# Paleoflood Hydrologic Techniques for the Extension of Streamflow Records

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Paleoflood hydrology includes geomorphic-botanic studies of the effects of ancient floods on the landscape and the study of ancient slack-water deposits. Slack-water deposits consist of sand and silt that accumulated relatively rapidly from suspension during major floods. Useful slack-water sediment accumulations occur along bedrock canyons at the mouths of tributaries and at other protected localities. Where individual flood-sedimentation units can be recognized, various dating techniques are used to assign ages to the responsible flood events. Problems with incomplete flood records at any one slack-water site, the relating of deposit heights to paleoflood stages, and the age relationships of dated materials to flood ages require the analysis and correlation of numerous sites and flood layers along a given river reach. Paleostage determinations and flood ages can be converted to discharge and recurrence-interval estimates for the large, rare floods recorded in a slack-water sequence. Flood-frequency curves can then be constructed by combining the paleoflood data with shorter-term stream-gage data.

Conventional engineering approaches encounter considerable difficulty in assessing the risks from rare, large flood events. The problem is especially difficult if the true return period of an event of extremely high magnitude is much larger than the period of existing records of streamflow and precipitation. Paleoflood hydrologic techniques have been developed to extend flood-frequency records into the geologic past (1, pp. 3-9; 2) and thereby to assess the true return periods of extreme events.

A significant design problem for large floods arises during the interpretation of hydrologic outliers. Outliers are data points that depart from the trend of the rest of the data on a flood-frequency curve (3). If an especially large flood outlier occurs in a given historic flow record, its inclusion in the analysis could result in the overdesign of flood-control works. An excellent example is the 1954 flood on the Pecos River, which exceeded all events in the previous 54 yr by about an order of magnitude. By paleoflood hydrologic analysis it was recently established that the return period of the 1954 flood event is at least 2,000 yr (4). However, without these data, expensive overdesign might result from overemphasis of the outlier in risk analysis. Alternatively, outliers may be underemphasized, which results in dangerous underdesign of flood-control works. Even the adjustment of outliers for historical data, as recommended by the U.S. Water Resources Council (3), can lead to underdesign when the length of the historical record is particularly short relative to the true recurrence interval of a catastrophic flood event.

## PALEOFLOOD HYDROLOGY

The underlying assumptions in hydrologic risk analysis are the subjects of continual research and scientific debate. Paleoflood hydrology has been developed not to answer questions about theoretical distributions of floods in time but simply to extend the length of hydrologic records by the use of stratigraphic geology and geomorphology (5, pp. 109-117). In this paper, therefore, two pragmatic questions will be addressed: What techniques are available for extending flood records into the geologic past? How can these techniques be moved from the realm of the geologist to that of the field engineer?

### Geomorphic-Botanic Methods

The morphologies of stream channels and their adjacent floodplains can be profoundly influenced by large floods. The effects of such catastrophic floods on the landscape and on vegetation may persist for extremely long periods, and these effects can be preserved by burial with flood debris. Soil formation is a useful indicator of flood frequency, because maturely developed soils can develop on a floodplain only when long time intervals occur between the influxes of new flood debris burying the land surface. Because floodplain soils may be rich in organic matter, radiocarbon dating of specific soil samples has proven useful in dating the past floods that deposited them or their precursor parent materials (6, pp. 189-217). Figure 1 shows a field example; radiocarbon dating of the insoluble residue fraction from soil humus yielded an age of 710 ± 50 yr BP for this ancient organic soil (6).

Because major floods can also erode older landforms on a floodplain, the truncation of dated landforms also can be a useful indicator of flood frequency. For example, Costa (7) found that an alluvial fan eroded by the Big Thompson Canyon flood in 1976 had remained intact for at least 10,000 yr before the flood. In geomorphic flood studies the investigator should attempt to find the youngest surface that has been either buried by the largest known flood or eroded by that flood. The age of that surface is then equivalent to the minimum recurrence interval of the flood. Examples of this relatively simple paleoflood technique are provided by Costa and Baker (8).

### Slack-Water Deposits

Slack-water deposits consist of sand and silt that accumulate relatively rapidly from suspension during major floods. Deposition is localized where the flow boundaries for the peak flood discharges result in sufficiently reduced current velocities relative

Figure 1. Buried soil (center) exposed in the eroded floodplain of Elm Creek, central Texas.

to the channel-center velocities. Confined bedrock canyons or relatively narrow valleys are ideal for slack-water deposition because large floods transform the whole canyon or valley bottom into a temporary flood channel. As discharge increases, the stage rises relatively rapidly because of the narrow valley (channel) walls. This situation is in contrast to that of a broad floodplain valley in which overbank flood flows spread over a wide valley bottom, which results in a relatively slow rise of stage with increasing discharge.

At the high stages achieved by floods in narrow gorges, sufficiently high velocities and shear stresses develop that allow sand and silt to be easily carried in suspension. The relatively coarse suspended load will have a high settling velocity and can easily settle in local zones of reduced flood-flow velocity. Thus, a requirement for useful slack-water flood records is that sufficiently coarse sediment be available in abundance for suspended transport by rare, high-magnitude floods. Figure 2, an aerial photograph taken at maximum flood stage, 3:00 p.m., August 3, 1978, shows the formation of a flood slack-water deposit. Note the prominent slack-water zone in the center, where flow has expanded below a constriction. Flood stage was approximately 10 m.

The local sites of slack-water deposition are of several common varieties. Abrupt channel expansions result in deposition because of flow separations (eddies) that develop downstream of a constriction.

Figure 2. Pedernalles River at Pedernalles Falls, central Texas, August 3, 1978.

Figure 3. Same reach of Pedernalles River as that in Figure 2, August 17, 1978.

Figure 4. Slack-water deposit (covered by trees at center) developed at mouth of tributary (lower center) to Pecos River in western Texas.

Figure 3 shows the slack-water sand accumulation at the former position of the flood eddy shown in Figure 2. Deposition may also occur upstream from channel constrictions because of backwater effects during large floods. Tributary mouths (Figure 4) are also common sites of slack-water deposition because the tributary valleys can be backflooded by large floods in the main channel. The eddies and slack-water zones at the tributary mouths result in flood deposition. Tributary valleys or canyons that join the main valley at an angle close to 90° appear to have the optimum geometry to generate slack-water deposition. Obstructions in the channel, such as large boulders and bedrock knobs, lead to accumulations of flood debris on their downstream ends. Bedrock caves along channel or valley walls can be especially important sites because (a) long-term preservation is likely for deposits and (b) the possibility exists that aboriginal human occupation has left datable material.

The long-term preservation of slack-water deposits may also be important for paleoflood hydrologic studies. Sites that hydraulically favor slack-water sediment accumulation at high flood stage may become eroded by low-stage flows. Thus, the meandering low-flow channel may cut into flood slack-water accumulations at meander bends and downstream of flood-flow channel obstacles. In this way, given sufficient time, low-level slack-water deposits may be completely removed from a canyon or valley. The field investigator must then search for locally preserved high-level remnants of the flood deposits. Even these may be difficult to find if valley-wall and slope processes have removed them. Protected sites near large boulders, in bedrock niches and caves, and in depressions on valley-side benches have been found to preserve flood deposits for the longest periods after extreme events. Deposits at tributary mouths are protected from main-channel low flows, but they are vulnerable to erosion by floods on the tributaries themselves. The optimum tributaries for slack-water deposit preservation are those with relatively small drainage areas or relatively low efficiencies for concentrating runoff or both. That is, the peak discharge per unit area generated by floods on these tributaries does not reach the levels necessary to completely remove slack-water sequences from the tributary mouths. Distinguishing tributary alluvium from the main-channel slack-water deposition is a related problem but usually poses little difficulty. Main-channel alluvium is often lithologically distinct,

Table 1. Localities of slack-water flood paleohydrology studies.

| Location | Investigator | Summary of Results |
|---|---|---|
| Pecos River, West Texas | R.C. Kochel, P.C. Patton, V.R. Baker | Recurrence interval of 1954 flood has been established as >2000 yr |
| Central Texas | P.C. Patton, V.R. Baker | Recurrence intervals of catastrophic floods have been established as several hundred years |
| South-central Utah | P.C. Patton, V.R. Baker | Flood-recurrence intervals of several hundred years have been established |
| Connecticut | P.C. Patton | Slack-water deposits document Holocene floods larger than the largest historic event |
| Central Virginia | R.C. Kochel | Tropical storms have left Holocene record of geomorphic flood effects |
| Central and North Australia | V.R. Baker, G. Pickup | Catastrophic floods have left spectacular accumulations of slack-water sediments |
| Eastern Idaho | V.R. Baker | Late Pleistocene and Holocene slack-water sequences record major floods |
| Skagit River, Washington | J.E. Stewart, G.L. Bodhaine | Paleoflood magnitudes of 1815 and 1856 floods have been reconstructed |
| Northern California | E. Helley, V.C. LaMarche | Radiocarbon and tree-ring studies of floods with recurrence intervals of hundreds of years have been made |

and the fines are deposited in the tributary valley, whereas the tributary alluvium is usually much coarser bedload, which is deposited downstream.

Despite the various limitations on slack-water site development and long-term preservation, a large number of paleoflood studies have now been carried out (Table 1). The relatively narrow valleys and canyons of the western conterminous United States; the dissected plateaus, hills, and piedmonts of the eastern states; and the various dissected uplands of the midcontinent are all favorable areas for the type of analysis reported in this paper.

ANALYZING PALEOFLOOD STRATIGRAPHY

The study of flood slack-water deposits uses the tools of the stratigraphic geologist: sediment analysis, description of soil profiles, dating techniques, and correlation. Extended discussions on stratigraphic techniques are available in textbooks on Quaternary stratigraphy (9,10); this background cannot be reviewed here. Rather, this section will list some specific techniques that the field experience to date (Table 1) has shown to be most useful.

Recognizing Individual Flood Sedimentation Units

A slack-water depositional site will often preserve the sedimentation units of numerous individual flood events, as shown in Figure 5 (note the laminated units of flood-deposited sand, each capped by fine-grained organic detritus). Distinguishing the individual floods is accomplished by a number of sedimentological techniques. Flood layers may be capped by indicators of subaerial exposure that followed recession of the flood hydrograph. Such indicators include relict mudcracks, cultural layers indicating aboriginal human occupation of the surface, and ancient soil profiles (paleosols). Layers of colluvium from the valley sides or layers of tributary alluvium may also indicate time breaks in the slack-water sedimentation corresponding to time intervals between flood events.

Properties of the individual flood layers themselves can be useful. Certain flood events may impart distinctive lithologic or textural properties or colors to their deposits. These properties result from variations in the locations of flood-generating storms over the drainage basin or variations in the flood hydrographs at the depositional site or both. Stratigraphic breaks between individual flood units may be marked by abrupt reversals in the vertical grain size trends of the deposit because of hydrograph influences. Cappings of silt, clay, or organic detritus commonly mark the top layer of an individual sandy flood-sedimentation unit (Figure 5). These fine particles are transported near the surface of the flood water and are normally the last materials to be deposited by a flood at a site.

Several difficulties must be kept in mind when flood sedimentology is studied. Bioturbation of slack-water sediments may destroy the depositional structures and textures that permit the recognition of individual flood units. Bioturbation is more common in humid regions and local climatic settings favoring lush vegetation and soil organisms. Abundant roots, insect burrows, worm tubes, and so on are clues to bioturbation of older slack-water deposits. Even where an undisturbed sequence is found, however, the possibility remains that the record may be incomplete. Erosion by tributary

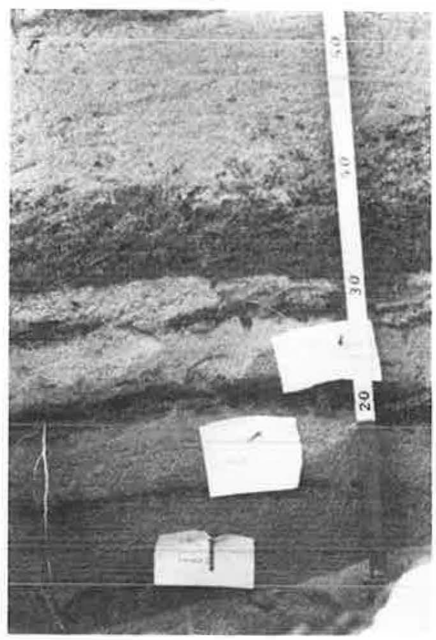


Figure 5. Slack-water sediments in the Katherine River Gorge, Northern Territory, Australia.

floods, deflation, and slope processes are among the actions that may remove part of the flood record at any one site. The way to minimize the error introduced by an incomplete record at one slack-water site is to study numerous sites along a given river reach and then to correlate flood layers between individual sites.

### Correlation

Correlation of the flood layers that correspond to individual flood events may be accomplished by lithologic or temporal means. The latter approach attempts to date individual layers or the intervals between those layers. In the next subsection dating techniques will be discussed in some detail. Unlike temporal correlations, lithologic correlation does not require datable materials and can be used at all localities.

Floods originating from different subbasins may be labeled by the distinctive source terrains of their sediments. This results in a recognizable lithology and mineralogy for some individual flood units. The duration and recession of flood hydrographs also exert an important control such that thicknesses, grain-size characteristics, and sedimentary structures may also be distinctive in given flood units. Also, the nature and duration of the time intervals between floods can be important in dictating the soil development properties, color, degree of induration, and colluvial burial of individual units. Finally, the stratigraphic positions of units of known age with respect to one another can be guides to what may be missing or present at any given study site.

### Dating Techniques

Slack-water deposits may be dated by both relative and absolute means. Absolute techniques allow a specific age to be assigned to the dated material, whereas relative techniques allow a qualitative comparison of ages between separate dated materials. Relative ages of units can be assessed by their degrees of alteration, soil formation, and burial position.

The occurrence of buried paleosols in slack-water sequences provides an important dating opportunity. Soils in floodplain alluvial settings are cumulative, continuously buried by new additions of alluvium. Generally soils are weakly developed because the rate of soil formation, such as the development of an organic-rich horizon, is simply too slow relative to the burial process. For a slackwater deposit that is high above the river-bed elevation, however, only rare floods can inundate the surface and thereby bury the developing A horizon (11). The result is a preserved paleosol the degree of development of which is a measure of the time interval between flood events. In the Pecos River region of western Texas, Kochel (12) found that at least 500 yr was required between flood events to generate a recognizable buried soil.

Radiocarbon dating is the most commonly employed absolute dating tool in paleoflood hydrology, although several other techniques are also available (Table 2). The method yields an age and standard deviation based on various laboratory procedures (13). Suitable materials for radiocarbon dating include various types of organic matter intercalated with the slack-water deposits. The organics may have been transported directly by the flood water. Litter, such as twigs, seeds, and leaves, may yield nearly synchronous ages to the flood events, because these materials decay rapidly on the ground surface and must be buried for preservation. Flood-transported logs and wood fragments, however, provide only maximum ages of the deposits because wood can be redeposited by floods that have eroded older deposits or it can be stable on the ground for many years, especially in arid climates. Water-transported charcoal poses a similar difficulty (14). Nevertheless, the charcoal and organic detritus associated with aboriginal human occupation can be synchronous with the interval between flood events, especially if the materials are buried by a subsequent flood. Tree stumps buried in their living position and burn zones from ground fires are also useful in marking a time zone, but such features are much less common than more problematic organic materials.

Organic soil horizons pose some difficulty for radiocarbon-dating procedures. The usual assumption in the technique is that the laboratory-determined date is a measure of elapsed time since the death of the organisms responsible for the analyzed organic matter. In soils, however, the accumulation of dead organic matter is a cumulative process. Radiocarbon dates on soils may therefore vary in age, and they will not necessarily represent the initial time of soil formation (15, pp. 77-88). Nevertheless, the oldest date obtained from a soil is the minimum age of soil formation. Because soluble humic acid is the most likely source of contamination in soil humus, the insoluble residue from soil humus is thought to represent the mean residence time of humus in a soil (16, pp. 63-75). Correlation of buried soils on paleoflood deposits is therefore best accomplished by comparing dates on insoluble organic residues. Comparison of these residue dates with dates on humic acid and on the total soil humus are likewise useful in interpreting the time interval over which the soil was developing before its burial by a subsequent flood. Patton and Baker (6, pp. 189-217) give an example of this application of paleosol study in evaluating ancient floods.

In general, the dating and time-stratigraphic correlation of individual flood deposits from one

**Table 2. Datable materials and dating techniques for flood slack-water sediments.**

| Type of Material | Dating Technique | Problem Encountered |
|---|---|---|
| Aboriginal artifacts | Archeological studies | Cultural time transgression |
| Buried trees | Dendrochronology | Cross-dating sequences need to be established |
| Organic matter in buried soils | Radiocarbon | Soils form and are contaminated until subsequent burial |
| Charcoal | Radiocarbon | Allochthonous (water-transported) charcoal may be much older than strata |
| Fine-grained flood-transported organics | Radiocarbon | Decay and contamination by younger roots |
| Flood-transported logs and wood fragments | Radiocarbon (and some dendrochronology) | Wood may be much older than strata |

locality to another are best accomplished by multiple sampling and by multiple techniques. A strategy should be developed so that this multiple approach yields independent checks on evolving hypotheses concerning flood ages and correlations of flood layers.

HYDROLOGIC ANALYSIS

The transformation of geologic studies of flood sediments to useful design data for flood-hazard management requires a closely knit set of assumptions and procedures. Most critical for establishing past flood magnitudes is the correlation of slack-water elevations to the responsible flood paleostages. Because even the deepest slack-water deposits will have had some water above them at peak stage, the deposit elevations themselves are minimum paleostage indicators. Two procedures can be used to minimize the errors introduced by this situation. The first is to study the deposits of a given flood event at numerous sites. Local conditions will generally allow preservation of the flood sediments at higher levels at some sites relative to others. In this way the maximum flood stage may be approached, but its actual value is always known to be somewhat larger.

A second procedure is to develop empirical correlations between the measured high-water surfaces of historic floods and the depths of deposits that they emplaced. These correlations are then used to correct the paleostage estimates from ancient slack-water deposits. The actual flood levels of historic floods can be determined from gage records, the observations of local residents, or from studies of isolated sediment pockets and drapes on hillsides that are temporarily preserved after a major event.

Another important assumption in paleoflood hydrology is that significant aggradation or degradation of the channel or both have not occurred in the time span represented by the slack-water sedimentary sequence. Generally the use of bedrock canyons and valleys will limit the influence of this factor, but any slack-water study of a long time span should document evidence for bed elevation changes that would alter the discharge calculations obtained from slack-water deposit elevations. Similarly a bedrock channel will minimize the occurrence of scour and fill during an individual flood event, which could complicate the interpretation.

Slope-Area Calculations

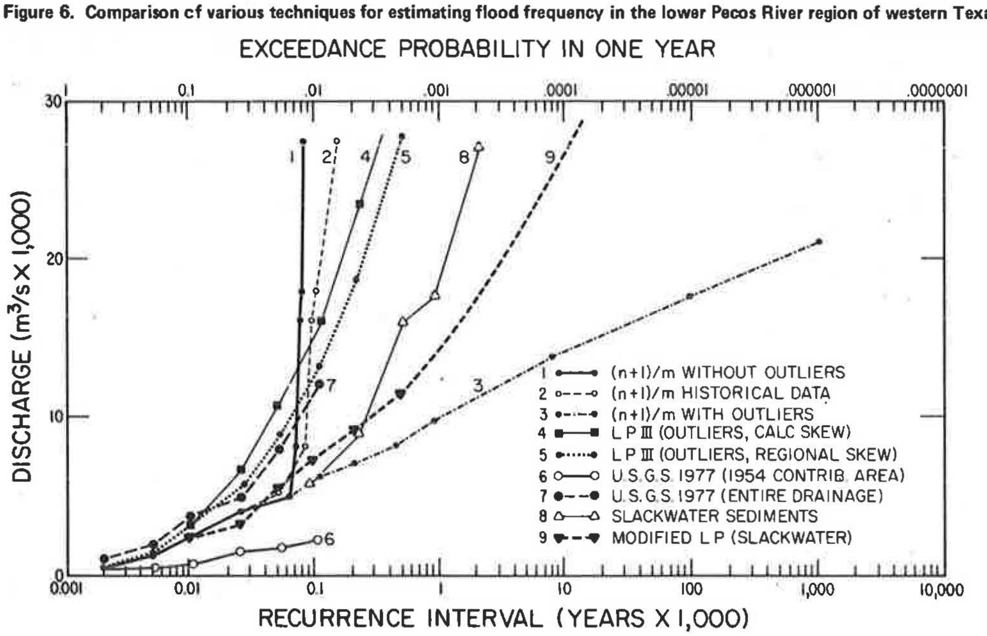
Once paleoflood stages have been established for each of the various slack-water deposit layers corresponding to individual floods, the investigator must transform those data into discharge estimates. This is accomplished by standard slope-area hydraulic calculations (17), which are easily performed on hand calculators (18). The necessary input data are as follows:

1. Cross sections at two (preferably three) locations (determine flow areas and hydraulic radii for stages up to the tops of flood slack-water accumulations),
2. Roughness coefficients (Manning n),
3. Slope of the flood-water surface (approximated as the fall in elevation for the tops of the slack-water sediment accumulations divided by the length of the reach between the cross sections), and
4. Energy coefficients (range 1.15 to 1.5 for natural streams).

Determining Flood Recurrence Intervals

When only one paleoflood event is recognized, the age of the youngest surface buried or eroded by the flood is the minimum recurrence interval of that event. When multiple events are recognized in a slack-water sequence, the magnitude of each should be determined as described above. Each event is then ranked; the ranking M = 1 is assigned to the largest, M = 2 to the second largest, and so on. The age of the oldest known flood in the sequence is assumed equivalent to the number of years of record (n). Each event can then be assigned a recurrence interval, calculated as (n + 1)/M. The probability that a flood of a given magnitude will be equaled or exceeded in any one year is simply the reciprocal of this recurrence interval. Because only the largest events, and therefore the longest recurrence intervals, are recorded in slack-water sequences, recur-

Figure 6. Comparison cf various techniques for estimating flood frequency in the lower Pecos River region of western Texas.



rence intervals for low-magnitude, high-frequency events must be obtained from gage records.

Flood recurrence intervals determined from slack-water sediments or from geomorphic-botanic analysis of ancient floods are generally plotted on flood-frequency curves by assuming various statistical distributions. Kochel and Baker (2) illustrate several plotting approaches for their study of the Pecos River paleohydrology in western Texas. In Figure 6, curves 1-7 illustrate techniques that rely only on gage data and historic data. Note that these curves assign either long recurrence intervals (>1 million yr) or short ones (100 to 500 yr) for the largest flood of record. Curves 8 and 9 incorporate slack-water data and show that the recurrence interval for the great flood of 1954 was between 2,000 and 10,000 yr. The standard procedure is to treat the slack-water data in the same way as historic flood data, which are incorporated along with stream-gage data into a log Pearson type III analysis according to Appendix 6 of U.S. Water Resources Council Bulletin 17B (3).

## CONCLUSIONS

The following conclusions have been determined:

1. Despite the special locations necessary for the accumulation and long-term preservation of slack-water deposits, numerous regions have been found to preserve these records of past floods.
2. Problems in the dating of individual flood layers and in relating slack-water deposit heights to paleoflood stages require that numerous sites be analyzed and correlated along a river reach of interest.
3. Multiple dating of different layers and materials is necessary to properly assign flood age estimates.
4. Flood slack-water deposits in areas of minimal aggradation or degradation will always provide minimum paleostage estimates unless corrected for depths of flood water above deposits.
5. Once the stratigraphic geologic interpretation has been accomplished for paleostage and age estimation, the calculation of paleoflood discharges and recurrence intervals is relatively straightforward.

## ACKNOWLEDGMENT

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