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Paleohydrology of flash floods in small desert watersheds in western Arizona

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Abstract. In this study, geological, historical, and meteorological data were combined to produce a regional chronology of flood magnitude and frequency in nine small basins (7–70 km^2). The chronology spans more than 1000 years and demonstrates that detailed records of flood magnitude and frequency can be compiled in arid regions with little to no conventional hydrologic information. The recent (i.e., post-1950) flood history was evaluated by comparing a 50-year series of aerial photographs with precipitation data, ages of flood-transported beer cans, anthropogenic horizons in flood sediments, postbomb ^{14}C dates on flotsam, and anecdotal accounts. Stratigraphic analysis of paleoflood deposits extended the regional flood record in time, and associated flood magnitudes were determined by incorporating relict high-water evidence into a hydraulic model. The results reveal a general consistency among the magnitudes of the largest floods in the historical and the paleoflood records and indicate that the magnitudes and relative frequencies of actual large floods are at variance with "100-year" flood magnitudes predicted by regional flood frequency models. This suggests that the predictive equations may not be appropriate for regulatory, management, or design purposes in the absence of additional, real data on flooding. Augmenting conventional approaches to regional flood magnitude and frequency analysis with real information derived from the alternative methods described here is a viable approach to improving assessments of regional flood characteristics in sparsely gaged desert areas.

1. Introduction

Worldwide, minimal data exist concerning the magnitude and frequency of flash floods in small desert watersheds (1–100 km^2). Thus determining the magnitude and frequency of flash floods in these areas with real flood information is often impossible. Western Arizona offers a case in point. This region has no stream-gaging network at present, and that which once existed was extremely sparse and maintained for less than 15 years. The density of meteorological stations in the region is also extremely sparse in relation to the overall spatial variability of rainfall typical of most desert areas [e.g., *Sharon*, 1972; *Osborn and Laursen*, 1973]. The only practical means by which the flood hydrology of this desert region can be evaluated using real flood information is through augmentation of the minimal "official" data with regional historical and paleoflood data on the magnitude and frequency of large floods over a broad range of time.

This paper outlines the results of an attempt to characterize the flood hydrology of a remote portion of the Sonoran Desert in western Arizona using an unconventional approach. The research effort involved the collection, analysis, and integration of paleoflood and historical flood data to decipher the magnitude and frequency characteristics of large flash floods in nine small watersheds ranging in drainage area from 9.7 to 68.5 km^2 (3.7 to 26.4 miles^2) in the Buckskin, Rawhide, and Artillery Mountains of west central Arizona (Figure 1). At each site, paleoflood stratigraphy was examined and compared to evidence relating to historical and recent occurrences of large floods. The temporal range of the flood data is more than 1200 years, constituting a significant and otherwise unattainable improvement in the scope of the available data on large floods in this region.

2. Overview of Region

The Buckskin, Rawhide, and Artillery Mountains are a series of desert mountain ranges separated by irregular alluvial basins along the lower Bill Williams River in western Arizona. The lithology of the mountains includes a range of igneous, metamorphic, and sedimentary rocks typical of a cordilleran metamorphic core complex [*Spencer and Reynolds*, 1989]. The intervening alluvial basins include a suite of late Tertiary and Quaternary alluvial deposits preserved as multiple levels of deposits and geomorphic surfaces including thick alluvial fills and thin alluvial veneers on planated bedrock surfaces. The Bill Williams River is a large regional drainage (area ~12,000 km^2) that bisects the study area and joins the Colorado River at Lake Havasu. Net downcutting by the Bill Williams through the Quaternary induced deep incision along all its small tributaries. This physiographic configuration is particularly well suited to a regional paleoflood study of small basins.

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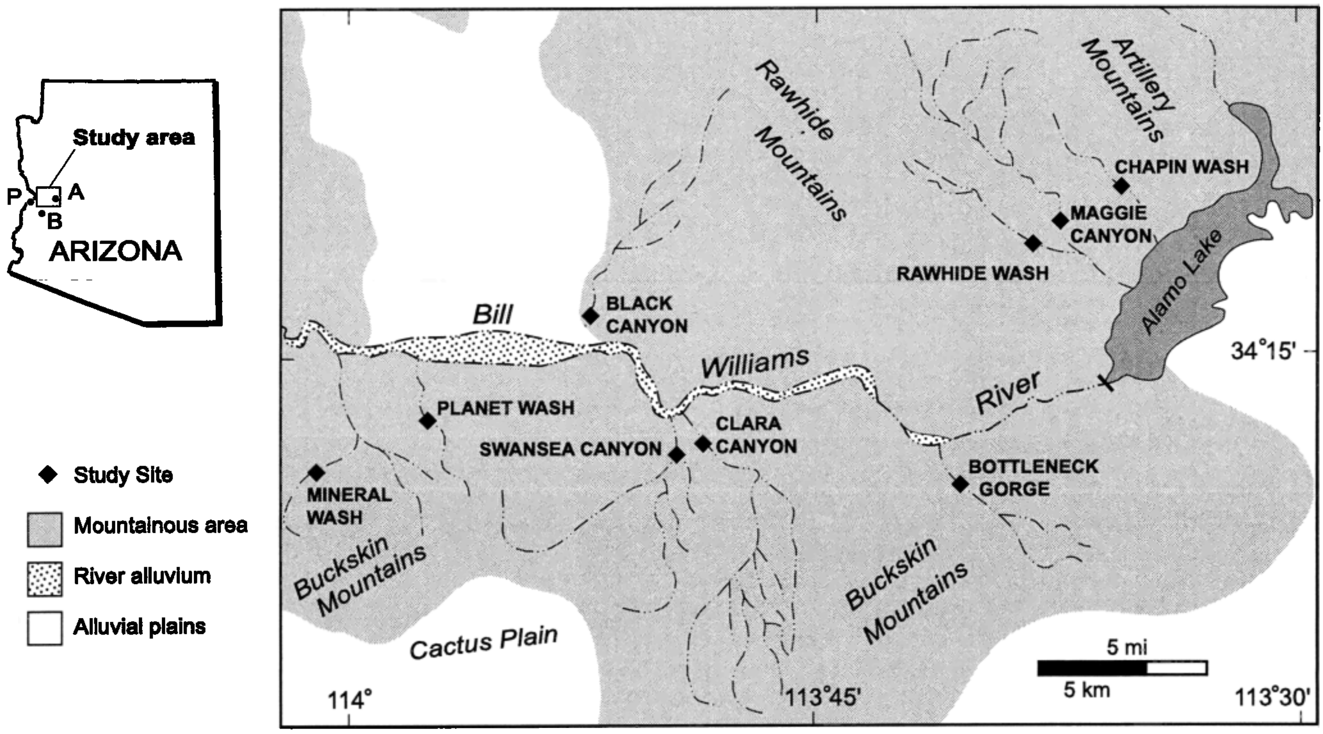

Figure 1. Maps showing the location of the study area in western Arizona and the location of the nine study sites. The sites of the nearest meteorological stations are shown on the inset map of Arizona (A, Alamo Dam; B, Bouse; and P, Parker).

2.1. Regional Flood Hydroclimatology and Hydrometeorology

The varied physiography of the Desert Southwest and its location between tropical and temperate latitudes result in a diverse flood regime [*Webb and Betancourt*, 1992; *Hirschboeck*, 1987]. Flooding in the region results from three primary storm types: (1) regional-scale winter frontal storms that frequently occur in late November through mid-March; (2) dissipating tropical cyclones that may occur in the late summer through early fall; and (3) widespread to commonly isolated convective thunderstorms from the "summer monsoon" that affects much of Arizona in early July through mid-September [*Sellers and Hill*, 1974; *Hirschboeck*, 1985, 1987; *Webb and Betancourt*, 1992].

2.2. Precipitation Characteristics

Annual precipitation data from meteorological stations in the general study area have a bimodal pattern with summer and winter maxima. The annual precipitation tends toward larger totals and higher intensities in the late summer and early fall because of summer thunderstorms and less frequent dissipating tropical cyclones. Evaluation of daily precipitation totals from the different storm types indicates that winter storms are almost always the least intense.

In low mountain ranges of west central Arizona, winter storms are the least likely to generate significant flooding because the area does not present a significant orographic influence to oncoming storms [*Hansen et al.*, 1977; *Hansen and Schwarz*, 1981]. The other two storm types can deliver large rainfall totals in absence of a strong orographic influence and result in the largest floods in the study area. The frequency of flooding from thunderstorms is probably higher because of the annual consistency in the occurrence of the summer monsoon; however, the regional impact of an extreme tropical cyclone related flood event is likely to be greatest [e.g., *Smith*, 1986; *Gatewood et al.*, 1946; *Durrenberger and Ingram*, 1978; *Roeske et al.*, 1978; *Aldridge and Eychaner*, 1984; *Saarinen et al.*, 1984; *Roeske et al.*, 1989].

3. Regional Flood History Reconstruction

The focus of this project was to reconstruct the magnitude and timing of flash floods using direct field evidence and indirect evidence from a variety of sources. The study area has physical and cultural characteristics that facilitated this effort. Culturally, the area has a history of mining and prospecting which increases the likelihood of finding cultural artifacts in association with historical flood deposits. Often, these artifacts can help constrain flood timing and occasionally may be useful in estimating peak stages of historical floods. Physically, the abundance of narrow canyons draining small, rugged basins into the Bill Williams River increases the likelihood of identifying several good quality paleoflood study sites in close proximity, and intermittent flows on the Bill Williams River periodically remove tributary flood deposits and create space for fresh and identifiable deposition. This also provides constraints on the timing of historical floods in the tributaries.

3.1. Paleoflood Hydrology

In a broad sense, paleoflood hydrology is the documentation and analysis of any type of physical evidence for flooding, geomorphic, sedimentologic, botanical, and cultural, for the purpose of extending flood records in time or generating records where none are otherwise available [e.g., *Baker*, 1987,

Table 1. Physical Characteristics of the Study Reaches

Site	Drainage Area, km^2	Number of Study Sites[a]	Control Section	Type of Control[b]	Scour[c]	Recent Flood Evidence	Paleoflood Stratigraphy
Planet Wash	6.9	1	likely	narrow section	no	yes	on site
Chapin Wash	9.6	1	yes	choke	no	yes	on site
Mineral Wash	12.4	1	yes	narrow section	no	yes	on site
Bottleneck Gorge	12.7	1	yes	choke	no	yes	none
Rawhide Wash	14.7	1	yes	choke	no	yes	on site
Black Canyon	28.2	2	yes	narrow section	no	yes	remote site
Swansea Gorge	48.5	2	likely	narrow section	no	yes	remote site
Clara Canyon	66.3	1	yes	narrow section	yes	yes	on site
Maggie Canyon	68.5	1	yes	choke	yes	yes	on site

[a] Here "1" indicates that the modeling reach contained flood stratigraphy; "2" indicates that the flood stratigraphy was located outside of the reach (i.e., a remote site).

[b] "Choke" indicates that the reach contained a definite critical depth control section (i.e., a bottleneck); "narrow section" indicates the presence of a constricted portion of the reach through which the model consistently predicted critical flow.

[c] "Yes" indicates that bed scour in the modeling reach was a potential source of uncertainty in the estimation of discharge and that the likely maximum geometry was used in the modeling.

1989; *Baker et al.*, 1988; *Jarrett*, 1991]. Data types used in this paleoflood study ranged from sedimentary flood deposits and other physical flood-related features (relict flotsam and erosion marks) to aerial photographs and cultural flotsam as diagnostic flood evidence. For extensive descriptions of paleoflood hydrology, see *Baker* [1987], *Kochel and Baker* [1988], *O'Connor and Webb* [1988], and *House and Pearthree* [1995].

3.2. Site Selection

The selection of appropriate study sites was a key element of this project. Because of their limited extent and typically high gradients, canyons draining small desert basins in southern and western Arizona generally are not characterized by good exposures of paleoflood stratigraphy, and rarely have records in excess of a few hundred years been reported (see discussions by *House* [1991] and *Martinez-Goytre et al.* [1994]). To minimize these limitations, this study was restricted to an area with the best potential to identify several good sites in close proximity.

A series of color, black and white, and color infrared aerial photographs was used to select study sites. Approximately 70 potential sites were identified and investigated in the field. Nine sites were studied in detail on the basis of the following criteria: presence of flood stratigraphy, geometry amenable to hydraulic modeling at or near the site of stratigraphy, evidence for a relatively recent large flood (i.e., within approximately the last 25 years), and accessibility. The nine sites chosen for detailed investigation are identified in Figure 1, and some of their important characteristics are described in Table 1.

3.3. Evaluation of Constraints on Flood Timing

To constrain the timing and relative frequency of flooding at each site as tightly as possible, we used a mixture of conventional and unconventional types of analysis. These included historical aerial photographs, anecdotal and historical accounts of flooding, regional hydrometeorological data, diagnostic, flood-borne cultural artifacts (mining debris and beer cans), and radiometric dating.

3.3.1. Aerial photograph chronology. A 42-year chronology of aerial photographs covering most of the study area was evaluated. The temporal range of the entire set of photographs was 1953–1995 and included photographs from 1953, 1964, 1972, 1973, 1976, 1978, 1979, 1980, 1985, 1987, 1992, 1993, and 1995. The photographs include a variety of scales (ranging from 1:6000 to 1:80,000) and film types (black and white, color, and color infrared).

The desert is an ideal environment for using aerial photos to ascertain flood timing because changes in channel characteristics are typically quite easy to detect. Also, in this example each study site is tributary to the Bill Williams River and terminates in the main channel of the river or on a flanking alluvial terrace. Large tributary floods result in either the deposition of an alluvial fan in the main channel of the river or produce changes in the terminal alluvial fan on a fluvial terrace (Figure 2). These changes are usually clearly recognizable on aerial photographs. Moreover, for those tributaries that deposit directly in the Bill Williams River, its intermittent flows periodically remove the sediment and create space for fresh deposition. Streamflow records can constrain the timing of floods or the duration of intervals with no flooding in periods that fall between the dates of the aerial photographs. Intermittent removal of deposits can also obliterate evidence of flooding that may have occurred between the photograph dates prior to a flow event in the Bill Williams. This approach can only provide a qualitative assessment of flood magnitude, but it serves a useful purpose when combined with inferences supported by other dating methods.

For each of the sites examined in this study, the photographs were examined in sequence, and changes (or lack thereof) from photograph to photograph were noted. In some cases, inadequate photograph coverage was a hindrance, and in the case of some extremely narrow gorges that empty into Alamo Lake (as of 1969), evaluating flood-related channel change using aerial photographs is not possible, and fluctuations in the lake level over time obliterate flood evidence at the canyon mouths.

3.3.2. Using historical artifacts to constrain the timing of large floods. Historical artifacts transported by or disturbed in some way by floods can be used to constrain the timing of flooding. In western Arizona, discarded beer cans are common artifacts found in association with recent flood deposits. Cans with discernible features can be dated with a resolution of generally 10 years to 1 year. Beer cans first went into mass production in 1936–1937 [*Cady*, 1976; *Martells*, 1976]. This effectively limits the maximum potential dating error to about 60 years; however, the oldest can collected in this study dates from approximately 1962, thereby establishing a maximum po-

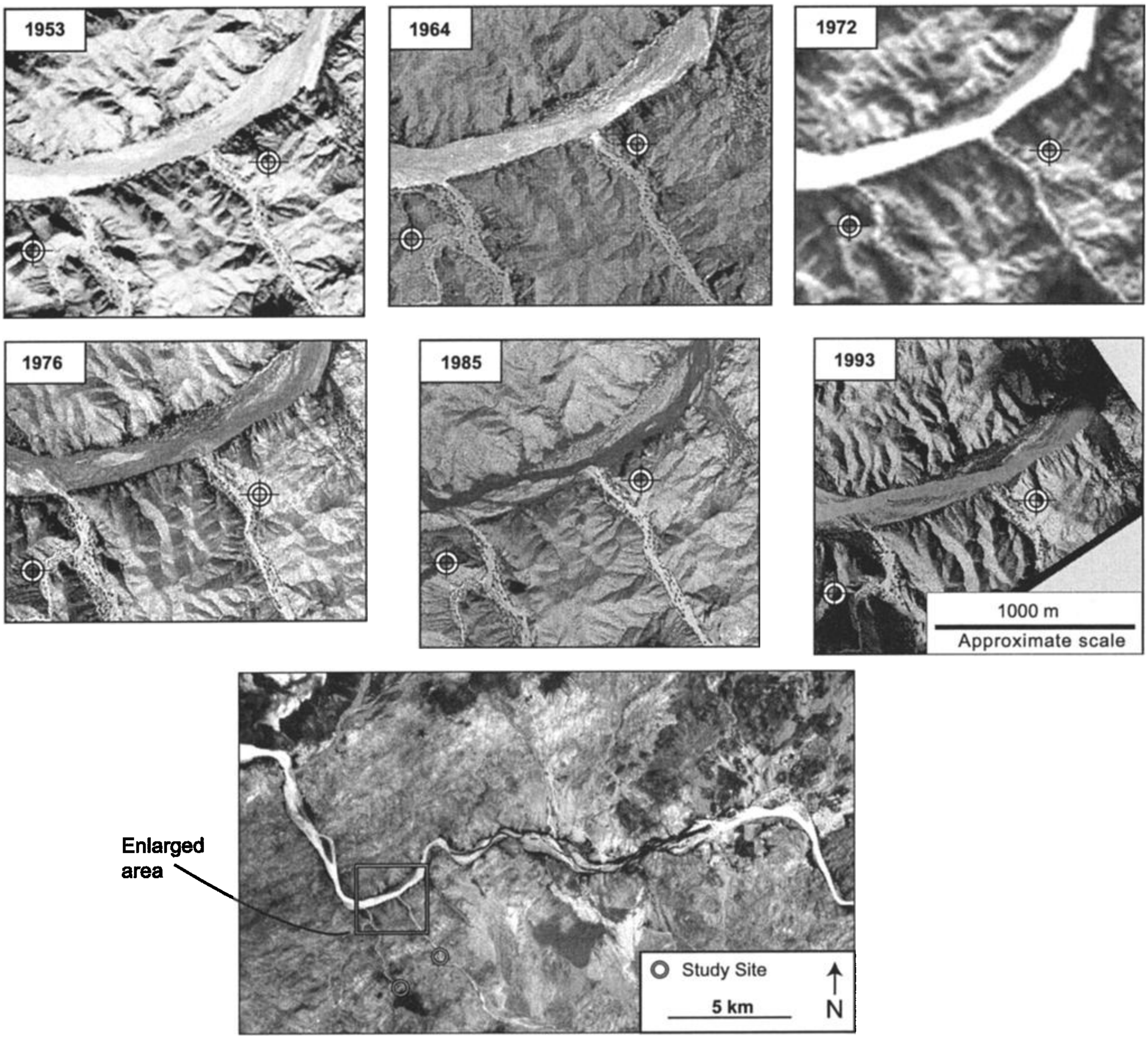

Figure 2. Comparative chronology of aerial photographs showing the mouths of (left) Swansea Gorge and (right) Clara Canyon where they debouch directly into the narrow canyon of the Bill Williams River. Scale is approximate as the photographs have been digitally manipulated for the best match. Note that the registration marks on each photograph indicate the same two points on the ground. Explanation of the photograph sequence is as follows: 1953, area below mouths completely cleared by prior flows on the (undammed) Bill Williams River; 1964, evidence for small fans (thus low to moderate flash floods) below mouths; 1972, areas cleared by last uncontrolled flood down Bill Williams River in 1969 (poor legibility at this scale but complete clearing of the channel is obvious in original photographs); 1976, large amount of deposition below mouth of Swansea Gorge and moderate to large amount below Clara Canyon; 1985, fans from 1976 still in place and modified by low flows on Bill Williams River; and 1993, photograph during "large" dam release down Bill Williams River (7000 feet^3/s or ~200 m^3/s), fans from 1976 flash floods being reworked and modified by flow but still somewhat intact. The smaller-scale photograph showing the location of the area of comparison is from 1972.

tential error of 34 years. This can be reduced through corroboration with other evidence. The residence time of a can in the fluvial system prior to being entrained in a flood is unknown and is the largest source of uncertainty.

Eleven identifiable, flood-borne beer cans collected in this project ranged in age from the early 1960s to the late 1980s. Beverage industry sources were consulted to determine the production date of each can. The production date of a flood-borne beer can provides a maximum age for the flood in question. Many cans have diagnostic design characteristics that can be dated. Older, weathered cans are often datable only by changes in can manufacturing and label design. With more recent cans it is possible to establish their exact date of manufacture from diagnostic label coding. Other diagnostic indications that can establish good age constraints include the following: the addition of the Surgeon General's warning (mandated November 1989), can contents expressed in metric units (around 1977), introduction of new brands, and changes in the style of the can opening (date varies).

3.3.3. Precipitation records. Precipitation data from the three meteorological stations closest to the study area, Parker, Bouse, and Alamo Dam (see Figure 1), also help to constrain the timing of some recent flood events. When these data are combined with other dating methods (aerial photographs and beer cans), some floods can be assigned to a likely calendar date. For example, if the timing of a flood can be confidently bracketed using the aerial photographs, then the precipitation records from the closest stations can be examined to identify periods of high precipitation totals. Daily precipitation amounts in excess of 50 mm (approximately 2 inches) were considered potential candidates for flash flooding in the period of interest (no hourly precipitation data were available from the stations). This value was selected arbitrarily as representative of above average precipitation to reflect relatively intense rainfall in the region and can only be considered as a proxy for an increased likelihood of flooding at one of the study sites.

In the period of record considered in this analysis, years with significant regional precipitation that directly impacted the three nearest meteorological stations include 1951, 1980, 1993, and 1995 (winter storms); 1951, 1976, and 1983 (tropical storms); and 1955, 1957, 1963, 1964, 1971, 1982, 1988, and 1995 (monsoon storms). The tropical storms and winter storms are regional in nature and are the most reasonably represented by the station data, but the scattered nature of summer thunderstorms in this and other desert regions [*Sharon*, 1972] ensures uncertainty because intense rainfall at one or more of the meteorological stations is not necessarily accompanied by intense rainfall at one of the study sites.

3.3.4. Stratigraphic analyses. Analysis of flood deposit stratigraphy can extend flood records significantly back in time. Stratigraphic sequences of fine-grained flood deposits can persist in desert canyons for hundreds to thousands of years in appropriate settings, usually small, protected areas where flow separation and suspended sediment deposition occurs during large floods. Good, but typically isolated, sites of paleoflood stratigraphy were identified at eight of the nine sites. At two sites the stratigraphy was not in an appropriate reach for flow modeling (Swansea Gorge and Black Canyon). In such instances, attempts were made to relate the modeling results from a nearby, more suitable reach to the flood stratigraphy.

Small trenches were excavated in flood deposits at each site. Typically, the flood deposits were examined near the outermost discernible edge of the uppermost deposit to ensure that the largest floods recorded at the site were recognized. Most of the stratigraphic sections that were encountered consisted of predominantly vertical stacks of flood deposits, although inset deposits were described at some sites.

Individual deposits were delineated using conventional stratigraphic and sedimentological criteria including distinct changes in grain size, induration, bioturbation, and/or coloration and the presence of intercalated hillslope colluvium [*Baker*, 1987, 1989; *Kochel and Baker*, 1988]. Occasionally, distinct marker horizons associated with tributary flooding or human disturbance (mining, in particular) were noted. These deposits were useful in establishing some limiting temporal constraints. In most cases, differentiation of individual flood deposits was relatively straightforward. However, because of bioturbation, pedogenesis, and the possibility for very thin deposits or only shallow flooding, it is impossible to be confident that every individual flood is recorded, or even left a record. Representative examples of stratigraphic sections described in this study are shown in Figure 3.

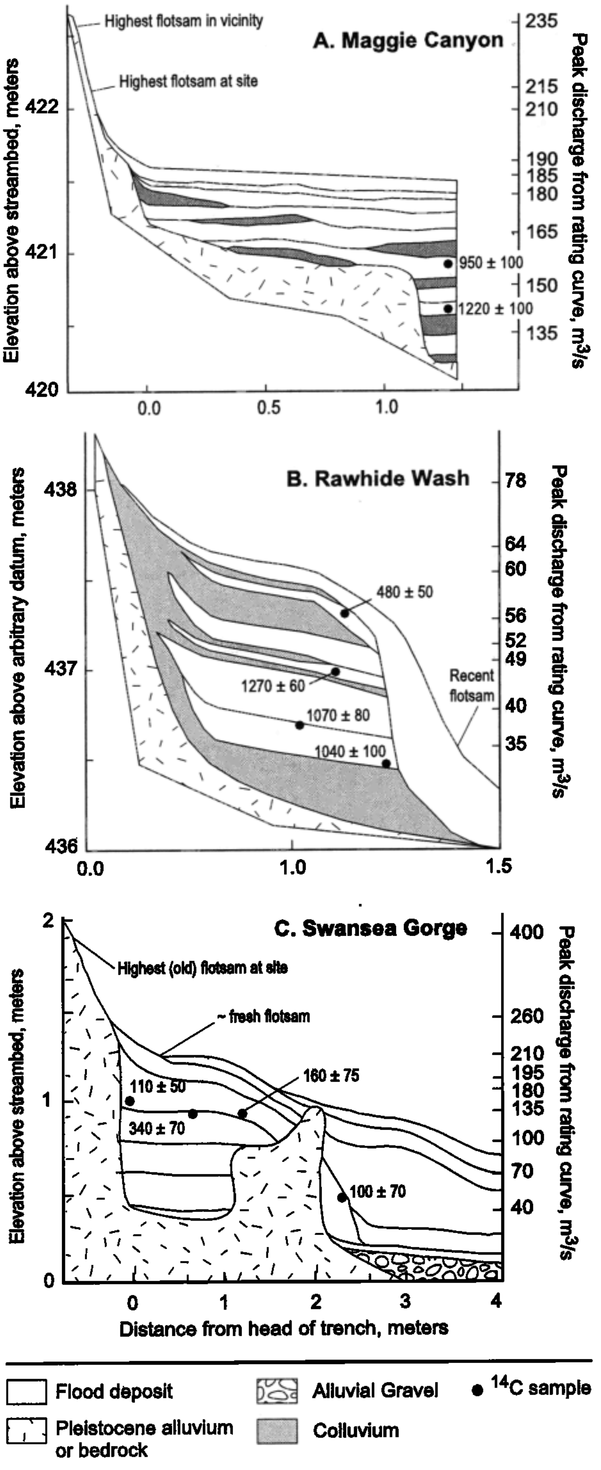

Figure 3. Flood stratigraphy of three representative sites. Note that scales and vertical exaggeration vary. Radiocarbon ages are shown in conventional years B.P. Rating curve from step backwater modeling of surveyed reach is shown along the right axis. Figure 3 is modified from *House* [1996].

3.3.5. Radiocarbon dating of flood deposits. Radiocarbon dating is the most commonly employed dating method in paleoflood studies [e.g., *Baker et al.*, 1988; *Ely et al.*, 1992; *Ostenaa et al.*, 1996]. Charcoal is often present in desert flood deposits. Uncharred organic detritus is less common. Important sources of uncertainty are associated with the interpretation of dates from charcoal found in or between flood deposits. Age estimates for detrital charcoal in fluvial sediment can give erroneous results if the intention is to precisely constrain the age of the flood. It is possible that charcoal can reside in a fluvial system prior to entrainment by a flood, and its actual age could possibly predate the age of the event by tens to hundreds of years [e.g., *Blong and Gillespie*, 1978].

In the course of this project, 22 datable samples were collected from flood deposits. Both in situ (inferred from abundance and position at stratigraphic contacts) and detrital charcoal was encountered. Conventional and calibrated dates are listed in Table 2 and depicted graphically in Figure 4. The time ranges in Figure 4 correspond to the 2σ error. Dates of 11 samples fall in the range of 1950 A.D. to 350 years B.P., an uncertain period for radiocarbon dating because of large changes in the global carbon budget. Calibrated ages from this interval are associated with several potential age ranges, and this can complicate interpretations, particularly if no older dates are available from lower in the section.

Also included in Table 2 are calibrations for post-1950 ("postbomb") dates for five detrital organic samples collected from recent flood deposits. Atmospheric nuclear bomb testing in the 1950s and 1960s increased ^{14}C activity in the troposphere to greater than 100% of normal in the early 1960s. These large, short-lived variations in ^{14}C activity allow for accurate age determinations by comparing the sample's ^{14}C activity to a curve of tropospheric ^{14}C activity appropriate to the latitude of the site. This method has achieved presumably annual resolution of flood dates in some arid region settings [*Baker et al.*, 1985] and has provided age estimates ranging from 1 to 25 years from assumed correlative flood dates in other settings [*Ely et al.*, 1992]. Values corresponding to multiple dates can be constrained with other types of information.

3.4. Flood Magnitude Estimation

The method of calculating paleoflood discharge described by *O'Connor and Webb* [1988] and *Baker* [1989] was employed in this study. The approach involves integrating paleoflood evidence into a step backwater modeling routine and inversely estimating discharge by comparing paleostage evidence with discharge-dependent water surface profiles.

3.4.1. Assumptions. The assumptions in calculating paleoflood discharges have been discussed extensively in the literature and are reviewed only briefly below. Modeling assumptions include the following [from *O'Connor and Webb*, 1988; *Hoggan*, 1989]: Flow is steady, gradually varied, and one-dimensional; channel geometry is stable; the energy slope of the peak flow is uniform between cross sections; and energy loss coefficients can be accurately estimated. Two assumptions are particularly relevant to paleoflood reconstruction: (1) Paleoflood evidence related to paleostage slackwater deposits represents a minimum peak flood stage, but other types of evidence may represent the peak water surface (flotsam) or provide a maximum bound on the peak stage (e.g., some flood scars or evidence of noninundation), and (2) scour or deposition in the channel over the time frame of the paleoflood record is negligible or can be accounted for in some way [*O'Connor and Webb*, 1988; *Baker*, 1989; *House and Pearthree*, 1995]. Restricting analysis to bedrock canyons reduces the violation of most of the assumptions.

3.4.2. Collection of topographic data. The hydraulic model requires accurate topographic information. Basic model input includes a sequence of channel cross sections, and use of the model for indirect discharge estimation requires the spatial arrangement of all extant historical and paleoflood evidence. In this investigation, up to 300 ground points in addition to explicit cross sections were surveyed in each reach to generate topographic maps to guide in cross-section location for modeling. This is a useful approach that ensures flexibility in characterizing the reach. An example of a topographic map used in the study is shown in Figure 5.

3.4.3. Flow modeling. The HEC-RAS step backwater flow-modeling package [*Hydrologic Engineering Center*, 1995a, 1995b] was used to calculate flood discharges. Model results from a range of discharges can be translated to rating curves at site(s) of the flood stratigraphy and other high-water evidence. Step backwater modeling in short, high-gradient reaches is subject to several uncertainties, in particular, the initial conditions (flow regime and starting water surface elevation) and the magnitude of energy loss coefficients. To minimize these, we chose sites with natural control sections. A particularly useful geometry was the "bottleneck," an extremely narrow constriction at the downstream end of a wider canyon. This type of reach is common in the study area. The bottleneck sections are hydraulic "chokes" and force the flow through critical depth, a condition with a unique relation to the peak discharge through the section. In open channels the state, or regime, of flow is defined by the Froude number (F):

$$F = v/\sqrt{gd},$$

where v is the average velocity, g is gravitational acceleration, and d is a length parameter related to the flow depth (either average depth or hydraulic depth). Critical flow is characterized by $F = 1$. In this situation the initial condition is known, and the discharge is a function of the channel geometry. Thus, if high-water evidence remains at the point where critical flow occurs, the discharge (Q_{yc}) can be readily computed given the cross-sectional area (A) and hydraulic depth (d) of the critical section:

$$Q_{yc} = A\sqrt{gd}.$$

However, it is not always likely that diagnostic high-water evidence will persist or even be deposited at the critical section; more likely, high-water evidence in this setting will be located in the hydraulically ponded zone upstream. Modeling uncertainties in this situation are reduced by the presence of a known condition at one of the cross sections in the reach.

The bottleneck sections offer a virtual guarantee of critical flow. They are also often associated with the accumulation of abundant fine-grained sediment and other high-water marks upstream from the constriction in areas well above and beyond the active channel. In reaches without bottleneck sections the presence of narrow cross sections in their middle or lower portions was a selection criterion. Although less severe than the bottlenecks, such constrictions were assumed to be likely control sections. In each case this presumption was supported by the flow modeling.

3.4.4. Energy loss coefficients. The flow model requires an estimate of channel roughness or Manning's n for the study reach. The selection of appropriate n values is problematic in

Table 2. Summary of Radiocarbon Ages for Samples Collected in This Study

Sample	Laboratory Code	Fraction Modern	$\partial^{13}C$	Radiocarbon Age, years B.P.	Calibrated Age, years B.P.[a]	Probability[b]
BC2-108	AA-17832	0.961 ± 0.0074	−24.5	320 ± 60	400 ± 50	0.773
					325 ± 15	0.227
BC2-145	AA-17833	0.947 ± 0.0055	−23.1	435 ± 50	495 ± 35	1
CC-411	AA-17167	0.967 ± 0.0069	−24.7	270 ± 60	395 ± 40	0.552
					310 ± 25	0.389
					162 ± 5	0.059
CCKH-7	AA-17034	0.953 ± 0.0057	−24.9	390 ± 50	470 ± 35	0.806
					343 ± 12	0.194
MC-4	AA-20436	0.889 ± 0.0106	−25.6	950 ± 100	848 ± 87	1
MC-5	AA-20437	0.859 ± 0.0105	−14.8	1220 ± 100	1158 ± 100	1
MW-1	AA-17829	0.928 ± 0.0054	−22.5	600 ± 50	615 ± 30	0.855
					559 ± 6	0.145
MW-4	AA-17830	0.870 ± 0.0023	−25	1120 ± 215	1086 ± 179	0.9
					845 ± 13	0.06
					804 ± 8	0.04
MW-5	AA-17831	0.967 ± 0.0055	−25.4	275 ± 50	397 ± 33	0.58
					306 ± 21	0.42
PW-2	AA-16763	0.983 ± 0.0065	−25.9	135 ± 55	258 ± 15	0.169
					210 ± 24	0.271
					106 ± 39	0.444
					25 ± 11	0.117
PW-3	AA-16665	0.992 ± 0.0066	−24.4	60 ± 50	240 ± 15	0.25
					118 ± 19	0.23
					61 ± 29	0.52
PW-4	AA-16666	0.970 ± 0.0062	−22.5	240 ± 50	409 ± 13	0.112
					296 ± 24	0.474
					205 ± 2	0.042
					170 ± 24	0.318
RW-10	AA-20228	0.879 ± 0.0010	−21.8	1040 ± 95	976 ± 83	0.842
					846 ± 18	0.115
					804 ± 9	0.043
RW-11	AA-21961	0.883 ± 0.0055	−23.2	1000 ± 50	935 ± 31	0.678
					845 ± 15	0.227
					804 ± 7	0.095
RW-5	AA-20225	0.942 ± 0.0056	−22.1	480 ± 50	521 ± 20	1
RW-6	AA-20226	0.981 ± 0.0057	−24.2	155 ± 50	267 ± 13	0.183
					199 ± 27	0.344
					144 ± 8	0.119
					91 ± 15	0.158
RW-8	AA-21874	0.876 ± 0.0082	−23.1	1070 ± 75	991 ± 71	1
RW-9	AA-20227	0.854 ± 0.0063	−23.9	1270 ± 60	1224 ± 55	0.892
					1152 ± 10	0.108
SG-1	AA-20156	0.980 ± 0.0092	−21.6	160 ± 75	267 ± 16	0.152
					181 ± 47	0.505
					95 ± 21	0.185
					20 ± 14	0.157
SG-3	AA-20158	0.986 ± 0.0064	−24.9	110 ± 50	242 ± 21	0.27
					95 ± 45	0.602
					36 ± 11	0.128
SG-6	AA-21744	0.959 ± 0.0088	−23.4	340 ± 75	440 ± 23	0.287
					365 ± 49	0.713
SG-C	AA-20849	0.988 ± 0.0091	−25	100 ± 75	242 ± 25	0.29
					82 ± 60	0.71
CW-2	AA-21775	1.090 ± 0.0131	−25.9	postbomb	1956–1957	
PW-1	AA-16762	1.414 ± 0.0076	−23.2	postbomb	1961–1962	
					1963–1964	
					1974–1975	
BNG-6	AA-17032	1.318 ± 0.0081	−25.1	postbomb	1961–1962	
					1978–1979	
CC2-108	AA-8223	1.133 ± 0.0011	−22.8	postbomb	1958–1959	
CC4-1	AA-8294	1.021 ± 0.0006	−24.8	postbomb	1956–1957	

[a] Calibration is from computer program of *Stuiver and Reimer* [1993] and data set of *Stuiver et al.* [1998].

[b] Relative area under probability distribution is associated with data calibration results to 1σ.

indirect discharge estimation. Uncertainty related to *n* values is one of the largest sources of error in flood estimates from high-gradient natural channels because no data exist for verification of Manning's *n* for extreme flood discharges [*Costa*, 1987; *Jarrett*, 1987, 1994; *Wahl*, 1994; *Glancy and Williams*, 1994]. Uncertainty is reduced in the backwater conditions associated with the bottlenecks where the predicted water surface profile is relatively insensitive to changes in Manning's *n* over a broad range of values [see, e.g., *Jarrett and Malde*, 1987; *House and Pearthree*, 1995].

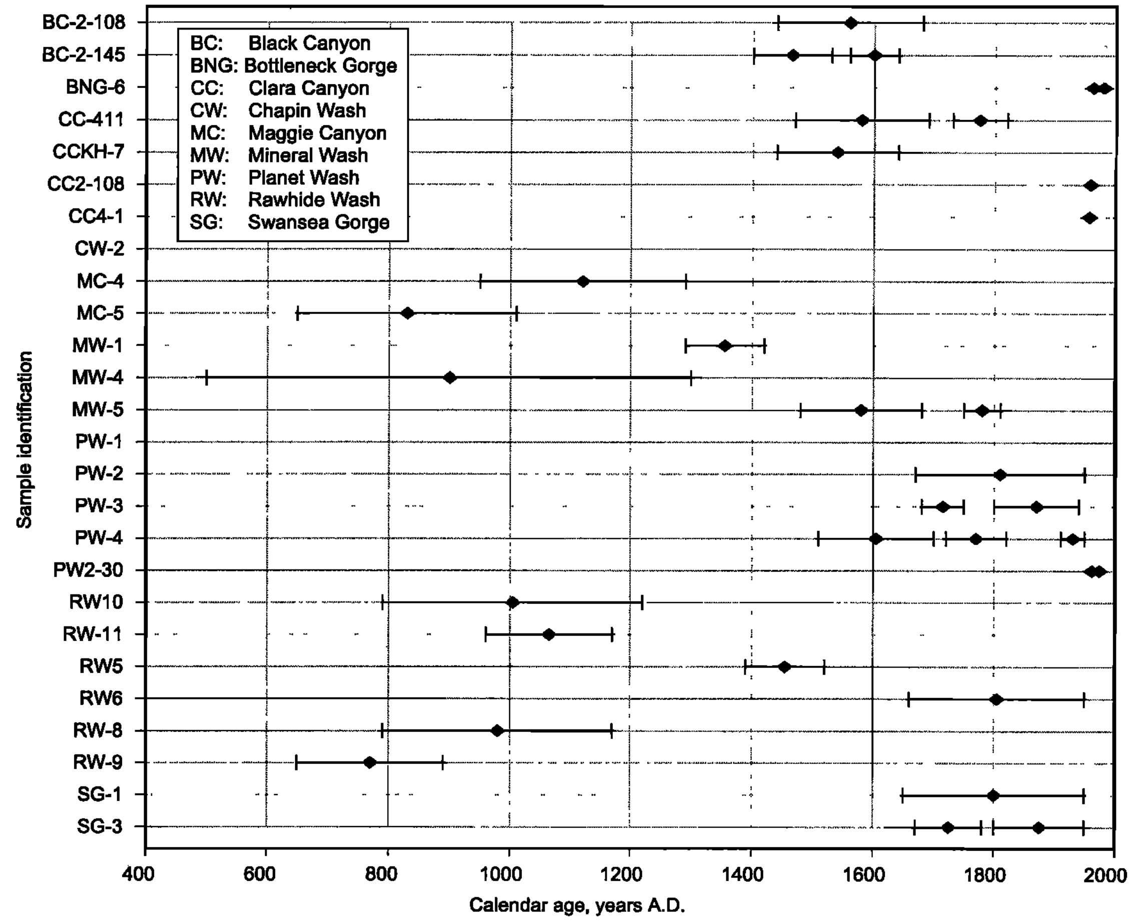

Figure 4. Temporal span of calibrated radiocarbon age estimates from samples collected in this study.

A presumably low composite *n* value of 0.04 was used in each of the nine study reaches to expedite the modeling at each site while ensuring that a conservative (i.e., higher rather than lower) estimate of peak discharges would result. Similarly, conservative values of 0.1 and 0.3 were assigned to loss coefficients associated with channel contraction and expansion, respectively. In conventional engineering analysis of relatively smooth transitions, recommended values for these coefficients range from 0.0 to 0.1 for contraction and 0.3 to 0.5 for expansion [*Hoggan*, 1989].

3.4.5. Final discharge calculation. Paleoflood magnitudes are calculated with the step backwater method by iterating input value of the discharge until a reasonable match is obtained between the modeled water surface profile and the best relict high-water marks (paleostage indicators (PSI) or until the various PSIs are bracketed by profiles associated with a narrow range of discharges. This is similar to conventional methods of flood discharges calculation [e.g., *Benson and Dalrymple*, 1967; *Dalrymple and Benson*, 1967], but typically restricts the analysis to stable channels and uses the step backwater method instead of the slope-area method. This model selection is the most logical in the paleoflood context because, unlike the slope-area method, calculated water surface profiles are independent of high-water marks. Results from representative study reaches are shown in Figure 6.

4. Discussion and Interpretation

Using the aforementioned approaches, this study has generated a record of large flash floods that spans nearly 1200 years in a remote region with essentially no conventional data for the magnitude and frequency of large floods. The record is intermittent, however, and its fidelity is limited by several uncertainties. Sections 4.1–4.4 summarize the flood history of each site in the context of the historical and the paleoflood records of large floods. Only the substantive results from the study as a whole are outlined here; more detailed information about each site is given by *House* [1996].

4.1. Historical Floods

The diagram in Figure 7 depicts the integration of the constraints on historical flood timing inferred from the types of information described previously. Large, light shaded portions of the graph show periods in which no evidence of significant flooding is evident from the aerial photographs, and arrows are used to indicate periods in which notable flooding occurred at a particular site. Dashed arrows indicate a likelihood of flooding, but evidence is inconclusive. Solid diamonds in boxes spanning a single year correspond to dates of floods that are confidently known from a combination of constraints; for example, combined beer can and aerial photograph evidence for the 1985 flood in Bottleneck Gorge indicated the specific month of the flood. In instances where the arrow spans several years but the box spans only one, the shaded portion is the most likely year of the flood.

Blank portions of the graph are periods in which information was not available to claim the occurrence or nonoccurrence of flooding. For example, floods on the Bill Williams River in 1966, 1967, and 1968 would probably have removed any evi-

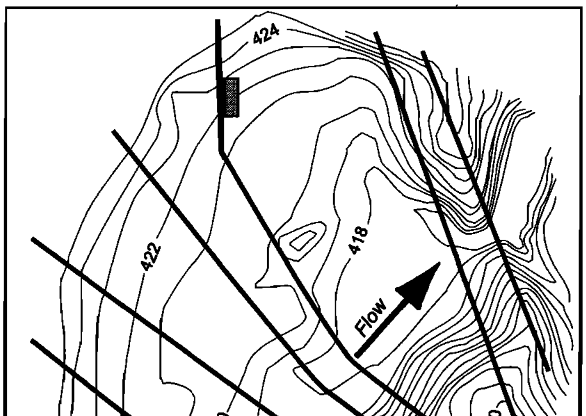

Figure 5. Topographic map of the Maggie Canyon study reach. The contour map is based on a triangular mesh smoothing routine applied to 267 surveyed points in the approximately 6000 m^2 reach. Cross sections used in the hydraulic modeling are shown, as is the site of flood stratigraphy.

dence of flooding from below the mouths of Swansea and Clara Canyons, thus making a determination for this period impossible without additional information. However, the lack of deposition below the mouths of each canyon in the 1973 photographs indicates no significant flooding between 1968 and 1973, a period of very low flow on the Bill Williams River.

The historical information is shown extending back to 1950, 3 years before the earliest series of aerial photographs. Very fresh appearing flood evidence appears below the mouths of Maggie Canyon and Chapin Wash in the 1953 photographs. These deposits probably postdate the Bill Williams River floods of 1937 and 1939, which are virtually certain to have cleared the areas below the canyon mouths. It is likely, but not certain, that they correspond to flash floods from a dissipating tropical storm on August 29, 1951, which is also the date of the largest recent flood on the Bill Williams relative to the photograph date. This storm also caused local flash flooding in parts of western Arizona and may have affected the eastern portion of the study area. A considerably more extreme episode of regional tropical storm–related flooding in September 1939 is very likely to have impacted each site examined in this study [*Gatewood et al.*, 1945].

4.2. Paleoflood Record

The results of the paleoflood analyses are summarized in Table 3, where the records are described in terms of the number of flood deposits, the duration of the flood record, and the maximum flood magnitudes at the site for which there is evidence. In some cases the number of flood deposits listed in Table 3 is less than the number counted in the field because the tally is limited to those deposits which can be assigned to a known interval of time. The reported flood magnitude range is bracketed by the minimum discharge associated with the flood stratigraphy and the maximum discharge associated with the highest extant flood evidence at the site; however, we were unable to place an upper constraint on the paleoflood magnitudes.

Paleostage estimates and related discharges derived from elevations of slackwater deposits are almost always minima [*Kochel and Baker*, 1988; *O'Connor and Webb*, 1988]. Their proximity to the peak stage is influenced by the geometry of the depositional area, flood duration, and total suspended sediment load. Also, the stratigraphic structure of the deposits complicates attempts to establish constraints on peak paleoflood discharges. Most stratigraphy examined in this study was composed of vertically accreting, progressively self-censoring stacks of flood deposits. This type of vertical accreting sequence imposes a gradually increasing level which subsequent floods must exceed in order to be recorded as a stratum. Thus the largest events over time are recorded, but the associated discharges are only minimum estimates in the absence of additional information. For this reason the record can be biased toward the largest and most recent floods. This stratigraphic situation has been described by *Baker* [1989] as a "worst case" because of poor constraints on the associated maximum flood stage. However, this type of situation is common in small basins with limited sites for deposit preservation, and it actually lends itself to evaluating relative flood frequency.

Progressively self-censoring flood deposits can provide useful information on relative flood magnitude and frequency when time range of the stratigraphy can be determined. It is possible to tally the number of events that have exceeded a minimum associated stage (by an unknown amount) in the known interval of time and thereby calculate the relative frequency of at least a range of discharges (see Table 3). It is also possible to interpret the stratigraphy in the context of flood discharges that have not been exceeded over specific time periods. This conceptual model is analogous to methods for incorporating paleoflood data and nonexceedance data into flood frequency analysis for sites with gaging records [*Stedinger and Cohn*, 1986; *Levish et al.*, 1994; *Ostenaa et al.*, 1996].

4.3. Regional Context of the Maximum Peak Discharge Estimates

The paleoflood data can be interpreted as measures of relative flood frequency (Table 3). Since only a range of discharges can be assigned to a known interval of time, this approach is somewhat limited in terms of precision, but the estimates are founded on real information that establishes a valid scientific context for comparison with regional flood frequency models. Although the regional flood record exceeds 1200 years at some sites, it is not of adequate resolution to evaluate hypotheses regarding time-variant trends in regional flood occurrence [e.g., *Ely*, 1997]. The resolution is adequate to evaluate regional flood frequency in general, however.

Conventional flood frequency analyses applied to this area are severely limited by lack of data. Nonetheless, for obvious regulatory and engineering reasons, there have been several attempts to develop statistical regional flood frequency relations for Arizona and other portions of the western United States that are similarly data-poor [*Roeske*, 1978; *Malvick*, 1980; *Reich et al.*, 1979; *Boughton and Renard*, 1984; *Thomas et*

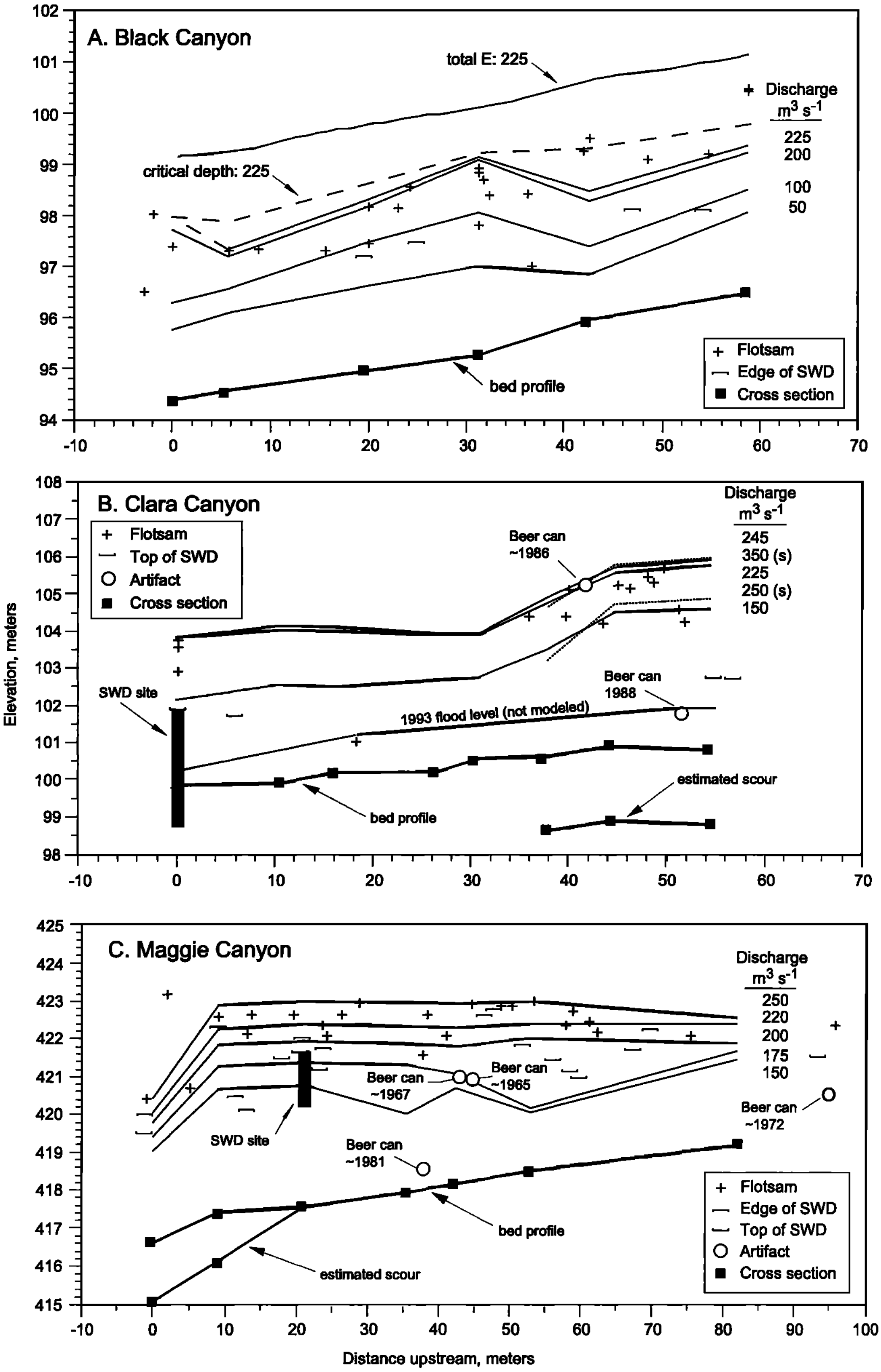

Figure 6. Water surface profile and high-water mark/paleostage indicator comparison for three representative reaches. (a) Black Canyon showing supercritical profiles modeled and compared to critical depth profile and total energy elevation for best discharge estimate of large flood in 1991. (b) Clara Canyon showing discharges modeled with respect to the present bed elevation and an estimated scour depth in the upper portion of the reach. The scour profiles are shown are dashed lines with corresponding discharges denoted by (s) in the explanation. (c) Maggie Canyon reach showing all discharges modeled with respect to the scour profile through the constriction. Scour depth is depth to bedrock measured at gorge entrance.

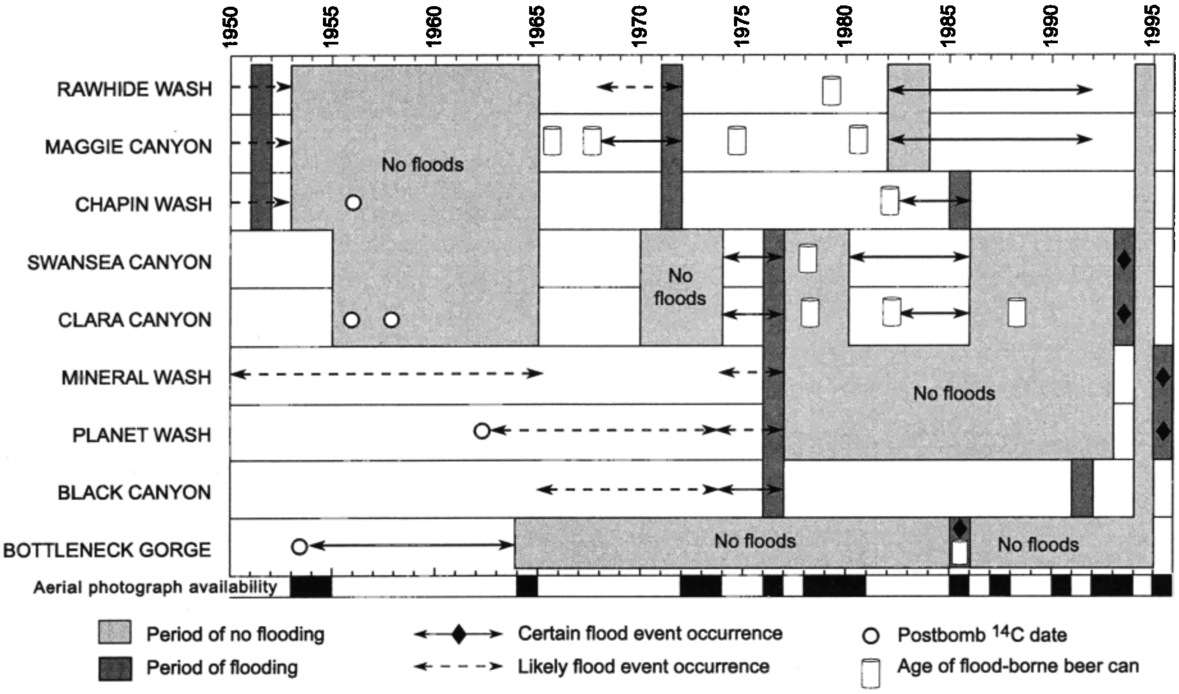

Figure 7. Reconstruction of the chronology of historical and recent floods at each of the study sites. See text for detailed explanation. Years with significant regional precipitation that directly impacted the three most proximate meteorological stations include 1951, 1980, 1993, and 1995 (winter storms); 1951, 1976, and 1983 (tropical storms); and 1955, 1957, 1963, 1964, 1971, 1982, 1988, and 1995 (monsoon storms). Dates of aerial photographs are indicated by solid rectangles along the horizontal axis. Uncertainty in flood timing is indicated by the length and line pattern of the arrows.

al., 1997]. In each case, regression equations relying on drainage area as the primary predictive variable were derived, allowing for a simple comparison with the paleoflood data (Figure 8 and Table 4). For example, at Rawhide Wash a flood of ~52–80 m^3 s^{-1} has occurred only 6 times over a 990-year period, corresponding to an average recurrence of 165 years. The record from Maggie Canyon indicates that a flood of ~135–250 m^3 s^{-1} has recurred on the average 6 times over approximately the last 1170 years, thus having an average recurrence interval of about 200 years. At Swansea Gorge, only four floods of 135–425 m^3 s^{-1} have occurred over the last 440 years, corresponding to an estimated relative frequency of approximately 110 years. These sites provide useful comparisons because of their long record lengths and similarities between the maximum and minimum threshold discharges. In instances where the threshold discharge is low in relation to the maximum discharge at the site and/or where the age control is inadequate, the relative frequency is less meaningful.

Although the data are not adequate for rigorously evaluating the veracity of the frequency predictions at each site, little correspondence is apparent between the empirical estimates and the relative frequency of large floods at the Rawhide, Maggie, and Swansea sites, for example. It is interesting, however, that (1), (2), and (3) predict 100-year flood magnitudes

Table 3. Summary of the Flood History and Relative Frequency of Large Floods at Each Site

Site	Number of Floods[a]	Maximum Discharge,[b] m^3 s^{-1}	Length of Flood Record,[c] years	Relative Frequency, years
Rawhide Wash	6	80	990	165
Maggie Canyon	6	250	1200	200
Chapin Wash	4	60	>100	>25
Swansea Gorge	4	425	440	110
Clara Canyon	5	350	440	88
Mineral Wash	5	50	640	128
Planet Wash	4	32	200	50
Black Canyon	7	225	435	62
Bottleneck Gorge	2	100	>50	>25

[a] This is the number of deposits that can be assigned to a known time interval.

[b] The largest discharge for which there is physical evidence at the site is indicated.

[c] This is determined as the difference between the midpoint of the calibrated calendar age range and the year 1996 A.D., which is the year the data were compiled. In absence of radiometric age control the record length is based on other constraints described in the text.

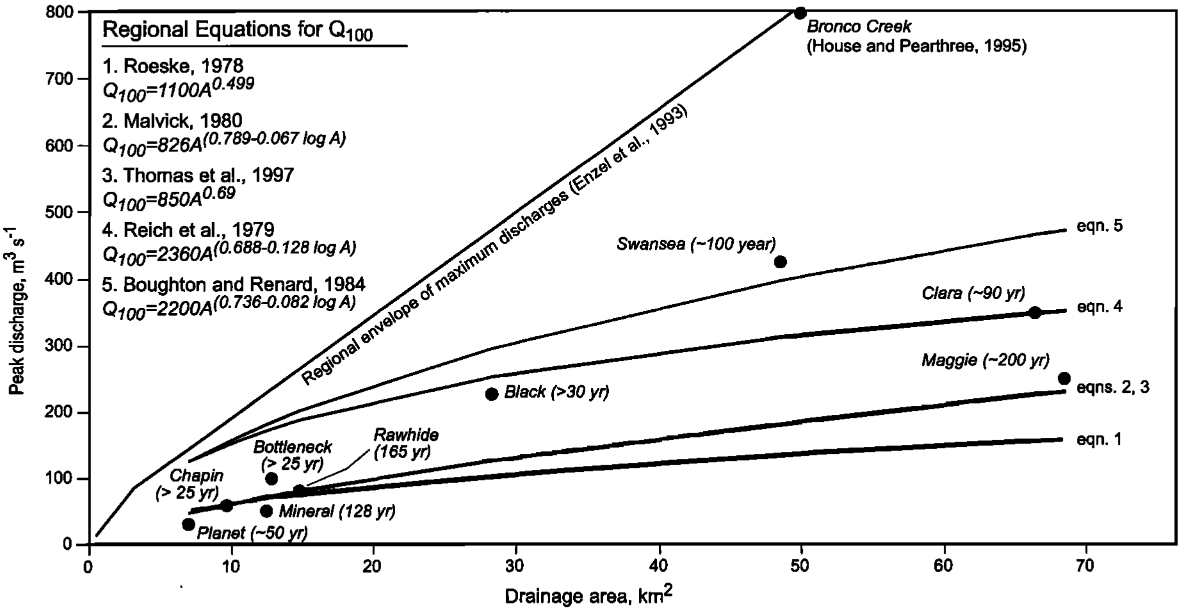

Figure 8. Comparison of maximum discharges estimated at each site to 100-year discharges predicted from regional equations and maximum discharges estimated from the regional envelope curve. The point from the revised Bronco Creek discharge estimate [*House and Pearthree*, 1995] is shown to illustrate the position of a truly extraordinary flood in the region.

consistent with several of the maximum estimated paleoflood discharges. Equations (4) and (5) (see Figure 8) both predict 100-year flood discharges that are greatly in excess of the estimated magnitudes of real floods that are likely to have much longer recurrence intervals and are probably overly conservative (Table 4). All the paleoflood data and frequency model predictions fall below the trend of the maximum known flood magnitudes in the region (Table 4, Figure 9, and section 4.4).

Comparison with the paleoflood data indicates that these equations are not clearly representative of regional flood characteristics. This is not surprising given the dearth of systematic data available to develop strong statistical relations. At best, they provide conservative estimates. Our intention is not to stress that the regional flood frequency models are flawed, only that they are handicapped by the absence of real information about large, rare floods and that such information is attainable via systematic collection of paleoflood data. A systematic approach to incorporating paleoflood data into regional flood frequency models would result in more realistic assessments of flood frequency.

4.4. Relation of Study Results to Regional Peak Discharge-Drainage Area Relations

Comparison of the flood data from this study to the largest known floods in the lower Colorado River basin support the hypothesis that a persistent upper limit to flood magnitudes exists in the region [*Enzel et al.*, 1993] and suggests the utility of this type of envelope curve for evaluating maximum flood potential in ungaged regions. The points other than the paleoflood data shown in Figure 9 include U.S. Geological Survey data for gaged and indirectly measured peak discharge estimates from southern and western Arizona and immediately

Table 4. Comparison of Maximum Flood Discharge Estimated at Each Study Site With 100-Year Flood Discharges Predicted With Regional Equations and the Maximum Discharge Estimated From the Regional Envelope Curve

			Q_{100} From Regional Equations[a]					
Site	Drainage area, km^2	Maximum Q, m^3 s^{-1}	(1)	(2)	(3)	(4)	(5)	Maximum Q From Envelope[b]
Planet Wash	6.9	32	51	50	48	125	125	175
Chapin Wash	9.6	60	60	62	59	149	154	225
Mineral Wash	12.4	50	68	75	71	171	181	275
Bottleneck Gorge	12.7	100	69	76	72	173	183	290
Rawhide Wash	14.7	80	74	85	80	187	201	325
Black Canyon	28.2	225	103	130	125	252	295	525
Swansea Gorge	48.5	425	134	184	182	311	396	800
Clara Canyon	66.3	350	157	222	226	347	466	1000
Maggie Canyon	68.5	250	160	227	230	350	473	1000

[a] Equation sources are as follows: (1), *Roeske* [1978] region 10; (2), *Malvick* [1980]; (3), *Thomas et al.* [1997]; (4), *Reich et al.* [1979]; and (5), *Boughton and Renard* [1984].

[b] Source is *Enzel et al.* [1993].

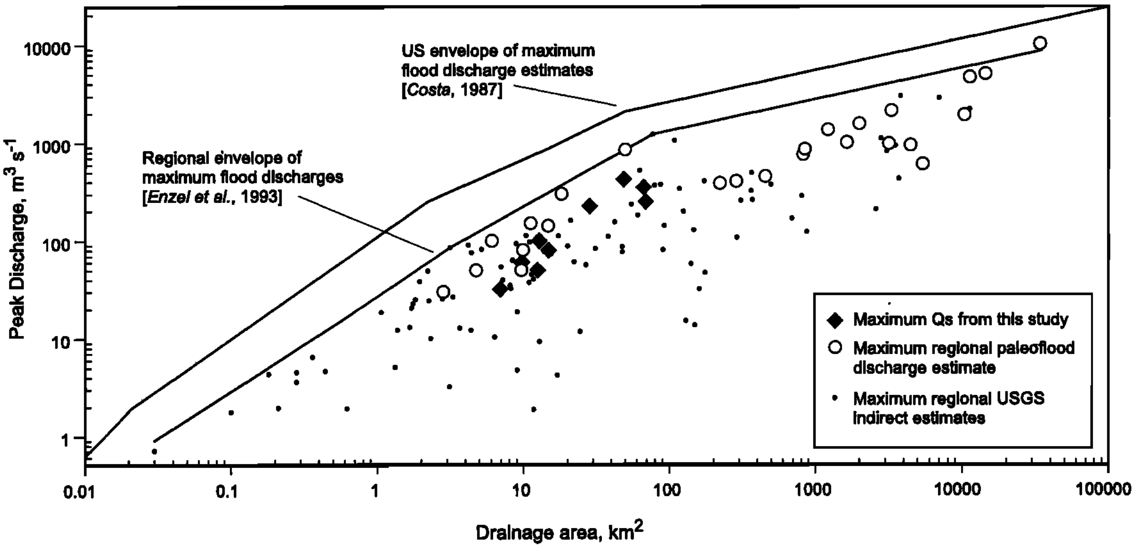

Figure 9. Comparison of maximum flood peak discharges estimated in this study to the regional envelope curve of maximum peak discharge versus drainage area in the lower Colorado River Basin [*Enzel et al.*, 1993] and to the envelope curve for the largest floods in the conterminous United States [*Costa*, 1987].

surrounding areas of California and Nevada. These are highlighted to convey the regional context of this study.

The position of the envelope curve illustrates the trend of regionally optimal combinations of storm precipitation and basin physiography [*Enzel et al.*, 1993]. Physiographic characteristics of specific basins impose limitations on what the net result of such optimal combinations are at a given site. This underscores the point that, in general, the regional envelope curve provides conservative values of maximum flood discharge as a function of drainage area (i.e., a worst case scenario) and that the likely maximum discharge in a specific basin is subject to unique physical constraints that may limit it to a value lower than implied by the regional envelope curve. Accordingly, values well in excess of the curve are suspect [e.g., *House and Pearthree*, 1995].

5. Conclusions and Recommendations

This report has outlined a systematic, multidisciplinary approach for collecting real information about extreme floods to develop a quantitative assessment of regional flood characteristics in a desert area where essentially no data on flooding had previously been reported. Comprehensive site selection combined with diverse methods of historical flood and paleoflood analysis allowed us to evaluate the regional flood hydrology and estimate the frequency of large floods over approximately the last 1000 years.

Nearly annual resolution of historical flood timing was attained using a combination of several historical data types. Greater resolution could have been attained using analytical radiometric dating techniques more extensively (e.g., ^{137}Cs and postbomb ^{14}C) [e.g., *Baker et al.*, 1985; *Ely et al.*, 1992]. Greater emphasis on these analytical approaches and historical archaeology is strongly recommended for any subsequent studies of this nature. Development of a detailed paleoflood chronology was hindered somewhat by an overall paucity of datable material and a preponderance of ^{14}C dates within about the last 350 years or so. The best sequences of flood deposits were found along the perimeter of broad channel reaches immediately upstream of very narrow channel constrictions or bottlenecks. Overall, this type of site had the best paleoflood evidence in terms of the record length, the relation of the stratigraphy to large floods, and a general amenability to hydraulic modeling.

The resulting regional flood chronology is the only spatially and temporally representative source of real data on flooding that is available for this arid region. Comparison of the results with regional flood frequency models indicates that the models are handicapped by lack of data and could probably be improved by systematically incorporating paleoflood information. The paleoflood data collected in this study are consistent with the regional envelope curve compiled by *Enzel et al.* [1993]. This suggests that the envelope curve (which is based on systematic, historical, and paleoflood peak discharges) may be an efficacious empirical tool for evaluating the extreme flood potential of small basins with reasonable confidence. In future studies, combining techniques for establishing bounds on maximum flood magnitudes [*Levish et al.*, 1994; *Ostenaa et al.*, 1996] with the enumeration of individual floods as described in this report would enable the compilation of a particularly robust envelope curve as well as a realistic characterization of regional flood hydrology.

The results of this study provide insights into the regional flood hydrology of western Arizona that could not have been obtained through any other means. This study presents a viable method that can be adapted to any region where flood data are lacking. Some relevant examples include flood hazardous desert areas undergoing rapid development, areas being evaluated for siting of small dams or bridges, and even areas under consideration for siting of critical facilities such as power plants or hazardous waste repositories. In these situations, valid and relatively rapid assessments of flood characteristics are required to guide realistic and cost-effective approaches to engineering design and flood control. Implementation of the techniques outlined here provides an important complement to statistical analysis of sparse data sets and is certainly preferable to instituting a regional stream-gaging network and waiting for large floods to occur.

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References

Aldridge, B. N., and J. H. Eychaner, Floods of October 1977 in southern Arizona and March 1978 in central Arizona, *U.S. Geol. Surv. Water Supply Pap., 2223*, 143 pp., 1984.

Baker, V. R., Paleoflood hydrology and extraordinary flood events, *J. Hydrol., 96*, 79–99, 1987.

Baker, V. R., Magnitude and frequency of paeleofloods, in *Floods: Hydrological, Sedimentological, and Geomorphological Implications*, edited by K. Beven and P. Carling, pp. 171–183, John Wiley, New York, 1989.

Baker, V. R., G. Pickup, and H. A. Polach, Radiocarbon dating of flood events, Katherine Gorge, Northern Territory, Australia, *Geology, 13*, 344–347, 1985.

Baker, V. R., R. C. Kochel, and P. C. Patton (Eds.), *Flood Geomorphology*, 503 pp., John Wiley, New York, 1988.

Benson, M. A., and T. Dalrymple, General field and office procedures for indirect discharge measurements, *U.S. Geol. Surv. Techn. of Water Resour. Invest. Book 3, Chap. A-1*, 30 pp., 1967.

Blong, R., and R. Gillespie, Fluvially transported charcoal gives erroneous ^{14}C ages for recent deposits, *Nature, 271*, 739–741, 1978.

Boughton, W. C., and K. G., Renard, Flood frequency characteristics of some Arizona watersheds, *Water Resour. Bull., 20*, 761–769, 1984.

Cady, L., *Beer Can Collecting*, 209 pp., Grosset and Dunlap, New York, 1976.

Costa, J. E., Hydraulics and basin morphometry of the largest flash floods in the conterminous United States, *J. Hydrol., 93*, 313–338, 1987.

Dalrymple, T., and M. A. Benson, Measurement of peak discharge by the slope-area method, *U.S. Geol. Surv. Techn. Water Resour. Invest., Book 3, Chap. A-2*, 12 pp., 1967.

Durrenberger, R., and R. Ingram, Major storms and floods in Arizona 1862–1977, *Precip. Ser., 4*, 44 pp., State of Ariz. Climatol. Publ., Tempe, 1978.

Ely, L. L., Response of extreme floods in the southwestern United States to climatic variations in the late Holocene, *Geomorphology, 19*, 175–201, 1997.

Ely, L. L., R. H. Webb, and Y. Enzel, Accuracy of post-bomb ^{137}Cs and ^{14}C in dating fluvial deposits, *Quat. Res., 38*, 196–204, 1992.

Enzel, Y., L. L. Ely, P. K. House, V. R. Baker, and R. H. Webb, Paleoflood evidence for a natural upper bound to flood magnitudes in the Colorado River Basin, *Water Resour. Res., 29*, 2287–2297, 1993.

Gatewood, J. S., F. F. Shrader, and M. R. Stackpole, Notable local floods of 1939, Part 1, Floods of September 1939 in Colorado River Basin below Boulder Dam, *U.S. Geol. Surv. Water Supply Pap., 967-A*, 37 pp., 1946.

Glancy, P. A., and R. P. Williams, Problems with indirect determinations of peak streamflows in steep, desert stream channels, in *Proceedings of the 1994 National Conference on Hydraulic Engineering*, pp. 635–639, Am. Soc. of Civ. Eng., Reston, Va., 1994.

Hansen, E., and F. Schwarz, Meteorology of important rainstorms in the Colorado River and Great Basin drainages, *Hydrometeorol. Rep., 50*, 167 pp., Natl. Ocean. and Atmos. Admin., U.S. Dep. of Comm., Silver Spring, Md., 1981.

Hansen, E., F. Schwarz, and J. Riedel, Probable maximum precipitation estimates, Colorado River and Great Basin drainages, *Hydrometeorol. Rep., 49*, 161 pp., Natl. Ocean. and Atmos. Admin., U.S. Dep. of Comm., Silver Spring, Md., 1977.

Hirschboeck, K. K., Hydroclimatology of flow events in the Gila River Basin, central and southern Arizona, Ph.D. dissertation, 325 pp., Univ. of Ariz., Tucson, 1985.

Hirschboeck, K. K., Hydroclimatically-defined mixed distributions in partial duration flood series, in *Hydrologic Frequency Modeling*, edited by V. P. Singh, pp. 199–212, D. Reidel, Norwell, Mass., 1987.

Hoggan, D. H., *Computer-Assisted Floodplain Hydrology and Hydraulics*, 518 pp., McGraw-Hill, New York, 1989.

House, P. K., Paleoflood hydrology of the principal canyons of the southern Tortolita Mountains, southeastern Arizona, *Ariz. Geol. Surv. Open File Rep. 91-6*, 22 pp., Ariz. Geol. Surv., Tucson, 1991.

House, P. K., Reports on applied paleoflood hydrological investigations in western and central Arizona, Ph.D. dissertation, 356 pp., Univ. of Ariz., Tucson, 1996.

House, P. K., and P. A. Pearthree, A geomorphologic and hydrologic evaluation of an extraordinary flood discharge estimate: Bronco Creek, Arizona, *Water Resour. Res., 31*, 3059–3073, 1995.

Hydrologic Engineering Center, *HEC-RAS, River Analysis System, User's Manual*, 148 pp., U.S. Army Corps of Eng., Davis, Calif., 1995a.

Hydrologic Engineering Center, *HEC-RAS, River Analysis System, Hydraulic Reference Manual*, 130 pp., U.S. Army Corps of Eng., Davis, Calif., 1995b.

Jarrett, R. D., Errors in slope-area computation of peak discharges in mountain streams, *J. Hydrol., 96*, 53–67, 1987.

Jarrett, R. D., Paleohydrology and its value in analyzing floods and droughts, *U.S. Geol. Surv. Water Supply Pap. 2375*, 105–116, 1991.

Jarrett, R. D., Historic-flood evaluation and research needs in mountainous areas, in *Proceedings of the 1994 National Conference on Hydraulic Engineering*, pp. 875–879, Am. Soc. of Civ. Eng., Reston, Va., 1994.

Jarrett, R. D., and H. E. Malde, Paleodischarge of the late Pleistocene Bonneville flood, Snake River, Idaho, computed from new evidence, *Geol. Soc. Am. Bull., 99*, 127–134, 1987.

Kochel, R. C., and V. R. Baker, Paleoflood analysis using slackwater deposits, in *Flood Geomorphology*, edited by V. R. Baker, R. C. Kochel, and P. C. Patton, pp. 357–376, John Wiley, New York, 1988.

Levish, D. R., D. A. Ostenaa, and D. R. H. O'Connell, A non-inundation approach to paleoflood hydrology for the event-based assessment of extreme flood hazards, paper presented at 11th Annual Conference, Assoc. of State Dam Safety Off., Lexington, Ky., 1994.

Malvick, A. J., A magnitude-frequency-area relation for floods in Arizona, *Res. Rep., 2*, 186 pp., Eng. Exp. Stn., College of Eng., Univ. of Ariz., Tucson, 1980.

Martells, J., *The Beer Can Collector's Bible*, 124 pp., Ballantine, New York, 1976.

Martinez-Goytre, J., P. K. House, and V. R. Baker, Spatial variability of small-basin paleoflood magnitudes for a southeastern Arizona mountain range, *Water Resour. Res., 30*, 1491–1501, 1994.

O'Connor, J. E., and R. H. Webb, Hydraulic modeling for paleoflood analysis, in *Flood Geomorphology*, edited by V. R. Baker, R. C. Kochel, and P. C. Patton, pp. 393–402, John Wiley, New York, 1988.

Osborn, H. B., and E. M. Laursen, Thunderstorm runoff in southeastern Arizona, *J. Hydraul. Eng., 99*, 1129–1145, 1973.

Ostenaa, D. A., D. R. Levish, and D. R. H. O'Connell, Paleoflood study for Bradbury Dam: Cachuma Project, California, *Seismotecton. Rep. 96-3*, 81 pp., U.S. Bur. of Reclam., Denver, Colo., 1996.

Reich, B. M., H. B. Osborn, and M. C. Baker, Tests on Arizona's new flood estimates, *Hydrol. Water Resour. Ariz. Southwest 9*, pp. 65–74, Univ. of Ariz., Tucson, 1979.

Roeske, R. H., Methods for estimating the magnitude and frequency of floods in Arizona, 82 pp., *Rep. ADOT-RS-15(121)*, Ariz. Dep. of Transp., Phoenix, 1978.

Roeske, R., M. Cooley, and B. Aldridge, *Floods of September 1970 in Arizona, Utah, Colorado, and New Mexico, U.S. Geol. Surv. Water Supply Pap., 2052*, 135 pp., 1978.

Roeske, R., J. Garrett, and J. Eychaner, Floods of October 1983 in southeastern Arizona, *U.S. Geol. Surv. Water Resour. Invest. Rep., 85-4225-C*, 77 pp., 1989.

Saarinen, T. F., V. R. Baker, R. Durrenberger, and T. Maddock Jr., *The Tucson, Arizona, Flood of October 1983*, 112 pp., Natl. Acad., Washington, D. C., 1984.

Sellers, W. D., and R. H. Hill, *Arizona Climate: 1931–1972*, 616 pp., Univ. of Ariz. Press, Tucson, 1974.

Sharon, D., The spottiness of rainfall in a desert area, *J. Hydrol.*, *17*, 161–175, 1972.

Smith, W., The effects of eastern north pacific tropical cyclones on the southwestern United States, *NOAA Tech. Memo NWS WR-197*, 229 pp., Natl. Ocean. and Atmos. Admin., Silver Spring, Md., 1986.

Spencer, J. E., and S. J. Reynolds (Eds.), Geology and mineral resources of the Buckskin and Rawhide Mountains, west-central Arizona, *Ariz. Geol. Surv. Bull. 198*, 279 pp., Tucson, 1989.

Stedinger, J. R., and T. A. Cohn, Flood frequency analysis with historical and paleoflood information, *Water Resour. Res.*, *22*, 785–793, 1986.

Stuiver, M., and P. J. Reimer, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program, *Radiocarbon*, *35*, 215–230, 1993.

Stuiver, M., P. J. Reimer, and T. F. Braziunas, High-precision radiocarbon age calibration for terrestrial and marine samples, *Radiocarbon*, *40*, 1127–1151, 1998.

Thomas, B. E., H. J. Hjalmarson, and S. D. Waltemeyer, Methods for estimating magnitude and frequency of floods in the southwestern United States, *U.S. Geol. Surv. Water Supply Pap.*, *2433*, 195 pp., 1997.

Wahl, K. L., Bias in regression estimates of Manning's n, paper presented at National Conference on Hydraulic Engineering, Buffalo, N.Y., Aug. 1–5, 1994.

Webb, R. H., and J. L. Betancourt, Climatic variability and flood frequency of the Santa Cruz River, Pima County, Arizona, *U.S. Geol. Surv. Water Supply Pap.*, *2379*, 40 pp., 1992.

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