Paleoflood hydrology and hydroclimatic change

Victor R. Baker
Department of Geosciences
University of Arizona
Tucson, Arizona
85721 U.S.A.

ABSTRACT Important recent advances have been made in the reconstruction and interpretation of ancient floods, particularly in the use of slackwater deposits and paleostage indicators (SWD-PSI). For certain appropriate geomorphic settings, relatively accurate estimates of paleoflood discharges and ages can be made over time scales of centuries and millennia. New statistical tools are available to extract the maximum information content from this unconventional hydrologic data. Preliminary SWD-PSI study results from the southwestern United States indicate that certain time intervals in the last several thousand years have been characterized by occurrences of extraordinary floods, while other intervals have been relatively free of such events. Hydroclimatic change is a likely cause of this nonstationarity.

Introduction

Paleoflood hydrology concerns the study of past or ancient flow events using physical or botanical information, irrespective of any direct human observation. The flow events usually have occurred prior to the possibility of direct measurement by modern hydrologic procedures, although paleoflood hydrologic techniques can be applied to modern floods at ungaged sites (Baker et al., in press). Recent advances in geochronology, flow modeling, and statistical analysis of paleoflood data have greatly increased the ability to extract useful hydrologic information from one variety of paleoflood investigation: slackwater deposit-paleostage indicator (SWD-PSI) studies (Stedinger & Baker, 1987). SWD-PSI investigations can provide reconstructions of discharges and magnitudes for multiple paleofloods with remarkably high accuracy over time scales of centuries and millennia. However, such SWD-PSI studies require special combinations of geological circumstances that must be carefully evaluated in each application.

An outline of SWD-PSI paleoflood hydrology

The methodology of SWD-PSI paleoflood hydrology is discussed by Baker et al. (1983) and by Baker (in press). This section will briefly review important aspects of that methodology, emphasizing recent research developments.
Slackwater deposits consist of sand and silt (sometimes gravel) that accumulate relatively rapidly from suspension during major floods, particularly at localities where flow boundaries result in markedly reduced flow velocities (Figure 1).

Other important paleostage indicators include silt lines, high level scour marks, and flood-modified vegetation.

Sites of slackwater sediment accumulation occur at the following locations: (i) tributary mouths, (ii) abrupt channel expansions, (iii) in the lee of bedrock flow obstructions, (iv) in channel-margin caves and alcoves, (v) at meander bends, and (vi) upstream of abrupt channel expansions.

Regional factors useful in locating river reaches appropriate for SWD-PSI studies include the following: (i) adequate concentrations of sand and silt in transport by floods, (ii) resistant-boundary channels not subject to appreciable aggradation, (iii) depositional sites with high potential for preservation of SWD-PSI features, and (iv) narrow, deep canyons or gorges in resistant geological materials.

Although initially developed and applied in arid and semiarid regions (Baker et al., 1979; Kochel & Baker, 1982; Kochel et al., 1982), SWD-PSI paleoflood hydrology has been extended to the study
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of humid-region rivers (Kochel & Baker, in press; Patton, in press).

(f) Computer flow models for step-backwater analysis are used to calculate water surface profiles for various discharges in appropriate SWD-PSI study reaches. Paleodischarges are determined by comparing elevations of the various paleostage indicators to the water surface profiles.

(g) Recent research has concentrated on strategies for reducing error in paleodischarge estimation. Important concerns in this regard include: (i) paleoflow cross-sectional stability, (ii) relatively deep paleoflows, and (iii) relatively uniform reaches.

(h) Long-term channel stability is necessary for accurate hydraulic calculations. This can be assured for reaches developed in bedrock, immobile sediment, or other resistant boundary materials.

(i) Narrow-deep channel cross sections are most useful, since increasing flood discharge results in relatively large stage increases (Baker, 1984).

(j) Accuracy of the predicted water-surface profiles can be improved when relatively large flows in a systematic gage record are available to test and calibrate the flow model (Ely & Baker, 1985; Partridge & Baker, 1987).

(k) At ideal SWD-PSI sites thick sequences of multiple sedimentation units record numerous paleofloods (Figure 2). Individual flood units are distinguished by sedimentologic properties such as the following: (i) silt-clay or organic drapes, (ii) buried paleosols, (iii) organic layers, (iv) intercalated tributary alluvium or slope colluvium, (v) abrupt vertical grain size variations, (vi) mudcracks, (vii) color changes, and (viii) induration properties.

(l) Recent advances in geochronology, particularly radiocarbon analysis (Baker et al., 1985), provide excellent opportunities to determine paleoflood ages. As little as 1 to 2 mg of elemental carbon can be analyzed by the new technique of tandem accelerator mass spectrometry (Taylor et al., 1984).

(m) The usual "worst case" end member for SWD-PSI paleoflood information content is a single, vertically-stacked sequence of slackwater deposits (Figure 2). In this case, an informational censoring level (the elevation of each succeeding deposit) increases with time.

(n) Most commonly, SWD-PSI sequences provide much more paleoflood information than in the worst-case scenario. This is achieved by lateral tracing of individual flood deposits to their highest elevations, by correlation of flood deposits among multiple sites, by documenting evidence of limiting high-water levels, and by studying inset stratigraphic relationships.

(o) The information content in SWD-PSI sequences can be structured for flood-frequency analysis through the concept of censoring levels. Flood experience for various time intervals is then analyzed in terms of exceedances or nonexceedances of the censoring levels or threshold discharges (Stedinger & Baker, 1987).

(p) The goal of stratigraphic analysis in SWD-PSI studies is to reconstruct a complete catalog of discharges exceeding censoring levels over specified time periods.

(q) New statistical tools are now available to make optimum use of the information content in appropriately structured paleoflood data (Stedinger & Cohn, 1986; Stedinger & Baker, 1987).
Figure 2 Photograph of The Alcove slackwater sedimentation site (Webb, 1985) on the Escalante River in south-central Utah.

Flood hydroclimatology

Conventional flood-frequency analysis relies on the following assumption: "... the array of flood information is a reliable and representative time sample of random homogeneous events" (U.S. Water Resources Council, 1981, p. 6). Two possible violations of this assumption may be induced by (1) a mixed underlying parent distribution for the flood events, and (2) variation through time in the mean
of the underlying probability distribution for flood recurrence (non-stationarity). Both of these situations may derive from climatologic causes (Hirschboeck, in press). Although short-term systematic records are generally ambiguous with regard to such interpretive problems, SWD-PSI paleoflood hydrology provides excellent opportunities to test assumptions. In southern Arizona, for example, annual flow peaks are dominated by floods induced by regional snowmelt, local summer convective storms, and winter frontal storms (Hirschboeck, 1985). More rarely, incursions by tropical storms lead to extraordinary floods that appear as outliers in the systematic flood records. Here the systematic flow record is biased toward one hydroclimatologically induced distribution: that controlling the relatively common, smaller annual floods. Only with the expanded time base provided by paleoflood hydrology can an adequate sample be achieved for the unusually large and rare floods related to another hydroclimatologically induced distribution.

Of course, paleoflood hydrology generally cannot identify the hydroclimatic cause for a given paleoflow event. Nevertheless, the time base of centuries or millennia is ideal for evaluating long-term trends. Knox (1985) documented a pronounced nonstationarity for upper Mississippi Valley floods over the past 9500 years. Early Holocene alluvial fills indicate very low probabilities for large floods between 6000 and 9500 yr B.P. Increased probabilities for large floods are evidenced by boulder gravel in overbank sediments deposited in the following age intervals: (1) 6000 to 4500 yr B.P., (2) 3000 to 1800 yr B.P., and (3) 1000 to 500 yr B.P. (Knox, 1985). Similarly, Patton & Dibble (1982) presented evidence from the Pecos River of western Texas that floods were relatively infrequent during an arid interval between approximately 9000 and 3000 yr B.P., but the extraordinary floods occurring in this interval were unusually large. Between approximately 3000 and 2000 yr B.P., a humid interval resulted in more frequent flooding, but flood magnitudes were moderated. The last 2000 years has been most similar to the early Holocene arid interval.

On a shorter time scale, detailed SWD-PSI studies also have an immense potential for evaluating nonstationarity. For the Columbia River in central Washington, Chatters & Hoover (1986) showed that during the approximate interval 1000 to 1400 A.D., large floods were three to four times more common than at present. Flood frequency characteristics similar to those at present prevailed from approximately 200 to 1000 A.D. and from approximately 1400 A.D. to present. This use of paleoflood hydrology illustrates the fallacy of overly simplistic characterizations of paleoflood records as illustrated by the computer simulations of Hosking & Wallis (1986). Rather than a vague rationalization with which to criticize paleoflood hydrologic studies (Hosking & Wallis, 1986), nonstationarity can be an object of scientific study utilizing the remarkable capability of SWD-PSI studies to generate accurate and complete paleoflood records.

Applications in the southwestern United States

Since 1981 the new procedure of SWD-PSI paleoflood hydrology has been used in a regional study of ancient floods in the southwestern United
States (Figure 3). One goal of this regional analysis has been to identify temporal and spatial patterns in extraordinary floods.

The paleoflood record of the Escalante River of south-central Utah (Figure 3) illustrates the trends seen at other study sites. Paleofloods documented by Webb (1985), Webb et al. (in press), and O' Connor et al. (1986) fall into major time groupings. During the period 2000 to 1300 yr B.P., floods were relatively small. Three major floods occurred between 1200 and 1000 yr B.P., including the largest flood of the record. This period was also one of major arroyo cutting and is well-documented throughout the southwestern U.S. No floods were recorded between 900 and 600 yr B.P., but three
floods were recorded between 600 and 400 yr B.P. The next major phase of flooding occurred in the last century, which is the period of most extensive arroyo formation in the region (Webb and Smith, 1986).

The most detailed long-term record of paleofloods in the Southwest occurs just southeast of Phoenix, Arizona (Figure 3). Prehistoric irrigation canals constructed by the Hohokam Indians are filled with flood deposits (Masse, 1981). Current research by J.E. Fuller (written communication, 1986) documents that, since 1100 yr B.P., the Hohokam canals recorded a minimum of 25 and a maximum of 30 floods that exceeded 5000 m$^3$s$^{-1}$. Of these the largest (>12,000 m$^3$s$^{-1}$) occurred about 1100 yr B.P., during a 250-yr period of pronounced flooding. Large floods again appeared in the last 400 years, including three exceedences of 7000 m$^3$s$^{-1}$. The last of these was the 1891 flood with a discharge of between 7000 and 8000 m$^3$s$^{-1}$.

Essentially the same timing of paleoflood events is observed on upstream reaches of the Salt River (Partridge & Baker, 1987) and the Verde River (Ely & Baker, 1985). Additional work on these streams and Tonto Creek (Figure 3) by J.E. O'Connor and J.E. Fuller (written communication, 1986) confirms the same sequence. The largest flood occurred approximately 1000 yr B.P. on both the Salt and Verde Rivers. Unusually large floods also occurred during the last century.

Discussion

All SWD-PSI paleoflood studies conducted thus far in Arizona and adjacent areas (Figure 3) reveal a remarkably consistent record. Certain time intervals during the past few millenia have been characterized by occurrences of extraordinarily large floods, while other intervals have been relatively free of such events. Major episodes of flooding occurred from approximately 1000 to 1200 yr B.P. and during the past century or two. A somewhat less intense phase of flooding occurred between approximately 400 and 600 yr B.P. Time intervals between these flood phases were characterized by fewer, smaller floods. In addition, there are many indications that channel entrenchment on alluvial streams (arroyo formation) was coincident with flood phases, while aggradation was generally coincident with phases of reduced flooding (Webb, 1985).

The regional coincidence of flood phases in the southwestern United States suggests a hydroclimatologic cause. A possible mechanism is the variable influence of tropical moisture in the region. Work on evaluating this mechanism is currently in progress.

Considerable potential exists for combining SWD-PSI paleoflood studies with other paleoclimatic indicators. For example, tests of nonstationarity in long-term flood series might be achieved by evaluating other paleohydrologic indicators. Long-term tree-ring series and regime-based paleoflow estimates (RBPE) both can be related to various measures of mean streamflow or mean floods. RBPE studies are accomplished in alluvial channels, which are much more common than the resistant-boundary (non-alluvial) channel conditions required for accurate SWD-PSI studies. Accurately dated mean flow estimates plus chronologies of other paleoclimatic indicators, such as pollen records, plant macrofossils, and isotopic records, can be
used to evaluate nonstationarity in paleoflood records and interpret
the role of climate change in generating such records. Past climatic
change may serve as a guide to the potential for future climatic
change. Precise data on the magnitudes of past hydroclimatic change
may prove useful in testing models intended to predict future change.

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