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14. ABSTRACT
Paleohydrology is the study of the evidence of the movement of water and sediment in stream channels before the time of hydrologic recorders, direct measurements, or historical observation. The usefulness of paleoflood data for risk analysis of U.S. Army corps of Engineers (Corps) projects is being investigated. This usefulness will depend on the accuracy and uncertainty of paleoflood estimates and their viability for integration into flood frequency analyses along with gaged data. This report will begin with a synopsis of past Corps policies, and the potential applications of paleohydrology to Corps projects. It will then present a review of different paleo field methods, and the applicability of these methods in different regions of the United States.

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Preface

Many parameters used in flood hydrology are, to various degrees, imprecise or inaccurate and thus induce uncertainty in key variables and decision-making parameters. The Corps has mandated that risk analysis is fundamental to Corps water resources investigations. To that end, the Corps has launched a research and development program to formulate an acceptable risk framework for prioritizing dam safety repair and rehabilitation work. Paleohydrology is a new source of data that may reduce uncertainty when used in the extension of historical records and the estimation of the frequency and magnitude of extreme flood events. This report is a product of the Corps' Dam Safety R&D program.

The genesis of this report is the result of feedback from attendees at the Second International Paleoflood Conference held by the American Geophysical Union in Prescott, Arizona in 1999. The primary author of this report is Jon Fenske of the U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC). Robert Jarrett of the U.S. Geological Survey provided technical recommendations and many key publications referenced in this report. Dean Ostenaa of the Bureau of Reclamation also provided many key publications referenced in this report. Arlen Feldman of HEC provided technical recommendations and in-depth peer review.

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Application of Paleohydrology to Corps Projects

I. Introduction

Paleohydrology can be defined as the study of the evidence of the movement of water and sediment in stream channels before the time of hydrologic recorders, direct measurements, or historical observation. The value of paleohydrology is that it is a potential source of long-term data that can be used in the extension of historical records and the estimation of the frequency and magnitude of extreme flood events. For example, geologic evidence of past flood events may be expressed as backwater sediment deposits in a stream tributary. The age of the deposits can be estimated using carbon-dating methods. The flow magnitude represented by the elevation of the deposits can be estimated using hydraulic modeling. This information on the age and magnitude of extreme flood events is then incorporated in flood frequency analysis. Paleohydrology is useful in estimating frequency curves, especially beyond the intermediate range of observed data i.e. 100-500 years. This additional source of information could be important to flood damage calculations, floodplain management, and dam safety evaluations.

There is substantial uncertainty and controversy in estimating magnitudes and frequencies of extreme floods larger than modern observations. Because of the unknown flood potential inherent in using relatively short traditional historical observations, and the potential catastrophic effects of dam failure, large-dam owners adopted the Probable Maximum Flood (PMF) concept. The PMF is the "flood that may be expected from the most severe combination of meteorologic and hydrologic conditions that are reasonably possible in a region" (U.S. Army Corps of Engineers, 1994). Paleohydrologic estimates of the maximum flood in a watershed are usually far less than PMF values calculated using classical hydrologic analysis methods. Several recent paleoflood studies, primarily conducted by the U.S. Geological Survey and the Bureau of Reclamation, demonstrated large differences between the maximum paleoflood estimates and the design PMF for various watersheds. Jarrett (1998) estimated the maximum flood, using paleohydrologic methods, in the past 10,000 years for Elkhead Creek is about 13% of the PMF estimate. Studies conducted by Jarrett and Costa (1988), Grimm (1993), Levish et al. (1994) and Ostenaa and Levish (1995) noted that the maximum estimated peak paleoflood flows averaged about 7% of the PMF. On the other hand, at least four floods larger than 70% of the PMF have been observed in the United States in the last 40 years (Bullard, 1986).

The usefulness of paleoflood data for risk analysis of U.S. Army Corps of Engineers (Corps) projects is being investigated. This usefulness will depend on the accuracy and uncertainty of paleoflood estimates and their viability for integration into flood frequency analyses along with gaged data. This report will begin with a synopsis of past Corps policies, and the potential applications of paleohydrology to Corps projects. It will then present a review of different paleo field methods, and the applicability of these methods in different regions of the United States.

II. Overview of Corps Project Analysis Methods

The Corps owns and operates 569 dams (Foster, 1999), the majority of which are in the central and eastern United States. Additionally, the Corps oversees about 8,500 miles of levees. As a dam builder, owner, and operator, a primary mission of the Corps is to assure that the dams are maintained and operated in a manner that minimizes public risk while protecting large federal infrastructure investments. About 28 percent of Corps dams have exceeded their projected 100-year economic design life (Foster, 1999). The Corps has launched a research and development program to formulate an acceptable risk framework for prioritizing dam safety repair and rehabilitation work (Foster, 1999).

A. Project Economic Evaluation

Many parameters used in flood hydrology are, to various degrees, imprecise or inaccurate and thus induce uncertainty in key variables and decision-making parameters. Risk is defined as the likelihood of the occurrence and the magnitude of the consequences of an adverse event. Uncertainty can be thought of as the "indefiniteness of some aspect of some values in the risk quantification process" (Moser, 1997). Thus, risk analysis is a method for performing studies in which uncertainties in technical data are explicitly taken into account. Quantitative risk analysis describes the uncertainties, and permits evaluation of their impact (U.S. Army Corps of Engineers, 1996). The objective of risk analysis is to maximize net economic benefits consistent with acceptable risk and functional performance.

Until recently, traditional Corps planning studies did not consider risk and uncertainty explicitly in plan formulation and evaluation (U.S. Army Corps of Engineers, 1996). Instead, risk and uncertainty was accounted for implicitly with arbitrarily selected factors of safety. "The Corps of Engineers have come to realize that this purely engineering approach to risk management is too simplistic and incomplete" (Moser, 1997). Currently, uncertainty in flood frequency is incorporated into plan formulation studies. Planning flood damage reduction projects requires information on discharge/frequency, stage/discharge, and stage/damage relationships at locations in a watershed where protection is to be provided. Such information is obtained from analysis of measured data, or is estimated by various statistical procedures and numerical modeling techniques. Figure 1 illustrates how damage-frequency relationships are computed considering risk and uncertainty (U.S. Army Corps of Engineers, 1996).

B. Dam Safety Analysis

The Probable Maximum Flood (PMF) is the current standard for the hydrologic design of large dams, especially for sizing spillways. The purpose of the PMF is to provide a design criterion to meet the engineering goal of no hydrologic-loading failures. The PMF does not incorporate a specific exceedance probability, but is generally thought to be well beyond the 10,000 year recurrence interval. The PMF is traditionally derived from runoff analysis of a Probable Maximum Precipitation (PMP) event. The PMP is "theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a geographical location at a certain time of year" (U.S. National Weather Service, 1982).

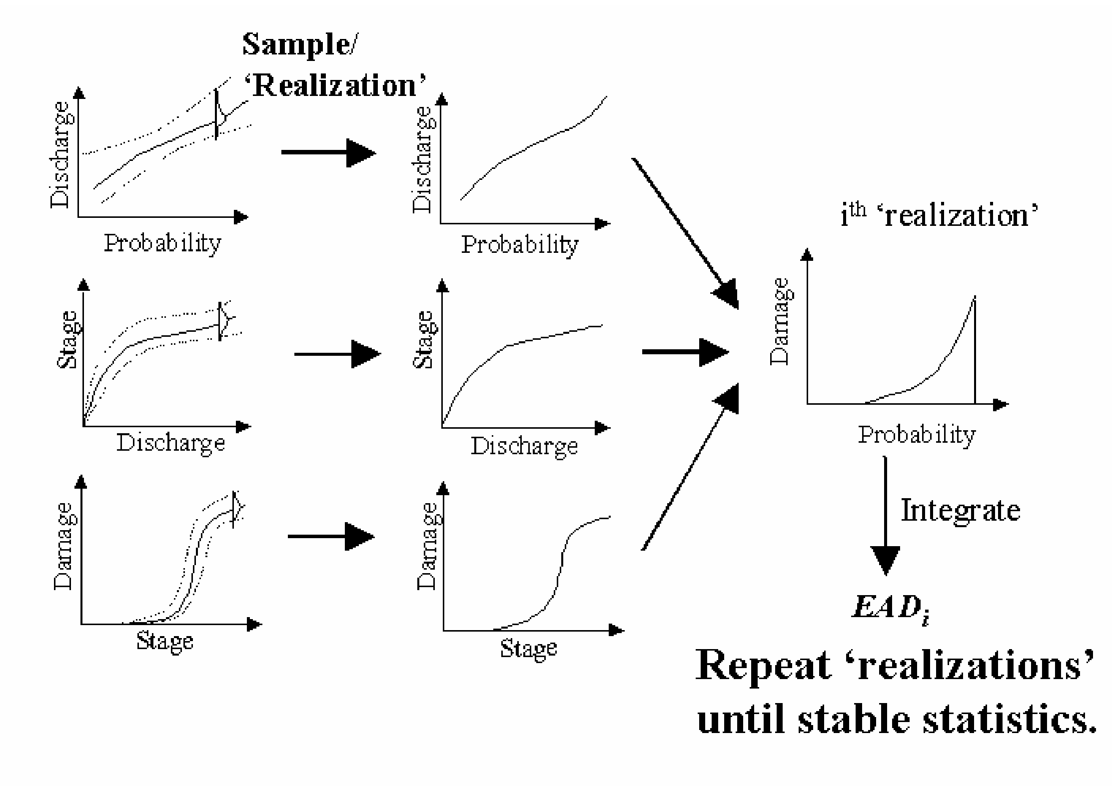

Figure 1 Calculation of Expected Annual Damage (EAD) considering risk and uncertainty (adopted from USACE, 1995).

III. Traditional Methods for Estimating Large Floods

Major floods and droughts have great environmental and economic impacts. In the United States, floods cause an annual average of 125 deaths and annual estimated damages of $2.4 billion (Federal Emergency Management Agency, 1997). This underscores the need for better understanding of hydrometeorologic processes, and related fluctuations in frequency and variability. Estimates of the magnitude of extreme floods are made by extrapolation from a flood-frequency curve to a given return period, or by hypothetically maximizing precipitation-runoff events.

Figure 2 presents the applicability of various methods in estimating the flow exceedance probabilities for a typical watershed. Streamflow statistics and hydrologic modeling are typically applicable up to the 0.5% (200 year) exceedance probability event. Data from paleofloods can potentially be applicable up to the 0.033% (3,000 year) exceedance probability event. Risk uncertainty is included in Figure 2 as the event conditional distribution. Event conditional distribution depicts the uncertainty of the flood magnitude at the specified recurrence interval.

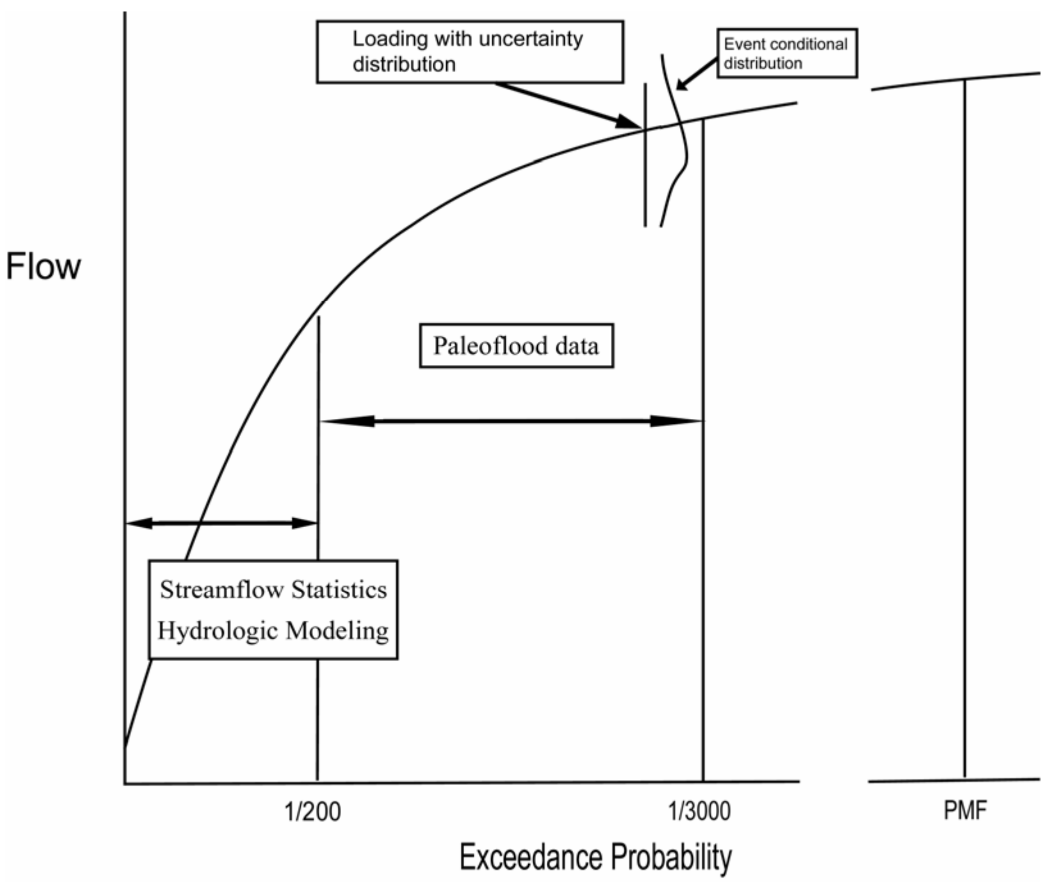

Figure 2 Applicability of flow frequency estimating methods (adopted from Nathan, 2001).

Three general methods for estimating the magnitude and frequency of extreme floods are: statistical analysis of stream-gage data; hydrologic modeling of historical and hypothetical storm events; and the regional extension of hydrologic characteristics through the use of envelope curves.

A. Statistical Analysis of Streamflow Data

Measured data, such as from streamflow gages, have been collected for as much as 100 years. Also, historic data, observations of episodic flood events and droughts before measured data were collected are available in the U.S. (Thomas, 1987). In Egypt and China, historic records are available for several thousands of years (Baker, 1987). Estimates of the frequency of occurrence and magnitude of major flood events are made through the statistical analysis of available data. These analyses yield flood probabilities with reasonable uncertainties for return periods about the length of the historic record (Figure 2).

B. Hydrologic Modeling

Computer models, such as the Hydrologic Engineering Center's Hydrologic Modeling System (U.S. Army Corps of Engineers, 2001a), can be used to simulate rainfall-runoff processes for a watershed. Synthetic storm events are typically used in a hydrologic model to estimate flow frequencies and design floods. Three general approaches are available for developing synthetic storms for use in hydrologic models: National Weather Service (NWS) storms for up to a 0.2 % (500 year) exceedance probability interval; NWS Probable Maximum Precipitation (PMP) storm events; and stochastic analysis of the precipitation history of a given region.

1. National Weather Service Specified Frequency Storms

The NWS analyzes historical storm statistics and provides storm magnitude and frequency information up to a 0.2 % (500 year) exceedance probability interval (U.S. Department of Commerce (now the National Weather Service), 1963). Hydrologic modeling is used to estimate the flood magnitudes that result from the frequency-based storm. Their assumption is that the frequency of the flood event is equal to the frequency of the storm event. The critical parameter in this method is the initial soil moisture conditions used in the hydrologic model.

2. Probable Maximum Precipitation

Estimates of the Probable Maximum Precipitation for a watershed are provided by the NWS (U.S. National Weather Service, 1982). The PMP is input into the hydrologic model to estimate the PMF of a watershed. The most severe hydrologic conditions, such as wet initial soil moisture, are usually assumed to compute the PMF.

3. Stochastic Analysis

Stochastic analysis of flood frequency involves a probabilistic approach to estimating frequency distributions of the many precipitation-runoff variables. A stochastic event-based rainfall-runoff model treats inputs as random variables instead of fixed values. Monte Carlo sampling procedures are used to allow the hydrometeorological input parameters to vary in accordance with that observed in nature while preserving the natural dependencies that exist between some climatic and hydrologic parameters.

A stochastic event-based model has the capability to simulate a wide range of hydrometeorological and watershed conditions. For example, for estimating the recurrence interval of large storms, the stochastic analysis would assume a distribution for all components and statistically sample storm size, storm area, storm location, and storm duration. A Monte Carlo analysis would be performed to estimate storm magnitudes and durations over a range of frequencies. The credible extrapolation of the Annual Exceedance Probability (AEP) is dependent on the nature of the available data. The maximum frequency storm that should be estimated is approximately equal to the square of the number of years of record, i.e. n^2 = maximum return interval (U.S. Army Corps of Engineers, 2001b). For example, a record of 100 years, will allow for an estimate up to a 0.01% (10,000 year) exceedance probability interval.

C. Regional Envelop Curves

In watersheds where gaging station records do not exist, regional extension of hydrologic and meteorologic properties can be used to estimate extreme floods. A regional analysis of streamflow attempts to extend existing records in space, and transfer streamflow characteristics recorded at gaging stations to ungaged sites (Riggs et al., 1980). Maximum runoff versus drainage area curves can be developed for a homogeneous hydrometeorologic region. Utilization of regional envelope curves assumes that the maximum flood rate in a basin is likely to be experienced in a nearby basin. Not all basins in a region are expected to have the maximum flood, but no basin is expected to have a flood that exceeds the envelope curve for a specific region.

D. Limitations of Traditional Methods

Conventional estimates of the frequency of large floods are derived from the extrapolation from short periods of record, sometimes with the addition of historical information. Gaged records often do not include large magnitude, low-frequency floods. Accurate flood-frequency relations including large floods are needed for both floodplain management and for the design of structures such as dams. Sensitivity analyses show that the addition of only one or two large paleofloods that span a range of hundreds to thousands of years can have a significant impact on the shape of the flood frequency curve (Ostenaa et al., 1996). In other words, paleohydrologic techniques offer a way to estimate historic floods at gage sites, thereby increasing the length of record and reducing the uncertainty in hydrologic analysis. Thus, paleohydrologic analysis may provide helpful flow frequency information for both relatively small floods (left side of Figure 2) and very large floods (right side of Figure 2).

For hydrologic dam safety, the critical issue is not the accurate estimation of a complete record of floods within the operating range of the structure, but rather the magnitude and frequency of floods that could challenge the operational capacity of the structure. Evidence of large magnitude, low-frequency floods can be provided by analysis of paleoflood data in many watersheds. Floods near the magnitude of the maximum paleoflood may be direct indicators of the likelihood of large floods that might compromise dam safety.

IV. Paleoflood Indicators of Large Floods

There are two general methods for estimating ancient flow histories of rivers. One method is to examine the effects of moving water on local geomorphology. A second method is to examine the potential effects of past flood events on the adjacent biosphere. Figure 3 presents some common indicators of past flood events. Geomorphic indicators include slackwater deposits, bars and terraces, and erosional scars. Biosphere indicators include tree ring analysis, tree scarring, and debris deposition.

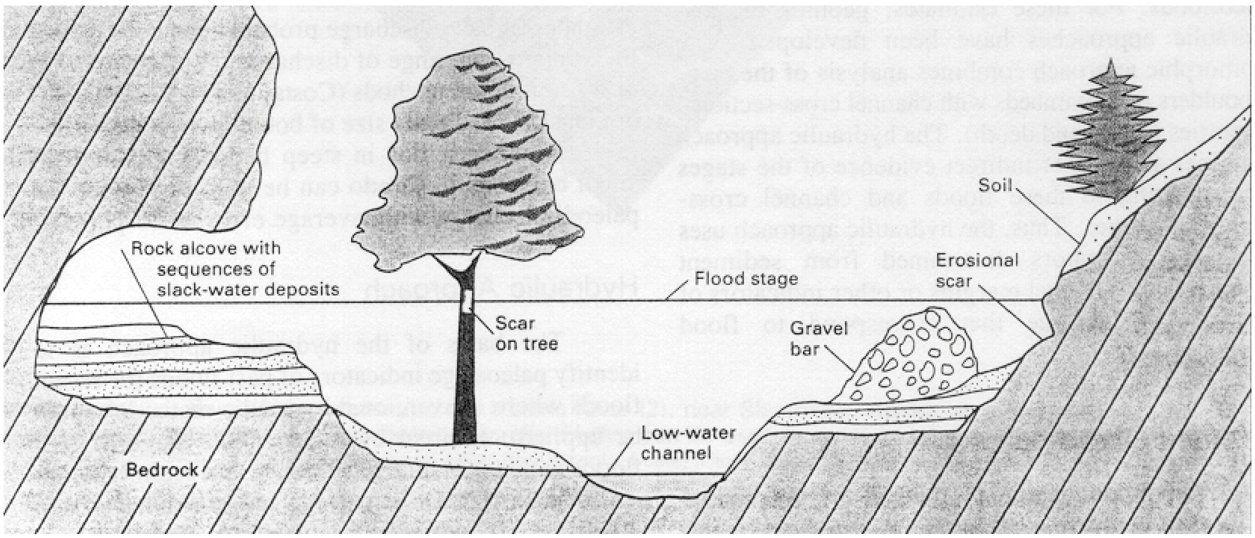

Figure 3 Cross section along a stream channel showing a peak flood stage and various paleostage features. (from Jarret et al., 2002)

A. Geomorphology

The age of stable geomorphic surfaces adjacent to streams and rivers is a direct indication of the potential risk of flooding in unregulated or unmodified channel systems (Costa, 1978). Three general geomorphic indicators are used to characterize discrete flood events from the past: 1) slackwater deposits, 2) erosion of tributary fans and terraces, and 3) estimates of flow strength (velocity, power) derived from studies of flood-transported gravels and boulders.

1. Slackwater Deposits

When flows are large enough, streambed and bank materials are mobilized and transported. This erosion is a function of stream power, specifically channel gradient and flow velocity. As gradient increases, smaller velocities and depths are required to move sediment on the bed of a stream. In locations where stream velocity, depth, and slope decrease, flowing water will begin to deposit previously eroded sediments.

Slackwater deposits are relatively fine-grained (usually fine sand and coarse silt) flood sediments deposited in floodplain areas that are sheltered from subsequent high velocity flood flows. Thus, slackwater deposits accumulate in floodplain regions where velocities are minimal during the time that inundation occurs. Slackwater sediments are rapidly deposited from suspension in sediment-laden waters at localities where the flow becomes separated from the main thread of flood flow. Four major geomorphic situations that provide favorable conditions for the deposition and continued accumulation of slackwater sediment sequences are: 1) mouths of tributaries; 2) shallow caves along the bedrock channel walls; 3) areas downstream from major bedrock and/or talus obstructions and areas of dramatic channel widening; and 4) areas of overbank accumulation on high terraces (Kochel and Baker, 1988).

Successful paleoflood reconstruction over long periods of time depends on the presence of continuous stratigraphic sequences of slackwater sediments. Long stratigraphic sequences occur where abundant slackwater sedimentation occurs during major floods, and where the sedimentation site is shielded from the erosive portions of subsequent tributary and mainstream flows. Discrimination of individual events in slackwater sequences can be based on radiocarbon dating, abrupt vertical changes in grain size, reversals of mean grain size trends, color changes, and colluvial horizons (Kochel and Baker, 1988). Figure 4 presents a cross section of a typical stratigraphic sequence.

The slackwater sediment approach is becoming widely used and, for the appropriate settings, may provide the most abundant and accurate source of data for determining the recent geologic history of multiple large flood events in a river basin. Slackwater sedimentation occurs in virtually all river systems, but is most pronounced in narrow, deep, entrenched bedrock canyons.

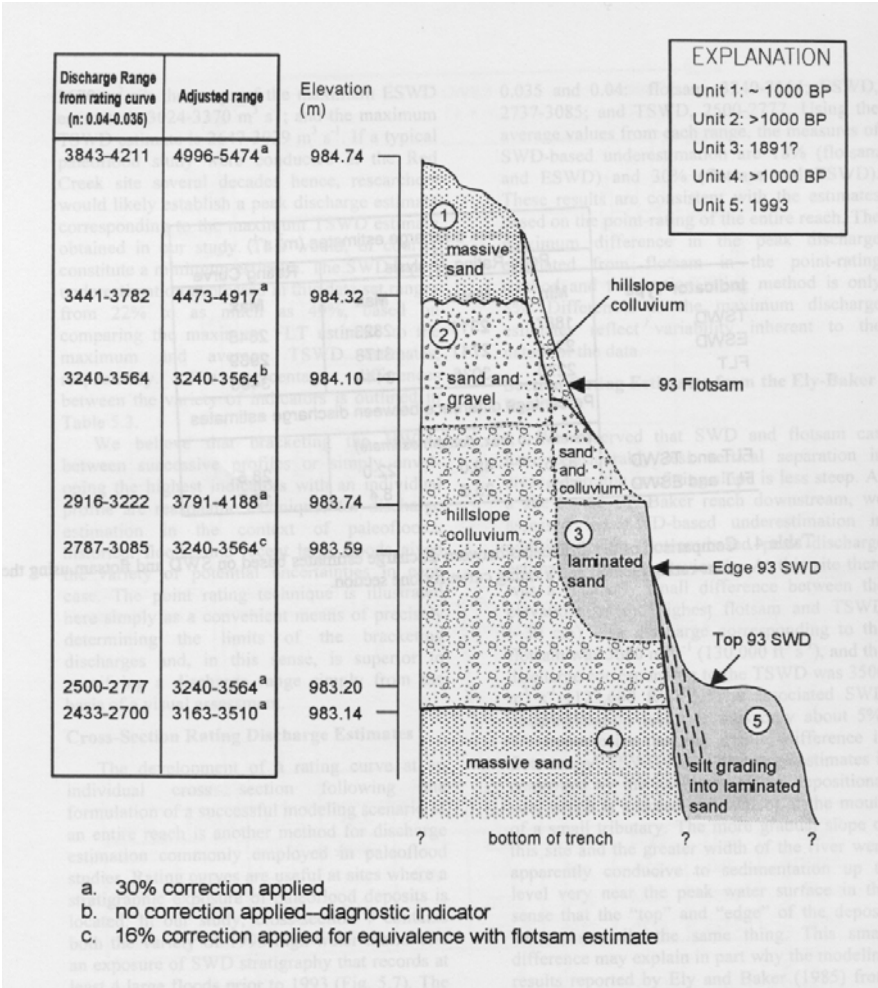

Figure 5. Stratigraphic section and peak discharge estimates using a rating curve developed for section 7 of the Red Creek study reach. Discharge estimates in the left column are obtained directly from stage of the deposit and the associated discharge. Adjusted discharge estimates account for the underestimation of peak stage associated with slackwater deposits in this reach. No correction is applied to the 1993 flotsam-based discharge estimate.

Figure 4   Cross-sectional stratigraphy of slackwater deposits. (from House, 1996)

2. Erosion of Fans and Terraces

Stream terraces are surfaces located adjacent to many streams which are underlain by stream-transported floodplain sediment. These surfaces are easily modified by flood inflows, and are thus reliable recorders of maximum flood stage through time. If ages can be determined for flood modified surfaces, the surfaces become conservative datums for the magnitudes of large floods. Likewise, the absence of features indicative of significant inundation is positive evidenceof nonexceedance of a specific limiting flood stage over the time spanned by the surface. Figure 5 presents a stream cross section which contains a terraced surface. Note that geologic features above the top of the terrace surface are described as positive evidence of long-term landscape stability.

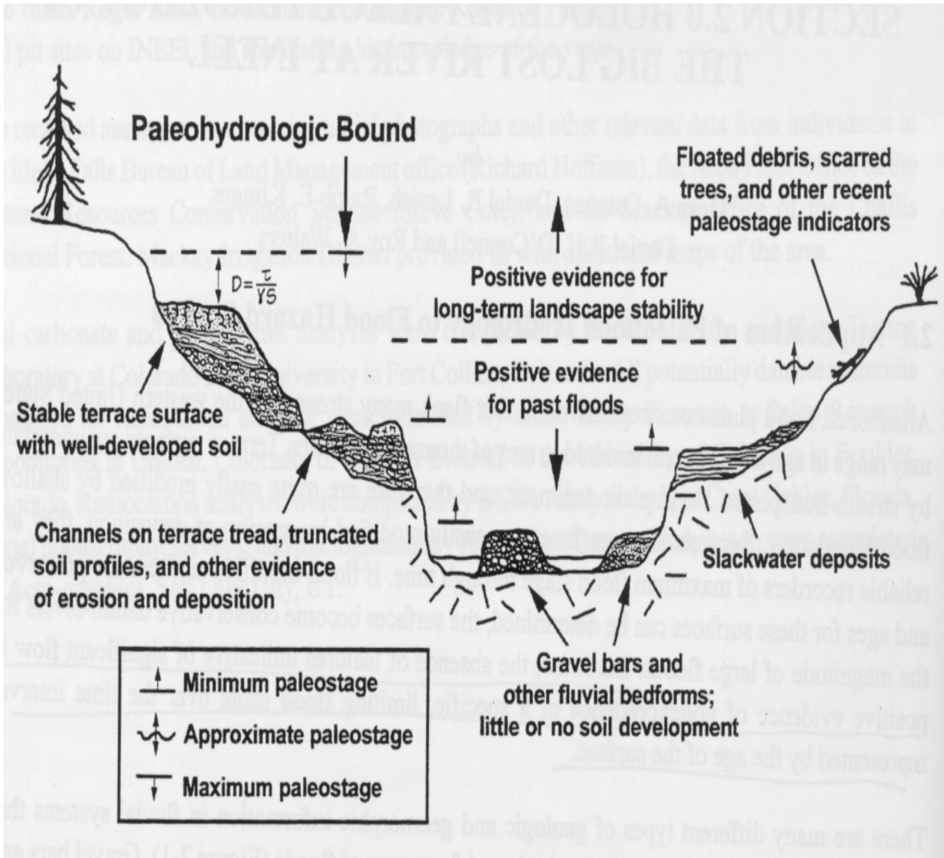

Figure 5 Stream cross-section containing slackwater deposits and terrace surface. (from Ostenaa et al., 1999)

<u>B. Analysis of Tree Rings</u>

The growth of trees produces an annual increment of tree rings. The width of tree rings is a function of temperature, light, moisture variations, and age of the tree. Trees typically grow for tens to several hundreds of years, and in some trees, for thousands of years (Jarrett, 1991). Tree-ring chronologies primarily provide a basis for evaluating long-term climatic changes. In drought-sensitive trees, the annual growth of rings is decreased during periods of water stress (or shortage) and increased during periods of water abundance. Tree ring width tends to decrease with increasing age of the tree, but tree ring width data can be adjusted to account for this. In areas adjacent to streams, tree rings have been used to estimate annual discharges and water-level changes (Stockton and Boggess, 1983). Additionally, Costa (1978) indicated that the age of trees growing on flood-deposited sediment or in flood scoured areas can be used to provide a minimum estimate of the years before present of the most recent flood event.

A common indicator of a flood event is the formation of scars from impact of floating debris. As depicted by Figure 6, analysis of scar location on tree rings can determine the year of flooding. Scars form along the upstream radius. The stage of a flood event can be estimated through the analysis of multiple cross-sections at specified tree height increments.

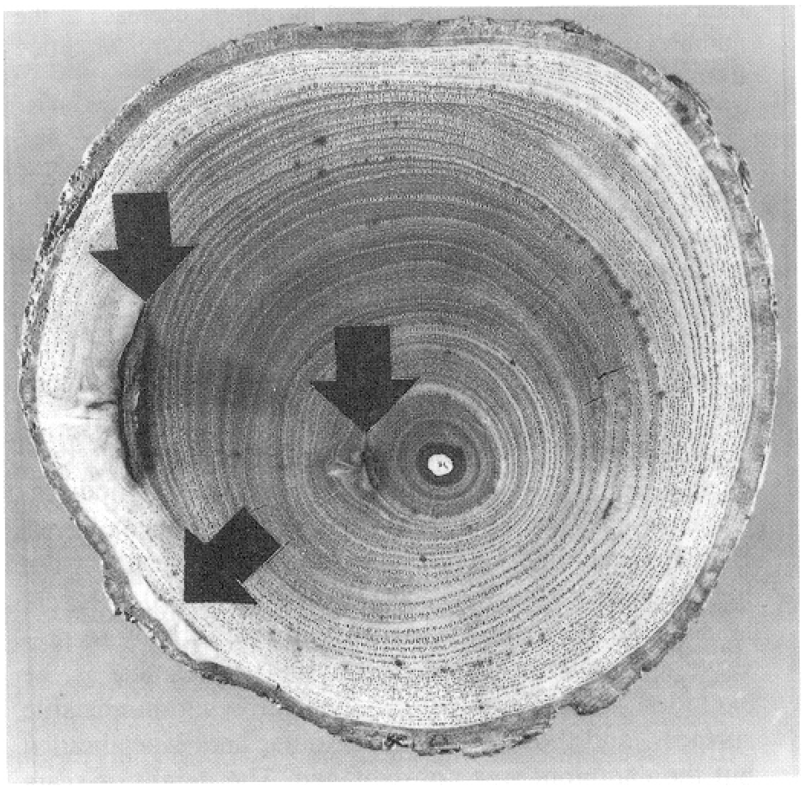

Figure 6 Impact scars healed by new growth. Three scars (arrows) are formed along the upstream-facing radius. (from Yanosky and Jarret, 2002)

V. Estimating Stage, Discharge, and Age of Paleofloods

A. Estimating Stage

1. Estimation of High Stage

As depicted by Figure 5, the upper terrace surface is not identical to the stream stage required to erode that surface. One source of uncertainty in paleoflood reconstructions is actual flood height inferred from the paleostage indicators (such as slackwater deposits and terraces). Scour lines and silt lines generally indicate high-water levels, but other commonly used paleostage indicators, such as slackwater sediments and debris accumulations, only represent minimum paleoflood stages. During a flood, slack-water deposits will generally accumulate to a level somewhat below the level of the maximum flood stage in slack-water areas. Comparison of the height of these deposits with the maximum documented heights of flood stages in the southwest portion of the Pecos River valley in Texas indicated that the height of the top sediments was lower by 10 to 20 percent than was the maximum height of the corresponding flood stage (Kochel and Baker, 1982). Jarret et al. (1999) performed studies of large floods on 95 streams primarily in the western United States. The tops of flood-deposited sediments were reliable paleostage indicators, typically within 0.06 m of adjacent high water marks, which were evidenced by fine, woody debris, leaves, grass, needles, and mud lines.

In general, an individual slackwater deposit elevation represents a minimal peak stage marker, resulting in a lower estimate of paleoflood discharge. Estimations of peak flood stage relative to the elevation of peak slackwater deposits are possible using several techniques. First, if there have been any historically large floods along the river where high-water marks can be documented by debris lines or by local residents, corrections can be made that are locally applicable for interpreting the difference between water stage and maximum slackwater sediment elevation. Another method to estimate paleoflood stage from slackwater sediments can be obtained by tracing flood units up tributaries to determine the elevation at which they pinch out. Finally, it may be possible to correlate slackwater deposits to preserved high-water mark indicators, such as silt lines and erosional trim lines in valley side soils.

2. Paleohydrologic Bounds

A paleohydrologic bound is a "time interval during which a given discharge has not been exceeded" (Ostenaa et al., 1997a). These bounds represent stages and discharges that have not been exceeded since the geomorphic surface of terraces have stabilized. The field expressions of paleohydrologic bounds are stable geomorphic surfaces at the extent of the ancient floodplain. These former floodplain surfaces are reliable indicators of flood stage through time. The depth of flow associated with a paleohydrologic bound, i.e. the depth of flood waters above the terrace, is one that is sufficient to cause modification of the geomorphic surface that is overtopped. The minimum overtopping depth required for initiation of large-scale erosion and deposition on the geomorphic surfaces can be evaluated formally in terms of a shear stress criterion or stream power (Baker and Costa, 1987) and directly compared to empirical data from historical flows. The depth of overtopping provides a limit for the maximum paleostage that might have occurred without leaving a recognizable geomorphic and stratigraphic limit (Ostenaa et al., 1997). This maximum paleostage, together with other geologic limits on channel geometry, provides the necessary input for hydraulic modeling to estimate maximum discharge for the paleohydrologic bound.

B. Estimating Discharge

1. Estimating Discharge as a Function of High Stage

A key element in paleoflood studies is the transformation of estimated stage information into discharge estimates. River hydraulics energy and momentum equations, e.g. Manning's equation, provide the means for estimating streamflow of flood events as a function of stage, slope, bed material, and cross section. Individual location floods may be estimated by the slope-area method (Mosley and McKerchar, 1993) or entire rivers may be simulated by computer models.

The most important requirement for accurate hydraulic modeling is an acceptably accurate characterization of channel geometry (O'Connor and Webb, 1988). The development of open channel flow step-backwater methods for use with computers (U.S. Army Corps of Engineers, 1997) has provided the opportunity to increase the accuracy of paleohydrologic studies through more precise modeling of large-discharge flow conditions.

Paleohydrologic estimates of past discharges should ideally be made from the study of long reaches of paleochannels preserved in alluvial-fill deposits or exposed on the land surface. Criteria in selecting suitable reaches for paleoflood analysis are the existence of multiple paleostage indicators preserved along the reach, and a stable channel environment. Typically, uncertainty of paleodischarge estimates derived from channel dimensions under the most favorable conditions is in the range of 75 to 130 percent (Costa, 1983; Gregory 1983).

2. Estimating Discharge as a Function of Flow Power

The magnitude of a paleoflood can also be estimated as a function of the force necessary to transport boulders present in channel deposits. Theoretical and regression equations that relate flow velocity to the size of particles transported were derived by Gregory (1983) and Williams (1983). Paleodischarge can then be estimated from mean-flow velocity and cross-sectional area.

The use of flow power to estimate paleodischarges is subject to a variety of limitations. Limitations include the assumption that particles of all sizes are available for transport and that average velocity and depth can be reconstructed from particle size with reasonable accuracy (Jarrett, 1991). Costa (1983) demonstrated that the size of boulders transported by large, modern floods in steep bedrock channels in small basins in Colorado can be used to reconstruct paleodischarge with an average error of 28 percent.

C. Estimating the Age of a Flood Event

There are four prominent methods for estimating the age of flood deposits; 1) radiocarbon dating; 2) relative position of deposits; 3) degree of weathering; and 4) tree ring analysis.

1. Radiocarbon Dating

Once the relative sequence and discharges of paleofloods are determined along a river reach, the absolute flood chronology can be established using radiocarbon (C^{14}) dating of organic materials. The age of deposited organic material is estimated through the application of the known decay rate of organic material from radioactive carbon-14 to stable carbon-12. Decomposed organic material can be found, in varying quantities, in sediment deposits and terraces. Materials used for radiocarbon dating can be wood, charcoal, leaves, humus in soil, and other organic material. Whenever possible, the most suitable material for dating paleofloods is the layer of fine-grained organic detritus that often occurs in the upper few centimeters of the sedimentation unit (Kochel and Baker, 1982). Rapid burial in slackwater sediments will usually result in a sample whose radiocarbon is nearly synchronous with the flood event (Kochel, 1980).

Webb et al. (1988), rated radiocarbon samples collected from flood deposits from best (1) to worst (5) as follows:

1) Flood transported organic material, consisting primarily of leaves and twigs, which would have a short residence time in the environment prior to entrainment in the flood.
2) Charcoal from in situ burned horizons.
3) Flood-transported wood, which may be significantly older than the flood event.
4) Flood-transported charcoal, which may have been redeposited from older sediments.
5) Organic material not in direct association with the flood deposit but provides an age constraint for the event.

Radiocarbon ages based on wood samples may not always correspond exactly to the precise timing of the flood that deposited the sediment containing the wood. In arid climates, wood can remain undecomposed on the surface for many years after the tree or plant dies. Additionally, large wood deposits may survive the reworking of older flood deposits and become incorporated onto the new deposits.

In general, paleoflood studies concern ages that do not pose major problems in relating calendar years to radiocarbon years. Since most paleoflood records are at least 1,000 years in length, radiocarbon age dating uncertainties are generally small in comparison. Recent advances in radiocarbon dating, such as the use of a tandem accelerator mass spectrometer, allow for dating extremely small samples with great accuracy (Baker, 1987). According to Stedinger and Baker (1987), samples having an age of 10,000 years can be dated with an uncertainty of less than 100 years.

2. Relative Age Dating

Relative age dating of deposits is dependent on the geologic principles of superposition and cross-cutting. The principle of superposition states that in undisturbed stratigraphic sequences, the oldest stratum is at the bottom and the youngest is at the top. The principle of cross cutting states that any geologic feature that cuts across a deposit must be younger than the deposit it cuts across. Analysis of stratigraphy does not provide absolute ages, but is a useful tool for enhancing understanding of the depositional history of the study area.

3. Age as a Function of Weathering

The ages of flood deposits can be estimated based on the degree of soil development, boulder weathering, and boulder burial. According to Jarrett (2002), the degree of surface-boulder weathering is an indicator of relative age. Older deposits generally have extensive surface pitting, rougher surfaces, and increased grain relief due to differential weathering of minerals. As less resistant minerals decompose, quartz grains tend to stand out in relief. The amount of cobble and boulder burial by hillslope colluvium also can be used to estimate the relative age of a deposit. The older the deposit, the greater the percentage of cobbles and boulders covered by colluvial deposits.

4. Tree Ring Analysis

Riparian trees commonly live hundreds of years and form annual rings that can be dated precisely. A common indicator of a flood event is the formation of scars from impact by floating debris (Figure 6). In addition to providing information about flood events, tree ring analysis also emphasizes hydrologic variability, most notably the frequency and magnitude of droughts, average monthly streamflow, and climate change.

VI. The Application of Paleohydrology in Different Hydrologic Environments

Several factors are required for the effective application of paleohydrology. These include: an environment which fosters the creation and preservation of geomorphological evidence; a consistent and measurable channel geometry; canyon topography where change in flow is not overly sensitive to change in stage; and an environment where the biological records of flood events are well-preserved.

A. Western United States

The western United States, with its mountainous regions and relatively arid climatic zones, is often conducive to paleoflood studies. Paleohydrologic analysis is best suited for defined stream channels in canyons, with easily measured cross-sections, where small changes in stage estimates are not sensitive to stream flow values. These type of canyons are common in the western United States. For most streams in the western U.S. it is possible to set bounds on the magnitude and frequency of floods through analysis of geomorphology and soil stratigraphy of terrace surfaces along streams. The relatively high gradient of streams in the west facilitates this analysis because even shallow inundation results in high stream power and shear stress that change the morphology of an inundated surface and leave a stratigraphic and geomorphic record (Osetenaa et al., 1997b). Additionally, river channels in the west commonly contain slackwater deposits and, thus, have been investigated more thoroughly than other areas (Baker, 1987).

Large areas of the west have arid or semi-arid climates. Arid conditions are advantageous for paleohydrologic analysis due to the sparsity of vegetation and accompanying bioturbation effects. Bioturbation is the disturbance of a stratigraphic deposit by plant and animal activity. In these arid areas (such as the southwest) rainfall is sporadic, yet occasionally intense.

A common protocol for the paleohydrologic analysis of a stream section in the western United States involves first the measurement of stage and, preferably, flow data of a recent flood event. This information, along with estimates of stream channel cross-sections and roughness, are integrated into a hydraulic model of the stream section. Through step-backwater modeling, discharge values can be simulated for a range of stages along the stream section. Paleohydrologic methods are then employed along the stream section to estimate the age and stage of extreme flood events. The magnitude of these flood events are simulated using the step-backwater model. Statistical methods can then be used to formulate flood frequency relationships.

B. Central United States

In the central United States, the relief is less dramatic and well-defined canyons are less common. In this environment, small changes in stream stage typically result in relatively large changes in stream discharge. Thus, there is a significant increase in the uncertainty of results from paleohydrologic analysis. Additionally, in the north-central United States, glaciation has erased much of the paleohydrologic evidence as recently as 10,000 years ago.

Stratigraphic relationships may be less distinct in humid, less mountainous regions of the central U.S. Foremost is the increased bioturbation by roots that occurs in humid regions because of higher vegetation density. In addition, the accelerated rate of pedogenesis (soil formation) in humid regions tends to homogenize slackwater sediments more rapidly than in arid regions. The net result is that greater care must be taken when interpreting slackwater sediments in a humid climate. Problems of slackwater sediment analysis in humid regions can be minimized by carefully selecting study sites that have suffered minimal disturbances by vegetation and erosion, and by using a greater number of sites for correlation purposes (Kochel and Baker, 1988).

Reconnaissance studies of slackwater sediment stratigraphies in southern Missouri and southern Illinois indicate that sites can be found in humid regions where stratigraphic disturbances are minimal (Kochel and Baker, 1988) . Knox and McDaniels (1999) investigated paleofloods on the Upper Mississippi River through analysis of stratigraphic records from well borings. Evidence of increased frequency of flooding in the mid-19th century was exhibited by a sharp increase in sedimentation rates.

C. Eastern United States

Many alluvial rivers in the eastern United States have bedrock reaches along their courses that can be used to obtain the conditions necessary for minimizing temporal instability of channel cross-sections. However, according to Kite, et al. (1999), "surface processes, bioturbation, and human activity limit the long-term preservation of slackwater deposits in the humid climate that prevails in the eastern United States". Additionally, lower sediment concentrations common in the eastern U.S. further contribute to the complex interaction of factors that determine the accuracy and durability of slackwater deposits.

According to studies performed on the Cheat River in West Virginia (Kite et al., 1999), paleoflood reconstruction from slackwater deposits of an unprecedented flood in 1985 resulted in an underestimation of discharge by over 40%. The 1985 flood was so much higher than the flood plain and terrace surfaces that it lapped upon steep colluvial slopes, well above the minor fluvial landforms favorable to deposition. A smaller (though still large) 1.0% (100 year) exceedance probability event in 1996 produced slackwater deposits with fairly accurate stage indicators. Computer modeling was used for step-backwater flood reconstruction based on these deposits and resulted in an estimation within a few percent of measured discharge. Thus, depositional evidence of moderate paleofloods in Appalachian canyons may have greater preservation potential than evidence of extreme floods. However the potential paleoflood records of many canyons have been obliterated by the development of canals, railroads, bridges, and highways.

Fuertsch (1992), estimated historical flood levels from flood-damaged trees located in constricted channels of the Shenandoah River, near Harper's Ferry, West Virginia. Skin porous species, such as ash, provided the most definitive ring boundaries, and thus the most accurate record of the time and stage of past flood events up to 150 years ago. These historical, botanical records were combined with gage records for flood-frequency analysis.

VII. Comparison of Paleofloods with other Large Floods

Paleoflood studies in California (Ostenaa et al., 1996), Oregon, Utah (Ostenaa et al., 1996), and Colorado (Jarrett, 1998) produced paleohydrologic bounds significantly below those previously estimated by simulated Probable Maximum Floods (PMF). Flood-frequency estimates based upon paleohydrologic bounds and the record of annual peak discharge estimates demonstrated that none come close to exceeding the PMF. As depicted in Table 1, estimates of 0.01% (10,000 year) exceedance probability flood magnitudes using paleohydrologic data were 5-26% of the hypothetical PMF.

Table 1: Comparison of 0.01% exceedance probability (10,000 year) peak discharge estimated from paleoflood studies (Ostenaa et al., 1996; Ostenaa et al., 1997, Jarrett, 1998) with simulated PMF peak discharge.

Location	Drainage Basin Area (km^2)	Estimated 0.01% Exceedance Probability (10,000 Year) Paleoflood, Discharge (m^3/sec)	Estimated PMF Peak Discharge (m^3/sec)	0.01% Exceedance Probability (10,000 year) Paleoflood as Percentage of PMF	Recorded Peak Discharge (m^3/sec)
South Fork Ogden River, UT	210	150	3,075	5	54
Santa Ynez River, CA	1,080	2,550	13,060	26	2,490
Ochoco Creek, OR	764	285	4,785	6	ungaged
Crooked River, OR	6,825	1,100	7,225	15	557
Elkhead Creek, CO	531	135	1,020	13	80

Conversely, Costa (1987b) provides a summary of the peak measured historic floods for a given drainage area size. All drainage basins were located in the United States. The PMF was calculated for nine of these sites by Bullard (1986). As depicted in Table 2, measured historic peak flood discharges were 65-91% of the PMF for the nine sites. Thus, PMF estimates appear

high when viewed in the context of 0.01% exceedance probability (10,000 year) paleofloods, yet
appear reasonable when viewed in the context of measured maximum precipitation-runoff events.

Table 2: Comparison of maximum measured discharge for a given basin size in the United States with simulated PMF (Costa, 1987b and Bullard, 1986)

Location	Date	Drainage Basin Area (km^2)	Peak Measured Discharge in U.S. for Basin in this Size Range (m^3/sec)	Estimated PMF Peak Discharge (m^3/sec)	Measured Discharge as a Percentage of PMF
Little Pinto Creek, Newcastle UT	8-11-64	0.78	74.5	84.7	88
Lane Canyon near Echo OR	7-26-65	13.1	807.1	883.6	91
Bronco Creek, Wikieup AZ	8-18-71	49.2	2,080	2,795	74
Eldorado Canyon, Nelson Landing NV	9-14-74	59.3	2,152	3,135	69
N. Fork Hubbard Creek, Albany TX	8-4-78	102	2,920	4,579	65
Jimmy Camp Creek, Fountain CO	6-17-65	141	3,510	5,409	65
Seco Creek near D'Hanis TX	5-31-35	368	6,510	9,901	66
W. Nueces River, Kickapoo Springs TX	6-14-35	1,041	16,425	19,569	84
Eel River, Scotia CA	12-23-64	8,063	21,300	28,151	76

VIII. Limitations of Paleoflood Methods

A drawback in the use of paleoflood methods is that it emphasizes the estimation of peak flows, and provides limited (or no) information on flow volume and durations. Additionally, the application of paleoflood hydrology appears best suited for arid areas with well delineated canyons, such as in the southwestern United States. Approximately 3/4 of Corps flood control projects are located in the central and eastern United States.

The use of any form of high-water indicator to estimate paleoflood discharge requires the acceptance of several qualifying assumptions. First, the slackwater deposits or flood terrace must be associated with the modern flood regime of the river. For example, significant climatic variations may cause adjustments in flood frequency that would be best treated separately from the modern conditions. A second important assumption is that the channel cross-sections of the mainstream and significant tributaries have remained relatively stable. A third assumption is that there has been negligible channel aggradation and degredation over the time period represented by slackwater sediments. A fourth assumption, necessary for using slackwater sediments or flood terraces to estimate paleoflood stage, is that their elevation records the maximum peak flood stage (Kochel and Baker, 1982). Additionally, downstream blockages or constrictions may have caused abnormally high deposits in regions of the channel.

Estimating of the age of the flood deposits is an additional uncertainty. The age of deposited organic material may not always correspond to the timing of the flood event. Furthermore, the uncertainty in radio-carbon dating methods can be significant when estimating the age of more recent 1.0% (100-500 year) exceedance probability flood events.

IX. Conclusion

Systematic hydrologic records, generally much less than 100 years long, rarely include infrequent and extraordinarily large floods, and as such, are not good indicators of extreme hydrologic variability. Paleohydrology, when used in conjunction with traditional flood frequency methods and other hydrologic methods (such as stochastic precipitation runoff), complements existing data and can be integrated in the analysis process and may allow for a more accurate estimation of long-term hydrologic records. Although it is possible to use paleofloods to extend and improve findings from traditional frequency analyses, great caution must be exercised to assess the climatic and land conditions at the time of the paleoflood. If those conditions were significantly different, then the paleoflood may only be helpful in determining changes that have occurred in various relationships, but may not provide useful input to the hydrologic record.

In the U.S., the Bureau of Reclamation, the Department of Energy, and the U.S. Geological Survey have substantive programs for the practical application of paleoflood hydrology to risk assessment. Baker (1999), contends that paleohydrologic data is analogous to paeleoseismic data, and the flood-frequency paradigm is actually a "bizarre philosophical construct that separates much of American flood science from the geophysical sciences of other natural hazards...In the case of earthquake risk assessment, it has been common practice to modify various statistical tools to fit the discovered realities of paleoseismic data. However, in the case of flood risk assessment, common practice has long presumed statistical tools themselves to constitute the science of flood frequency analysis" (Baker, 1999).

Public perception of methods used for evaluating dam safety is an important concern. According to Baker (1998) "social and behavioral scientists have long argued that human beings base their actions on percepts, i.e. concrete specifics of their experience. Thus, the commonly held ideal of basing policy, decisions, and public actions on the best possible science encounters a conflict in belief systems. A possible resolution of this dilemma lies in the use of observational components". An important aspect of paleohydrology in dam safety and floodplain delineation is that it provides the public with observed data to which they can relate. Non-scientists may find it more believable that geological evidence, outside the world of computer models and statistical analysis indicates that a flood of such a magnitude is possible.

Routine use of paleohydrologic information in applied flood hazard evaluations in the United States has been slow despite continuing research over the past three decades. As the Corps moves away from a deterministic decision framework and into a risk analysis probabilistic decision framework, there are increasing needs for robust methods for the probabilistic estimation of extreme floods. For many Corps applications, estimates of the magnitude of floods with recurrence intervals in the range of 1 in 500 years are often needed for project analysis and floodplain management. Probabilities of extreme floods up to the Probable Maximum Flood are also needed for dam safety risk analysis. Paleohydrology may provide a useful record of extreme-flood history to assist in extending the flood-frequency analysis process to include rare events not in the recent record. Paleohydrology, in conjunction with other evolving methods such as stochastic precipitation runoff analysis, should further enhance our ability to estimate extreme floods.

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