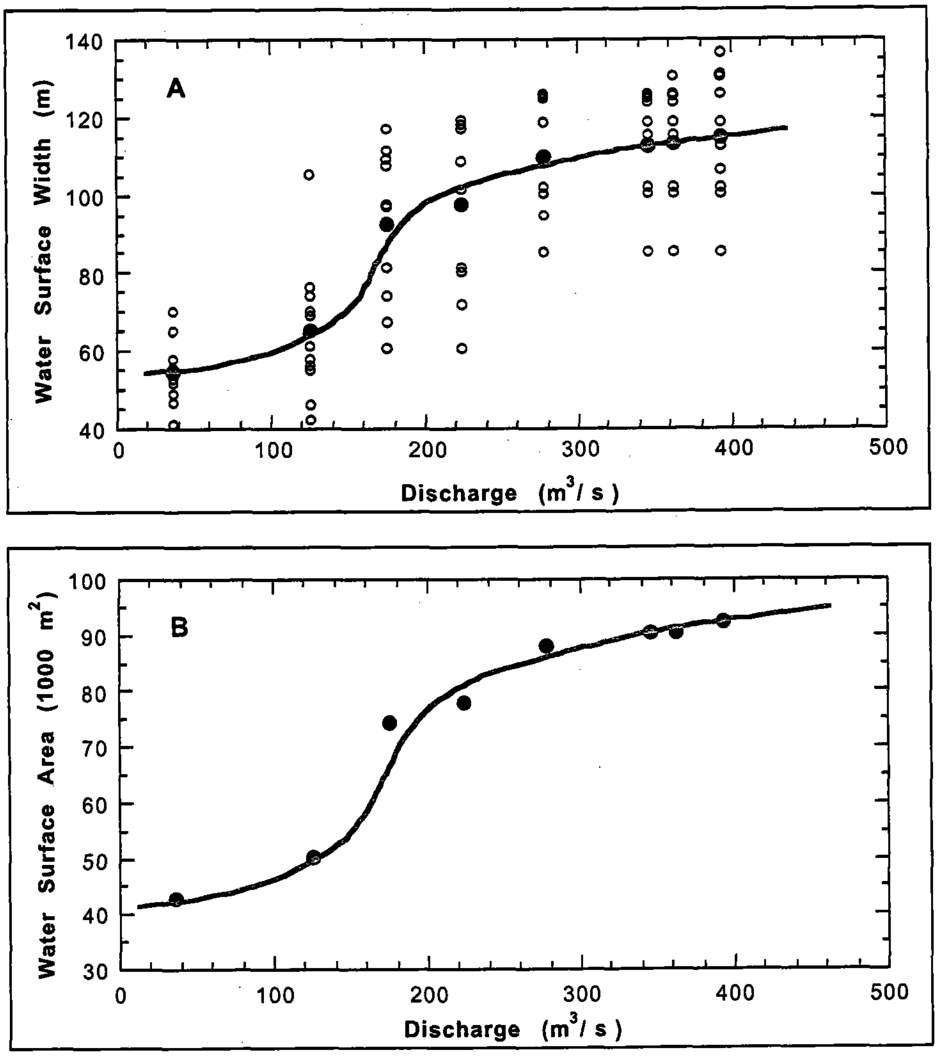


Figure 22. Changes in water surface width (a) and wetted area (b) with discharge, RM 176.

280 m^3/s (~10,000 cfs). This flow level corresponds to the threshold for initial motion recommended in the previous reports (*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000).

Reach-average estimates of flow depth, H, and flow velocity, U, are plotted as power functions of discharge in Figure 23, forming the so-called at-a-station hydraulic geometry relations (*Leopold and Maddock*, 1953). The exponent in the relation for depth (0. 26) is relatively low in comparison to typical values and low in comparison to the value expected for steady uniform flow. The observation that depth changes slowly with discharge reflects the fact that, in this case, width increases rapidly in the range of low to intermediate discharges; in other words, at these flow levels most of the increase in flow volume occurs as a change in width. This effect carries over into the modeled estimates of shear stress, as discussed below. The exponent in the relation for velocity (0.36) is typical of values observed in other rivers (*Leopold and Maddock*, 1953). Otherwise, it is worth noting the relatively high value of U at Q = 125 m^3/s. This is not an error, but instead reflects locally high velocities produced when most of the flow is contained within the baseflow channel.

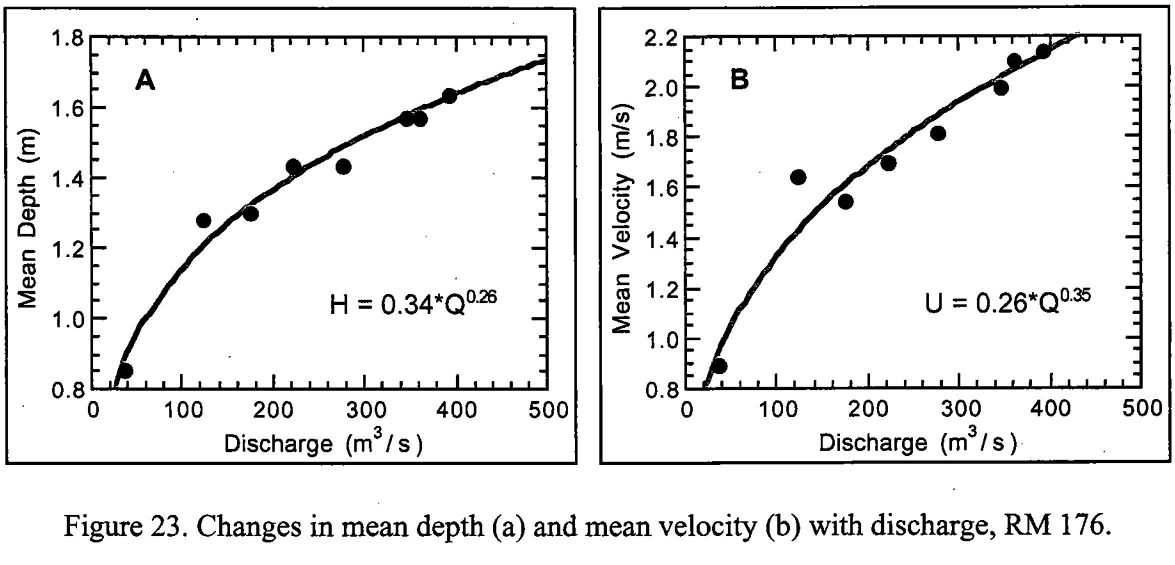


Figure 23. Changes in mean depth (a) and mean velocity (b) with discharge, RM 176.

The one-dimensional hydrodynamic model described earlier was used to calculate flow depths and water surface elevations for each cross section for each of the eight discharges listed in Table 4. The model has one free parameter, Manning's *n*, which was adjusted through trial-and-error until there was reasonably good agreement between modeled and measured water surface elevations. The differences between modeled and measured water surface elevations are generally less than 10 cm, and in a few cases up to 20 cm (Fig. 24).

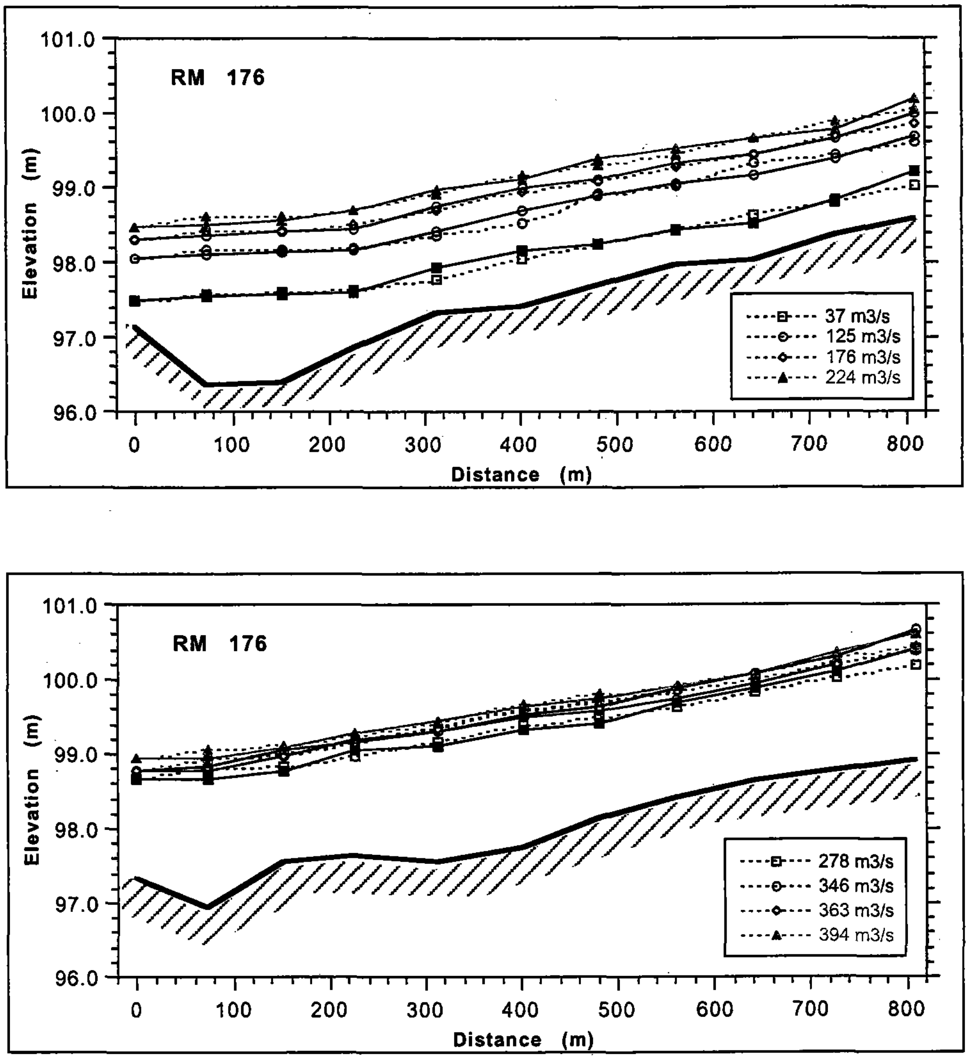


Figure 24. Comparisons between modeled and measured water surface elevations, RM 176. Upper panel shows data from lower flows, lower panel shows data from higher flows.

As the plots on the preceding page show, the flow depth through the study reach increases rapidly over the range of low to intermediate discharges, and more slowly thereafter. It is also evident that the water-surface profile becomes more uniform as the depth and discharge increase. The adjustments in depth and slope both influence changes in boundary shear stress, τ, which are used as the basis for estimating thresholds for bed load transport. Recall that the boundary shear stress is calculated using equation 3, with the observed depth, h, and the modeled energy slope, S_e. Figure 25 plots the modeled values of boundary shear stress versus discharge for the range of observed flows. The individual points represent the modeled values of boundary shear stress at each of the cross sections in the study reach, and the smooth curve represents the best-fit relation.

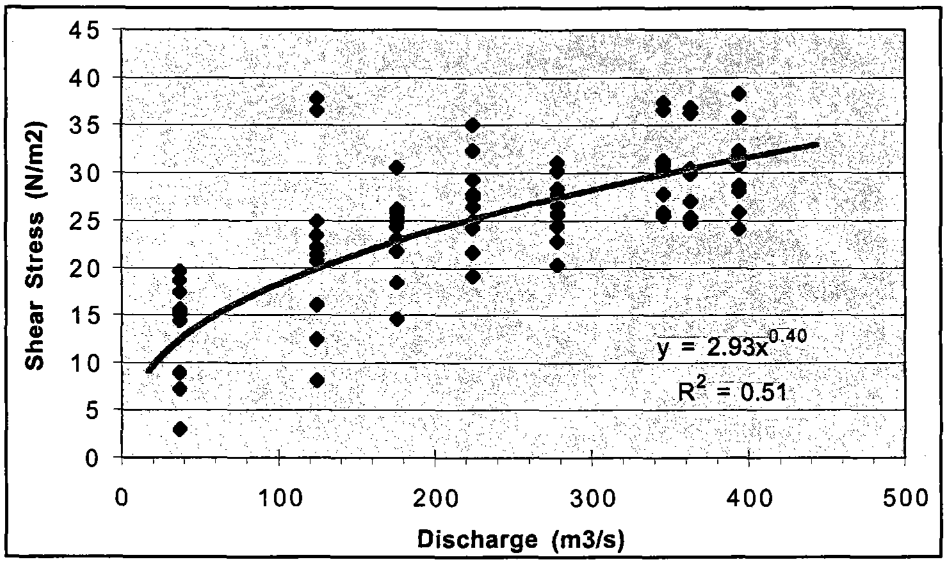


Figure 25. Relation between shear stress and discharge, RM 176

The results shown above indicate that, for a given discharge, the shear stress can vary appreciably from one cross section to another. The greatest range in shear stress occurs at a discharge of 125 m^3/s, which was the second lowest discharge modeled. At this discharge, all of the flow at the study site is confined with the baseflow channel; locally, this produces relatively high mean velocities and high values of shear stress. The two points that lie far above the curve in Figure 25 correspond to the riffle located in the span between cross sections 5, 6 and 7. At a discharge of 125 m^3/s, the flow through these sections is only about 1 m deep; however, because the velocity is very high (up to 2.5 m/s), the energy slope through these sections is also relatively high, i.e. roughly 50% higher than the reach average. With a slight increase in discharge at these sections, flow begins to overtop the bar surface, causing an abrupt increase in width and roughness, and a corresponding drop in velocity and shear stress. At a discharge of 175 m^3/s the flow through these sections still has an average depth of only about 1 m; however the area of the channel bed that is inundated at this flow is considerably higher, thus the velocity and friction slope decrease and rapidly converge on the reach-average values.

The smooth curve running through the data in Figure 25 defines a reach-average relation for the boundary shear stress as a function of discharge,

$$\tau = 2.93\ Q^{0.40} \qquad (r^2 = 0.51)$$

where τ is in N/m^2 and Q is in m^3/s. The exponent in this equation (0.40) is somewhat lower than values derived from field studies in other reaches of the Colorado River, but not anomalous in a hydraulic or geomorphic sense (*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000). This equation can be used with information on grain size to assess the validity of previous estimates of the threshold for initial motion, based on (1), the relation for dimensionless shear stress, τ^*. Recall that the relation for τ^* represents a force balance between the fluid stress, τ, acting on the bed versus the resistance provided by the unit weight of the grains, which scales with their diameter, D. The stress given in the above equation represents the total fluid force averaged over the entire channel reach; thus a reach-average estimate of τ^* can be obtained by balancing this force against the reach-average median grain size, D_{50}. The average D_{50} of the bed surface sediment in the study reach is 0.069 m. Normalizing the individual values of τ by the average D_{50} of 0.069 m (and appropriate constants) gives the relation shown below (Fig. 26). This relation is identical to the one shown above, except in this case the dimensionless shear stress is used as the dependent variable; the coefficient in the best-fit relation changes accordingly but the exponent is the same (0.40).

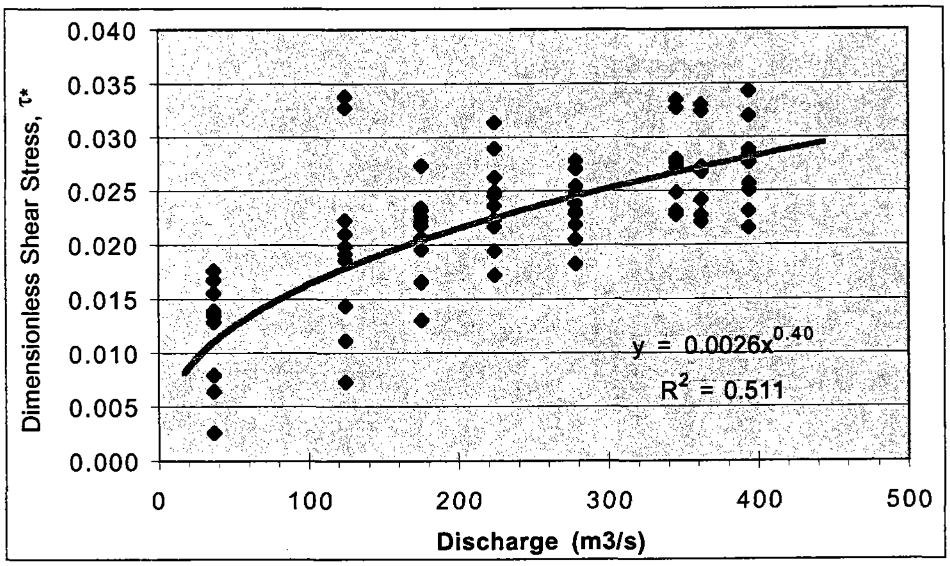


Figure 26. Relation between dimensionless shear stress and discharge, RM 176, assuming constant grain size.

The threshold dimensionless shear stress, τ^*_c, for initial motion in this reach was estimated to be 0.025, based on the relation of *Mueller et al.* (2005) with a reach-average slope of 0.002. The relation shown above indicates that this threshold is reached at a discharge of 286 m^3/s. This value is within 3% of the previous recommended discharge for initial motion, Q_c = 278 m^3/s (*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000).

The smooth curve defining the reach-average dimensionless shear stress was developed for a single grain size, which simplifies the analysis, but does not account for the fact that the grain size varies from place to place. Fortunately, during the most recent drought year streamflows in the 15-mile reach dropped to the point where it was possible to wade the channel and sample the bed surface in all but the very deepest parts of the channel (fine sediment covering higher surfaces on subaerially exposed bars was ignored). These measurements indicate that the bed sediment is generally coarser in the thalweg than it is on the bars, as expected. However, the difference in grain size is not very large, except in the sections spanning the riffle (sections 5-6). The riffle includes many boulders and large cobbles, leading to a coarse-tailed grain size distribution (D_{50} ~100 mm). In addition there is an short segment of channel between sections 5 and 6 that is floored by bedrock. The presence of bedrock and coarser-than-average sediment within this part of the study reach is indicative of locally high shear stresses produced at certain flows.

Table 5. Comparison of bed surface samples taken from exposed bars and deeper parts of the channel, RM 176. Samples at cross sections 1-5 were taken only across the submerged portion of the channel; samples at the other cross sections were taken across exposed bar surfaces and across deeper parts of the channel.

	morphology	median grain size, exposed bar (mm)	median grain size, thalweg (mm)
XSECT 1	run		60
XSECT 2	pool		--
XSECT 3	pool		52
XSECT 4	pool		59
XSECT 5	riffle		99
XSECT 6	riffle	62	80
XSECT 7	run	80	84
XSECT 8	run	76	76
XSECT 9	run	--	--
XSECT 10	run	74	61
XSECT 11	run	--	--

To examine the importance of spatial variations in grain size, the modeled estimates of τ^* were re-calculated using a "local" grain size for each cross section. The local grain size was determined by taking the average of several values, centered around the section. Calculations for higher flows were based on samples from the thalweg as well as exposed bar surfaces, since these areas would both be under water. Calculations for lower flows were based only on samples from the thalweg. The effect of using spatially variable grain sizes in the model is to reduce the estimates of τ^* slightly, as shown in Figure 27. The inclusion of coarser sediment in certain areas of the channel has the most noticeable effect on flow conditions in the riffle, and then mostly only in the intermediate range of flows, 125-224 m^3/s. At those flows, the shear stress through the riffle is quite high because the energy slope is high; however, when the shear stress produced by those flows is balanced against the coarser bed grain sizes, the modeled values of τ^* through the riffle decrease substantially (Fig. 27). The net effect of using spatially variable (and generally coarser) grain sizes is to reduce the potential for bed load transport at flows much less than about 300 m^3/s, thus that value is retained as the threshold discharge for initial motion.

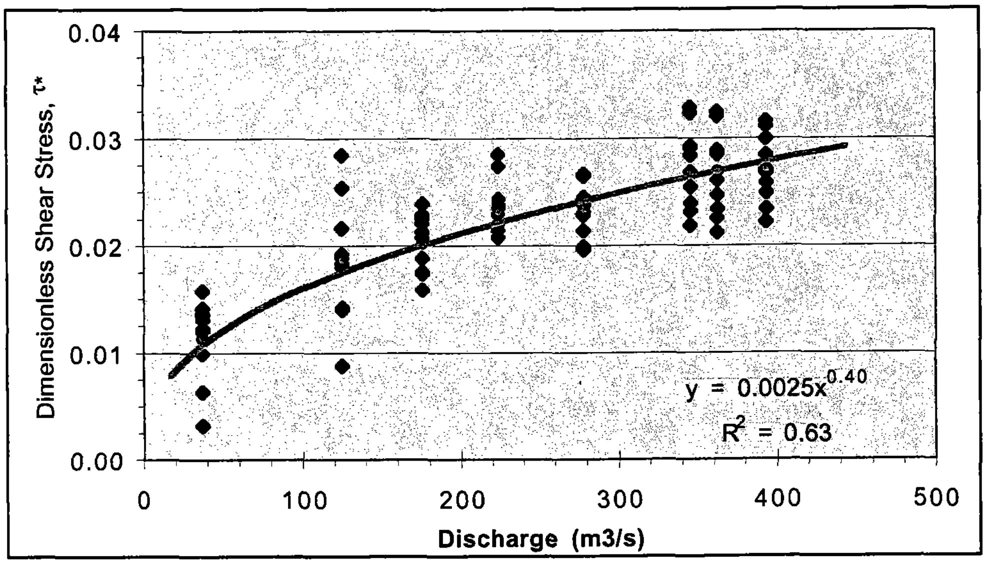


Figure 27. Relation between dimensionless shear stress and discharge, RM 176, after adjusting for spatial variations in grain size.

QUALITATIVE MEASUREMENTS AND OBSERVATIONS

The analysis and results discussed in the preceding sections provide quantitative information on the geomorphic effects of managed and naturally occurring streamflows in the 15-mile reach of the Colorado River. The field surveys and modeling results generally support the recommendations from previous studies. Further evidence of the geomorphic effects of flow levels is illustrated below with ground-based photographs taken at various times for different purposes. The first set of photographs (Fig. 28) shows results from an experiment in 2001 that was used to assess the extent of bed material entrainment within small areas (patches) of the bed. Rectangular patches of the bed surface were washed using a portable water pump and cordless drill; the surface was then allowed to dry, and spray painted brightly colored paint. Each patch was located with the total station and photographed. The patches were relocated after the peak in snowmelt runoff and photographed again.

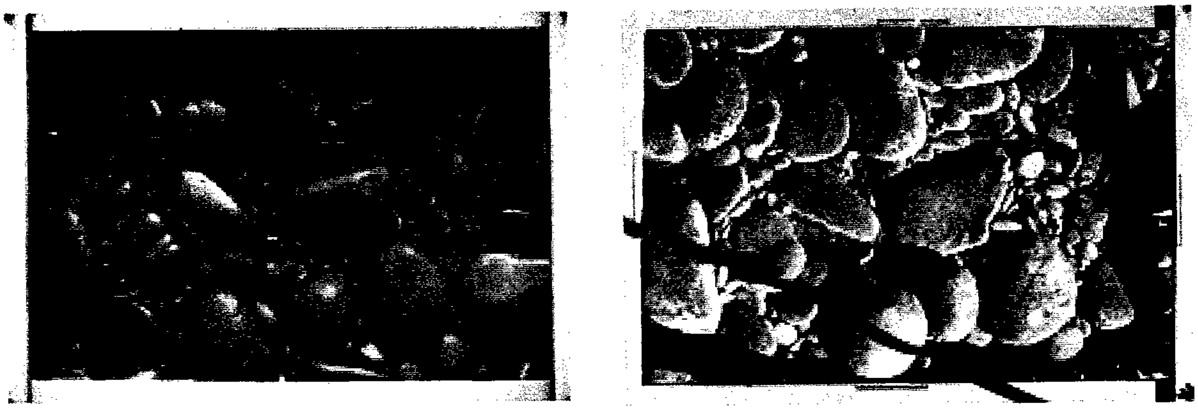


Figure 28. Before- and after-photographs of painted rocks at cross section 7, RM 176.

The patch shown above was submerged under ~1 m of water during the peak discharge in 2001 (227 m^3/s). The shear stress in the vicinity of the patch under these conditions would be about 20 N/m^2, which is 30% less than the threshold for motion. The photographs show that the majority of rocks within the patch did not move; however, it is possible to identify several rocks that did move, consistent with the expectation that small fractions of the bed surface are mobilized by flows lower than the reach-average threshold for initial motion (~50% of the bankfull discharge). This discharge falls well short of a "channel maintenance flow", but is nonetheless capable of mobilizing a handfull of rocks within an area of a few square meters.

The most vivid illustration of discharge-related changes in channel properties within this segment of the Colorado River is the dramatic growth in vegetation on low-lying bar surfaces. Figure 29 compares downstream views of the Colorado River, taken four years apart at the same location on the lateral bar at RM 176. This location was essentially devoid of vegetation in 2000 but is covered with waist-high tamarisk by 2004. The bar surface show in these photographs was

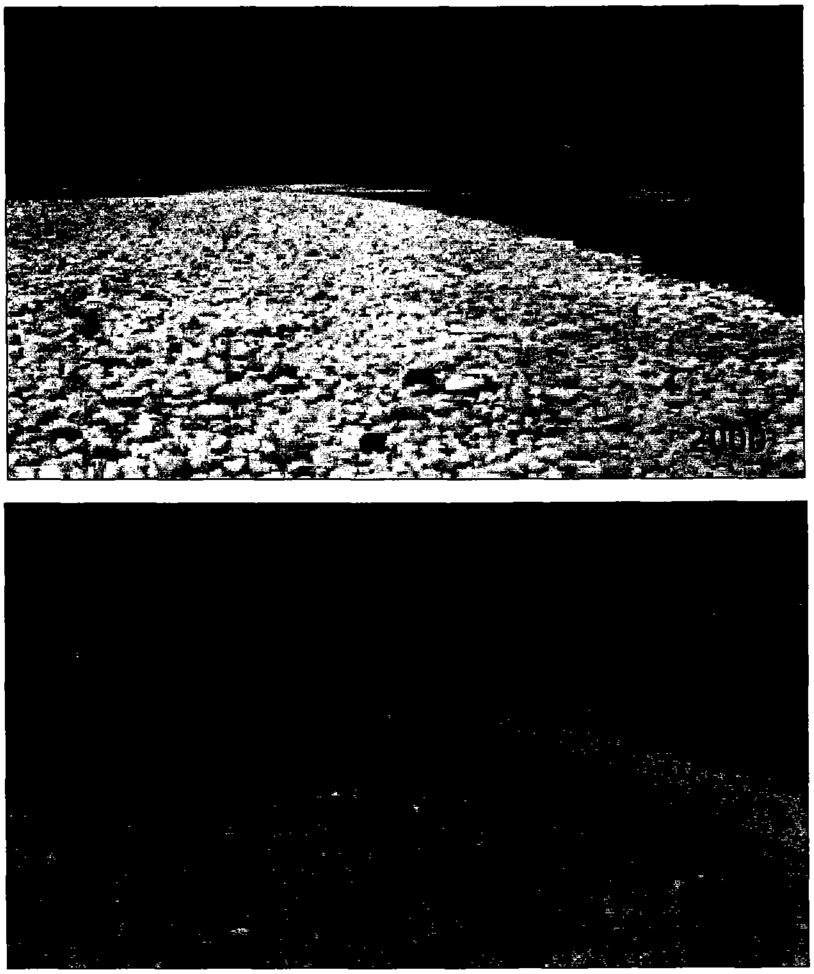


Figure 29. View downstream showing growth of vegetation on the lateral bar, RM 176.

inundated periodically over the period of time covered by the photographs, however, the plants would not have become established if the sediment forming the bed surface had been mobilized to any extent in any of these years. Vegetation growth on these low-lying surfaces is ubiquitous, and provides clear evidence that bed load transport within this reach of the Colorado River is very limited at flows much less than half the bankfull discharge.

SUMMARY and CONCLUSIONS

This study coincided with a period of intense drought with very low runoff produced throughout the upper Colorado River basin. Streamflow records maintained by the USGS suggest that water years 2002-2004 were perhaps the lowest in the upper Colorado River basin in the last 100 years. Nonetheless, coordinated reservoir operations were implemented for 7 days in 1998 and 10 days in 1999, resulting in increases in discharge of 40-56 m^3/s (1500-2000 ft^3/s), in the 15-mile reach. The bypass flows were successful in boosting background flow levels by 10-15%, which was sufficient to mobilize the bed material in a number of places in the 15- and 18-mile reaches. The limited availability of water in subsequent years prevented further tests of the geomorphic effects of bypass flows. Flows that did occur in 2000-2004 were generally well below average, thus thresholds for mobilizing the bed material were exceeded very infrequently. Over the 7-year period of the study, the discharge required to produce initial motion (~1/2 the bankfull discharge) was exceeded for a total of 78 days, which is only about 1/3 the frequency recommended in previous reports. The discharge required to completely mobilize the bed (bankfull discharge) did not occur at all.

Geomorphic changes in the 15- and 18-mile reaches were monitored using periodic surveys of main-channel cross sections and backwaters, and comparative analysis of aerial photographs taken in 1993 and 2000. These measurements indicate that, overall, the large-scale morphology of the Colorado River has changed little in the last decade. Vertical and lateral deposition of fine sediment occurred in all of the side channels monitored, however, the changes detected in these features were again relatively minor.

Additional analyses of suspended sediment records from gauging stations in the study area reconfirm the importance of late-spring flows for carrying sediment. The analysis indicates that roughly 80% of the sediment carried in suspension consists of silt- and clay-sized particles. Concentrations of suspended sediment at all gauging stations are consistently higher on the rising limb of the hydrograph than they are on the falling limb, thus the total annual sediment load is dominated by late-spring flows. Both sediment concentration and water discharge are high in the spring, thus the total annual sediment load is dominated by flow conditions during this period of time. About 20% of the total suspended sediment load consists of sand. This sediment reaches a peak 2-3 weeks after the peak in water discharge, and not far in advance of the typical period of time when Colorado pikeminnow are preparing to spawn. It is not clear that the sand moving at this time of the year represents a problem in an ecological sense; however, it is evident that the sand has the potential to move either in suspension or in contact with the bed, with the threshold occurring at flows between 125 and 150 m^3/s (4500-5500 ft^3/s).

Intensive field measurements, coupled with results from one-dimensional hydraulic model, were used to assess variations in flow properties with discharge in a 0.8-km study reach. The field measurements indicate that there is a relatively abrupt transition in the water-surface width and wetted area of the channel between discharges of 125 and 175 m^3/s (4500-6200 ft^3/s). At discharges < 125 m^3/s most of the flow is confined to the baseflow channel, and more than half the channel perimeter is dry. At discharges > 125 m^3/s flow begins to cover low-lying bar surfaces; width increasing steadily from there until ~280 m^3/s when most of the channel bed is inundated. This discharge is consistent with flow-modeling results indicating that the threshold for initial motion of the bed material in this reach is exceeded at a discharge of 286 m^3/s. That value is within 3% of the value recommended in previous reports. Adjusting the model results to account for spatial variations in grain size increases the threshold slightly, indicating there is very little bed load transport within the reach at flows less than 300 m^3/s (~10,600 ft^3/s).

The results discussed in this report are broadly consistent with the results presented in previous reports, therefore, all of the previous recommendations are retained. It is assumed that periodic movement of the gravel bed material of the Colorado River is important for maintaining habitats used by native fishes and other aquatic organisms. It also assumed that periodic movement of the bed material is important for maintaining a channel with some morphologic complexity or heterogeneity. Finally, it is assumed that the mass balance of sediment carried by the Colorado River must be maintained over the long run, otherwise there will be continued narrowing and simplification of the channel, and a loss of associated habitats. Specific recommendations for discharges that will achieve these purposes are discussed below.

RECOMMENDATIONS

The results and observations discussed in this report are broadly consistent with the recommendations given in previous reports, although the effects of some flow levels, such as the bankfull discharge, could not be assessed since these flows did not occur. Nonetheless, nothing observed over the course of this study suggests that the previous recommendations should be changed, therefore, the target flows discussed in earlier reports (*Pitlick et al.*, 1999; *Pitlick and Cress*, 2000) are retained. The recommendations are are listed here as flow categories, with each category having an set of intended purposes, a target frequency and a target duration. If new information on the ecological or geomorphological effects of the recommended flows becomes available, and if there is a consensus among biologists and hydrologists that adjustments within the flow categories need to be made, the recommendations should be revised accordingly.

A. **Category**: Flows > 621 cms (22,000 cfs)

Purpose: Flows exceeding 621 cms (22,000 cfs) are required to overtop the floodplain on a widespread basis. Overbank flows entrain coarse particulate organic matter from the floodplain, thus providing nutrients for stimulating primary productivity. Flows that reach or exceed the bankfull discharge are likewise capable of mobilizing most of the framework particles forming the substrate (bed) of the river. Periodic mobilization of nearly all substrate particles is required to change channel morphology and maintain habitat complexity necessary for different ecological purposes. In addition, such flows should occur with sufficient frequency (see below) to maintain the mass balance of sediment through the critical reaches, so as to limit deposition in secondary channels and narrowing of the main channel.

Duration: 5 days per year, averaged over a period of several years

Frequency: One out of every three years

B. Category: > 283 m^3/s (10,000 cfs)

Purpose: A discharge of approximately 283 m^3/s (10,000 cfs) is required to initiate bed-material transport (limited movement of gravel and cobble substrates) on a widespread basis. Periodic movement of the bed material in most of the reach is necessary for maintaining clean (silt-free) substrates in frequently used habitats such as riffles and runs; removal of interstitial fine sediment from riffles likewise improves habitat for benthic invertebrates. A discharge of 10,000 cfs reaches flow stages equal to about 2/3 of the bankfull depth, thus, at this flow level, most low-lying bars are covered with a substantial depth of water (a few feet or several 10s of centimeters). At these flows much of the bed is mobile and the potential exists to disturb emerging vegetation such as tamarisk. In addition, at this flow level, many secondary channels are inundated, thus the potential exists to flush fine sediment from backwaters.

Duration: 30 days per year, averaged over a period of several years

Frequency: Every other year

C. Category: 115 – 155 m^3/s (4,000 – 5,500 cfs)

Purpose: Flows in the range of approximately 115 – 155 m^3/s (4,000 – 5,500 cfs) are required to keep sands finer than 0.5 mm in suspension over riffles. Riffles provide spawning habitat for Colorado Pikeminnow, thus it is important to keep sands from accumulating on the bed during this critical time. Otherwise, riffles provide productive habitat for other native fishes and benthic invertebrates. This should be considered a provisional recommendation, to be evaluated with field data over a period of several years.

Duration: 10 days per year, on the receding limb of the annual hydrograph; in typical years, this would occur in the period from late June to early July.

Frequency: Annually

REFERENCES

Ashworth P.J. and R.I. Ferguson, 1989, Size-selective entrainment of bed load in gravel bed streams, *Water Resources Research*, *25*, 627-634.

Church, M., M.A. Hassan, and J.F. Wolcott (1998), Stabilizing self-organized structures in gravel-bed streams, *Water Resources Research*, *34*, 3169-3179.

Dietrich, W.E., 1982, Settling velocity of natural particles, *Water Resources Research*, 18, 1615-1626.

Einstein, H.A., 1950, The bed load function for sediment transportation in open channel flows, *Technical Bulletin 1026*, U.S. Department of Agriculture.

Gomez, B., 1994, Effects of particle shape and mobility on stable armor development, *Water Resources Research*, 30, 2229-2239.

Iorns, W.V., C.H. Hembree, and G.L. Oakland, 1965, Water resources of the upper Colorado River basin- Technical Report, *U.S. Geological Survey Professional Paper 441*.

Konrad, C.P., Booth, D.B., Burges, S.J., and Montgomery, D.R., 2002, Partial entrainment of gravel bars during floods, *Water Resources Research*, 38, 10.1029/2001WR000828.

Lagory et al., 2003

Leopold, L.B. and T. Maddock, 1953, The hydraulic geometry of stream channels and some physiographic implications, *U.S. Geological Survey Professional Paper 252*.

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, *U.S. Geol. Surv. Water Supply Pap. 2358*.

Lisle, T.E., J.M. Nelson, J. Pitlick, M.A. Madej, and B.L. Barkett, 2000, Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. *Water Resources Research*, 36, 3743-3756.

Mueller, E. R., J. Pitlick, and J.M. Nelson, 2005, Variation in the reference Shields stress for bed load transport in gravel-bed streams and rivers, *Water Resources Research*, v. 41, W04006, doi:10.1029/2004WR003692

Nordin, C.F. and J.P. Beverage, 1965, Sediment transport in the Rio Grande, New Mexico, *U.S. Geological Survey Professional Paper 462-F*, 35 pp.

Osmundson, D.B. and L.R. Kaeding, Recommendations for flows in the 15-mile reach during October-June for maintenance and enhancement of endangered fish populations in the upper Colordao River, *Final Report, U.S. Fish and Wildlife Serv.*, Grand Junction, 1991.

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., R.J. Ryel, V.L. Lamarra, and J. Pitlick, 2002, Flow-sediment-biota relations: Implications for river regulation effects on native fish abundance, *Ecological Applications*, v. 12, p. 1719–1739.

Parker, G., and C. M. Toro-Escobar, 2002, Equal mobility of gravel in streams: The remains of the day, *Water Resources Research*, 38(11), 1264, doi:10.1029/2001WR000669.

Parker, G., P. C. Klingeman, and D. B. McLean, 1982, Bedload size distribution in paved gravel-bed streams, *J. Hydraul. Div. Am. Soc. Civ. Eng.*, 108, 544–571.

Pitlick, J., M. Van Steeter, R. Cress, B. Barkett, and M. Franseen, 1999, Geomorphology and hydrology of the Colorado and Gunnison Rivers and implications for habitats used by endangered fishes, Final Report, U.S. Fish and Wildlife Service, Grand Junction, 64 pp.

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*, *34*, 303-316.

Pitlick, J. and R. Cress, 2000, Longitudinal Trends in Channel Characteristics of the Colorado River and Implications for Food-Web Dynamics, *Final Report, U.S. Fish and Wildlife Service*, Grand Junction, 57 pp.

Pitlick, J. and R. Cress, 2002, Downstream changes in the channel geometry of a large gravel bed river, *Water Resources Research*, *38*, 1216, doi:10.1029/2001WR000898.

Pitlick, J. and P.R. Wilcock, 2001, Flow, sediment transport, and aquatic habitat in large rivers, in *Geomorphic Processes and Riverine Habitat*, edited by J. Dorava, F. Fitzpatrick, D. Montgomery and B. Palcsak, pp. 185-198, AGU, Washington, D.C.

Topping, D.J., D.M. Rubin, and L.E. Vierra, 2000, Colorado River sediment transport: !. Natural sediment supply limitation and the influence of Glen Canyon Dam, *Water Resources Research*, 36, 515-542.

Van Steeter, M.M. and J. 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.

Wilcock, P.R., 1998, Two-fraction model of initial sediment motion in gravel-bed rivers, *Science*, 280, 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*, 29, 1297-1312.

Wolman, M.G., 1954, A method of sampling coarse river-bed material, *Transactions American Geophysical Union, 35*, 951-956.