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

Final Report
Recovery Program Project Number 85A

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EXECUTIVE SUMMARY

The 15-mile and 18-mile reaches of the Colorado River in western Colorado provide important habitat for two endangered fishes: the Colorado pikeminnow (Ptychocheilus lucius), and the razorback sucker (Xyrauchen texanus). 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 modified 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.

Coordinated reservoir operations were implemented for 7 days in 1998, the initial year of this study. Runoff that bypassed reservoirs in 1998 increased daily discharges into the 15-mile reach by a maximum of about 60 m$^3$/s (~2100 ft$^3$/s). Similar procedures were implemented for 10 days in 1999; these flows increased daily discharges in the 15-mile reach by a maximum of about 70 m$^3$/s (~2500 ft$^3$/s). The bypass flows were successful in boosting background discharges by 10-15%, which appeared to be sufficient to mobilize small proportions of the bed in the 15- and 18-mile reaches. Conditions reflecting widespread entrainment and transport of the bed material (complete mobilization) were not evident in 1998 or 1999. The limited availability of water in subsequent years, 2000-2004, prevented further tests of the geomorphic effects of bypass flows. U.S. Geological Survey analyses of streamflow records in the upper Colorado River basin suggest that water years 2002-2004 were perhaps the driest in the last 100 years. Flows that did occur during the drought period were far below average, thus thresholds for mobilizing cobble- and gravel-sized sediment were not exceeded very frequently. Over the 7-year period of the study, the discharge required to produce initial motion in the 15-mile reach (~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) was never exceeded.

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 fine 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. Both sediment concentration and water discharge are highest during the late-spring rise in flow, thus the total annual sediment load is dominated by conditions during this period of time (late May-early June). 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 sand has the potential to move either in suspension or in contact with the bed, with the threshold in transport mode occurring at flows between 125 and 150 m³/s (4400-5300 ft³/s).

Intensive field measurements, coupled with results from a one-dimensional hydraulic model, were used to assess variations in flow properties with discharge in a 0.8-km study reach. Field measurements within the reach 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 m³/s (4400-6200 ft³/s). At discharges < 125 m³/s most of the flow is confined to the baseflow channel, and more than half the channel perimeter is dry. At discharges > 125 m³/s flow begins to cover low-lying bar surfaces; width increasing steadily from there until ~280 m³/s (10,000 ft³/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 gravel and cobble bed material in this reach is exceeded at a discharge of 286 m³/s (10,100 ft³/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 movement of cobble- and gravel-sized sediment within the reach at flows less than 300 m³/s (~10,600 ft³/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 limiting the growth of non-native vegetation, especially tamarisk, thereby maintaining an active channel with some morphologic complexity and habitat 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:
A. **Category:** Bankfull Discharge

15-Mile Reach: 608 m$^3$/s (21,500 ft$^3$/s)

18-Mile Reach: 979 m$^3$/s (34,600 ft$^3$/s)

**Purpose:** Flows that reach or exceed the bankfull discharge are 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. Flows exceeding the bankfull level will inundate the floodplain in selected areas. Overbank flows entrain organic matter from the floodplain, thus providing nutrients to stimulate primary productivity. Bankfull flows should occur with sufficient frequency (see below) to maintain the mass balance of sediment, so as to limit deposition in secondary channels, prevent further narrowing of the main channel and limit the growth of non-native vegetation on low-lying gravel bars.

**Duration:** 5 days per year, averaged over a period of no more than three years

**Frequency:** No less than one out of every three years

B. **Category:** Discharge for Initial Motion (approximately one-half the bankfull discharge)

15-Mile Reach: 278 m$^3$/s (9,800 ft$^3$/s)

18-Mile Reach: 548 m$^3$/s (19,400 ft$^3$/s)

**Purpose:** Flows equal to one-half the bankfull discharge produce limited entrainment of cobble- and gravel-sized sediment on the channel bed. Partial transport of the bed material is necessary for maintaining clean (silt-free) substrates, especially in frequently used habitats such as riffles and runs; removal of interstitial fine sediment from riffles likewise improves habitat for benthic invertebrates and other native fishes. At this discharge most low-lying bars are covered with a substantial depth of water (many 10s of centimeters), thus most of the bed is inundated. At these flows framework grains start to move 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:** at least 30 days per year, averaged over a period of no more than two years

**Frequency:** No less than one out of every two years
C. Category: Discharge for Suspending Sand in Riffles

- **15-Mile Reach**: 125-150 m$^3$/s (4,400-5,300 ft$^3$/s)
- **18-Mile Reach**: 275-330 m$^3$/s (9,700-11,700 ft$^3$/s)

**Purpose**: Discharges in this category are recommended to keep sands finer than about 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 on the falling limb of the hydrograph when spawning normally occurs. This recommendation should be considered provisional, 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**: Every year

A matrix summarizing the above flow recommendations is given on the following page (Table ES-1). The matrix lists thresholds and durations of discharges that perform important geomorphic functions, and discusses the purposes of different flow levels in terms of the expected geomorphic responses. The matrix can be used by the coordinated reservoir operations group to tailor operations to target multiple objectives of habitat maintenance and creation in alluvial reaches of the Colorado River near Grand Junction.
Table ES-1. Flow matrix for the 15-mile and 18-mile reaches of the Colorado River.

<table>
<thead>
<tr>
<th>Category</th>
<th>Discharge</th>
<th>Flow Conditions and Intended Purposes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15-mile</td>
<td>18-mile</td>
</tr>
<tr>
<td>A</td>
<td>608 m³/s</td>
<td>979 m³/s</td>
</tr>
<tr>
<td></td>
<td>(21500 ft³/s)</td>
<td>(34600 ft³/s)</td>
</tr>
<tr>
<td>Duration:</td>
<td>5 days/year, averaged over no more than three years</td>
<td></td>
</tr>
<tr>
<td>Frequency:</td>
<td>No less than one out of every three years</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>278 m³/s</td>
<td>548 m³/s</td>
</tr>
<tr>
<td></td>
<td>(9800 ft³/s)</td>
<td>(19400 ft³/s)</td>
</tr>
<tr>
<td>Duration:</td>
<td>at least 30 days/year, averaged over a period of no more than two years</td>
<td></td>
</tr>
<tr>
<td>Frequency:</td>
<td>No less than one out of every two years</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>125-150 m³/s</td>
<td>275-330 m³/s</td>
</tr>
<tr>
<td></td>
<td>(4400-5300 ft³/s)</td>
<td>(9700-11700 ft³/s)</td>
</tr>
<tr>
<td>Duration:</td>
<td>10 days per year, on the receding limb of the hydrograph</td>
<td></td>
</tr>
<tr>
<td>Frequency:</td>
<td>Every year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Bankfull discharge: This discharge will mobilize cobble- and gravel-sized sediment on most of the channel bed; widespread mobilization of coarse substrates is required to create and maintain the suite of habitats used by native fishes.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Flows leading up to the bankfull discharge transport a large proportion of the total annual sediment load; maintaining the sediment-transport capacity of the river is the key to limiting further channel narrowing and reduction in habitat complexity.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Flows exceeding the bankfull level inundate limited portions of the floodplain; overbank flows entrain coarse particulate organic matter from the floodplain, providing nutrients to stimulate primary productivity.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o One-half the bankfull discharge: This discharge will mobilize coarse sediment on limited portions of the channel bed; partial transport is important for removing interstitial fine sediment to improve riffle and run habitats used by native fishes.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o This flow inundates most low-lying gravel bars, thus limiting the growth of woody plants, especially tamarisk, that can stabilize channel bars once they become established</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Most of the channel perimeter is inundated by this flow; the increase in wetted area provides additional habitat for aquatic organisms, including native forage fishes, and benthic invertebrates.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Approximately one-fourth of the bankfull discharge: Discharges in this range are needed to keep fine-medium sand in suspension over riffles. Concentrations of suspended sand appear to reach a peak after the peak in water discharge, roughly at the time of year when Colorado pikeminnow are preparing to spawn.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Riffles provide spawning habitat for Colorado pikeminnow; it is important to keep sand from accumulating on the bed during the period of spawning to increase spawning success.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>o Sand can move in either in suspension or in contact with the bed; sand moving in contact with the bed moves more slowly through the system, increasing the tendency for fines to accumulate in the bed, potentially limiting native fishes use of riffle and run habitat.</td>
<td></td>
</tr>
</tbody>
</table>
INTRODUCTION

Alluvial and canyon-bound reaches of the Colorado River in western Colorado and eastern Utah provide important habitat for four endangered fishes in the upper Colorado River basin—the Colorado pikeminnow (*Ptychocheilus lucius*), the razorback sucker (*Xyrauchen texanus*), the humpback chub (*Gila cypha*) and bonytail (*Gila elegans*). 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 the 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 fine gravel 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 habitats in the 15- and 18-mile reaches, and the abundance of potential prey fishes, that draw Colorado pikeminnow upstream as they mature. Razorback sucker were once found in the 15- and 18-mile reaches, but these fish are now very rare and their habitat requirements are not well 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 24 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 scattered throughout the upper basin; individually, they are not large in comparison to 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 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 to municipalities and projects east of the continental divide. Diversions remove an average of about 14% of the annual native flow of the Colorado River above the 15-mile reach, although in some years as much as 30% of the annual flow is taken out of the upper 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. 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 average shear stresses that are about 1.5 times the critical shear stress for bed load transport; this discharge is sufficient to fully mobilize the bed material and 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 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. Verify discharge thresholds for coarse-sediment transport.

4. Examine processes of fine-sediment transport and deposition on the falling limb of the hydrograph.

5. Develop a matrix which can be used by the coordinated reservoir operations group to tailor operations to target multiple objectives of habitat maintenance and creation.

6. 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 physical characteristics of these reaches are described in detail in a number of previous reports and papers [Osmundson and Kaeding, 1991; Osmundson et al., 1995; Van Steeter and Pitlick, 1998; Pitlick and Van Steeter, 1998; Pitlick et al., 1999; Pitlick and Cress, 2000; Pitlick and Cress, 2002; Osmundson et al., 2002]. The channel pattern of the Colorado River 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 a braided-like pattern; however, in a long-term sense, this segment of the Colorado River is geomorphically stable, meaning that in most places the overall pattern and position of the channel are changing relatively slowly.

![Figure 1](image)

**Figure 1.** Location of the Colorado River and Gunnison River near Grand Junction, Colorado. The 15-mile reach includes the channel segment between Palisade, CO, and the confluence with the Gunnison River. The 18-mile reach includes the segment from the Gunnison River to Loma, CO. The inset box, labeled Figure 6, indicates the location of the reach used for detailed studies of sediment transport and channel change near river kilometer (RK) 283.
Floodplains and low lying alluvial surfaces border the channel of the Colorado River through much of the study area (Fig. 2). In a number of places, particularly in the 15-mile reach, the river flows against steep bluffs underlain by Mancos shale bedrock. Elsewhere, the channel is confined locally by concrete rip rap and artificial levees. The constraints imposed by levees and rip rap are most noticeable in the channel reaches in the immediate vicinity of Grand Junction. Outside of Grand Junction, most of the bank stabilization efforts have been initiated by local land owners, who follow the practice of placing concrete rip rap along the banks to slow erosion.

Floodplains and low-lying bar surfaces 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 (*Tamarix chinensis*) and Russian olive (*Elaeagnus angustifolia*). Sustained low flows during the 2002-2004 drought have allowed both native and non-native plants to colonize mid-channel bars and bank areas that would normally be inundated for several weeks during the period of snowmelt runoff (illustrated in the figure below and on the front cover).

**Figure 2.** Upstream view of the Colorado River near RK 283 (RM 176) in the 15-mile reach.

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 layer) 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. 3a). 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. 3b).
Figure 3. Grain size distributions of the bed surface (armor) layer based on pebble-counts in different locations in (a) the 15-mile reach and (b) the 18-mile reach. The light blue lines indicate individual samples, while the dark blue lines indicate the average for each 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 with the GPS at evenly spaced, 0.8-km intervals along the channel. Subsequently, the raw data were corrected with differential post-processing techniques, using base-station measurements collected 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. 4). 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 4](image-url)

**Figure 4.** Longitudinal profile of the Colorado River between Palisade, CO, and Westwater, UT. Individual data points were measured with a mapping grade global positioning system (GPS). Distances are given in river kilometers (RK = 1.61 mile), measured upstream from the confluence of the Colorado River and the Green River. Bars below the data indicate boundaries between the 15-mile reach (15M), 18-mile reach (18M), and Ruby-Horsethief Canyon reach (RH). The Gunnison River joins the Colorado River at RK 275.

As noted in the introduction, natural streamflows of the Colorado River are regulated by a series of storage reservoirs and water diversions upstream of the study area. Most of the reservoirs in the upper Colorado River basin were constructed in the period between 1950 and 1966. These reservoirs were built primarily to store spring runoff, which is then moved through a series of tunnels and transbasin diversions to supply municipalities and irrigation projects on the east of the continental divide. Although reservoir operations affect both the timing and magnitude of peak snowmelt flows in the study area, runoff from unregulated tributaries is still sufficient to produce a prominent peak in the annual hydrograph. Runoff from late-summer thunderstorms can elevate streamflows and increase turbidity for several days. Peaks produced by these storms are generally small in comparison to the annual snowmelt peak.
The Colorado River carries moderately high sediment loads, increasing downstream from about $1.5 \times 10^6$ metric tons per year at the US Geological Survey (USGS) gauging station near Cameo, CO, to about $3.4 \times 10^6$ 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 annual sediment load consists of fine sediment (silt and sand) that is 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 annual 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**

*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 measurements of water quality, including water temperature, dissolved oxygen, dissolved solids, major ions, and suspended sediment. Gauging 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). Streamflow data for the individual gauges are available for the following periods of record: Cameo gauge, 1934-present; Palisade gauge, 1990-present; State Line gauge, 1952-present; and the Gunnison River gauge, 1902-present.

Measurements of suspended sediment have been taken periodically at three of these four gauging stations. The sediment 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 suspended sediment finer than 0.0625 mm, which is the break between silt- and sand-size particles. The record from the Gunnison River gauge includes 306 measurements of discharge and suspended sediment concentration taken 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 taken 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) were 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 ft³/s 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 15- and 18-mile 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 (RK 300-250), and they were flown at the same scale (1: 6000), in late summer with the river flowing at similar discharges at the time of the photography. In 2000 the discharge in the 15-mile reach at the time of the photography was 36.6 m$^3$/s (1290 ft$^3$/s), which is nearly identical to the 1993 discharge of 37 m$^3$/s (1310 ft$^3$/s). In 2000 the discharge in the 18-mile reach at the time of the photography was about 115 m$^3$/s (4060 ft$^3$/s) which is 15% lower than the 1993 discharge of 135 m$^3$/s (4770 ft$^3$/s). 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 boundaries between individual river miles (Fig. 5). 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.

![RK 251](image)

**Figure 5.** Segment of the Colorado River near Fruita, CO, RK 251, showing delineation of channel features (blue = main channel, green = side channels).
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. 5). 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.

**Cross Section Surveys:** Detailed measurements of channel properties and bed material characteristics were taken in a 1-km long reach centered around RK 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. 6). In addition the study reach includes property on the south bank that was obtained by the U.S. Fish and Wildlife Service and the Bureau of Reclamation, and it is therefore relatively easy to access.

![Figure 6](image.png)

**Figure 6.** 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-meter 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 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 size distribution of the bulk 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. 7) 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 7. Grain size distributions of subsurface sediment at 3 locations in the 15-mile reach.](image-url)
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 closely 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 RK 283 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 RK 283 (RM 176) study site.**

<table>
<thead>
<tr>
<th></th>
<th>Bankfull Width (m)</th>
<th>Bankfull Depth (m)</th>
<th>Median Grain Size, $D_{50}$ (mm)</th>
</tr>
</thead>
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<tr>
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<td>60</td>
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<tr>
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<tr>
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<td>59</td>
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<td>81</td>
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<tr>
<td>XSECT 7</td>
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<td>1.96</td>
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<tr>
<td>XSECT 8</td>
<td>148</td>
<td>1.98</td>
<td>76</td>
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<tr>
<td>XSECT 9</td>
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</tr>
<tr>
<td>XSECT 11</td>
<td>163</td>
<td>1.80</td>
<td>-</td>
</tr>
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<td><strong>Site average</strong></td>
<td><strong>127</strong></td>
<td><strong>1.90</strong></td>
<td><strong>69</strong></td>
</tr>
<tr>
<td><strong>15-mile reach average</strong></td>
<td><strong>134</strong></td>
<td><strong>2.54</strong></td>
<td><strong>58</strong></td>
</tr>
</tbody>
</table>

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 Fine Gravel:** Seasonal transport of sand and fine gravel over bars and riffles was monitored by installing a series of stream-bed sediment traps at various locations. The traps consist of 20-cm diameter coffee cans mounted within a piece of plastic pipe, both placed vertically and flush with the bed surface (Fig. 8). 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, refilled with clean gravel and placed back in the bed. In general it was not possible to retrieve the cans in flows more than ~0.5 m deep. Sediment samples taken from the traps were subsequently sieved at 1/2 phi intervals.
Figure 8. 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 17 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 RK 283. 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 (1300-13900 ft$^3$/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, $\tau$. 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:

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

(1)

where $\rho_s$ and $\rho$ 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 $\tau^*$ 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 $\tau^*$ exceeds a threshold or critical value, $\tau^*_c$. Results from field and laboratory studies suggest that values of $\tau^*_c$ may be affected by several factors, including
particle shape [Gomez, 1994], sand content [Wilcock, 1998], spatial variations in bed texture [Lisle et al., 2000; Konrad et al., 2002; Church et al., 1998], and variations in relative roughness and average channel gradient [Mueller et al., 2005]. In addition, there is a practical problem of defining the onset of motion or the degree of bed mobilization, i.e. whether bed load transport involves only a few of the coarse clasts or many clasts. Finally, some gravel-bed rivers can carry significant amounts of sand-sized sediment; this presents a potential problem because sand moves at flows much lower than those required to move the coarser framework grains, plus sand can move either as bed load or suspended load, depending on the flow level and local shear stress. Such is the case in the Colorado River. Thus, it is possible to distinguish three separate phases of bed load transport: the first phase, involving movement of sand and fine gravel over an otherwise stable bed surface, is termed overpassing (Ashworth and Ferguson, 1989); the sediment moved in this phase is not the same as 'wash load' (the sediment supplied from sources other than the bed itself), and in fact may represent a significant proportion (> 20 %) of the total annual bed load carried by a gravel river (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, 1993]. A recent analysis of bed load transport thresholds by Mueller et al. (2005) indicates that partial transport begins at flows equal to about 67% of the bankfull discharge. The third bed load transport phase, involving motion of most all particles on the river 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 forming the channel boundary.

The flow levels or discharges required to reach the transport phases discussed above are determined by selecting a threshold value of \( \tau^* \) and solving (1) for the corresponding shear stress, \( \tau \). 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 \( \tau^* \) due to sediment sorting, imbrication, and the sand-content of the bed surface layer. Indeed, this study was motivated in part by uncertainties associated with the choice of the critical \( \tau^* \). 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 throughout 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 the average channel gradient and bed roughness increase. For each of the data sets, 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, \( \tau^*_r \), associated with a small, non-zero bed load transport rate. The resulting estimates of \( \tau^*_r \), were then correlated to the reach-average channel slope,
giving the values shown in Figure 9. A least squares fit of the data in this figure gives the following equation:

\[ \tau^* = 2.18S + 0.021 \]  

(2)

where \( S \) is the average channel gradient. This relation is statistically significant (\( r^2 = 0.70 \) and \( p \approx 0.001 \)), and indicates that \( \tau^* \) increases linearly with increasing channel gradient. This result is counterintuitive, but explained by hydrodynamic effects associated with poorer sorting and high roughness of the bed material in high-gradient channels. The monitoring site near RK 283 has an average gradient of \( S \approx 0.0020 \), thus the estimated \( \tau^* \) for that location is 0.025.

**Figure 9.** Variation in \( \tau^* \), as function of slope with error bars indicating potential range of \( \tau^* \) 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 the analysis (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, \( \tau \), is the force per unit bed area acting in the direction of flow,

\[ \tau = \rho g R S_e \]  

(3)

where \( \rho \) 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 \( \rho \) and \( g \) are constant, (3) shows that \( \tau \) 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 essentially the same, depending on the topography and sinuosity of the channel reach. Changes in channel width and/or bed level caused by pools and riffles force the water to accelerate (or decelerate), adding to the fluid force produced solely by the weight of the water moving downstream. The effects of these flow accelerations can be accounted for using the one-dimensional equation for gradually varied flow, which can be written as follows,

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

where \( S_e \) is the streamwise energy gradient (also termed the friction slope), \( H \) is the total energy, \( z \) is the average bed elevation, \( h \) is the average flow depth (approximately equal to the hydraulic radius, \( R \)), and \( U^2/2g \) is the velocity head. The first term on the right hand size of (4), \( dz/dx \), is the bed surface slope, which may be either positive or negative. The second term, \( dh/dx \), is the water surface slope, which also can be either positive or negative. These two terms are typically of the same magnitude, thus they are both important; however, 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 water as it flows 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 [Henderson, 1966], 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 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 below-average years, 2000, 2001, and 2003 (Table 2). The 2002 water year stands out as the most extreme of these. In 2002 the peak discharge of the Colorado River near Cameo was only 121 m³/s (4260 ft³/s) (Table 2); 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 was only 82 m³/s (2890 ft³/s) (Table 2). This flow occurred in September, thus it was not associated with snowmelt; it ranks as the second lowest peak in the 96-year period of record for this gauge. The 2004 peaks rank as the third and fourth lowest values at the Cameo and Whitewater gauges, respectively.

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

<table>
<thead>
<tr>
<th>COLORADO RIVER NR CAMEO, CO, USGS 09095500</th>
<th>Peak Discharge (m³/s)</th>
<th>Percent of Average</th>
<th>Annual Discharge (m³/s)</th>
<th>Percent of Average</th>
<th>Annual Runoff (ac-ft)</th>
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</table>

<table>
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<th>COLORADO RIVER NR PALISADE, CO, USGS 09106150</th>
<th>Peak Discharge (m³/s)</th>
<th>Percent of Average</th>
<th>Annual Discharge (m³/s)</th>
<th>Percent of Average</th>
<th>Annual Runoff (ac-ft)</th>
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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 peak discharges and lower annual runoff. Figure 10 shows trends in annual runoff at the two gauges immediately upstream of the 15-mile reach, Colorado River near Palisade and Colorado River near Cameo, respectively. The record for the Palisade gauge is relatively short (14 yr), thus not particularly useful for assessing recent hydrologic trends. The record from this gauge suggests that prior to 1998 annual runoff was equally divided between above-average and below-average years (Fig. 10a). The record for the Cameo gauge, which extends back to the early 1930s (Fig. 10b), shows that the sequence of low-flow years from 1998 to 2004 was unusual in comparison to any equivalent period prior to 1950. However, since 1950, there have been at least two other strings of dry years. From 1954-1969, for example, the average annual discharge at Cameo was exceeded in only four years, or half the expected number. The period from 1987 through 1992 is likewise characterized by a series of below-average water years. The 2000-2004 drought was the most severe of these low-flow periods, and it should be a cause for concern if strings of low-flow years occur more often in the future, whether due to planned depletions or changes in climate.
The flow recommendations provided in our previous reports (Pitlick et al., 1999; Pitlick and Cress, 2000) focused on physical processes of sediment transport, under the assumption that these processes are important for maintaining habitats used by the native fishes and other aquatic organisms. The previous recommendations targeted two separate stages of bed-load transport: (i) initial motion, corresponding to flows equal to approximately 1/2 the bankfull discharge, and (ii) complete mobilization, corresponding to flows equal to the bankfull discharge. Table 3 lists specific values of these discharges for the 15- and 18-mile reaches, along with the recommended durations of these discharges (days per year), and the number of days/year that those discharges were observed during the period 1998-2004. These 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 of the bed sediment...
(~1/2 the bankfull discharge) were not exceeded very often over the duration of the study period—only about 1/3 of the recommended frequency. The target flows for complete mobilization of the bed (the bankfull discharge) were not exceeded in any year. The flows observed during the study period, 1998-2004, thus fall far short of the recommendations given previously.

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).

<table>
<thead>
<tr>
<th></th>
<th>15-Mile Reach</th>
<th>18-Mile Reach</th>
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<tr>
<td><strong>Threshold flows:</strong></td>
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<tr>
<td>$Q_c = 278 \text{ m}^3/\text{s}$</td>
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<td>30</td>
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<tr>
<td>$Q_b = 608 \text{ m}^3/\text{s}$</td>
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<td>5</td>
</tr>
<tr>
<td>$Q_c = 548 \text{ m}^3/\text{s}$</td>
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<td>$Q_b = 979 \text{ m}^3/\text{s}$</td>
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** Recommended Frequency (days/yr) **

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<tr>
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** Observed Frequency (days/yr) **

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** Average Frequency (days/yr) **

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*Coordinated Reservoir Operations*

Peak snow-water equivalents and reservoir pool levels in the Colorado River basin were sufficiently high in the first two years of this study—1998 and 1999—to allow a portion of the runoff to bypass upper basin reservoirs (coordinated reservoir operations were also implemented in 1997, before this study was initiated). Plans were in place to bypass flows in 2000; however, warm spring weather 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. The upper panel in Figure 11 shows that these releases increased daily discharge in the 15-mile reach by ~60 m³/s (~2,100 ft³/s) and extended the duration of peak runoff by several days. In 1999, coordinated reservoir operations were implemented for 10 days (lower panel, Fig. 11), resulting in the release of an additional 40,000 acre-feet. These releases increased peak daily discharges in the 15-mile reach by 70 m³/s (~2,500 ft³/s).
Figure 11. Daily discharge during the periods of peak snowmelt runoff in 1998 and 1999, Colorado River, below Grand Valley diversion, near Palisade, Colorado. Dotted lines indicate discharges that would have occurred without coordinated reservoir operations.

The increases in discharge produced by the bypass flows in 1998 and 1999 were not large in comparison to the total runoff (Fig. 12), and the flows produced were only 10 to 15% higher than the background discharge in the 15-mile reach. Nonetheless, 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. The volumes of water released were a small fraction of the total storage capacity of the upper basin reservoir system. Second, the bypass flows were successful in boosting background
flow levels within a specific window of time, making it more likely that the discharges needed to mobilize gravel- and cobble-sized sediment were exceeded in a number of places in the 15- and 18-mile reaches. Without the bypass flows, bed load transport would have been more limited, non-native vegetation would have become established on bars sooner, and the observed sequence of snowmelt flows would have fallen even further short of the previous flow recommendations. Having said that, it is important to recognize that there are clear limits on the potential uses and benefits of bypass flows. Given the limited storage capacity of the upper basin reservoir system, it is unlikely that flows generated by coordinated reservoir operations in the future will be much larger than those generated in 1998-99, particularly if there are further depletions in water supply and/or changes in climate, leading to lower annual runoff.

![Graph showing daily discharges for the period of snowmelt runoff in 1998 and 1999, Colorado River below Grand Valley diversion, near Palisade, Colorado, USGS gauge 09106150.](image)

**Figure 12.** Daily discharges for the period of snowmelt runoff in 1998 and 1999, Colorado River below Grand Valley diversion, near Palisade, Colorado, USGS gauge 09106150.
Changes in Channel Morphology

Cross-section Measurements: Survey measurements of the 11 main-channel cross sections in the reach near RK 283 (RM 176) show that changes in the overall morphology of the Colorado River were relatively minor during the monitoring period (Fig. 13). Minor amounts of bank erosion (< 2 m) occurred at several of the cross sections, but the topography of the study reach remained essentially unchanged. Enlarged views of the secondary channel that runs along the south (river left) side of the study reach show that minor amounts of sediment were deposited along the right bank (Fig. 14); however, overall, the topography of the secondary channel changed little during the monitoring period.

Figure 13. Main channel cross sections of the Colorado River near RK 283 (RM 176). Dashed line indicates the bankfull flow level.
Scour and fill were monitored at three other secondary channels in the 15- and 18-mile reaches. One of these sites is located several hundred meters downstream of the reach discussed above, at RK 282 (RM 175.5). Two other sites are located in the 18-mile reach, one at RK 261, the other at RK 257 (RM 162 and 160, respectively); these sites were first surveyed in 1993 as part of an earlier study (Pitlick et al., 1999). The secondary channel at RK 282 is short and moderately sinuous, whereas the other two secondaries are relatively long and straight. Figure 15a shows that a substantial amount of sediment was deposited in the secondary at RK 282 in the first two years of monitoring; subsequently, in 2002, the mouth of the secondary was dammed by beavers, blocking flow to the main channel. Sedimentation in the other secondary channels was minor in comparison. The secondary at RK 261 aggraded by 0.2 to 0.5 m between 1995 and 2001 (Fig. 15b), but otherwise remained open to the main channel. The secondary channel near RK 257 changed very little, except for deposition of a small berm along the right bank (Fig. 15c).
Figure 15. Cross sections of secondary channels/backwaters in the 15- and 18-mile reaches.
Comparison of Aerial Photographs: The analysis of aerial photographs suggests that locally there were some changes in the planimetric area of individual features from 1993-2000. Among the mapping units, it appears that bar area increased, side-channel area decreased, and main-channel area remained about the same (Fig. 16). It is important to note, however, that much of the change in bar and side-channel area occurred in the 18-mile reach, where flows were lower at the time of the photography in 2000 versus 1993. Flows levels in the 15-mile reach (RK 275-298) were similar in 2000 and 1993, thus changes there are real. The measurements show that side channels were abandoned near RK 295 and RK 279, and there was an increase in bar area and channel complexity at RK 282 (Fig. 16a). Overall, it appears that losses in side-channel area were offset by gains in bar area, thus it does not appear that the channel became much less complex between 1993 and 2000. Whatever the case, the changes measured during this period were small in comparison to changes measured over longer time periods (Pitlick et al., 1999).

Figure 16. Change in planimetric area of features within the Colorado River; (a) absolute change in area, and (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 these 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 17 plots suspended sediment relations for the Colorado River near Cameo, CO. The panel on the left (Fig. 17a) 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. 17b) plots suspended sediment load, \( Q_s \), (metric tons per day) versus instantaneous water discharge. The load is calculated from \( Q_s = 0.0864 \times C_s \times Q \), where the constant 0.0864 is a factor for converting units.

The data in Figure 17a 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. 17b). 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 late-summer thunderstorms, however, since flows are 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. Knowing the percentage of sand, the total suspended sediment load can be proportioned between the sand fraction and the silt-clay fraction. Figure 18 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 more scatter in the relation between discharge and silt-clay fraction than there is in the relation between discharge and sand fraction. This observation suggests that amount of silt and clay carried in suspension is driven primarily 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 18](image_url)

**Figure 18.** 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 18 shows that there is 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 loads are governed more by flow hydraulics than 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 values shown in the preceding figures, suggests one of two things: (i) the supply of sand is generally depleted over the period of the hydrograph, thus the same discharge carries a lower sand load after the peak than prior to the peak, or (ii) the sand available is becoming coarser over the period of the hydrograph, thus less sand is carried in suspension and more sand is moving as bed load, which is not measured. It is not possible to distinguish between these effects without specific data characterizing the evolution of the grain size of the suspended load over the hydrograph. Whatever the case, it is not uncommon for the size distribution of the suspended sediment to change over time as finer or coarser bed material becomes available. For example, measurements taken on the Colorado River in Grand Canyon prior to the construction of Glen Canyon dam show that the grain size of the suspended sediment generally increased on the receding limb of the hydrograph [Topping et al., 2000]. Similarly, sediment measurements and bed material samples taken on the Rio Grande in the 1950s likewise show that both the load and the bed material became coarser over the period of the hydrograph [Nordin and Beverage, 1965]. Based on these studies and observations on the Green River (J. O’Brien, personal communication), it is likely that the transport patterns in the Colorado River reflect a seasonal redistribution of sand, which moves into temporary storage in pools during low flows, then is remobilized and put into suspension during high flows. If there is a natural tendency for suspended sediment to coarsen with the passage of the hydrograph, then further reduction in the duration of high flows could lead to a significant reduction in the total sediment load of the Colorado River, causing further losses in channel capacity and in-channel habitats.

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 - December 31, regardless of the year in which they were taken. Figure 19 shows the synthetic time series of discharge and suspended sediment concentration for the Colorado River near Cameo, CO. The irregular patterns reflect the fact that the data are arranged by 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. 19a). 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 19. Annual trends in discharge and suspended sediment concentration, (a) Colorado River near Cameo, (b) Gunnison River near Grand Junction, and (c) Colorado River near Colorado-Utah state line (see text for explanation of the data series and trendlines).
Figures 19b and 19c plot similar relations for the Gunnison River and the Colorado River near the CO-UT state line. The patterns observed at these sites are similar to those observed at Cameo, although not as clear because there are fewer observations. In both cases there is a period from May through June when sediment concentrations are higher overall, and it appears that the peak in sediment concentration precedes the peak in water discharge by perhaps several weeks.

Figure 20 displays time-series trends in the percentage of sand in suspended sediment samples. In contrast to the trends shown in the preceding figures, it appears that the peak in percent sand occurs 2-3 weeks after the peak in water discharge; this trend is particularly evident in the time series for the Cameo gauge (Fig. 20a). The trends at the other gauges are not as well defined, but in both cases it appears that the peak in percent sand follows the peak in water discharge.

Figure 20. Trends in discharge and percentage of sand in suspended sediment samples, (a) Colorado River near Cameo, CO; (b) Gunnison River near Grand Junction, and (c) Colorado River near Colorado-Utah state line (shown on next page).
The trends in transport shown in the preceding figures indicate that in typical years as much as 40% of the suspended sediment carried by the Colorado River and the Gunnison River consists of sand-sized sediment. In addition it appears that the peak in sand transport follows the peak in water discharge. Very similar trends were observed in measurements of suspended sediment in the Colorado River in Grand Canyon prior to the construction of Glen Canyon dam (Topping et al., 2000), thus the lag in transport appears to be a natural tendency for rivers in this region. If so, it is reasonable to assume that the native fishes have evolved to cope with these conditions. The timing of the peak in sand transport is of potential interest ecologically because it coincides roughly with the period of time when Colorado pikeminnow are preparing to spawn. If flows on the receding limb of the hydrograph decrease rapidly, such that sand drops out of suspension and begins moving as bed load, then it will move much more slowly through the system. This would happen naturally, but it leads to a question whether the transition in transport mode has moved forward in time as a result of water withdrawals and reservoir operations, and if so, does this affect pikeminnow spawning success, or the fishes preferences for spawning in certain areas?

**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 results from the trap measurements. Hydrographs for the period of snowmelt runoff are shown for each of the years in which the traps were used, 1998-2001. The vertical lines on the hydrographs indicate specific dates that the trap samples
Figure 21. Panels on the left show hydrographs, 1998-2001, with gray lines indicating dates that bed sediment traps were retrieved. Right, size distributions of sediment collected in traps.
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 that had accumulated over the previous 9-10 months. For comparison, these figures also show the grain size distribution of the bulk bed material (red lines), as determined from three samples of the subsurface sediment, i.e. the material beneath armor layer.

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 subsurface sediment- the sediment beneath the armor layer. The median grain size of the trapped sediment is often between 0.1 and 0.5 mm (fine-medium sand), whereas the median grain size of the subsurface sediment is about 30 mm (gravel). However, it is evident that the sand-sizes which are common in the traps are also found in appreciable quantities in the bed (up to 20%, depending on size class), indicating that some of the sand caught in the traps exchanges with sand stored in the bed. Sand-sized sediment is thus a non-negligible component of the bed material load of the Colorado River, i.e. proportion of the total load which is derived from the bed (the other component—wash load- is derived from sources outside the channel and is not found in appreciable quantities in the bed; silt and clay fall into that category in this case).

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 about 300 m$^3$/s (10600 ft$^3$/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 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 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 the 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 receding-limb flows to keep fine to medium sands in suspension over the most productive and important habitats (riffles), particularly during the period when pikeminnow are likely to spawn. The criterion for suspension is based on an relation for estimating the settling velocity, $w_s$, of natural particles as a function of grain size and shape [Dietrich, 1982]. When the fluid shear velocity, $u_*= (ghS_e)^{1/2}$, exceeds the settling velocity of a given 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 of 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 RK 283 (discussed in the next section), a discharge of 125 m$^3$/s (4400 ft$^3$/s) should be sufficient to keep particles finer than 0.5 mm in suspension over riffles.
**Evaluation of Flow Hydraulics and Transport Thresholds at RK 283:** The reach selected to evaluate the geomorphic effects of augmented and naturally occurring flows is located in the 15-mile reach, about 2 km downstream of the Corn Lake State Wildlife Area and the Highway 141 bridge. The study reach is relatively straight (Fig. 22) 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 study reach, and a relatively deep pool at the lower end of the reach (Fig. 22). A secondary channel occurs along the south bank; the lower end of this channel becomes a backwater at lower flows. The average bankfull channel width of the study reach 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 394 m$^3$/s (1300-13900 ft$^3$/s). These measurements were used with data from the cross-section 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 22](image)

**Figure 22.** Delineation of in-channel habitats within the RK 283 (RM 176) study reach.
**Figure 23.** Locations of channel cross sections within the RK 283 (RM 176) study reach.

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

<table>
<thead>
<tr>
<th>Discharge (ft³/s)</th>
<th>Discharge (m³/s)</th>
<th>Ratio to Critical Q₁</th>
<th>Ratio to Bankfull Q₂</th>
<th>Average Depth (m)</th>
<th>Average Velocity (m/s)</th>
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</table>

1. Critical discharge is the flow that exceeds the critical shear stress for initial motion of the bed material.
2. Bankfull discharge is the flow that exceeds the threshold for complete mobilization of the bed material.
Flow levels within the study reach were measured at discharges ranging from base flow 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. 24a), which is less than half the average bankfull width. At this flow the wetted area of the channel is ~40,000 m² (Fig. 24b) and more than half of the channel perimeter is dry. Flow stays within the baseflow channel until the discharge reaches approximately 140 m³/s (~5000 ft³/s), 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. 24a, b). The width and wetted area increase slowly thereafter; most of the channel bed is inundated once the flow reaches about 280 m³/s (~10,000 ft³/s). This flow level corresponds to the threshold for initial motion recommended in the previous reports (Pitlick et al., 1999; Pitlick and Cress, 2000)

Figure 24. Changes in (a) water surface width and (b) wetted area with discharge, RK 283.
Reach-average estimates of flow depth, $h$, and flow velocity, $U$, are plotted as power functions of discharge in Figure 25, forming 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 similar to typical values (*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 25](image-url)  
**Figure 25.** Changes in (a) mean depth and (b) mean velocity with discharge, RK 283.
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. 26).

**Figure 26.** Comparisons between modeled and measured water surface elevations, RK 283. Upper panel shows lower flow levels, lower panel shows higher flow levels. The differences in bed profile in upper and lower panels reflect changes in average bed elevation that occur as higher parts of the channel become inundated; the differences are not due to scour and fill.
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, $\tau$, 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 27 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 27. Relation between shear stress and discharge, RK 283](image)

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 (4400 ft$^3$/s), which was the second lowest discharge modeled. At this discharge, nearly all of the flow at the study site is confined within the baseflow channel; locally, this produces relatively high values of mean velocity and shear stress. The two points that lie far above the curve at a discharge of 125 m$^3$/s correspond to the riffle that spans the channel through cross sections 5 and 6. At this flow, the depth through these sections is only about 1 m; however, because the mean velocity is 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 (~6200 ft$^3$/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 27 defines a reach-average relation for the boundary shear stress as a function of discharge,

$$\tau = 2.93 \, Q^{0.40} \tag{5}$$

where $\tau$ is in N/m$^2$ and $Q$ is in m$^3$/s; this equation is statistically significant ($r^2 = 0.51, p < 0.001$). The exponent in the 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 sense (Pitlick et al., 1999; Pitlick and Cress, 2000). This equation can be used with information on grain size to assess previous estimates of the threshold for initial motion, based the relation for dimensionless shear stress, $\tau^*$, given by equation 1. Recall that the relation for $\tau^*$ represents a force balance between the fluid stress, $\tau$, acting on the bed versus the resistance provided by the 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 $\tau^*$ 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 $\tau$ by the average $D_{50}$ of 0.069 m (and appropriate constants) gives the relation shown below (Fig. 28). 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 28. Relation between dimensionless shear stress and discharge, RK 283, assuming no spatial variation bed surface grain size.
The threshold dimensionless shear stress, $\tau^*$, for initial motion in this reach was estimated to be 0.025, based on the relation of Mueller et al. (2005), using 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 (10100 ft$^3$/s). This value is within 3% of the previous recommended discharge for initial motion, $Q_\text{c} = 278$ m$^3$/s (9800 ft$^3$/s) (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 2004 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 5-7). The riffle includes many boulders and very large cobbles, leading to a coarse-tailed grain size distribution ($D_{50} \sim 100$ 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, RK 283. 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.

<table>
<thead>
<tr>
<th></th>
<th>morphology</th>
<th>median grain size, exposed bar (mm)</th>
<th>median grain size, thalweg (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XSECT 1</td>
<td>run</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>XSECT 2</td>
<td>pool</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>XSECT 3</td>
<td>pool</td>
<td>52</td>
<td></td>
</tr>
<tr>
<td>XSECT 4</td>
<td>pool</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>XSECT 5</td>
<td>riffle</td>
<td>99</td>
<td></td>
</tr>
<tr>
<td>XSECT 6</td>
<td>riffle</td>
<td>62</td>
<td>80</td>
</tr>
<tr>
<td>XSECT 7</td>
<td>run</td>
<td>80</td>
<td>84</td>
</tr>
<tr>
<td>XSECT 8</td>
<td>run</td>
<td>76</td>
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<tr>
<td>XSECT 9</td>
<td>run</td>
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<td>--</td>
</tr>
<tr>
<td>XSECT 10</td>
<td>run</td>
<td>74</td>
<td>61</td>
</tr>
<tr>
<td>XSECT 11</td>
<td>run</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
To examine the importance of spatial variations in grain size, the modeled estimates of $\tau^*$ 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 particular cross section. Calculations for higher flows were based on samples taken from deeper portions of the channel, as well as exposed bar surfaces, since both of these areas would be under water. Calculations for lower flows were based only on samples from submerged portions of the channel. The effect of using spatially variable grain sizes in the model is to reduce the estimates of $\tau^*$ slightly, as shown in Figure 29. 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 from 125 to 224 m$^3$/s (4400-7900 ft$^3$/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 in the riffle, the modeled values of $\tau^*$ decrease substantially (Fig. 29). 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 (10600 ft$^3$/s), therefore, that value is retained as the threshold discharge for initial motion.

![Figure 29](relation_between_dimensionless_shear_stress_and_dischargeRK283)

**Figure 29.** Relation between dimensionless shear stress and discharge, RK 283, 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 flows in the 15- and 18-mile reaches of the Colorado River. The field surveys and modeling results generally support the results from previous studies and the recommendations given in previous reports. Further evidence of the geomorphic effects of spring flows is illustrated below with ground-based photographs of the channel of the Colorado River taken at various times. The first set of photographs (Fig. 30) 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 a cordless drill. The surface was then allowed to dry, and the rocks were spray painted with 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 30: Before- and after-photographs of painted rocks at cross section 7, RK 283. The yellow frame measures 50 cm in length by 30 cm in height.](image)

The patch shown above was submerged under about 1 m of water during the peak discharge in 2001 (227 m³/s or ~8000 ft³/s). The boundary shear stress in the vicinity of the patch under these flow conditions would have been about 20 N/m², which is 30% less than the estimated threshold for motion of the median grain size ($D_{50} = 80$ mm at that location). The photographs show that the majority of rocks within the patch did not move. However, it is possible to identify several rocks that appear to have moved, or were transported into or out of the patch during the period of peak flow. This observation is consistent with the expectation that small fractions of the bed surface are mobilized by flows lower than the reach-average threshold for initial motion (assumed to be 50% of the bankfull discharge, or 278 m³/s). While a discharge of 227 m³/s falls well short of a “channel maintenance flow”, this flow is capable of mobilizing a handful 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 31 compares downstream views of the Colorado River, taken four years apart at the same location on the lateral bar at RK 283. This location was essentially devoid of vegetation in 2000 but is covered with waist-high tamarisk by 2004. The bar surface shown in these photographs was 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.

Figure 31. View downstream showing growth of vegetation on the lateral bar, RK 283.
SUMMARY and CONCLUSIONS

This study was initiated to assess how elevated flow levels produced by coordinated reservoir operations in the upper Colorado River basin affect conditions in the 15- and 18-mile reaches. In 1998, the initial year of the study, coordinated reservoir operations were implemented for 7 days. Runoff was allowed to bypass reservoirs, increasing daily discharges into the 15-mile reach by a maximum of about 60 m$^3$/s (~2100 ft$^3$/s). Similar procedures were implemented for 10 days in 1999; these flows increased daily discharges in the 15-mile reach by a maximum of about 70 m$^3$/s (~2500 ft$^3$/s). The bypass flows were successful in boosting background discharges by 10-15%, which appeared to be sufficient to mobilize small portions of the bed material in the 15- and 18-mile reaches. Conditions reflecting widespread entrainment and transport of the bed material (complete mobilization) were not evident in 1998 or 1999. Limited snowpack and runoff in subsequent years, 2000-2004, prevented further tests of the geomorphic effects of bypass flows.

U.S. Geological Survey analyses of streamflow records in the upper Colorado River basin suggest that water years 2002-2004 were perhaps the driest in the last 100 years. Flows that did occur during the drought period were far below average, thus thresholds for mobilizing cobble- and gravel-sized sediment were not exceeded very frequently. Over the 7-year period of the study, the discharge required to produce initial motion in the 15-mile reach (~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) was never exceeded.

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 relatively minor.

Analyses of suspended sediment records from gauging stations in the study area reconfirm the importance of late-spring flows for carrying sediment. 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 most of the total annual sediment load is carried by flows 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 period of time when Colorado pikeminnow are typically 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 in transport mode occurring at discharges between 125 and 150 m$^3$/s (4500-5500 ft$^3$/s).

Intensive field measurements, coupled with results from a 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 increases 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, which was based on flow modeling at a number of other sites, plus analyses of reach-wide trends in channel morphology, average gradient, and bed material properties.

Over the 7-year period of the study, and especially during the 2002-2004 drought, there were few flows high enough to mobilize very much of the bed material of the Colorado River. As a result, native and non-native woody plants, such as sand bar willow, cottonwood and tamarisk, were able to colonize low-lying bars throughout the study area. Plants grew vigorously on bars that would normally be inundated by 1-2 m of water during the period of spring runoff. The current distribution and health of vegetation provides the clearest evidence that movement of coarse substrates in the study area was very limited, as these plants would not have become established if there had been appreciable movement of the bed material. It is very likely that some bars will be permanently stabilized as plants become more deeply rooted and grow in size, thus increasing flow resistance and deposition of fine sediment. As time goes on, fluvial/hydraulic processes will compensate for the growth of vegetation by forcing more and more of the flow against any unvegetated banks, and at that point the channel should widen (assuming it is not constrained by levees or rip-rap). Whatever the sequence of events, the creation and maintenance of habitats used by the native fishes will be largely dependent on the frequency and duration of sediment-transporting flows.

**RECOMMENDATIONS**

The results and observations discussed in this report are broadly consistent with information given in previous reports, although the geomorphic effects of flow levels such as the bankfull discharge could not be assessed since these flows did not occur. The results and conclusions from this study are nonetheless helpful in refining criteria for flows that perform important geomorphic functions, under the assumption that these functions are beneficial to the native
fishes and the ecosystem which supports them. The first two recommendations listed below focus on additional work that might be done to establish the importance of different flow levels on geomorphic processes in the 15- and 18-mile reaches. The third set of recommendations focuses on specific flow levels (magnitude, frequency and duration), and discusses the rationale and intended geomorphic effect of each flow level. The flow recommendations are then summarized in the form of a matrix which can be used to assist federal and non-federal reservoir operators in planning future water-management activities, including bypass flows.

1. Channel Monitoring: This study coincided with a period of very intense drought, thus there were limited opportunities to assess the geomorphological or ecological benefits of high-than-average discharges. Sufficient background information exists in various places near Grand Junction to evaluate the geomorphic effects of these flows when they do occur. The Recovery Program should support continued monitoring of geomorphic changes at representative sites, but perhaps only in association with high-flow events, e.g. flows greater than about 2/3 of the bankfull discharge. This is not to say that lower flows do not have important and potentially adverse ecological effects, because they almost certainly do; however, the level of information gained from cross section surveys and hydraulic modeling is relatively coarse in comparison to the detail needed to understand ecosystem processes.

2. Sand Transport: The sediment data collected in this study are consistent with previous USGS measurements in showing that the Colorado River continues to transport sand well after the peak in the annual hydrograph. Sand has the potential to move either in suspension or in contact with the bed, depending on flow level, thus the mode of transport strongly affects the rate that sand moves through the system. The USGS measurements show that the percentage of sand being carried in suspension typically reaches a peak after the peak in water discharge, at about the same time of year when Colorado pikeminnow are preparing to spawn. It was suggested that spawning success might be affected by a shift in the timing of this transition, with sand dropping out of suspension earlier now than before. Therefore, the Recovery Program should consider funding additional USGS studies of sediment transport (suspended load and bed load), most likely at the Palisade gauge, but perhaps also at the State Line gauge. These studies should focus not only on trends in sediment concentration, but also on trends in the grain size distribution of the suspended load, as well as the bed load.

3. Flow recommendations: The observations and measurements made over the course of this study reinforce conclusions and inferences made in previous studies (Pitlick et al., 1999; Pitlick and Cress, 2000), therefore, the target flows recommended for achieving a range of geomorphic effects are retained. The recommendations are listed here as flow categories, with each category having a set of intended purposes, a target frequency and a target duration. The duration and frequency of flows are based on a block of water years, 1978-2000, which are representative of contemporary conditions, absent extreme droughts or further storage and/or depletions (Table 6).
The period from 1934-1949 is representative of more natural conditions that existed prior to water development; however, it is known from previous geomorphic studies that the Colorado River was 10-15% wider then than it is now (Pitlick et al., 1999; Pitlick and Cress, 2000), thus frequencies of specific discharges are not entirely comparable— a discharge of 600 m³/s occurring today would fill the channel to the bankfull level, but the same discharge occurring in the 1940s would probably not have reached bankfull, because the channel was wider then. The block of years from 1950-1977 includes the main period of water development, thus much of the runoff produced in the upper basin at that time was likely going into storage as these reservoirs were coming on line. The block of years used in developing flow recommendations thus represents a compromise between conditions as they were historically and conditions as they are now.

Table 6. Frequency of specific discharges for individual time periods. The discharge levels correspond to the recommended flow categories listed below. Frequencies are based on the daily flow record of the Colorado River near Cameo, USGS gauge 09095500.

<table>
<thead>
<tr>
<th>Category</th>
<th>Q (m³/s)</th>
<th>Q (ft³/s)</th>
<th>1934-1949</th>
<th>1950-1977</th>
<th>1978-2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>608</td>
<td>21500</td>
<td>7</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>B</td>
<td>278</td>
<td>9800</td>
<td>44</td>
<td>29</td>
<td>34</td>
</tr>
<tr>
<td>C</td>
<td>142</td>
<td>5000</td>
<td>81</td>
<td>63</td>
<td>73</td>
</tr>
</tbody>
</table>

A. **Category**: Bankfull Discharge

15-Mile Reach: 608 m³/s (21,500 ft³/s)

18-Mile Reach: 979 m³/s (34,600 ft³/s)

**Purpose**: Flows that reach or exceed the bankfull discharge are 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. Flows exceeding the bankfull level will inundate the floodplain in selected areas. Overbank flows entrain organic matter from the floodplain, thus providing nutrients to stimulate primary productivity. Bankfull flows should occur with sufficient frequency (see below) to maintain the mass balance of sediment, so as to limit deposition in secondary channels, prevent further narrowing of the main channel and limit the growth of non-native vegetation on low-lying gravel bars.

**Duration**: 5 days per year, averaged over a period of no more than three years

**Frequency**: No less than one out of every three years
**B. Category:** Discharge for Initial Motion (approximately one-half the bankfull discharge)

15-Mile Reach: 278 m$^3$/s (9,800 ft$^3$/s)

18-Mile Reach: 548 m$^3$/s (19,400 ft$^3$/s)

**Purpose:** Flows equal to one-half the bankfull discharge produce limited entrainment of cobble- and gravel-sized sediment on the channel bed. Partial transport of the bed material is necessary for maintaining clean (silt-free) substrates, especially in frequently used habitats such as riffles and runs; removal of interstitial fine sediment from riffles likewise improves habitat for benthic invertebrates and other native fishes. At this discharge most low-lying bars are covered with a substantial depth of water (many 10s of centimeters), thus most of the bed is inundated. At these flows framework grains start to move 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:** at least 30 days per year, averaged over a period of no more than two years

**Frequency:** No less than one out of every two years

**C. Category:** Discharge for Suspending Sand in Riffles

15-Mile Reach: 125-150 m$^3$/s (4,400-5,300 ft$^3$/s)

18-Mile Reach: 275-330 m$^3$/s (9,700-11,700 ft$^3$/s)

**Purpose:** Discharges in this category are recommended to keep sands finer than about 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 on the falling limb of the hydrograph when spawning normally occurs. This recommendation should be considered provisional, 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:** Every year

**4. Flow Matrix:** A matrix summarizing the above flow recommendations is given on the following page (Table 7). The matrix lists thresholds and durations of discharges that perform important geomorphic functions, and discusses the purposes of different flow levels in terms of the expected geomorphic responses. The matrix can be used by the coordinated reservoir operations group to tailor operations to target multiple objectives of habitat maintenance and creation in alluvial reaches of the Colorado River near Grand Junction.
Table 7. Flow matrix for the 15-mile and 18-mile reaches of the Colorado River.

<table>
<thead>
<tr>
<th>Category</th>
<th>Discharge (15-mile)</th>
<th>Discharge (18-mile)</th>
<th>Flow Conditions and Intended Purposes</th>
</tr>
</thead>
</table>
| A        | 608 m³/s (21500 ft³/s) | 979 m³/s (34600 ft³/s) | • Bankfull discharge: This discharge will mobilize cobble- and gravel-sized sediment on most of the channel bed; widespread mobilization of coarse substrates is required to create and maintain the suite of habitats used by native fishes.  
• Flows leading up to the bankfull discharge transport a large proportion of the total annual sediment load; maintaining the sediment-transport capacity of the river is the key to limiting further channel narrowing and reduction in habitat complexity.  
• Flows exceeding the bankfull level inundate limited portions of the floodplain; overbank flows entrain coarse particulate organic matter from the floodplain, providing nutrients to stimulate primary productivity. |
| Duration: 5 days/year, averaged over no more than three years | Frequency: No less than one out of every three years |
| B        | 278 m³/s (9800 ft³/s) | 548 m³/s (19400 ft³/s) | • One-half the bankfull discharge: This discharge will mobilize coarse sediment on limited portions of the channel bed; partial transport is important for removing interstitial fine sediment to improve riffle and run habitats used by native fishes.  
• This flow inundates most low-lying gravel bars, thus limiting the growth of woody plants, especially tamarisk, that can stabilize channel bars once they become established  
• Most of the channel perimeter is inundated by this flow; the increase in wetted area provides additional habitat for aquatic organisms, including native forage fishes, and benthic invertebrates. |
| Duration: at least 30 days/year, averaged over a period of no more than two years | Frequency: No less than one out of every two years |
| C        | 125-150 m³/s (4400-5300 ft³/s) | 275-330 m³/s (9700-11700 ft³/s) | • Approximately one-fourth of the bankfull discharge: Discharges in this range are needed to keep fine-medium sand in suspension over riffles. Concentrations of suspended sand appear to reach a peak after the peak in water discharge, roughly at the time of year when Colorado pikeminnow are preparing to spawn.  
• Riffles provide spawning habitat for Colorado pikeminnow; it is important to keep sand from accumulating on the bed during the period of spawning to increase spawning success.  
• Sand can move in either in suspension or in contact with the bed; sand moving in contact with the bed moves more slowly through the system, increasing the tendency for fines to accumulate in the bed, potentially limiting native fishes use of riffle and run habitat. |
| Duration: 10 days per year, on the receding limb of the hydrograph | Frequency: Every year |
REFERENCES


APPENDIX

Peer Review Comments and Author’s Responses

A draft copy of the report was sent out for technical review in September, 2005. Over the period of the next three months comments were received from five reviewers:

- Joe Lyons, U.S. Bureau of Reclamation
- Kirk LaGory, Argonne National Laboratory
- Jimmy O’Brien, TetraTech
- Doug Osmundson, U.S. Fish and Wildlife Service
- Melissa Trammell, National Park Service

Comments from Jimmy O’Brien, Doug Osmundson, and Melissa Trammell were supplied to the author as MS-Word documents, and are included in the following pages. Joe Lyons provided a paragraph of comments and a marked-up paper copy of the draft report. Kirk LaGory provided a marked-up copy of the draft report but no detailed written comments.

The comments from all of the reviewers were considered, and in most cases these comments and suggestions were incorporated into the revised report. The Response to Reviews Comments which follows the text of their documents focuses on the primary concerns of the reviewers. Suggestions for changes in spelling, wording or context were incorporated into the revised report as necessary.
PROPOSAL TITLE: Colorado River Channel Monitoring

PRINCIPAL INVESTIGATORS: Dr. John Pitlick, Department of Geography, University of Colorado

Rating: Excellent - E  Good - G  Fair - F  Questionable - Q

1) EVALUATION OF THE PROPOSED SCOPE OF WORK

a) Evaluation Factors

<table>
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<th>Rating</th>
<th>Description</th>
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<td>G</td>
<td>Clear, measurable objectives with specific timeframes</td>
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<tr>
<td>E</td>
<td>Relevance of objectives to recovery</td>
</tr>
<tr>
<td>G</td>
<td>Description of methods or approach, validity of methods, appropriateness of statistical analyses</td>
</tr>
<tr>
<td>G</td>
<td>Integration with existing knowledge / incorporation of relevant scientific literature</td>
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<tr>
<td>G</td>
<td>Feasibility and probability of achieving the stated objectives</td>
</tr>
<tr>
<td>E</td>
<td>Timeliness of proposed work</td>
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</table>

b) Overall Evaluation: (Check one box only)

- [ ] Excellent
- [x] Good
- [ ] Fair
- [ ] Questionable

2) BUDGET EVALUATION: Underestimated (-) Appropriate (x) Overestimated (+) Unknown (?)

Personnel (-) Equipment (-) Travel (-) Materials (x) Other (x) TOTAL (-)

FOR RECOVERY PROGRAM STAFF USE ONLY:

3) EVALUATION OF PRINCIPAL INVESTIGATORS

<table>
<thead>
<tr>
<th>Rating</th>
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<td>Knowledge of, and experience in, the proposed area of work</td>
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<td>Significance of previous contributions in this area of work</td>
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<td>Group integration, cohesiveness, and collaboration (if appropriate)</td>
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4) DETAILED COMMENTS

Explain the basis for your evaluation. The strengths and weaknesses of the proposed scope of work should be discussed, with specific comments on the potential contribution to recovery of the endangered fish in the upper Colorado River basin and on the background of the investigators in relation to the current application. Please provide any recommendations for improving the study proposal.

General Comments:

Overall this is a very good study and report. The recommendations for target flows, frequency and duration are excellent and within the scope of tenements of the Recovery Program. As shown in Table 3, the recommended higher threshold flows were not experienced during the period from 1998 to 2004. The report states on page i that “(t)he limited availability of water in subsequent years prevented further tests of the geomorphic effects of bypass flows.” It is recommended that this study be extended until a period of several successive years of high flows have been monitoring for cobble bed movement and channel morphology changes in the 15 Mile and 18 Mile Reaches. This study is a good argument for having contingency plans to delay or extend studies undertaken during low flow drought periods that require high flow data. Forcing the completion of studies within a time frame during low flows limits the ability of the researcher to meet objectives and perhaps draw definitive conclusions. The researcher may have to rely on extrapolation of low data and study results to meet the objectives requiring a high flow analysis. The comment on page 26, that the frequency of threshold discharges during the period from 1998 to 2004 … “provide an indication of the ability of the Recovery Program to meet the flow recommendations given in previous studies and reports…” exemplifies this problem as well as being a delineator of the success of the program.

Specific Comments:

The following specific comments are relatively minor when considered in relationship to the overall contribution of the study to the Recovery Program.

1. It is noted that the objectives listed on page 5 of the report do not correspond exactly to the objectives in the provided Proposed Scope of Work for Project 85A. The Project 85A objective in the provide Scope of Work “(t)o develop a matrix which can be used by the coordinated reservoirs operations group to tailor reservoir operation to target multiple objectives of habitat maintenance and creation” was not addressed in the report. Storage and seasonal runoff conditions under which coordinated reservoir operations should be evaluated and would be a significant contribution to the Recovery Program. The figures on page 27 which illustrated the reservoir release in 1998 and 1999 are unreadable.

2. The nature of bed material in the 15 Mile and 18 Mile Reaches indicates that the sand sized sediment in this reach is supply controlled. The sediment supply to these reaches is controlled in part by the seasonal storage and delivery from upstream pool reaches. This process of storage and release would account for some of the variability between the peak discharge and peak suspended sediment concentration at the various gages shown in Figures 17 and 18. On page 41, the statement is made that “(i)f sand was moving through this river system as a wave or pulse, then there should be 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 is transport is derived locally, i.e. for the channel bed, rather discrete sources upstream.” This is
true if “derived locally” refers to the pool reaches upstream rather than more distant tributary watersheds. A similar pattern of sediment movement has been observed at the Jensen gage on the Green River in response to sediment storage and delivery from the Island Park/Rainbow Park reach. The sand collects and forms into waves in the Island Park reach in a seasonal redistribution. The sand waves store near the lip of Cross Mountain Canyon where it is delivered to the Jensen gage with the start of the spring runoff.

The sand supply to the 15 Mile and 18 Mile Reaches is of critical importance to this study and should be addressed in more detail regarding tributary inflows associated seasonal storms and potential upstream storage reaches. The only comments provided regarding sediment supply is “…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…” and “(m)uch of the fine sediment is derived from surface erosion of friable sedimentary rocks underlying Roan Mesa.”. This general assessment that does not shed much light on the nature of sand sized sediment movement through the study reaches or its tributary sources.

3. The term “granules” is used several times throughout the report. How does this term relate to the conventional, clay, silt, sand, gravel, cobble, boulder size fractions?

4. It is stated in the report that “(t)he single most important thing that can be done to maintain habitats used by 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 the low velocity areas, resulting in further channel simplifications and narrowing.” While this intuitively correct, the key factor controlling the rate of channel narrowing is vegetation encroachment in the active channel. The sediment provides the substrate for the vegetation, but until the vegetation is established, sediment remobilization at high flows is always possible. Once vegetation is established in the channel, the potential for removing the vegetation and mobilizing the sediment is significantly reduced. In general, tamarisk plants that attain a three year growth will not be removed by subsequent spring high flows. Bankfull discharge (> 621 cms) with a frequency of one out of every three as recommended in the report is critical to avoid vegetation establishment in the channel. If flows do not exceed bankfull for any consecutive 3 year period, some channel narrowing may occur with vegetation establishment in the active channel that can only be removed in the future by mechanical techniques. On page 57, it is noted, that “…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.” The statement is critically important and it should be emphasized that tamarisk plants need to be removed within the first 2 to 3 years of growth or the majority of the plants cannot be removed by high flows in subsequent years.

5. The sediment traps were an innovative approach to collecting low flow sediment movement over a cobble bed. The conclusion that the Colorado continues to transport fine-medium sand during periods of low flow is justifiable. It should be noted, however, that because of the nature of the trap, the ability of the fine-medium sand to exchange with the bed is limited. Berry (1985) thesis “Bedload Transport Processes in a Cobble Bed Channel,” and the 1984 companion reports on the Yampa River Cobble Reach by O’Brien presented the concept from flume studies that sand could be scoured from a cobble bed up to mean one cobble diameter below the bed surface without initiating cobble motion. The exchange of sand between the flow and the substrate will effect the interstices size distributions. In the O’Brien report, the critical shear stress parameter was also assumed to be 0.03, but it is agreed that this value does vary and it is likely to be slightly lower for most cobble bed reach in the range from 0.025 to 0.030.

6. The comment, “…if there is a natural tendency for the grain size distribution of the suspended sediment in the Colorado River to coarsen with time…” is confusing. It was intended that this statement reflect that the suspended load can become more coarse during the recessional limb of
the hydrograph. A coarsening of the suspended load is a physical process that reflects a change in the relationship between the fine sediment moving as wash load and the bed material load. This comment however would infer that the supply of fine sediments decreases as the discharge decreases which is true except that much of the system wide fine sediment loading may be in response to seasonal thunderstorms. In several places in this paragraph, the wording should be changed from “…becoming coarser with time…” to “becoming coarser over the seasonal hydrograph…” or “…becoming more coarse with the recessional limb of the seasonal hydrograph.”

7. The last sentence on page 37, “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 the contemporary theories for equilibrium transport in gravel-bed channels (Parker et al, 1982 and Toro-Escobar, 2002)” is not an appropriate interpretation of the concept of equal mobility of gravel in rivers. The concept of equal mobility is that the average size distribution of the gravel portion of the bed load is approximately equal to the gravel distribution of the substrate. A direct comparison of the gravel moving transport in the Colorado River with the channel substrate is necessary to draw this conclusion.

8. Figure 28 is fascinating and it is likely that much more information could be drawn from the measurement of cobbles that moved or didn’t move that would support the concept of equal mobility for gravel bed streams. There are a number of particles that were wedged between larger cobbles that were mobilized including a large one at the bottom of the figure. It may be possible to calibrate the critical shear stress parameter from scaling the larger particles missing in the ‘after-photograph’. It is interesting to note that similar photographic and paint methods were employed at Mather’s Hole on the Yampa River in 1983 and 1984.

9. On page 21, “…undulations in the bed caused by pools and riffles…” should be reworded to “…undulations in bed profile caused by pools and riffles…”. It is suggested that the rest of sentence starting with “…producing a net fluid force…” be deleted. Actually, the entire discussion on page 21 and 22 is overly simplistic and poorly worded and should be deleted because it doesn’t add anything to the report.

10. Page 28, the comment “(s)ome water was “lost” in the process…” should be expanded. Is this figure of speech or does it refer to actual floodwave attenuation and losses due to diversion, infiltration and evaporation?

11. The cross section resurveys illustrated on pages 29 thru 32 were completed at different times on different years throughout the seasonal hydrograph (May 98, Aug 98, Oct 99 and July 01). It is recommended that the resurveys be conducted at the roughly same time prior to and immediately following the peaks flows (perhaps in April and July) so that channel response to the spring runoff can be quantified.

This review will be considered by Recovery Program staff and the Biology Committee. If you desire anonymity, please do not sign below. The Recovery Program sincerely appreciates your assistance.

NAME: Jimmy S. O’Brien, Ph.D., P.E. DATE: 10/17/05
Review of Final Draft Report:

‘Channel monitoring to evaluate geomorphic changes on the main stem of the Colorado River’

Author John Pitlick; Geography Department, University of Colorado, Boulder

Reviewer: Doug Osmundson, Fish Biologist, USFWS

This report provides summary information on a 1998-2004 geomorphic study of the ‘15-mile reach’ of the upper Colorado River located near Grand Junction, Colorado. Its stated purpose was to assess the effects of coordinated reservoir releases and normal snowmelt flows on geomorphic processes. In addition, conditions in one specific reach were monitored to verify earlier estimates of flow thresholds necessary for various levels of sediment transport.

The report is thorough and well-written. In addition, the author has obviously made an attempt to explain geomorphology concepts in a way understandable to those outside the discipline, while retaining the rigor and documentation required and expected from peers. For me, a non-specialist, this made reading the report both interesting and enjoyable and greatly facilitated my ability to understand and critically review the report.

Much can be said that is positive about this report. However, to aid the author in improving this draft, my comments will focus on questions that I have.

Executive Summary

Page i, line 3: As far as we know the 15- and 18-mile reaches do not provide important habitat for the humpback sucker.

Page i, lines 17-18: The word ‘nonetheless’ seems out of place because the coordinated reservoir releases were in years other than those described as drought years.

Page iii, line 14: I am a little confused here by the term ‘bedload transport’. Based on definitions given elsewhere in the report, I would consider sand moving along the bed, out of suspension, to be included as part of the bedload when transported (defined as “overpassing” on page 18). This evidently occurs during flows less than 4,000 cfs. Or do sand particles, as they fall out of suspension, automatically deposit, getting lodged within the framework particles? I would think much of it would continue moving along the bed. If so, is the 10,000 cfs threshold referred to in line 14 referring instead to framework particles only as the ‘bedload’?

Introduction

Page 2, line 4: Are there 25 reservoirs or 24 (see page 9)?

Page 3-4, summarized recommendations: The recommendations provided here are aimed at maintaining the 30-day annual average of $\frac{1}{2}$ bankfull flows and 5-day annual average of bankfull flows as calculated for the 1978-1997 period of record. Some explanation is needed regarding
why maintaining the status quo of a highly depleted, post-development block of years is desirable. Why is this the standard that we should aspire to meet? Have the fish done well under these conditions? Perhaps provide some explanation that these years represent a suite of both low-flow and high-flow years, or something.

**Study Area**

Page 9, lines 2-5: Much of this repeats what was already described in the Introduction (page 2).

**Methods**

Page 16, last line: Is a 20-cm coffee can 20 cm in diameter or in depth?

Page 17, line 3: Editorial comment: who does “us” refer to? There is only one author.

**Results**

Page 23 and elsewhere throughout the report: In some places in the report, discharge reported in cubic meters per second is followed parenthetically by the same discharge in cubic feet per second. This is very helpful to those of us readers accustomed to using the cfs term. However, reporting discharge both ways is not done consistently throughout the report. It would be helpful if it was.

Page 23, bottom paragraph: It’s hard to tell from fig. 9 that runoff was equally divided between above- and below-average years prior to 1998 because there is no average line provided on the graph. Also, any calculated ‘average’ is dependent on the block of years chosen for averaging. Obviously, with a 14-year period of record at Palisade, starting in 1990, coming up with an average prior to 1998 (n = 8 years) is not particularly useful.

Page 25, lines 4-6: This statement downplays the significance of back-to-back low water years. However, only recently (1987-1992 and 2000-2004) have there been 6 and 5 year blocks of consecutive years with below-average flows. Will there be more of these in the future? Probably, as noted by the author. However, it is also worth noting that such blocks did not occur during the period of record prior to water development in the upper Colorado River and should now be considered a cause for concern. Global warming coupled with planned future depletions will likely result in a greater frequency of such extended depleted conditions. At this point in time we do not know all the ecological ramifications of such events. We do know that tamarisk invasion on banks occurs during these periods leading to channel narrowing. It becomes increasingly hard to uproot these in subsequent years, the longer the root systems remain undisturbed.

Page 27, line 2: If coordinated reservoir releases were made in 1997, as well as 1998 and 1999, why are the results from 1997 not reported here?

Page 28, line 6: was this “fraction” released a large or small fraction, i.e., 1/10th or 9/10s?
Page 28, bottom paragraph and elsewhere in report: There should be consistency in reporting river locations in either river kilometers or river miles (or both together). Pages 8 and 12 use RK, whereas RM is used here.

Page 33, line 1: Is the intent here to say ‘…mostly due to lower flow levels at the time of photography in 2000 as compared to 1993...’?

Page 33: How is the change in channel complexity measured or reported in Fig. 14? It looks like the reduction in percent area of side channels in the 15-mile reach is 0-70% depending on location. Increases in side channels was as high as 100% in another location. From an ecological perspective, loss of habitat in one location is probably okay if it is created or expanded in another location. However, net loss is a concern. It would be good if the net change in total area and net percent change could be reported for each of the 15-mile and 18-mile reaches. As written, whatever net changes there are trivialized by describing them as “small (<20%)”. I would say that a 19% loss of side channel area in 7 years (1993-2000) is huge. Was any photographic analysis of backwater area done here, as was done in the earlier studies?

Page 35, first paragraph: The hysteresis effect described here and in previous reports is interesting because it tells when suspended sediment loads and concentrations are highest, i.e., on the rising limb of the spring snowmelt hydrograph. However, it would be good if the author could lend some interpretation to this here. As flows rise in the spring, are deposits of fines stored in the bed being released and carried in suspension until they are depleted from the bed sometime prior to the peak? Or is it because low elevation snow banks melt first and it is these local areas that supply the bulk of the washload at this time. Snow melt may be complete in these areas early and erosion of fines would taper off. The peak usually occurs when warm days and nights finally arrive in the high country and the remaining high-elevation snow comes down at once without a lot of attendant fine sediment. Some such explanation would be welcomed.

Page 37, last sentence: I’m interested in this discussion of sand in the bed. But I am unclear of the implications of the statement here. Does “…sand in transport…” refer only to suspended load, or does it include bedload sand.? What is meant by “…exchanges in equal proportions with the sand stored in the bed…”? I’m picturing sand moving along the bed, filling framework voids, but continuing to move. Deposited sand eroding out and being replaced by more sand coming from upstream existing in dynamic equilibrium. Am I misconstruing the author’s meaning here? If so, why would the fact that the suspended load being made up of 20% sand (the rest being silt and clay) have any relation to the fact that the bulk bed material including rocks etc. (clearly not previously in suspension) is also made up of 20% sand? The connection is unclear.

Page 39, Fig. 17-B: It is pretty hard for me to look at this graph and conclude that sediment concentration in the Gunnison peaks several weeks prior to the discharge peak. It looks like the peaks coincide.

Page 44, last sentences: Most of the sand in the traps must have been sand that came out of suspension or was traveling as bedload. Yet the traps were operated during runoff at flows in
many cases greater than 125 m$^3$/s; hence, the sand should have stayed in suspension according to Dietrich's relations and the author’s calculations. So why did the traps fill with sand?

Page 46: Table 4: What does ‘n’ refer to? It generally refers to sample size, yet evidently refers to something else here. Some kind of key to the acronyms such as the footnotes for the observed/threshold discharges would be helpful.

Observations

Page 56, first 4 lines: Here initial motion is described as occurring at 50% bankfull. Elsewhere in the report, such as p. 61, initial motion is described as occurring at 2/3 bankfull depth. Am I missing something here?

Also, I was under the impression that initial motion is that discharge at which a few framework rocks somewhere on the bed begin to move in a sporadic, but not widespread, basis. But this definition seems to fit the situation here with the painted rocks where a few were found to move. Is the additional part of the former definition (not explained here) that this threshold is reached only when such sporadic movement occurs at 50% of the sites? Rocks at the painted rock location were beginning to move at flows 30% less than the initial motion discharge. Was this because this location was one of only a few (something less than 50%) where rocks were beginning to move?

Summary

Page 57, Fourth line of Conclusions: Again, the word “nonetheless” seems out of place here (see second comment under executive summary).

Also, why not report here what happened with the 1997 releases?

Page 58, End of middle paragraph: This seems to be one of the more biologically relevant points of discussion offered here. What happens to spawning substrate when sand goes from traveling in suspension to traveling as bed load as the flows drop below 5000 cfs? Pikeminnow spawn during the descending limb of the hydrograph at various temperatures above 16-18 C. Are sites selected for spawning those that will maintain sand in suspension longer than other sites? What happens to sand at spawning riffles versus riffles not selected for spawning? Pikeminnow in the Grand Valley generally spawn in July. Historic mean July flows (1902-1937) in the 15-mile reach were 7,212 cfs. However, during 1954-1989, mean July flows have been 4,341 cfs (Osmundson and Kaeding 1991). Perhaps spawning occurrence in the 15-mile reach is low because sand travels as bedload through potential riffle sites now during most years. Perhaps spawning in the 15-mile reach occurred more frequently in the past because this threshold was met more often. Just a thought…

Another thought: The sand traps were placed in the channel and monitored during runoff. It would be interesting to see how quickly they would fill if monitored during base flow. This might give an idea of the amount of sand traveling through the reach during the fish growing season when invertebrate production is important and may be affected by interstitial filling. Too
late now for this study, but in addition to the spawning issue, would perhaps provide a link between sediment transport and biology.

**Recommendations**

Page 60, Category A, Duration and Frequency: This recommendation has always been confusing to me. I admit it’s hard to come up with a better and equally flexible way to prescribe a flow recommendation. But it seems the frequency and duration is somewhat contradictory. The frequency is one of three years and the duration is five days *averaged over several years*. To meet the frequency criteria, you need to meet the threshold flow on average once every three years. In the other two years the threshold is not met (zero days). So when it does occur, it would need to last 15 days for the 5 day per year average to be met. Or does the recommendation mean that the threshold could be met for one day in one year out of six so long as it is met for 29 days in another year out of those six (5 days on average)?

Page 60, Category A, Purpose: I would add that fines deposited within framework particles within run habitats need to be periodically removed on a widespread basis to improve invertebrate standing crops. There exists literature that can be cited for support.

Page 61, second to last line in Category B: At 10,000 cfs “much of the bed” is not mobile unless I have misunderstood much of this. Would it be more accurate to say 50% of the bed is beginning to become mobile at 10,000 cfs.

Page 61, Category C, Duration: Add a spawning temperature component to the recommendation, such as “…late June to early July *when temperatures exceed 18 C.*”

Thanks very much for the opportunity to comment on this excellent report.

D. Osmundson
December 2, 2005
REPORT TITLE: Channel Monitoring to evaluate geomorphic changes on the main stem of the Colorado River.

AUTHORS: John Pitlick

PROJECT NUMBER: 85

RATING SUMMARY: (check one)

Accept  X Accept after minor revision  Reconsider after major revision  Reject

GUIDELINES FOR REVIEWERS

The attached report has been submitted to the Recovery Program for acceptance as final. The Program asks your assistance in judging this report’s technical merit. Please include in your review both general and specific comments on the report’s technical merit, strengths and weaknesses. Either type your comments on the next page or reverse side of this form, or attach your comments to the form. Written comments, if legible, may be placed directly on the manuscript; alternatively, numbers may be placed on the manuscript to correspond to numbered, typed comments.

General Comments:

1. Scientific soundness
2. Degree to which conclusions are supported by the data
3. Organization and clarity
4. Cohesiveness of argument
5. Length relative to amount of information
6. Conciseness and writing style

Specific Comments:

Please support your general comments with specific evidence. Comment on any of the following matters that significantly affected your judgement of the report:

1. Presentation -- Does the report tell a cohesive story? Is a tightly reasoned argument evident throughout? Where does the report wander from this argument? Does the report address the objectives as presented in the scope of work? Do the title, abstract, introduction, and conclusions accurately and consistently reflect the major point(s) of the report? Is the biological significance of the results clearly stated? Are the objectives clearly stated? Is the writing concise, easy to follow, interesting? Are the findings well integrated with existing knowledge?
Presentation is good, writing is all of the above. The objectives were addressed as far as hydrology would allow. However, it is unclear whether the recommended discharges apply to the 15 mile reach, or the 18 mile reach, or both. I can assume they apply only to the 15-mile reach since that would be consistent with earlier reports, but you need to make that clear. However, the study was intended to cover both the 15- and 18-mile reaches, so why no recommendations for the 18-mile reach?

In the SOW, the objectives include:

1. Provide Channel monitoring to evaluate rates of channel change and geomorphic effects of coordinated reservoir releases and normal snowmelt flows.

2. Refine previous estimates of gravel and cobble mobility by verifying thresholds for coarse sediment transport.

3. Define the window of time of peak sediment delivery from unregulated tributaries.

4. Assess problems associated with fine sediment deposition and decreases in interstitial void space.

5. Compare and contrast effects of augmenting flows on the ascending and descending limbs of the annual hydrograph.

6. To develop a matrix which can be used by the coordinated reservoirs operations group to tailor reservoir operation to target multiple objectives of habitat maintenance and creation. The matrix will relate flows to the physical characteristic of the river need for endangered fish recovery an example of a similar matrix developed for the San Juan River.

7. 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 their flow recommendations as appropriate.

In your report, you have addressed 1, 2, and 7. You have partially addressed 3 – you defined the peak time of sediment carried by the main channel, but did not directly link that to peak sediment delivery by unregulated tributaries. On 4, the problems associated with fine sediment deposition were discussed, but not really assessed. It appears that you may have combined objectives 4 and 5 in the report. However, the effects of augmenting flows on the ascending limb were not discussed, only those effects on the descending limb. Is there an accompanying matrix as described in Obj. 6?

2. **Length** -- What portions of the report should be expanded? Condensed? Combined? Deleted? Please explain how the study changed from a 4 year study (1998-2001) as specified in the SOW, and the time period when all the work was done, to a 7-year study through 2004, as it is described in the report. The only analysis presented that was done after 2001 was a pair of photos taken in 2000 and 2004 showing growth of tamarisk on a gravel bar. While this is interesting and potentially important information, I’m not sure it justifies calling this a 7 yr
study. If additional field work was done after 2001, why are those data and analyses not included? Otherwise, length is appropriate.

3. Methods -- Are they appropriate? Current? Described clearly enough so that the work could be repeated by someone else?
Methods fine near as I can tell although I’m not a geomorphologist.

4. Data presentation -- Are the results clearly presented? When results are stated in the report, can you verify them easily by examining tables and figures? Are any of the results counterintuitive? Are tables and figures clearly labeled? Well planned? Too complex? Necessary?

See comments below

5. Statistical design and analyses -- Are they appropriate for the data and correctly applied? Can the reader readily discern which measurements or observations are independent of which other measurements or observations? Are replicates correctly identified? Are significance statements justified?

6. Errors -- Point out any errors in technique, fact, calculation, interpretation, or style.

7. Citations -- Are all (and only) pertinent references cited? Are they provided for all assertions of fact not supported by the data in this report?

8. Recommendations -- Are management implications identified? Are the recommendations technical sound? Are they supported by the results of this and other research? Would implementing the recommendations contribute to recovery?

The first two recommendations are consistent with previous reports. The third is a bit of a departure. Earlier in the report you note that ‘...there are clear limits on the potential uses of bypass flows...’ [to augment peak flows] due to limits in storage on the upper Colorado River. Augmenting post-peak flows as well would then necessarily require more storage? But more storage would likely negatively impact peak flows. So, in a trade-off, which is more important? Could we do both if necessary without additional storage?

COMMENTS: (may be attached on a separate sheet of paper, if desired)

This report is a good follow up to earlier studies. It is unfortunate the hydrology during the study did not support a more thorough evaluation of geomorphic changes due to recommended changes in flow. Would you recommend further monitoring?

Some of my comments are questions needing clarification. Please clarify in the text of the report as well as in a response to comments.

Pg i. Para 1. No hyphens in species names. Cypha should be lower case. I think you should add bonytail to the list as they are being reintroduced in both reaches. And actually, the 18-mile
reach does not provide habitat for humpback chub (Gila cypha). They occur downstream in the Black Rocks reach as you point out in the introduction.

Pg i. Para 2. Delete ‘Nonetheless’. Since it happened before the drought, it’s not unexpected that it was done. (Also on pg 57).

Pg 1. Same comments as pg i above.

Pg 1. end of page. The parenthetical about razorback sucker using the reaches for similar reasons as the pikeminnow seems to imply that they too are drawn to an abundance of prey fishes; this is not correct since they are not piscivorous. However they may be drawn to higher biomass of invertebrates and other habitat features.

Pg 2. full para 1. last sent. Does the statement that diversions remove 14% to 30% of the native flow apply to both reaches, or just one? Which one?

Figure 2. darker lines are shown for RM 177.3 (A), and RM 162.4 (B). Any significance to that? If so, explain in text and in figure.

Pg 19. end of page. Insert period between ‘rate’ and ‘The’ And top of next page, insert space between Figure and 8.

pg 26. suggest adding average values to table.

Pg 27. Fig 10. Can’t read this graph – delete fill color.

Pg 28. I don’t think its unfortunate that only half the annual flow of the Colorado River can be stored – presumably you say unfortunate because more storage would allow greater bypass flows in dry years. But that is ironic since the bypass flows are only needed because the natural flow has been diverted and diminished.

Pg 39. last sentence above figure. ‘were’ should be ‘where’

Pg 41. last sentence. does the question ‘...is there a reason to be concerned about changes in the timing of the peak?’ refer to the peak of sand transport, or the peak discharge?

Pg 42. 3rd line. Pikeminnow should be lowercase.

Pg 42-43. Discussion of sediment traps. There is no way to tell from the figure how the sediment in the traps changed over time within a year. You describe in the text how the distribution of sediment size changed over time, but it is not shown in the figure. Perhaps you could color code the lines by date, so all the sediment traps on one date have a specific color. Figure – need to add a legend, with additional info as mentioned above.

Pg 56. last sentence above figure. ‘show’ should be ‘shown’
Conclusions: last para. You state three major assumptions on which the recommendations are based. But these ‘assumptions’ are more than just that – they are supported by data in yours’ and others’ studies. I suggest you rephrase this paragraph to emphasize that these statements are supported by data.

This review will be considered by Recovery Program staff and the Biology Committee. If you desire anonymity, please do not sign below. The Recovery Program sincerely appreciates your assistance.

NAME: __Melissa Trammell____________ DATE: __10/25/05__
Author’s response to reviewers’ comments:

1. Comments from J. Lyons:

   The majority of comments from this reviewer were editorial in nature (mistakes in spelling, punctuation, etc.); these were noted, and the text was changed accordingly. The most substantive comment from this reviewer was a suggestion to more fully explain the differences in bed elevations shown in Figure 26. This was done (see figure caption).

2. Comments from K. LaGory:

   This reviewer likewise pointed out a number of mistakes in spelling and punctuation; these were noted, and the text was changed accordingly. Additional suggestions from this reviewer were incorporated into the report as follows:

   a) Page 10 now lists specific values of discharge in the 15- and 18-mile reaches at the time of the aerial photography.

   b) Pages 23-24: Graphs depicting changes in discharge due to coordinated reservoir operations have been redrawn (the same request came from all the reviewers)

   c) Pages 31-36: The section discussing seasonal trends in suspended sediment has been modified in response to questions and concerns from several reviewers, including K. LaGory. The response to comments from Jimmy O’Brien provides more detail on this discussion.

   d) Pages 50-53, flow recommendations: The reviewer questioned the basis for assigning specific durations and frequencies to each of the recommended flow levels. To address this concern, a table showing differences in flow frequencies for three separate time periods was added to the recommendation section. A discussion of the relevance of flow frequencies for different periods now precedes the discussion of the recommendations. The durations and frequencies of the recommended flow levels are based on the “recent” flow record from the Cameo gauge, using the period 1978-2000 as the basis for setting target frequencies (see Table 6). Other time periods are considered to be either unrepresentative of contemporary conditions, or undesirable from a geomorphic standpoint. The author recognizes that there are several problems in trying to set targets for flow frequency and flow duration in a managed river. As discussed in previous reports and in this report the magnitudes of various flows are assigned on the basis of specific geomorphic threshold, whereas frequencies and durations are assigned on the basis of contemporary hydrologic conditions.

3. Comments from Jimmy O’Brien:

   This reviewer provided a number of perceptive and thoughtful comments. The responses given below focus on the main points raised in the review:

   a) The reviewer noted that the objectives listed on page 3 do not correspond exactly to the objectives in the Proposed Scope of Work for Project 85A; another reviewer (Melissa Trammell) also commented on this, noting that the specific objective of
developing a “flow matrix” was not met. To correct this, the report now includes a flow matrix, which appears in the Executive Summary (Table ES-1) and in the Recommendations (Table 7).

b) The reviewer comments that sand-sized sediment in this reach is supply controlled, and offers a number of additional comments on the processes of sand transport. The text of the report has been revised to reflect a number of these comments; however, the author does not agree with some of the reviewer’s interpretations. For example, there isn’t much evidence in the Colorado River that sand is stored in pools upstream of the study area, as appears to be the case in the Green River; it seems just as likely that sand is stored in pools throughout the study area. The text of the report has been changed accordingly. Elsewhere, the reviewer comments that there is not much detail given concerning the source of sand. The author does not understand this comment, since pages 30-36 discuss sand in detail. The data presented in the report show than a non-negligible fraction of the sand carried by the Colorado River is derived from the channel bed (ultimately it is all derived from the watershed, but ~20% of the bed material consists of sand, which can only get there by exchanging with the material in transport). It is important to recognize this, because it affects how you approach the problem of channel-maintenance flows, i.e., whether transport rates are governed by the supply or by the hydraulics of the flow. The distinction between supply-limited and capacity-limited transport depends on the grain size. Nobody would say that the Colorado River is supply limited with respect to gravel; likewise, probably everybody would say that the Colorado River is supply limited with respect to clay (and maybe silt). Sand fits in between, thus there is a danger in generalizing about sand transport in rivers such as this.

c) Comment 4 focuses on the potential impacts of vegetation growth on channel narrow. This point is noted and now discussed in more detail in the Summary and Conclusions. Disturbance of vegetation is also given as one of the intended purposes of flows approaching bankfull.

d) Comment 5 describes the reviewer’s own experience and observations of sand/gravel interactions; this appears to be more of a remark than a suggestion or concern.

e) Comment 6: The wording in the discussion of sand transport has been changed to reflect the concerns raised by the reviewer.

f) Comment 7: The reference to equal mobility has been dropped.

g) Comment 8 appears to more of a remark than a concern.

h) Comment 9: The reviewer suggests that the discussion of the equation for gradually varied flow is simplistic and unnecessary. It’s not clear where the concern lies, thus the author has retained the discussion of this equation in the report, primarily for the benefit of non-specialists (see comments from Doug Osmundson).

i) Comment 10: Wording was changed.

j) Comment 11: This comment is primarily a suggestion for conducting field surveys. It is not clear that the timing of the survey measurements in this study introduced a significant problem in the analysis and interpretation of the data.
4. Comments from Doug Osmundson:

This reviewer provided a number of perceptive and thoughtful comments. Suggestions for changes in wording or context were incorporated in the report as necessary. The main points listed in the review were addressed as follows:

a) The wording was changed in several places in the report to distinguish between the different components of bed load- the movement of sand versus the movement of “framework” grains (cobble- and gravel- sized sediment).

b) The rationale for using a particular block of years to develop flow recommendations is given later in the report, in the RECOMMENDATIONS.

c) The first 8 comments listed under RESULTS are primarily requests for clarification and rewording; these comments were incorporated into the report as requested.

d) The reviewer asked for some clarification in the discussion of sand transport, similar to some of the comments from J. O’Brien. Several editorial changes have been made in the section discussing sand transport to address the concerns raised by the reviewers. Some of the concerns are open-ended questions; however, in other cases the wording has been changed to try to clarify important points, such as the transition between sand moving in suspension and sand moving as bed load.

e) The wording within the sections discussing differences between peaks in water discharge and peaks in sediment concentration was changed in several places.

f) Comment on accumulation of sand in traps: Sand accumulated in traps at all flows; this might seem unclear, perhaps because the suspended sand is envisioned as a cloud of particles moving along with the flow, never in contact with the bed. In fact, particles move continuously between the bed and the flow; if the system is in steady state, the number of particles being entrained by the flow is balanced by the number of particles being deposited.

g) Column listings for Table 4 were changed.

h) The two comments listed under OBSERVATIONS were addressed; however, it should be noted that there isn’t a 1:1 relation between depth and discharge (see Fig. 25). The depth changes rapidly in the range from low to intermediate discharges, and more slowly thereafter; thus a river may indeed reach 2/3 of the bankfull depth at 50% of the bankfull discharge. Also, the definition of ‘initial motion’ is open to interpretation- there’s always a chance that some rock somewhere on the bed will move, even at low flows. The criteria for initial motion used here is based on a specific value of the dimensionless shear stress, \( \tau^* = 0.025 \), which represents the point at which some of the framework grains on the bed are beginning to move.

i) The comment referring to page 58 of the SUMMARY appears to be more of a remark than a suggestion for clarification. The potential ecological effects of sand dropping out of suspension on the receding limb of the hydrograph are discussed earlier in the report, and listed as a recommendation for future work.

j) The RECOMMENDATIONS have been reworded to address the concerns raised by the reviewer.
5. Comments from Melissa Trammell:

   Again, the review comments provided here were extremely thorough and helpful. Individual comments on wording/spelling were incorporated into the report as necessary. Other more detailed comments were addressed as follows:

   a) The reviewer suggested that the report should include flow recommendations for not just the 15-mile reach, but also the 18-mile reach. This was done.

   b) The reviewer suggests that some of the objectives listed in the scope of work were not addressed completely. This is a matter of interpretation, or perhaps a difference in how the objectives of the report were phrased. The only element missing from the draft report was the flow matrix. The flow matrix is now included in the final report.

   c) Comment on the duration of the study: The reviewer questions why the report includes results beyond the period specified in the scope of work. It is not clear to the author why this presents a problem. The report is admittedly late, but there is no reason to restrict the information in the report to a specific time period, especially if it helps guide recovery program efforts.

   d) Among the detailed comments, most all of the suggestions for changes in wording and/or clarification in figures were taken into account, and the text and/or figures were modified accordingly. Discussion of species location and use of habitats has been clarified; Figure 2 has been changed; average values were added to Table 3; figures showing changes in discharge as a result of coordinated reservoir operations have been redrawn; wording regarding reservoir storage and bypass flows has been changed (see p. 24); and the discussion of sand transport and potential ecological effects of changes in the transport mode (suspension vs. bed load) has been edited. The figure showing grain size distributions of the sediment caught in the traps is already quite complex; adding color lines w/ a legend for each line would make this an exceedingly busy figure, therefore, this suggestion was not incorporated into the report. Finally, the wording leading up to the recommendations has been changed.