1. Introduction

In the previous paper [Van Steeter and Pitlick, this issue], we showed that significant geomorphic changes have taken place in alluvial reaches of the Colorado River near Grand Junction, Colorado, and that there has been a loss of potentially important habitat used by the endangered Colorado squawfish (Ptychocheilus lucius). The principal mechanisms of channel change in our study reaches involved lateral accretion and narrowing of the main channel, and infilling of backwaters and side channels. Narrowing appears to have been most rapid during periods when high flows were less frequent and annual sediment loads were lower than the long-term average. The present paper takes the next step of addressing the question of what can be done to improve or expand squawfish habitats in the Grand Junction area.

Fish population studies by Osmundson and Burnham [1996] indicate that there are perhaps only about 600 Colorado squawfish remaining in the upper Colorado River (defined here as the reach upstream from the confluence with the Green River, Utah, to Palisade, Colorado). The largest concentration of adult Colorado squawfish in the upper Colorado River is found in reaches near Grand Junction. Presumably they congregate here because food sources and key habitats such as spawning bars and backwaters are relatively abundant compared to reaches downstream. Studies of the dispersal patterns of larval Colorado squawfish indicate that spawning areas are widely distributed along the upper Colorado River [McAda and Kaeding, 1991]. This finding is in contrast to the Green River system, where squawfish migrate to certain spawning bars annually [Obrion, 1987; Tyus and Karp, 1989; Harvey et al., 1994]. It is not clear why the same species behaves differently in one river versus another, but the data from the upper Colorado River suggest that squawfish spawning is less site-specific than previously thought and that a wide range of conditions may exist on spawning bars [Stanford, 1994]. Similar comments apply to backwaters and other low-velocity habitats that adult squawfish use for shelter and feeding. The characteristics and abundance of these habitats vary widely from reach to reach, as does the frequency with which Colorado squawfish use them [Osmundson et al., 1997].

In this paper we develop criteria for flows that will maintain or improve habitats used by Colorado squawfish. Given the wide range in habitat characteristics, we believe that the processes of habitat formation and maintenance in the upper Colorado River are best studied using a broad-based geomorphic approach. Accordingly, we formulated three objectives for this study. Our first objective was to determine what flows are required to mobilize gravel on a widespread basis and to keep fine sediment (silt and fine sand) from accumulating in the bed. Fine sediment has probably always been a major constituent of the total sediment load of the upper Colorado River, but there are certain times, for example, in low-flow years or after the peak in the annual snowmelt hydrograph, when silt and sand tend to build up on the bed. Fine sediment can degrade the quality of spawning bars and fill the interstices in the bed where aquatic organisms live. It has been shown in many studies that fine sediment cannot be winnowed (or flushed) from appreciable depths within the bed unless the framework particles themselves are moved [Diplas, 1994; Kondolf and Wilcock, 1996]; thus periodic movement of gravel is required to remove infiltrated fine sediment.

A second and closely related objective was to determine what flows carry the majority of the sediment load. If no further habitat is to be lost, the main channel and associated side channels must be maintained in their present condition. To do
this, all of the sediment supplied to the reach must be transported out of the reach; any sediment that is not transported through will be stored somewhere. The most likely sites of storage are low-velocity side channels and near-bank areas where adult squawfish are often found [Van Steeter and Pitlick, this issue]. Thus we consider whether there exists an optimum flow or range of flows that transports the majority of the annual sediment load and thereby minimizes deposition in side channels.

Our third and final objective was to evaluate the potential for creating new habitat. We approached this problem by studying recent channel changes and the existing characteristics of the river, especially the bank-full hydraulic geometry. Gravel-bed rivers form their channels as a result of bed load transport and bank erosion [Hickin and Nanson, 1984], and the theory developed by Parker [1979] is useful in connecting these two processes. Parker [1979] reasoned that a gravel-bed river will adjust its width and depth to a discharge that produces an average boundary shear stress \( \tau \) about 20% higher than the critical shear stress \( \tau_c \). At discharges much higher than this, particles on the banks will begin to move and the banks will erode, causing the channel to widen. If channel widening continues, however, the depth and shear stress will decrease until, eventually, particles in the near-bank region stop moving, and the banks stabilize. Parker [1979] developed this theory for straight channels with uniform depth. We might expect sinuous rivers with irregular bed topography and vegetated banks to widen at perhaps higher shear stresses [cf. Andrews, 1984], but whatever the specific value, a criterion of this type is useful for estimating a threshold for channel widening, and the creation of bars and additional new habitat.

2. Study Area and Methods
2.1. Reach Characteristics

The study area encompasses 90 km of the Colorado River in western Colorado and eastern Utah (Figure 1). This segment of the river provides important habitat for the endangered Colorado squawfish (\textit{Ptychocheilus lucius}) and razorback sucker (\textit{Xyrauchen texanus}) and marks the upstream limit of their range in the main stem of the Colorado River. The study area is further subdivided into three contiguous reaches: the 15-mile reach (as it is referred to) extends from Palisade, Colorado, to the confluence with the Gunnison River in Grand Junction; the 18-mile reach (as it is referred to) extends from the Gunnison River to Ruby-Horsethief Canyon near Loma, Colorado; and the Ruby-Horsethief Canyon reach extends from Loma to Westwater, Utah (Figure 1). The drainage area at the upper end of the study area is about 22,700 km\(^2\), and the drainage area at the lower end of the study area is about 46,200 km\(^2\).

The 15- and 18-mile reaches are mostly alluvial, although in many places one bank is formed by either bedrock or artificial revetments. The channel pattern alternates between single-thread and multithread, suggesting that the river is geomorphically active and perhaps near a threshold for braiding. The habitat diversity associated with this channel pattern may explain why Colorado squawfish tend to congregate here. The Ruby-Horsethief Canyon reach is more incised and single-thread, but a discontinuous floodplain is present along one or both banks, so the river is free to adjust almost everywhere. The river is gravel bed throughout all three reaches. The banks and adjacent floodplain are composed of silt and fine sand covered with dense thickets of the nonnative tamarisk (\textit{Tamarix chinensis}) and russian olive (\textit{Elaeagnus angustifolia}) and the native sandbar willow (\textit{Salix exigua}) and cottonwood (\textit{Populus deltoides}).

The annual hydrograph of the upper Colorado River is dominated by spring snowmelt that usually peaks in late May or early June. The natural flow regime is affected by storage in upstream reservoirs and irrigation withdrawals [Van Steeter and Pitlick, this issue]. The U.S. Geological Survey (USGS) operates several streamflow gauging stations in the study area. A gauge located about 20 km upstream from the study area near Cameo (9095500, Figure 1) has been in operation since 1934, a gauge at the upstream end of the study area near Palisade (9106150, Figure 1) has been in operation since 1991, and a gauge at the downstream end of the study area near the

![Figure 1](image-url). Map of the Grand Valley area showing the locations of gauging stations and specific study reaches.
Colorado-Utah state line (9163500, Figure 1) has been in operation since 1951.

2.2. Field Studies

Field studies were conducted from 1993 through 1995 to monitor geomorphic changes in side channels and backwaters, to determine the average characteristics of the main channel (width, depth, slope, and grain size), and to develop flow and sediment transport models. Prior to the start of the 1993 snowmelt runoff, we selected three side channel–backwater sites for detailed study; these sites are typical of the habitats used by Colorado squawfish [Stanford, 1994; Osmundson et al., 1995]. Figure 2 shows a site in the 18-mile reach that is formed by a permanent island. This side channel conveys water at moderate to high flow but becomes a backwater at low flow. The other sites differ from this one mostly in terms of the amount of time that water flows through the side channel, as opposed to backing up from the main channel; one is a through-flowing side channel above moderate discharge, and the other is a backwater at all but the highest flows. At each site a series of cross sections were surveyed around the head and mouth of the side channel. These areas control flow and sediment transport through the side channel and thus determine whether deposits accumulate at the mouth of the side channel and limit access for the fish.

The general characteristics of the main channel were determined by surveying 58 cross sections at 1.6-km intervals from Palisade, Colorado, to Westwater, Utah (Figure 1). These cross sections constitute, in effect, a random sample of the hydraulic geometry of the channel. These data are important if we are to specify conditions under which the main channel is formed and maintained. The main channel cross sections were surveyed with an electronic theodolite (total station) and a motorized raft equipped with a reflecting prism and depth sounder. The bank-full width $b_h$ and depth $h_b$ at each cross section were identified in the field by what was usually a clear break in slope between the channel and the floodplain. We resurveyed 12 of these cross sections (every fifth one) in September 1995 after a period of high flows.

Reach-average slopes through the 15- and 18-mile reaches were determined from 1:24,000 topographic maps with a 10-foot (3-m) contour interval. The average slope of the Ruby-Horsethief Canyon reach was measured with a global positioning system (GPS) capable of resolving elevations to less than 1.0 m with differential post processing. We found that slopes determined with the GPS did not differ appreciably from slopes measured off topographic maps.

Samples of the surface bed material (pavement) were taken from 18 gravel bars, spaced about 5 km apart. Bar surfaces were sampled at low flow using a point count of 200 particles. Bulk samples of the subsurface sediment (subpavement) were taken at eight locations (about every 10 km). These samples were taken by excavating about 100 kg of sediment from beneath the pavement layer, sieving the coarse fraction (>32 mm) in the field, and the fine (<32 mm) fraction in the laboratory. We did not find large variations in the size distribution of the bed material. Most of the pavement samples have a median grain size $D_{50}$ between 40 and 60 mm, and most of the subpavement samples have a $D_{50}$ between 25 and 40 mm (Figure 3). The ratio of pavement $D_{50}$ to subpavement $D_{50}$ is about 2, which is typical for gravel rivers with mobile beds [Lisle, 1995].

In addition to these reach-scale measurements, we selected seven additional sites where we made more detailed measurements to model the relation between discharge and average boundary shear stress. The locations of these sites are shown in Figure 1, and their average characteristics are summarized in Table 1. The sites are all in single-thread reaches about 0.5 km long. At each site we surveyed six to eight cross sections spaced about one channel width apart. Figure 4 shows detailed views of two of these study sites and selected cross sections of the channel.

The key problem in estimating thresholds for sediment transport and channel change is to develop appropriate measures of the boundary shear stress $\tau$ and the critical shear stress $\tau_c$. The average boundary shear stress is given by

$$\tau = \rho \ g \ h \ S_f$$

where $\rho$ is the density of water, $g$ is the gravitational acceleration, $h$ is the flow depth, and $S_f$ is the friction slope or streamwise energy gradient. We used a series of observations over a range of discharges to calibrate a one-dimensional hydraulic model for each of the seven study reaches. The model finds $S_f$ from a step-wise solution to the momentum equation:
where \( u \) is the mean velocity, \( S_o \) is the channel bed slope, and \( x \) is the downstream direction [Henderson, 1966; Dingman, 1984]. The model results allow us to evaluate the boundary shear stress and roughness (Manning’s \( n \)) for a range of discharges.

In the absence of direct observations of particle entrainment (from tracer gravels or bed load samples), the only practical means for estimating \( \tau_c \) is to use the Shields criterion:

\[
\tau_c^* = \frac{\tau_c}{(\rho_s - \rho) g D}
\]

where \( \tau_c^* \) is the critical dimensionless shear stress (or Shields stress), \( \rho_s \) is the density of sediment, and \( D \) is the particle diameter. In the last decade there has been much discussion over appropriate values of \( \tau_c^* \) and the reasons for its variation. It is now well established that \( \tau_c^* \) varies inversely with the ratio of the individual grain size \( D_i \) to the median grain size \( D_{50} \). (see review by Gomez [1995]). However, specific forms of the relation between \( \tau_c^* \) and \( D_i/D_{50} \) appear to vary from river to river, as does the criterion for incipient motion, defined for each grain size by a minimum value of \( \tau_c^* \). Parker et al. [1982] suggested that an appropriate minimum value for incipient motion of the \( D_{50} \) of the surface sediment is \( \tau_c^*_{50} = 0.03 \). We have some evidence that the bed material of the Colorado River begins to move near this value, but we emphasize that at \( \tau_c^*_{50} = 0.03 \), very few particles of any size are moving and bed material transport rates are very low. This condition is sometimes referred to as one of “marginal transport” [Andrews, 1994]. A second and higher transport stage, termed “significant motion” [Andrews, 1994], is characterized by continuous movement of particles and much higher transport rates. In terms of a Shields stress, this stage is not as well defined, but data presented by Wilcock and Southard [1989] and Pitlick [1992] suggest that significant motion occurs in the range \( 0.045 < \tau_{50}^* < 0.06 \). At stages much higher than this (say, \( \tau_{50}^* > 0.09 \)), transport is so vigorous that gravel bed forms begin to develop.

Finally, we used existing discharge-duration data and sediment-transport relations to determine the effective discharge, defined here as the discharge, or range of discharges, that transports the greatest portion of the annual sediment load [Wolman and Miller, 1960]. The effective discharge was determined by dividing the series of daily discharges at the Cameo and state line gauging stations into 34 separate discharge classes, calculating the total load (suspended plus bed load) for each discharge, and multiplying the total load by the frequency of flows in each class. Suspended sediment loads were calculated using rating curves of sediment concentration and discharge developed with USGS data from the Cameo and state line gauging stations. Bed load transport rates were calculated using the modeled discharge-shear stress relations described above, and the empirical bed load function of Parker et al. [1982]. Parker et al.’s bed load function is

\[
W^* = 0.0025 \exp \left[ 14.2(\phi_{50} - 1) - 9.28(\phi_{50} - 1)^2 \right] \quad (4a)
\]

\[
0.95 < \phi_{50} < 1.65
\]

\[
W^* = 11.2 \left( 1 - \frac{0.822}{\phi_{50}} \right)^{4.5} \quad (4b)
\]

\[
\phi_{50} > 1.65
\]

where

\[
W^* = \frac{q_b (\rho_s/\rho - 1)}{\sqrt{g (h S)^{1/2}}}
\]

and

\[
\phi_{50} = \frac{\tau_{50}^*}{\tau_c^*}
\]

In the last two equations, \( q_b \) is the volumetric bed load transport rate and \( \phi \) is the transport stage; \( \phi \) is further defined in terms of a reference Shields stress \( \tau_c^* \) that produces a small

![Figure 3. Grain size distributions of surface and subsurface sediment samples from the upper Colorado River. Samples were taken throughout the study area.](image-url)
Figure 4. Detailed maps showing study reaches at the (a) Palisade and (b) state line gauging stations plus selected channel cross sections at each site. The dashed lines on the cross sections indicate bank-full flow.
transport rate of a particular size, in this case the $D_{50}$. Conceptually, $\tau^*_{r}$ is very similar to $\tau^*_{t}$. Parker et al. [1982] suggested $\tau^*_{r} = 0.086$, but this value was with reference to the $D_{50}$ of the subsurface sediment, which is typically much less than the $D_{50}$ of the surface sediment. To account for this difference, and the difference between $\tau^*_{r}$ and $\tau^*_{c}$ (typically about 20%), we adjusted the value of $\tau^*_{r}$ down to 0.033 [see Parker and Klingeman, 1982; Andrews, 1994]. This adjustment gives a relation consistent with the earlier assumption about the minimum critical Shields stress for the $D_{50}$.

3. Results

3.1. Geomorphic Response to Recent Flow Events

Hydrographs of snowmelt runoff from 1993 to 1995 show that recent flows of the upper Colorado River have ranged from below average to above average (Figure 5). In 1993 the volume of runoff was above average, and peak discharges were the highest since 1984. The peak discharge at the Cameo gauge in 1993 was 660 m$^3$/s, with a return period of 3.5 years; the peak discharge at the state line gauge was 1255 m$^3$/s, with a return period of 6.6 years. In 1993 the mean annual flood ($Q_{maf}$) was exceeded for 11 days at the Cameo gauge and for 21 days at the state line gauge (in these reaches the $Q_{maf}$ is about 75% of the bank-full discharge). In 1994 the volume of runoff was below average, as were peak discharges (Figure 5). The peak discharge at the Cameo gauge in 1994 was 357 m$^3$/s, with a return period of 1.2 years; the peak discharge at the state line gauge was 385 m$^3$/s, also with a return period of 1.2 years. In 1995 the volume of runoff and peak discharges were again above average (Figure 5). The peak discharge at the Cameo gauge in 1995 was 838 m$^3$/s, with a return period of 9 years; the peak discharge at the state line gauge was 1396 m$^3$/s, also with a return period of 9 years. In 1995 the $Q_{maf}$ was exceeded for 28 days at the Cameo gauge and for 45 days at the state line gauge. In the period prior to reservoir construction (1934–1949) the $Q_{maf}$ was exceeded, on average, about 10 days per year at the Cameo gauge. The study period was thus one of above-average runoff, not only in comparison to the previous 8 years but also in comparison to earlier periods when flows were less regulated.

Geomorphic changes observed along the main channel during the study period were not particularly striking given this sequence of flow events. Measurements of 12 main channel cross sections prior to and after the period of very high runoff in 1995 show that localized scour and fill occurred at some sections (Figure 6), but that little change occurred at most sections. Data presented by Osmundson et al. [1995] suggest that the river was more active in some places, and there was
clear evidence that bar surfaces had been extensively re-worked, but sites of widespread bank erosion or scour and fill were not apparent in our surveys.

We observed more noticeable geomorphic changes at our backwater and side channel study sites, particularly at the mouths of the backwaters. Figure 7 shows a series of measurements of cross sections across the mouths of each of the backwaters. In most cases, fine sediment present in April 1993 was scoured from the mouths of the backwaters, and they were enlarged. The pattern of scour was not consistent, however, making it difficult to generalize on the basis of these few observations. The mouth of the backwater near river mile (RM) 160 scoured 0.5 m in the first year, but not much thereafter (Figure 7a); the mouth of the backwater near RM 162 changed little in the first 2 years, then scoured 1.0 m in 1995 (Figure 7b); and the mouth of the backwater near RM 176 scoured some every year, eventually eroding by 2.5 m (Figure 7c). Two other backwaters monitored by the U.S. Fish and Wildlife Service (USFWS) scoured by similar amounts in 1993 [Osmundson et al., 1995]. The changes observed during
these 3 years support the view that high flows are necessary for keeping backwaters open, but the effects clearly vary from site to site.

In the previous paper [Van Steeter and Pitlick, this issue], we showed that about 1/4 of the side channel and backwater habitat in the upper Colorado River has been lost since the late 1930s. We associated these losses with decreases in sediment load that occurred during periods of below-average discharge. The above results, on the other hand, indicate that higher-than-average discharges cannot completely reverse the trend of channel simplification, especially if vegetation becomes established and has a chance to mature. Certain types of vegetation, such as tamarisk and willow, are very hearty and difficult to remove. Referring back to the photograph of our side-channel study site (Figure 2), note the thicket of mature tamarisk in the center of the island, the low-lying vegetation (willow) covering the area around the head of the side channel, and the line of dark vegetation (sedges) growing on the sediment exposed along the edge of the side channel. The willow at the head of the side channel has been inundated for many years.

Figure 7. Sequence of cross-section measurements showing varying amounts of scour at the mouths of side channels near (a) RM 160, (b) RM 162, and (c) RM 176.
weeks over the period of our study, yet there has been little change in the density and condition of these plants. Our observations here and elsewhere suggest that vegetation has a pronounced effect on the stability of the channel, and it will be difficult to create significant amounts of additional habitat by simply manipulating the hydrograph to produce higher discharges. This is not to say that higher discharges do not serve other important geomorphic or ecologic purposes. As we show in the next sections, higher discharges are critical for maintaining the quality of existing habitats and for preventing further losses in habitat by carrying the sediment through the reach.

3.2. Development of Discharge-Shear Stress Relations

The reaches used to model the relations between discharge $Q$ and average boundary shear stress $\tau_*$ typically encompass one riffle-pool-run sequence. Runs are generally long in comparison to riffles and pools; thus changes in the reach-average hydraulic conditions are dominated by what occurs in the runs. At low $Q$ the water-surface slope through a run is usually less than the reach-average slope, whereas over a riffle, the local slope may be very steep, differing from the reach-average slope by a factor of 10 or more. As $Q$ increases there is a tendency at most of our sites for the slope to increase over runs and decrease over riffles such that the water-surface profile becomes smoother and steeper (Figure 8a). The one exception to this is the site at the state line gauge (RM 134), where a downstream riffle and bend cause the water surface slope to decrease over riffles such that the water-surface profile becomes smoother and steeper (Figure 8b). However, the decrease in slope is not so large that it offsets the increase in depth, so $\tau_*$ still increases with $Q$. Overall, our calculated energy slopes do not diverge much from the measured or calculated water-surface slopes. This indicates that the local boundary shear stress is dominated by the pressure-gradient force (represented by the third term on the right-hand side of (2)) and that the effects of convective acceleration (second term, right-hand side of (2)) are of lesser importance.

Combining the continuity equation and a flow resistance equation and by assuming uniform flow, it is easy to show that $\tau \propto Q^a$, with $a < 1$ [Ferguson, 1994]. The result is a concave-down relation between $Q$ and $\tau$. However, if the slope increases significantly with discharge, or the roughness decreases, the relation between $Q$ and $\tau$ (or $\tau^*$) will be more linear ($a \to 1$), or perhaps even concave-up ($a > 1$). Given that runs are the predominant morphologic unit in the upper Colorado River and that there is a tendency for the water-surface slope to increase through runs, our modeled relations between $Q$ and $\tau^*$ are for the most part linear (Figure 9). We emphasize this point because it indicates that $\tau^*$ increases roughly in proportion to $Q$ across a wide range of discharges. This is very important with respect to sediment loads because typically, sediment transport rates increase as a power function of $\tau^*$, which means that higher discharges will carry a much larger proportion of the total sediment load.

Table 2 lists for each site the discharges that produce reach-averaged values of $\tau^* = 0.030$ and $\tau^* = 0.047$, and the percentage of time that these flows are equaled or exceeded. Although there is about a 30% range in the discharge required to produce given values of $\tau^*$ within reaches upstream and downstream of the Gunnison River, the duration of these flows is consistent through all reaches. Discharges corresponding to $\tau^* = 0.030$ are exceeded about 7% of the time, or 26 days per year on average (Table 2). An equivalent instantaneous peak discharge occurs in about 2 out of every 3 years [Van Steeter, 1996]. Our cross-section measurements indicate that this flow is about 1/2 of the average bank-full discharge and about 2/3 of the average bank-full depth. Discharges corresponding to $\tau^* = 0.047$ are exceeded about 2% of the time, or 8 days per year on average (Table 2). This discharge coincides with the bank-full level (see below). An equivalent instantaneous peak discharge occurs about once every 4 to 6 years [Van Steeter, 1996].

We have good field evidence that the threshold for bed material transport in the Colorado River is near $\tau^* = 0.030$. In 1993 and 1995, reach-averaged values of $\tau^*$ exceeded 0.040 in many places, and it was clear from looking at exposed gravel bars that much of the bed material moved. In 1994, a low flow year, reach-averaged values of $\tau^*$ ranged from 0.020 to 0.027,

![Figure 8. Water-surface profiles at two step-backwater study sites. Lines indicate modeled energy and water-surface profiles, and symbols indicate observed water-surface elevations.](image-url)
and it was clear that little if any of the bed material moved. However, in May 1996, while floating through the Ruby-Horsethief Canyon reach, we repeatedly heard the pinging sound of bed load moving over riffles. The discharge at the state line gauge at that time was 600 m$^3$/s. At this discharge the predicted reach-averaged values of $\tau^*$ at our two study sites in Ruby-Horsethief Canyon (RM 139 and RM 134) are 0.030 and 0.033, respectively.

### 3.3. Downstream Hydraulic Geometry

Figure 10 summarizes downstream trends in the bank-full width, $b_h$; depth, $h_b$; and dimensionless shear stress, $\tau^*_b$, of the main channel. The values of $b_h$ and $h_b$ are based on field measurements at individual cross sections; the values of $\tau^*_b$ are calculated using (3), with reach-averaged estimates of $S$ and $D_{50}$, and cross section values of $h_b$. Figure 10a shows that there is no significant downstream trend in $b_h$. Apparently, the supply of water and sediment from the Gunnison River at RM 170 has little effect on the bank-full width of the Colorado River. Figure 10b, on the other hand, shows that $h_b$ increases downstream, from an average of 2.5 m in the 15-mile reach to 3.5 m in the Ruby-Horsethief Canyon reach. Part of the increase in $h_b$ is due to the effects of the Gunnison River, but the trend in $h_b$ is more systematic than step-like. We do not have a clear explanation for this, other than to suggest that it may take many kilometers for some rivers to adjust morphologically to tributary inputs. The third plot in this series (Figure 10c) shows that $\tau^*_b$ maintains a consistent value of 0.047 through all three reaches. The consistency in $\tau^*_b$ results from the combined effects of the downstream increase in $h_b$ and the downstream decrease in $S$ and $D_{50}$ (Table 1).

Figure 10c is particularly significant because it shows that the bank-full hydraulic geometry of the upper Colorado River is related in a consistent and physically meaningful way to a gravel transport threshold, that is, that the bank-full width and depth of the river are adjusted to a discharge that produces an average boundary shear stress $\approx 1.5$ times the critical shear stress. We interpret this result to mean that the channel of the upper Colorado River is more or less in equilibrium with the present flow and sediment transport regime, altered as it is.
The width, depth, and slope are adjusted to maintain sediment transport capacity through all three reaches, as indicated by the uniform values of $b_s$ and $\tau^*$$_b$. Furthermore, the reach-average value of $\tau^*$$_b$ = 0.047 defines a threshold for bank erosion and channel widening, which is essential if new bars and additional habitat are to be created. We emphasize, however, that this is a minimum value, and discharges that reach this level will probably not cause widespread bank erosion. Indeed, snowmelt flows in 1993 and 1995 were higher than bank-full for several weeks, yet bank erosion was relatively localized. It appears that much higher discharges, such as those that occurred in 1983 and 1984, are needed to initiate widespread changes in channel morphology. We modeled the peak discharge of the 1984 flood to match the observed gauge height at the state line gauge and found that this flow produced a $\tau^*$ of 0.06–0.07, depending on the assumptions used in the model. We do not know whether this site experienced much bank erosion in 1984, but it was clear that bank erosion was significant in many of the reaches near Grand Junction during the 1983 and 1984 floods.

3.4. Calculation of Effective Discharge

Given the importance of both fine and coarse sediment, we made separate estimates of the discharges that are most effective for transporting the suspended load, $Q_s$, and those that are most effective for transporting the bed load, $Q_b$. Figure 11 shows the results of this analysis for the Palisade and state line gauges (RM 184 and 134, respectively). The vertical bars in Figure 11 show the frequency distribution of daily discharges, and the lines indicate separate magnitude-frequency relations for bed load, suspended load, and total load. The abscissa is scaled in logarithmic units to emphasize the skewed bimodal shape of the flow frequency distribution; the left mode corresponds to fall and winter base flows, whereas the right mode corresponds to spring and summer snowmelt flows. When plotted this way it is clear that base flows occur a much higher percentage of the time than snowmelt flows but that the latter carry a much higher proportion of the annual sediment load, $Q_l$ (Figure 11). These plots also show that the suspended load $Q_s$ far outweighs the bed load $Q_b$. We are confident that this is not a result of using an empirical equation to calculate $Q_b$ because the calculated unit bed load transport rates (3–4 kg/m/s at the highest discharge) are very reasonable in compari-

![Figure 10](image)

**Figure 10.** Downstream trends in (a) bank-full width, (b) bank-full depth, and (c) bank-full dimensionless shear stress of the upper Colorado River. Dashed lines indicate the mean values for the entire reach. The confluence with the Gunnison River is at RM 170.

![Figure 11](image)

**Figure 11.** Results of the magnitude-frequency analysis at the Palisade and state line gauging stations (RM 184 and 134). The vertical bars show the frequency distribution of daily discharges. The separate dashed and solid lines show magnitude-frequency relations for suspended load, $Q_s$, bed load, $Q_b$, and total load, $Q_l$. 
son to rates that have been measured in other active gravel-bed rivers [Reid and Laronne, 1995; Pitlick, 1992]. At both sites there are two peaks in the magnitude-frequency relation (Figure 11). As far as we know, there is nothing physically meaningful about the two peaks, and they exist primarily because of particular combinations of flow frequency and sediment transport rate. At the Palisade gauge (RM 184) the peaks in the magnitude-frequency relation occur at discharges of 500 and 650 m$^3$/s (Figure 11). Daily discharges in this range occur about 2% of the time (an average of 7 days per year) and transport approximately 30% of the annual load. At the state line gauge (RM 134), the peaks in the magnitude-frequency relation occur at discharges of 700 and 1000 m$^3$/s (Figure 11). Discharges in this range occur 2.5% of the time (an average of 9 days per year), and transport 30% of the annual load, the same as at the Palisade gauge. At both sites, more than 80% of the average annual sediment load is carried by the highest 10% of all flows. The relative efficiency of higher flows is illustrated well by water years 1993 and 1995, which were both above average. Using data from the state line gauge, we estimate that the Colorado River carried 40% more sediment in 1993 and 1995 than it carried in the previous 8 years (1985–1992). In this sense the upper Colorado River acts more like a much smaller upland stream than a large lowland river (see compilations by Ashmore and Day [1988] and Nash [1994], which show that the duration of the effective discharge increases with drainage area; data presented by these authors suggest that for rivers with drainage areas greater than 10$^4$ km$^2$, the effective discharge is exceeded about 10% of the time).

In some previous studies it has been shown that the effective discharge bears a close relation to the bank-full discharge [Wolman and Miller, 1960; Andrews, 1980], whereas in other studies this does not appear to be the case [Pickup and Warner, 1976; Nolan et al., 1987]. Our results may shed some light on this question if we consider the magnitude-frequency relations for $Q_e$ and $Q_b$ separately. The relations in Figure 11 indicate that the effective discharge for $Q_e$ is in the range of intermediate flows (500 to 650 m$^3$/s in the 15-mile reach and 700 to 1000 m$^3$/s in the 18-mile and Ruby-Horseshief Canyon reaches). These flows are somewhat less than the bank-full discharge. If we consider only the relations for $Q_b$, a slightly different result emerges. At the Palisade gauge, the peak in the magnitude-frequency relation for $Q_b$ occurs at a discharge of 650 m$^3$/s, and at the state line gauge the peak in the $Q_b$ relation occurs at a discharge of 1150 m$^3$/s. These discharges correspond very nearly to the average bank-full discharge and the discharge that produces reach-averaged values of $\tau^* = 0.047$. Perhaps it is coincidental that the two discharges correspond, but we reason that they should be similar: the effective discharge for bed load has to be greater than the flow that produces an average $\tau^* = 0.030$ because below this, no transport occurs. Conversely, the effective discharge should not be greater than the bank-full discharge because according to the arguments presented above, the channel should widen at flows that produce a bank-full $\tau^* > 0.047$. Thus, even if the value of the effective discharge is determined empirically, we believe that in most gravel-bed rivers it should be near the bank-full discharge.

The results of the magnitude-frequency analysis have important implications with respect to channel maintenance. If the upper Colorado River is to be maintained in its present condition, then all of the sediment supplied to the reach must be carried through the reach. The effective discharge relations presented above show how the river accomplishes this task under the present hydrologic regime. Another way to approach this problem, however, is to consider using reservoir releases to manipulate the hydrograph and optimize sediment transport for a given set of flow conditions. To illustrate what this might achieve, we considered two scenarios: (1) maintain the same annual discharge, meaning no further depletions of water, but change reservoir operating procedures to augment flows on the rising limb of the hydrograph; and (2) allow for a 5% depletion in the total volume of water but again augment flows on the rising limb of the hydrograph. We focus on the rising limb of the hydrograph because this is when tributaries in the lower part of the basin are delivering sediment to the main stem. Theoretically, rising-limb flows could be augmented by releasing less water in the winter and allowing more water to bypass the reservoirs in the spring.

Figure 12 shows that by augmenting snowmelt discharges in the moderate to high range (300–800 m$^3$/s), the annual suspended sediment load of the Colorado River near Cameo could be increased by 15% without any net loss of water. The benefits of augmenting higher flows (>800 m$^3$/s) are even greater, but this opportunity is not likely to present itself often. In addition, the risks associated with adding to discharges that are already high may make this option unfeasible. The greater efficiency of moderate to high discharges is a consequence of the nonlinear relation between discharge and sediment load: A given increment of discharge will have a much greater effect on sediment loads at higher discharges than at lower discharges. Because of this nonlinear effect, it is possible to manipulate the hydrograph in ways that increase annual sediment loads yet allow for water depletions. Figure 12 shows that the total sediment load can be increased by 10%, even with a 5% depletion, provided that additional water is delivered near the hydrograph peak.

Figure 12. Effective discharge relations for the Colorado River near Cameo under different flow augmentation scenarios. Each scenario uses the existing sediment concentration-discharge relation for discharges that occur prior to the peak of snowmelt [see Van Steeter and Pitlick, this issue] and (a) the existing prepeak flow duration curve; (b) a modified flow duration curve with an increased number of days with moderate to high flow (300–800 m$^3$/s), reduced number of days with moderately low flow, and no net change in annual runoff; and (c) a modified flow duration curve, similar to Figure 12b but with 5% depletion in annual runoff.
4. Discussion

The results of this study indicate that fish habitats in the upper Colorado River are maintained by flows ranging from about half bank-full up to the bank-full discharge. Flows in the lower end of this range initiate gravel transport on a widespread basis and are therefore important for flushing fine sediment from the bed. Flows in the upper end of this range carry the majority of the annual sediment load and erode fine sediment from side channels and are therefore important for maintaining existing backwater habitats. In addition, it appears that these higher discharges define a lower limit for the onset of bank erosion and the formation of bars and side channels that might serve as new habitat.

Although our results are broadly consistent along a 90-km reach of the upper Colorado River, they define general, rather than site-specific, criteria for maintaining fish habitat. We have proposed discharges that are likely to achieve a certain purpose on a widespread basis, and perhaps not on smaller scales. Studies of spawning bars on the Yampa River, for example, indicate that locally high shear stresses in small chute channels can maintain gravel transport and keep fine sediment from accumulating on the bed long after the peak in snowmelt runoff [Harvey et al., 1994]. The results of the Yampa River study imply that moderate to high flows may not be necessary for maintaining spawning-bar habitats, contrary to what we have suggested. However, since no one knows specifically where squawfish spawn in the upper Colorado River (spawning has been observed at several sites, but not repeatedly), it seems most reasonable at this point to recommend discharges that will affect the largest amount of potential spawning habitat as well as habitats used by native forage fish, macroinvertebrates, and other members of the food chain.

We showed that it may be possible to allow future depletions to the annual hydrograph of the upper Colorado River and still carry the same sediment load, provided that flows on the rising limb of the snowmelt hydrograph can be augmented by reservoir releases. Although this idea is compelling, there are several practical limitations to consider before reservoirs releases can be attempted. First, the upper Colorado River is not controlled by a single large dam like the reaches further downstream, for example, in Grand Canyon. Flow in the upper Colorado River is controlled by a series of relatively small reservoirs, most of which are far upstream from the critical reaches. Individually, these reservoirs have neither the storage capacity nor the ability to bypass water in the way that this was done in Grand Canyon in 1996. Added to this, the reservoirs in the upper Colorado River basin are managed through complex agreements between federal and state agencies and water conservancies. Thus it will require a coordinated effort among different reservoir operators to generate significantly higher flows in the upper Colorado River. Given these limitations it may not be realistic to consider reservoir releases in some years. In a relatively dry year, for example, it may not be possible to release enough water to reach the gravel transport threshold, and it would clearly be a waste of water to attempt this. However, in a near-average year, it may be possible to augment snowmelt discharges such that this threshold is exceeded. A goal of future work is to examine these options in more detail and refine flow recommendations for the 15- and 18-mile reaches as necessary.

A second limitation to consider regarding the potential merits of reservoir releases is that the upper Colorado River has a gravel-cobble bed, and large-scale changes in the geomorphology of the river generally come about only as a result of significant bed load transport. Most gravel-bed rivers, including the upper Colorado River, do not reach high bed load transport stages ($\tau \gg 3\tau_c$) except during very large floods. It is unlikely that reservoir releases could produce these conditions in the upper Colorado River. The potential may exist for generating flows that produce moderately high shear stresses ($\tau = 1.5\tau_c$), which would help maintain spawning-bar and backwater habitats, but it is unlikely that flows in this range would create significant amounts of new habitat. This contrasts with conditions in Grand Canyon, where there was an abundant supply of sand on the river bed prior to the experimental flood in 1996 [Andrews, 1991; Collier et al., 1996]. This flood was high enough to put a large amount of sand into suspension, and transport it rapidly toward the channel margin; within a few days, extensive new beaches and potential habitat had been formed [Andrews et al., 1996]. We emphasize the differences in the hydrology and sedimentology of the upper and lower Colorado River because there will undoubtedly continue to be pressure on dam operators to release flows to restore the ecological functions of this river, but it cannot be assumed that similar methods, applied over short timescales, will produce equivalent benefits on different reaches.

5. Summary and Conclusions

Alluvial reaches of the Colorado River near Grand Junction, Colorado, appear to be very important for the endangered Colorado squawfish. There is clear evidence that the fish continue to spawn in these reaches, and that spawning sites are widely distributed throughout the area [Mcada and Kaeding, 1991]. Side-channel and backwater habitats are also found throughout the 15- and 18-mile reaches. Until specific key habitats are identified and studied in more detail, instream flow recommendations for these reaches should be based on general criteria; that is, the recommended discharges should achieve the desired effects on a widespread basis.

Above-average snowmelt discharges in 1993 and 1995 caused widespread bed material transport in the upper Colorado River. Gravel bars were reworked nearly everywhere, and much fine sediment was flushed from the bed. However, flows of this magnitude cannot be expected to occur very often, nor is it likely that reservoirs could generate discharges this high unless runoff was already above average. Modeled relations between discharge and shear stress presented here indicate that gravel begins to move at discharges of 225–320 m$^3$/s in the 15-mile reach, and 440–620 m$^3$/s in the 18-mile and Ruby-Horsethief Canyon reaches. These discharges are exceeded about 26 days per year under the present hydrologic regime.

The bank-full hydraulic geometry of the upper Colorado River is very consistent throughout our study reaches. Our data indicate that the width and depth of the upper Colorado River are set by a flow that produces an average boundary shear stress about 1.5 times the critical shear stress. The fact that the hydraulic geometry is related in a consistent and physically meaningful way to a gravel transport threshold suggests that prescribed discharges are likely to achieve the same results in many places.

Our observations of side-channel and backwater habitats indicate that appreciable amounts of fine sediment were removed from the mouths of backwaters by high flows in 1993 and 1995. It is not clear that the observed changes represent
significant improvements in habitat quality, but the data presented in the accompanying paper [Van Steeter and Pitlick, this issue] suggest that without higher flows there is a tendency for side channels to fill in. It is also clear that if no additional habitat is to be lost, then all of the sediment must be carried through these reaches. We have shown that moderate to high discharges are most effective for doing this. Under the present hydrologic regime, 80% of the sediment load is carried by the highest 10% of all discharges.

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