

**PALEOFLOOD HYDROLOGY OF THE  
PRINCIPAL CANYONS OF THE  
SOUTHERN TORTOLITA MOUNTAINS,  
SOUTHEASTERN ARIZONA**

by

P. Kyle House

Arizona Geological Survey  
**Open-File Report 91-6**

September 1991

**Arizona Geological Survey**  
416 W. Congress, Suite #100, Tucson, Arizona 85701

*This study was undertaken in conjunction with the Arizona Geological Survey, the University of Arizona Dept. of Geosciences, and the Pima County Department of Transportation and Flood Control District. It is contribution #11 of the Arizona Laboratory for Paleohydrological and Hydroclimatological Analysis.*

This report is preliminary and has not been edited  
or reviewed for conformity with Arizona Geological Survey standards

## ABSTRACT

A detailed paleoflood investigation was performed in five canyons supplying flood flows to the piedmont of the Tortolita Mountains. The results of the study reveal large discrepancies between theoretical estimates of 100-year peak discharges and maximum apparent paleoflood discharge estimates derived from the analysis of geologic effects of flooding preserved in each canyon.

Paleoflood reconstructions were accomplished for stable (bedrock-controlled) reaches in each canyon. The levels of the highest discernible paleostage indicators were related to water surface profile elevations derived from the HEC-2 step-backwater flow modeling routine in order to develop magnitude estimations.

Accurate estimation of paleoflood frequency was possible in one canyon, Prospect Canyon, in which a charcoal sample provided a maximum limiting age of 710 +/- 80 yrs. B.P. for a flood with a magnitude of  $40\text{-}50 \text{ m}^3 \text{ s}^{-1}$ . The published theoretical estimate for the 100-year discharge in this canyon is  $185 \text{ m}^3 \text{ s}^{-1}$  (FEMA, 1989). Frequency estimates in the other canyons are relative and based on the likely rates of geomorphic processes in this region. By these criteria, the highest preserved evidence of flooding in hillslope and stable-channel geomorphology is very likely to be representative of at least the 100-year event.

The results of this study indicate that the 100-year discharge estimates used by the Federal Emergency Management Agency (FEMA) in the development of flood insurance rate maps (FIRMs) for the Tortolita Piedmont are significantly overestimated. The role that these discharges play in the subsequent extent of flood zones on the piedmont is uncertain and not addressed in this report (but this point should be addressed in the future). The fact that these discharges were derived from Pima County's standard theoretical rainfall-runoff model suggests that the model is not representative of the specific natural processes occurring in the Tortolita Mountain area. It is likely that this point holds true for small desert mountain watersheds in general. This conclusion is supported by the paleoflood investigation as well as comparisons to the maximum recorded rainfall-generated floods in the conterminous United States and southern Arizona.

## INTRODUCTION

Paleoflood reconstructions were performed in five principal canyons of the Tortolita Mountains (fig. 1) through application of the slackwater deposit-paleostage indicator

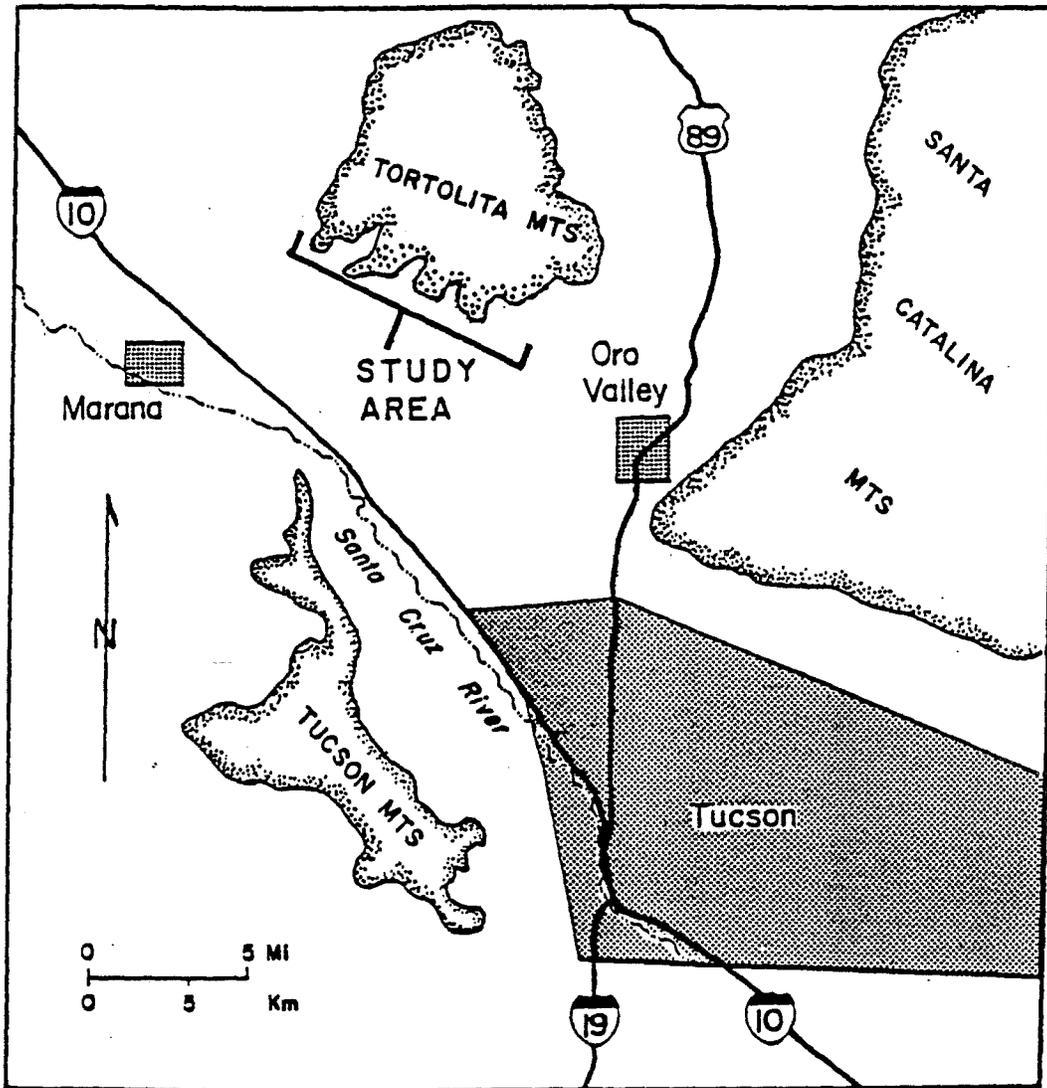


Figure 1. General location map of study area

(SWD-PSI) technique (Baker, 1987). The primary purpose of the investigation was to reconstruct the paleoflood history of each canyon as preserved in the on-site geologic evidence, thereby allowing for the comparison and/or testing of regulatory 100-year discharge estimates derived from the Pima County Flood Control District's standard theoretical rainfall-runoff model. Results from the aforementioned model are used for a variety of floodplain management strategies including the setting of flood insurance rates. A brief description of the paleoflood reconstruction methodology is presented below and is followed by the results of the analysis.

### **Geological Flood Studies**

In geological flood studies, causative flood processes are inferred from their effects on landscapes, vegetation, and fluvial sediments. Because this approach generates information from real, site-specific physical evidence of flooding, it is independent of empirical/theoretical methods that derive knowledge from mathematical idealizations and assumptions concerning the nature of real-world processes. Geological flood analysis therefore constitutes an independent test of these types of approaches.

### **Paleoflood Hydrology: SWD-PSI Methodology**

Paleoflood hydrology is a type of geological flood analysis based on the detailed examination of various forms of physical evidence of flood occurrences prior to, or unrecorded by, direct measurement or historical observation (Baker, 1989). Paleoflood hydrologic studies analyze and document actual extreme flood events that have impacted specific fluvial systems. These studies provide a means of understanding the physical nature of actual flood processes in specific areas and their associated magnitude-frequency characteristics.

The most direct and accurate method of paleoflood magnitude-frequency reconstruction is slackwater deposit-paleostage indicator analysis (SWD-PSI). This technique documents specific types of geological evidence of flood occurrence in fluvial environments amenable to hydraulic modeling and relates their heights to paleoflood levels. Step-backwater flow modeling techniques are employed to reconstruct associated flood magnitudes. If possible, paleoflood age estimates are established using various techniques of geochronology; those most appropriate include: radiocarbon, thermoluminescence, and dendrochronology of flood-scarred trees.

The most important considerations in applying the SWD-PSI methodology are site selection and proper field interpretation of the physical evidence of flood occurrence(s). It is essential that the nature of the various types of paleostage indicators be understood in relation to the magnitude and frequency of the event(s) responsible for their emplacement.

***Slackwater Deposits.*** Flood slackwater deposits consist predominantly of fine-grained sediments (silt, sand, and occasionally gravel) that accumulate in channel locations characterized by radical velocity attenuation during high flows (Baker and Kochel, 1988). Areas of ineffective flow during extreme floods most conducive to slackwater deposit accumulation include: backflooded tributary mouths, areas downstream of channel obstructions, eddy areas associated with abrupt channel contractions or expansions, and broad overbank areas (Kochel and Baker, 1988). Slackwater deposits occur in both alluvial and non-alluvial stream systems, but it is in non-alluvial settings (e.g. bedrock canyons) where they have the greatest potential for accumulation and preservation. Non-alluvial channels also provide the optimum boundary conditions for accurate hydraulic reconstruction of multiple paleofloods because of their long-term stability.

The relationship between the height of a slackwater deposit and peak paleoflood stage depends upon the depositional environment. Pronounced areas of ineffective flow (e.g. backflooded tributary mouths and areas of flow separation) promote very rapid deposition of suspended load which may occur up to, or very near, the actual water surface ; but, because there can be a variable water surface elevation above the associated slackwater deposits, they represent **minimum stage estimates** (Kochel and Baker, 1988). Thus, the corresponding discharges are generally minimum estimates. This constraint can be lessened by estimates of maximum stage based on field evidence of the non-occurrence of floods above a given level.

In ideal conditions of accumulation and preservation, multiple flood events may be represented in thick slackwater deposit sequences. The differentiation of individual deposits in such a sequence is possible using specific sedimentologic criteria. Features such as erosional contacts between successive units, pronounced vertical grain size contrasts, buried soil horizons, organic layers, and layers of intercalated tributary alluvium are the most common characteristics observed in the field (Baker, 1987).

***Other Paleostage Indicators.*** Other useful paleostage indicators are not sedimentary in origin. The features most commonly employed in paleoflood analysis include: scour lines, silt lines, flood debris, flood damaged vegetation, flood-related vegetation

distributions, as well as geomorphic evidence of flood non-occurrence (Hupp, 1988; O'Connor et al., 1986; Partridge and Baker, 1987; Jarrett, 1990).

The relationship between the height of certain paleostage indicators and peak paleoflood stage may be complicated by hydraulic conditions associated with their emplacement. In many cases, features such as accumulations of flood debris and scour lines may be in areas of flow obstruction or channel curvature that produce anomalous, localized elevations of water surfaces. In these circumstances, the height of the indicator will probably represent either the maximum stage or a level between the maximum stage and the energy grade line elevation for a specific discharge (O'Connor and Webb, 1988). A range of potential discharges can be defined using the discharge with a water surface elevation corresponding to the height of the indicator as a maximum estimate, and the discharge with the energy grade line elevation corresponding to the height of the indicator as a minimum. When paleostage indicators such as scour lines and silt lines are located in areas characterized by near uniform flow conditions, they provide excellent estimates of maximum paleoflood stage.

### **Paleoflood Age Estimation**

A principal goal of a comprehensive paleoflood analysis is to establish a chronological assessment in conjunction with flood magnitude estimations. In order to achieve the most accurate age estimate, datable material incorporated into slackwater deposits must be recovered and the relationship between its stratigraphic position and the age of deposit emplacement must be determined.

Radiocarbon dating methods applied to organic material (charcoal, vegetative material) incorporated in slackwater deposits is the most common means of paleoflood age estimation. Conventional methods of radiocarbon dating can be used on relatively large samples of organic material (several grams), and recent developments in the use of tandem accelerator mass spectrometry (TAMS) make it possible to estimate the age of very small samples of organic material (< .3 grams).

Other age-estimating techniques applicable to paleoflood frequency analysis are: relative dating of features affected (or not affected) by the event; correlation of deposits with those of known ages; degree of soil development in slackwater deposits, and dendrochronological analysis of trees directly (scarring, burial) or indirectly (germination in deposits) impacted by flooding (Baker, 1987; Hupp, 1988).

## Assumptions

The SWD-PSI methodology has a set of specific assumptions that are a consequence of the use of both step-backwater modeling and the conceptual framework of paleoflood reconstruction.

The assumptions of step-backwater modeling include the following (modified from Hoggan, 1989):

1. Flow is steady.

*Depth, velocity and discharge remain constant at a point over time.*

2. Flow is gradually varied.

*Depth and velocity vary gradually with distance down the channel.*

3. Flow is one-dimensional (with correction for horizontal velocity distribution).

*Streamlines are assumed to be parallel.*

4. Channels have small slopes ( $< 0.10$ ).

5. Friction slope (averaged) is constant between two adjacent cross sections.

6. Rigid boundary conditions exist.

The assumptions of paleoflood analysis include the following:

1. Modeled cross sections are stable and represent the geometry impinged upon by the paleoflood.
2. A known amount, or a negligible amount of erosion or deposition has occurred in the channel subsequent to the flood event.
3. Channel and overbank roughness values at the time of flood occurrence were similar to those at the time of analysis.
4. The entire length of the modeled reach was simultaneously affected by the peak discharge.

The most important, and most limiting assumptions of paleoflood analysis are those that relate to the channel geometry. In reaches that are not bedrock-floored, it is impossible to reconcile the present bed geometry with that at the time of the paleoflood(s) in question without a wealth of stratigraphic and geochronologic control.

In the absence of such control, discharge estimates can only be presented as minimums. This condition is not usually a serious problem in bedrock canyons.

### **Site Selection and Hydraulic Modeling**

Proper site selection is fundamental to the application of the SWD-PSI method. For the purposes of hydraulic modeling, reaches for paleoflood reconstruction should be carefully chosen so as to not violate the assumptions of gradually varied flow listed above. Thus, ideal conditions occur at fairly straight reaches in bedrock canyons with sites conducive to slackwater deposit accumulation. For increased accuracy, it is advantageous to have critical-depth control sections at the upstream or downstream end of the reach. Several cross-sections that accurately characterize the channel geometry and all identified paleostage indicators in selected reaches need to be carefully surveyed (the paleostage indicators do not necessarily need to be located at the chosen cross sections). Aberrations in channel geometry such as abrupt expansions, contractions, or distinct slope changes should be accurately characterized by multiple cross sections.

In this study, hydraulic modeling for paleoflood magnitude determination utilized the HEC-2 water surface profile program (Hydrologic Engineering Center, 1982). This is a step-backwater routine that requires input consisting of: channel geometry in the form of cross sections, energy loss coefficients for channel and overbank areas, discharge, flow regime, and initial water surface elevation estimates for the specified discharges. Model output consists of water surface elevations at each cross section for each discharge as well as a variety of hydraulic parameters that allow for evaluation of the modeled flow conditions.

Step-backwater modeling is employed in the analysis of paleofloods because of its proven superiority over other methods of discharge estimation. Other methods are best suited for uniform flow conditions (Manning equation, Chezy equation), or restrict cross section locations to sites of paleostage indicators (slope-area method). Also, the step-backwater method provides the most accurate results because it is based on a more rigorous evaluation of energy losses and maximizes the use of channel geometry. These characteristics combine to produce a *theoretically* correct water surface profile for a given discharge (Cook, 1987).

Paleoflood magnitude determinations are achieved through comparison of computed water surface profiles of various discharges with the elevations of the identified paleostage indicators (O'Connor and Webb, 1988). Such comparison allows for the determination of potential discharge ranges based on variations in the heights of

correlative slackwater deposits and other paleostage indicators. In situations where no stratigraphic correlations are possible, relative relationships can be established based on constraining the levels of paleostage indicators between successive water surface profiles.

## **THE TORTOLITA CANYON PALEOFLOOD STUDY**

### **Study Characteristics**

This study represents the first attempt to apply the SWD-PSI methodology to paleoflood reconstruction in stream systems with relatively small drainage basins (< 25 km<sup>2</sup>). Previous paleoflood investigations in Arizona have focused on significantly larger systems, including the Salt River (Fuller, 1987; Partridge and Baker, 1987), the Verde River (Ely and Baker, 1985), and Aravaipa Creek (Roberts, 1987). These studies were based primarily on the analysis of the stratigraphy and age-relationships of multiple, correlative slackwater deposits traceable over significant distances.

A distinguishing characteristic of this study is the overall lack of multiple, correlative slackwater deposits in all but one of the five canyons examined (Prospect Canyon). All other reaches contain small, isolated deposits which were employed in the analyses; but correlation is limited to relative elevation relationships as opposed to age and/or stratigraphic relationships. This distinct lack of correlative deposits in these small canyons may be attributed to several factors: a supply limitation (particularly of silt-sized particles); the presence of relatively few areas conducive to significant slackwater deposit accumulation and preservation; inadequate peak discharges for the transportation of suspended bed materials into sites conducive to deposition and preservation; and/or spatial and temporal variability of extreme events. To supplement the scattered slackwater deposits, this study used many other paleostage indicators when appropriate such as: flood debris (flotsam), silt lines, and scour marks.

### **Site Selection**

All principal drainages in the study area were examined for paleoflood reconstruction potential. Five canyons proved adequate for the analysis--Cochie Canyon, Wild Burro Canyon, Ruelas Canyon, Prospect Canyon, and Canada Agua-1 (Fig. 2). No reaches in other canyons in the southern part of the range were deemed suitable for the hydraulic analysis.

Study reaches within each canyon were chosen with careful consideration given to the assumptions of both step-backwater flow modeling and paleoflood reconstruction. In

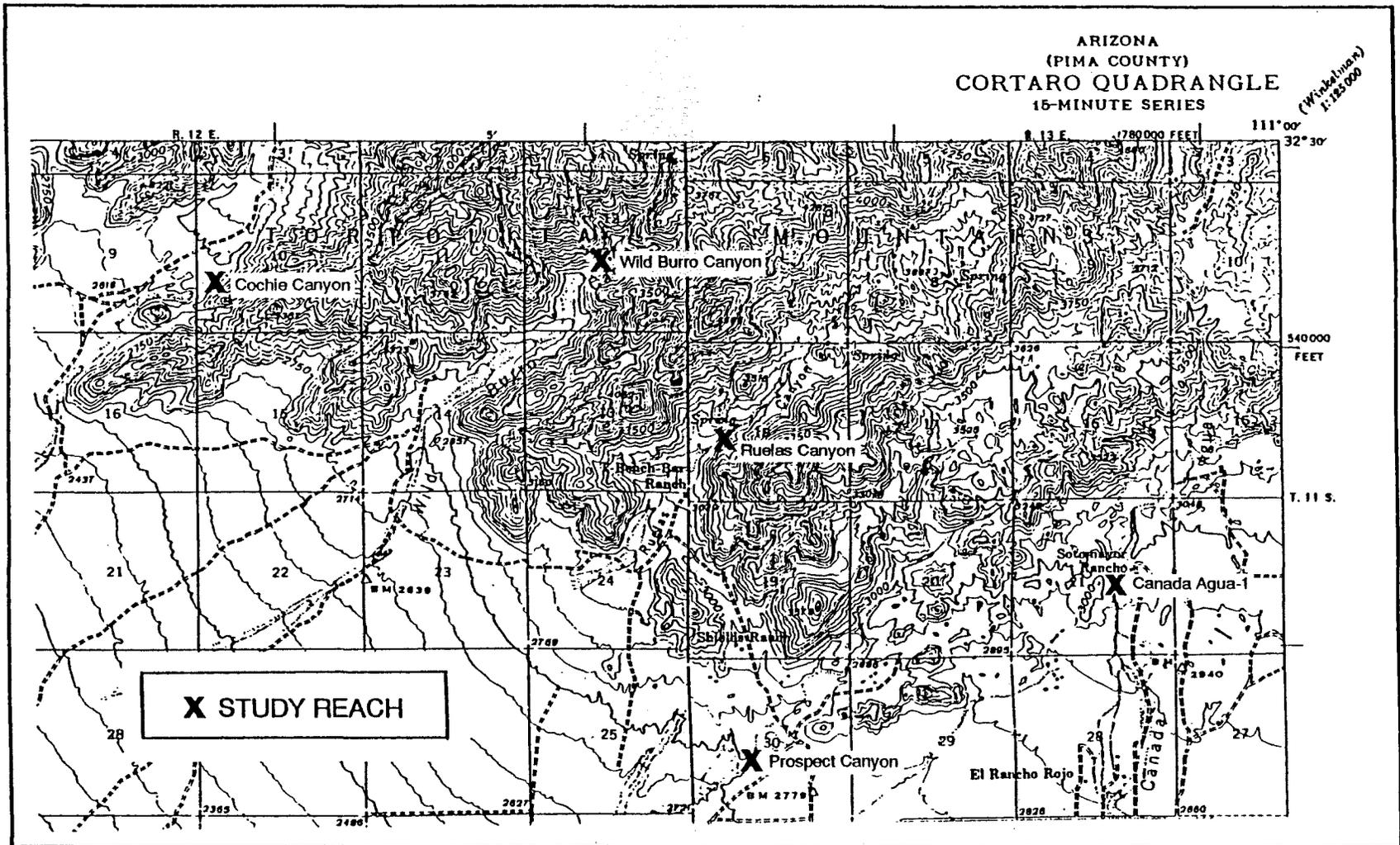


Figure 2. Location map of canyon reaches used in the paleoflood analyses

practice, reaches were selected with primary consideration given to hydraulic characteristics to minimize any uncertainties due to irregular flow conditions. Thus, non-alluvial (bedrock) reaches with relatively regular alignment and no obvious evidence of marked channel instability (i.e. on-going aggradation or degradation) were chosen. Each reach was characterized by an alluvial bed with undetermined depths of fill, thus all discharge estimates must be interpreted as minimum estimates. Because all reaches were located in narrow canyons with confining bedrock walls, it is very likely that the depth of fill in each reach is quite small. Upon selection, each reach was thoroughly examined for slackwater deposits and paleostage indicators.

Each reach was also examined for materials appropriate for paleoflood age-estimation; particularly, charcoal and organic matter incorporated into slackwater deposits and trees suitable for dendrochronological analysis. The general lack of large slackwater deposits in most of the reaches and the lack of available funds forestalled the extensive use of radiocarbon analysis. No flood-scarred trees suitable for dendrochronological analysis were found in any of the modeled reaches.

All reaches and identified flood deposits were surveyed in detail using a theodolite and electronic distance meter. Multiple reaches were surveyed in canyons when possible in order to refine the results using the best profile(s) for peak discharge determination. In all, twelve surveys were performed in the five canyons.

### **Hydraulic Modeling**

In addition to proper site selection, important components of the hydraulic analysis of each canyon reach include the choice of initial water surface elevations associated with specified discharges, flow regime specification, and energy loss coefficients.

*Initial Water Surface.* The choice of the initial water surface elevation for each modeling run is relatively subjective, but not of critical importance if a reasonable value is chosen. Because of the nature of paleoflood reconstruction, the discharge is the primary unknown variable, and its associated water surface elevation at the initial cross section is essentially a secondary unknown that usually cannot be assessed directly. The iterative nature of step-backwater analysis serves to reduce the degree of uncertainty associated with initial conditions (assuming an appropriately long reach has been chosen) (Chow, 1959 p. 275).

The condition of critical depth was chosen to represent the initial water surface elevation for the analysis of each reach. This choice was made for three primary reasons:

1. It allowed for a uniformity of approach in the analysis of each canyon.

2. Flow consistently modeled so near critical in every reach that critical depth provided a better estimate than an arbitrary choice.
3. The condition of minimum specific energy provides for the most logical initial condition for step-backwater analysis when the flow regime is unknown.

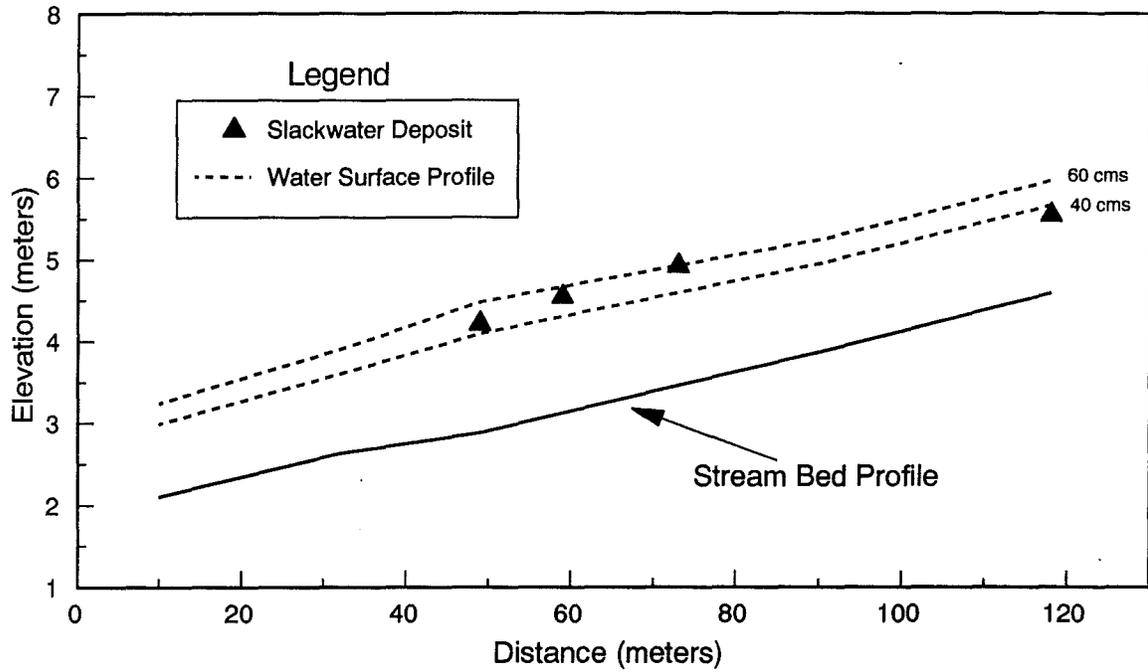
*Flow Regime.* The choice of the correct flow regime for step-backwater calculations is essential because it governs the direction in which the computations proceed through the reach (upstream for subcritical flow and downstream for supercritical flow). If computations are carried through the reach in the wrong direction, the computed water surface profile will tend to diverge from rather than converge to the correct solution (Chow, 1959 p. 275). In most cases, an incorrectly specified flow regime will result in an irregular water surface profile that is recognizably incorrect (i.e. highly irregular); but in other cases the flow may be so near critical conditions that the difference between the profiles may be negligible and subsequent selection of the appropriate flow regime may be difficult. The latter situation was common in the analysis of the Tortolita canyons.

There is a significant degree of uncertainty concerning the reality of sustained supercritical flow occurring in natural channels, so the assumption of supercritical flow for the purpose of modeling in these environments may not be valid (Jarrett, 1982; Hoggan, 1989). However, in the case of the steep reaches (typically > 2%) analyzed in the Tortolitas, the assumption of supercritical flow is not unreasonable (particularly for peak flow conditions).

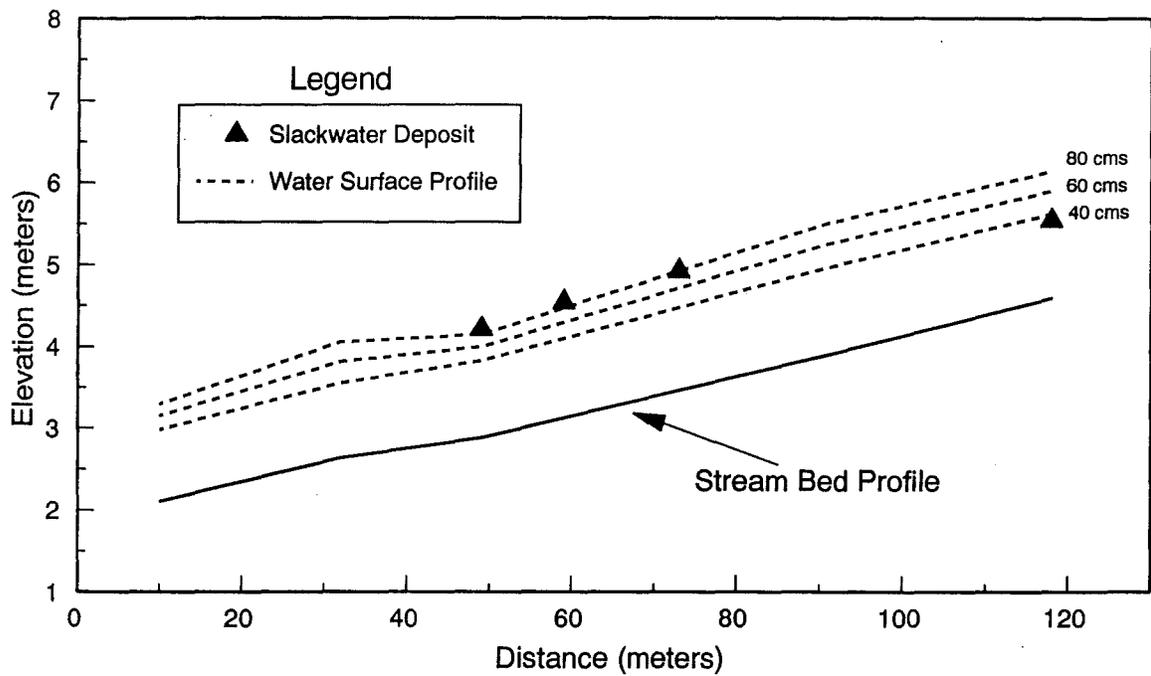
The use of supercritical profiles in the analysis of paleofloods in this project allows for the establishment of the largest **minimum discharge estimates** for the **maximum apparent paleoflood** in each canyon. Each reported range in the final analysis has the maximum subcritical estimate as its lower end and the maximum supercritical estimate as its upper end.

*Energy Loss Coefficients.* The types of energy loss coefficients required in the hydraulic computations include estimates of Manning's "n" (to evaluate friction losses) and expansion and contraction coefficients (to evaluate transition losses).

The choice of roughness coefficients ("n") to characterize natural channel reaches is a particularly subjective aspect of any hydraulic analysis, but it is substantially more subjective in paleoflood analysis because channel roughness conditions (particularly the density of vegetation) at the time of the flood are usually unknown. Channel roughness coefficients used in this study ranged from 0.035-0.04 depending on the character of the bed material and the steepness of the channel (Jarrett, 1984); overbank roughness coefficients used to characterize the canyon walls in each reach ranged from 0.07-0.15



**Figure 3a.** Cochie Canyon reach 2, subcritical water surface profile and paleostage indicator comparison



**Figure 3b.** Cochie Canyon reach 2, supercritical water surface profile and paleostage indicator comparison

depending on the surface characteristics (weathered rock or vegetation communities of varying densities) (Chow, 1959). Large ineffective flow areas were treated using the HEC-2 ineffective flow option (X3 card). Less significant areas of ineffective flow were characterized by high roughness coefficients ( $> 1.0$ ).

Expansion and contraction coefficients are used to evaluate energy losses associated with changes in channel geometry and serve to maintain the assumption of gradually varied flow. Values of the expansion and contraction coefficients used in all reaches in this study were 0.1 and 0.3 respectively. These are conventional values for fairly uniform reaches and were chosen specifically because none of the modeled reaches was characterized by radical expansions and/or contractions.

***Final Profile Selection.*** In the final analysis the best, or only, reach from each canyon is depicted in a graphical comparison of computed water surface profiles and paleostage indicators. Discharge estimates are based on the agreement between the water surface profiles and the levels of the various indicators. Due to uncertainties in correlation among indicators, discharge ranges that effectively constrain multiple indicators are reported as representative of probable minimum paleoflood discharges. Because the analysis focused on the highest apparent evidence of flooding, the discharges are reported as corresponding to the **maximum apparent paleofloods** in each canyon.

In the examination of the profiles, emphasis is placed on the paleostage indicators in the portions of the reaches furthest from the initial cross-section. This is because the step-backwater calculations become increasingly accurate as they proceed through the reach away from the first section. Note that calculations begin at the downstream section in subcritical analysis, and at the upstream section in supercritical analysis.

## RESULTS

### Cochie Canyon

The better of two reaches surveyed in Cochie Canyon (Reach 2) is 118 m long (390 ft.) and partitioned into five cross sections. It has a contributing drainage area of 9.8 km<sup>2</sup> (3.8 mi<sup>2</sup>). The highest discernible paleostage indicators in the reach are several slackwater deposits in a zone of channel expansion near the middle of the reach, and one deposit nearer the effective flow channel at the upper end of the reach.

The comparisons shown in figures 3a and 3b indicate that the best subcritical estimate is in the range 40-60 m<sup>3</sup> s<sup>-1</sup> (1415-2120 ft<sup>3</sup> s<sup>-1</sup>) and the best supercritical estimate is in the range 60-80 m<sup>3</sup> s<sup>-1</sup> (2120-2825 ft<sup>3</sup> s<sup>-1</sup>).

## Wild Burro Canyon

One of five reaches investigated in Wild Burro Canyon proved adequate for paleoflood analysis. The study reach was located approximately 2 miles above the mountain front in the only well-confined stretch with significant paleoflood information present. The study reach is approximately 63 m (207 ft.) long and partitioned into seven cross sections. It has a contributing drainage area of  $11.1 \text{ km}^2$  ( $4.3 \text{ mi}^2$ ). Paleostage indicators of the largest discernible flood are relatively abundant throughout the reach. Those utilized in the analysis included: flood debris, slackwater flood deposits, and an obvious scour mark on a hillslope at the lower end of the reach.

The comparisons shown in figures 4a and 4b indicate that the best subcritical estimate is in the range  $80\text{-}100 \text{ m}^3 \text{ s}^{-1}$  ( $2825\text{-}3530 \text{ ft}^3 \text{ s}^{-1}$ ) and the best supercritical estimate is in the range  $100\text{-}120 \text{ m}^3 \text{ s}^{-1}$  ( $3530\text{-}4240 \text{ ft}^3 \text{ s}^{-1}$ ).

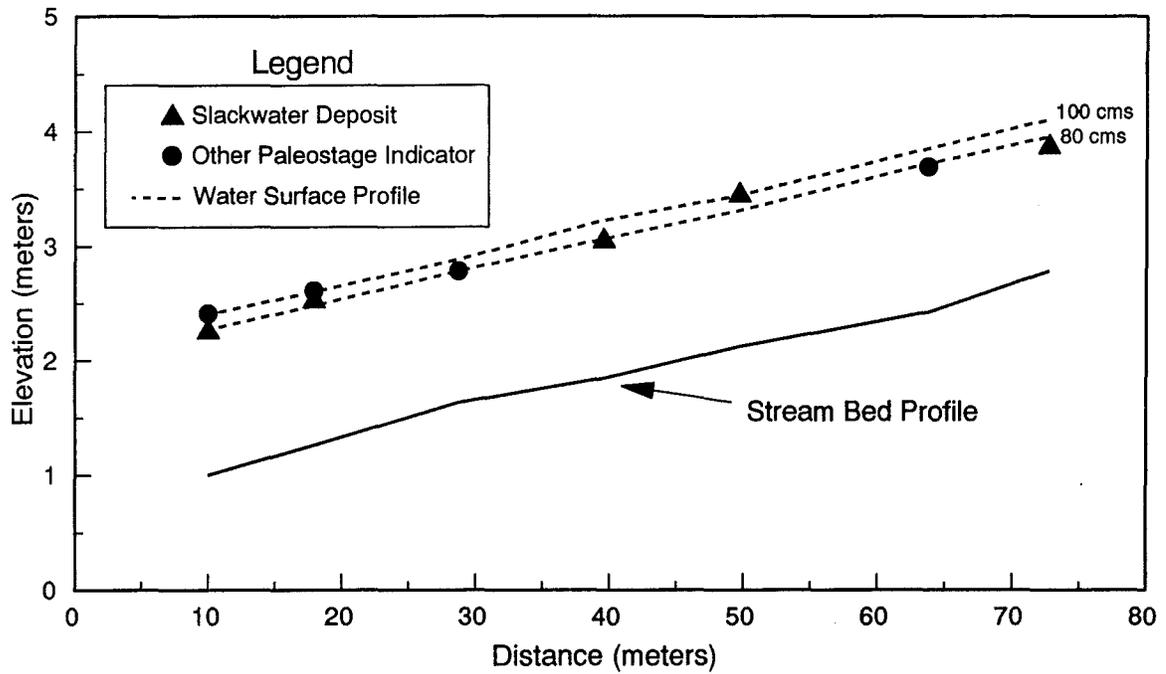
This flood has been accurately dated to July 27, 1988. The dating is based on several lines of evidence: eyewitness accounts prior to and following the event, dates on beverage containers incorporated into flood debris, and analysis of the weather radar data for that specific day. It is the largest flood apparent throughout the lower portions of the canyon and eliminated most evidence of previous, smaller floods. In some ideal places, stratigraphic evidence of at least two earlier floods can be found beneath the recent flood deposit. Organic material from these deposits has not yet been dated.

The youth of this event enabled paleoflood reconstruction with a minimum of uncertainties concerning channel geometry and correlation among paleostage indicators. For these reasons, the near-critical flow conditions are taken as representative of extreme floods experienced by the small, steep canyons investigated in this study.

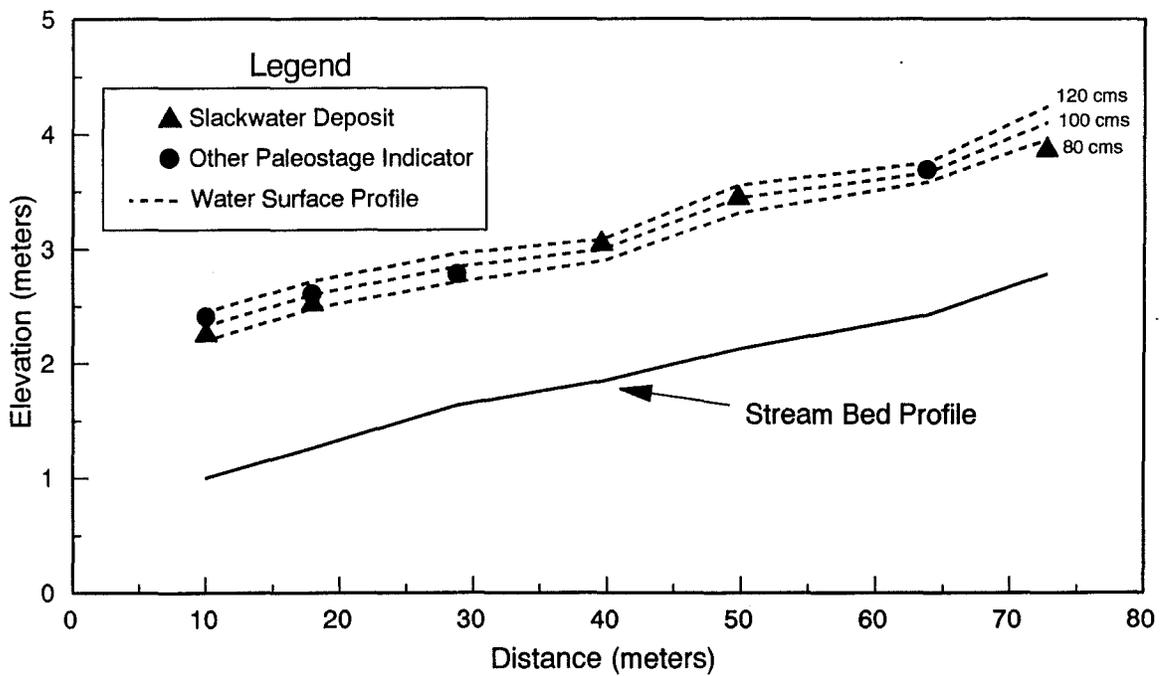
## Ruelas Canyon

One reach was surveyed in Ruelas Canyon. It has a contributing drainage area of  $6.0 \text{ km}^2$  ( $2.3 \text{ mi}^2$ ). Because of limitations in favorable geometry, the study site was located along a channel bend. Attempts were made to account for possible superelevation of the water surface along the outer bank at cross sections near the point of maximum curvature of the reach.

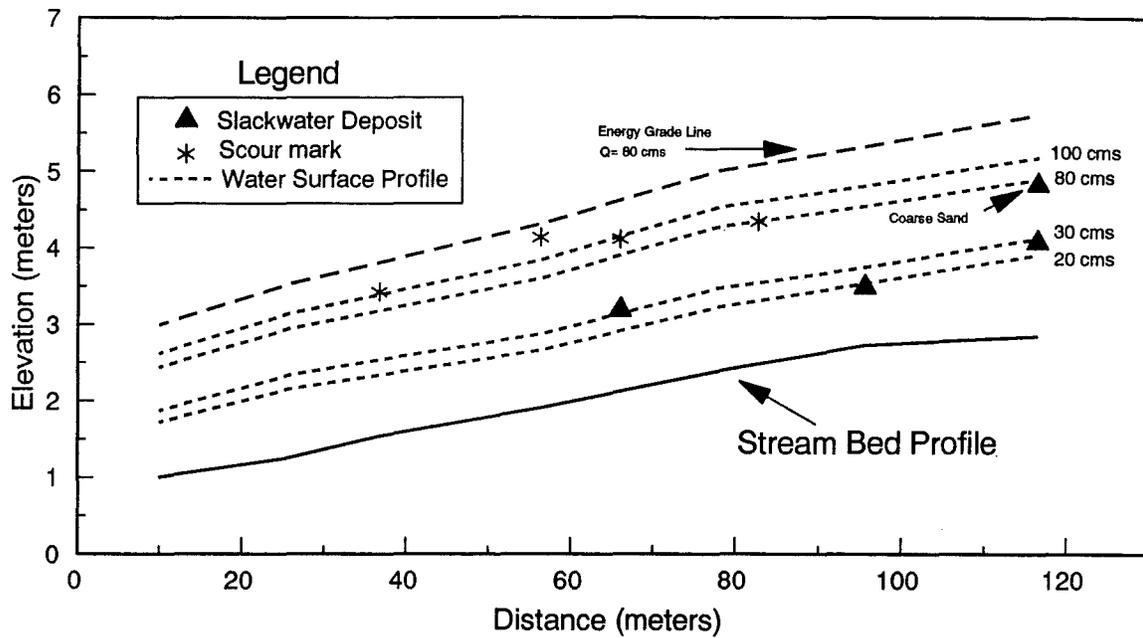
The study reach was 120 m (394 ft.) long and partitioned into seven cross sections. Identified paleostage indicators consisted of 3 slackwater deposits from an apparently recent event, a deposit of coarse sand in the grooved surface of a large boulder near the bank; and several perceptible scour marks along the outer bank of the curving section.



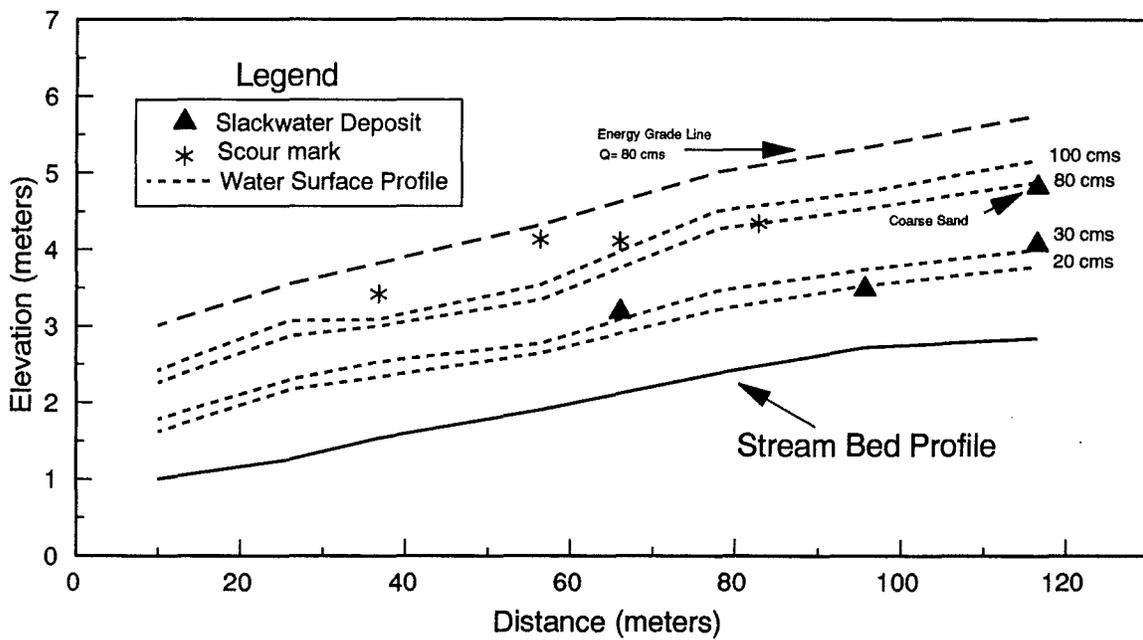
**Figure 4a.** Wild Burro Canyon, subcritical water surface profile and paleostage indicator comparison



**Figure 4b.** Wild Burro Canyon, supercritical water surface profile and paleostage indicator comparison



**Figure 5a.** Ruelas Canyon, subcritical water surface profile and paleostage indicator comparison



**Figure 5b.** Ruelas Canyon, supercritical water surface profile and paleostage indicator comparison

The latter two features were used in estimating the magnitude of the maximum apparent paleoflood.

In order to assess the possibility of superelevation in relation to the scour line, the energy grade line elevations associated with specific discharges were considered in conjunction with the computed water surface elevations. Constraining the scour marks between an energy grade line profile and a water surface profile results in a range of potential discharges. The comparisons in figures 5a and 5b indicate that both the best subcritical and supercritical estimates are in the range  $80\text{-}100\text{ m}^3\text{ s}^{-1}$  ( $2825\text{-}3530\text{ ft}^3\text{ s}^{-1}$ ).

### **Prospect Canyon**

The study reach chosen in Prospect Canyon proved to be an excellent setting for paleoflood reconstruction. The reach chosen for analysis is characterized by a prominent bedrock constriction between two wider reaches, both confined by indurated Pleistocene sediments (Pearthree et al., 1990). Directly above and below the constriction are wide ineffective flow zones with significant accumulations of slackwater sediments.

The study reach is approximately 100 m (328 ft.) long and partitioned into seven cross sections. It has a contributing drainage area of  $9.6\text{ km}^2$  ( $3.7\text{ mi}^2$ ). Paleostage indicators employed in the analysis were two distinct slackwater flood deposits found in three different locations--two above the constriction, and one below. In one of the sites, only the upper unit was apparent. Field observations suggest that the slackwater deposits are stratigraphically correlative.

The graphical comparisons shown in figures 6a and 6b indicate that the lower flood unit best corresponds to the subcritical range of  $15\text{-}20\text{ m}^3\text{ s}^{-1}$  ( $530\text{-}710\text{ ft}^3\text{ s}^{-1}$ ) and the supercritical range of  $20\text{-}30\text{ m}^3\text{ s}^{-1}$  ( $710\text{-}1060\text{ ft}^3\text{ s}^{-1}$ ); whereas the upper flood unit best corresponds to the subcritical range of  $30\text{-}40\text{ m}^3\text{ s}^{-1}$  ( $1060\text{-}1415\text{ ft}^3\text{ s}^{-1}$ ) and the supercritical range of  $40\text{-}50\text{ m}^3\text{ s}^{-1}$  ( $1415\text{-}1765\text{ ft}^3\text{ s}^{-1}$ ).

A charcoal sample obtained from the lower slackwater deposit was analyzed and provided an age estimate of 710 +/- 80 years before 1950 A.D.. The sample was found interspersed throughout the upper portion of the deposit in a stratigraphic horizon interpreted as a buried erosion surface. Thus, it is most likely a remnant of a ground fire at the position of collection, and its estimated age represents a minimum limiting age for the lower unit and a maximum limiting age for the upper unit. This implies that the

largest flood recorded in the geomorphology of this reach in at least the last 670 years had a magnitude in the range of  $40\text{-}50\text{ m}^3\text{ s}^{-1}$  ( $1415\text{-}1765\text{ ft}^3\text{ s}^{-1}$ ).

### Canada Agua-1

Only one short reach was found to be adequate for analysis in Canada Agua-1. The chosen reach is 33 m (108 ft.) long and partitioned into four cross sections. It has a drainage area of  $4.7\text{ km}^2$  ( $1.8\text{ mi}^2$ ). Identified paleostage indicators include five scattered slackwater flood deposits, two of which represent the highest flood preserved in the site's geomorphology.

The comparisons shown in figures 7a and 7b indicate that the best subcritical estimate is in the range  $20\text{-}30\text{ m}^3\text{ s}^{-1}$  ( $710\text{-}1060\text{ ft}^3\text{ s}^{-1}$ ) and the best supercritical estimate is in the range  $40\text{-}50\text{ m}^3\text{ s}^{-1}$  ( $1415\text{-}1765\text{ ft}^3\text{ s}^{-1}$ ).

## DISCUSSION

### Summary of Results and Data Comparisons

The results of the paleoflood analyses and those of various other attempts to establish 100-year flood magnitudes for the major Tortolita drainages are shown in table 1.

Canyon	FEMA $Q_{100}$	Area $\text{km}^2$	PIMA $Q_{100}$	Area $\text{km}^2$	HEC-1 $Q_{100}$	Area $\text{km}^2$	Paleo. $Q_{\text{max}}$	Area $\text{km}^2$
Cochie	189	11.4	170	9.9	--	--	80	9.8
Wild Burro	270	18.1	280	14.6	300	18.5	120	11.1
Ruelas	170	9.3	185	8.4	180	8.8	100	6.0
Prospect	185	8.8	130	6.5	225	14.0	50	9.6
Canada Agua	125	5.4	120	5.3	185	13.5	50	4.7

**Table 1.** Comparison of discharge estimates from four separate analyses of the principal canyons of the southern Tortolita Mountains (all discharges in cubic meters per second). See text for explanation of each type of estimate.

The first two columns show, respectively, the published 100-year regulatory discharges and the contributing drainage area to the concentration point designated in the analysis. These particular values were used to model flood hazards on the piedmont reach below each canyon for the purpose of setting flood insurance rates. The next two pairs of

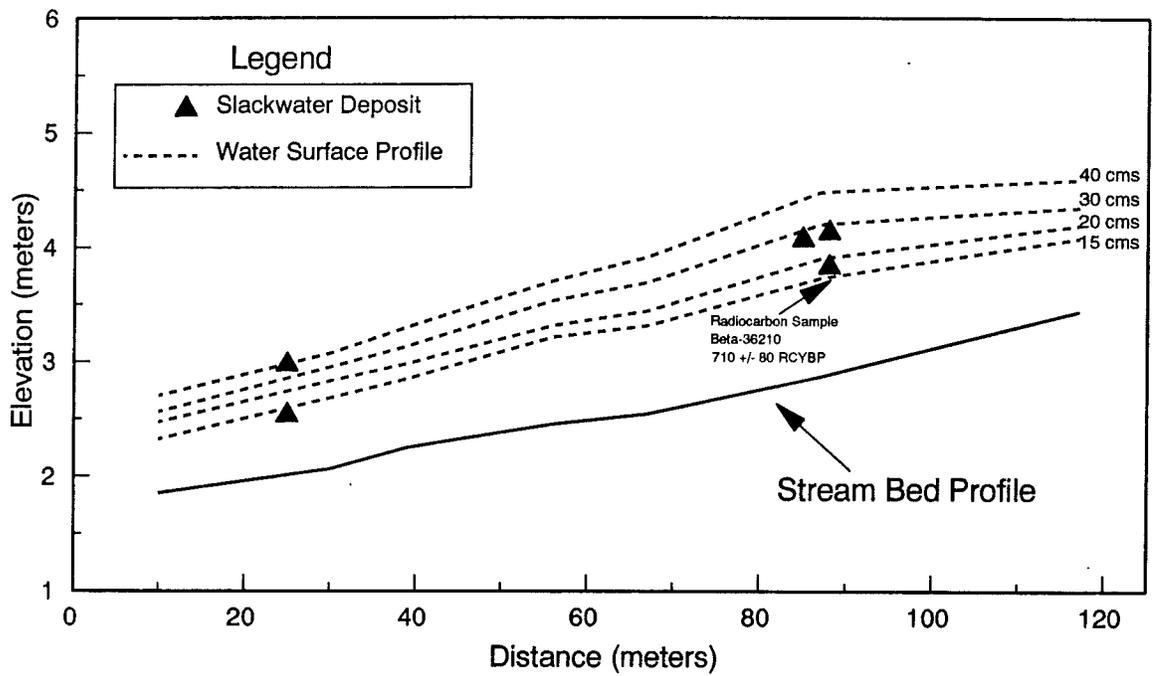


Figure 6a. Prospect Canyon, subcritical water surface profile and paleostage indicator comparison

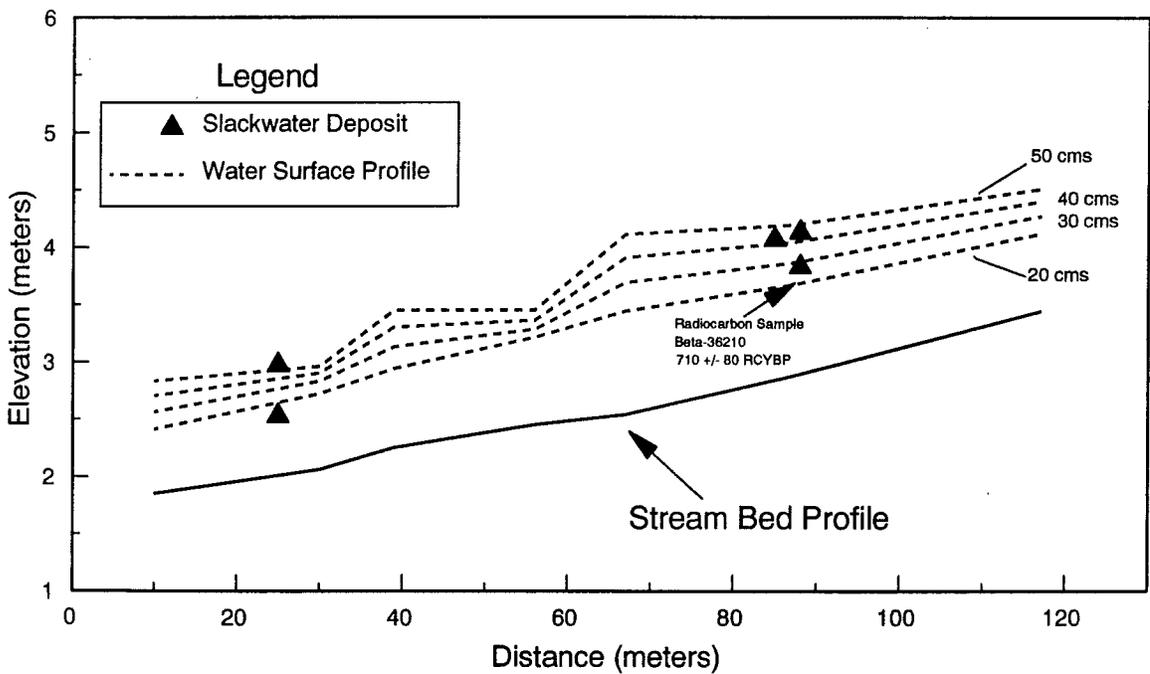
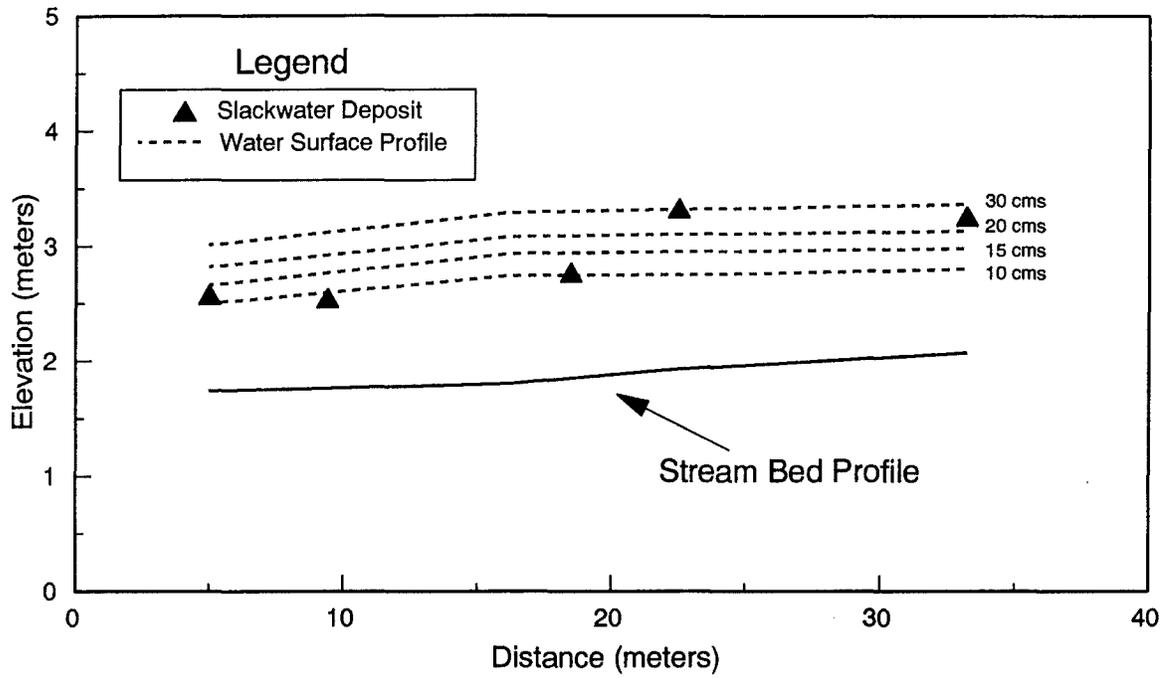
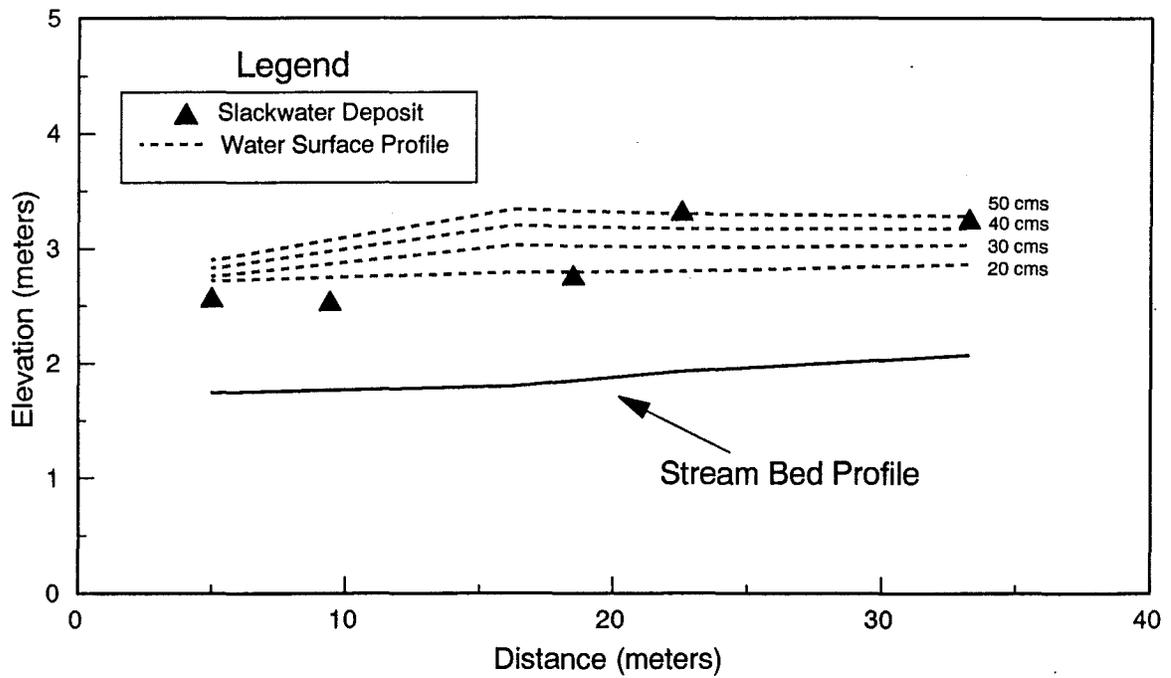


Figure 6b. Prospect Canyon, supercritical water surface profile and paleostage indicator comparison



**Figure 7a.** Canada Agua-1, subcritical water surface profile and paleostage indicator comparison



**Figure 7b.** Canada Agua-1, supercritical water surface profile and paleostage indicator comparison

columns contain values and related drainage areas established in two attempts to reevaluate the analyses that generated the discharge values in the first column. The values shown in columns 1 and 3 were derived from the Pima County Flood Control District's standard rainfall-runoff model (Zeller, 1979). Those shown in column 5 were derived using the HEC-1 rainfall-runoff model (Hydrologic Engineering Center, 1982). The final two columns contain the upper end of the estimated magnitude range of the largest apparent paleoflood for each canyon followed by the contributing drainage area to the study reach.

All of the values in table 1 are expressed as unit discharges (discharge per unit drainage area) in table 2. These normalized values are presented to allow for direct comparison of the data. Unit discharge values should not be interpreted as realistic assessments of drainage basin response, because it cannot be tacitly assumed that the entire drainage basin contributes runoff to the peak discharge of a given flood event without independent evidence of such. This is particularly true for small drainage basins that are most responsive to flooding induced by localized convective thunderstorms (Osborn and Laursen, 1973; Jarrett, 1990). Thus, for a specific discharge, correction for contributing drainage area will increase the corresponding unit discharge value. This is an important consideration in the case of the theoretically-derived unit discharge values which are relatively high without such a correction. For instance, Jarrett (1990) used geomorphological criteria for delineating the contributing drainage area to a large flood in The Sweetwater Creek Basin in Colorado. He arrived at a unit discharge of  $18 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$  and reports that this is the largest known unit discharge in the Colorado River Basin *in Colorado*. Although this example comes from a different climatic region, it does provide an interesting perspective on the values shown in table 2.

CANYON	FEMA $Q_{\text{unit}}$	PIMA $Q_{\text{unit}}$	HEC-1 $Q_{\text{unit}}$	SWD-PSI $Q_{\text{unit}}$
Cochie	17	17	--	8
Wild Burro	15	19	16	11
Ruelas	18	22	21	17
Prospect	21	20	16	5
Canada Agua	23	23	14	11

**Table 2.** Data from table 1 expressed as unit discharges

The normalized values in table 2 provide the best illustration of the relative differences between the values reported in table 1. There is an appreciable discrepancy between the theoretically-derived values and those derived from the direct analysis of actual flood events. In order to assess the significance of this discrepancy, it is necessary to understand the nature of the paleoflood estimates in terms of how they relate to the theoretically-derived regulatory flood values as well as to values based on empirical relationships. Also important is how both types of data relate to recorded extreme flood events in general, particularly events in southern Arizona.

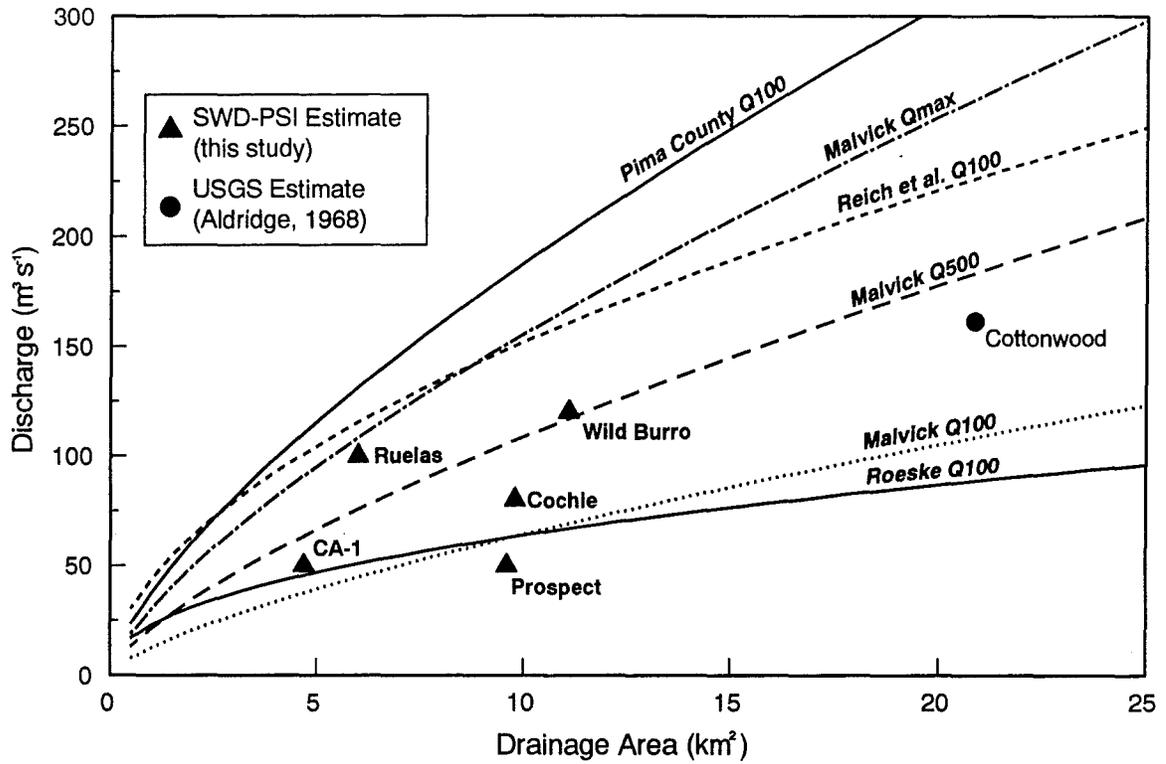
### **Nature of the Tortolita Paleoflood Data**

A degree of uncertainty exists in the paleoflood methodology as outlined earlier, but the method's fundamental basis is the direct analysis of the physical nature of discrete, extreme flood events in specific areas. Uncertainties in theoretical approaches exist as well, and they build upon uncertainties from the fundamental assumptions upon which these approaches are based (hypothetical frequency distributions, inadequate data bases, design storm estimates, etc.). The utility of the information generated in this study is that it serves as an independent test of the regulatory flood magnitudes derived from the theoretically based rainfall-runoff modelling for the same area. This is a very important test because, in order to validate theoretically based characterizations of a natural phenomenon, it is imperative to compare them with characterizations derived from direct analysis of that phenomenon (Baker et al., 1990).

The paleoflood magnitude estimates are not presented (and should not be interpreted) as definitive estimates for flood events of specific recurrence intervals. Values derived from paleoflood analyses, though, should be given due consideration as reference values against which the reasonableness of results from theoretical methods should be evaluated.

The importance of this type of evaluation is clearly illustrated in figure 8, in which the paleoflood data is shown in relation to a regression line based on two sets of theoretically-derived values for the five Tortolita drainages relevant to this study (columns 1 and 3 in table 1). Also depicted in the figure are several curves derived from empirically based regional-regression equations for southern Arizona. The empirical relationships were derived from different types of statistical analysis of recorded flood events in southern Arizona (Reich et al., 1979; Roeske, 1978; Malvick, 1980).

This plot illustrates several important points. It is clear that the theoretical estimates are significantly higher than those derived from other techniques, and this discrepancy exists even in relation to empirical estimates of maximum expected discharge and 500-



**Figure 8.** Comparison of discharge estimates for the principal canyons of the southern Tortolita Mountains: empirical, theoretical and geological

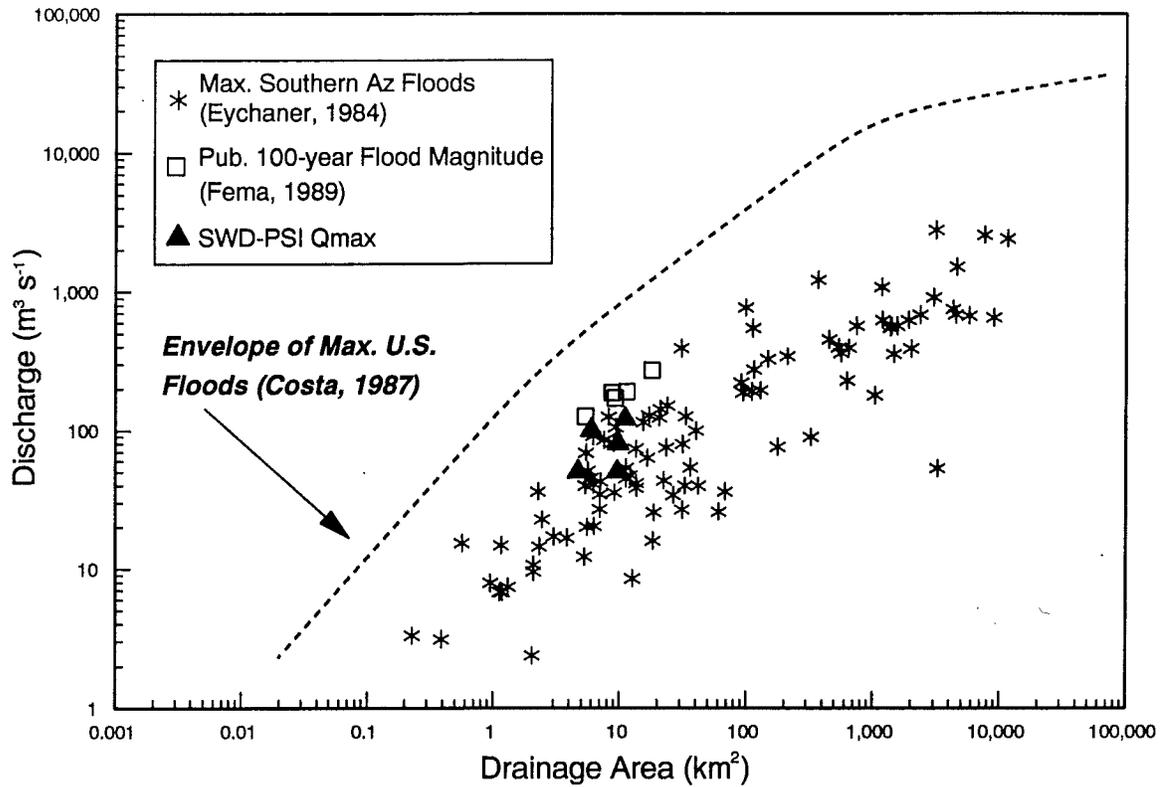
year discharge. The inclusion of the paleoflood data serves to establish a context in which to evaluate all depicted methods as they relate to the measured flood characteristics of the Tortolita area. Also shown in the plot is a magnitude estimate made by the USGS following an extreme flood in Cottonwood Canyon in 1961 (Aldridge, 1968). This canyon was not examined in this study, but it is a principal drainage in the western Tortolita Mountains. The estimate is included as further support for the contention that the theoretical 100-year flood magnitudes are substantially overestimated, and that the paleoflood values are more representative of low-frequency flood magnitudes in this area.

As a further comparison, figure 9 relates the paleoflood estimates and the theoretical estimates to envelope curves of the largest recorded rainfall-runoff floods in the conterminous United States and the largest gaged floods in southern Arizona (1915-1981). In principle, an envelope curve based on a spatially and/or temporally broad data base is probably indicative of an inherent physical (atmospheric) limit for rainfall generation and consequent drainage basin response (Costa, 1987; Wolman and Costa, 1982). Therefore, the values that define the envelope may approximate the values for the maximum possible rainfall-generated flood for a drainage basin of a given size. The position of the Southern Arizona curve below that of the US curve is most likely a consequence of specific hydroclimatologic controls operating in this region. Separation of floods by region is probably the most realistic way to view this type of data (Crippen, 1982).

The fact that the theoretically-derived estimates of the 100-year flood for each canyon fall on, if not just above the envelope of southern Arizona floods indicates that they are very likely overestimated. They may, in fact, approximate the maximum possible discharge values as opposed to 100-year flood magnitudes for each of the canyons. The placement of the paleoflood values within the clustering of southern Arizona floods provides further support for the contention that these are valid estimates of low frequency, high magnitude events in this region.

### **Paleoflood Frequency Considerations**

The significant discrepancy between the paleoflood data and the theoretically derived data is obvious. Because the larger theoretical estimates are designated as regulatory 100-year discharges, it would be instructive to determine the relative frequency of each of the paleofloods. This would allow for more detailed evaluation of the significance of the discrepancy.



**Figure 9.** Flood magnitude-area relationships: published theoretical 100-year discharge estimates (FEMA, 1989) and largest apparent paleoflood estimates for the principal canyons of the southern Tortolita Mountains (this study) shown in relation to the largest recorded rainfall-generated floods in the conterminous United States (Costa, 1987) and southern Arizona (Eychaner, 1984)

Unfortunately, it was not possible to construct valid flood frequency curves for each canyon because of the overall lack of evidence of multiple, correlative paleofloods preserved in any of the study reaches. Furthermore, single quantitative frequency assessments were impossible in all but one canyon because of the lack of both datable flood deposits and flood-scarred trees suitable for dendrochronological analysis. Though not adequate for regulatory purposes, it is possible to establish a qualitative assessment of the relative frequencies of the paleofloods in each canyon.

*Longevity of Slackwater Deposits and Other Paleostage Indicators.* The paleoflood analyses focused primarily on the highest evidence of flooding preserved in each canyon's geomorphology. Thus, the age of the particular flood in question is directly related to the rates of the various geomorphic processes that tend to obliterate the associated physical evidence.

Numerous paleoflood studies have documented the longevity of slackwater deposits in amenable environments. Slackwater deposit sequences in portions of the Pecos River, Texas, have been found to be in excess of 5000 years in age (Kochel, 1988); deposits in portions of the Salt River, Arizona, have been dated as far back as 600 years B.P.; and deposits near the Verde River, Arizona, have provided age estimates in the range of 1000 years B.P. (Ely et al., 1988). This study, in the analysis of slackwater deposits in Prospect Canyon, has shown that the flood record in the Tortolita area can be extended up to at least 600 years.

Other paleoflood studies and related studies of flood geomorphology provide valuable information concerning the amount of time that specific features can persist on the landscape. Baker and Partridge (1987) claim that flood scars (scour marks) in stable hillslope soils can persist for at least 600 years, and possibly as much as 1000-2000 years. Jarrett (1987) documents the persistence of vegetative flood debris for up to 100 years in portions of the Colorado Front Range (a climate with a more severe weathering regime than southern Arizona).

In terms of the weathering regime in semi-arid portions of southern Arizona, it is very likely that the features employed in the paleoflood analyses of the Tortolita canyons can persist on the landscape for an approximate range of 100-700 years; thus it is very probable that the paleofloods are representative of floods with recurrence intervals greater than 100 years.

## CONCLUSIONS

The paleoflood data presented here are not purported to represent definitive design predictions for the 100-year flood or other event of a specific frequency for each of the canyons. Instead, relative to the arguments outlined above, these values are real information very probably representative of low frequency ( $> 100$  year) events in this region. The range in estimated paleoflood magnitudes among the canyons suggests that an equal range of frequencies may be represented.

Prospect Canyon provides the best opportunity for directly comparing and contrasting the different values. The paleoflood analysis in Prospect Canyon shows that the largest flood to have occurred in the last 700 years is less than 50% of the published theoretical estimate of the 100-year flood (FEMA, 1988). There is not enough magnitude-frequency data to claim that this estimate represents the magnitude of the so-called "700-year flood", but the existing information (geomorphic and radiometric) implies that a flood of this magnitude has a significantly low frequency of occurrence ( $>> 100$  years).

The most striking aspect of the results of the paleoflood analysis is the fact that the reconstructed discharge estimates are considerably less than both the estimates employed by FEMA in the flood insurance study of the Tortolita Piedmont, and those derived from subsequent theoretical analyses intended to reevaluate them. An important issue is the overestimation of flood hazards on the piedmont that has inevitably resulted from the use of such high discharges. This is a topic that certainly deserves further attention.

The significant discrepancy between the theoretically derived data sets and the discharge estimates derived from on-site geologic evidence (and even that derived from regional-regression equations) suggests that the modeling procedure may greatly overestimate 100-year flood magnitudes in this area. Based on the graph in figure 8, it is reasonable to conclude that the use of a given regional regression equation may result in less overestimation, be much easier to use, and yet still provide reasonably conservative estimates that meet regulatory standards. A more detailed analysis involving the comparison of regional paleoflood information with a large number of regional-regression equations would enable informed selection of the most appropriate equation. This is a viable research topic that should be pursued further. Equally important is the necessity for reassessment of the theoretical model's treatment of low frequency events. It is clear that the method (at least in the cases outlined above) consistently overestimates the magnitude of 100-year discharges in undeveloped basins.

Inaccuracies in rainfall-runoff modeling routines for arid and semiarid regions are well recognized and attributed primarily to the large spatial and temporal variability of

flood producing events (particularly in the case of small drainage basins), the lack of adequately large data bases for model testing, and the complex nature of desert runoff-producing processes in general (Pilgrim et al., 1988). Based on these considerations alone, the use of *untested* rainfall-runoff models for the purposes of engineering design and floodplain management in these regions borders on irresponsibility.

The results of this analysis firmly accentuate the need for the scientific verification and/or testing of theoretical models designed to provide flood magnitude estimates for purposes of floodplain management. As this investigation has demonstrated, techniques of paleoflood hydrology can provide an excellent check on the validity of theoretically-derived regulatory flood magnitude estimates. Because paleoflood reconstructions are based on site-specific geomorphic evidence of flooding, they provide the only data representative of the actual flood hazard characteristics of a given area with no valid records of observation, and can provide data concerning extremely rare events in areas with records of observation. Therefore, they constitute an independent test of values derived from both empirical and theoretical methods. In the context of floodplain management, to avoid such a test and, in effect, ignore some of the most relevant data without legitimate rationale may very likely result in misrepresentation of the potential flood hazards in a given area (Baker et al., 1990). This is an unfortunate and undesirable situation for any agency that claims to control flood hazards from a basis of understanding the nature of flooding.

## REFERENCES

- Aldridge, B.N., 1968, Flood of September 13 near Marana, Arizona: *in* Summary of Floods in the United States During 1962, J.O. Rostvedt, ed., U. S. Geological Survey Water Supply Paper 1820, p. 105.
- Baker, V.R., 1987, Paleoflood hydrology and extraordinary flood events: *in* W.H. Kirkby, S.-Q. Hua, and L.R. Beard, eds., Analysis of Extraordinary Flood Events: Journal of Hydrology, v. 96, p. 79-99.
- Baker, V.R., 1988, Flood sedimentation in bedrock fluvial systems: *in* Flood Geomorphology, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., Wiley, N.Y., p. 123-138.
- Baker, V.R., 1989, Magnitude and frequency of palaeofloods: *in* Floods: Hydrological, Sedimentological and Geomorphological Implications, K. Beven and P. Carling, eds., Wiley, N.Y., p. 171-183.

- Baker, V.R., Ely, L.L., and O'Connor, J.E., 1990, Paleoflood hydrology and design decision for high-risk projects: in Chang, H.H., and Hill, J.C., eds., *Hydraulic Engineering, Vol. 1, Proceedings of the 1990 National Conference*: New York, American Society of Civil Engineers, p. 433-438.
- Cella Barr Associates, 1987, Tortolita Fan Area Basin Management Plan Phase 1- Existing flooding conditions, and Phase 1A-Interim Floodplain Management Policies: Tucson, Arizona.
- Cella Barr Associates, 1989 [Unpub.], Final Report: Tortolita area basin management plan: Tucson, Arizona.
- Chow, V.T., 1959, *Open-Channel Hydraulics*: McGraw-Hill, N.Y., 680 p.
- Cook, J.L., 1987, Quantifying peak discharges for historical floods: *in* W.H. Kirkby, S.-Q. Hua, and L.R. Beard, eds., *Analysis of Extraordinary Flood Events*. *Journal of Hydrology*, v. 96, p. 29-40.
- Costa, J.E., 1987, A comparison of the largest rainfall-runoff floods in the United States with those of the People's Republic of China and the world: *in* W.H. Kirkby, S.-Q. Hua, and L.R. Beard, eds., *Analysis of Extraordinary Flood Events*: *Journal of Hydrology*, v. 96, p. 101-115.
- Crippen, J.R., 1982, Envelope curves for extreme flood events: *Journal of the Hydraulics Division, ASCE*, v. 108, p. 1208-1212.
- Ely, L.L., and Baker, V.R., 1987, Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona: *Physical Geography*, v. 6, p. 103-126.
- Ely, L.L., O'Connor, J.E., and Baker, V.R., 1988, Paleoflood Hydrology of the Salt and Verde Rivers, central Arizona, *in* U.S. Committee on Large Dams, Eighth Annual Lecture Series Notes, Salt River Project, Phoenix, Arizona, p. 3.1-3.35.
- Eychaner, J.H., 1984, Estimation of the magnitude and frequency of floods in Pima County, Arizona, with comparisons of alternative methods: USGS Water-Resources Investigations Report 84-4142, 69 p.
- Federal Emergency Management Agency, 1989, Flood Insurance Study: Pima County, Arizona, unincorporated areas, Vol. 1, p. 29-30.
- Fuller, J.E., 1987, Paleoflood hydrology of the alluvial Salt River, Tempe, Arizona: M.S. Thesis, University of Arizona, Tucson.
- Hoggan, D.H., 1989, *Computer-Assisted Floodplain Hydrology and Hydraulics*: McGraw-Hill, N.Y., 518 p.

- Hupp, C.R., 1988, Plant ecological aspects of flood geomorphology and paleoflood history: *in* Flood Geomorphology, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., Wiley, N.Y., p. 335-356.
- Hydrologic Engineering Center, 1981, HEC-1 flood hydrograph package users manual: Davis, California, U.S. Army Corps of Engineers, 190 p.
- Hydrologic Engineering Center, 1982, HEC-2 water surface profiles program users' manual: U.S. Army Corps of Engineers, Davis, CA.
- Jarrett, R.D., 1987, Flood Hydrology of Foothill and Mountain Streams in Colorado: Ph.D. Dissertation, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, 239 p.
- Jarrett, R.D., 1984, Hydraulics of high gradient streams: *Journal of Hydraulic Engineering*, v. 110, no. 11, p. 1519-1539.
- Jarrett, R.D., 1990, Paleohydrologic techniques used to define the spatial occurrence of floods: *Geomorphology*, v. 3, p. 181-195.
- Kochel, R.C., 1988, Extending stream records with slackwater paleoflood hydrology: Examples from west Texas: *in* Flood Geomorphology, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., Wiley, N.Y., p. 377-391.
- Kochel, R.C. and Baker, V.R., 1988, Paleoflood analysis using slackwater deposits: *in* Flood Geomorphology, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., Wiley, N.Y., p. 357-376.
- Malvick, A.J., 1980, A magnitude-frequency-area relation for floods in Arizona: Research Report #2 Engineering Exp. Station, College of Engineering, University of Arizona, Tucson, Arizona, 186 p.
- O'Connor, J.E., Webb, R.H., and Baker, V.R., 1986, Paleohydrology of pool and riffle pattern development, Boulder Creek, Utah: *Geological Society of America Bulletin*, v. 97, p. 410-420.
- O'Connor, J.E., and Webb, R.H., 1988, Hydraulic modeling for paleoflood analysis: *in* Flood Geomorphology, V.R. Baker, R.C. Kochel, and P.C. Patton, eds., Wiley, N.Y., p. 393-402.
- Osborn, H.B., and Laursen, E.M., 1973, Thunderstorm runoff in southeastern Arizona: *Journal of the Hydraulics Division, ASCE*, v. 99, n. HY7, p. 1129-1145.
- Partridge, J.B., and Baker, V.R., 1987, Paleoflood hydrology of the Salt River, Arizona: *Earth Surface Processes and Landforms*, v. 12, p. 109-125.
- Pearthree, P.A., Demsey, K.A., Onken, J., and Vincent, K., 1990, A geomorphic assessment of fluvial behavior in flood-prone areas on the southern piedmont of

the Tortolita Mountains, Pima County: Unpub. Report (Draft) to the Pima County Flood Control District.

- Pilgrim, D.H., Chapman, T.G., and Doran, D.G., 1988, Problems of rainfall-runoff modelling in arid and semiarid regions: *Hydrological Sciences Journal*, v. 33, n. 4, p. 379-400.
- Reich, B.M., Osborn, H.B., and Baker, M.C., 1979, Tests on Arizona's new floods estimates: *in Hydrology and Water Resources of Arizona and the Southwest*, University of Arizona, v. 9, p. 65-74.
- Roberts, L.K., 1987, Paleohydrologic reconstruction, hydraulics, and frequency-magnitude relationships of large flood events along Aravaipa Creek, Arizona: M.S. Thesis, University of Arizona, Tucson.
- Roeske, R.H., 1978, Methods for estimating the magnitude and frequency of floods in Arizona: Final Report ADOT-RS-15-121, USGS, Tucson, Arizona, 82 p.
- Wolman, M.G., and Costa, J.E., 1982, Envelope curves for extreme flood events, Discussion: *Journal of Hydraulic Engineering*, v. 110, p. 77-78.
- Zeller, M.E., 1979, Hydrology Manual for Engineering Design and Flood Plain Management Within Pima County, Arizona: Tucson, Arizona: Pima County Department of Transportation and Flood Control District, 122 p.