# Paleoflood Hydrologic Research in the Southwestern United States

Robert H. Webb and Sara L. Rathburn

**Paleoflood hydrology is a cross-discipline between geomorphology and hydrology that uses geologic evidence to estimate discharges for historic and (or) prehistoric floods. Analysis of fine-grained flood deposits has been used to estimate the magnitude and date of occurrence of floods on rivers and streams in the southwestern United States. These flood deposits and other geologic evidence of floods, termed paleostage indicators, are emplaced along the margins of channels from streamflows with high concentrations of suspended sediment. Dates for floods are determined from historic records, analysis of scarred or damaged trees, relative ages of soils developed on flood deposits, and radiocarbon dating of organic material entrained in flood deposits. Flood discharges can be estimated from paleostage indicators by using the step-backwater method in which the channel is either assumed or demonstrated to be stable. A comparison of the techniques that have been used reveals inconsistencies caused by a rapidly evolving discipline, and standardized procedures are needed for the analysis of flood deposits. The three case studies presented illustrate the use of paleohydrologic data with gaging data for estimating flood frequency using maximum-likelihood techniques. Maximum-likelihood techniques for fitting probability distributions can explicitly account for the uncertainties inherent in paleoflood data and provide greater flexibility in the use of paleoflood records with gaging records in flood-frequency analysis, thereby yielding improved estimates of design floods with large recurrence intervals.**

Fluvial paleohydrology is the interdisciplinary study of the past movement and distribution of water and sediment in river channels. Paleohydrology links conventional engineering and hydrologic techniques of discharge calculation and flood-frequency analysis with the geologic emphasis on stratigraphy, sedimentology, and geomorphology. One approach used in paleohydrologic research is the documentation of fluctuations in channel morphology with time to estimate changes in hydrologic conditions (*1*); this approach is used mainly in paleoclimatic studies on alluvial rivers (*2, 3, 4*). A second approach uses geologic evidence to reconstruct the magnitude and frequency of past floods in bedrock channels (*5–9*). Although its origins can be traced to the early 19th century (*10*), paleohydrologic research has grown substantially in the last decade.

Estimation of the magnitude and frequency of past streamflow floods (paleofloods) has been based on bankfull-discharge relations (*1, 11*), the size of boulders transported during floods (*9*), or geologic evidence of maximum flood stages (*5–7*). In the southwestern United States (fig. 1) the most common technique for estimating discharges uses relict geologic evidence of water-surface elevation, or paleostage indicators. These paleostage indicators include fine-grained flood deposits (termed "slackwater deposits," (*5*), see fig. 2), silt lines correlative with flood deposits (*12*), and erosional scars cut into hillslopes (*13*). Flood discharges required to emplace the paleostage indicators are estimated from hydraulic equations, and the date of the flood is determined by a variety of techniques, including radiocarbon dating.

Paleohydrologic research using paleostage indicators has increased steadily since the late 1970s. Rivers in Texas (*14–16*), Arizona (*13, 17–20*), and Utah (*12, 21, 22*) in the United States (fig. 1, table 1) and in the Northern Territory of Australia (*23–25*) have been studied. As research involving paleostage indicators has developed, many techniques have been used in estimating discharges and dating floods. Development of efficient statistical techniques for incorporating paleohydrologic and historic information in flood-frequency analyses (*26–30*) will undoubtedly encourage further applications of paleohydrology to estimate the magnitude and frequency of floods.

This paper reviews the techniques used in paleohydrologic studies of rivers in the arid and semiarid southwestern United States and illustrates the use of paleoflood data derived from analysis of fine-grained flood deposits with gaging data in flood-frequency analysis. Other reviews of paleohydrologic research in this region are given in references elsewhere (*5–7*). The inaccuracies and imprecision in paleohydrologic techniques are emphasized and are explicitly incorporated in frequency analyses of gaging records from three rivers in the Southwest.

## PALEOSTAGE RESEARCH TECHNIQUES

### Accumulation Sites and Stratigraphy

Fine-grained flood deposits are commonly preserved along bedrock channels in the southwestern United States. These sediments are deposited from sediment-laden waters in zones of reduced flow velocities during floods (*5*). Tributary mouths, channel margins upstream of contractions and downstream of expansions, and rock shelters or caves above the low-flow channel are typical accumulation sites for flood deposits (fig. 2). If the depositional sites are protected from subsequent erosion, thick sequences of deposits will accumulate as successive floods either overtop or erode into the side of the deposit (*5, 12*).

The stratigraphy of fine-grained flood deposits contains evi-

---

U.S. Geological Survey, 300 West Congress Street, Tucson, Arizona 85701-1393.

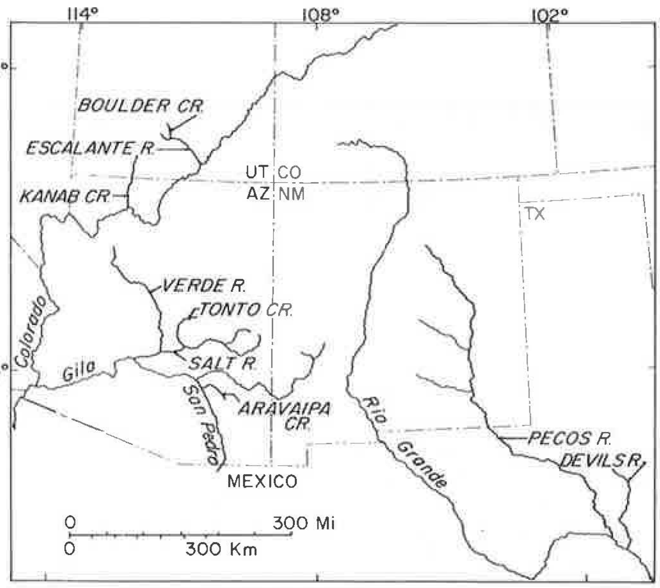


**FIGURE 1 Rivers in the southwestern United States for which paleohydrologic data have been collected.**

dence of discrete floods, and organic material entrained in the deposits can be used to develop a chronology of such floods. Flood deposits may have characteristic sedimentary structures, such as climbing ripples or crossbedding, or they may have no structures (*5*). Deposits created by unique floods may be separated using many criteria, including drapes of silt or organic debris between layers representing different floods, abrupt stratigraphic breaks including unconformities, differences in grain-size distributions, differences in weathering characteristics, and changes in color of sediments (*5*). Discontinuous flood deposits along a channel may be correlated using stratigraphic position, radiocarbon dating, color, or li-

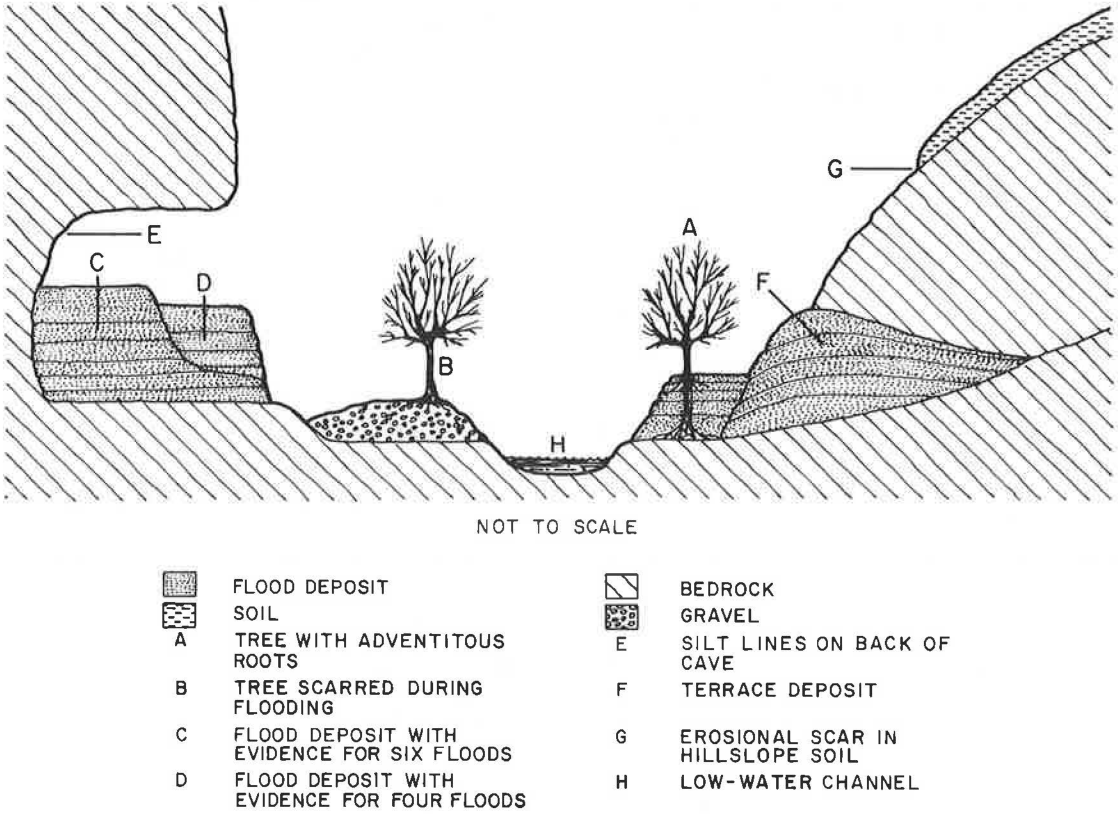


**FIGURE 2 Schematic diagram of a typical flood-deposit site showing the types of evidence used in dating floods and estimating discharges [modified from Baker (*6*)].**

TABLE 1 SUMMARY OF PREVIOUS STUDIES OF PALEOHYDROLOGY OF RIVERS OR CREEKS IN THE SOUTHWESTERN UNITED STATES

| Name | Area ($km^2$) | Number of paleofloods | Largest recorded flood ($m^3/s$) | Date | Length of paleoflood record (years) | Method used for estimating discharge | Number of sections | Reference |
|---|---|---|---|---|---|---|---|---|
| | | | | TEXAS | | | | |
| Pecos | 9,500 | 30 | 27,400 | 1954 | 9,530 | ME | 1 | 14 |
| Devils | 7,100 | 0 | 16,700 | 1954 | 8,730 | ME | 1 | 14 |
| | | | | UTAH | | | | |
| Escalante | 810 | 18 | 720 | 950 | 2,100 | SBW | 10 | 22 |
| Boulder Cr | 450 | 3 | 400 | 1650-1950 | 1,000-1,100 | SBW | 27 | 21 |
| | | | | ARIZONA | | | | |
| Verde | 15,000 | 10 | 5,400 | <950 | 1,010 | SBW | 20 | 17 |
| Salt | 11,000 | 14 | 4,600 | <950 | >600 | SBW | 24 | 13 |
| Salt | 21,000 | 27 | 11,900 | 850 | 1,100 | SBW | 12 | 18 |
| Aravaipa | 1,340 | 6 | 970[a] | unknown | 1,100 | SBW | 28 | 20 |
| Tonto Cr | 1,630 | 4-5 | 1,000[a] | 1980 | 280 | SBW | 13 | 19 |
| Kanab Cr | 5,370 | 10-12 | 600 | 1550 | 500 | SBW | 11 | |

[a] Discharges are lower than maximum discharge reported by U.S. Geological Survey.

**[Dates of floods are given in calendar years A.D. that were obtained in some cases from conversion of radiocarbon dates. ME--Manning's equation, SBW--step-backwater method. Data from Kanab Creek is from S.S. Smith, University of Arizona, unpublished data]**

thology. Flood deposits may represent vertically-aggrading sections, where each successive flood must be larger than the previous flood (*5, 14, 15*), or inset deposits within the flood deposits may imply that all floods exceeding a fixed stage will have stratigraphic evidence preserved (fig. 2) (*12, 21, 22*).

The type of flood deposit studied is important to the statistical treatment and determination of a censoring threshold, which is a discharge that is either exceeded or not exceeded over a known length of time (*28*). The main objective is to verify that all floods that exceeded the censoring threshold left stratigraphic evidence. Such verification is difficult to obtain, but studies of deposits associated with known historic floods (*12, 13, 14, 17, 19, 20, 23, 25*) suggest that stratigraphic evidence would have been preserved if other larger floods had occurred. The censoring threshold in paleoflood data typically is high in terms of recurrence interval, as the examples presented later in this paper show.

### Dating Techniques

Dates for paleofloods are obtained using several different techniques, each of which has an associated degree of uncertainty. Radiocarbon dating of organic material entrained in or associated with the flood deposit is the standard method for dating flood deposits (*5*). Radiocarbon dates are reported in years before present (yrs BP) with A.D. 1950 as the calendric date for a radiocarbon date of 0 yrs BP. Use of radiocarbon analyses allows the dating of floods that have occurred over the past 50,000 years, if evidence for the floods is preserved. Radiocarbon dates typically have an uncertainty inherent in the counting techniques that ranges at best from ±40 years on young (less than 10,000 yrs BP) samples to ±1,000 to 2,000 years on older (greater than 20,000 yrs BP) samples. Uncertainties can be much larger if very small samples of organic material are analyzed. Floods that occurred after A.D. 1950 can be dated to the nearest year using ultramodern radiocarbon dates, which are based on the excess amounts of 14C in the atmosphere that resulted from aboveground nuclear tests (*24*).

Radiocarbon dating of flood deposits assumes that organic material in flood deposits is contemporaneous with the flood that deposited it (*5, 22*). This assumption may or may not be valid. For example, charcoal in a flood deposit may have been created by a fire during the year in which the flood occurred, or the charcoal may have been reworked from older alluvial deposits and may yield a date much older than the date of the flood. Organic debris in the deposit, especially leaves and small twigs, represent the most recent growing season before the flood and thus accurately represent the date of the flood (*6*). Radiocarbon dating of organic litter, or material that accumulated on the surface of a deposit between floods, has been used to constrain the dates for subsequent floods (*14, 22*). Contemporaneity of organic material with the flood deposit is the most important assumption involved in radiocarbon dating of past floods.

Other methods used for obtaining absolute or relative ages of flood deposits include dendrochronology (*31*), soil development (*13, 14*), association of historical or archaeological artifacts in deposits (*12–14, 18, 21*), and historic records such as personal accounts or newspaper articles (*14, 22*). Dendrochronology is used to date floods to the nearest year by studying the damage inflicted on trees growing adjacent to the channel (fig. 2). Burial of trees in flood deposits encourages the growth of adventitious roots, which sprout from the buried trunk of the tree and can be dated using dendrochronologic methods (*31*). Trees unaffected by floods, but which bracket the age of deposits by their growth position, also have been used to constrain the date of floods (*13, 19*). Use of soil development as a relative dating tool introduces large uncertainties in the dating of floods because soils cannot be accurately dated; however, soil development is a useful correlation tool in the absence of organic material. Artifacts can be used to determine whether floods are historic, and archaeological artifacts can be used to date flood deposits as accurately as radiocarbon dating if the artifacts can be placed within a regional archaeological chronology (*13, 21*).

## Estimation of Discharge

Two methods have been used to estimate discharges from paleostage evidence. The first estimates of discharges for paleofloods in the southwestern United States (*5, 14*) were obtained using Manning's equation:

$$Q = \frac{1}{n} A\ R^{2/3}\ S^{1/2} \qquad (1)$$

where $Q$ = discharge in cubic meters per second ($m^3/s$); $n$ = a roughness coefficient called Manning's $n$; $A$ = cross-sectional area ($m^2$); $R$ = hydraulic radius (m); and $S$ = friction slope of the water surface. The channel conveyance, $K$, is defined as:

$$K = \frac{A\ R^{2/3}}{n} \qquad (2)$$

For solution of equations 1 and 2, one cross-sectional area is required with the top of the flood deposits serving as a water-surface elevation (*14*). Use of only one cross section implies that the section used is representative of the local channel conditions, which may not be accurate. Because many flood deposits were in tributary mouths away from the main channel flow (*14*), the height of some deposits may represent a fraction of the total energy of flow instead of just the energy associated with the velocity. The water-surface slope used in Manning's equation was first assumed to equal the channel slope (uniform flow), and it was increased to 1.25 times the channel slope after the initial discharge estimates were found to be much less than the discharges recorded at gaging stations (*14*). Finally, a least-squares curve fitting revealed that discharges estimated from known water-surface elevations were 1.6 to 2.0 times larger than the discharges estimated using the height of flood deposits as the water-surface elevation (*14*). The results of this study (*14*) show that considerable uncertainty in discharge estimates can result from use of Manning's equation alone.

The step-backwater method (*32*) is most commonly used for estimating the discharges of paleofloods from paleostage indicators (*12, 13, 17, 18, 19, 20, 21, 22, 23, 25*). The step-backwater method combines energy losses associated with channel resistance, as calculated from equation 2, with conservation of energy and mass equations. Conservation of energy is calculated from the equation:

$$h_1 = h_2 + (h_L)_{12} + \epsilon\Delta(h_v)_{12} \qquad (3)$$

where $h$, the total flow head, is calculated from:

$$h = z + \frac{V^2}{2g} \qquad (4)$$

and where $(h_L)_{12}$ = head loss, which is proportional to the discharge and reach length between sections 1 and 2 and inversely proportional to $K$; $\varepsilon$ = energy-loss coefficient, which conventionally is 0.5 in expanding reaches and 0.0 in contracting reaches (*32*); $\Delta(h_v)_{12}$ = difference in velocity head between sections 1 and 2; $z$ = water-surface elevation; $V$ = flow velocity (the correction coefficient, $\alpha$, is assumed equal to 1 (*32*)); and $g$ = gravitational acceleration. The velocity head is calculated from:

$$h_v = \frac{V^2}{2g} \qquad (5)$$

The conservation of mass equation is:

$$Q = A_1V_1 - A_2V_2 \qquad (6)$$

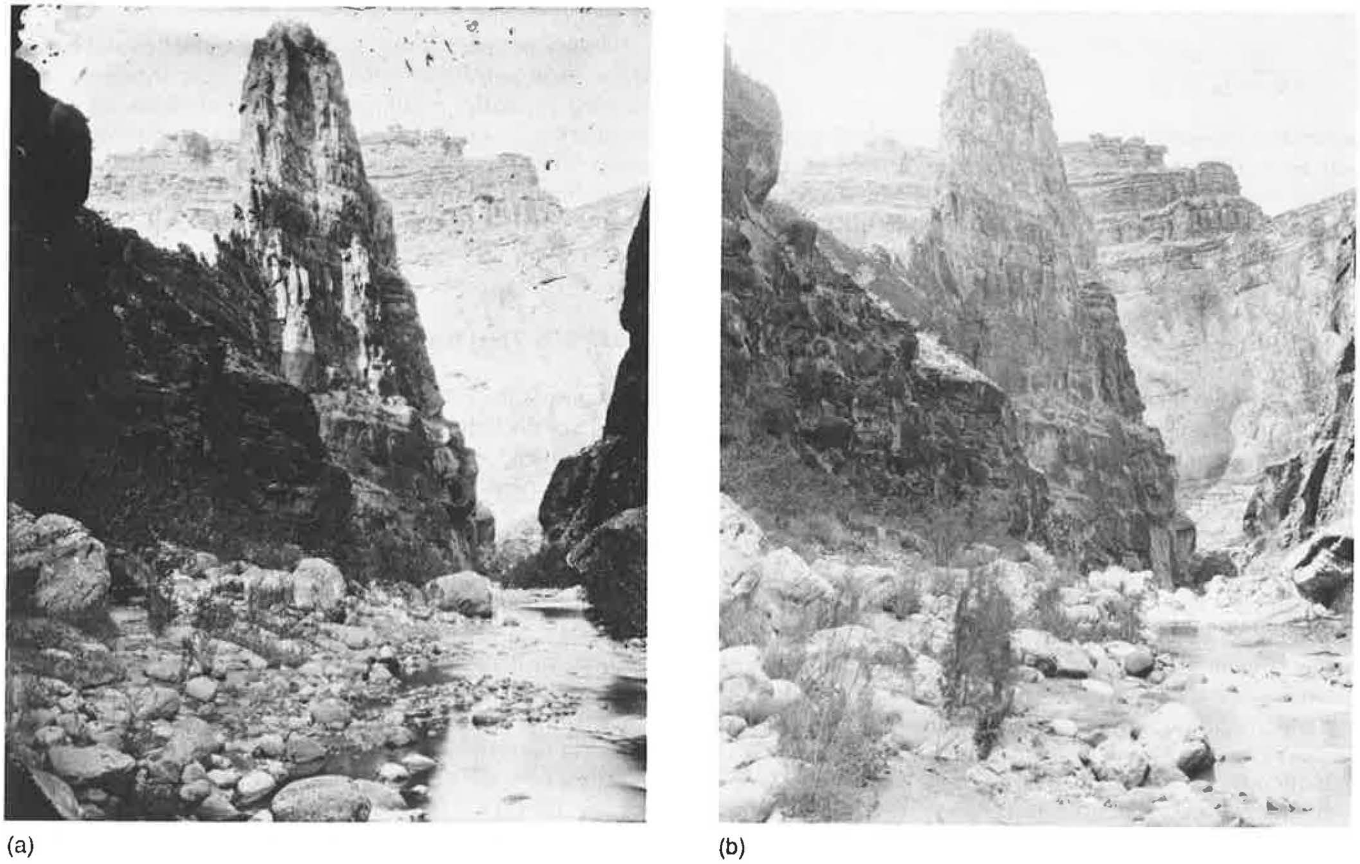
Details of the calculations in the step-backwater method are presented elsewhere (*32, 33*). In the step-backwater method, stages are estimated at specific cross sections for given discharges. Water-surface profiles for various discharges are compared with the heights of flood deposits or other paleostage indicators until a discharge that best approximates the paleostage indicators is accepted.

With the step-backwater method, the stages associated with various discharges are estimated independently from paleostage indicators, because the method is independent of evidence for water-surface elevation. Flood deposits represent minimum water-surface elevations (*5*), and definition of cross-sectional areas by paleostage indicators results in minimal estimates of discharge. Paleostage indicators may not provide a continuous record of water-surface profile through a reach; however, by using the step-backwater method, additional cross sections without paleostages can be used to account for nonuniform flow conditions.

Assumptions concerning the effective flow area, hydraulic interpretation of paleostage indicators, and choice of energy-loss coefficients cause uncertainties in discharge estimates. Use of the step-backwater method requires the assumption of one-dimensional flow in the channel reaches. Uncertainties in the sizes of ineffective flow areas or eddies cause errors in the discharge estimates. Flood deposits are assumed to represent the water-surface profile of the mean channel flow. Use of flood deposits in tributary canyons, which are removed from the flow in the main channel, will introduce errors in discharge because these deposits are indicative of both the main-channel velocity head and some fraction of the total energy head. Finally, choice of Manning's *n* values and energy-loss coefficients introduces additional uncertainty in discharge estimates, although uncertainties associated with reasonable values of Manning's *n* and energy-loss coefficients are much less than the uncertainties in cross-sectional data (*33*).

Discharges estimated for paleofloods have inherent uncertainty because of the potential for channel change between floods. Channel cross sections are measured decades to thousands of years after the flood has occurred. For this reason, paleofloods are studied in bedrock channels where the channel generally is stable (fig. 3) and cross sections change little between floods. The little historic change in sediment storage along rivers with drainage areas greater than 10,000 km$^2$ in southern Utah found by Graf (*34*) indicates that long-term aggradation and degradation are minimal. Changes in alluvial channels during the period of paleohydrologic record have been estimated and used in discharge estimates for paleofloods (*18, 22*). Uncertainties in discharge data estimated from paleostage indicators should be carefully evaluated before the data are used in flood-frequency analysis.

Discharge estimates for historic floods based on paleostage indicators compare favorably with discharges recorded at gaging stations or discharges estimated immediately after the flood, although some notable discrepancies have been found (*13, 19, 20*). These discrepancies—usually an underestimation of the discharge recorded at gaging stations—have been explained either by differences in discharge-estimation technique (*19*) or by flow from tributaries between the flood-deposit site and the gaging station (*13*).


(a)

(b)

**FIGURE 3 The Pinnacle, Kanab Canyon, Utah. (a) Taken in October 1871 by Jack Hillers (Hillers photograph number 629, U.S. Geological Survey photograph library, Denver, Colorado). (b) Taken in September 1985 by Robert H. Webb. The channel morphology has changed little since 1871.**

## USE OF PALEOFLOOD DATA IN FLOOD-FREQUENCY ANALYSIS

### Previous Analyses Using Paleohydrologic Data

Flood frequency analysis in the United States is done by fitting a Pearson type III distribution (*35*) to log-transformed flood data. The merits and disadvantages of this method have been discussed elsewhere (*28, 36, 37, 40*), and the fitting of other probability distributions has been attempted in only one paleohydrologic study in the southwestern United States (*39*). The Water Resources Council methods (*35*) are based on a method of moments fitting of the log-Pearson type III distribution. Without historical or paleoflood data, the gaging data are fitted to the distribution by calculating the mean, standard deviation, and skew coefficient of the log-transformed discharges. The log-Pearson type III curve is defined by:

$$\log_{10}(Q) = \overline{X} + k\overline{S} \tag{7}$$

where $Q$ = discharge; $\overline{X}$ = mean of the discharge data; $\overline{S}$ = standard deviation of the discharge data; and $k$ = a factor that is a function of the skew coefficient and the recurrence interval. Equation 5 is modified when historical or paleoflood data are included in the analysis (*35*). Criticisms of this method for use with historical information are presented in papers by Cohn and Stedinger (*26–29*).

Plotting-position formulae are used to graphically present the data, and one general equation for plotting position given in the Water Resources Council methods (*35*) is:

$$P = \frac{(m - a)}{(N - 2a + 1)} \tag{8}$$

where $P$ = probability of exceedence; $m$ = rank of discharges with $m = 1$ for the largest; $N$ = number of years of record; and $a$ = factors that are dependent upon the distribution. For the commonly used Weibull plotting position, $a = 0$. Equation 8 is modified in several different ways to account for statistical differences between systematic gaging data and historical or paleoflood data (*28, 35, 38*). Previous attempts to extend the effective length of gaging records with paleoflood information generally have used either Weibull plotting positions or a method of moments fitting of the log-Pearson type III distribution (*5, 12, 13, 14, 15, 16, 22*). The type of plotting position used in plotting paleohydrologic data with gaging data creates less variability than the inherent variability in the sampling of the population from which the flood data arise (*38*).

Methods that differ from the Water Resources Council methods have been proposed for the treatment of paleoflood information (*26, 28, 29, 38*). Stedinger and Cohn (*28*) propose the maximum-likelihood method for using paleoflood and gaging record data to fit probability distributions. With that method, paleoflood information can be treated either as Type I censored data (*26, 29*) or binomial-censored data (*26, 28*). Paleofloods can be described by a single discharge, a range in discharges, or a threshold exceedence. The lack of floods over a given time period (negative evidence) can be used in this type of analysis by establishing a threshold with no exceedences. The paleoflood information is used with or without gaging data in a likelihood function, which is maximized to obtain parameter estimates of a selected probability distribution. Details of the technique applied to several probability distributions are given in 26 and 27. General maximum-likelihood estimators for the log-Pearson type III distribution have been developed and applied to paleoflood data for the Salt and Verde Rivers in Arizona (*39*).

The maximum-likelihood method using censored data has been shown to be more flexible, efficient, and robust in Monte Carlo tests (*28*) than the Water Resources Council methods (*35*). Use of paleoflood data increases the effective record length, or number of years of gaging data that would produce the same mean square error as a combination of gaging and paleoflood data (*28*). The effective record length increases from the length of the gaging record to two-thirds the length of the paleoflood record when fitting the two-parameter log-normal distribution if the censoring threshold is at the 90th percentile (*28*). For a censoring threshold at the 99th percentile, the effective record length is approximately one-fifth the length of the paleoflood record. Similar increases in effective record length have been obtained for three-parameter distributions (*29*).

Standard errors of estimate are a function of the mean, standard deviation, and length of record and can be used to describe the precision of flood recurrence-interval estimates. In this paper, standard errors are calculated using the methods presented in 41 for the log-Pearson type III distribution. The standard error of estimate of distributions fit with gaging records versus distributions fit with gaging and paleoflood records are compared to show the ability of paleoflood data to decrease the standard error, and thus increase the precision, of recurrence-interval estimates.

Because of uncertainties in discharge estimates and dating of floods in paleoflood studies, and because thresholds can be used explicitly, maximum-likelihood methods appear to be ideal for the analysis of paleoflood and gaging-record information. The following three case studies demonstrate the use of maximum-likelihood techniques in fitting the log-Pearson type III distribution to gaging data and paleoflood information.

### Example 1: The Pecos River, Texas

In studies of the Pecos River in western Texas (fig. 1), flood-frequency distributions have been estimated from a long gaging record and paleoflood data near the river's juncture with the Rio Grande (*5, 15, 16, 40*). The gaging record for the Pecos River is unusual because of two extreme floods. Hurricanes in 1954 and 1974 resulted in floods with peak discharges of 27,400 m³/s and 16,100 m³/s near the juncture with the Rio Grande (*5*). When the Water Resources Council methods (*35*) are applied, the two floods are identified as outliers, or floods that do not appear to arise from the same population as the other floods. Estimates of the 100-year flood ranged from 2,300 to 35,000 m³/s using nine different treatments of the data and four methods of estimating flood quantiles from the data (*5*). Estimates of the recurrence interval for the 1954 flood have ranged from 80 to 10,000,000 years (*16*). Lane's (*40*) estimate for the recurrence interval of the 1954 flood ranged from 380 to 85,000 years.

The paleoflood record for the Pecos River consists of 9,600 years of record with evidence of 20 floods above 1,600 m³/s (fig. 4). Because of the potential for nonstationarity caused

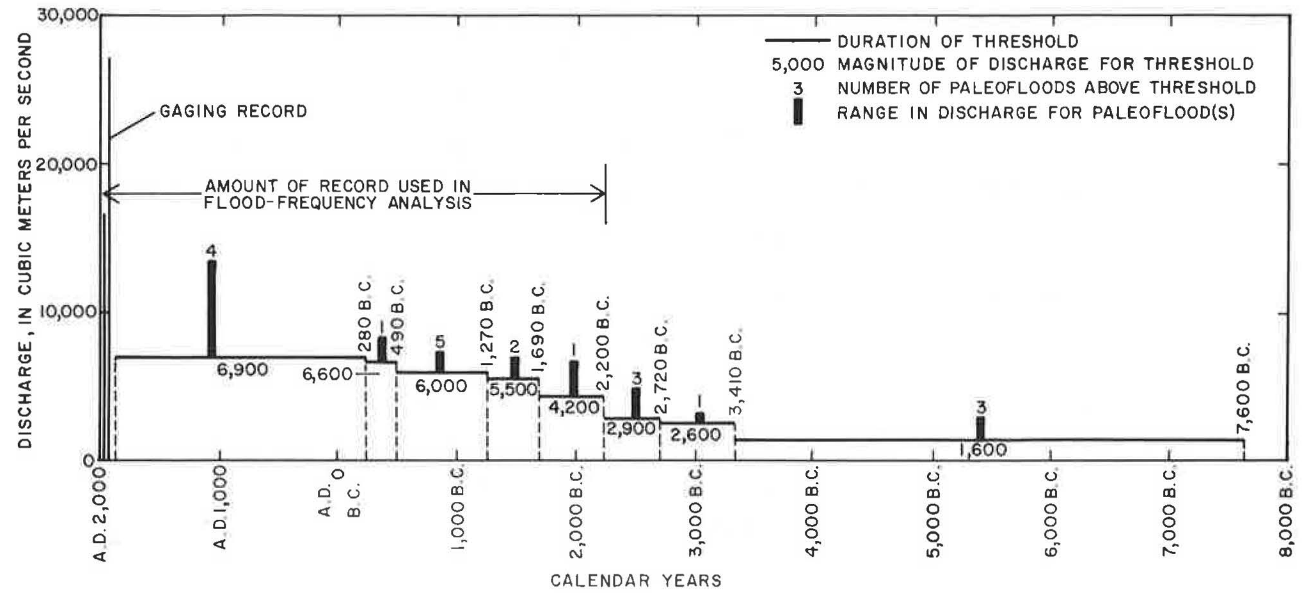


**FIGURE 4** The paleoflood record for the Pecos River, Texas.

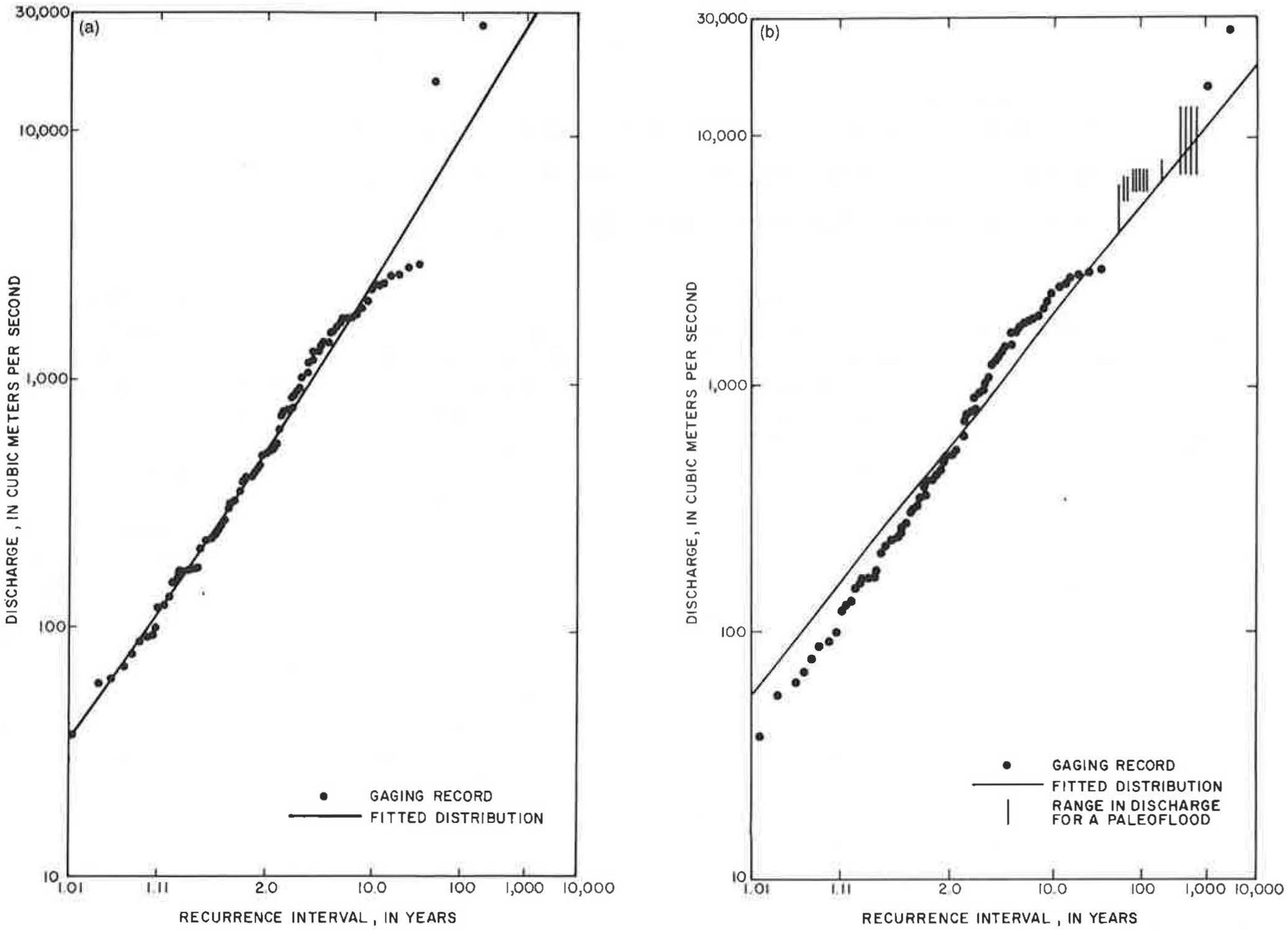


**FIGURE 5** Flood-frequency analysis for the Pecos River,Texas. (a) Maximum-likelihood analysis using the gaging record alone. (b) Maximum-likelihood analysis using the gaging record and 4,236 years of paleoflood record as censored data.

TABLE 2 SUMMARY OF FLOOD-FREQUENCY ANALYSES FOR THE ESCALANTE, PECOS, AND DEVILS RIVERS USING PALEOHYDROLOGIC INFORMATION

| Record used | Method | Total record length (years) | Mean of log discharge | Standard deviation of log discharge | Skew | 100-year flood ($m^3/s$) |
|---|---|---|---|---|---|---|
| PECOS RIVER, TEXAS | | | | | | |
| G | MM | 86 | 2.74 | 0.53 | 0.17 | 11,200 |
| G | ML | 86 | 2.74 | 0.52 | 0.10 | 9,900 |
| GP | MLC | 4,236 | 2.71 | 0.39 | -0.09 | 4,400 |
| DEVILS RIVER, TEXAS | | | | | | |
| G | MM | 77 | 2.70 | 0.76 | 0.02 | 30,100 |
| G | ML | 77 | 2.77 | 0.74 | -0.21 | 23,400 |
| GP | MLC | 1,300 | 2.74 | 0.53 | -0.10 | 4,500 |
| ESCALANTE RIVER, UTAH | | | | | | |
| G | MM | 28 | 1.29 | 0.51 | -0.50 | 190 |
| GP | MLC | 1,536 | 1.35 | 0.51 | 0.05 | 370 |

[G, gaging record only, GP, gaging and paleoflood records, MM, method of moments, ML, maximum likelihood method, MLC, maximum likelihood method with censored paleoflood data. Logarithms are base 10.]

by climatic change during the last 10,000 years (*15, 16*), only the last 4,000 years of the record were used in the maximum-likelihood analysis. Discharges were estimated for paleofloods using Manning's equation and one cross section (*14*). Seven radiocarbon dates were used for dating floods spanning the last 4,000 years. Because the discharges were estimated using Manning's equation and one cross section, and because the water-surface slope was considered equal to or 1.25 times the channel slope, the reported discharges (*14*) were considered imprecise. In order to account for the imprecision in discharge estimates in the maximum-likelihood analysis, all of the floods observed in each time interval were considered to have the same range in discharge. The upper limit of the range was the value of the largest flood estimate that occurred in the time interval. In order to account for the possibility of a lower water-surface slope, the threshold and lower limit of the range were established by decreasing the water-surface slope to 0.75 times the channel slope. The gaging record used in this study is from A.D. 1900 to 1985 (86 years). The influence of dams in the headwaters is considered negligible for peak flood flows (*40*).

Comparison of maximum-likelihood analyses of the gaging record of the Pecos River alone (fig. 5A) and the gaging record with paleoflood information (fig. 5B) indicates a difference in the estimated recurrence intervals for the 1954 flood. The moments of the log-Pearson type III distribution for both treatments are given in table 2. Use of the maximum-likelihood technique with paleoflood information provides a better fit for the 1954 flood with the rest of the population than the fit obtained from an analysis of the gaging record alone (fig. 5B). Standard errors for the 50- and 100-year floods are 10 and 11 percent, respectively, for the distribution obtained using the gaging record. Standard errors for the 50- and 100-year floods decrease to 7 percent for both recurrence intervals when the paleoflood information is included in the maximum-likelihood analysis (table 3). The lowest threshold for the paleoflood record—4,200 m³/s (fig. 4)—is at the 97 percent quantile on the distribution fitted to gaging and paleoflood data (fig. 5B). Extrapolating from data for three-parameter distributions presented in 29, the effective systematic record length for the Pecos River is as much as 2,600 years when the paleohydrologic and gaging data are used together in the maximum-likelihood analysis.

### Case 2: The Devils River, Texas

The Devils River in west Texas (fig. 1) provides a different test for the use of paleoflood data in flood-frequency analysis. The gaging record for the Devils River is 77 years in length.

TABLE 3 SUMMARY OF STANDARD ERRORS FOR THE 50- AND 100-YEAR FLOODS ESTIMATED FOR THE PECOS, DEVILS, AND ESCALANTE RIVERS

| | STANDARD ERRORS FOR 50-YEAR FLOOD | | | |
|---|---|---|---|---|
| | Gaging record | | Gaging and paleoflood records | |
| River | (m$^3$/s) | (percent) | (m$^3$/s) | (percent) |
| Pecos River, Texas | 730 | 10 | 240 | 7 |
| Devils River, Texas | 4,520 | 29 | 420 | 6 |
| Escalante River, Utah | 80 | 32 | 31 | 12 |

| | STANDARD ERRORS FOR 100-YEAR FLOOD | | | |
|---|---|---|---|---|
| | Gaging record | | Gaging and paleoflood records | |
| River | (m$^3$/s) | (percent) | (m$^3$/s) | (percent) |
| Pecos River, Texas | 1,130 | 11 | 300 | 7 |
| Devils River, Texas | 9,020 | 38 | 420 | 7 |
| Escalante River, Utah | 140 | 43 | 46 | 12 |

[Standard errors are calculated using the methods presented in 41, equations 16-21]

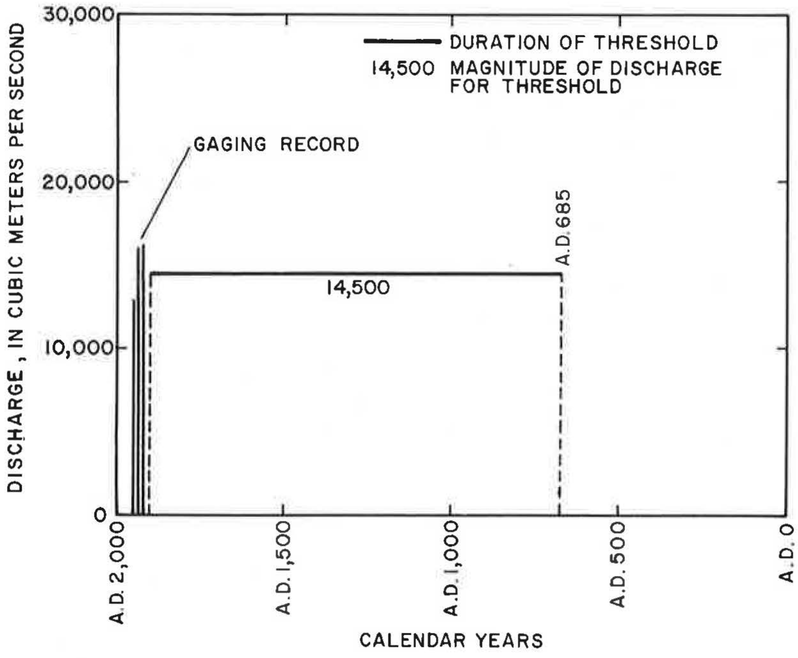


FIGURE 6 The paleoflood record for the Devils River, Texas.

No floods are identified as outliers; however, three unusually large floods of 16,700, 16,400, and 13,300 m³/s have been recorded (*14*). The 100-year floods estimated by the method of moments and the maximum-likelihood fitting are 30,100 and 23,400 m³/s, respectively (table 2). The difference between the two methods is primarily in the value estimated for the skew coefficient. The skew estimated from the Water Resources Council methods is 0.02, whereas the skew estimated for maximum-likelihood analysis is −0.21 (table 2).

The paleohydrologic record for the Devils River is complex and cannot be correlated temporally with the record for the adjacent Pecos River (*14*). Since A.D. 685, however, no paleofloods larger than approximately 14,500 m³/s (fig. 6) have occurred (*14*). This lack of exceedence (negative evidence) can be used to define a nonexceedence censoring threshold in a maximum-likelihood analysis. The resulting flood-frequency relation (fig. 7) indicates that the recurrence intervals for a given discharge are generally greater when the paleoflood information is used. For example, the estimate of the 100-year flood decreases from 23,400 to 4,500 m³/s when paleoflood information is used in the maximum-likelihood analysis. Standard errors for the 50- and 100-year floods are 29 and 38 percent, respectively, for the distribution estimated from the gaging record. Standard errors for the 50- and 100-year floods decrease to 6 and 7 percent, respectively, when the paleoflood information is used in the analysis (table 3). The censoring threshold of 14,500 m³/s is at the 99.2 percentile in the fitted distribution (fig. 7). Effective record length, as extrapolated from 29, increases from 77 to as much as 670 years with the use of the paleoflood evidence, even though no floods were observed.

### Case 3: The Escalante River, Utah

The Escalante River in south-central Utah (fig. 1) has a potentially nonstationary record of flood frequency (*42*) that may be better explained by paleohydrologic data (fig. 8). The alluvial tributaries in the headwaters became deeply incised during to flooding between A.D. 1909 and 1940 (*12, 42*). Discharges of four historic floods that occurred between A.D. 1909 and 1932, which were reconstructed using paleohydrological techniques (*22*), are five to six times larger than the largest floods recorded in a discontinuous 28-year gaging record from A.D. 1943 to 1955 and 1972 to 1986. Analysis of the four historic floods with the gaging record using the Water Resources Council methods (*35*) resulted in a 100-year flood more than twice the 100-year flood estimated from the gaging record alone (fig. 9A; *22*). Analysis using the gaging record and an increasingly larger length of historic record, on the basis of historic and paleoflood information that indicates a lack of large floods, resulted in a monotonic decrease in the 100-year flood to that estimated using the gaging record alone (*42*).

The paleoflood record for the Escalante River is approximately 2,000 years, and evidence has been found for nine prehistoric and four historic floods (fig. 8; 22). Paleofloods were dated using 12 radiocarbon dates, tree-ring evidence indicating the lack of floods, and historic records (*22*); and discharges were estimated from one site the step-backwater method. The paleoflood information can be interpreted in terms of censoring thresholds, and discharges can be assigned ranges to reflect the imprecision of discharge estimates (fig. 8). Thresholds were established as the discharges required to reach the bases of flood deposits because stratigraphically inset relations in the deposits (see fig. 2) suggest that any floods greater than the bases of the deposits would leave depositional evidence. Discharges for the paleofloods were given ranges according to the uncertainty in the discharge estimates (*22*). Whereas the historic flood record may be nonstationary in the time domain, nonstationarity is reduced in the time and frequency domain of the entire paleoflood record (fig. 8).

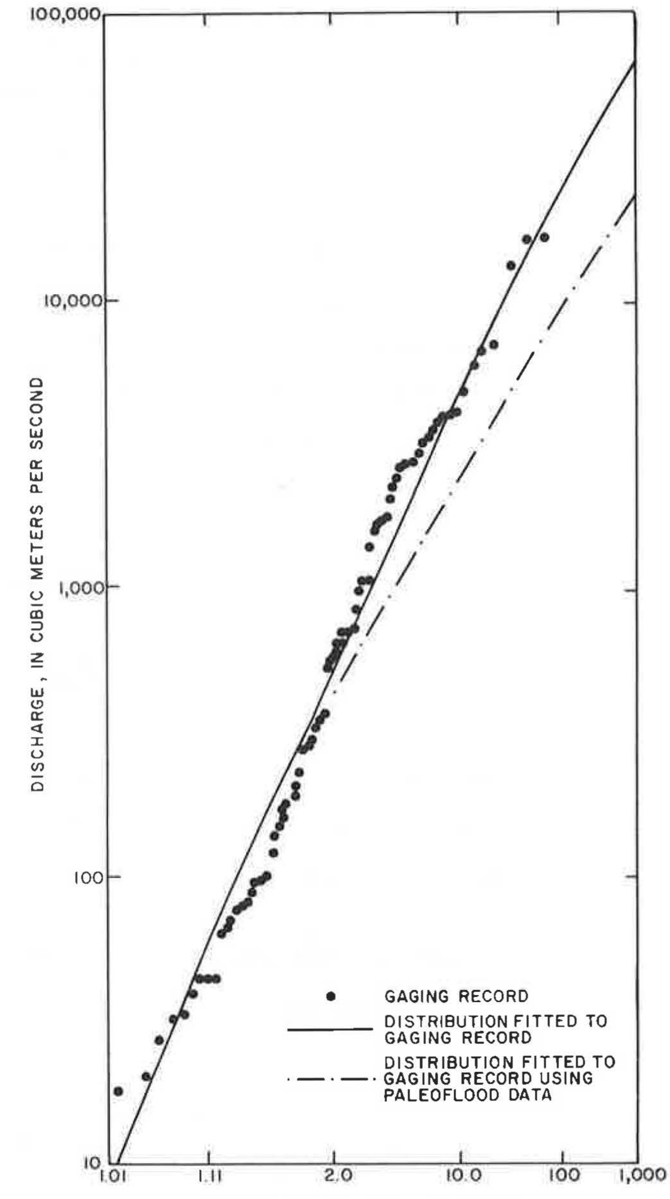


**FIGURE 7 Maximum-likelihood analysis of flood frequency for the Devils River, Texas. Plotting positions for discharges are based on gaging record only.**

Use of the maximum-likelihood fitting resulted in an estimate of the 100-year flood (370 m³/s) that is between the estimates of the 100-year flood from the gaging record alone

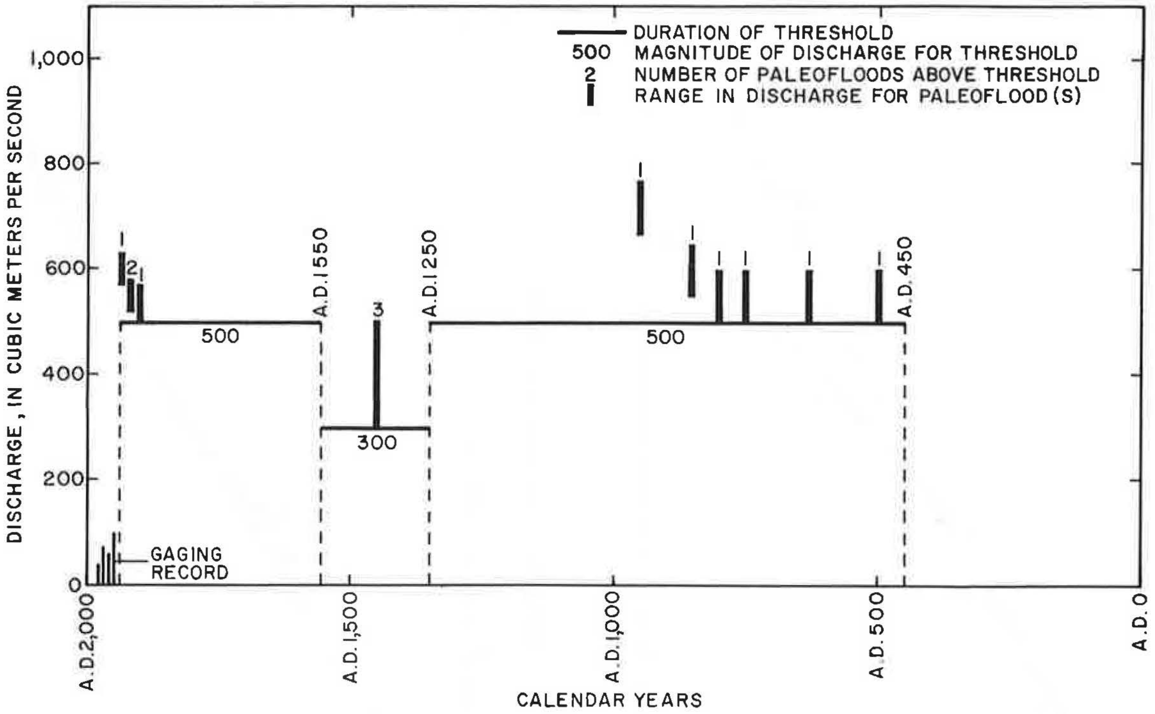


**FIGURE 8 The paleoflood record for the Escalante River, Utah.**

(190 to 330 m³/s) and from the combination of gaging record and historic flood records (480 to 700 m³/s, (*42*)). The skew coefficient estimated from the gaging record, using the Water Resources Council methods, is −0.5 compared with near 0 or positive skew coefficients estimated from the gaging and paleoflood records (table 2). The contrast between the analyses using gaging data alone and gaging data and historic flood data (fig. 9A) is largely a result of the negative skew coefficient estimated from the gaging data alone. Standard errors for the 50- and 100-year floods are 32 and 43 percent, respectively, when the distribution is fitted using the gaging record. Standard errors for the 50- and 100-year floods decrease to 12 percent when the entire paleoflood record is used. Because the lowest censoring threshold is approximately at the 98 percent quantile, the effective record length, extrapolated from 29, may be as much as 1,000 years when the paleoflood information is included.

## DISCUSSION AND CONCLUSIONS

Recent paleoflood hydrologic studies of the southwestern United States use paleostage indicators to reconstruct the dates and discharges for past floods. As the science has evolved, different techniques have been used in the analysis of paleofloods. Early studies used Manning's equation with one cross section, and the water-surface slope was estimated from the present channel slope. The most recent studies have used the step-backwater method with as many as 27 cross sections. The step-backwater method explicitly accounts for nonuniform flow and eliminates the need for assumptions concerning the water-surface slope. Both methods require the assumption of a stable channel, which can usually be demonstrated in bedrock channels.

Methods used in dating paleofloods have not changed as much as methods used in estimating discharges. Radiocarbon dating of organic material entrained in flood deposits is used primarily to estimate the age of paleofloods. Radiocarbon dates are measured with a standard deviation and therefore have an explicit uncertainty. The contemporaneity of floods with the organic material entrained in the flood deposit is the most important source of uncertainty in the dating of paleofloods. Other methods, including dendrochronology, soil development, and correlation of artifacts, also have been used in dating of paleofloods.

Paleohydrologic information, although imprecise, is useful in flood-frequency analyses using maximum-likelihood techniques. As shown in the case study of the Pecos River, imprecise data consisting of large ranges in the possible discharges for floods can still be used in a flood-frequency analysis. Lack of paleofloods, or negative evidence, can also be useful in flood-frequency estimates, as shown in the case study of the Devils River. Finally, the case study of the Escalante River showed that use of paleoflood information may be helpful in flood-frequency analyses of a potentially nonstationary record by increasing the length of record and decreasing the effects of large floods on the shape of the distribution. In all cases, the effective record length of the paleoflood and gaging data would be expected to be several times the length of the gaging record alone.

Use of the maximum-likelihood method gives an appropriate weight to paleohydrologic data in flood-frequency analysis. The discharge of a paleoflood can be expressed as a range instead of a value, which may imply a misleading accuracy. Because maximum-likelihood analysis can use ranges, the uncertainty inherent in paleohydrologic data can be built into flood-frequency analyses. As shown in table 3, use of paleoflood data significantly decreases the standard error of

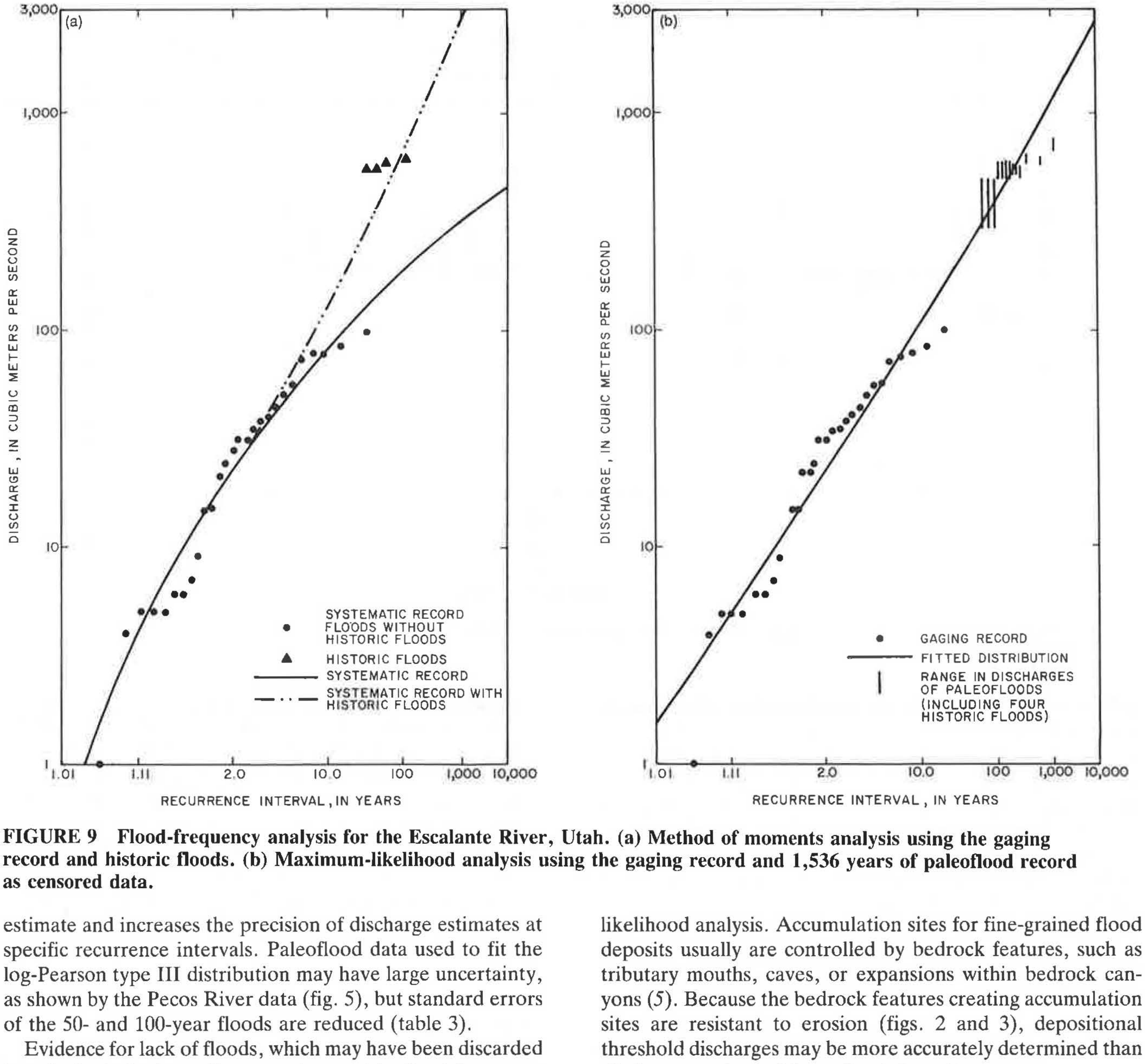


**FIGURE 9 Flood-frequency analysis for the Escalante River, Utah. (a) Method of moments analysis using the gaging record and historic floods. (b) Maximum-likelihood analysis using the gaging record and 1,536 years of paleoflood record as censored data.**

estimate and increases the precision of discharge estimates at specific recurrence intervals. Paleoflood data used to fit the log-Pearson type III distribution may have large uncertainty, as shown by the Pecos River data (fig. 5), but standard errors of the 50- and 100-year floods are reduced (table 3).

Evidence for lack of floods, which may have been discarded in paleohydrologic studies, may be used in flood-frequency analyses and provide useful information. In the case of the Devils River, lack of large floods over 1,267 years of paleoflood record significantly decreased the estimate for the 100-year flood by 80 percent. The decrease is caused by a decrease in the standard deviation (table 2). The fact that floods above a certain threshold did not occur on a river, as indicated by the lack of paleoflood stratigraphy in certain time intervals, can be important in describing the flood history and estimating flood frequency. If flood-frequency estimates are the desired goal of paleoflood hydrologic studies, the data requirements for maximum-likelihood analysis can be used to guide field data collection. Dating of individual floods is not required; the most important age controls on paleofloods are the beginning and ending dates for discharge thresholds or minimum discharge required for the preservation of paleostage indicators. These thresholds are not usually explicitly determined in paleoflood studies, although this information alone is important in determining the censoring levels for maximum-likelihood analysis. Accumulation sites for fine-grained flood deposits usually are controlled by bedrock features, such as tributary mouths, caves, or expansions within bedrock canyons (*5*). Because the bedrock features creating accumulation sites are resistant to erosion (figs. 2 and 3), depositional threshold discharges may be more accurately determined than discharges estimated from flood deposits.

## ACKNOWLEDGMENTS

The authors thank J. R. Stedinger, Cornell University, and T. A. Cohn, U.S. Geological Survey, for providing the use of a computer program for fitting paleoflood data using maximum-likelihood methods. The authors greatly benefited from stimulating discussions of flood-frequency analysis with Stedinger and Cohn. V. R. Baker, University of Arizona, gave advice and help that was greatly appreciated. The authors also thank V. R. Baker, B. M. Reich, J. R. Stedinger, and E. Wohl for reviewing the manuscript.

## REFERENCES

1. G. P. Williams. *Paleohydrologic equations for rivers. Developments and applications of geomorphology*. J. E. Costa and P. J.

Fleisher, eds., Springer-Verlag Publishing, Berlin, Germany, pp. 343–367. 1984.

2. V. R. Baker and M. M. Penteado-Orellana. Adjustment to Quaternary climatic change by the Colorado River in central Texas. *Journal of Geology*, v. 85, pp. 395–422. 1977.
3. G. H. Dury. *Theoretical implications of underfit streams*. U.S. Geological Survey Professional Paper 452-C, 43 pp., 1965.
4. S. A. Schumm. *River adjustment to altered hydrologic regimen–Murrumbidgee River and paleochannels, Australia*. U.S. Geological Survey Professional Paper 598, 65 pp., 1968.
5. R. C. Kochel and V. R. Baker. Paleoflood hydrology. *Science*, v. 215, pp. 353–361, 1982.
6. V. R. Baker. Paleoflood hydrology and extraordinary flood events. *Journal of Hydrology*, in press.
7. V. R. Baker, R. C. Kochel, P. C. Patton, and G. Pickup. Palaeohydrologic analysis of Holocene flood slack-water sediments. *Special Publications of the International Association of Sedimentologists*, v. 6, pp. 229–239, 1983.
8. J. E. Costa. Holocene stratigraphy in flood frequency analysis. *Water Resources Research*, v. 14, no. 44, pp. 626–632, 1978.
9. J. E. Costa. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. *Geological Society of America Bulletin*, v. 94, pp. 986–1004, 1983.
10. J. E. Costa. A history of paleoflood hydrology in the United States, 1800–1970. *EOS*, v. 67, no. 17, pp. 425, 428–430, 1986.
11. M. G. Wolman. The natural channel of Brandywine Creek, Pennsylvania. *U.S. Geological Survey Professional Paper 271*, 56 pp., 1955.
12. R. H. Webb. Late Holocene flooding on the Escalante River, south-central Utah. Ph.D. dissertation, University of Arizona, Tucson, 204 pp., 1985.
13. J. B. Partridge and V. R. Baker. Palaeoflood hydrology of the Salt River, Arizona. *Earth Surface Processes and Landforms*, v. 12, pp. 109–125, 1987.
14. R. C. Kochel. Interpretation of flood paleohydrology using slack-water deposits, lower Pecos and Devils Rivers, southwestern Texas. Ph.D dissertation, University of Texas, Austin, 364 pp., 1980.
15. P. C. Patton and D. S. Dibble. Archeologic and geomorphic evidence for the paleohydrologic record of the Pecos River in west Texas. *American Journal of Science*, v. 282, pp. 97–121, 1982.
16. R. C. Kochel, V. R. Baker, and P. C. Patton. Paleohydrology of Southwestern Texas. *Water Resources Research*, v. 18, no. 4, pp. 1165–1183, 1982.
17. L. L. Ely and V. R. Baker. Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona. *Physical Geography*, v. 6, no. 2, pp. 103–126, 1985.
18. J. E. Fuller. Paleoflood hydrology of the alluvial Salt River, Tempe, Arizona. M.S. thesis, University of Arizona, Tucson, 70 pp., 1987.
19. J. E. O'Connor, J. E. Fuller, and V. R. Baker. *Late Holocene flooding within the Salt River basin, central Arizona*. University of Arizona, Tucson, Department of Geosciences paper, 84 pp., 1986.
20. L. K. Roberts. Paleohydrologic reconstruction, hydraulics, and frequency-magnitude relationships of large flood events along Aravaipa Creek, Arizona. M.S. thesis, University of Arizona, Tucson, 63 pp., 1987.
21. J. E. O'Connor, R. H. Webb, and V. R. Baker. Paleohydrology of pool-and-riffle pattern development: Boulder Creek, Utah. *Geological Society of America Bulletin*, v. 97, pp. 410–420, 1986.
22. R. H. Webb, J. E. O'Connor, and V. R. Baker. Paleohydrologic reconstruction of flood frequency on the Escalante River, south-central Utah. *Flood Geomorphology*. V. R. Baker, R. C. Kochel, and P. C. Patton, eds., John Wiley and Sons, New York, 1988.
23. V. R. Baker, G. Pickup, and R. H. Webb. Paleoflood hydrologic analysis at ungaged sites, central and northern Australia. *Regional Flood Frequency Analysis*. Singh, V. P., ed., D. Reidel Publishing Company, Boston, pp. 321–334, 1987.
24. V. R. Baker, G. Pickup, and H. A. Polach. Radiocarbon dating of flood events, Katherine Gorge, Northern Territory, Australia. *Geology*, v. 13, pp. 344–347, 1985.
25. V. R. Baker and G. Pickup. Flood geomorphology of the Katherine Gorge, Northern Territory, Australia. *Geological Society of America Bulletin*, v. 98, pp. 635–646, 1987.
26. T. A. Cohn. The incorporation of historical information in flood frequency analysis. M.S. thesis, Cornell University, Ithaca, New York, 79 pp., 1984.
27. T. A. Cohn. Flood frequency analysis with historical flood information. Ph.D. dissertation, Cornell University, Ithaca, New York, 144 pp., 1986.
28. J. R. Stedinger and T. A. Cohn. Flood frequency analysis with historical and paleoflood information. *Water Resources Research*, v. 22, no. 5, pp. 785–793, 1986.
29. J. R. Stedinger and T. A. Cohn. Historical flood frequency data: Its value and use. *Regional Flood Frequency Analysis*. V. P. Singh, ed., D. Reidel Publishing Company, Dordrecht, Boston, pp. 273–286, 1987.
30. J. R. Stedinger and V. R. Baker. Surface water hydrology: Historical and paleoflood information. *Reviews of Geophysics*, v. 25, no. 2, pp. 119–124, 1987.
31. S. Clark. Potential for use of cottonwoods in dendrogeomorphology and paleohydrology. M.S. Thesis, University of Arizona, Tucson, 52 pp., 1987.
32. J. Davidian. Computation of water-surface profiles in open channels. *U.S. Geological Survey Techniques in Water-Resources Investigations*, Book 3, Chapter A14, 48 pp., 1984.
33. J. E. O'Connor and R. H. Webb. Hydraulic modeling for paleoflood analysis. *Flood geomorphology*. V. R. Baker, R. C. Kochel, and P. C. Patton, eds., John Wiley and Sons, New York, 1988.
34. W. L. Graf. Late Holocene sediment storage in canyons of the Colorado Plateau. *Geological Society of America Bulletin*, v. 99, pp. 261–271, 1987.
35. Water Resources Council. *Guidelines for determining flood flow frequency*. U.S. Water Resources Council, Washington, Bulletin 17B, 28 pp., 1981.
36. W. O. Thomas, Jr. A uniform technique for flood-frequency analysis. *Journal of Water Resources Planning and Management*, v. 111, pp. 321–337, 1985.
37. J. R. Wallis and E. F. Wood. Relative accuracy of log-Pearson III procedures. *Journal of Hydraulic Engineering*, v. 111, pp. 1043–1056, 1985.
38. R. M. Hirsch and J. R. Stedinger. Plotting positions for historical floods and their precision. *Water Resources Research*, v. 23, no. 4, pp. 715– 727, 1987.
39. J. R. Stedinger, R. Therivel, and V. R. Baker. *Flood frequency analysis with historical and paleoflood information*. Phoenix, Arizona, U.S. Committee on Large Dams, Eighth Annual Lecture Series Notes, Salt River Project, in press.
40. W. L. Lane. Paleohydrologic data and flood frequency estimation. *Regional Flood Frequency Analysis*. Singh, V. P., ed., D. Reidel Publishing Company, Boston, pp. 281–295, 1987.
41. J. R. Stedinger. Confidence intervals for design events. *American Society of Civil Engineers, Journal of Hydraulic Engineering*, v. 109, pp. 13–27, 1983.
42. R. H. Webb and V. R. Baker. Changes in hydrologic conditions related to large floods on the Escalante River, south-central Utah. *Regional Flood Frequency Analysis*. Singh, V. P., ed., D. Reidel Publishing Company, Boston, pp. 306–320, 1987.