96

Difficulties of Identifying Design Discharges in Steep, Coarse-Grained Channels in the Arid Southwestern US.

Michael D. Harvey[1] and Robert A. Mussetter[2]
[1,2] Mussetter Engineering, Inc., 1730 S. College Avenue, Suite 100, Fort Collins, CO: PH (970) 224-4612; FAX (970) 472-6062; email: mikeh@mussei.com; bobm@mussei.com

Abstract

A study of three locations in a 16-km reach of the lower Verde River in Arizona demonstrates the problem of identifying generalized design flows in the arid and semi-arid regions of the southwestern US, where flow regimes are highly variable and often non-continuous, where coarse bed material is supplied locally by steep ephemeral–flow tributaries, and where channel morphologies are forced by large, infrequent floods, canyon walls, tributary fans and alluvial terraces. At the three sites, channel slopes vary from 0.0027 to 0.0041, and the median size of the surface bed materials ranges from 81 to 145 mm. Hydraulic analysis (HEC-RAS) showed that, depending on the definition used, the bankfull discharge at the three sites ranges from 450 to 1,900 cms (1.7- to 8-yr RI), the critical discharge ($\phi' = 1$) for bed-material mobilization ranges from 398 to 811 cms (1.6- to 3.8-yr RI), and significant sediment transport ($\phi' > 1.5$) occurs at flows between 989 and 1,740 cms (4- to 8-yr RI). At any given flow above the critical discharge at one location, bed material can be immobile, in transport, or being deposited at any of the other two locations. Selection of flows for engineering design or restoration purposes in rivers with similar conditions is, therefore, highly constrained by local conditions, and site-specific geomorphic, hydraulic and sediment-transport analyses are required rather than generalized relations based on assumed relations between bankfull discharge, flood frequency, and effective discharge.

Introduction

In low gradient, alluvial streams in humid climates, where the bankfull discharge has a recurrence interval of approximately 1.5 to 2 years, there is a reasonable basis for relating the bankfull discharge to the channel forming, or dominant discharge, that can then be used for engineering design or restoration purposes (Wolman and Leopold, 1957; Andrews, 1984). In contrast, identification of design flows for engineering or restoration purposes in steep, externally-forced-configuration rivers (Grant and Swanson, 1995; Montgomery and Buffington, 1997; Curran and O'Connor, 2003) in arid and semi-arid regions of the southwestern U.S. is considerably more complex. Graf (1983) has argued that dryland channels are not equilibrium forms, and that as a result it is not possible to define a dominant discharge (Graf, 1988). Larger and more infrequent flows are more geomorphically effective (Baker, 1977), and dryland rivers transport 60 percent of their sediment loads in 10-year or larger events (Neff, 1967). Compound or braided channels with poorly defined floodplains between bounding terraces make identification of bankfull capacity very difficult, and large, infrequent floods tend to have a strong influence on channel geometry that in turn confines subsequent lower magnitude flows

(Graf, 1988). Local tributary contribution of sediments causes great variation in the distribution of particle sizes that comprise the bed of dryland rivers (Rhoads, 1986).

The purpose of this paper is to present the results of an investigation of channel capacity and critical discharges for bed-material mobilization and bed material transport at three locations within a 16-km reach of the Verde River in Arizona (Figure 1) that was conducted to identify flows required for habitat restoration purposes.

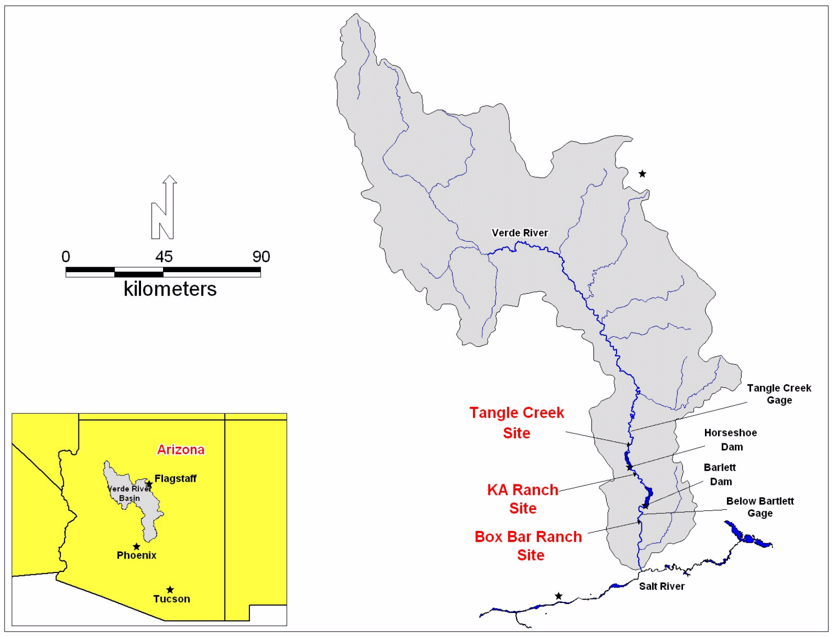

Figure 1. Map showing the locations of the three sites in the lower Verde River basin.

Study Area and Site Characteristics

The Verde River drains an area of about 17,000 km^2, and flows through the highlands and valleys of central Arizona (Figure 1). The physiography and geology of the region are transitional between the high elevation, relatively flat Colorado Plateau physiographic province and the lower elevation Basin and Range province. In the reach of interest, the Verde River is entrenched into a relatively narrow, deep canyon from upstream of Horseshoe Reservoir to just downstream of Bartlett Reservoir, where the valley bottom widens, and the river is less confined. The long period of downcutting by the Verde River has created a series of terraces that flank the river ranging in age from early-Pleistocene to late Holocene. In general, the older terraces are more erosion-resistant than the younger terraces. Long-term downcutting and the relative erodibility of pre-Quaternary bedrock and basin-fill units effectively control the extent and character of the Quaternary alluvial deposits along the Verde River. In common with most canyon-bound rivers, local constrictions and expansions in the valley cause localized accumulations of alluvial sediments (Harvey et al., 1993).

Three sites in relatively wide segments of the valley where alluvial deposits were present were chosen for this investigation. The Tangle Creek site is located just downstream of the USGS gage, the KA Ranch site is located about 3 km downstream of Horseshoe Dam, and the Box Bar Ranch site is located about 4 km downstream of Bartlett Dam (Figure 1). Bed and bar material gradations at each of the sites were developed from pebble counts (Wolman, 1954) of the surface sediments. Between 13 and 26 cross sections were surveyed at each site, and a 0.6-m contour interval map of each site was developed photogrammetrically. One-dimensional HEC-RAS models were developed for each of the sites from the topography. The unimpaired hydrologic record for the three sites was established from the USGS Tangle Creek gage (0908500). Mean daily flow records extend from 1945 to the present, and a record of peak flows is available for 1891, 1906, 1916, 1920 and 1925 to the present. The largest floods in the period of record are due to winter precipitation in the November through March period, rather than summer thunderstorms (Ely and Baker, 1985).

The Tangle Creek site is about 1,300 m long, and the width of the valley bottom is about 200 m. The site is bounded along both sides by Pleistocene and Holocene age terraces and alluvial fans, and moderately lithified pre-Quaternary basin-fill sediments. The active channel width is about 100 m, and it is flanked by narrow bands of riparian vegetation. In the lower two-thirds of the site, the active channel is flanked along the left bank by a very sparsely vegetated gravel-cobble bar that represents a high-flow chute-channel that is confined on its left margin by a Holocene-age terrace. In the upper third of the site, the chute channel is separated from the main channel by a relatively high-elevation vegetated bar. The downstream hydraulic control for the site is created by a constriction caused by the presence of erosion-resistant, late- to mid-Pleistocene-age coalesced fans on the right bank, and a late-Holocene-age terrace on the left bank. The median size (D_{50}) of the riffle sediments averages 81 mm, and the average D_{84} (size for which 84 percent of the sample is finer) is 123 mm. The average D_{50} of the lower elevation bar surface sediments is 49 mm, and the D_{50} of the high elevation bar sediments is 73 mm. The corresponding D_{84} values are 83 and 113 mm, respectively.

The KA Ranch site is about 1,000 m long and is located within a section of the Verde River valley that is about 660 m wide. Within the site, the active channel width is about 150 m. The site is located in a depositional zone upstream from a valley constriction, located about 0.6 km downstream, that is caused by the presence of more erosion-resistant basin-fill outcrop on the right bank and older alluvial terraces and tributary fan sediments on the left bank. Further enhancing the depositional nature of the site is the presence of two large tributaries that episodically deliver significant quantities of sediment to the river. Davenport Wash is located on the left bank at the upstream end of the site, and an unnamed arroyo is located on the right bank. Sediments delivered by the right bank arroyo have formed a large alluvial fan that has prograded out onto the valley floor. The left valley wall throughout the site is composed of basin-fill sediments that also crop out on the right valley wall immediately downstream of the site. The right valley wall along most of the site is composed of old alluvial and fan sediments into which the present arroyo is inset. Morphologically, the site is characterized by an approximately 66-m wide low-flow channel that is fringed by riparian vegetation. A large, sparsely vegetated cobble-gravel bar separates the main channel from a chute channel that is located on the margin of the valley floor and runs along the base of the bounding alluvial fan and terraces for much of the length of the site. The D_{50} and D_{84} sizes of the riffle sediments are 146 and 231 mm, respectively. The low elevation bar has a D_{50} of 73 mm, and the D_{50} of the high elevation bar is 105 mm. The corresponding D_{84} sizes are 118 and 207 mm, respectively. The sediments that compose the riffle, low bar and high bar surfaces at this site are somewhat coarser than those on the corresponding surfaces at the Tangle Creek site, due probably to the steeper channel slope and local tributary contribution of sediments.

The Box Bar Ranch site is about 1,600 m long and is located in a section of the Verde River valley that is about 1,300 m wide. The active channel at the site is about 200 m wide, and is flanked on the left side by a Holocene terrace that was overtopped by the large floods that occurred in the early part of the 20th century. The upper portion of the site is flanked by an older, higher terrace, but the remainder of the site is flanked by both late- and early-Pleistocene age alluvial sediments that are dissected by a number of relatively small active arroyos. The site is located in a depositional zone upstream of a valley constriction located about 0.6 km downstream that is caused by the presence of more erosion resistant older alluvial deposits on the right bank and outcrop of the Needle Rock Formation on the left bank. Morphologically, the site is characterized by an approximately 200-m wide active channel that is separated from a chute channel that runs along the left side of the site for most of its length by a sparsely vegetated gravel-cobble bar. The average D_{50} of the riffles is 95 mm, and the D_{84} is 164 mm. The low elevation bar has a D_{50} of 54 mm, and the high elevation bar value is 67 mm. The corresponding D_{84} values are 107 and 121 mm, respectively.

Historical Changes

In arid climates and canyon-bound rivers, most changes in river characteristics are driven by relatively infrequent floods (Baker, 1977; Graf, 1988). Paleoflood studies of the Verde River have identified a number of very large floods within the last 1,000 years, the largest of which may have been on the order of 5,500 cms (House et al., 1995). Table 1 summarizes the modern peak flood record at the Tangle Creek gage.

Table 1. Summary of peak flood records at Tangle Creek gage.

Year	Magnitude (cms)	Recurrence Interval (yr)
1891	~4,200	>50
1906	2,700	18
1920	2,680	17
1938	2,825	20
1952	2,300	14
1978	2,580	15
1979	2,660	16
1980	2,680	17
1993	4,100	50
1995	3,050	23

Comparison of the flood-frequency curves for the Tangle Creek gage and the Below Bartlett gage (USGS Gage 09510000) shows that because of the relatively low storage volumes of Horseshoe and Bartlett Dams (combined storage volume is 354,000 ML), the dams have little effect on the magnitude of floods with a recurrence interval of 10 years or greater (Figure 2).

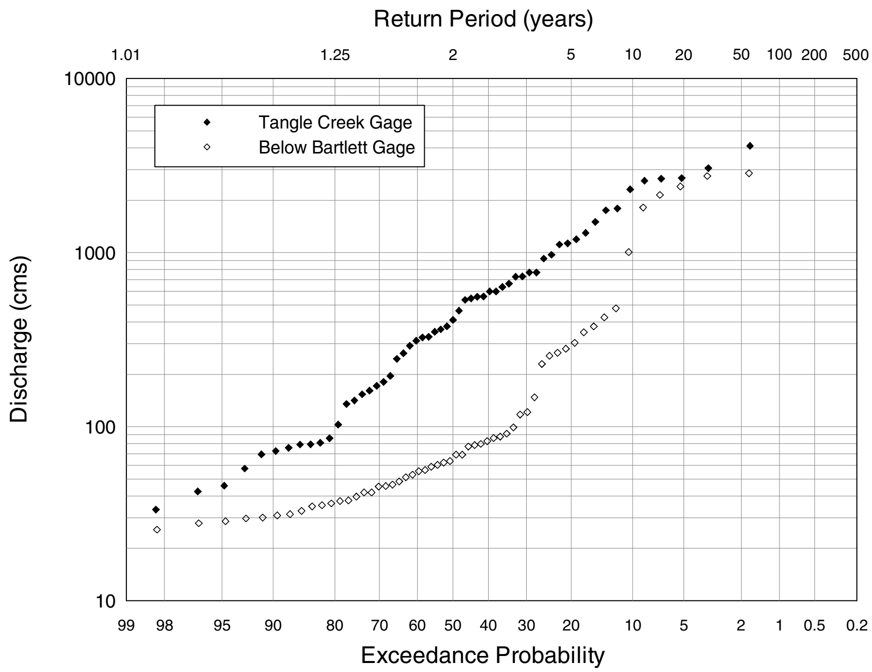

Figure 2. Flood-frequency curves based on plotting positions for the USGS Tangle Creek and below Bartlett gages.

Flood-driven changes at the three sites can be evaluated by examining a time series of aerial photographs (1934-2002). In general, because of the relatively confined nature of the sites, the morphological characteristics of the sites do not change greatly following large floods, but the amount of woody vegetation within the site does, and is thus an index of flood-induced changes. At the Tangle Creek site, the 1934 photo showed very little within-channel vegetation following the floods of 1906 and 1920 (RI 17 to 18 years). Between 1934 and 1968 there was a substantial increase in vegetation throughout the site, probably because the two floods in this period (1938 and 1952: 15-20-yr RI) occurred in the earlier part of the period. Very little vegetation was present on the 1980 photo following floods in 1978, 1979 and 1980 (RI 15-18 yrs). Comparison of the 1980 and 1992 photos showed vegetation recovery throughout the site during this period when there were no large floods. However, the floods of 1993 (50-yr) and 1995 (23-yr) again removed all of the vegetation. The general pattern of vegetation encroachment between large flood events and subsequent removal during floods with recurrence intervals exceeding about 15 years is most likely attributable to the relatively confined nature of the site and the resulting high energy during large flood events (Friedman and Auble, 1999).

A very similar pattern of vegetation establishment and removal was also observed at the KA Ranch site over the same time periods. However, probably because of the wider valley bottom (660 m) and the presence of two sediment supplying tributaries at the head of the reach, there was some adjustment of the site morphology as a result of the 1993 and 1995 floods. The location of the main channel was shifted and new chute channels developed during these floods. At the Box Bar Ranch, because of the greater valley bottom width (1,300 m), the patterns of vegetation establishment and removal between 1934 and 1992 were quite different from the two upstream sites. In general, there was a continuous increase in vegetation throughout the time period, which implies that the floods with recurrence intervals up to about 20 yrs have little effect on this site. The floods of 1993 and 1995 caused some localized removal of vegetation and some morphological changes to the site. Therefore, it appears that at this site much larger floods than the 50-yr event are required to cause significant morphological or vegetational changes.

Bankfull Discharge, Incipient Motion and Sediment Transport

One-dimensional HEC-RAS hydraulic models were developed for each of the three study sites in order to evaluate inundation of the channel and bars, incipient motion and sediment transport for a range of modeled flows. Flow conditions at all of the sites are very complex, with flow breakouts at high flows, multiple flow paths, and low areas in the overbanks that are not connected to the main channel. To account for this complexity, each continuous well-defined flow path was analyzed using a separate reach in the hydraulic model. The discharge in each reach was determined automatically using the split-flow routine in HEC-RAS that balances the computed energy grade-line elevation at the upstream end of each branch. Less well-defined flow paths were accounted for using the HEC-RAS ineffective flow-area options to ensure that low areas not connected to the main channel did not flow until the intervening high ground was overtopped, and to ensure reasonable flow continuity in the overbanks from cross section to cross section. Because the nature of the flow paths change with discharge (areas with well-defined separate flow paths at low flows become connected at high flows), different model configurations were used at each site for specific ranges of discharge. The hydraulic models at each site were verified, to the extent possible, with water-surface elevations measured at the time of the cross-section surveys and surveyed high-water marks from recent floods (February and March, 2003).

Bankfull Discharge

For the inundation analysis, the hydraulic models were run for a range of flows from very low flows up through the 100-yr event (5,650 cms). Results from the models were then used to develop water-surface elevation versus discharge rating curves for each of the surveyed cross sections. Where multiple flow paths existed at a particular cross section, separate rating curves were developed for different portions of the cross section. Modeled water-surface elevations for discharges covering the range of modeled flows were then plotted on the cross sections to show the extent of inundation that would occur at different flow levels. Figure 3 shows average (26 cross sections) water-surface elevations on a typical cross section for the Tangle Creek site. The low bar is inundated at a flow of about 450 cms (1.7-yr RI), the channel capacity is about 1,900 cms (8-yr RI), and the high bar is inundated by flows higher than 1,900 cms (> 8-yr, RI). Figure 4 shows average water-surface elevations (35 cross sections) on a typical cross section for the KA Ranch site. The low bar is inundated at a flow of about 605 cms (3-yr RI), the channel capacity is about 1,559 cms (7-yr RI), and the high bar is inundated by flows higher than 1,559 cms (> 7-yr, RI). Figure 5 shows average (23 cross sections) water-surface elevations on a typical cross section for the Box Bar ranch site. The low bar is inundated at a flow of about 565 cms (2.5-yr RI), the channel capacity is about 1,412 cms (6-yr RI), and the high bar is inundated by flows higher than 1,412 cms (> 6-yr, RI).

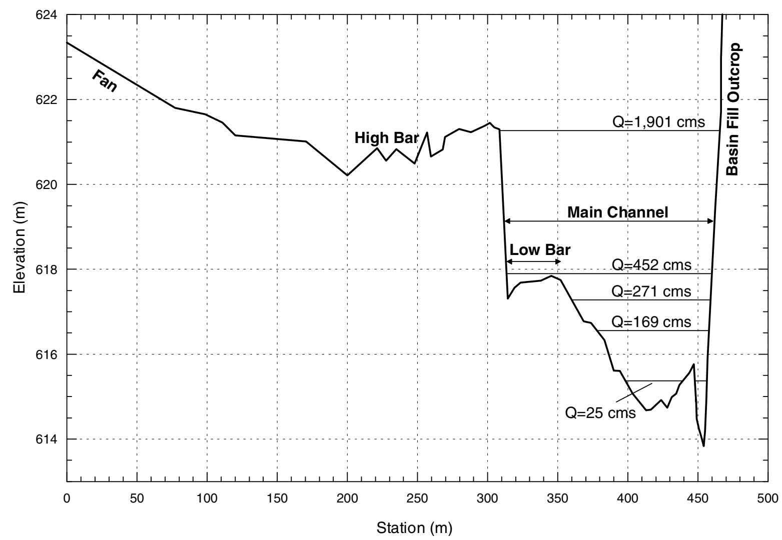

Figure 3. Typical cross section of the Tangle Creek site showing the geomorphic features of the site and the water-surface elevations for a range of flows between 25 and 1,901 cms.

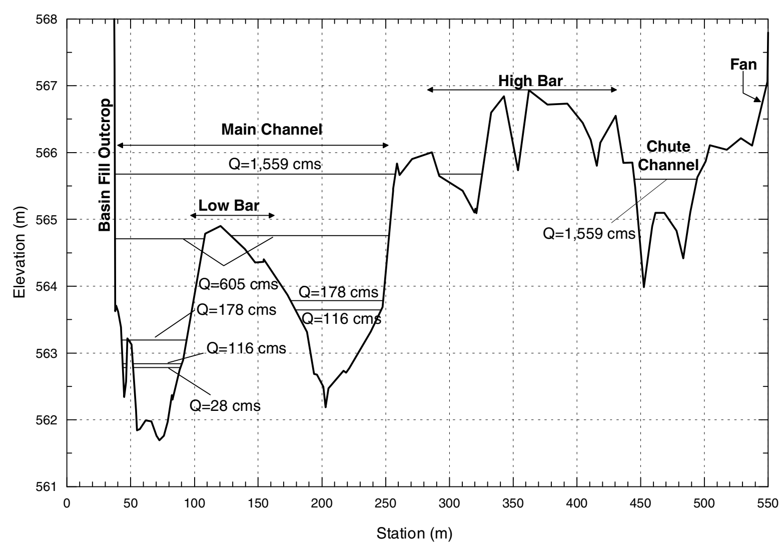

Figure 4. Typical cross section of the KA Ranch site showing the geomorphic features of the site and the water-surface elevations for a range of flows between 28 and 1,559 cms.

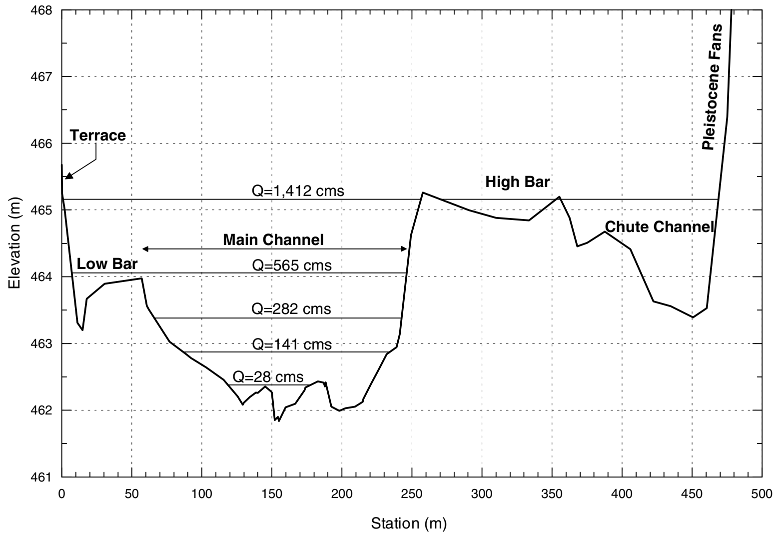

Figure 5. Typical cross section of the Box Bar Ranch site showing the geomorphic features of the site and the water-surface elevations for a range of flows between 28 and 1,412 cms.

Based on the plotted water-surface elevations it could be argued that the top of the low bars is the bankfull discharge (450-605 cms) since it meets that morphological definition of the bankfull stage, and the recurrence interval for the low-bar overtopping flows is between 1.7 and 3 years (Wolman and Leopold, 1957; Williams, 1978). However, the geomorphic significance of the bankfull flow is that it provides a reasonable upper limit of within-channel energy that can be characterized by a sharp break in the discharge-stage or discharge-shear stress curve when the flows are no longer confined. Clearly, at these sites on the Verde River, the upper limit of within–channel energy occurs at the top of the high bars, where the recurrence interval of the overtopping flows is between 6 and 8 years. Therefore, on a purely morphologic basis this range of flows (1,400-1,900 cms) could be classified as the bankfull flow, and potentially could be chosen for engineering design or environmental restoration.

Incipient Motion and Sediment Transport

Before flows can be adopted for design or restoration purposes, it must be shown that they are capable of mobilizing and transporting the channel boundary sediments. Incipient-motion and sediment-transport analyses were, therefore, conducted. The shear stress required for bed mobilization was estimated using the Shields (1936) relation:

$$\tau_c = \tau_{*c}(\gamma_s - \gamma)D_{50} \tag{1}$$

where τ_c is the critical shear stress for particle motion, τ_{*c} is the dimensionless critical shear stress (0.03: Parker et al., 1982; Andrews, 1984), γ_s is the unit weight of sediment (26 kN/m^3), γ is the unit weight of water (9.8 kN/m^3), and D_{50} is the median particle size of the bed material (mm). In performing the incipient-motion and bed-material transport analysis, the bed shear stress due to grain resistance (τ') was used rather than the total shear stress. The grain shear stress is computed from the following relation:

$$\tau' = \lambda Y' S \tag{2}$$

where Y′ is the portion of the total hydraulic depth associated with grain resistance (Einstein, 1950), and S is the energy slope. The value of Y′ is computed iteratively by solving the semilogarithmic velocity profile equation:

$$\frac{V}{V_*'} = 5.75 + 6.25\,log\left(\frac{Y'}{k_s}\right) \tag{3}$$

where V is the mean velocity, k_s is the characteristic grain roughness of the bed (3.5 D_{84}: Hey, 1979) and V_*' is the shear velocity due to grain resistance:

$$V_*' = \sqrt{gY'S} \tag{4}$$

Normalized grain shear stress (ϕ′) is the ratio of the grain sheer stress (τ′) to the critical shear stress for particle mobilization (τ_c). When ϕ′ is equal to 1 the bed material begins to mobilize, and substantial sediment transport occurs when ϕ′>1.5 (Mussetter et al., 2001).

To evaluate the flows required to mobilize the sediment on the bed it was necessary to estimate the distribution of the grain shear along each cross section. The lateral flow distribution was estimated by assuming that the flow varies with the distribution of conveyance across the section. The conveyance for a particular subsection of the cross section is:

$$K_i = \frac{1.486}{n_i} A_i R_i^{2/3} \tag{5}$$

where K_i is the conveyance for subsection i, n_i is the Manning's *n*-value for subsection i, A_i is the area for subsection i, and R_i is the hydraulic radius for subsection i. The discharge in subsection i is then computed as:

$$Q_i = Q_T \frac{K_i}{K_T} \tag{6}$$

where Q_i is the discharge in subsection i, Q_T is the total discharge, and K_T is the total conveyance determined by summing the subsection conveyances. With the flow distribution known, the other hydraulic variables necessary to determine the grain-shear distribution are computed.

The critical flows required for incipient motion (ϕ′=1) of the bed and low- and high- bar sediments at each of the sites, and their recurrence intervals are summarized in Table 2.

The recurrence intervals for the range of critical discharges for the bed material at the three sites are similar to those of the flows that inundate the low bars (1.7-3 yrs). Similarly, the recurrence intervals for the critical discharges for the low-bar sediments at the 3 sites is in the same range as that required to just overtop the high bars (6-8 yrs). Mobilization of the high bar sediments at all of the sites requires flows with recurrence intervals in excess of the 60-year event. Therefore, within and between sites, it is likely that at the same flows, sediment will be either immobile, being transported, or being deposited. Based on the incipient motion data it could be argued that the channel dimensions are adjusted to either the low-bar (450-605 cms) or high-bar (1,400-1,900 cms) "bankfull" flows.

Table 2. Critical discharges for bed, low-bar and high-bar sediments.

	Tangle Creek	KA Ranch	Box Bar Ranch
Average Critical Discharge–Bed (cms) RI (yrs)	461 1.8	811 3.8	398 1.6
Average CriticalDischarge –Low Bar (cms) RI (yrs)	1342 6	1158 5	1695 7
Average Critical Discharge–High Bar (cms) RI (yrs)	4802 65	>5650 >100	4520 60

However, for design or restoration purposes, flows must be able to transport the bed material. Table 3 summarizes the flows required to provide significant sediment-transport rates ($\phi' > 1.5$) for the bed and bar sediments at each of the three sites. As shown in Table 3, the recurrence intervals for the flows that cause significant transport of the bed material are similar to the high bar "bankfull" flows (6-8 yrs), but they range from 4 yrs at the Tangle Creek site, which is the most confined, to 8 years at the KA Ranch site. From the perspective of selecting a design discharge, the sediment transport data suggest that the high-bar "bankfull" flows are probably the most appropriate at each site, but there is quite a difference in the required flows (989-1,740 cms) between the sites.

Table 3. Flows required for significant sediment transport at the three sites.

	Tangle Creek	KA Ranch	Box Bar Ranch
Average Discharge–Bed (cms) RI (yrs)	989 4	1740 8	1342 6
Average Discharge–Low Bar (cms) RI (yrs)	2260 15	2994 21	3249 23
Average Discharge–High Bar (cms) RI (yrs)	>5650 >100	>5650 >100	>5650 >100

Conclusions

This study of three locations in a 16-km reach of the lower Verde River in Arizona demonstrates the problem of identifying generalized design flows in the arid and semi-arid regions of the southwestern US. Depending on the definition used, the bankfull discharge at the 3 sites ranges from 450 to 1,900 cms (1.7- to 8-yr RI), the critical discharge ($\phi' = 1$) for bed material mobilization ranges from 398 to 811 cms (1.6- to 3.8-yr RI), and significant sediment transport ($\phi' > 1.5$) occurs at flows between 989 and 1,740 cms (4- to 8-yr RI). At any given flow above the critical discharge at one location, bed material can be immobile, in transport, or being deposited to another site. Selection of flows for engineering design or restoration purposes should be based on the ability of the flows to transport the bed material, and therefore, in rivers with similar conditions site-specific geomorphic, hydraulic and sediment-transport analyses are required rather than generalized relations based on assumed relations between bankfull discharge, flood frequency, and effective discharge.

Acknowledgements

This study was conducted for the Salt River Project and ERO Resources Corporation and we thank them for their permission to publish this paper. We thank S.A. Schumm for reviewing an earlier draft of the manuscript.

References

Andrews, E.D., 1984. Bed material entrainment and hydraulic geometry of gravel-bed rivers in Colorado. Geological Society of America Bulletin 95, March, pp. 371-378.

Baker, V.R., 1977. Stream Channel Response to Floods, with Examples from Central Texas. Geologist Society of America Bulletin, v. 86, pp. 1057-1071.

Curran, J.H. and O'Connor, J.E., 2003. Formation and evolution of valley-bottom features, Lower Deschutes River, Oregon. *In* A Peculiar River: Geology, Geomorphology and Hydrology of the Deschutes River, Oregon. Water Science and Application 7, J.E. O'Connor and G.E. Grant, Editors, 95-120.

Einstein, H.A., 1950. The bedload function for sediment transportation in open channel flows. U.S. Soil Conservation Service, Tech. Bull. No. 1026.

Ely, L.L. and Baker, V.R., 1985. Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona. Physical Geography 5, 2, pp. 103-126.

Friedman, J.M. and Auble, G.T., 1999. Mortality of riparian boxelder from sediment mobilization and extended inundation. Regulated Rivers: Research and Management 15, John Wiley & Sons, Ltd., pp. 463-476.

Graf, W.L., 1983. Flood-related channel changes in an arid region river. Earth Surface Processes and Landforms, v. 8, pp. 125-139.

Graf, W.L., 1988. Fluvial Processes in Dryland Rivers. The Blackburn Press, New Jersey, 346 p.

Grant, G.E. and Swanson, F.J., 1995. Morphology and processes of valley floors in mountain streams, Western Cascades, Oregon. AGU Geophysical Monograph 89, pp. 83-102.

Harvey, M. D., Mussetter, R.A., and Wick, E.J., 1993. A Physical Process-biological Response Model for Spawning Habitat Formation for the Endangered Colorado Squawfish, Rivers, v. 4, no. 2, pp. 114-131.

Hey, R.D., 1979. Flow Resistance in Gravel-Bed Rivers. ASCE, Journal of the Hydraulics Division, v. 105, no. HY4, pp. 365-379.

House, P.K., Pearthree, P.A., and Fuller, J.E., 1995. Hydrologic and paleohydrologic assessment of the 1993 floods on the Verde River, Central Arizona. Arizona Geological Survey Open-File Report 95-20, December, 23 p.

Montgomery, D.R. and Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geol. Soc. Amer. Bull., v.109, pp. 596-611.

Mussetter, R.A., Harvey, M.D., Zevenbergen, L.W. and Tenney, R.D., 2001. A comparison of one- and two-dimensional hydrodynamic models for evaluating Colorado pikeminnow spawning habitat, Yampa River, Colorado. *In* Applying Geomorphology to Environmental Management, D.J. Anthony, M.D. Harvey, J.B. Laronne and M.P. Mosley (eds), Water Resources Publications, Highlands Ranch, CO., 361-380.

Neff, E.L., 1967. Discharge frequency compared to long-term sediment yields. Publ. Int. Assoc. Sci. Hydrol., 75, pp. 236-242.

Parker, G., Klingeman, P.C., and McLean, D.G., 1982. Bed load and size distribution in paved gravel-bed streams. ASCE, Journal of the Hydraulics Division, 108(HY4), Proc. Paper 17009, pp. 544-571.

Rhoads, B.L., 1986. Process and response in desert mountain fluvial systems. Ph.D. dissertation, Dept. of Geography, Arizona State University, Tempe, Arizona.

Shields, A., 1936. Application of similarity principles and turbulence research to bed load movement. California Institute of Technology, Pasadena; Translation from German Original; Report 167.

Williams, G.P., 1978. Bank-full discharge of rivers. Water Resources Research, v.14(6), pp. 1141-1153.

Wolman, M.G., 1954. A method for sampling coarse river bed material. Transactions of American Geophysical Union, v.35 (6), pp. 951-956.

Wolman, M.G. and Leopold, L.B., 1957. River floodplains: some observations on their formation. USGS Prof. Paper, 282-C, pp. 86-109.