A GEOMORPHOLOGIC AND HYDRAULIC EVALUATION OF AN EXTRAORDINARY FLOOD DISCHARGE ESTIMATE: BRONCO CREEK, ARIZONA

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Abstract

Geomorphologic and hydraulic methods were used to evaluate the reported magnitude of an extraordinary flood in west-central Arizona. The peak discharge of the Bronco Creek flood of August 19, 1971 was estimated by the U.S. Geological Survey (USGS) as 2080 $m^3 s^{-1}$ (73,500 $ft^3 s^{-1}$) from a 50 km^2 (20 mi^2) basin. As such, it stands as one of the world's largest known rainfall-generated floods to come from a basin of this size. It is likely that the USGS estimate is too high because of the application of the slope-area method in a high gradient alluvial channel with unstable boundaries.

We evaluated the Bronco Creek flood discharge using paleohydrological techniques to estimate peak discharges in stable, bedrock-controlled channel reaches near the mouths of the 3 major sub-basins of the watershed. Our estimates were derived from the integration of relict high-water indicators into a fixed-boundary hydraulic model (HEC-2). Our final estimate of 800 $m^3 s^{-1}$ (28,200 $ft^3 s^{-1}$) is based on summing the sub-basin estimates and adjusting for the 18% difference in contributing drainage area between our sites and the original site. The new, lower estimate fits with regional trends in flood magnitude-drainage area relationships, is more consistent with hydrologic and meteorological data for the time surrounding the event, and is more realistic in terms of the likely flow hydraulics through a major bridge constriction.

The large discrepancy between our estimate and the previous one is best explained by the boundary conditions in the reaches selected for analysis in each study. The original estimate was made with a 4-section slope-area calculation in a long, high-gradient (~3%) alluvial channel averaging 122 m (400 ft) wide. Analysis and comparison of historical aerial photos indicates that the flood changed the channel pattern from braided with vegetated bars to straight, wide, and devoid of vegetation. Asynchronous attainment of peak discharge and maximum cross-sectional area in the channel and uncertainties about channel roughness probably account for much of the overestimation. In our study, we modeled flow in bedrock reaches with well-preserved high-water marks to avoid such uncertainties in boundary conditions. The results illustrate some of the principal sources of error affecting indirect estimates of extreme floods in alluvial streams.

Introduction

The estimated peak discharge of the Bronco Creek, Arizona flood of August 19, 1971, stands as one of the largest rainfall generated floods in the world to come from a ~50 km^2 (20 mi^2) drainage basin (Costa 1987a, 1987b). The estimate of 2080 $m^3 s^{-1}$ (73,500 $ft^3 s^{-1}$) (Aldridge, 1972) departs sharply from regional flood discharge–drainage area trends defined by maximum paleoflood, historical, and observed flood discharges in the region (Enzel and others, 1993). The reported flood magnitude also corresponds to the theoretical 100-year flood on the 7250 km^2 (2800 mi^2) Big Sandy River (Garrett and Gellenbeck 1991), of which Bronco Creek is a minor tributary that accounts for less than 0.1% of the total basin area. There are also several problematic hydraulic and hydrologic implications of the estimate involving unreasonably high velocities below a bridge opening and extreme flood wave attenuation downstream on the Big Sandy River.

Because of these anomalous characteristics, the veracity of the flood estimate has been questioned before (e.g. Carmody, 1980; Baker and Costa, 1987), but no previous attempts have been made to thoroughly evaluate it. Our investigation of the original study reveals the incorporation of several tenuous assumptions into the flood reconstruction and associated corroborative efforts; however, little information is available from which to evaluate the corroborative methods. The lack of detailed documentation and substantiation for such a large flood estimate is unfortunate and is a problem recognized in relation to other anomalously high discharge estimates (Jarrett, 1994). In terms of flood hydrology and potential flash flood magnitudes in the western United States, the veracity of such an extraordinary estimate should be critically evaluated to ensure that its use in the context of regional flood frequency analysis or basic hydrological research is warranted. For example, the discharge estimate for the Bronco Creek flood has been cited as one example of an actual historic flood that approached the magnitude of the estimated probable maximum flood (PMF) for the basin (Bullard, 1986).

In light of these concerns, we evaluated the original estimate using several approaches, including: (1) examination of all available information (published and unpublished) concerning the original computations, assumptions, and corroborative efforts; (2) reconstruction of flow hydraulics using paleohydrological procedures in bedrock canyon reaches at three sites in the basin; (3) examination of pre-flood and post-flood aerial photographs; and (4) review of the

available regional hydrological and meteorological data for the dates of and surrounding the flood. Our interpretation of the results of these inquiries leads to the conclusion that the original estimate maybe overstated by as much as 250%.

This study highlights many problems in acquiring accurate indirect discharge estimates for extreme floods in unstable (alluvial) channels and emphasizes the need to attempt to adequately substantiate all questionable extreme flood discharge estimates. In addition to describing the specific approach employed in re-evaluating the Bronco Creek flood, this paper also suggests some general approaches to assessing the accuracy of extreme flood estimates.

The Bronco Creek Flood: Hydrology and Meteorology

The Bronco Creek watershed is located at the southern end of the Hualapai Mountains in west-central Arizona (figure 1). It occupies a transitional zone between the Sonoran and Mojave deserts and the climate is relatively arid. The average annual precipitation at nearby Wikieup, Arizona is approximately 240 mm (9.4 in). The basin is slightly elongated in a predominantly east-west direction. Most of the watershed is underlain by Precambrian granitic gneiss. The remaining portion of the watershed (the easternmost end) is underlain by deeply dissected late Tertiary basin fill deposits. Vegetation and soil cover within the basin are generally sparse. The Bronco Creek watershed consists of three primary sub-basins: Bronco Creek, Greenwood Wash (informally named here), and Bronco Wash (figure 2). Topographic relief in the watershed is approximately 950 m. The basin is mountainous, but with variable relief and ruggedness (figure 2). Ruggedness increases to the south and east within the watershed.

Detailed information about the storms responsible for the Bronco Creek flood is not available because there are no official meteorological stations in the immediate area. Three separate convective thunderstorms reportedly struck the Bronco Creek Basin on the day of the flood (Aldridge, 1972). An unofficial rain gage in Wikieup, approximately 2 miles northwest of the basin center, recorded about 76 mm (3 in) of precipitation in 45 minutes. The few official meteorological stations within this portion of west-central Arizona recorded relatively high daily precipitation totals (25 - 61 mm) on August 19. The flood occurred in the midst of a particularly wet summer in Arizona in which several record monthly precipitation totals were recorded (NOAA, 1971).

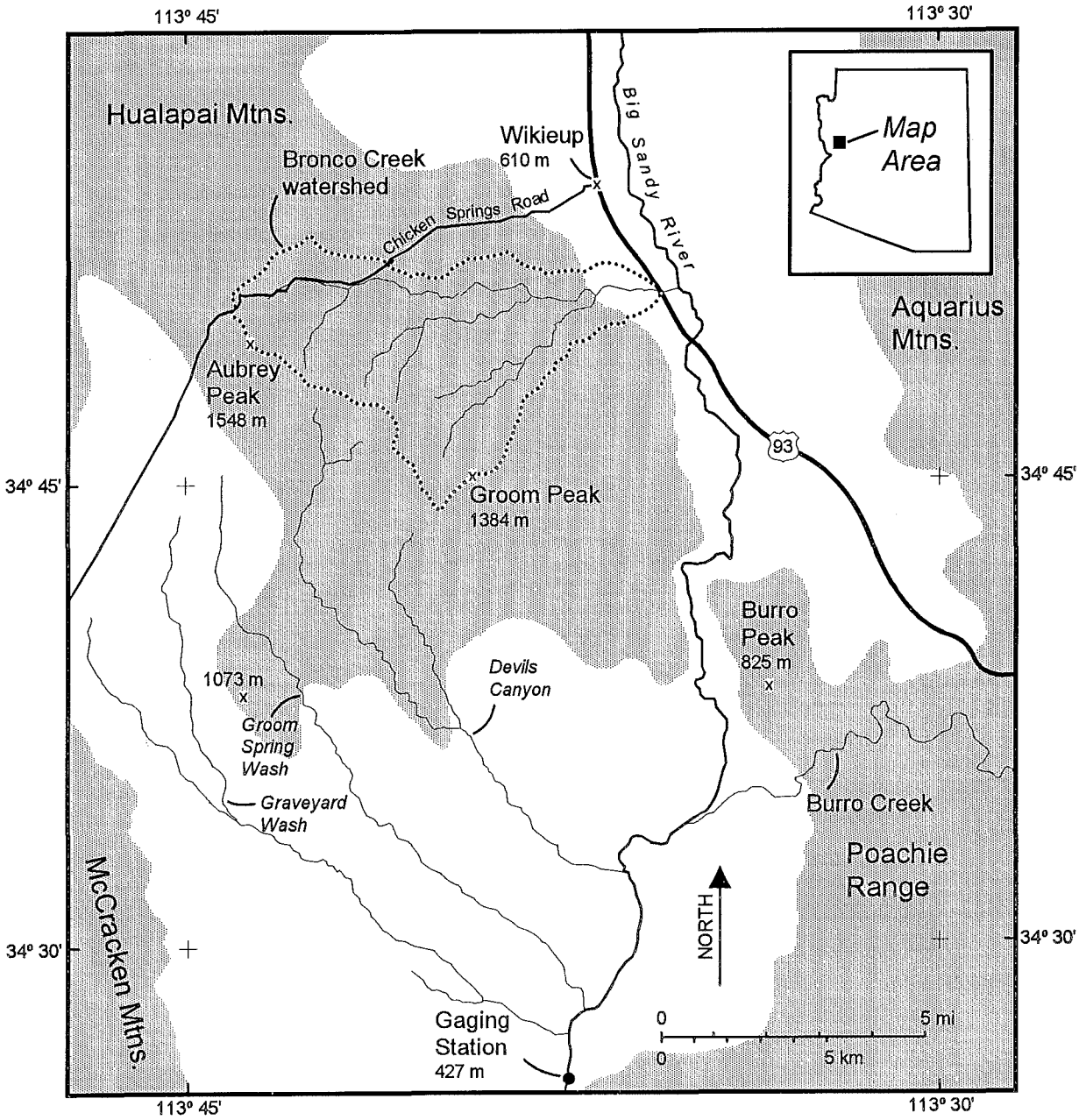

Figure 1.
Location map showing the regional setting of the Bronco Creek Watershed.

Bronco Creek flows into the Big Sandy River 0.6 km (0.4 mi.) below the site of the original indirect discharge estimate. A continuous-recording gage on the Big Sandy River (USGS gage # 09424450) is approximately 18.4 miles downstream of the mouth of Bronco Creek. The drainage area to the gage is about 7252 km^2 (2800 mi^2). The gage recorded its annual maximum peak discharge of 292 $m^3 s^{-1}$ (10,300 $ft^3 s^{-1}$) at 11:00 PM, August 19, 1971. This is the largest peak discharge recorded in the summer on this stream to date. Photographic, hydrologic, and meteorological information that we have examined suggest that several sources contributed to flow in the Big Sandy River on August 19. Several lines of evidence lead us to conclude that the flood occurred on August 19, and not August 18, as originally reported (USGS unpublished data, 1971; Aldridge, 1972).

Bronco Creek Peak Discharge Estimates

The original peak discharge estimate was made near the mouth of Bronco Creek using a four-section slope area calculation in an alluvial reach approximately 300 m (980 ft) long ending about 305 m (1000 ft) above the US highway 93 bridge. This estimate was corroborated with an assessment of flow velocity based on channel slope and sediment characteristics (Aldridge 1972) and with a critical-depth calculation above the constriction at the bridge crossing. The reported discharge estimate of 2080 $m^3 s^{-1}$ was rated as "poor" (USGS unpublished data, 1971), implying an uncertainty of +/-25% (Benson and Dalrymple, 1967).

The new estimate reported in this study is a composite of peak flow reconstructions from bedrock canyon reaches of the three primary sub-basins of the Bronco Creek watershed and a correction factor for omitted drainage area (figure 2). Our goal in the evaluation of the original estimate was to model flow in channel reaches with stable boundaries (i.e. bedrock canyons) that retain good high-water marks. The sub-basin sites are the first reaches upstream where the bed and banks are formed in bedrock. The locations of the three sites in relation to the site of the original estimate are shown in figure 2. The contributing drainage areas to each reach are: Bronco Wash, 14.0 km^2 (5.4 mi^2); Greenwood Wash, 9.2 km^2 (3.5 mi^2); and Bronco Creek, 16.6 km^2 (6.4 mi^2). This gives a composite drainage area of 39.8 km^2 (15.3 mi^2) compared to 48.4 km^2 (18.7 mi^2) for the contributing area to the site of the original estimate. Thus, in total, the new sites constitute a contributing drainage area 18% smaller than the site of the original estimate.

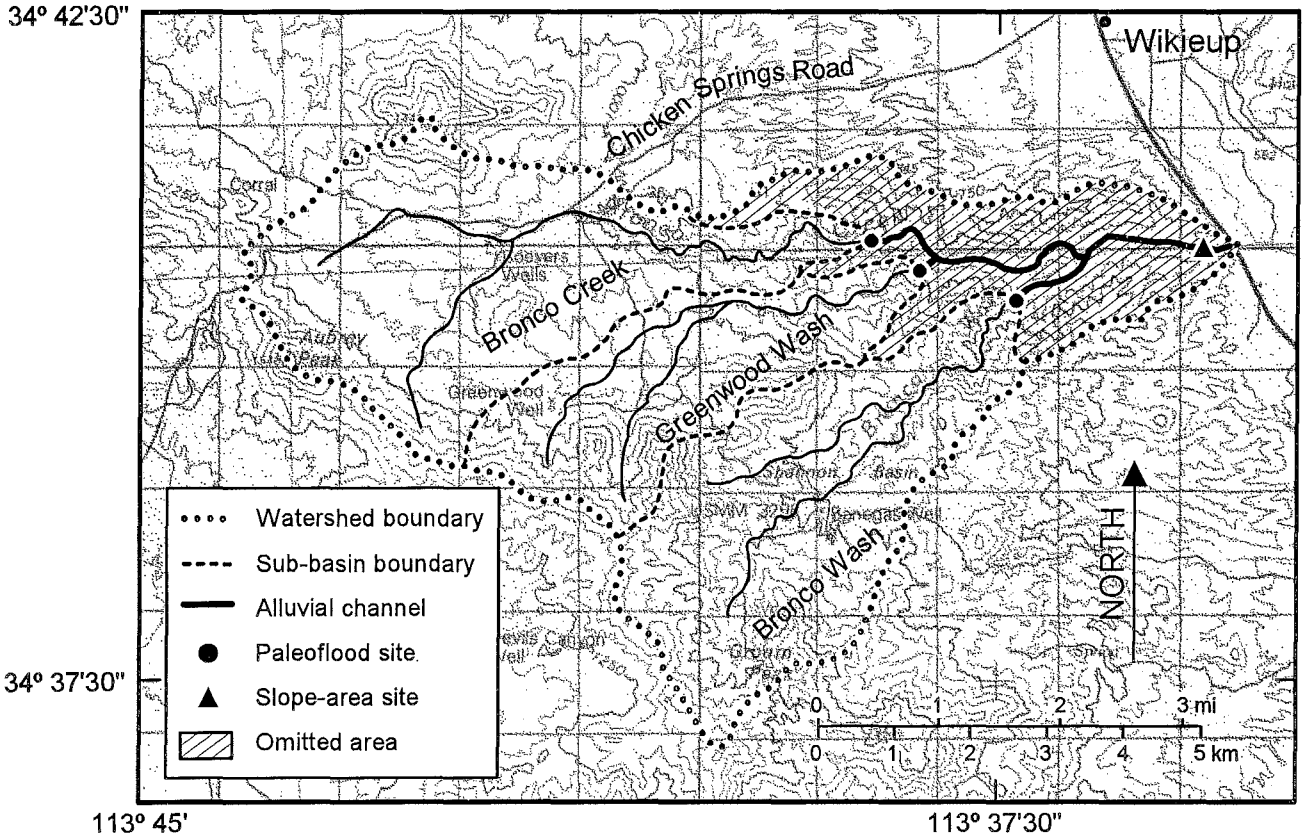

Figure 2.
Map of the Bronco Creek Watershed showing topography, sub-basin boundaries, study site locations, and extensive alluvial channel reaches.

Discharge Reconstruction Methodology

We used techniques of paleoflood hydrology to estimate peak discharges in the three sub-basins. In general, paleoflood hydrology refers to the study of extreme floods that occurred prior to, or in absence of instrumental observation or historical documentation (Baker, 1987, 1989). One of the most significant contributions of paleoflood hydrology to flood hydrology in general is its demonstration of the longevity of various types of flood evidence in certain fluvial settings and its consequent extension of flood records by 100s to 1000s of years (e.g. Kochel, 1988; Jarrett, 1991; Ely and others, 1993; O'Connor and others, 1994). The term "paleoflood hydrology", however, is also appropriate for studies of documented floods (modern or historical) that employ the same methodological procedures.

The slackwater deposit-paleostage indicator (SWD-PSI) method of paleoflood reconstruction produces the most accurate estimates of paleoflood magnitudes (Baker 1989). It involves the integration of various types of high-water indicators (slackwater deposits and paleostage indicators) into a step-backwater modeling routine such as HEC-2 (Hydrologic Engineering Center, 1985) to obtain discharge estimates. Slackwater deposits consist of accumulations of silt, sand, and occasionally gravel that fall rapidly out of suspension in areas of reduced flow velocity during floods (Kochel and Baker 1988). Other paleostage indicators include features not uniquely sedimentary in origin, including: flotsam lines, piles of flood debris, flood scars on vegetation, upper limits of erosion on canyon side slopes, flood-related vegetation distributions, and evidence for non-inundation (for detailed explanations of the SWD-PSI method see: Baker 1987; Stedinger and Baker 1987; Kochel 1988; Kochel and Baker 1988; O'Connor and Webb, 1988; and Baker, 1989). Computed water surface profiles are compared to the elevations of the high-water indicators, and a discharge, or range of discharges, is estimated through a visual assessment of the best overall agreement between the predicted profile and the high-water indicators in the modeled reach (O'Connor and Webb, 1988).

This approach is similar to other, more conventional approaches to indirect discharge estimation (Benson and Dalrymple 1967; Dalrymple and Benson, 1967), but it does differ in some important respects. Paleoflood studies place stronger emphasis on choosing reaches with stable or easily inferred boundary conditions. This aspect of site selection is driven by model assumptions and the fact that such stable channel settings are the most conducive to the long term preservation

of flood evidence (Baker and Kochel, 1988). Also, most recent paleoflood studies have used step-backwater modeling as opposed to the slope-area method.

The step-backwater method is preferred in the context of paleoflood reconstruction because of the model structure. Water surface profiles calculated by the step-backwater method are solely a function of discharge, channel geometry, and selected energy-loss coefficients. Cross sections are located to best characterize the channel geometry. Therefore, the calculated water-surface profiles are independent of the paleostage (high-water) evidence. In contrast, in the slope-area method, the water-surface profile is specified by the high-water marks, and the discharge is determined by the hydraulic characteristics of the channel and the specified water-surface profile. While this may seem preferable, there are two important problems associated with specifying the water-surface profile on the basis of high-water marks: 1. the estimated discharge is especially sensitive to the accuracy of the high-water marks; and 2. the cross sections used to define the channel geometry are restricted to locations of high-water evidence.

Assumptions

The set of limiting assumptions in the SWD-PSI method combines those associated with the flow model and with its application in the paleoflood context. The principal assumptions are as follows (modified from O'Connor and Webb, 1988; Hoggan 1989; and Baker, 1989): (1) flow is steady, gradually varied, and one dimensional; (2) the channel cross-section boundaries are stable; (3) the energy slope is uniform between cross-sections; (4) the cross-section characteristics and the estimated energy loss coefficients are representative of those affected by the flood(s) in question; (5) the high-water marks accurately represent the stage of the flood(s) in question– slackwater deposits represent a minimum peak flood-stage, but other types of paleostage indicators may represent the highest water surface (flotsam), or provide a maximum bound on the peak stage (e.g. some flood scars, or evidence of non-inundation); (6) finally, it is assumed that a either a negligible amount of scour or deposition has occurred in the channel in the time since the flood peak, or any that has occurred can be accounted for in some way.

Obviously, many of these assumptions apply to most types of indirect discharge estimation; however, their relative importance increases with the amount of time that has passed between the occurrence of the flood(s) and the attempts to reconstruct them. Focusing the modeling efforts in

bedrock canyons helps to minimize the violation of most of the assumptions and the effects of time-variant changes in channel geometry.

Energy Loss Coefficients

The selection of energy loss coefficients for indirect estimates of the peak discharges of extreme floods is a process fraught with uncertainty (e.g. Jarrett, 1984, 1987). We visually estimated roughness coefficients for our modeling from the basis of engineering convention. There are no verification studies of roughness coefficients for large floods in this specific type of environment. In certain situations, the uncertainty about roughness was reduced because we concluded that critical flow conditions existed at channel constrictions in the Bronco Wash and Greenwood Wash reaches. Under critical depth conditions, the discharge is independent of the roughness coefficient. However, in other portions of these reaches, and the entire Bronco Creek reach, the selection of roughness coefficients has a significant effect on the estimated discharges.

We assume that the ranges of values used in each reach are reasonable according to engineering convention, but they may actually be underestimated. Jarrett (1984) developed an empirical equation for estimating n in high gradient channels by comparing data from 75 sites in Colorado:

$$n = 0.39S^{0.38} R^{-0.16} \quad (1)$$

The equation is applicable for streams with slopes from 0.002 to 0.052, and hydraulic radii from 0.15 to 2.13 m.

According to equation (1) the values we used in each reach may be understated by as much as 50% as will be shown in the site descriptions to follow. However, the applicability of the equation to backwater conditions above the constrictions is questionable (Jarrett, 1984) as is its applicability to steep, ephemeral streams in arid regions. The use of the equation (1) to determine Mannings n values in our modeling efforts would reduce the estimated discharges.

Final Discharge Selection

In the each of the three Bronco Creek basin sites described below, we were able to identify abundant evidence of maximum flood stages. In attempting to identify the effects of the 1971 flood, we emphasized the highest discernible evidence of flooding in each reach. Because of the relatively recent occurrence of the event, we found numerous delicate high-water marks (i.e.

flotsam). We relied primarily on the flotsam deposits becasue they are likely to accurately mark the maximum stage of the flood that emplaced them.

Slackwater deposits identified in each reach were used as supporting evidence for the selection of the highest flotsam deposits. Due to their relationship to the associated flood, they are taken to represent the minimum water surface elevation. Recent work on the 1993 floods in Arizona indicates that slackwater deposits can be as much as 2 meters below the water surface (as defined by flotsam deposits) of the flood that emplaced them (House and others, unpublished data). The average difference was found to be about 1 meter. The distribution of similar high-water indicators in the three Bronco Creek reaches is consistent with this observation.

We also used discernible scour marks and trim lines on confining canyon walls and adjacent hillslopes to constrain the maximum water surface elevation at sites where these features were present. As in the case of flotsam deposits, these features are typically close to the maximum flood stage or slightly above it due to the nature of their emplacement. Trim lines, or erosional scars in hillslope materials, often indicate mass movement involving material slightly above the peak flood stage in a manner similar to flood-related bank failures along alluvial streams. Both trim lines and scour marks commonly occur in areas of local wave action or superelevation of the water surface and thus their elevation may be more accurately representative of the total energy of flow (i.e. the elevation of the energy grade line) (O'Connor and Webb, 1988).

In most paleoflood studies, particularly those based principally on the use of slackwater deposits of some antiquity, discharges are reported as ranges inferred from bracketing high-water marks between successive water surface profiles (O'Connor and Webb 1988, Baker, 1989). In this study, we relied primarily on diagnostic evidence of peak flood stage (flotsam), and secondarily on slackwater deposits. Our goal was to provide the most precise maximum estimate possible within the constraints of the paleoflood methodology. Thus, our reported estimates represent the highest reasonable discharge for each site.

Bronco Wash

The Bronco Wash site is a bedrock canyon reach characterized by a tight constriction in the middle segment. The constriction occurs as a v-shaped notch formed in a resistant bedrock ridge. Above the constriction, flotsam and slackwater deposits are in a configuration suggesting that ponding develops during high flows. Thus we treated the constriction as a critical depth section.

High-water marks adjacent to the channel enabled us to establish the depth of flow in the constriction. Above and below the constriction, the channel is characterized by some coarse bed load (cobbles to boulders) and smooth but irregular protrusions of bedrock in the stream bed. The constricted sections were characterized by smooth bedrock floors and walls. We chose *n* values for the channel bottom ranging from 0.04 to 0.06. Estimated values for the confining walls ranged from 0.04 to 0.08 based on the amount of vegetation. Equation (1) predicts a composite value of 0.12 for this reach.

The computed water surface profile is compared to the high-water marks in figure 3a. We modeled subcritical flow in two sub-reaches separated by the short reach of assumed rapidly varying flow just below the constriction. The lower reach is approximately 35 m (115 ft) long and characterized by 3 cross-sections, the upper reach is approximately 25 m (82 ft) long and characterized by 4 cross-sections. An excellent match was obtained for the constriction, and a reasonable match for the reach immediately upstream. The computed profile is about 1 m higher than the highest slackwater deposits above the constriction. The downstream water-surface profile approximately matches two high-water marks. The estimated peak discharge is 215 $m^3 s^{-1}$ (7600 $ft^3 s^{-1}$).

Greenwood Wash Site

Like the Bronco Wash reach, the Greenwood Wash reach consists of a bedrock canyon with a pronounced constriction. In Greenwood Wash the constriction is located at the downstream end and also corresponds to the brink of a 2 m waterfall. For these reasons we believe that the flow was critical at the constriction. We chose *n* values very similar to those used in modeling Bronco Wash. The channel was characterized by scattered, coarse bed load and irregular protrusions of bedrock. The constricted sections were characterized by smooth bedrock floors and walls. We chose *n* values for the channel bottom ranging from 0.04 to 0.06. Values for the confining walls ranged from 0.04 to 0.08 based on the amount of vegetation. Equation (1) predicts a composite value of 0.12 for this reach.

We modeled flow through 6 cross-sections in a reach approximately 36 m (118 ft) long. The water surface profiles corresponding to our analysis are shown as figure 3b. In this instance we show both the predicted subcritical and supercritical flow profiles for the same discharge. The relationship between the high-water indicators and each profile is suggestive of a composite

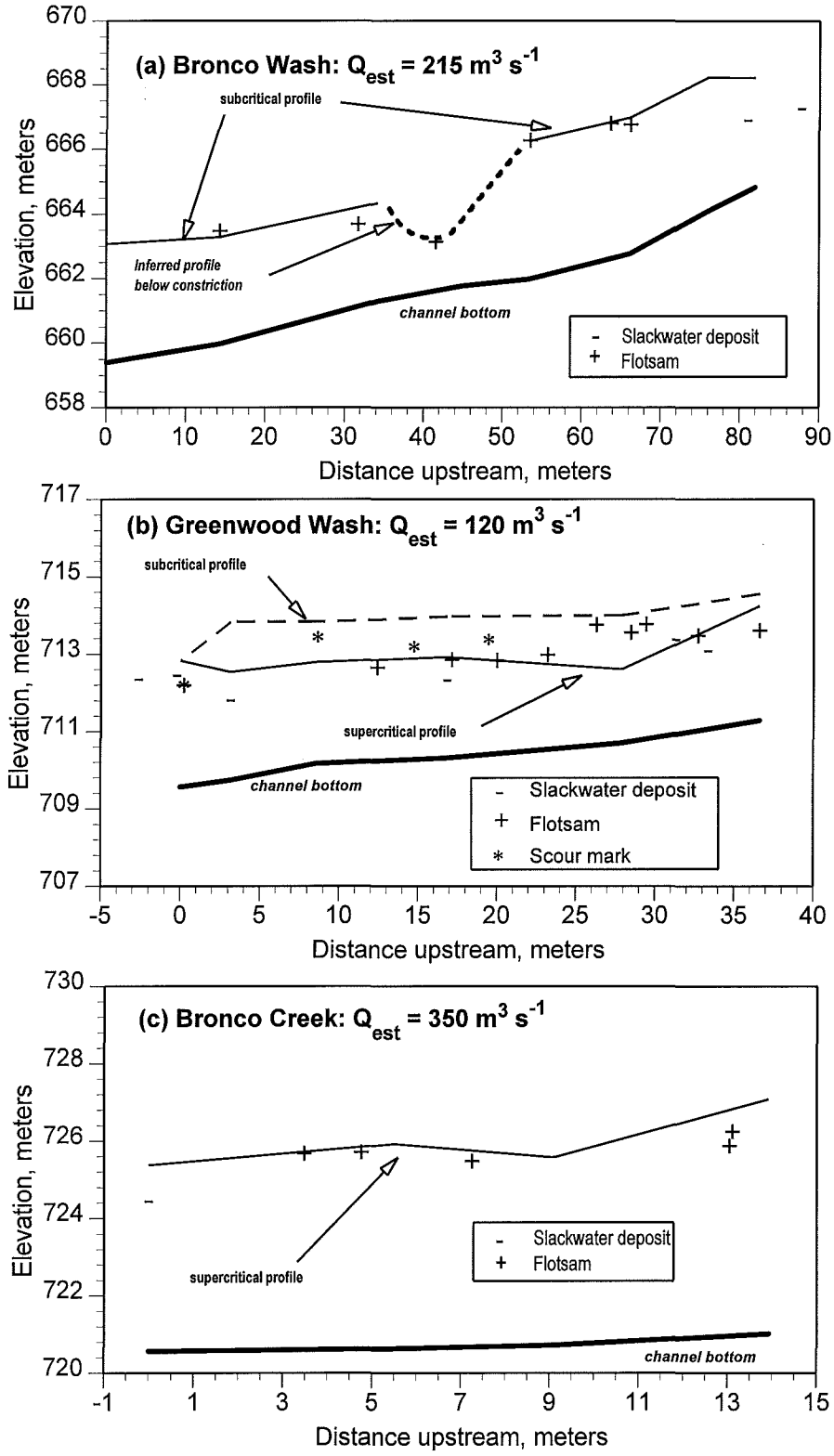

Figure 3. Water surface profile and high- water indicator comparison for each of the sub-basin study reaches.

profile with two undular hydraulic jumps, one in the upper portion of the reach and the other at the downstream end due to the constraint provided by the constriction. The discharge estimate for this reach is 120 $m^3 s^{-1}$ (4240 $ft^3 s^{-1}$).

Bronco Creek Site

The Bronco Creek site differs from the previous ones in that it contains no control section. In trying to maximize the contributing drainage area we were limited to one relatively short reach characterized by nearly vertical bedrock walls and a flat bottom. The reach is essentially a deep, smooth, bedrock chute so we used a composite *n* value of 0.035 for the entire reach. Equation (1) predicts a composite value ranging from 0.07 to 0.11 for this reach; however, the hydraulic radius for each section is slightly larger than the maximum value for which the equation was verified.

We modeled flow through 4 cross-sections in a reach approximately 15 m (49 ft) long. Because of the characteristics of the reach (short, steep, straight, and smooth), we concluded that a supercritical profile would be the most appropriate. We achieved a good match of the profile for 350 $m^3 s^{-1}$ (12,360 $ft^3 s^{-1}$) with several deposits of flotsam located along the margin of a horizontal bedrock bench along the right margin of flow approximately 6 meters above the channel bottom (figure 3c). The relatively high discharge estimate obtained for this reach is supported by extensive channel modification in Bronco Creek in the upper basin and in the long alluvial reach above the confluence with Bronco Wash. The assumption of supercritical flow in this reach makes the discharge estimate a definite maximum.

The Role of Contributing Drainage Area in Affecting the Peak Discharge

Site selection in this analysis was a compromise between identifying reaches with stable boundaries and maximizing the contributing drainage area to each site. This resulted in an 18% decrease in the drainage area contributing to our sites as compared to that contributing to the site of the original estimate. It may generally be expected that the smaller contributing drainage area associated with our estimate would produce a correspondingly lower peak discharge; however, we believe that the sub-basin estimates probably account for most, if not all of the flood runoff.

Small-scale aerial photos (1:129,000) taken approximately 1 year after the flood reveal striking channel modifications wrought in portions of the Bronco Creek watershed and adjacent basins. Stereoscopic analysis of these photos under 4x magnification allows for a qualitative

assessment of channel change due to the flood and therefore of the likely source area for the runoff. The photos show that tributary channels in the upper and middle portions of the basin and the entire length of the trunk streams that convey runoff out of the basin were subject to severe modification due to the flood runoff. Evidence for modification includes cleared channels appearing as bright white streaks in black and white photos and altered channel patterns evident from comparison with earlier photographs. For example, in an alluvial stretch of Bronco Creek in the upper Bronco Creek sub-basin there is clear photographic evidence for major channel modifications where the channel is crossed by Chicken Springs Road (see figure 2). We visited this site and found abundant geomorphic evidence attesting to the large magnitude of the 1971 flood. No tributary reaches in the lower portion of the basin appear to have been similarly modified. Using this evidence of channel change, the photos suggest that the majority of the flood runoff originated in the upper and middle portions of the basin. Therefore, our estimates probably include most, if not all of the drainage area that contributed to the flood. Field inspection by one of the original investigators several weeks after the flood corroborates our conclusion (H.W. Hjalmarson, written communication, 1994 and unpublished data, 1971).

Our analysis of the post flood photographs also indicates that two basins adjacent to the divide of the Bronco Creek watershed, Devils Canyon and Groom Spring Wash, and at least one further to the west, Graveyard wash (see figure 1), may have been affected by the same series of storms and experienced large floods. In the case of the Devils Canyon and Groom Spring Wash watersheds the relation is the most clear and direct due to its contiguity to the upper portion of the Bronco Creek watershed where the storm was probably concentrated; however, evidence for flooding in the non-contiguous basin, though clear in photo comparisons, cannot be as easily related to the Bronco Creek event. This information coupled with the lack of obvious channel changes in tributaries draining the lower portion of the basin argues for an upper basin source area.

Correction for Omitted Area

We applied a correction factor to account for the 18% difference in drainage area in the unlikely event that it did contribute significant runoff to the flood peak. The omitted area is slightly smaller than the drainage area of the Greenwood Wash sub-basin, so we multiplied it by the unit discharge of Greenwood Wash to obtain the value 113 $m^3 s^{-1}$ (4020 $ft^3 s^{-1}$). Adding this to

the other sub-basin estimates gives the total estimated basin runoff value of 800 $m^3 s^{-1}$ (28,200 $ft^3 s^{-1}$). Because this correction may give an exaggerated estimate by invoking flow that did not occur, we believe that it effectively accounts for potential uncertainties in each of the flow estimates, and that the composite value represents a reasonable maximum.

There are several aspects of our composite peak discharge estimate that make it relatively generous: (1) we assume that the hydrographs from each sub-basin combined such that the total peak is equal to the sum of the three peaks; (2) in the correction for the omitted drainage area described above, we used the unit discharge of a discrete sub-basin to estimate the discharge associated with a non-integrated portion of the watershed that corresponds almost entirely to hillslope source areas in the lower basin; (3) in estimated the peak discharge at each site, we assumed critical and supercritical flow conditions, thus resulting in maximum estimates; (4) in estimating the cumulative discharge, we are assuming negligible infiltration and attenuation in the alluvial reaches below each site and in the wide, 3.2 km alluvial reach that leads to the bridge; and (5) we used roughness coefficient values in portions of the reaches that may be underestimated by as much as 50%.

Other Constraints on the Peak Discharge

There are three additional constraints on the peak discharge of the Bronco Creek flood. Each is independent of the reconstructions performed in carrying out this study and is supportive of a lower discharge than that originally reported.

Highway 93 Bridge Crossing

The US Highway 93 bridge crossing provides an independent means of assessing the relative accuracy of the original discharge estimate and the composite estimate from our analysis. The bridge causes a major contraction and has a stable geometry (except for the bed elevation). Thus the bridge opening served as a hydraulic control on the flood. The original investigation used this site as support for the slope-area estimate; however, the assumed critical-depth section was located upstream of the constriction (Aldridge, 1972, 1978; and USGS, unpublished data, 1972). It is more likely that the critical section would be located somewhere within the constricted reach (e.g. Chow, 1959, p. 475).

In addition to the geometry of the bridge crossing, there is more specific evidence attesting to the hydraulic constraint provided by the contraction. The original field survey notes show that the drop in the water surface through the bridge constriction approached 5.8 m (19 ft) (Aldridge, 1978). Furthermore, local ponding or "pile-up" of flow at the upstream side of the bridge can be inferred from the original survey data, an eyewitness account, and post-flood photographs. Given these lines of evidence, it is reasonable to assume that critical depth was probably crossed somewhere within the bridge constriction. The reach hydraulics probably consisted of supercritical flow some distance upstream of the bridge (including the slope-area reach) that eventually passed through a hydraulic jump to subcritical flow where the impinging flow was backed-up at the upstream side of the bridge. The radical drop in the water surface through the bridge marks the transition back to supercritical flow which probably continued downstream until the channel reached the Big Sandy River floodplain (see Chow 1959, p. 475 figure 17-14d, for a representative profile). The original critical section was located at a site of probable subcritical flow above the bridge.

We also evaluated our estimate with a simple analysis of the flow hydraulics through the bridge. Using the stable bridge geometry and a discharge of 800 $m^3 s^{-1}$ (28,200 $ft^3 s^{-1}$) we calculated a critical depth of approximately 3 m (10 ft) associated with the geometry of the constriction. Figure 4 shows the water surface profile above and below the bridge as taken from the original survey notes and from figure 3 in Aldridge (1978). The profile shown through the bridge is our inference. The location of the original critical section upstream of the bridge is identified and the critical depth profile associated with 800 $m^3 s^{-1}$ through the constriction is also shown. Clearly, the flow profile crossed this depth somewhere in the constriction. This is not conclusive evidence for that specific discharge, but the most plausible hydraulic situation inferred from this scenario is commensurate with a lower discharge. In fact, an early report on the original study noted that a velocity in excess of 23 m s^{-1} (75 ft s^{-1}) would have been required to convey the estimated discharge of 2080 $m^3 s^{-1}$ at the estimated depth of 1 m in the reach just downstream from the bridge (Aldridge 1978). This physically untenable situation should have been interpreted as an indication that the discharge estimate was probably too high.

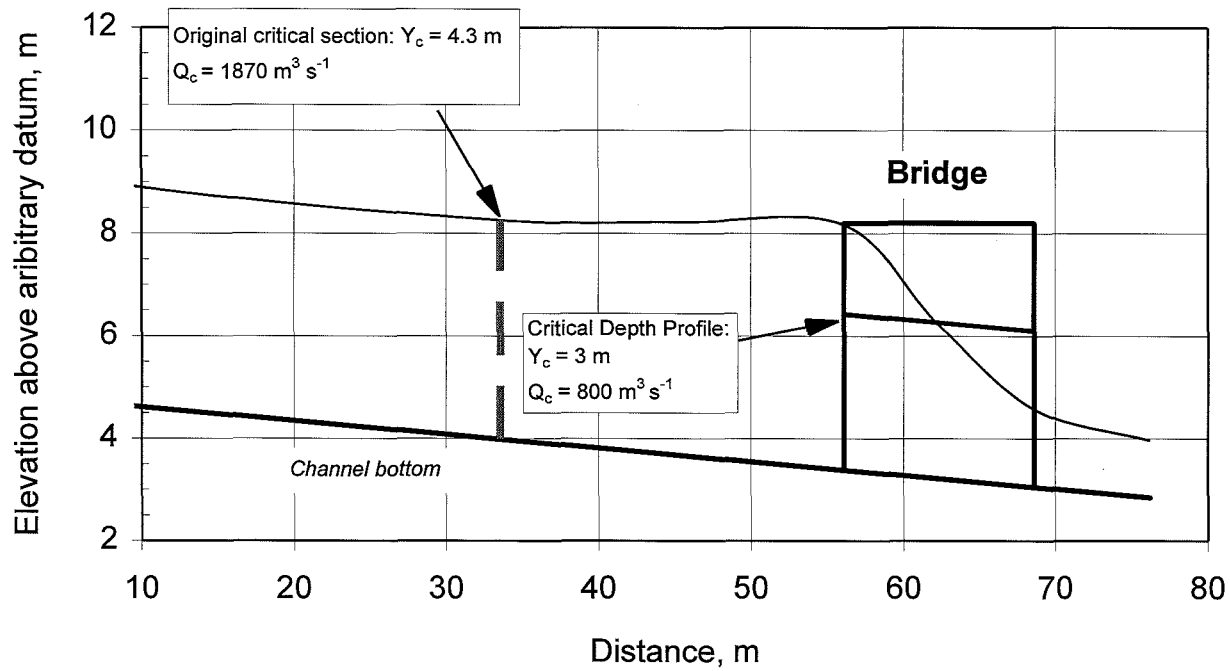

Figure 4.
Water surface profile of the Bronco Creek flood through the US Highway 93 bridge crossing (data taken from Aldridge, 1978, and USGS, unpublished data, 1971). The plot identifies the location of the original critical-depth section and shows the profile corresponding to the critical depth associated with the new composite discharge estimate of 800 $m^3 s^{-1}$ through the constriction. The water surface profile through the bridge is an inference based on the estimated depths above and below the bridge reported by the original field party.

An Independently Derived Composite Discharge

About 2 weeks after the flood, the chief investigator of the original field party independently assessed the magnitudes of the flows emanating from the 3 major sub-basins of the Bronco Creek watershed. He obtained a composite discharge estimate of 1100 $m^3 s^{-1}$ (38,000 $ft^3 s^{-1}$) using 1-section slope-conveyance calculations in alluvial reaches downstream from the sites that we studied (H.W. Hjalmarson, personal communication, 1994, and unpublished data, 1971). This composite estimate was obtained from alluvial reaches using an approximate method that often exaggerates peak discharge (Jarrett, 1987).

Meteorological and Hydrological Evidence from Other Sites

We noted previously that the Big Sandy River recorded its annual maximum peak discharge of 292 $m^3 s^{-1}$ (10,380 $ft^3 s^{-1}$) at 11:00 PM August 19, the day of the Bronco Creek flood. The gage is less than 31 km (19 mi.) downstream from the mouth of Bronco Creek. Of that length, approximately 25 % is within a narrow, bedrock canyon, the remainder is in a broad alluvial channel. If the original discharge estimate for Bronco Creek constituted the bulk of that peak discharge, it would have been attenuated by more than 85%.

The Bronco Creek flood probably did not constitute all of the runoff on the Big Sandy River on August 19. Limited regional peak flow data indicates that other small tributary basins experienced flooding that day. Two meteorological stations within the watershed of Burro Creek (1580 km^2), the largest tributary to the Big Sandy River (see figure 1), recorded 6.1 cm and 2.5 cm of precipitation on the 19th, respectively. Also recall that there is evidence suggesting that basins contiguous with the Bronco Creek watershed were subject to precipitation from the same series of storms and probably also experienced large flow events. Streams draining these basins enter the Big Sandy River about 21 km (13 mi.) below the mouth of Bronco Creek.

The Big Sandy River hydrograph for the period August 19 through August 21, 1971 has two distinct peaks (figure 5) that may indicate the occurrence of extreme flooding from both sides of the drainage divide along the perimeter of the Bronco Creek basin. The first peak at the Big Sandy gage is probably related to the floods generated in Devils Canyon and Groom Spring Wash, which enter the Big Sandy channel 6.4 km (4 mi.) and 2.4 km (1.5 mi.), respectively, above the gage (figure 1). The Devils Canyon and Groom Spring Wash flood waves would reach the gage

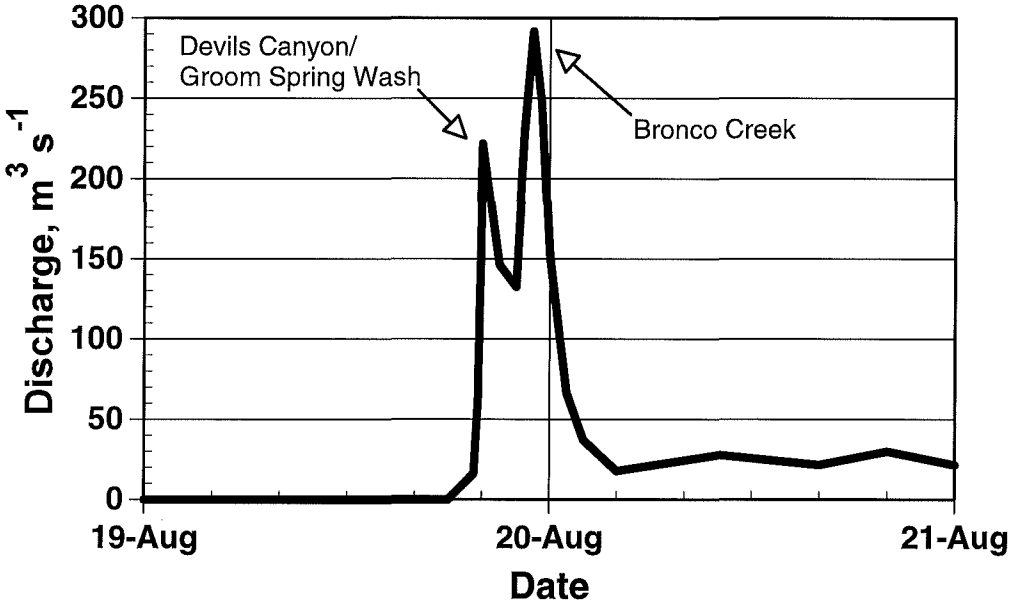

Figure 5.

Flood hydrograph for the Big Sandy River (USGS gage #09424450) for the period 12 AM, August 19, 1971, through 12 AM, August 21, 1971. The two flood peaks on August 19 are 220 $m^3 s^{-1}$ at 8 PM and 290 $m^3 s^{-1}$ at 11 PM, and are inferred to be from Devils Canyon and Bronco Creek, respectively.

before the Bronco Creek flood wave because of shorter travel distances through relatively high-gradient tributary channels.

The Big Sandy hydrograph is useful in evaluating the magnitude of the Bronco Creek flood. The Bronco Creek flood wave was superposed on the latter portion of the Devils Canyon/Groom Spring Wash flood hydrograph, and probably on portions of hydrographs from other tributaries of the Big Sandy. Thus, the Big Sandy's hydrograph is a composite of flood hydrographs from a variety of sources, not solely Bronco Creek. The argument for attenuating a flood discharge from 2080 to 294 $m^3 s^{-1}$ in a 30 km long channel is thus further strained by the necessity to account for other, potentially large sources of inflow and the consequent superposition of flood hydrographs.

Impact of Channel Change on Peak Discharge Estimates

The composite discharge estimate from this study differs from the original USGS estimate by nearly a factor of three. We propose that the major contributing factor to this large difference is that the original estimate is based on post-flood channel characteristics (roughness and geometry) not representative of those of the channel when it conveyed the peak discharge. This problem is particularly critical in the analysis of peak flow in alluvial streams (e.g. Jarrett, 1987; Quick, 1991). Dynamic adjustments that occur in the bed and banks of an alluvial stream during the passage of a flood wave may result in the final geometric configuration being very different from that associated with the peak discharge.

The channel segment where the first estimate was made underwent a dramatic change in morphology as a consequence of the flood (figure 6). Vegetated bars were completely removed or buried by sediment and the channel pattern was transformed from braided with multiple channels to a single, wide, straight channel. Varying amounts of bank widening occurred throughout the reach, and a large fan was deposited below the mouth of Bronco Creek which obliterated riparian vegetation and buried a meander bend of the Big Sandy River. These facts have been noted previously(Aldridge 1972, 1978), but their potential impacts on the estimated discharge were not assessed.

We documented amounts and types of channel modifications in the lower reach of Bronco Creek using large-scale pre-flood (November, 1963) and post- flood (September, 1971) photographs (1: 24,000 and 1:8,000 respectively). We used stereoscopic analysis of the two

photographs in figure 8 to quantify the types and amounts of change that occurred. The principal types of changes involved removal of vegetated bars and channel widening. Measurements of change were made at 13 sections along the reach shown in the photos (figure 7). The graphs show the variation in total channel width and cleared channel width from 1963 to 1971. It is likely that all of the changes are due to the 1971 flood. The "cleared width" line is the increase in the width of channel areas with no significant vegetative cover. It is primarily a proxy for the change in channel roughness, although it probably also accounts for a significant change in channel geometry. The "total width" line is the amount of bank retreat along the perimeter of the reach. It represents the amount of channel widening that occurred and is thus primarily a geometric variable. The locations of each section used in the slope-area computation are also shown on the plot. The modeled reach was most drastically affected by a change in cleared width, but significant changes in total width also occurred.

In establishing an indirect estimate for an extreme flood in this type of channel, one must make some critical, untestable assumptions concerning the timing of the transformations in roughness and geometry. The most critical assumption is that the post-flood channel geometry is essentially the same as that during the peak discharge. This assumption is particularly tenuous in alluvial channels in which the synchronous attainment of maximum discharge and maximum cross-sectional area is unlikely. Alluvial channels respond dynamically to the passage of a flood wave. The bed and banks are progressively modified by the flow. The timing of the attainment of maximum depth, stage, cross-sectional area, and discharge is probably variable both among different streams and among floods in the same stream. It is possible that, due to lateral and vertical scour, the maximum discharge in an alluvial channel may actually be associated with a flood stage lower than that inferred from the highest water surface indicators in the reach. The highest high-water marks may be emplaced by overbank flow preceding maximum scour in the channel.

In the reach chosen for the slope-area calculation, channel widening occurred; however, the most significant change in the reach involved the removal of bars and vegetation. The morphological alterations of the channel of Bronco Creek must certainly have had a pronounced effect on the channel conveyance, a fundamental component of the discharge calculation. For example, if it is assumed in section #4 (see figures 6 and 7) that the depth of flow was 2 m, the

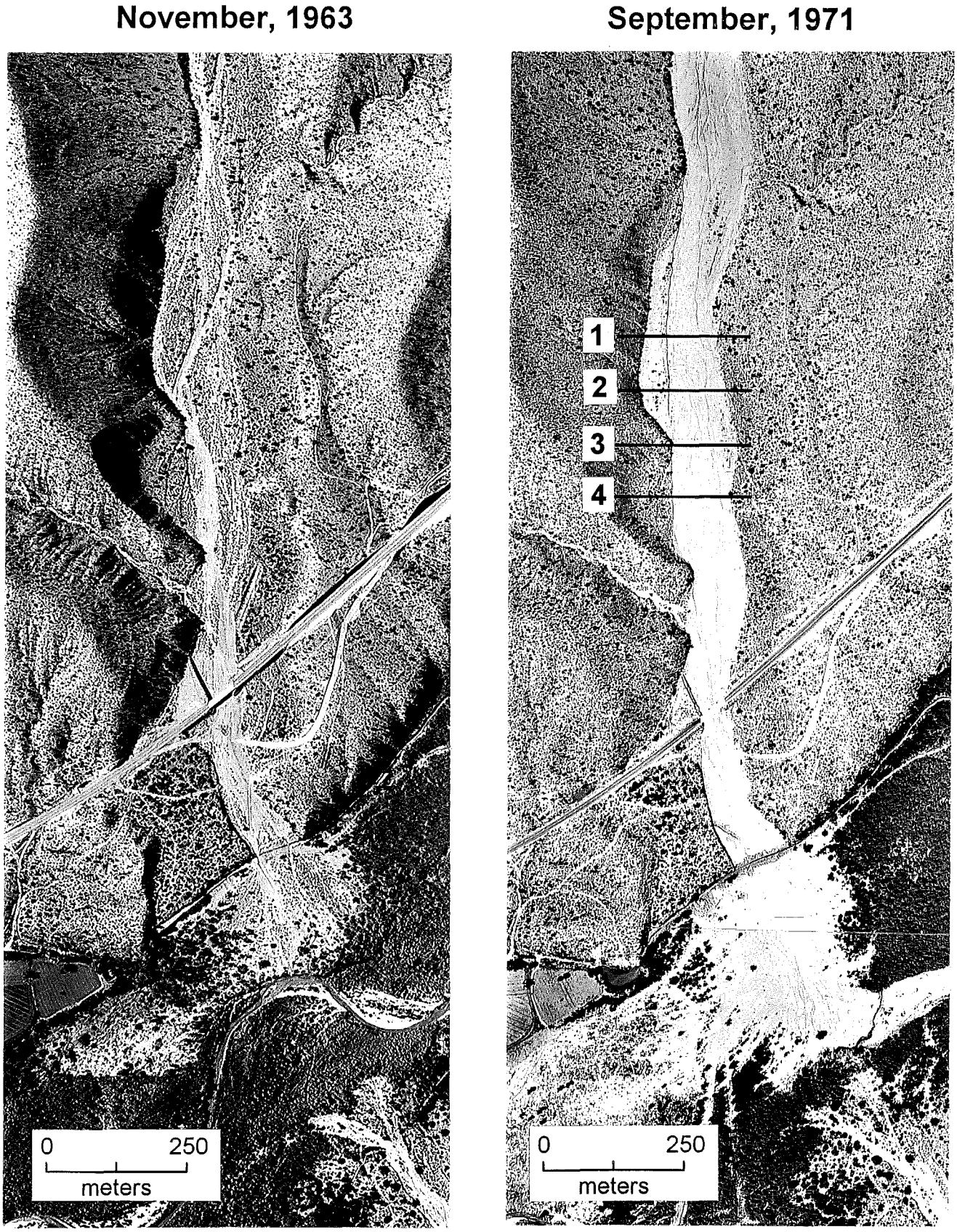

Figure 6. Comparison of aerial photographs of the lower reach of Bronco Creek. The pre-flood photo is from November, 1963, and the post-flood photo is from September, 1971. Note in particular the amount of channel clearing, the large fan deposited below the mouth, and the location of the slope-area reach.

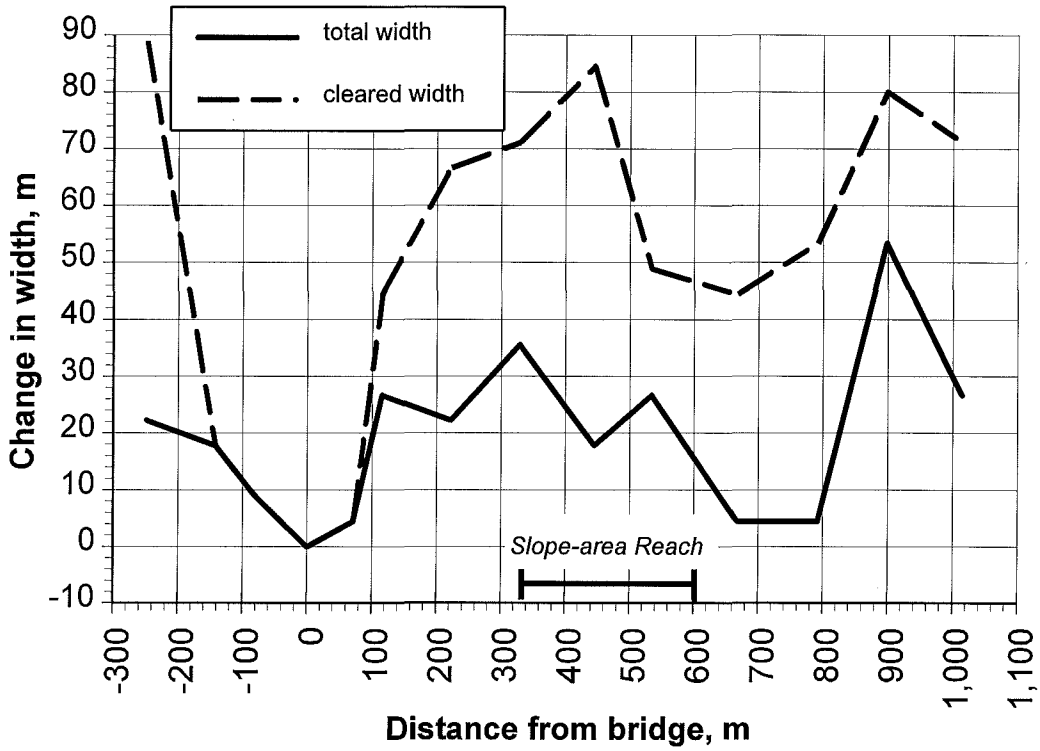

Figure 7.
Graph showing the amount of channel change due to the 1971 flood measured at 13 sections along the length of the lower reach of Bronco Creek. Measurements were made using stereoscopic analysis of pre-flood and post-flood aerial photographs shown in figure 6. See text for explanation of "total width" and "cleared width".

amount of bank retreat accounts for an area of about 70 m^2. Taking an average bar elevation of 1 m, the maximum amount of cross-sectional area accounted for by bar removal is also about 70 m^2. This results in a maximum change in cross-sectional area of 140 m^2 or slightly more than 56% of the post flood value of 250 m^2 (USGS, unpublished data 1971). Combining this with the effect of the potential underestimation of the roughness coefficient would lower the estimated discharge considerably.

An extension of the channel geometry problem involves channel roughness. In general, the selection of roughness coefficients is a largely subjective procedure. In a stream with the morphological characteristics of Bronco Creek there is little basis for making a truly informed decision (Glancy and Williams, 1994). We are not aware of any study that has verified Mannings *n* for an extreme flood in a wide, steep, ephemeral, sand and gravel bedded alluvial channel. In the case of Bronco Creek, this already tenuous procedure was further complicated by the fact that the channel underwent a striking morphological transformation during the flood. This profound change probably had a major effect on the effective roughness of the channel due to the removal of hundreds of shrubs and small trees as well as changes in channel alignment (figure 8). Developing an estimate of roughness based on the post-flood configuration of the channel requires the assumption that the pre-flood roughness elements were completely obliterated before the peak occurred. This scenario is unlikely because the removal of some material (particularly rooted plant material) is a progressive phenomenon occurring throughout the passage of the flood wave.

Regional Flood-Drainage Area Relationships

The over-estimation of the peak discharge of the Bronco Creek flood does not negate the fact that it was an exceptionally large flood for the region. Each of the new estimates (sub-basin and composite) is in accordance with the maximum flood discharge-drainage area trend defined by paleoflood, historical, and gaged flood data from Arizona (figure 8). The envelope curve shown in figure 8 has been proposed as an approximation of some type of physical limit on flood magnitudes in the lower Colorado River basin (Enzel and others 1993). The consistency of the relationship between the new Bronco Creek estimates and the regional envelope supports this hypothesis. It also underscores assertions made by previous authors that any flood estimate

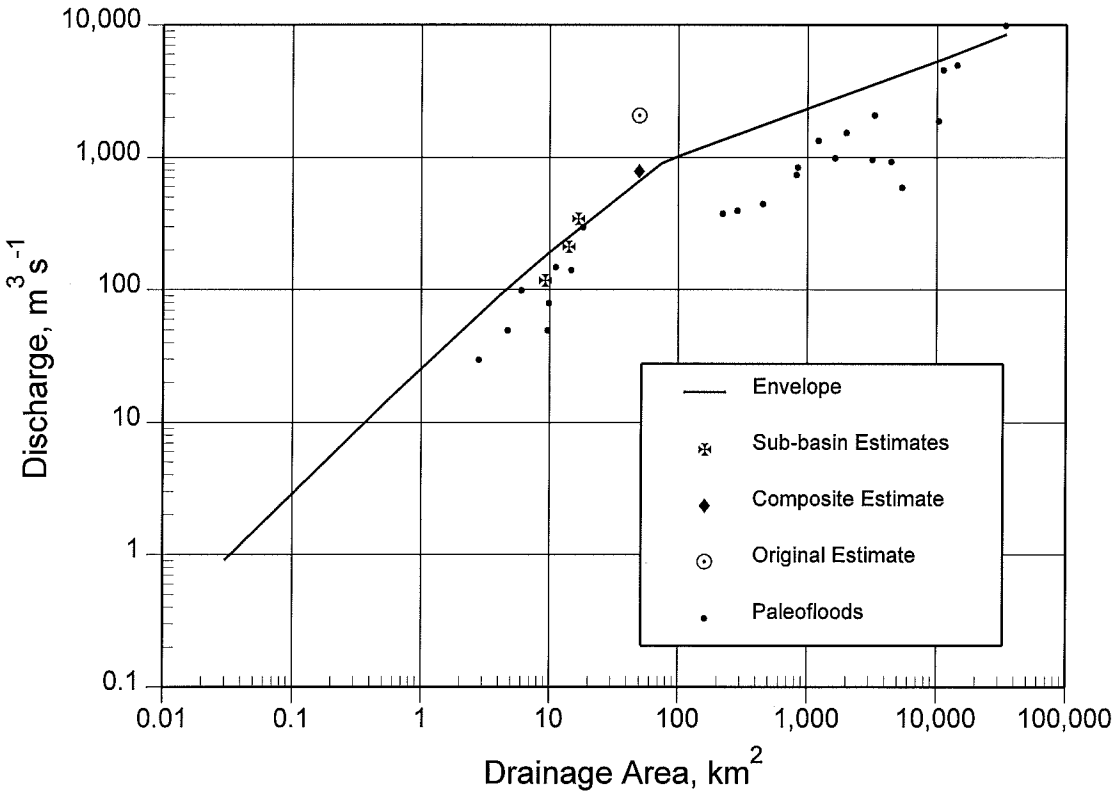

Figure 8.
Comparison of the original Bronco Creek flood estimate, the new sub-basin estimates, and the new composite estimate (corrected for omitted drainage area) to the envelope curve of the maximum gaged floods, historical floods, and paleofloods in the Colorado River Basin (modified slightly from Enzel and others, 1993).

exceeding the value approximated by a regional envelope curve with a sufficiently broad spatial and temporal data base should be evaluated for potential errors in estimation (Wolman and Costa 1984, Costa 1987a, and Enzel and others 1993).

The original Bronco Creek flood estimate is one of two significant regional outliers that depart sharply from the general trend; the Eldorado Canyon, Nevada flood of September, 1975 is the other (Glancy and Harmsen 1975). Its estimated magnitude is remarkably similar to that of the Bronco Creek flood: 2152 $m^3 s^{-1}$ from 59.3 km^2 compared to 2080 $m^3 s^{-1}$ from 49.2 km^2. The two watersheds are similar in terms of basin morphometry and general location. For these reasons the two estimates are often presented as mutually reinforcing examples of the potential magnitude of extreme floods that can occur in small basins in arid portions of the southwestern United States. Based on the results of our research we believe that the Eldorado Canyon flood is the sole regional outlier.

Conclusion

We have presented a variety of hydraulic, hydrologic, and meteorologic evidence indicating that the original estimate for the Bronco Creek, Arizona flood of August 19, 1971 was overestimated by nearly a factor of three. The primary reason for this overestimation was the selection of an alluvial reach for the indirect determination of discharge. The subsequent acceptance of such an anomalously high discharge was due to failure to critically evaluate it in the context of other types of readily available information.

In this paper, we have demonstrated a multifaceted approach to assessing the accuracy of indirect flood discharge estimates. We propose that some variation of this approach should be used to check flood magnitudes that depart markedly from regional flood characteristics, or that imply unlikely hydraulic and hydrologic phenomena.

Providing accurate assessments of magnitudes of extreme floods from small, mountainous basins in the southwestern United States is extremely important. Little data exists for this type of physical setting even though it is ubiquitous in the region. Much of the development in the Southwest exists and continues to take place on piedmont areas directly below this type of drainage basin. Thus the need for reliable data on the magnitudes of rare floods is clear. However, the need for good data transcends practical questions of public safety and the economics of

avoiding over-design of hydraulic structures and improperly zoned floodplains. Developing a realistic perspective on the actual ranges of extreme flood magnitudes in different environments is of critical importance to the scientific advancement of the study of floods. If the primary data of interest are not at least approximately correct, then it is likely that any related conclusions are unreliable.

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