Paleoflood Hydrology and Historic Flood Analysis in the upper Verde River basin, central Arizona

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ABSTRACT

Hell Canyon and Sycamore Canyon are major ungaged tributaries in the upper Verde River basin of central Arizona. Gage data imply that the record discharge of 1507 cms on February 20, 1993 at the Verde River gage near Clarkdale, Arizona was derived primarily from these tributaries.

Reconstructions of 1993 flows measure 800-900 cms in Sycamore Canyon and 600-700 cms in Hell Canyon. Historic and pre-historic flood sequences were examined in various stratigraphic exposures in these canyons; as many as 11 floods are recorded at any one site. The 1993 floodwaters typically overtop all prior flood stratigraphy; however, dendrochronology suggests that similar floods occurred prior to the gage record. These results confirm that Hell Canyon and Sycamore Canyon are major contributors to floods on the Verde River in both the historical and paleoflood record.

INTRODUCTION

Scope and Purpose

Paleoflood hydrology is an interdisciplinary approach used to study historic and prehistoric records of floods in river systems around the globe and is applicable to a wide range of scientific topics and practical problems. By extending the flood record beyond a relatively short historical data set, geologists are able to extract more representative samples of the largest floods for flood frequency analysis and to address long-term issues such as aggradation and degradation in the fluvial system, as well as flood-climate linkages for a particular region . The method produces results which are very useful and needed in urban planning, flood control procedures, and reservoir operation (Stedinger and Cohn, 1986; Hereford, et al., 1996; Graf, et al., 1991; Patton, 1977; Costa, 1978; Macklin, et al., 1992).

The slackwater deposit-paleostage indicator (SWD-PSI) technique in paleoflood hydrology allows for indirect discharge measurements following a flood by using features which record the height of the flood waters (Baker, 1987; Kochel and Baker, 1982; Patton, et al., 1979). Slackwater deposits are fine-grained deposits, typically composed of silt and sand, which accumulate in backwater zones where reduced velocities allow fine particles to fall from suspension. Reaches most conducive for preserving slackwater deposits include those that have fixed channel boundaries and features which initiate flow separation, such as alcoves, channel constrictions, minor tributary mouths, or bedrock obstructions. Paloestage indicators include all other high water marks such as flotsam piles and mats, scour lines, non-exceedance indicators, water stains on trees and bedrock, and tree scars.

High water evidence is used to estimate peak flow by fitting surveyed high water marks to water surface profiles computed from slope-area analysis or the step-backwater method (O'Connor and Webb, 1988). HEC-2 or HEC-RAS programs (Hydraulic Engineering Center, 1995) utilize data in a step-backwater modeling routine. This model is very efficient when experimenting with several values of discharge or other variables, since numerous water surface profiles can be generated simultaneously.

Recent storms in Arizona during the winter of 1993 provided an opportunity for utilizing the SWD-PSI technique to reconstruct discharges in ungaged river reaches and furthermore, to use them as guides for interpreting the paleoflood record. In the Verde River basin, central Arizona, these storms resulted in large-scale floods unprecedented in the historic record. House and Hirschboeck (1997) designate four primary storm events during the winter of 1993: January 6-9, January 13-19, February 7-10, and February 18-21 (House and Hirschboeck, 1997). These storms varied in their intensity throughout the basin; timing of gaged flows pinpointed the basin areas hit hardest by each storm and demonstrated that source areas for peak flows on the Verde may comprise only a small fraction of the entire basin (House, et al., 1995).

On the upper Verde River, the late February flood generated record peaks at USGS stream gages. Antecedent conditions, as well as rain on snow in the upper elevations and high daily rainfall totals on the 19th and 20th were the primary factors in the resultant record runoff volumes measured on February 20, 1993 at the Paulden, Clarkdale, and Camp Verde gages along the Verde River, estimated at 657, 1506, and 3370 m^3s^{-1}, respectively (House and Hirschboeck, 1997). Tributaries between the Clarkdale and Camp Verde gages also recorded large-magnitude flows; however, their record-breaking events occurred during January of the same year (Table 1).

Timing of peak flows on the upper Verde River show that the upstream gage at Paulden almost always peaks after the peak at Clarkdale. Thus, little runoff from the upper basin contributed to the record peak at Clarkdale, making ungaged tributaries between the two gages responsible for the primary portion of floodwaters at the Clarkdale gage. Reconnaissance of Hell Canyon and Sycamore Canyon, the dominant tributaries between the gages, revealed surficial evidence of extreme recent flows. Stratigraphic sequences of flood deposits present in each canyon also document historical and prehistoric large floods. This project utilizes the preservation of paleofloods and recent extreme floods to document the historical and paleoflood record in tributary canyons and to evaluate their potential for generating large floods on the Verde River.

During the course of this study, I employed a number of different strategies, including hydraulic modeling, stratigraphic analysis, dendrochronology, and gaged data examination. Section 1 reviews previous work and describes the setting of the study area in terms of physiography, basin morphometry, channel bedload characteristics, and general meteorology. Section 2 analyzes the February 18-21,

Gage name	Q peak (cms)	Time (February 20, 1993)
Verde near Paulden	657	0945
Verde near Clarkdale	1507	0400
Oak Creek near Cornville	736	0330
Wet Beaver Creek	107	0130
West Clear Creek	195	0100
Verde near Camp Verde	3370	1100

Table 1. Discharge gage data and timing of the late February flood event. Shown are selected gages on the mainstem and tributaries of the Verde River.

1993 flood of record. Section 3 catalogues tributary slackwater sediments, while Section 4 discusses late Holocene terraces. Finally, Section 5 summarizes the project's overall results and implications.

Physiography

The Verde River basin encompasses diverse terrain, extending from the Basin and Range province through the Central Highlands and into the southernmost portion of the Colorado Plateau in northern Arizona. The main stem of the Verde River originates above Chino Valley and flows southeast to Paulden, where it begins its descent through the Verde River canyon (Figure 1). Adopting a more southerly drainage route, it enters the Central Highlands below Verde Valley and after passing through Horseshoe and Bartlett Reservoirs below Tangle Creek, it joins the Salt River east of Phoenix. The Salt River then joins the Gila River near Laveen, Arizona.

The study area encompasses Sycamore Canyon and Hell Canyon and comprises some of the most diverse topography and greatest relief in the Verde watershed. Both drainages flow to the south; Hell Canyon enters the Verde along with two other small drainages, MC Canyon and Bear Canyon, just downstream of Paulden, Arizona. Sycamore Canyon meets the Verde River approximately 2.2 km (1.4 miles) north of thegage near Clarkdale. These currently ungaged[1] watersheds constitute the primary

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[1] During 1965-1972, the U.S. Geological Survey maintained stream gages in Hell Canyon and Sycamore Canyon at Hell Canyon near Williams, Arizona and Volunteer Wash near Bellmont, Arizona, respectively.

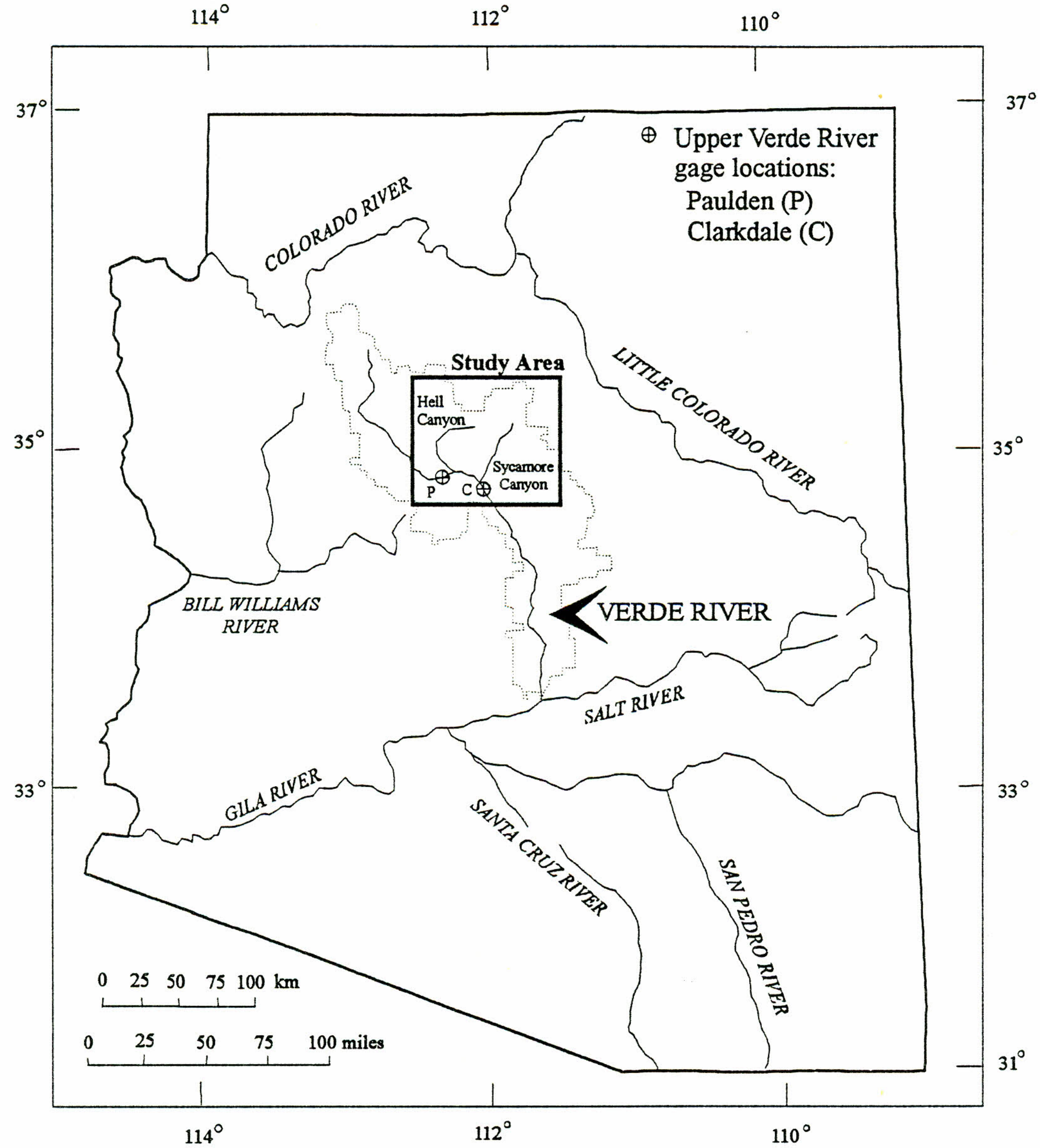


Figure 1. Study area location.

portion of watershed area between the Paulden and Clarkdale gages, and are major contributors to floods in the upper Verde River basin.

Previous Work

Previous work in paleoflood hydrology on the Verde River has focused on documenting flood records on the lower portion of the unregulated Verde River downstream of the gage at Camp Verde, while ongoing research addresses the basin as a whole.

Ely and Baker (1985) examined the paleoflood record on the mainstem between the gage below East Verde River and the gage below Tangle Creek. This study provided evidence for the validity of the SWD-PSI method, in which hydraulic reconstructions for the 1951 and 1980 floods matched well with gaged data downstream, underestimating flow by 15-20% at the most. A maximum of 10 distinct floods were documented, the highest having a peak discharge of 5000-5400 cms and dating at 1010 ± 95 years B.P. The second highest deposit in the stratigraphy, interpreted as the 1891 flood deposit, had an associated radiocarbon date of 223 ± 70 years B.P. and a peak discharge of 3500-3800 cms. A flood frequency curve was fitted to the paleoflood data and historical records, placing the largest of these events at a 1000-year recurrence interval and the 1891 event at a 500-year recurrence interval.

In an attempt to test the reproducibility of the latter study, O'Connor, et al. (1986) documented a reach near Red Creek, upstream from the reach of Ely and Baker (1985). Although the relative chronology and magnitude of events was consistent between sites, discharge estimations for historic floods, such as the 1891 flood, were significantly less; in addition, evidence for the oldest and largest flood in the Ely-Baker reach was not found.

Renewed interest in the Verde in the 1990's was precipitated by extreme floods during the winter of 1993 whose magnitude was unprecedented in the gaged record on the Verde River. The occurrence of record peaks at many of the stream gages provided a unique opportunity to study paleofloods on the Verde in the context of a large magnitude, record-breaking event.

House, et al. (1995) studied the January and February flood peaks of 1993, focusing on the Red Creek (O'Connor, et al., 1986) and Ely-Baker (1985) reach in order to resolve discrepancies between the reaches, evaluate and refine discharge estimates with different types of water surface indicators, and place the 1993 flood in the context of flood chronologies and hydraulic reconstructions of the 1980's. Fitting water surface profiles to slackwater deposits and high water marks, House, et al. 91995) found that flow is underestimated by approximately 30% when using the tops of slackwater deposits versus diagnostic high water indicators (i.e., flotsam) in well-confined reaches such as the Red Creek reach and by 5-10% in wider reaches with lower gradients as in the Ely-Baker reach. Discharge estimates from previous studies as well as their own study are revised based on these findings. Putting their discharge calculations into flood frequency analysis, they estimate 100-year flood discharge and 500-year flood discharge as 4,020 m^3s^{-1} and 5,350 m^3s^{-1} at Tangle Creek.

Based on adjusted flow values and an additional slackwater site in the Red Creek reach, the study also resolves discrepancies in flood magnitude and stratigraphy between the reaches. The study reinterprets the O'Connor, et al. (1986) 1891 deposit as that of 1938 and provides evidence for a higher 1891 deposit as well as two floods >1000 yrs. B.P., the youngest of which was tentatively correlated to Ely and Baker's >1000 yrs. B.P. unit. All three of these units are shown to be larger than the 1993 floods.

House, et al. (1995) also examined the gage record of the 1993 floods and demonstrated that peak flows at an upstream gage may follow peak flow at downstream gages so that peaks in the upper basin have variable contribution to flood peaks in the lower basin. This relation is due to the interplay between basin shape and the distribution of meteorological events over the watershed, in which a very small portion of the basin may contribute the majority of flow to the peak discharge. This type of system behavior has been documented by other flood studies in Arizona as well (Aldridge and Eychaner, 1984; Aldridge and Hales, 1984; Chin, et al., 1991).

House and Hirschboeck (1997) described the factors that culminated in extreme flooding events in Arizona in the winter of 1993. These factors can be separated into three categories: local, short term events, such as precipitation events, regional or long-term conditions such as climatic variables and patterns, and watershed physiography.

Within the Central Highlands portion of Arizona, where the study area is located, mechanisms which generate the largest floods are related to winter frontal storms enhanced by orographic effects, in which antecedent moisture followed by heavy precipitation produces extreme events. Rain-on-snow scenarios, common in Central Highland basins, are especially important and are associated with rapid warming and cooling trends which accumulate snowpack and melt snowpack in conjunction with high daily rainfall totals. These types of conditions provide the optimum scenario for generating an extreme event such as those which occurred in 1993 (House and Hirschboeck, 1997).

Basin Geology

Major units which comprise the Sycamore Canyon watershed include Paleozoic sedimentary rocks such as the Tapeats sandstone, Martin limestone, Redwall limestone, Supai Formation, Coconino sandstone, Toroweap Formation, and Kaibab limestone. Of these formations, canyon walls are mainly composed of the Martin and Redwall, which are the cliff-formers, and the Supai Formation, which is somewhat recessive above the canyon walls. Also constituting canyon walls and portions of the watershed are Cenozoic basalts and sedimentary rocks, such as the late to middle Miocene (Reynolds, 1988) Hickey Formation, composed of interfingering relict channel deposits, basin fill, and volcanic flows. In the vicinity of Sycamore Canyon, the basalts cap Black Mountain and other high elevations. The Verde and Perkinsville Formations are similar to the Hickey Formation in that they also contain intertonguing basalts and gravel deposits; however, the Verde Formation also contains extensive lacustrian deposits, which are late Tertiary, or Plio-Pleistocene in age (Jenkins, 1923; Mahard, 1958, Lehner, 1958). Basalts intermediate in age between the Hickey and Verde/Perkinsville Formation, cap the northern wall near the mouth of Sycamore canyon. In the uppermost portion of its watershed, Sycamore Canyon drains volcanic rocks of the San Francisco volcanic field, which range from Holocene to late Pliocene in age. These rocks are mainly basalt with minor rhyolitic and andesitic components (Lehner, 1958).

Hell Canyon has a similar stratigraphic sequence, although a significantly greater portion of its watershed drains basaltic rocks of Pliocene to late Miocene in age. From Drake, Arizona to the confluence of Hell Canyon and the Verde River, channel walls are composed of the Redwall, Martin, and Supai Formations successively downstream; above Drake, canyon walls and the surrounding drainage area are formed in basalts with tuff and agglomerate present locally. Patches of Kaibab Limestone and Coconino Sandstone dot the upper watershed, as well as andesite flows, dikes, and plugs on Bill Williams Mountain. Remnant Quaternary surfaces of sand, silt, and gravel are also found in the lower to middle portions of Hell Canyon watershed (Arizona Bureau of Mines, 1958; Moore, R.T., and others, 1960).

Basin Morphometry

Basin morphometry may be an important factor for some drainage basins in their ability to generate large floods in conjunction with meteorological conditions (Baker, 1977; Patton and Baker, 1976; Costa, 1987; Gregory, 1976). Morphometric parameters for ungaged tributaries in the study area were compared to those for gaged streams on the middle Verde River in order to assess their capability for generating large floods.

The following morphometric characteristics were calculated for Sycamore Canyon, Hell Canyon, MC Canyon, and Bear Canyon within the study area and Oak Creek Canyon, Wet Beaver Creek and West Clear Creek outside of the study area (Table 2; Figure 2): basin area (*A*), drainage density (*DD*), gradient (*S*), relief (*R*), relief ratio (*RR*), ruggedness number (*Rg*), and elongation ratio (*Re*). Methods used to calculate parameters follow the

Watershed	Area (*A*)	Drainage Density (*DD*)	Gradient (*S*)	Relief (*R*)	Ruggedness number (*Rg*)	Relief Ratio (*RR*)	Elongation ratio (*Re*)
Units	km^2	km/km^2	km/km	m	km^2/km^2	km/km	km/km
Sycamore Canyon	1,229	8.0	0.015	1650	14.9	0.026	0.63
Hell Canyon	613	5.0	0.016	1580	7.7	0.049	0.87
MC Canyon	162	4.3	0.036	1080	4.6	0.042	0.55
Bear Canyon	86	6.5	0.026	1110	7.0	0.043	0.40
Oak Creek Canyon	919*	6.2	0.007	1386	8.6	0.019	0.46
Wet Beaver Creek	624*	5.4	0.013	1367	7.4	0.032	0.66
West Clear Creek	287*	5.5	0.023	1495	8.2	0.026	0.33

* Parameters derived from basin area above the gaging station of each tributary.

Table 2. Morphometric parameters for selected tributaries in the upper and middle Verde River basin. Basin morphometry, independent of meteorological variables, shows that Sycamore Canyon has the greatest potential of any of the studied basins to generate large floods. This evaluation is based on its relative size, shape, relief, gradient, and ruggedness number.

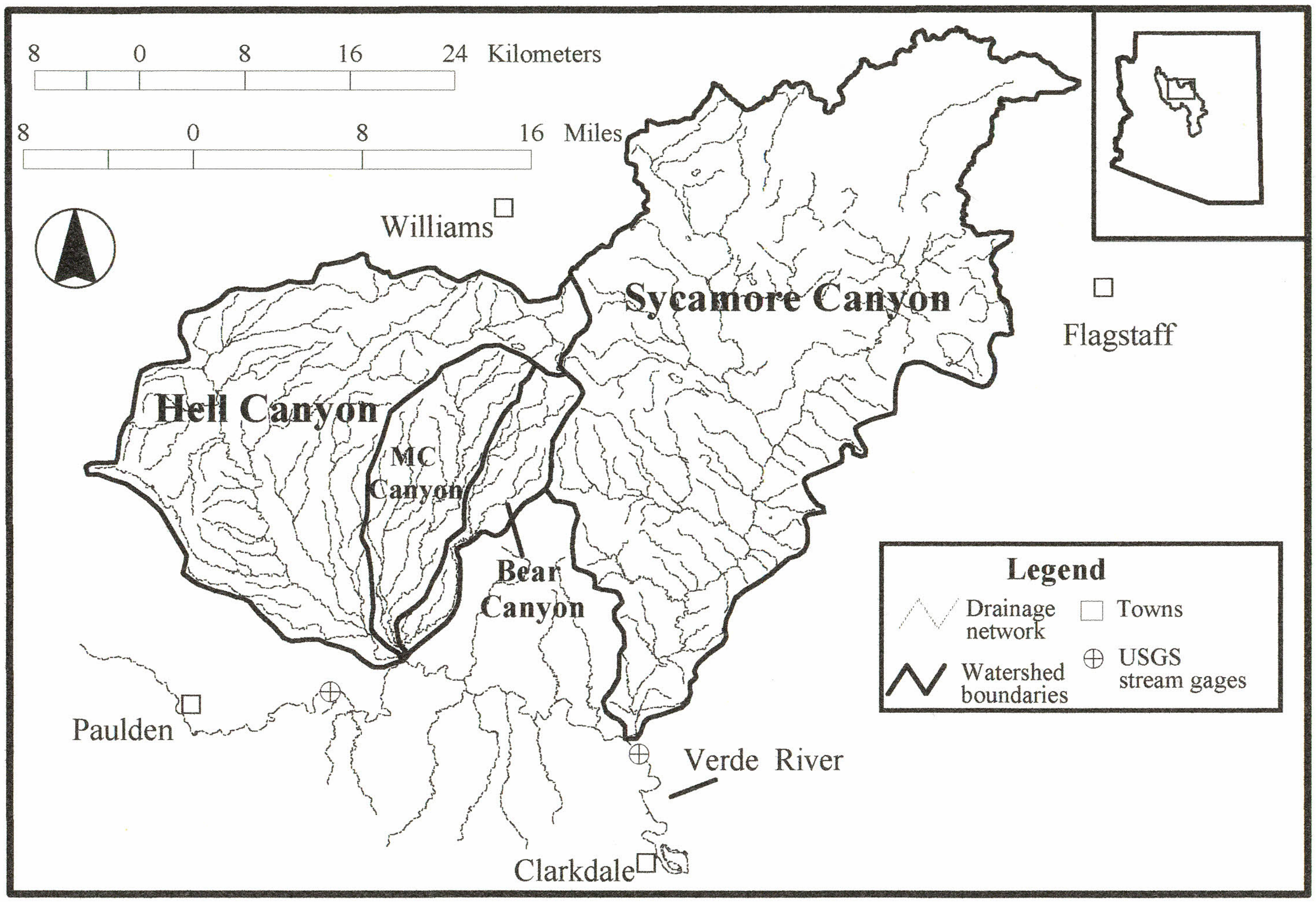


Figure 2. Basin morphometry study location

procedures of Schumm (1956), Melton (1957), Strahler (1957), and Costa (1987). Drainage density was calculated by the line intersection method, which estimates drainage density by measuring the number of intersections per unit map distance along a transect and derives a relation between this measurement and the drainage density parameter (Carlston and Langbein, 1960; Mark, 1974; McCoy, 1971). Based on the findings of Patton and Baker (1976), I use the following equation developed by McCoy (1971), where:

$$\text{Drainage Density (DD)} = 1.8 + 1.27N/L \qquad (1)$$

where N=number of stream intersections along a transect
L=length of transect (miles)

Comparison of Hell Canyon and Sycamore Canyon with gaged tributaries of Oak Creek, Wet Beaver Creek and West Clear Creek suggests that the basins share similar characteristics but also show important differences. Sycamore Canyon exhibits the greatest area, relief, drainage density, and ruggedness number, suggesting that it has the greatest potential to generate large flows. Its high elongation ratio attests to its overall circular shape and points to a flashy flood response; the headwaters of the basin are even more equidimensional so that runoff should rapidly concentrate in the upper canyon and move efficiently through a relatively straight channel in the lower canyon. It is most similar to the Oak Creek Canyon drainage, which has experienced peak flows up to ~800 cms in recent decades. Oak Creek is smaller in size and gentler in gradient than Sycamore Canyon; morphometric parameters indicate that peak flows may be reduced in size relative to Sycamore Canyon.

Hell Canyon can be compared to Wet Beaver Creek and West Clear Creek. These basins are similar in all parameters except elongation ratios, such that Hell Canyon is more equidimensional, and may concentrate its flow more rapidly to generate larger peaks. Based on this, Hell Canyon should be capable of generating peak flows on the order of 500-700 cms which correspond to maximum peak flows at Wet Beaver Creek and West Clear Creek stream gages.

Bedload Characterization

For Hell and Sycamore Canyons, a random sampling technique was employed to characterize bedload. This data was used to estimate channel roughness and to perform a paleocompetence study in reaches used to model the 1993 peak flow in Hell Canyon and Sycamore Canyon. Three separate samples were taken for each canyon: a general sampling of the channel, and more detailed samples of two model reaches in each canyon. We sampled every 15 meters during the general channel survey and every 5 meters within the model reaches. The long, intermediate, and short (a, b, and c) axes of each particle were measured and recorded along with the lithology and color of the particle. In the event that a particle was partially buried and too large to unearth, minimum diameters were measured. Sample sizes ranged from n values of 200 for each general sampling and 100 for each study site. We also sampled the 25 largest clasts for each study site to document the maximum bedload size available to be transported; although only the 5 largest particles were used in the analysis, a sample size of 25 ensured that we would obtain the largest in the channel.

Results of the bedload sampling are shown in Figures 3 and 4, where cumulative frequency, expressed in percent greater than a given measurement value, is plotted against b-axis measurements. Although the modeled reaches in both Sycamore Canyon and Hell Canyon are less than one mile apart along the distance of the main channel, lower reaches display a decrease in sediment size when compared to upper reaches. This is a well-accepted concept in geomorphology, where particle size decreases with distance from the source (Brierley and Hickin, 1985; O'Connor, 1993; Pettijohn, 1949; Parker, 1991a; Parker, 1991b; Paola, et al., 1992). Particle size differs between canyons, in that all measured clasts in Sycamore Canyon are smaller than or equal to 70 cm in intermediate diameter, whereas bedload in Hell Canyon measures up to 240 cm in diameter in the general sampling data set. Selecting only samples from Hell Canyon with a b-axis of 70 cm or less shows that Hell Canyon still has a higher percentage of larger particles within this range, presumably due to shorter transport distances. (Figure 3).

Bedload in the modeled reaches in Hell Canyon is significantly smaller than that of overall channel sampling (Figure 4), as these reaches were chosen partly for their smaller bedload size to reduce turbulence in the channel. In Sycamore Canyon, bedload sizes generally bracket the random channel sampling; b-axis measurements range from 0.1 to 70 cm, in which 90% of particles are less than 30 cm in the downstream reach and less than 47 cm in the upstream reach.

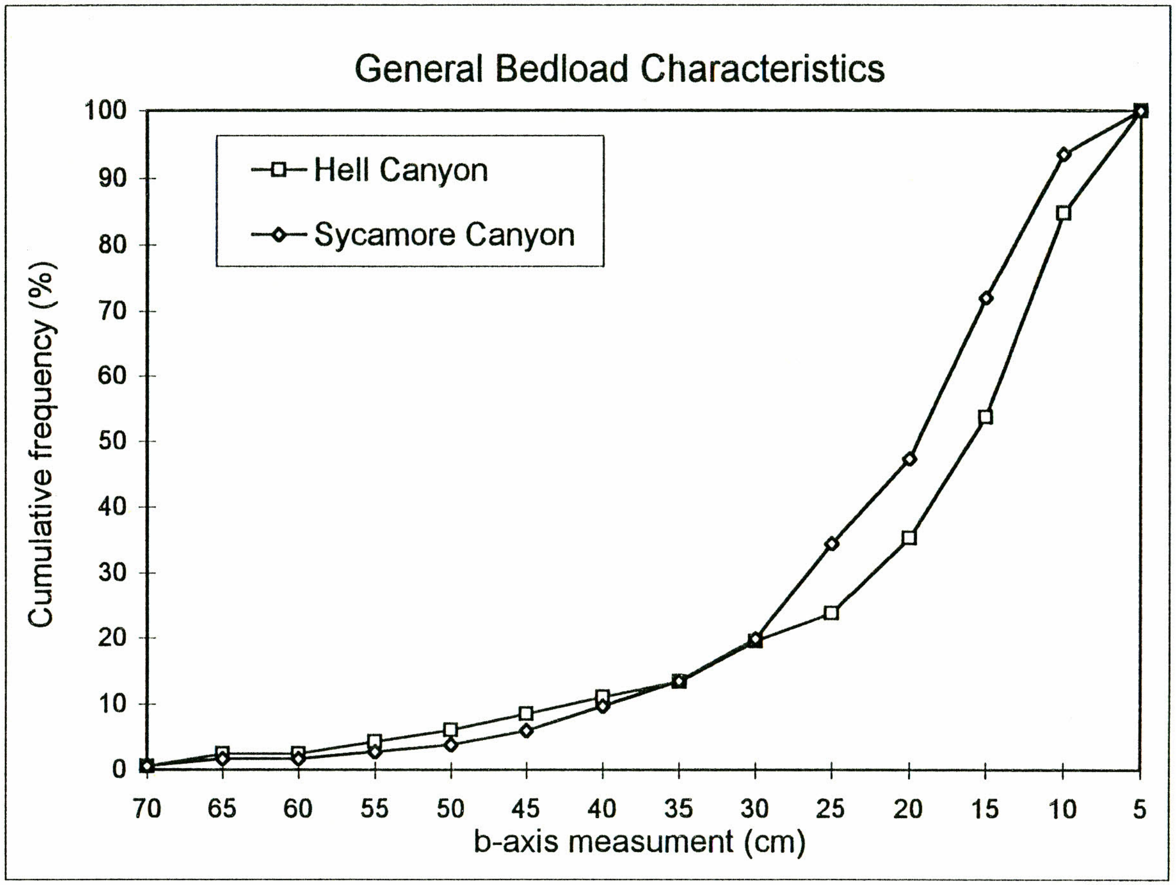
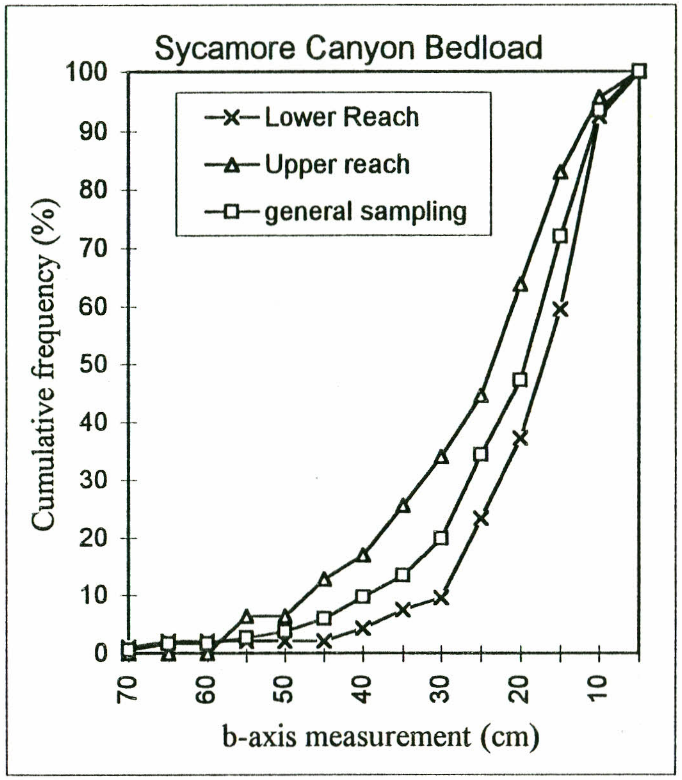
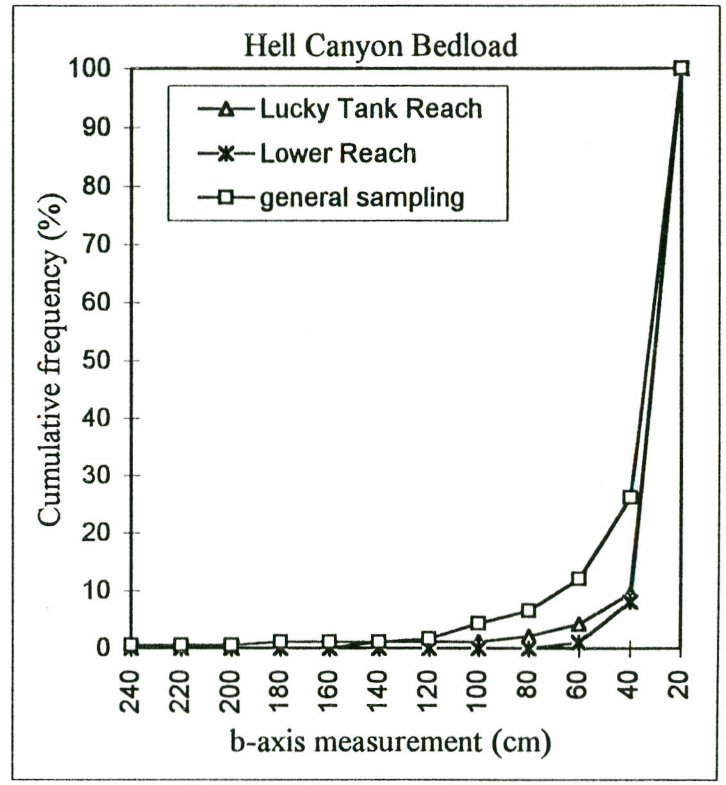


Figure 3. General bedload sampling, Sycamore Canyon and Hell Canyon. Percent greater than a given measurement is plotted against b-axis measurements for particles with diameters of 70 cm or less. Although bedload size distribution is similar, Hell Canyon contains a greater percentage of large particles.



(A)



(B)

Figure 4. Bedload Characterization for Sycamore Canyon (A) and Hell Canyon (B). Hell Canyon modeling reaches have a smaller bedload compared to the general sampling, while Sycamore Canyon model reaches bracket the general sampling. Note that particle size decreases from upstream to downstream reaches.

General Meteorology of Storm Events

Regional meteorological and hydrological data from storms that have impacted the upper Verde River basin show similar large-scale mechanisms and basin responses to recent large-magnitude events. Large storms and floods in the gage record of both Paulden and Clarkdale include: Feb.28-Mar.6, 1978, Dec. 17-23, 1978, Feb. 14-16, 1980, Feb. 18-21, 1980, Jan. 7-9, 1993, Feb. 18-21, 1993, Feb. 14-17, 1995, and Mar. 5-8, 1995.

The largest floods are from frontal and convective winter storms occur in the winter months that carry above normal amounts of moisture into the southwest. In this region, precipitation is enhanced by orographic effects from the Mogollon Rim which serves as a NW-SE barrier to northeastward-moving moist air. The storms are generally characterized by anomalous hydroclimatological conditions, in which a blocking high pressure ridge creates split westerly flow such that a jet stream track occurs further south than normal, and allows moisture to be delivered to the Southwest. This track becomes strengthened as the trough deepens and may become stationary, allowing precipitation to fall over the region for a number of consecutive days. This jet stream condition may occur many times throughout the winter to steer storms over the region. Rapid warming and cooling trends create antecedent conditions conducive to flooding as subsequent storms develop. Some of the antecedent conditions which have been present in the studied floods include: high soil moisture content, above average precipitation preceding the event, and high water content in snow. Rain-on-snow conditions are also important at higher elevations, especially for the 1993 event; however, flooding reports have not documented this occurrence for other floods (Aldridge and Eychaner, 1984; Aldridge and Hales, 1984; Chin, et al., 1991).

For all of the storms studied, runoff derived from a storm has a greater time of concentration above the Paulden gage than in the portion of the watershed between the Paulden and Clarkdale gages, such that the peak discharge at Paulden <u>follows</u> the peak discharge at Clarkdale. This probably does not reflect the timing of the storm event, but instead a circuitous drainage path and attenuation in Sullivan Lake above the Paulden gage (Aldridge and Hales, 1984). Knowing this relation, we can assume that most of the peak discharge at the Clarkdale gage is generated by watersheds located between the two gages.

1993 FLOOD ANALYSIS

Meteorological Conditions

The general meteorology of the winter of 1993 is summarized in the following paragraphs (see House and Hirschboeck, 1997 for a more detailed discussion). The general circulation pattern during the winter of 1993 was characterized by the development of a high pressure area in the eastern North Pacific Ocean which generally persisted through the winter. This persistent high pressure caused a branching of the polar jet stream and forced the associated Pacific storm tracks further north and south than they would normally occur. This brought greater cyclonic storm activity across the state of Arizona. Sea surface temperatures (SST's) remained above normal from December 1992 through February 1993 such that warm moist air from the eastern Pacific was delivered to Arizona, increasing rainfall totals during the winter months. Persistence of the large scale circulation anomaly and the repeated occurrence of split westerly flow also acted to increase precipitation above normal levels, create antecedent conditions conducive to flooding, and bring frontal passages through the area, initiating cooling trends and warming trends. Storms occurred during both warm and cool episodes; rainfall was the dominant precipitation type during warm events while cool events were associated with the accumulation of snowpack and at higher elevations. Rapid transitions between warming and cooling trends produced rain-on-snow events and resultant floods on the downstream Verde River.

The largest flood ever recorded at the Clarkdale gage occurred on February 20, 1993. Conditions were such that moisture from the southwest into central Arizona occurred in conjunction with a warming trend and rapid snowmelt on February 17th. On February 18th and 19th, two fast-moving frontal passages created high daily totals of precipitation which fell on snowpack around the Flagstaff area (Figure 5).

Gage data

Precipitation gages

Precipitation gages in the Upper Verde River basin show antecedant rainfall on the 18th and 19th of February with the highest daily totals on the 19th and extending into the 20th (Figure 6), when the peak of record was measured at the gage near Clarkdale. The heaviest precipitation was recorded at the highest elevation gages near Flagstaff (Pulliam Airport), Williams, and Ashfork, Arizona which measured totals of 130 mm, 146 mm, and 37 mm, respectively on the 19th and 20th of February, 1993. These gages are located near the headwaters of Sycamore Canyon and Hell Canyon and suggest that rainfall within the upper portions of these drainage basins was heavy during the February 1993 event. Rain-on-snow was a factor only at the gages near the Flagstaff area; judging from the research of House and Hirschboeck (1997), it is likely that the majority of existing snow was melted during the warming trend on the 17th.

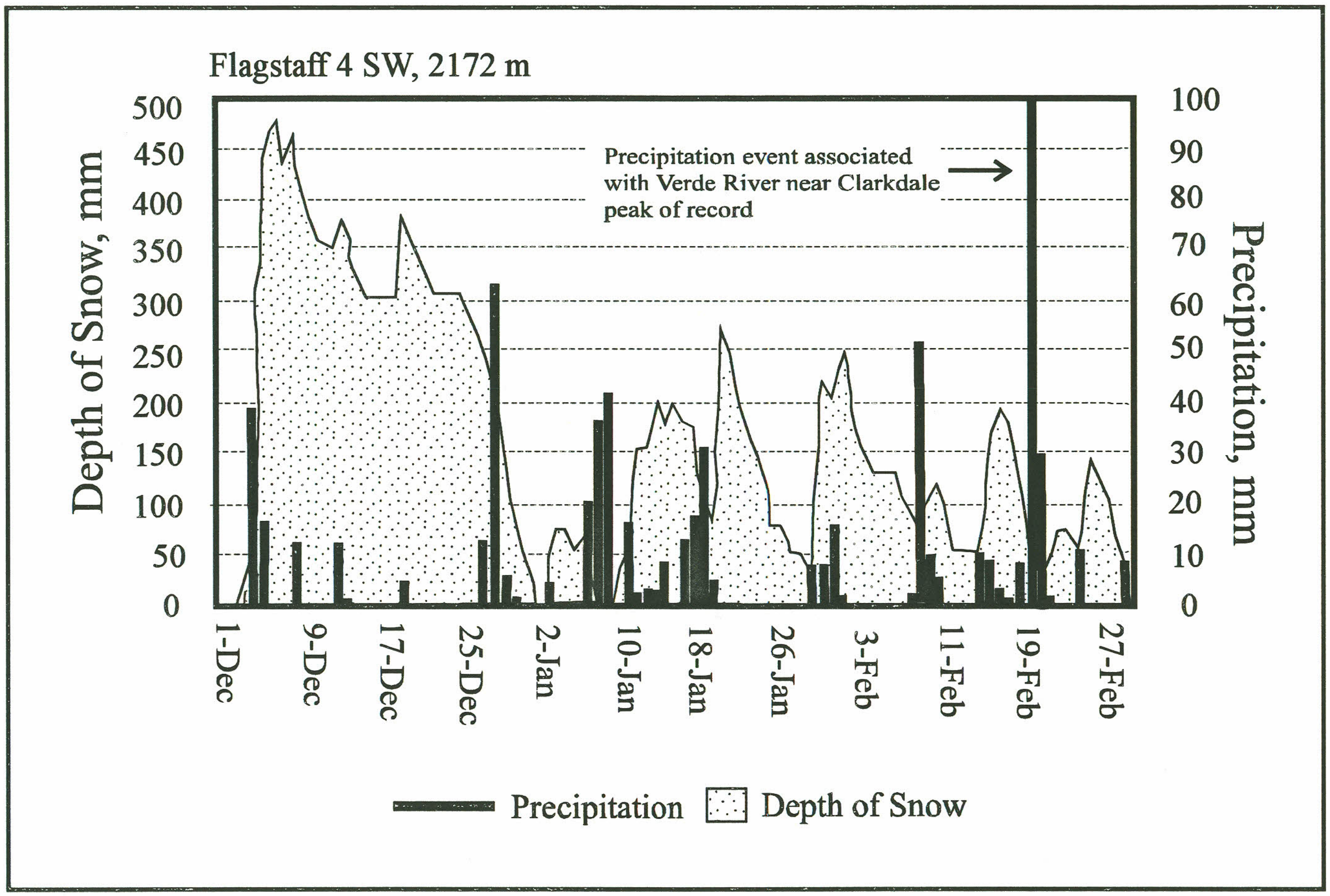
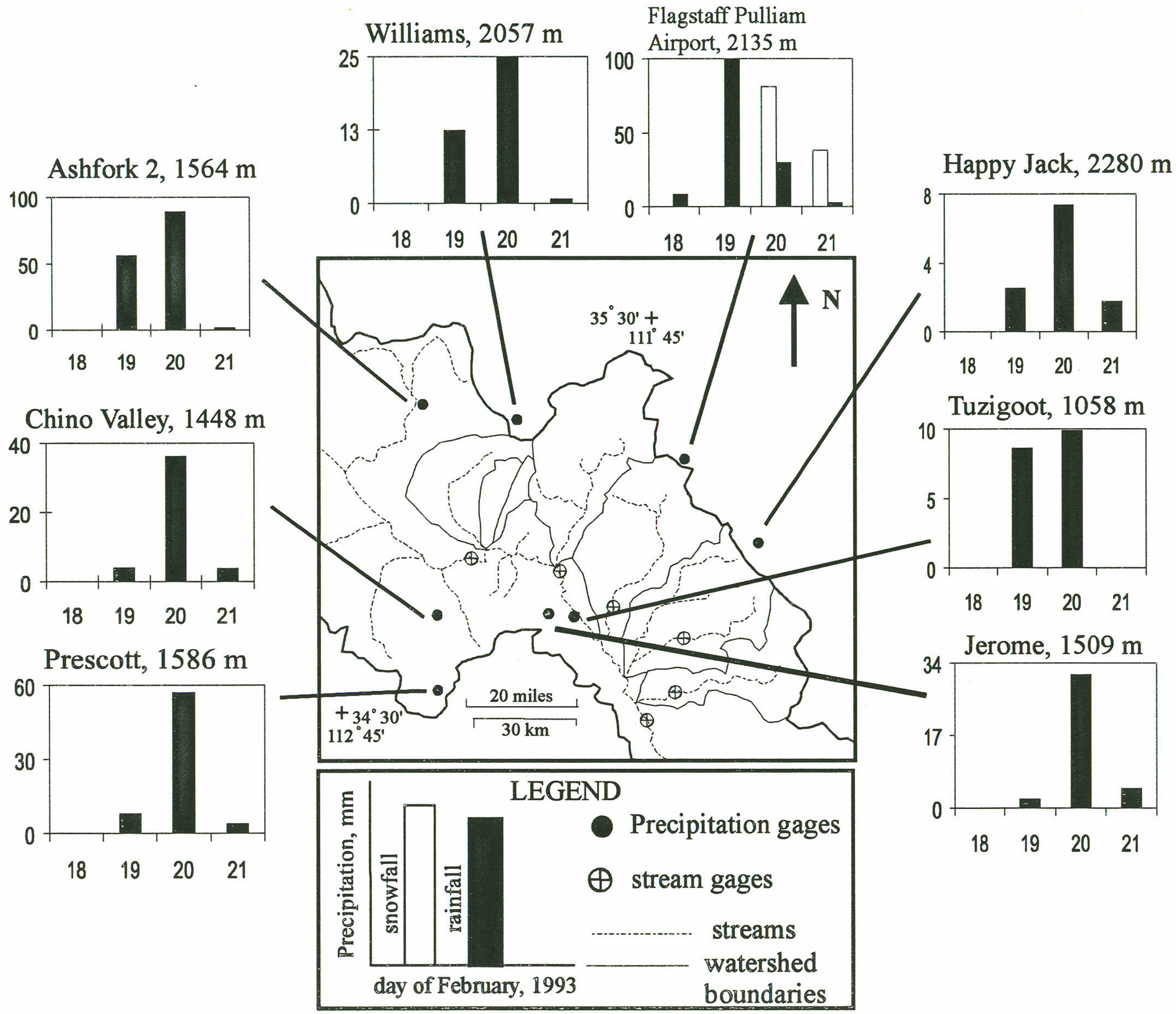


Figure 5. Precipitation and snowpack record, December through February, 1993
(modified from House and Hirshboeck, 1997)

Figure 6. Regional precipitation pattern of late February, 1993. Although rainfall is recorded regionally on February 19th and 20th, heaviest events were at high elevations. Lower elevations, such as Verde Valley and Chino Valley, received lesser amounts of precipitation (mm).


Williams, 2057 m
Flagstaff Pulliam Airport, 2135 m
Ashfork 2, 1564 m
Happy Jack, 2280 m
Chino Valley, 1448 m
Tuzigoot, 1058 m
Prescott, 1586 m
Jerome, 1509 m
18 19 20 21
35° 30' + 111° 45'
+ 34° 30' 112° 45'
N
20 miles
30 km
LEGEND
Precipitation, mm
snowfall
rainfall
day of February, 1993
Precipitation gages
stream gages
streams
watershed boundaries

Other gages within the region did not have a significant snowpack prior to the 17th warming event. Although they show accumulations of rainfall during these dates, totals are lower. For instance, the Seligman gage records a cumulative rainfall of 31 mm, while Chino Valley received 33 mm on February 19th and 20th. Gages in lower Verde Valley also record the event with 19 mm at Tuzigoot on the 20th and 10 mm at Happy Jack Ranger Station. Thus, regional data suggest that storm effects were felt throughout the study area and correspond to flood peaks measured at the Paulden and Clarkdale gages (Earth Info., Inc., 1996).

Stream gages

Streamflow data from the Paulden and Clarkdale gages demonstrate the ability of an elongated drainage basin to experience localized flooding with little or no contribution to downstream flood peaks. From February 19-22, 1993, gage data shows a pronounced lag in flood peaks between the Clarkdale and Paulden gages such that the upstream Paulden gage peaks at 657 m^3s^{-1}, approximately 5 hours and 45 minutes after the peak of 1507 m^3s^{-1} at Clarkdale (Figure 7). This relation holds true for other large floods in the historic record such as those in 1978, 1980, as well as smaller peaks in 1995 (Figure 8; Table 3), in which the lag between the Clarkdale and Paulden gages ranges from 5 to 8 hours.

Judging from these data, it is unlikely that discharges from the gage at Paulden contribute significantly to the peak flow at Clarkdale in the historic record; therefore,

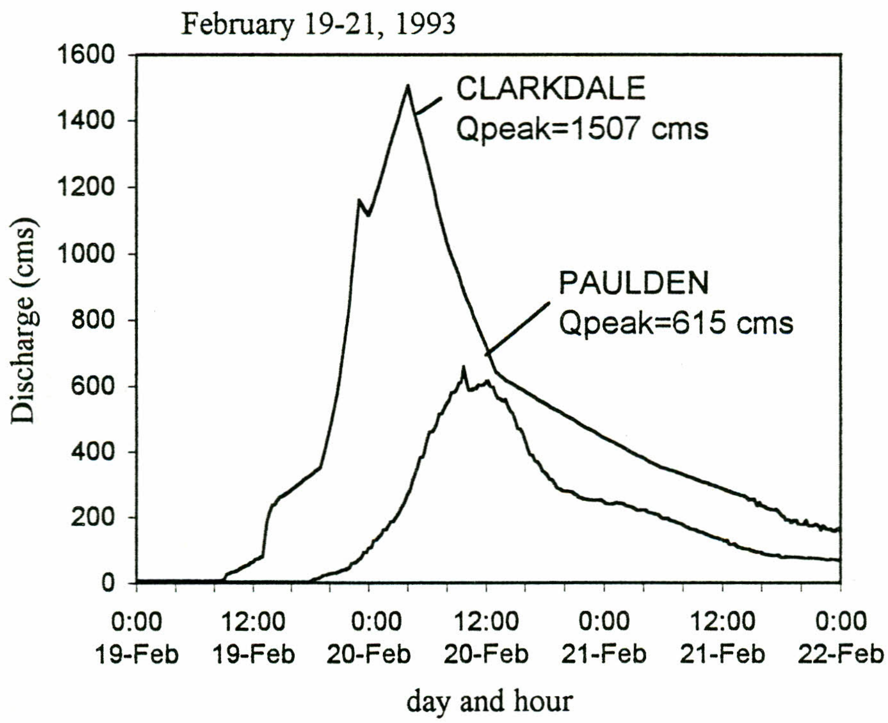


Figure 7. Gage relations in the upper Verde River basin. Note that the upstream gage at Paulden peaks *after* the downstream gage at Clarkdale; this suggests that the majority of peak flow at Clarkdale originates in watersheds between the gages.

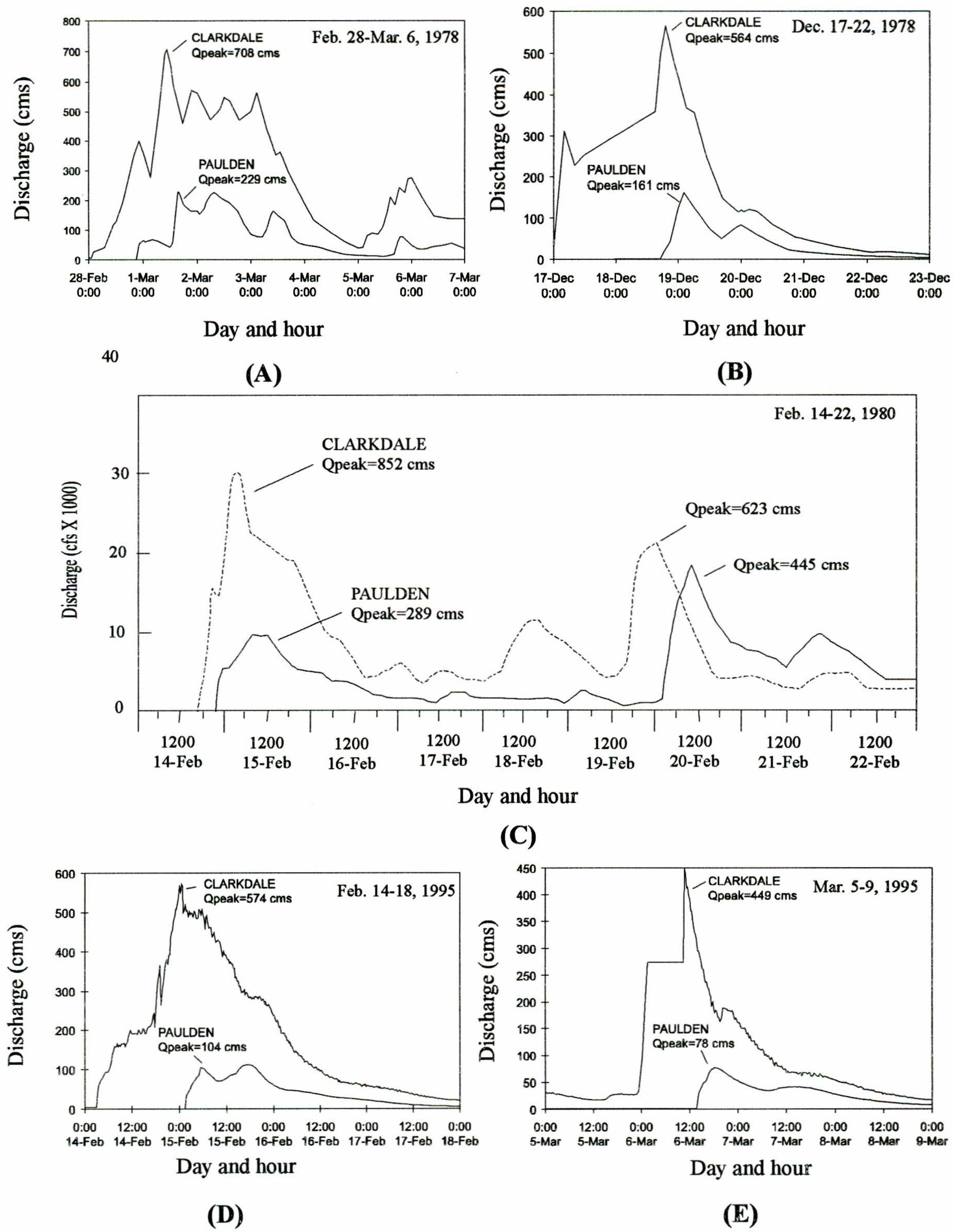


Figure 8. Historic flood hydrographs. Hourly gage data demonstrate the lag between the Paulden and Clarkdale gages during runoff events: (A) Feb. 28-Mar.6, 1978; (B) Dec. 17-22, 1978; (C) Feb. 14-22, 1980 (Modified from Chin, et.al, 1991); (D) Feb 14-18, 1995; (E) Mar. 5-9, 1995. Data obtained from the United States Geological Survey.

	CLARKDALE Q peak			PAULDEN Q peak			
Date	Time (hours)	cms	cfs	Time (hours)	cms	cfs	Lag in peaks (hours)
1918	Unknown	1005	35500		-------	-------	Unknown
2/21/20		1433	50600		-------	-------	Unknown
12/06/66	1500	637	22500		-------	-------	
12/07/66		-------	-------	2100	35	1250	6:00
2/09/76	1500	510	18000	2115	122	4340	6:15
3/01/78	1030	708	25000	1530	228	8080	5:00
2/15/80	0300	852	30100	0830	287	10200	5:30
2/19/80	Unknown	623	22000				
2/20/80				0645	442	15700	Unknown
1/08/93	1300	745	26300	1930	255	9060	6:30
1/17/93	0700	558	19700	1500	216	7670	8:00
2/20/93	0400	1507	53200**	0945	654	23200	5:45
2/15/95	0030	575	20300	0530*	104	3679	16:45
3/06/95	Unknown	606	21400	1815	77	2740	Unknown

*Qpeak most likely to be associated with peak at Clarkdale. A larger discharge occurs at Paulden at 1715 of 112 cms.
**denotes peak of record

Table 3. Peak discharge values for the largest floods recorded a t the Clarkdale gage. Lag between the Pauden and Clarkdale gages ranges from 5 to 8 hours.

Clarkdale peak discharges are dominated by ungaged tributaries between the Paulden and Clarkdale gages. Hell Canyon and Sycamore Canyon are the primary watersheds between these gages, along with the smaller drainages of MC Canyon and Bear Canyon. Small tributaries which do not form sizable drainage networks enter from the south side of the Verde River and between Bear Canyon and Sycamore Canyon drainages.

Flow Reconstructions

Methods

To quantify each tributary's contribution to the peak at Clarkdale, the study reconstructed discharge through Hell Canyon and Sycamore Canyon. Flow was modeled through each study reach using the HEC-RAS gradually varied flow computation model (Hydraulic Engineering Center, 1995). The HEC-RAS model uses a step-backwater, or standard step routine based on the principle of conservation of energy. The flow model assumes steady uniform flow in a fluid with low sediment concentrations.

Reaches were chosen based on the following criteria:

1. Conformity to ideal conditions for the step-backwater model, such that reaches:

    (a) are relatively straight and have lengths of 100 m or greater;
    (b) have a fixed boundary, constrained by bedrock or steep colluvuial slopes;
    (c) have little vegetation and boulders in the channel which increase turbulence;
    (d) have fairly uniform channel widths to minimize contraction and expansion losses;
    (e) have no sizable secondary channels to create divided flow scenarios;
    (f) have no large tributaries entering within the reach whose discharge is unaccounted for (Dalrymple and Benson, 1967).

2. Presence of slackwater deposits and other high water indicators within the model reach.

3. Location in the drainage system, preferably in the most downstream portions of the drainage to capture the full discharge from each basin.

With these considerations in mind, I evaluated study sites for each drainage, choosing two reaches to increase the reliability of discharge estimates. Following reach selection, we surveyed cross sections to capture channel geometry within the reach, as well as high water marks and slackwater deposits. The cross sectional data was then fitted to a straight line to reflect the true width of the channel and entered into the HEC-RAS model. High water marks were plotted at their appropriate locations and heights on a longitudinal profile. In choosing a best estimate, water surface profiles were fitted to the high water marks on the longitudinal profile.

To obtain a reasonable starting point for each HEC-RAS model, flow was assumed to be at or near critical such that critical depth was computed at the downstream end; corresponding discharges which fit high water marks along the length of the reach were used as a starting point. In further runs, Manning's n values were varied along with discharge to obtain the best fit. This worked rather well for Hell Canyon reaches which suggests that peak flow was at or near critical during this event. In Sycamore Canyon, high water marks were well above critical depth; therefore, depths corresponding to flotsam and other high water marks at downstream cross sections were used as a starting known water surface at the most downstream cross section. The models experimented with a number of roughness coefficients (n) ranging from 0.035-0.060 in order to obtain the best fit to the water surface profile. This particular range of coefficients was based on similarities between channel characteristics and textbook criteria for selecting appropriate *n* values (Bedient and Huber, 1992; Chow, 1959). Composite n values were used so that the entire channel cross section was specified as the main channel. Expansion and contraction coefficients were maintained at default values of 0.1 and 0.3, as channel dimensions are fairly uniform within each reach.

Flow models were chosen based on (1) how well they fit the high water marks, and (2) the robustness of the model itself, such that the energy equation was balanced and few errors were reported. Because channel gradients are relatively steep (~.015), energy slopes, conveyance ratios and velocity heads were greater than default values between cross sections, so that cross section interpolation was used in some cases to diminish error messages.

Sycamore Canyon

The Sycamore Canyon study reaches are located approximately two to three kilometers (one to two miles) into the canyon upstream of the confluence of Sycamore Creek and Verde River (Figure 9). The lower reach was chosen for its downstream location and preservation of slackwater deposits at both ends of the reach, and fresh high water marks within the reach.

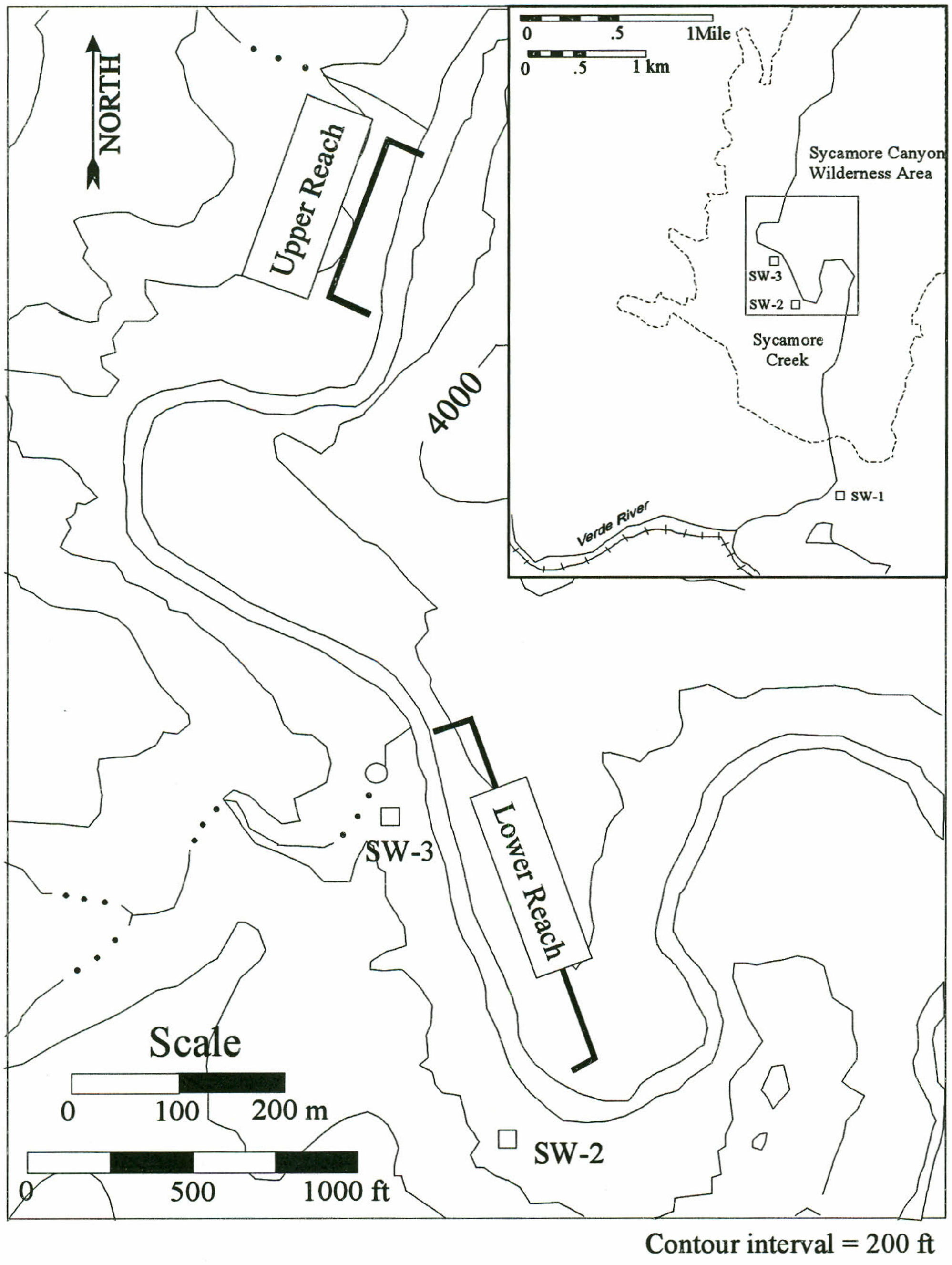


Figure 9. Location of Modeling reaches and slackwater deposits, Sycamore Canyon.

A first attempt at modeling was made which incorporated a bend in the reach at its downstream end. A second model disregarded this bend and began the modeling routine upstream of the first three cross sections. The latter was chosen to reconstruct the February 1993 flood.

Using high water marks and the step-backwater procedure, a reasonable conservative estimate of 800 m^3s^{-1} was calculated for the lower reach (Figure 10). The model fits best in the upstream portion of the reach; no attempt to fit the highest flotsam in the lowest cross sections was successful. Thus, flotsam in the lower portions of the reach is actually higher than the conservative estimate and may be due to backflooding as the channel takes a sharp bend to the northeast and decreases abruptly in width as well as superelevation of the water surface on the outside of the bend. Extensive slackwater deposits in this area testify to a large zone of flow separation and backwater effects.

An upstream reach in Sycamore Canyon was also modeled to provide a second estimate of the February 1993 discharge. A conservative estimate of 900 m^3s^{-1} was computed from the HEC-RAS flow routine, which is fairly consistent with the model of the lower reach (Figure 11). Although the model is a good fit, a number of high water marks lie above the modeled discharge; these could be due to local run-up, where flow over large boulders or vegetation super-elevates flotsam against trees and other obstructions in the channel (Benson and Dalrymple, 1967; O'Connor and Webb, 1988).

Both models in Sycamore Canyon use a composite n value of 0.045 from a recommended value of 0.045 to 0.050 for "mountain streams in clean loose cobbles or rivers with variable section and some vegetation growing in banks"(Ince, 1997); the value

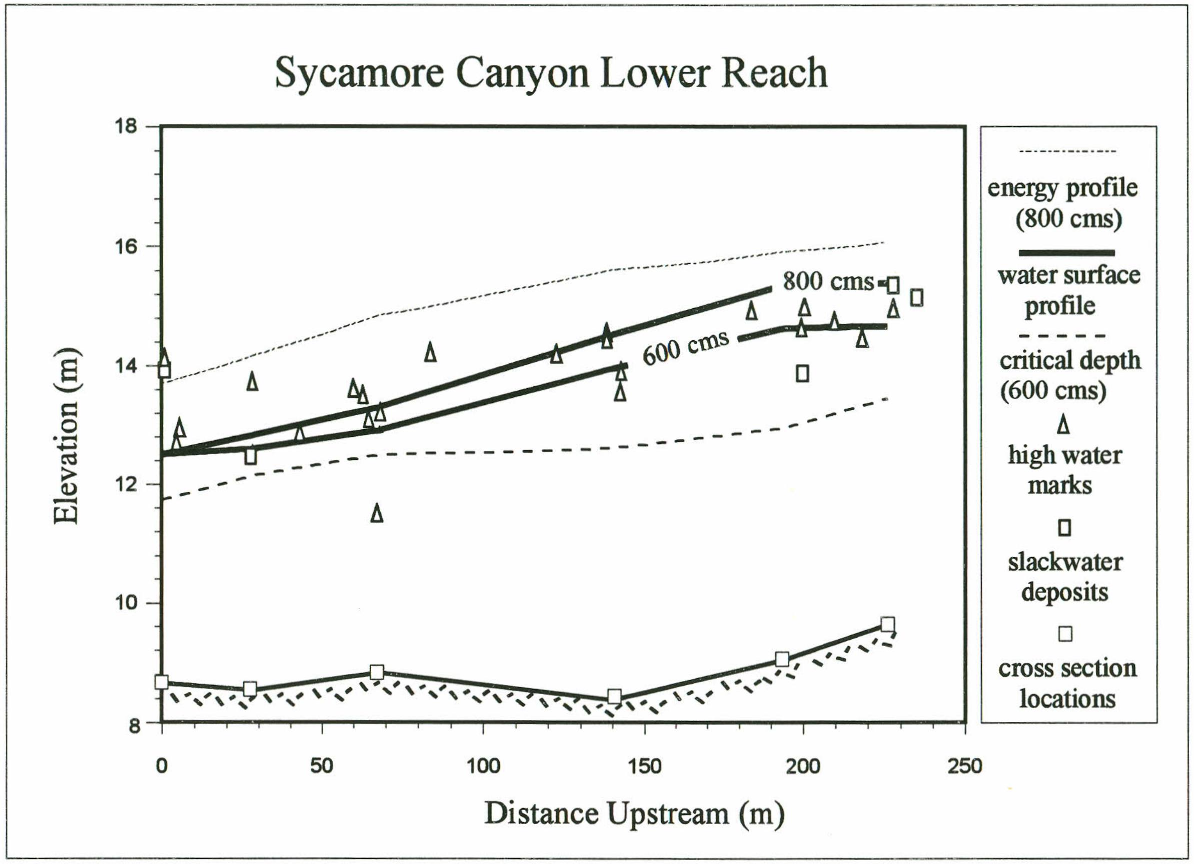


Figure 10. HEC-RAS modeling results, Sycamore Canyon, lower reach. Flow was modeled subcritically with an initial water surface elevation of 12.3 m and a composite n value of 0.045. A reasonable conservative estimate measures 800 cms with 600 cms as a lower constraint. The most uncertain portion of the model occurs at the downstream end, where water surface profiles underfit high water marks considerably.

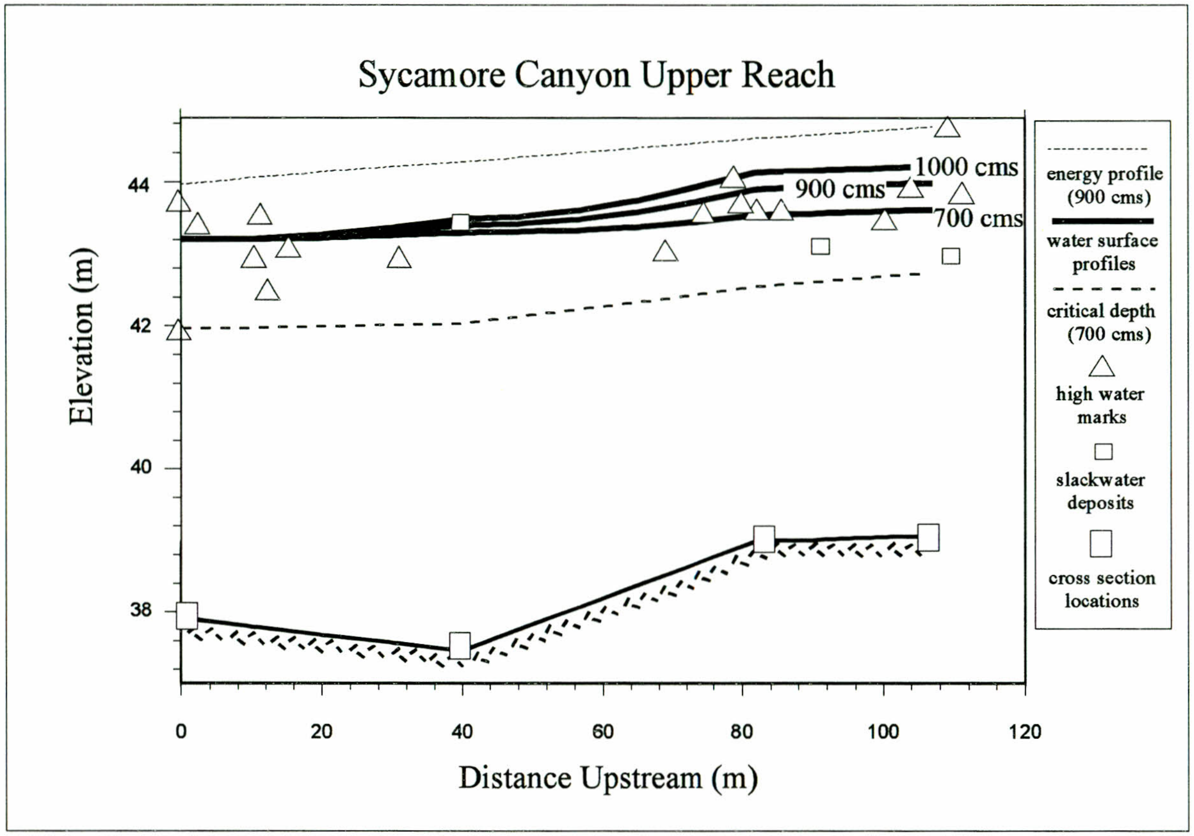


Figure 11. HEC-RAS modeling results, Sycamore Canyon upper reach. Flow was modeled using a subcrtical flow routine with an initial water surface elevation of 43.2 m and a composite n value of 0.045. The 900 cms profile constrains most high water marks and is the preferred conservative estimate for the reach.

also fits within Bedient and Huber's (1992) range of 0.045-0.060 for natural channels of rough weeds and stones. Both models also use an initial water surface elevation based on the furthest downstream cross sections, as opposed to beginning with critical depth. Critical depth calculations were much lower than surveyed high water marks; flow models using this condition at the downstream end or using an initial water surface elevation higher than 12.3m in the lower reach and 43.2 m in the upper reach produced large and unreasonable discharges which overestimated high water marks at the upstream end and approached the discharge estimate at Clarkdale.

Hell Canyon

Modeling reaches in Hell Canyon were selected based on their compliance with assumptions in the step backwater method (Figure 12). Emphasis was placed on reaches which were located in the most downstream portions of the watershed and which had the smallest overall bedload to minimize roughness elements in the channel reaches.

Assuming that peak flow was at or near critical depth, I first experimented with a number of discharges and compared the fit of the water surface profiles to definitive high water marks within the reach. Other initial conditions were experimented with; however, those models which used critical depth as a starting water surface fit considerably better. Both the lucky tank reach and lower reach models use a composite n value of 0.050; this value seems to fit the data well and is consistent with n value descriptions mentioned previously for such channel characteristics.

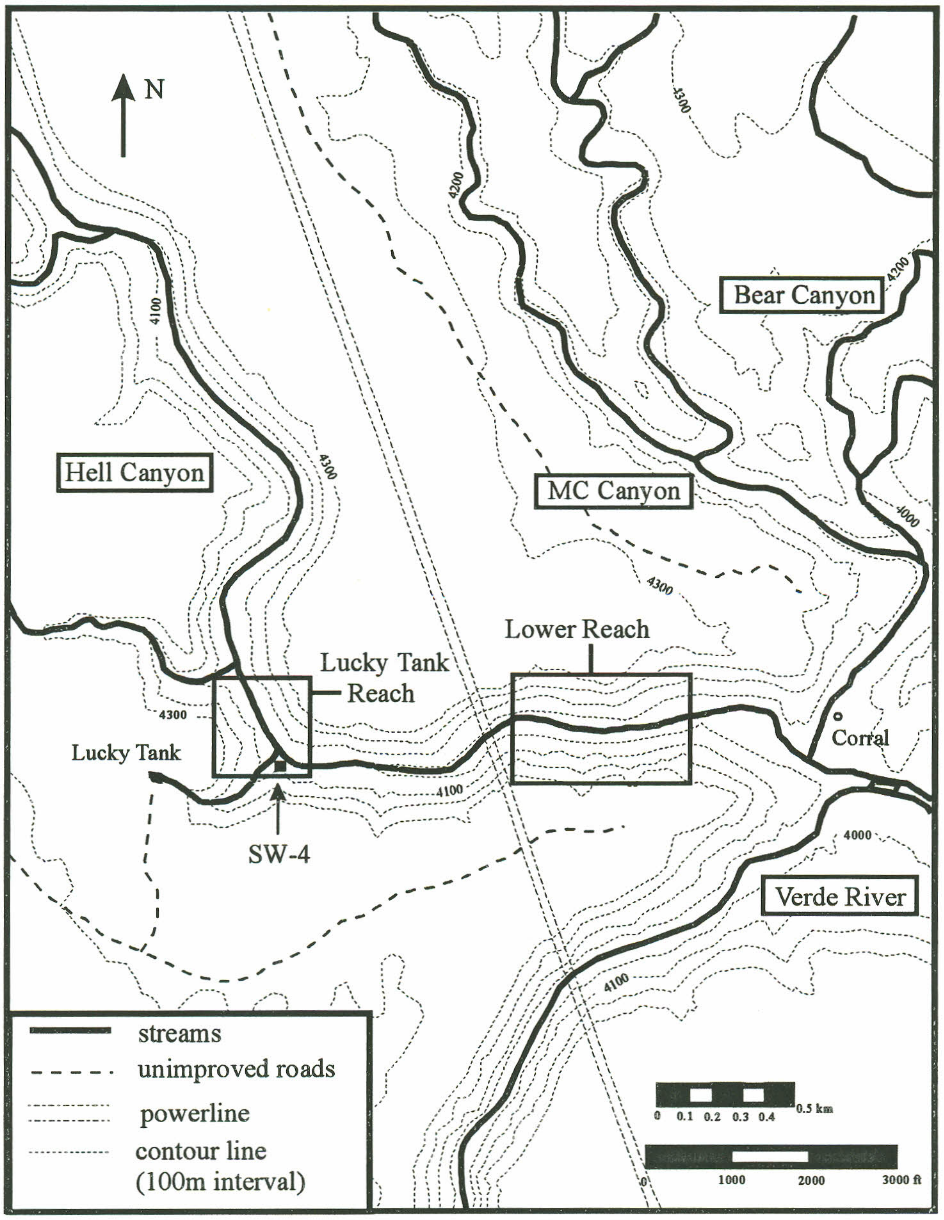


Figure 12. Location of modeling reaches and slackwater deposits, Hell Canyon

The lower reach is located approximately 600 meters upstream from Hell Canyon's confluence with Bear Canyon and MC Canyon. The downstream half of the reach in the upstream direction is confined by indurated alluvial terraces, whereas the upstream half is constrained by bedrock walls and steep colluvial slopes.

A conservative estimate of 700 m^3s^{-1} is calculated, which fits the highest flotsam; a considerable cluster of flotsam points are also constrained by the 500 m^3s^{-1} water profile with a lower bound of 400 m^3s^{-1} (Figure 13). Slackwater deposits in each reach were anomalously high in their elevations relative to the 1993 flotsam and may be from an event prior to 1993.

Lucky tank reach in Hell Canyon measures a flow between 400 and 600 m^3s^{-1}, with 600 m^3s^{-1} as a conservative estimate (Figure 14). The model brackets high water marks very well; however, the upper cross sections contain few high water marks and therefore extend the model upstream but do not constrain the flow.

Synthesis and Discussion

Assumptions and Limitations

In every hydraulic reconstruction, a number of assumptions and limitations exist. The step backwater model assumes steady uniform gradually varied flow; however, turbulence due to channel roughness is known to occur and can be observed in almost any high-gradient mountain stream (Jarrett, 1984).

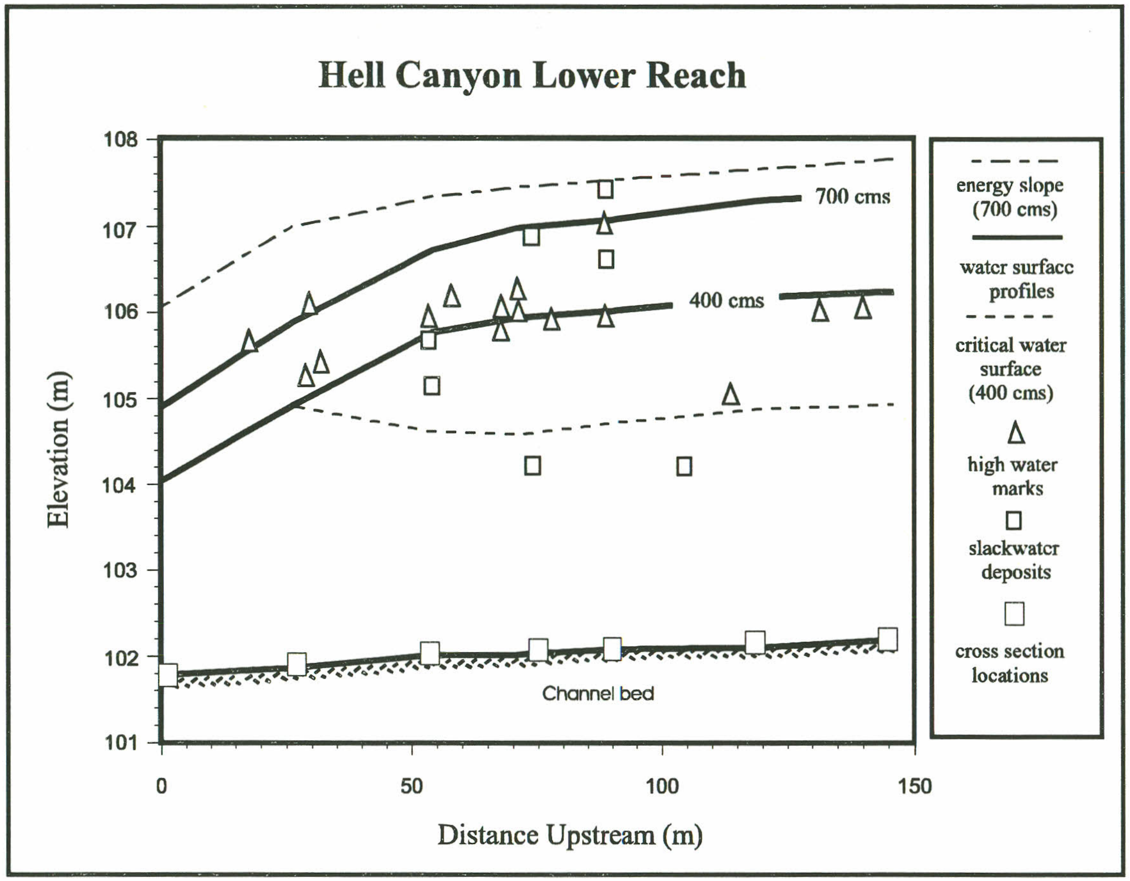


Figure 13. HEC-RAS modeling results, Hell Canyon lower reach. Flow was modeled subcritcally with a starting water surface of critical depth and a composite n value of 0.050. High water marks indicate that a conservative estimate for peak flow measures 700 cms; a lower bound is estimated at 400 cms.

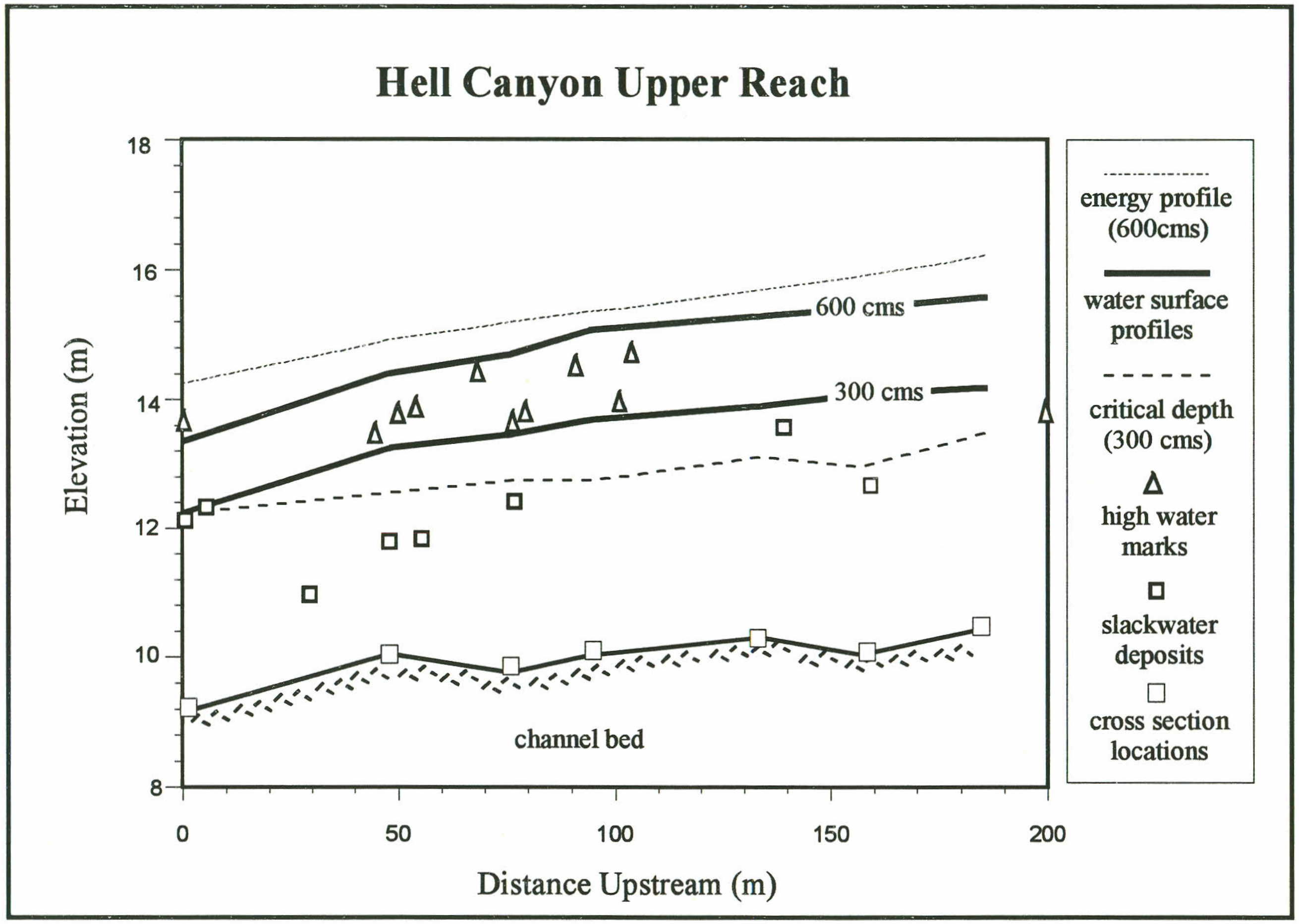


Figure 14. HEC-RAS modeling results, Hell Canyon upper reach. Flow was modeled using a subcritical flow routine, a starting water surface of critical depth, and a composite n value of 0.050. The conservative estimate for this reach is 600 cms, with a lower bound of 300 cms.

Manning's n values are an approximation and conform to conventional values; in contrast Jarrett (1987) suggests that many studies underestimate the value of Manning's *n*. The equation developed in his study is only applicable to streams with gradients between 0.002 to 0.052 and hydraulic radii of 0.15 to 2.13. Because hydraulic radii of channel cross sections in the modeled reaches are beyond the range of Jarrett's equation, his findings may not be applicable to the present study.

Although discharge values produce the greatest changes in the fit of a water surface profile to high water marks, *n* values play a lesser yet significant role. For instance, an n value of 0.045 in the Lucky tank reach, Hell Canyon, underestimates the highest HWM at 600 cms while the 0.050 profile constrains the data point but forces the model to extend cross sections above surveyed points, which are nonexceedance indicators (Figure 15). The preferred *n* value thus occupies a range between 0.045-0.050. Ely (1985) similarly finds that cross section geometry and discharge values are the variables which change the water surface profile most dramatically. Similarly, O'Connor and Webb (1988) state the large variations in *n* values account for 25% of the variation produced by differing discharges.

In the step-backwater method, channel slope is used as an initial approximation for frictional slope and energy slope; channel irregularities may create energy losses greater than what energy loss coefficients account for. Flow routines are modeled as subcritical because flow models did not produce a valid result when run supercritically; in addition, previous work in paleoflood hydrology reconstructions and many empirical studies confirm that flow in steep rough channels typically maintain froude numbers less than unity

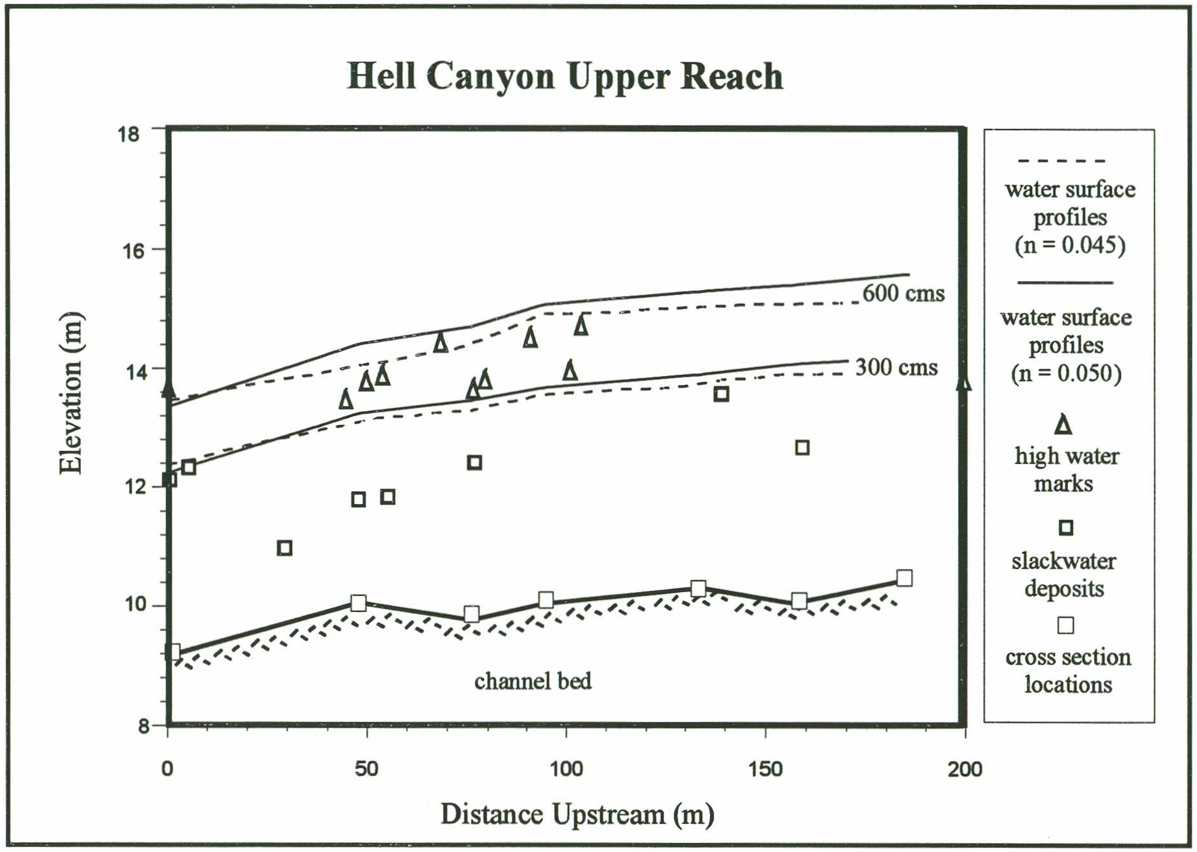


Figure 15. HEC-RAS modeling results for *n* values of 0.045-0.050. A 0.045 *n* value underestimates the highest HWM between the second and third cross sections; however, discharge upstream may be overestimated by the higher *n* value, as cross section end points must be extended vertically in order to compute the 600 cms water surface profile. The preferred *n* value is thus *between* 0.045 and 0.050.

even with large peak discharges (Ely and Baker, 1985; O'Connor, et al., 1986; Partridge and Baker, 1987; Jarrett, 1984; Webb, 1985).

The HEC-RAS model itself is originally designed for low-gradient, sandy bed channels; as a result, default values are set so that models in steep channels have energy losses between cross sections which are greater than default values. Interpolating cross sections is helpful in some cases, and does not signficantly change the model results. Resolution of discharge values is limited by the range in elevations of surveyed high water marks and the fit of models to these high water marks; however, the range of discharges does not exceed 25% of the median value.

Evaluation of Discharge Estimates

In this section, model results are evaluated to determine if peak flow values are reasonable. By computing a unit discharge for each basin using the discharge estimate for the late February event at the Clarkdale gage, peak runoff should be approximately 690 cms for Sycamore Canyon and 344 cms for Hell Canyon (Table 4). Modeled values are much larger than this and combined are greater than the peak discharge at Clarkdale, disregarding minor drainages such as MC Canyon and Bear Canyon.

Despite large model-predicted values, five lines of evidence suggest that discharge estimates for these tributaries may in fact be reasonable: (1) Unit discharge assumes that runoff is uniformly distributed throughout the watershed; considering the rainfall and snowfall records for the event, this is certainly not the case. (2) Expansions at tributary mouths may cause attenuation of flood peaks downstream from modeled reaches.

	Contributing Area			Discharge (m^3s^{-1}) Qu=0.56 cms/km^2 =51.4 cfs/mi^2		HEC-RAS Maximum Q	
Units	km^2	mi^2	%	cms/km^2	cms/mi^2	cms	cfs
Sycamore Canyon	1229	474	46	690	24364	900	32000
Hell Canyon	613	237	23	344	12182	700	24700
Totals	1842	711	69	1034	36546	1600	56500

Table 4. Independent constraints on Q peak. Unit discharge calculations provide an independent estimate of relative contributions from Hell Canyon and Sycamore Canyon for the late February 1993 flood. Calculated values are much lower than estimates from discharge reconstructions, which sum to more than the peak discharge at Clarkdale (1507 cms; 53200 cfs). This does not include the additional contributions from minor drainages and tributaries within the watershed.

Extensive boulder bars with abundant vegetation occupy the confluence areas of major tributaries with the Verde and must inhibit runoff as it emerges from tributary channels of steeper gradients and smaller widths. (3) Qualitative flood routing suggests that flood peaks from various sources would be out of phase with each other. For instance, basin shape may exhibit a flashier flood response in an equidimensional basin such as Hell Canyon, while peak flow may occur later in elongated drainage basins such as MC Canyon and Bear Canyon. (4) The Verde tributaries Oak Creek, Wet Beaver Creek, and West Clear Creek have experienced similar discharges relative to basin size. Record peak discharges are measured as 748, 702, and 453 m^3s^{-1}, respectively. Because Sycamore Canyon has greater area than any of these tributaries, and Hell Canyon is greater than two (Wet Beaver Ck and West Clear Ck.), discharges may be larger in the basins of this study. (5) In the context of regional envelope curves, the estimate is reasonable, such that an upper limit for a basin with watershed area of 1,229 km^2 is ~1500 cms and for 613 km^2 is ~1100 cms (Enzel, et al., 1992). In sum, discharge estimates based on HEC-RAS modeling are reasonable but should be noted as maximum values for the modeled reaches.

Slackwater deposit data points

The plotting of high water marks on a longitudinal profile shows that slackwater deposits thought to represent the 1993 water surface are not at a consistent level below other water surface indicators, as has been noted in other studies (House, et al., 1995). A number of possible explanations should be noted. First, it may be the case that some of the measured high water marks represent deposition at different times during the flood such that the highest data points were deposited at peak flow and lower points during the falling limb of the flood hydrograph. Sediment levels could also reflect a mix of floods and may not singularly represent the flood of 1993.

Evaluation of stream competence

Bedload dominates the fluvial system in the study area. In ungaged reaches which lack slackwater deposits or high water marks, a competency study may be the only viable method for paleohydraulic analysis. Previous studies have used bedload data to assess the transport of particles by computing conditions for entrainment and maintained transport and by generating predictive regression equations which relate particle size to parameters such as unit stream power and shear stress (Baker and Ritter, 1975; Costa, 1983; O'Connor, 1993; Williams, 1983). Imbrication of stream particles in the studied reaches provides evidence for transport of all but the largest clasts. This study uses this evidence to assess the validity of using regression curves to determine the transport of available particles as well as to evaluate model peak flow values.

Unit stream power (ω) and shear stress (τ) were computed for the maximum reconstructed discharges in the study reaches and compared to ω and τ values from regression curves for the five largest boulders in each reach. The equations used are as follows:

Shear stress (τ)

$\tau = 0.17d^{1.0}$ (Williams, 1983)
$\tau = 0.056d^{1.213}$ (Costa, 1983)

$\tau = 0.33d^{1.12}$ (O'Connor, 1993)
$d = 65\tau^{0.54}$ (Baker, 1975)

where τ = shear stress (Nm^{-2})
d = intermediate axis diameter (mm)

Unit stream power (ω)

$\omega = 0.079d^{1.3}$ (Williams, 1983)
$\omega = 0.009d^{1.686}$ (Costa, 1983)
$\omega = 0.1d^{1.71}$ (O'Connor, 1993)

where ω = unit stream power (Wm^{-2})
d = intermediate axis diameter (mm)

Results from these equations suggest that all but the largest boulders in the channel are capable of transport during large flows (Table 5). Among various relations, results are fairly consistent, with the exception of data from O'Connor (1993). He suggests two reasons for this discrepancy: (1) Values represent depositional conditions, or those conditions necessary to maintain transport, whereas comparative equations represent entrainment conditions, or values necessary to inititate transport; (2) O'Connor's study used energy slope whereas other authors used channel bed slope as an approximation for energy slope. The exception is Baker and Ritter (1975), who also report energy slope. An example from Sycamore Canyon upper reach shows that these two relations may overestimate boulder transport capability. The largest boulder in this reach measures 2850 mm in intermediate diameter and shows no imbrication and a deep scour hole on its downstream side. Although rounded, this particle did not appear to be transported in 1993; however, estimations from Baker and Ritter (1975) and O'Connor (1993) show that

(A)

Reach Name	Unit Stream Power (ω)	Shear Stress (τ)
Sycamore LR (800 cms)	1229	404
Sycamore UR (900 cms)	1122	377
Hell LR (700 cms)	2053	356
Hell UR (600 cms)	1760	458

(B)

	Unit Stream Power (ω)			Shear Stress (τ)			
particle intermediate diameter (mm)	Costa (1983)	O'Connor (1993)	Williams (1983)	Baker & Ritter (1975)	Costa (1983)	O'Connor (1993)	Williams (1983)
Sycamore LR							
2250	4037	85	1801	709	652	142	382
2100	3593	78	1646	624	600	132	357
970	977	30	603	149	235	55	165
1350	1706	45	927	275	351	80	230
1300	1601	43	883	257	335	77	221
Sycamore UR							
2850	6013	114	2449	1098	869	185	484
1450	1925	49	1017	314	383	87	246
1750	2642	62	1299	445	481	107	298
1050	1116	33	669	173	259	60	178
1300	1601	43	883	257	335	77	221
Hell LR							
2650	5319	1392	2228	960	795	171	450
2780	5766	1511	2371	1049	843	180	473
1280	1560	401	865	249	329	76	218
1320	1643	423	900	264	342	78	224
1280	1560	401	865	249	329	76	218
Hell UR							
2900	6192	1624	2505	1134	887	189	493
2500	4821	1260	2065	861	741	160	425
2100	3593	935	1646	624	600	132	357
1580	2224	575	1137	368	425	96	268
1620	2320	600	1174	386	438	98	275

Table 5. Unit stream power and shear stress parameters. Unit stream power (Wm^{-2}) and shear stress (Nm^{-2}) are calculated for (A) discharge reconstructions and (B) largest bedload in each reach. Shaded boxes represent the estimates below which minimum conditions are met for bedload transport (LR=lower reach; UR=upper reach; LT=Lucky tank).

stream power and shear stress were great enough for transport.

Disregarding data from these sources, peak flow estimates seem reasonable in that their shear stress and stream power values support field observations of transport of all but the largest particles during the late February flood of 1993. However, results vary among equations such that no clear relation can be discerned. Complex interaction between flow transport factors such as particle shape, size, orientation, degree of rounding, and hiding effects most certainly defy the production of a single equation to predict boulder transport. Detailed discussions of the many complications in bedload transport are provided by authors mentioned above as well as others including Graf, 1971; Gessler, 1971; Nevin, 1946; Novak, 1973; Bradley and Mears, 1980; Burkham, et al., 1980; Ethridge and Schumm, 1978; Gage, 1953; Grozier, et al., 1976; Inbar and Schick, 1979. The reader should refer to these for a thorough review of the assumptions and limitations of competency studies.

SLACKWATER STRATIGRAPHY AND TREE RING ANALYSIS

Methods

Slackwater deposits document the paleoflood record in two out of four of the selected reaches, and at the confluence of Sycamore Creek and Verde River. Stratigraphic analysis can help to ascertain the length of record that slackwater deposits represent and to compare the associated flood magnitudes to that of the 1993 event.

Aerial photos served as excellent reconnaissance tools in site selection, where sites were located on the basis of channel morphometry and field checked for their feasibility. Preferable sites were those which contained evidence for the 1993 water surface elevation, and which most closely adhered to ideal conditions for step-backwater modeling.

To describe the slackwater deposits, a combination of surface pits on the tops and upper slopes of the deposits, and trenches along the sides were excavated and described from the basis of sedimentologic, geomorphic, and pedologic criteria. Flood packages were defined using the following features (Baker, 1987):

changes in color
abrupt changes in texture
truncation of sedimentary structures
differences in soil structure
distinctive concentrations of charcoal
Presence of irregular erosional contacts
interbedded colluvial layers, composed of locally derived angular clasts

The analysis conveys the minimum number of flood units present at the selected sites and uses a combination of criteria to define each flood layer when possible. Detrital charcoal samples were collected and dated radiometrically; my ability to place age constraints on the deposits was mainly limited by finances rather than the availability of datable material, as charcoal was abundant in several of the deposits.

A dendrochronology study of trees rooted in the flood deposits was also undertaken to provide a dating tool independent of radiocarbon analysis. A number of species occupied slackwater surfaces; however, only the Hackberry (*Celtis reticulata*) and Velvet Ash (*Fraxinus velutina*) cores were used in the study. These species have been used previously and have been known to crossdate well and to provide accurate dating (Salzer, et al., 1996). Two cores were taken from each tree using increment bores and mounted according to standard procedures of the University of Arizona Tree Ring Laboratory. Variations in ring width were then transferred to skeleton plots (Stokes and Smiley, 1996). Plotting was performed on both sides of the tree to obtain most precise ring count for the tree. Samples were crossdated within the site and against the Flagstaff Master chronology, which is essentially a compilation of tree ring chronologies around the Flagstaff area produced by dendrochronologists at the University of Arizona Laboratory of Tree Ring Science. Crossdating within a site and against a master chronology ensures that the most accurate ring count is obtained.

Stratigraphic Descriptions

The following sections describe the flood units present in the slackwater deposits of Hell canyon and Sycamore Canyon.

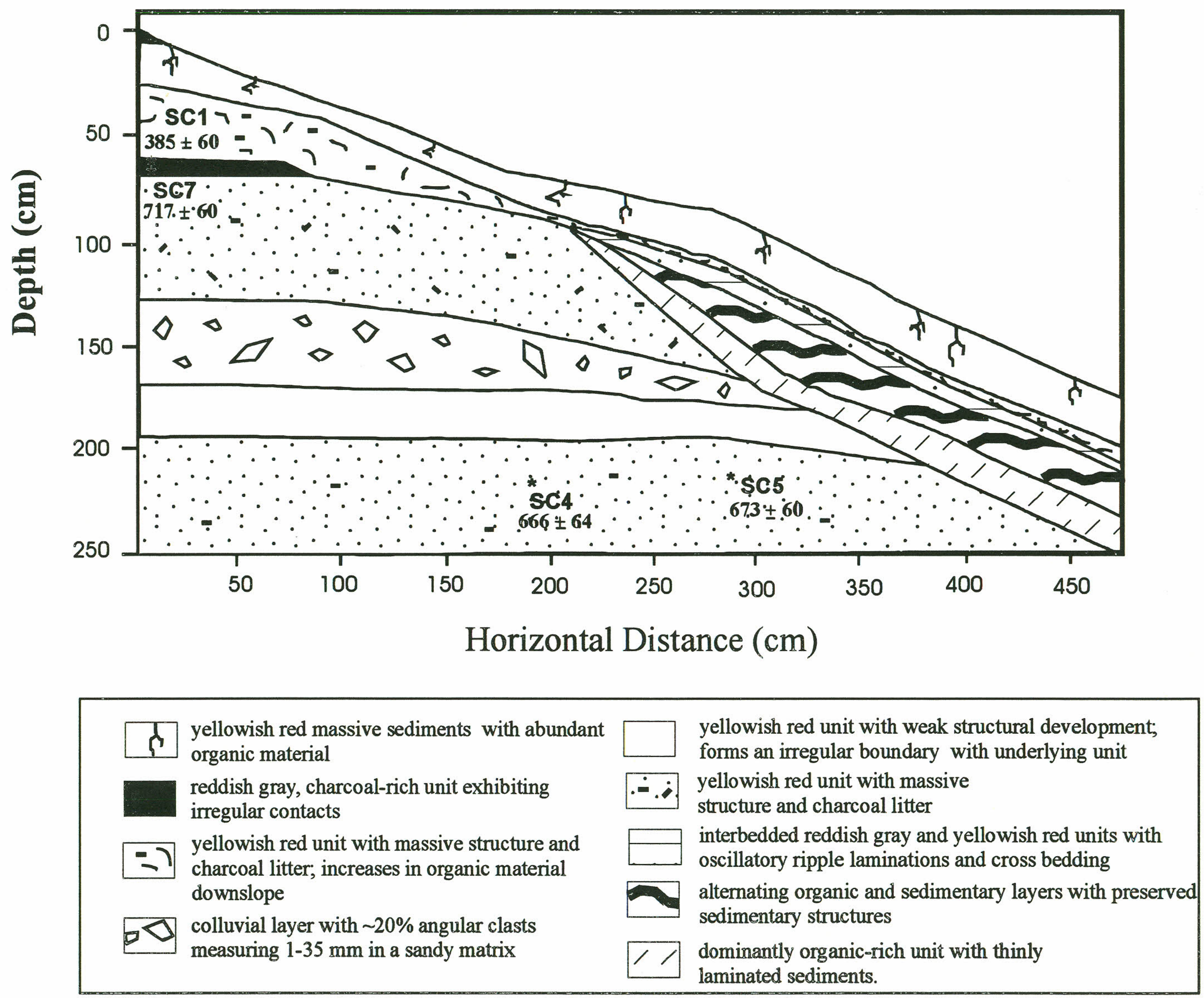
Sycamore Canyon, Lower Reach

Deposits in the lower reach of Sycamore Canyon are located beyond the first tortuous bend at the lower end (site SW-2) and upper end (site SW-3) of the modeling reach. Generally, units within each sequence are very fine to fine sandy loams with very weak to weak structural development. Site SW-2 is characterized by an older sequence of five flood deposits inset by four organic-rich units with abundant sedimentary structures (Figure 16). Nearest to the surface, a massive flood unit overtops both sequences. Site SW-3 records a minimum of 5 floods with massive unit A inset against the older sequence (Figure 17).

Colluvial layers derived from local hillslopes are present near the base of the described units and can be used as stratigraphic markers to tentatively link SW-2 and SW-3 flood deposit sequences. A gray-brown unit distinct in coloration and concentration of charcoal fragments is found near the upper portions of both SW-2 and SW-3 and provides a more certain correlation. This deposit was dated 385 ± 60 years B.P. (cal AD 1492 to 1575 and cal AD 1599 to 1680) (SC-1)[2] and 717 ± 60 years B.P. (cal AD 1322 to 1350) (SC-7) at SW-2. (Table 6). Two separate samples from a lower layer in the same

[2] All calibrated dates are reported as calendar years AD with 1σ, 68% probability.

Figure 16. SW-2 Trench site description (following page). SW-2 is characterized by an older sequence of flood deposits dating between ~170 and 650 years B.P. by tree ring and radiocarbon analysis. This sequence is inset by a younger sequence of organic-rich units which are believed to be historic in age.


Depth (cm)
0
50
100
150
200
250
Horizontal Distance (cm)
50
100
150
200
250
300
350
400
450
SC1
385 ± 60
SC7
717 ± 60
SC4
666 ± 64
SC5
673 ± 60
yellowish red massive sediments with abundant organic material
reddish gray, charcoal-rich unit exhibiting irregular contacts
yellowish red unit with massive structure and charcoal litter; increases in organic material downslope
colluvial layer with ~20% angular clasts measuring 1-35 mm in a sandy matrix
yellowish red unit with weak structural development; forms an irregular boundary with underlying unit
yellowish red unit with massive structure and charcoal litter
interbedded reddish gray and yellowish red units with oscillatory ripple laminations and cross bedding
alternating organic and sedimentary layers with preserved sedimentary structures
dominantly organic-rich unit with thinly laminated sediments.

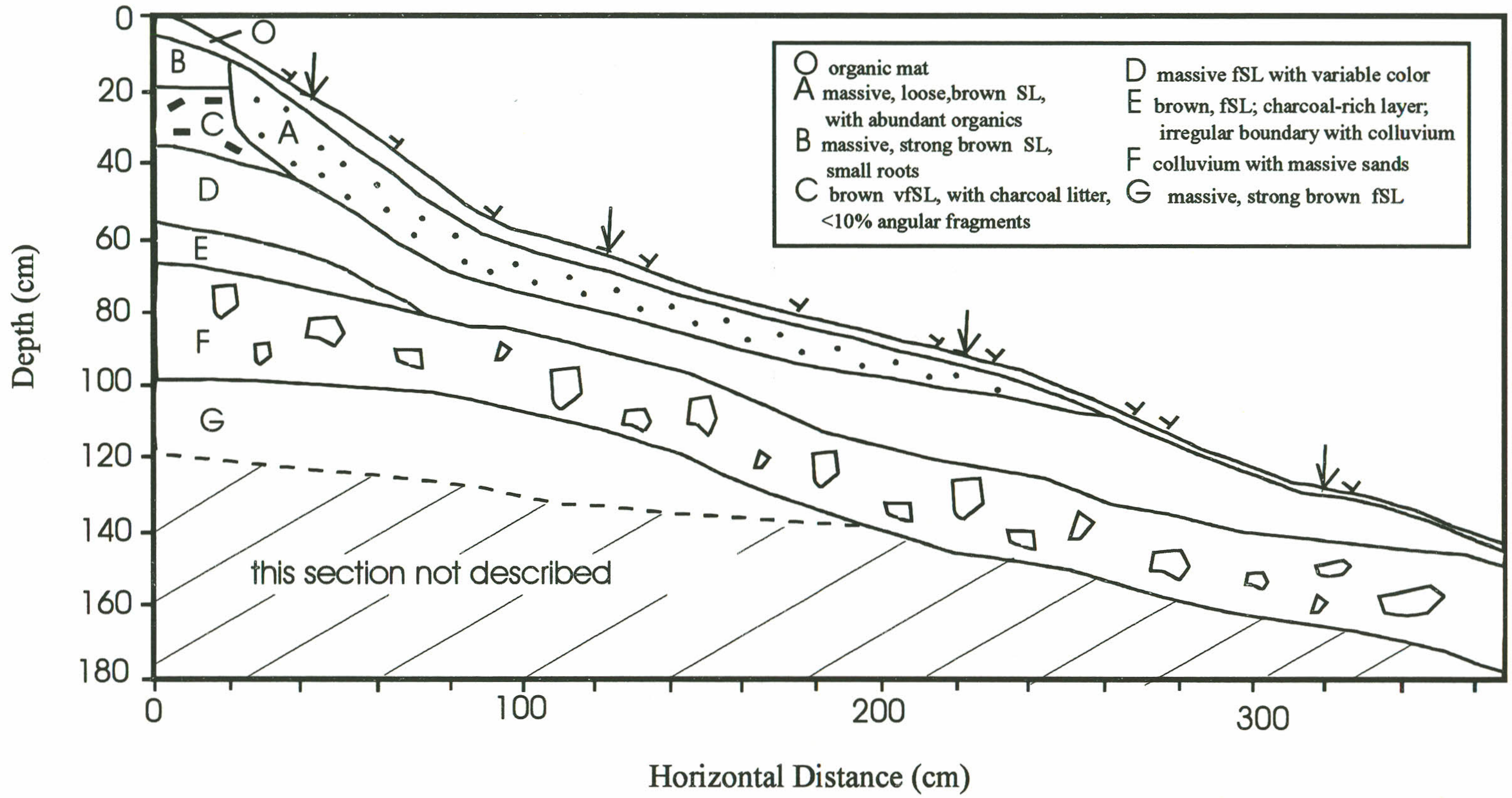


Figure 17. SW-3 Trench site description

Site	Sample	Radiocarbon Age (yrs. B.P.)	Calibrated Age Calendar years AD (1σ, 68% probability)
SW-1	SCC-8	80 ± 64	1735 to 1782 1974 to 1997
	SCC-9	120 ± 30	1685 to 1740 1810 to 1930
SW-2	SC-1	385 ± 60	1492 to 1575 1599 to 1680
	SC-7	717 ± 60	1322 to 1350
	SC-4	666 ± 64	1332 to 1442
	SC-5	673 ± 60	1332 to 1440
SW-4	HC-7	104 ± 64	1728 to 1797 1851 to 1983

Table 6. Radiocarbon analyses of stratigraphic sequences. Shown are the results of samples submitted for radiocarbon analyses for stratigraphic sites in Hell Canyon and Sycamore Canyon in radiocarbon ages (yrs. BP) and calibrated ages (cal AD).

sequence were also dated, and have ages of 666 ± 64 cal. yrs. B.P. (cal AD 1332 to 1442) (SC-4) and 673 ± 60 cal. yrs. B.P. (cal AD 1332 to 1440) (SC-5).

The age of SC-7 and SC-1 within the same unit provide an age spread of ~300 years. The statistically indistinguishable dates in the lower unit provide greater confidence in assigning a younger age to the charcoal rich deposit than that of the ~700-year-old date. It may be possible that sample SC-7 was reworked and incorporated into the younger flood deposit. Previous studies have documented this problem with detrital charcoal and their potential to provide erroneous dates for fluvial deposits (Blong, 1978).

Flotsam from the 1993 flood occurs on the top surface of the sequence of slackwater deposits, and is evidence for its inundation during the February 1993 flood. Sediment deposited by this flood is most likely the massive unit of fresh sediment which drapes the surface at SW-2 and may be contained within unit A at SW-3. SW-3 shows little evidence of deposition downstream of the trench site where a scoured vertical face preserves the older sequence with no insets present. Flotsam present on the top of this surface suggests that the 1993 flood overtopped the sequence but did not deposit sediment on the surface.

A number of hackberry trees (*Celtis reticulata*) on the upper slackwater surfaces of both SW-2 and SW-3 (Figure 18) were cored to obtain a constraint on the top of each stratigraphic sequence. The oldest trees on these surfaces are composed of three specimens with ring counts of 159-170 on SW-2 and four cores with ring counts of 135, 144, 152, and 156 at SW-3. In terms of calendar years, these surfaces must have been in place prior to 1827 and 1841, respectively. Some evidence of tree burial was noted at

Figure 18 Hackberry trees on SW-2

SW-2, in which certain trees may be buried by approximately 22 cm of sediment. This sediment most likely is the deposit from the late February flood of 1993.

Younger trees were also sampled on these surfaces to aid in cross-dating. On SW-2, cores were collected from the colluvial slope directly adjacent to the slackwater sequence and from the slope and surface of SW-3. Attempts at cross-dating the samples within the site and against the Flagstaff Master chronology were successful only in part. Tentative matches could be made between many of the samples to obtain a date for the innermost ring; however, suppressed growth periods in the longer tree ring records made the identification of ring width patterns and consequently crossdating impossible during these portions of the tree's life.

Sycamore Canyon, Confluence

Site SW-1 is located at the base of the trailhead in Sycamore canyon, as the canyon takes a sharp bend to the right and increases in channel width, creating a depositional zone on the left bank. The sequence of deposits is characterized by an indurated gravel layer at its base, followed by a series of 11 distinct fine-grained deposits and locally intervening colluvial wedges (Figure 19). Layers are continuous for a distance of 20 m along the face of the deposit, with the exception of the basal layers and the upper 15 cm of the sequence. The upper 25 cm consists of alternating thin red and brown fine sandy loam units, followed by a distinctive gray, charcoal-rich layer, of similar color and texture as unit D documented at flood deposits upstream. Lower flood units are massive and well bioturbated, containing abundant charcoal litter. A red silt cap underlain by a

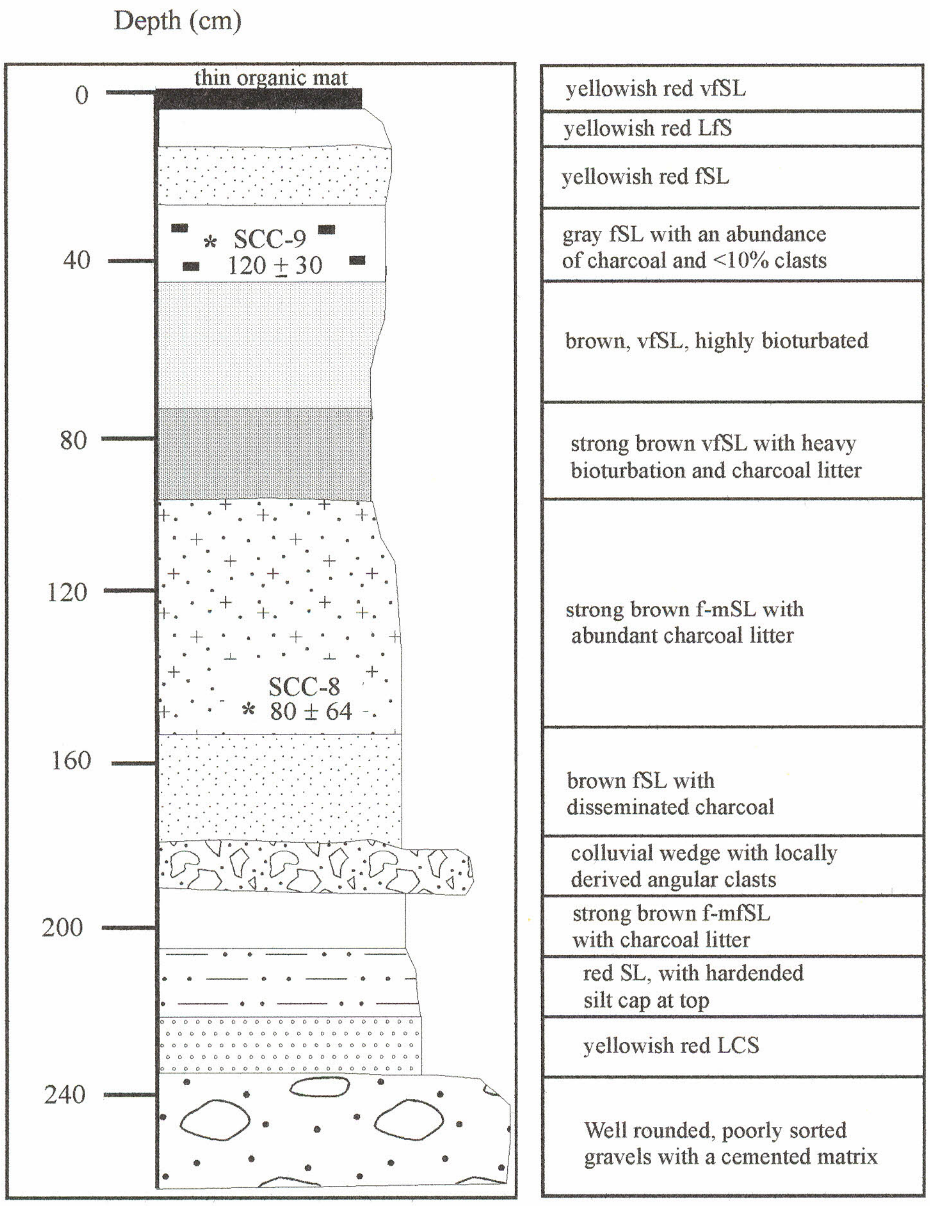


Figure 19. Stratigraphy of SW-1, near the trailhead of Sycamore Canyon.

yellowish red loamy coarse sand was found at this particular site; however, this unit was not observed at other localities along the deposit face due to slumping of overlying material. The entire deposit has been scoured into a vertical face so that the fine grained portion has receded relative to the more resistant cobble layers, and tree roots protrude from the deposit at various levels. No conclusive evidence of flood sediments or flotsam from the 1993 event was found on top of this deposit. Scour and flood debris on the nearby gravel bar indicates that the reach was flooded in 1993. Characteristics of site SW-1 suggest that the 1993 flood was mainly an erosional event which scoured the deposit face and exposed roots, but did not exceed the height of the deposit.

Radiocarbon analysis of SW-1 resulted in an anomalously young date (SCC-8) of 80 ± 64 yrs. B.P. (cal AD 1685 to 1740 and cal AD 1810 to 1930) taken at a depth of 154 cm. Two lines of evidence suggest that this age is anomalously young for its position in the stratigraphic sequence:

(1) Radiocarbon dates
A unit defined at ~40 cm depth in the profile has a radiocarbon age of 120 ± 30 yrs. B.P. (cal AD 1735 to 1782 and 1858 to 1974) (SCC-9). When calibrated, sample SCC-9 falls within A.D. 1675-1770 or A.D. 1800-1940. This unit contains abundant charcoal and is very similar in color and texture to the gray charcoal-rich deposit at SW-2 which dates at 470 ± 135 cal. yrs. B.P. Both of these age estimates are older than (SCC-8) which was sampled at a greater depth in the profile.

(2) Tree Ring Analysis
An Ash tree (*Fraxinus velutina)* previously rooted in the top of SW-1 has been exhumed such that the base of the tree corresponds to the SW-1 surface (Figure 20). The tree itself is in poor condition and rotted in the center, having minimum ring counts of 87 and 97 years. A root attempting to stabilize the tree in the eroding substrate has a minimum ring count of 47.

Figure 20 Velvet Ash at SW-1

If ring counts and the radiocarbon date at SW-1 represent accurate ages for this deposit, then a considerable amount of sediment must have accumulated in a very short amount of time. The radiocarbon date appears suspiciously young when error bars from the (SCC-8) are considered in addition to an unknown number of annual rings in the ash tree so that there is an overlap in age.

What are the possible explanations for this anomalously young radiocarbon date? First, humic acids may not have been completely removed, which would contaminate the sample with recent material and give it an anomalously young date. Second, burrowing animals may transport younger material to lower depths in the sequence if the sequence is highly bioturbated. If we assume that pre-treatment procedures are adequate, transport is the most likely explanation.

Hell Canyon, Upper Reach

The slackwater deposit found at the upper reach is the only one investigated in Hell Canyon. Both a surface pit and trench were dug and found to record a minimum of 6 distinct flood events. The surface pit shows distinct alternating units of red, loose sediment with thinner clay and silt rich units (Figure 21). A reddish unit could be traced from the bottom of the surface pit to the top of the trench, linking the stratigraphic descriptions together. Connections are shown as dashed lines, as they are inferred and many of the thin units must pinch out before the trench. Generally, the trench shows inset coarse units intertonguing with weakly developed fine sandy loams.

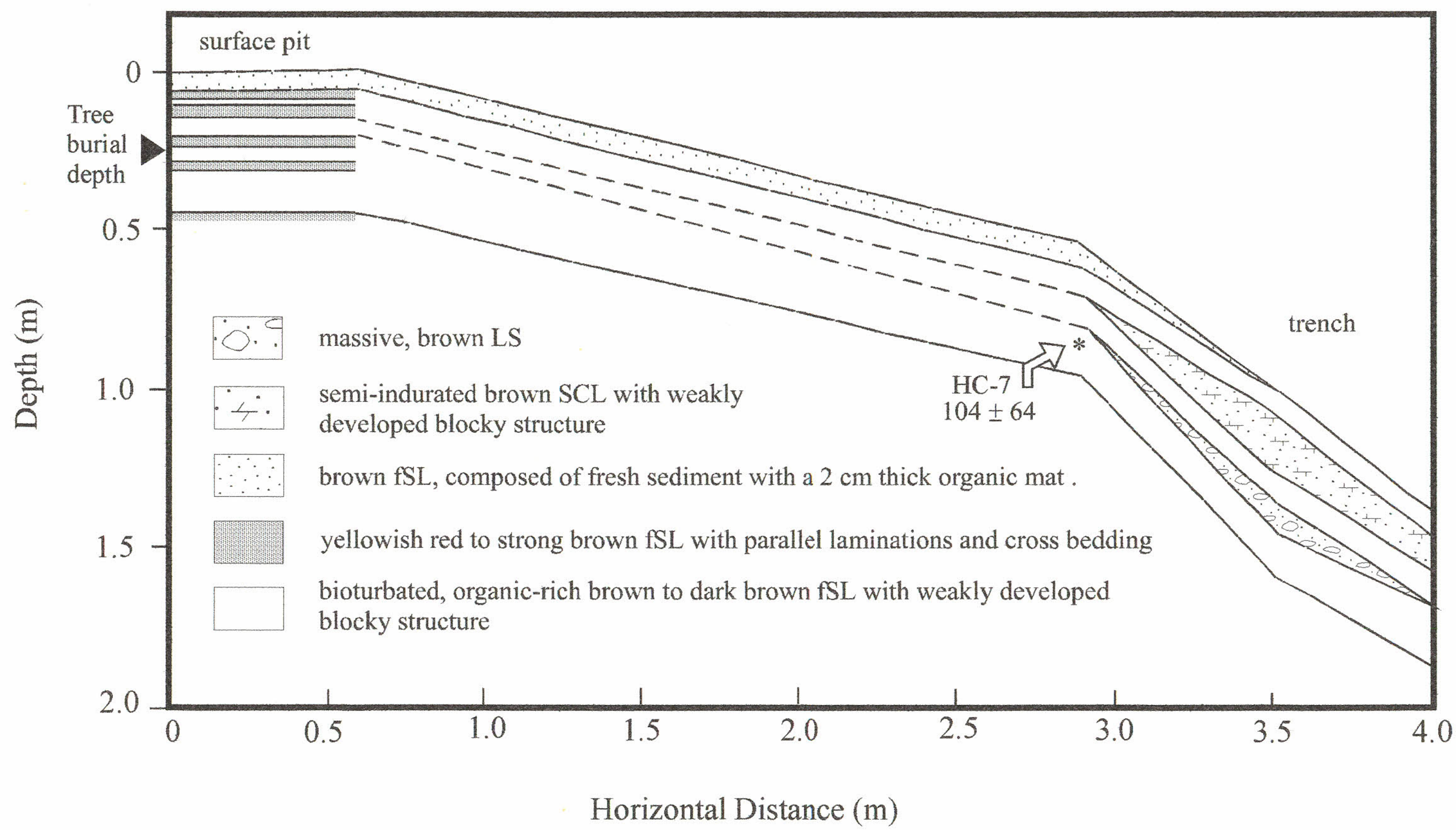


Figure 21. Hell Canyon Lucky Tank stratigraphic sequence.

A number of Hackberry (*Celtis reticulata*) trees were observed to be growing in the slackwater deposit. Four trees were cored, three of which were growing on the slackwater slope while the fourth and largest was rooted on the top of the surface. The cores cross date well within the site and moderately well with the regional Flagstaff chronology. The largest tree (Figure 22), growing on the top of the deposit, is buried to a depth of approximately 25 cm by flood deposits and has a minimum ring count of 90 years. In the context of the trench and surface pit, the tree appears to be rooted in the lowermost unit which the trench and surface pit share in common. A radiocarbon date taken from this unit yields a radiocarbon age of 104 ± 64 yrs. B.P. (cal AD 1728 to 1797 and cal AD 1851 to 1983). Thus, radiocarbon age and tree ring analysis contend that this surface must have been deposited prior to 1907; all other units must post-date 1907 as they bury this tree.

Synthesis and Discussion

Slackwater deposits in Sycamore Canyon and Hell Canyon preserve thinly laminated sedimentary structures, ranging from symmetrical ripple laminations to indistinct trough cross beds. These are most commonly found in the insets sloping from the top surface. Many of these insets also contain abundant organic material.

Deeply buried deposits do not display sedimentary structures but are instead massive, exhibiting only weak structural development. It is possible that bioturbation may destroy some sedimentary features; however, a semi-arid environment may preserve delicate laminations for long periods of time, such as the features preserved in the

Figure 22. Hackberry trees on SW-4 slackwater sequence

Missoula flood deposits in eastern Washington (Baker, 1973). It is also possible that no sedimentary structures formed during deposition. This is consistent with the description of a slackwater deposit, in which sediments falling from suspension would preserve no sedimentary features (Sanders, 1963). Geologists have postulated that a high rate of sedimentation may produce massive sedimentary sequences, such that sediment fallout precludes the formation of any sedimentary structures (Blatt, et al., 1972; Boggs, 1987; Moore and Scruton, 1957). Moore and Scruton (1957) also suggest that structureless deposits may form from uniform conditions of deposition or in reworked material. Hattingh and Zawada (1996) would argue against these explanations; using relief peels on flood deposits along South African rivers, they demonstrate that many sedimentary structures, primarily horizontal laminations, are preserved in sediments described as structureless. (Hattingh and Zawada, 1996).

For both canyons, the deposits vary in color, from grayish brown to reddish brown. Gray to brown layers are generally thicker deposits with abundant to disseminated charcoal littered throughout the layers. Units which are in the mid-section to lower in the stratigraphy generally have greater abundance of charcoal. Charcoal is assumed to have been carried in flows generated in the forested upper basin where forest fires are most likely to occur. Unit D is unusually rich in charcoal; its gray color has made it a diagnostic stratigraphic marker in Sycamore Canyon slackwater deposits.

Redder units are generally thin, occasionally discontinuous, and preserve little charcoal. These units may result from local slope wash or localized flow events at lower elevations in the drainage basin. For instance, deposits from recent local flows have a red color similar to reddish units in the stratigraphic sequences.

Stratigraphic and tree ring data are markedly variable from site to site in regard to the number of flood units preserved and their placement in time (Table 7). Tree rings suggest that the majority of stratigraphy in Sycamore Canyon predates the gage record at Clarkdale. For instance, SW-1 preserves 11 units, the upper most unit having been deposited by 1907. SW-2 and SW-3 vary in the number of units preserved, especially in the historic record, as SW-2 preserves one inset in contrast to four at SW-2. Top surfaces, however, have similar ages according to minimum ring counts. In contrast, the stratigraphic record in Hell Canyon is very young, with all units deposited within the gage record.

Although tree ring and radiocarbon analysis suggest that a large portion of the stratigraphy pre-dates the gage record on the mainstem Verde, insets are relatively fresh and should correspond to large floods recorded at the Clarkdale gage. The largest floods at the Clarkdale gage, depicted as they would occur in a slackwater deposit show that events most likely to be preserved are as follows (Figure 23):

February 20, 1993
January 8, 1993
February 19, 1980
March 1, 1978
February 20, 1920
1918
1891[3]

---

[3] The flood of 1891 occurred prior to the gage record at Clarkdale; however, historic accounts relate this flood as being large and regional in extent. This information must be used with caution as the magnitude of the event is unknown.

Site	Tree Ring count	Corresponding Calendar Year	Location on site	Total units	Historic units
SW-1	97 87 49	1900 1910 1948	Top* Top* Root	11	0 ?
SW-2	170 167 166 166 159 158 83 31	1827 1830 1831 1831 1838 1839 1914 1966	Top Coll. Top Coll. Top Coll. Coll. Coll.	10	5
SW-3	156 152 144 135 90 76 60 49	1841 1845 1853 1862 1907 1919 1937 1948	Top Top Top Top Top Top Top Slope	6	1
SW-4	90** 59 54 44	1907 1938 1943 1953	Top Slope Slope Slope	6	6

* denotes extrapolation
**buried to a depth of 25 cm

Table 7. Summary table of tree ring data and flood units preserved at each site. "Top" and "Slope" refer to positions on slackwater surfaces; "Coll." refers to trees sampled on colluvial slopes.

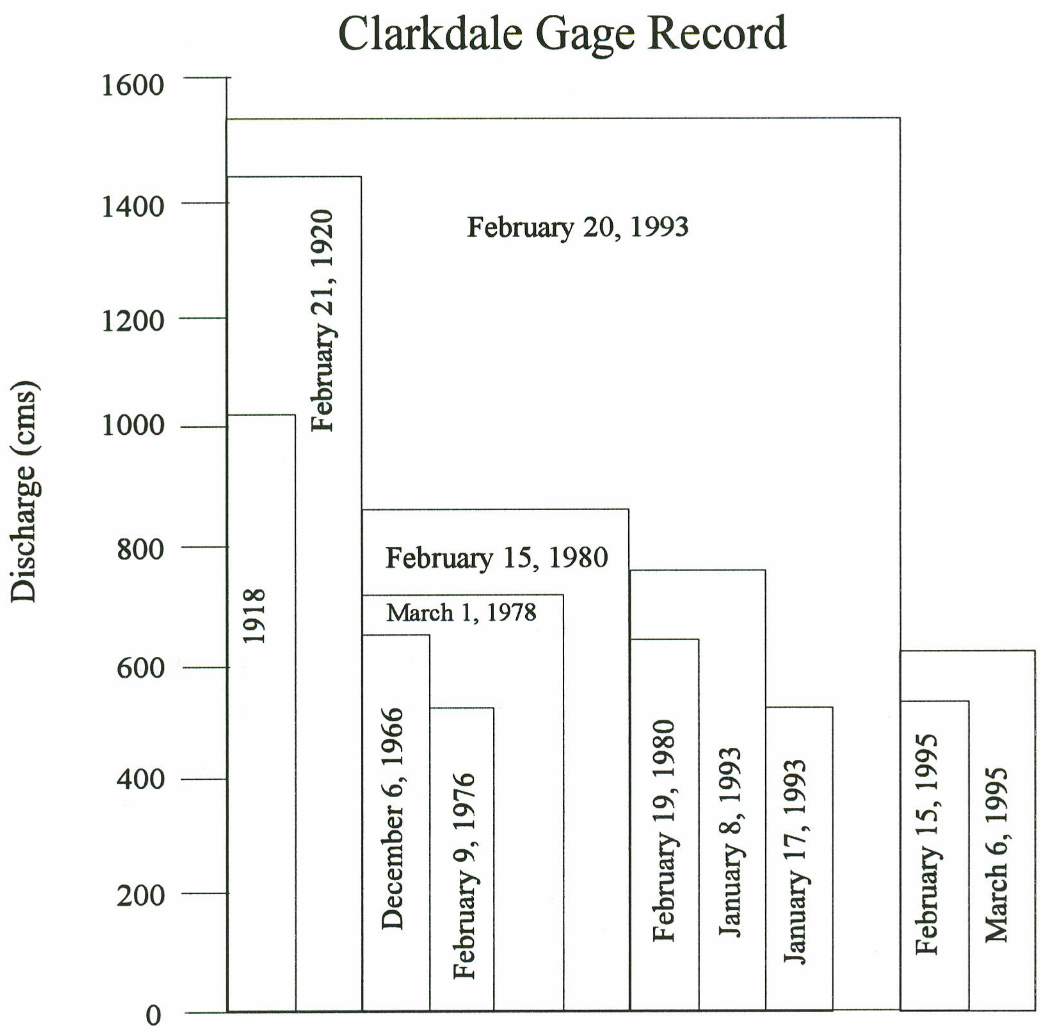


Figure 23. Schematic diagram of the Clarkdale gage record. This figure depicts the largest floods above 500 cms at the Verde River gage near Clarkdale as they would be preserved in the stratigraphic records of Hell Canyon and Sycamore Canyon, assuming no erosion. For instance, the flood of 1920 occurs early in the record and would be inset by younger, smaller floods of 1980 and 1978; all stratigraphy would be overtopped by the late February flood in 1993. This diagram follows Figure 9 in House, et al., 1995.

Thus, SW-1 should record no historic floods; SW-2 is most likely to preserve 1891 and 1920 events on top (Figure 24). Assuming that units are inset rather than connected with units on the upper surface, events of 1918, 1978, 1980, January 7-9, 1993, and February 18-21, 1993 are most likely to be preserved on the SW-2 slope. SW-3 preserves one inset which is presumably the late February event of 1993. SW-4 in Hell Canyon may record large magnitude events of 1891, 1918, 1920 and 1993. It is unknown with what floods the insets would correspond.

When comparing results to the previous work of Ely (1985) on the Verde River, it is difficult to say whether any of the flood deposits correlate. Radiocarbon dates do not; the oldest deposit found in this particular portion of the basin is approximately 650 years B.P. whereas Ely has found a deposit which dates >1000 years B.P. based on detrital charcoal and archaeological materials. She also found Pleistocene deposits with Stage III carbonate. This is not problematic, however, as recent floods in 1993 have demonstrated that meteorological events may produce localized floods in an elongated basin which encompasses diverse terrain.

Sycamore Canyon and Hell Canyon stratigraphic sequences are relatively young compared to stratigraphic work in progress along the mainstem Verde River. Sequences such as those near Bear Siding on the upper Verde River record floods as old as 2500 years B.P., while the Sheep Bridge site on the lower Verde River above the Tangle Creek gage records floods which are ~600 years B.P. and older. At sites along the Verde, the highest flood is larger than any event in 1993 and dates at ~300-400 years B.P. (House, written communication). Sycamore Canyon and Hell Canyon do not record this deposit,

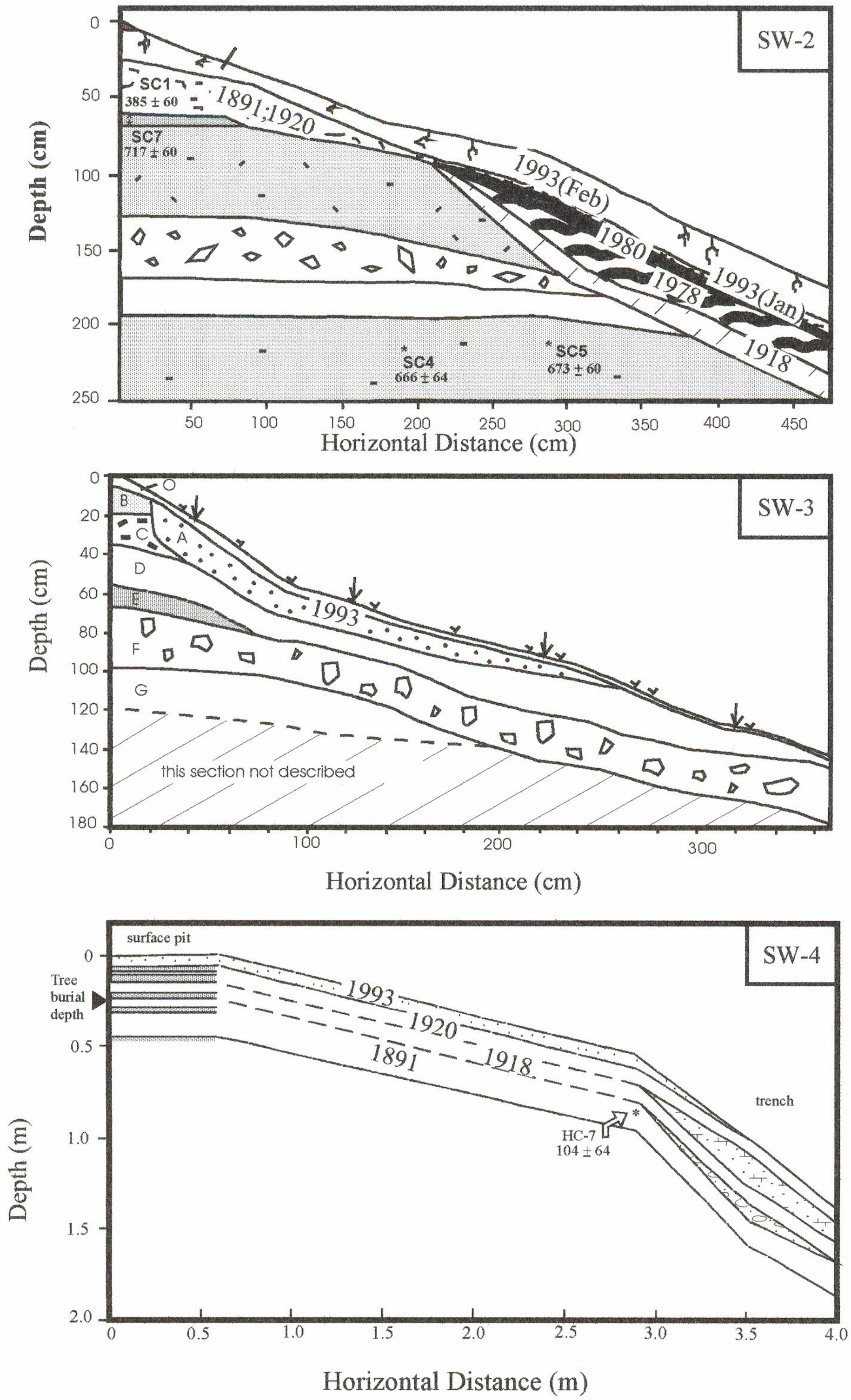


Figure 24. Slackwater deposits with hypothesized flood dates in historic units. Units were assigned ages based on stratigraphic position and flood chronology at the Clarkdale gage.

although flood units with similar dates have been found in Sycamore Canyon. Thus, evidence suggests that this flood occurred, at least in Sycamore Canyon, but was of lesser magnitude than floods of similar age on the mainstem.

LATE HOLOCENE TERRACES

At the confluence of tributaries with the Verde River, terraces have developed which appear to have little carbonate development or induration to indicate exposure for long periods of time (Figure 25). Pearthree (1996) describes these surfaces as part of the geologic floodplain, composed of gravely beds overtopped by fine-grained sediments, and inundated only marginally by the largest floods such that flood waters are shallow and there is little impact on vegetation. House and Pearthree (1993) map the terrace at the confluence of Sycamore Creek and the Verde River as Yt, or late Holocene (<5ka) noting that the terrace exhibits little soil development and is subject to inundation only during the largest floods.

The surfaces are very similar to slackwater deposits found within the canyons in that they consist of fine-grained alluvium, and are located directly adjacent to the channel bed. They often have indurated gravel units at their base and are much more extensive than slackwater deposits. Preliminary work suggests that they do not correlate well with tributary slackwater deposits; this may be due to the resolution of radiocarbon dating as well as interbedded tributary and Verde River sediments.

Units comprising the cut bank terrace of the Sycamore Canyon-Verde River confluence (Figure 26) consist of reddish-brown to brown sandy loams with a minor amount of coarse material and organic matter. Near the midsection of the description, an increase in clay and silt is evident along with littering of charcoal throughout the unit. Color is variable within these units, in which clay layers interfinger with coarser sediments. Lower

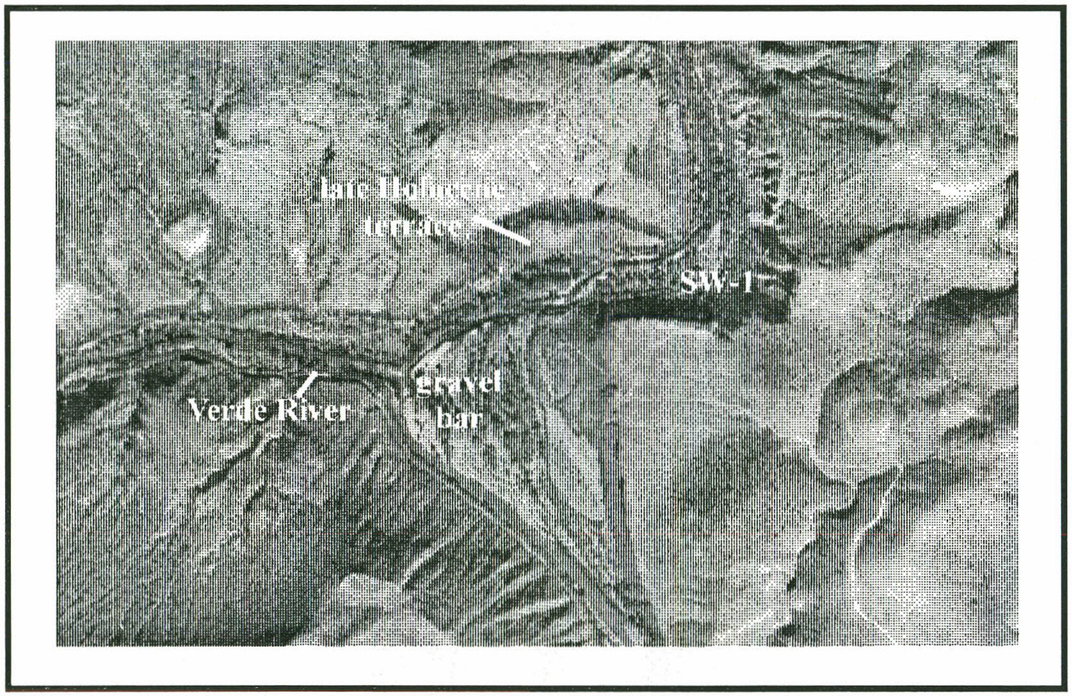


Figure 25. Late Holocene terrace, Sycamore-Verde confluence

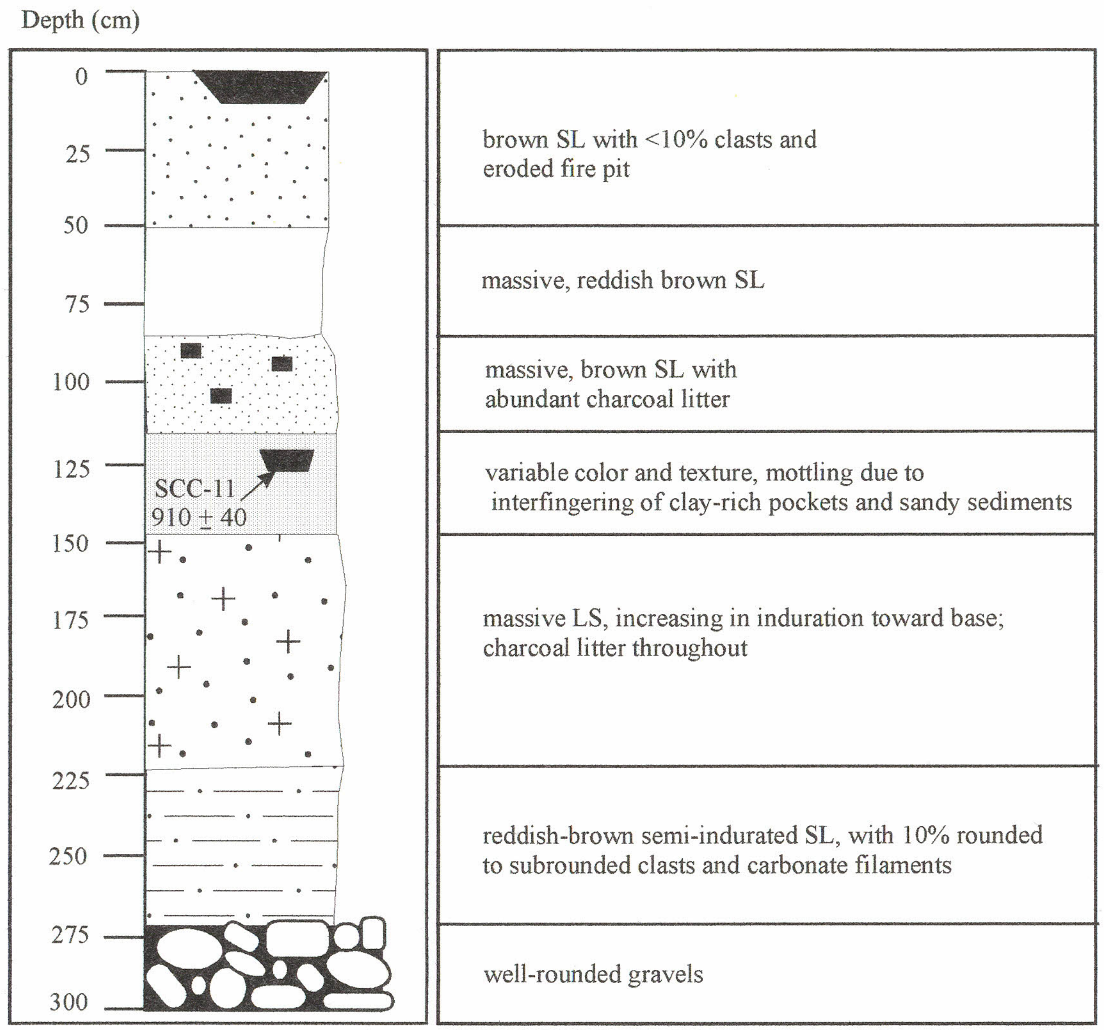


Figure 26. Late Holocene terrace stratigraphic sequence, Verde River-Sycamore Creek confluence (SL=Sandy Loam; LS=Loamy Sand).

units consist of a loamy sand, which increases in induration toward its base, and a reddish-brown semi-indurated sandy loam with carbonate filaments and 10% rounded to subrounded clasts. Well-rounded river gravels define the base of the sequence. A particularly rich pocket of charcoal (SCC-11) was sampled 132-143 cm from the surface and dated at 910 ± 40 yrs. B.P., suggesting that terrace formation is contemporaneous, at least in part, with depositional sequences at slackwater sites.

The location of the terraces in the river system suggest that they have formed as separate drainage sources combine, and create a zone of backwater, allowing fine sediment to drop from suspension. At the Sycamore Canyon-Verde River confluence, personal communication with terrace landowners and field checking of the surface indicate that this surface was not inundated by the flows of 1993. The Hell Canyon terrace, at its most upstream extent in Hell Canyon, shows that the 1993 floodwaters inundated gullies in the terrace, but did not reach the top of the surface.

Using evidence from the stratigraphic record, work on Colorado Plateau rivers reveals cycles of deposition alternating with erosion and nondeposition (Hereford, et al., 1996; Hereford and Webb, 1992; Graf, et al., 1991). On the Colorado River in the eastern Grand Canyon, debris fans and alluvial terraces point to alternating deposition and erosion (Hereford, et al. 1996). Depositional periods occurred from A.D. 700-1200, in which Pueblo II alluvium accumulated, and from A.D. 1400-1800, forming the Upper Mesquite terrace alluvium. It is noteworthy that the radiocarbon date from the terrace deposit falls in the middle of the first alluvial period, at approximately 1000 A.D., while dates from slackwater deposits are found within the second alluvial period from approximately 1350

A.D. to 1600 A.D. In a similar study of the Paria River Canyon in northern Arizona and southern Utah, Graf, et al. (1991) study trends in precipitation to determine possible correlations with periods of alluviation. Findings indicate that a decrease in tropical cyclones and winter frontal systems coincides with flood plain alluviation such that floods are large enough to overtop the channel banks but not powerful enough to erode them. They also postulate that climate must be the underlying factor causing changes in sedimentation style, since changes are observed regionally; factors such as local vegetation and land use changes must play a secondary role. In addition, they note that since 1980, floods have not overtopped the floodplain near the Paria River gage, suggesting that the system is in a period of erosion and nondeposition.

A situation similar to studies of Colorado Plateau streams may occur for tributaries in the upper Verde River basin, in which flood deposits are periodically flushed from the system, initiating a new period of deposition. Ages from slackwater deposits are relatively young, the oldest of which is ~650 cal years B.P. As these canyons have existed prior to this age, it is likely that sequences older than this have existed in the past.

The limited data that have been collected from Late Holocene surfaces precludes any definitive statements which relate terrace formation and slackwater deposition; from preliminary work, terraces seem to be semi-contemporaneous with slackwater sites. They may have begun their formation during the same period; however, terraces have become isolated from floods which occur in the system while slackwater surfaces remain active in the present flooding regime.

SUMMARY AND CONCLUSIONS

The Verde River basin encompasses diverse terrain, extending from the Basin and Range Province in southern Arizona to the southernmost portions of the Colorado Plateau defined by the Mogollon Rim escarpment in central Arizona. The upper Verde River basin is located in central Arizona in the Central Highlands Province and is characterized by high relief, steep gradient tributaries which drain the Mogollon Rim escarpment.

Hell Canyon and Sycamore Canyon, major ungaged tributaries in the upper Verde River basin, show evidence for extreme flows during the flood of Feb. 18-21, 1993 and also paleoflood evidence in the form of slackwater deposits. This project was able to quantify the discharge from these tributaries and to study the paleoflood record in the context of this recent large-magnitude event.

General meteorological conditions associated with the peak discharge on Feb. 20, 1993 included blocking high pressure in the northern latitudes of North America associated with split westerly flow which displaced the jet stream further south than it would normally occur. This brought greater storm activity across the state of Arizona. Furthermore, moisture from the eastern Pacific Ocean served to increase precipitation above normal for the 1993 winter (House and Hirschboeck, 1997).

In the storm of Feb. 18-21, antecedent conditions along with rain-on-snow in the upper elevations and heavy precipitation at lower elevations combined to produce a runoff event unparalleled in the gage record on the upper Verde River (House and Hirschboeck, 1997). The Verde River gage near Clarkdale peaked at 1507 m^3s^{-1} and occurred *before* the Paulden peak of 657 m^3s^{-1} upstream. For this event as well as many others in the historic record, lags between peaks at gages suggest that tributaries between the gages contribute the majority of flow to peaks at Clarkdale, of which Hell Canyon and Sycamore Canyon comprise 69% of the drainage area.

Flow reconstructions estimate maximum discharges of 900 cms in Sycamore Canyon and 700 cms in Hell Canyon. These estimates are reasonable based on regional flood envelope curves, unit discharge calculations, and morphometric data of similar gaged tributaries; however the estimates should be regarded as maximum values.

Stratigraphic descriptions and tree ring analysis record a maximum of 11 floods at any one site with variable preservation of historic and pre-historic units. SW-2 and SW-3 slackwater deposits in Sycamore Canyon are characterized by an older sequence inset by organic-rich units believed to be historic. Tree-ring data suggest that an older flood sequence pre-dates the historic record, being deposited prior to 1827 and 1841 at SW-2 and SW-3 stratigraphic locations and prior to 1907 at SW-1.

Late Holocene terraces seemed to have formed contemporaneously, at least in part with slackwater deposits within the canyons; however, terraces have become isolated from floods which occur in the system while slackwater surfaces remain active in the present flooding regime. Results from the study indicate that Hell Canyon and Sycamore Canyon are capable of generating large-magnitude flows and are significant contributors to floods on the Verde River in both historic times and in the paleoflood record.

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