13 Paleo- and Historical Flood Hydrology

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13.1 INTRODUCTION

Paleofloods are past or ancient floods that are indicated through natural recording processes. The recordings of paleofloods occur because of direct causal connections of past floods to deposition, erosion, or other markings that can subsequently be documented by investigators with appropriate experience for their interpretation. More specifically, paleofloods are defined (Baker, 1987) as floods that occurred prior to either (1) systematic measurement of flood flows using modern hydrological procedures (e.g., at stream gauges or by surveys conducted after directly observed flood events), or (2) other observation and recording by human agents (in which case the floods are termed "historical floods"). The natural archives of paleofloods extend the information on flooding well beyond the limitations of time and location imposed by opportunities afforded to qualified hydrologists for direct measurement of ongoing or very recent flooding. This is especially important in regard to the largest and most intense flood phenomena because (1) these are rare and thus highly unlikely to be observed on human timescales, and (2) they can be so energetic as to destroy the recording instrumentation at gauging stations and/or induce changes in cross-sections that introduce immense error to estimations of flow magnitudes and frequencies.

Historical floods are also past flood events, but their documentation involves some kind of human recording that does not follow scientific/engineering hydrological protocols. Such human recording might include such things as flood marks inscribed on canyon walls, chronicles, books, memoirs, newspapers, journals, diaries, weather journals, technical reports, flood maps, paintings, engravings, or photographs (Brázdil et al., 2006; Glaser et al., 2010). Although history broadly involves the study of the past, it is common practice to view time prior to human records as "prehistory." Both historians and geologists study the past, and the designation "paleo" commonly gets applied to what geologists infer from Earth's sediments, landforms, and rocks, in contrast to what historians glean from documents, journals, photographs, and other human recordings.

Both paleofloods and historical floods are components of a very broad range of historical, botanical, and geological evidence that can be assessed for the scientific understanding of flooding phenomena (Wilhelm et al., 2018). These are parts of the larger science of paleohydrology

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(Baker, 2014), which has recently been undergoing rapid transformation through (1) the use of new geochronological methods for the accurate dating of past flood events, (2) the application of improved hydraulic and hydrological modeling procedures for quantifying paleohydrological evidence (e.g., Benito and O'Connor, 2013), and (3) incorporation of paleohydrological databases into machine learning procedures.

13.2 HISTORICAL FLOOD HYDROLOGY

Historical floods have long been of interest to hydrologists, but most often this interest has been secondary to conventional stream gauging because historical evidence is not collected according to established protocols for doing hydrological science, and this evidence does not comprise the kind of systematic record that lends itself to conventional flood-frequency analysis. An exception to the general relegation of historical flood information to secondary status in flood hydrology occurred during the last century in China, so this experience will be briefly recounted as a case study.

Because of war and upheaval during the first half of the 20th century, China had an insufficient network of long-term stream gauging stations to provide the data needed for estimating engineering design floods of very high magnitude and very low probability. In 1960 China had a network of 3,611 stream gauging stations, but only 4% of these had record lengths longer than ten years (He, 2010). This led to huge errors in estimating engineering design floods in regard to flood risks posed to many ongoing water-resources development projects. As a remedy to this situation, a national program for investigating historical floods was initiated in the 1950s (Luo, 2006). The book *Compilation of Investigated Historical Flood in China* (Luo, 2006) documents more than 20,000 historical flood events along 5,544 river reaches, representing most of China's rivers. In one example, the 1482 extraordinary flood events of the Qinhe River were recorded by numerous old folk tales, inscriptions, flood marks, and historical literature, all of which formed the basis for estimating the peak stage and associate discharge of the flood event (Luo, 2006).

The application of historical flood data to the estimation of design floods became common engineering practice in China, even achieving the approved engineering status of being a normative method required by Regulation SL44-2006 – the Regulation for Calculating Design Flood of Water Resources and Hydropower Projects (China Ministry of Water Resources, 2006). This is the regulation for calculating design floods for water resources and hydropower projects, and it constitutes the industrial standard for hydraulic and hydroelectric engineering in China. It states that because of insufficient conventional hydrological data on extreme floods,

> *it is required* not only to take full advantage of measured data but also to extensively collect all kinds of related hydrological information. There are plenty of records for rainstorms and floods, like literary inscriptions, folklore, flood marks in the field and so forth. These precious historical flood data play a key role for improving the quality of design flood calculations. Hence, *it is required* to take full advantage of historical flood data and historical rainstorm data, no matter in which way the design flood is estimated.
>
> **(emphasis added – Regulation SL44-2006, China Ministry of Water Resources)**

This requirement to use historical flood data contributed to one of the world's greatest engineering projects. The 1870 flood of the Jialing and upper Chang Jiang (Yangtze) Rivers, the largest flood since 1153 AD, was historically documented by detailed descriptions and by inscriptions and/or flood marks at more than 90 sites along 450 km of river reaches (Figure 13.1). These depictions were used to generate the high water-level profiles, peak discharge estimates, and other properties for the 1870 flood in order to estimate the design flood for the massive Three Gorges Dam (Zhan and Xie, 2001).

China's extensive and systematic program of historical flood investigations not only yielded a great deal of data and experience, but it also promoted the development of new methods that

FIGURE 13.1 Flood inscription for 1870 Yangtze River flood event.

proved essential for doing paleoflood hydrology. Historical records were not always available at desired locations, and the periods for historical records were commonly found not to be long enough for useful extrapolation. Moreover, there were variations in reliability for human documentation because it was not collected according to scientific/engineering protocols. As a result, some Chinese hydrologists began to recognize the importance of natural evidence of the past floods and utilized that evidence to quantify peak discharges (Xu, 1982; Shi et al., 1985; Zhan, 1988; Guo, 1988).

13.3 THE SCIENTIFIC AND ENGINEERING DEVELOPMENT OF PALEOFLOOD HYDROLOGY

Paleoflood hydrology (PFH) combines recent advances in geological/geochronological studies of natural evidence for past flooding with hydraulic modeling to quantify the hydrological attributes of ancient flooding, in the absence of direct human observation/recording (Baker, 1987, 2000, 2017). PFH is most effective for producing records of the most extreme floods, phenomena that are commonly either missed or poorly measured by conventional hydrological stream gauging, the record lengths of which rarely extend more than several decades. PFH produces extreme flood data records that can extend back thousands of years, and it also provides for the objective hydrological/hydraulic quantification of subjective historical observations made by humans before the advent of modern hydrological measurements.

As part of the larger science of paleohydrology (Baker, 2014), PFH encompasses many types of flood paleoflow indicators. These include the use of various empirically derived relationships to estimate the magnitudes of relatively high-frequency paleoflood magnitudes for alluvial rivers (e.g., Dury, 1976; Williams, 1984); the effects of extreme flooding on trees that grow on floodplains or along valley bottoms (Ballesteros-Cánovas et al., 2015); and the sizes of flood transported or deposited boulders, relating them to mean flow velocity, bed shear stress, or stream power per unit area (e.g., Baker and Ritter, 1975; Costa, 1983). Wilhelm et al. (2018) provided a complete review for all forms of paleoflood study. The present chapter will focus on the varieties of PFH that are moving into conventional engineering practice, as noted above for the case of Chinese historical flood hydrology.

Though the geological roots of PFH extend back into the 19th century (Baker, 2008), it was not until the 1970s that a systematic program of PFH research began with studies of extreme past flooding in the south-central US. In that program, Baker (1975, 1977) and colleagues (Patton and Baker, 1977;

Baker et al. 1979) initiated, developed, and named what we now term "paleoflood hydrology" (Kochel and Baker, 1982). The intention was to synthesize two somewhat different approaches to the scientific study of floods, geological and hydrological. The geological approach emphasizes the recognition of various signs or indicators that can be interpreted by the experienced geological investigator as evidence for past flood processes. The relevant signs or indicators may consist of flood deposits, flood erosion marks, or other evidence of past high-water levels (Figure 13.2). The experienced geological flood investigator works out the time sequence of past flood events in much the same way that a time sequence of past biological organisms can be worked out through paleontological studies of their fossil forms preserved in sedimentary strata. The sequential layering of flood sediments is most effective for this purpose (Figure 13.3). The time sequences at multiple sites along a river reach are used to make discoveries about the nature of the flooding, including its patterns in time and space.

Recent technological advances have greatly improved the ability to date ancient flood events. The tool that was first applied in the initial phases of PFH development was the radiocarbon dating of organic material intercalated with the flood deposits (e.g., Baker et al., 1985). This method is applicable to paleofloods during the time frame of greatest interest for applied studies, the last 10,000 years or so. Recent developments in tandem accelerator mass spectrometry now allow organic grains with a mass of only a few milligrams to be dated within an error range of several decades. Of course, many flood deposits do not contain organic material. This void has now been filled by the geochronological tool of optically stimulated luminescence dating, which makes possible the direct dating of mineral grains of quartz and feldspar that were transported by paleofloods (e.g., Rittenour, 2008). Another new geochronological tool, terrestrial cosmogenic nuclide dating, makes possible the direct dating of flood-eroded rock surfaces and flood-transported boulders (e.g., Balbas et al., 2017).

The original formulation of PFH recognized the need to employ hydraulic engineering to quantify the geological interpretations made from the various indicators of paleoflood stages. Initially used to quantify the immense flooding that occurred during the last ice age (Baker, 1973), PFH was found to apply to the analysis of past flooding in the geological period of climates most similar to that of today, essentially equivalent to the past 10,000 years. Paleoflood stages were converted to discharges using simple hydraulic formulae, such as the Manning equation and slope-area methods, which relate the discharge of paleofloods to channel cross-sectional areas, flow depths, energy

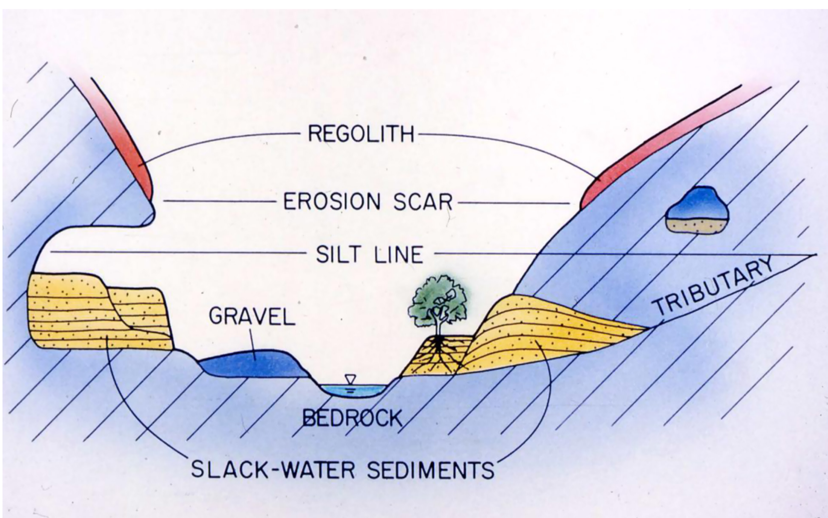

FIGURE 13.2 Idealized cross-section of a bedrock stream canyon such as commonly occurs in the southwestern US. Shown are various kinds of features that can be related to the paleohydraulic conditions responsible for their emplacement (see Baker, 1987, 2000; Kochel and Baker, 1988; Benito and O'Connor, 2013).

FIGURE 13.3 Slackwater deposit along Escalante River, south-central Utah, USA.

slopes, and measures of flow resistance. Starting in the 1980s computer flow models began to be employed in the PFH research to perform hydraulic step-backwater calculations in one dimension along the thread of main channel ways (e.g., Ely and Baker, 1985; Baker and Pickup, 1987). Multiple cross-sections are used along a channel reach that is long enough to achieve an energy-balanced calculation of multiple water-surface elevations for various potential paleoflood discharges. By matching the flood paleostage evidence to the calculated water-surface profiles paleodischarges are estimated. More recently further increases in computational capability have enabled the use of two-dimensional flow models. These are appropriate for the more complex channel geometries that pose problems for accurate representation in the one-dimensional models.

The hydrological approach to flood studies developed out of origins in which hydrology acted as a scientific arm for practical hydraulic engineering. The latter is concerned with the design of hydraulic structures, such as large dams. Since these structures can be at risk from extremely large floods, it is necessary to generate the numerical measures of risk that can be used to achieve designs within some level of tolerance. Risk in this context is defined as the peak flood discharge multiplied by the probability for its exceedance or non-exceedance. The necessary probability estimates for risk assessment are achieved through a flood-frequency analysis of the available systematic stream-gauge data. Given the lack of information on extremely large, rare floods, the prediction of flood probabilities for risk analysis must entail certain assumptions, including (1) that floods are random in time and space, (2) that the floods at a specific place, such as at a stream-gauging station, arise from a single probability distribution, and (3) that the mean and variance for this probability distribution are time-invariant, i.e., that these statistical moments are stationary in time. Modern hydrological research has shown that all these assumptions are wrong to varying degrees

(Baker et al., 2002), though they continue to be applied because of the necessity to make engineering design decisions in the light of what is presumed to be a lack of data on extremely large, rare floods. Of course, such a presumption can lead to ignorance or even blanket dismissal of exactly the kind of data that can be provided through the study of paleofloods. Such an ignoring or dismissal of the facts of nature is unscientific.

13.4 SWD-PSI PALEOFLOOD HYDROLOGY

Though there are many techniques available for the quantitative analysis of past flood parameters (Baker, 2014) the most accurate method in the paleoflood hydrology (PFH) involves slackwater deposits and paleostage indicators (SWD-PSI) that can be found in stable-boundary fluvial reaches (Baker, 1983, 1987; Kochel and Baker, 1982, 1988). Slackwater deposits are mainly sand, but also gravel conveyed in suspension during highly energetic flood flows and deposited in appropriate, protected riverine settings. In these environments, during especially intense flooding, sedimentary particles with sufficiently high settling velocities accumulate relatively rapidly from suspension in areas of flow separation and slackwater, such as at the mouths of back-flooded tributaries or in bedrock alcoves set into canyon walls (Baker, 1984). The resulting slackwater deposits (SWDs) commonly comprise thick accumulations (Figure 13.3), in which individual sandy layers correspond to the causative flood events, and layers of non-flood materials or boundaries between the SWD layers correspond to intervals between the flood events (Figure 13.4). Actual field examples of SWD sections rarely contain as many elements as in the idealized example shown in Figure 13.4. The nature of the preservation sites for the SWDs is such that they are protected from the erosive action of later floods.

SWDs are deposited by flood flows, so their elevations represent the minimum stage levels reached by those floods. The evidence provided by SWDs can be augmented with other paleostage indicators (PSIs) some of which provide maximum indicators of paleoflood stages. The combination of the SWD and PSI evidence comprises a mode of investigation that has come to be known as SWD-PSI paleoflood hydrology (Baker, 1987). A SWD-PSI paleoflood hydrological investigation proceeds according to a sequence of stages, as follows: (1) identification in the field of key locations exhibiting the SWD-PSI evidence and relatively stable flow boundaries, as common in bedrock stream channels; (2) detailed documentation of the stratigraphy and geochronology of the slackwater deposits and any other paleoflood evidence; (3) hydraulic analyses of the stable-boundary fluvial reaches containing the SWD-PSI evidence; (4) relating of the paleostage data to the hydraulics; and (5) using the paleoflood data for scientific or engineering purposes, including flood-frequency analysis. Stages (1) and (2) are largely geological, while steps (3) and (4) are largely hydrological engineering. Step (5) can be either. The stable flow boundaries are needed to reduce uncertainties when performing the hydraulic analyses (stages 3 and 4).

Figure 13.5 shows the results of a hydraulic step-backwater analysis for multiple SWD elevations along a bedrock-confined reach of the Colorado River in east-central Utah. Greenbaum et al. (2014) provide a complete discussion of that study.

13.5 APPLIED PALEOFLOOD HYDROLOGY

The geological aspect of paleoflood hydrology emphasizes the recognition of various signs or traces that can be interpreted by the experienced geological investigator as evidence for past flood processes (Kochel and Baker, 1988). It is applicable to fundamental science problems, including the nature of bedrock erosion in rivers (Baker and Kale, 1998). The hydrological/engineering aspect of paleoflood hydrology emphasizes design criteria for hydraulic structures, such as large dams, and numeric measures of risk that can be used to achieve designs within some level of tolerance (Baker et al., 1987, 1990).

Some of the original PFH work in the US during the 1970s and 1980s received considerable criticism from segments of the hydrology/engineering community. As reviewed by Baker et al. (2002),

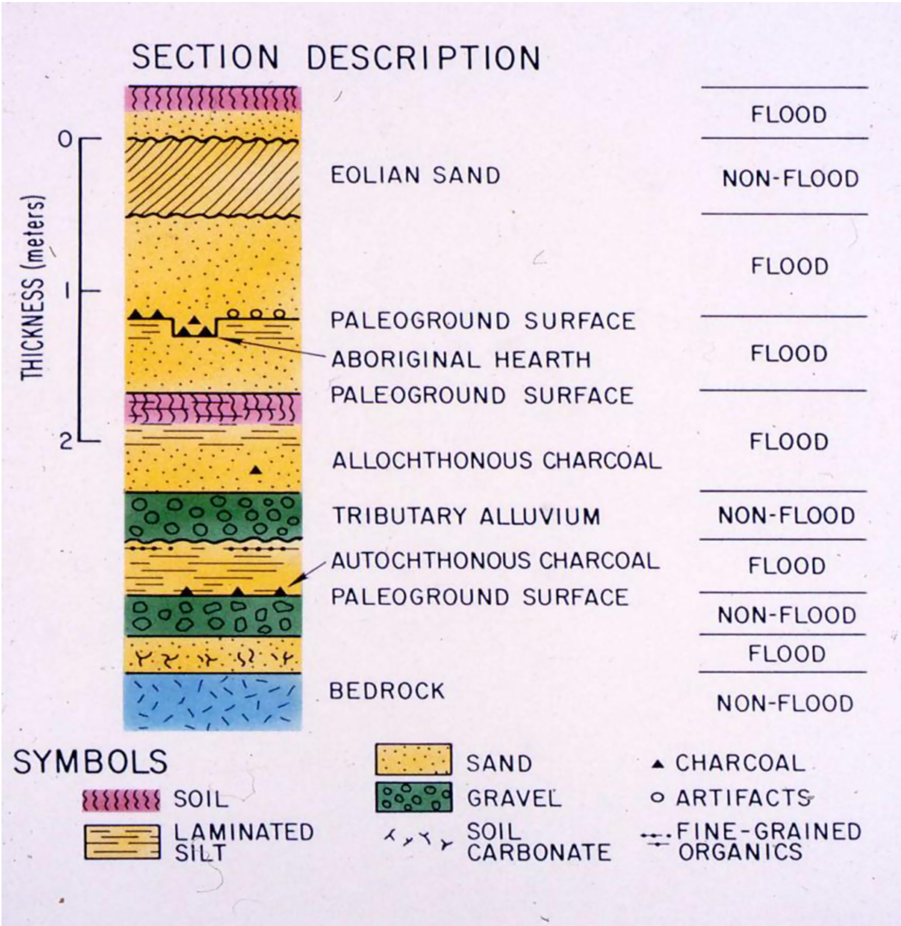

FIGURE 13.4 Idealized stratigraphic section of a slackwater sedimentary sequence containing six flood event deposits and several nonflood deposits. Note the presence of several kinds of materials that can be used for geochronology. It is unlikely that this degree of complexity would be found in any one slackwater section.

the concerns included (1) the impossibility of determining the ages for very ancient floods, (2) the impossibility of accurately determining the discharges for ancient floods, (3) the lack of appropriate statistical procedures for incorporating paleoflood data into risk analyses, and (4) the presumption that future changes in climate and/or land-use practice will invalidate the incorporation of information on past floods into the statistical analyses that determine the risk of future floods. As noted above, concerns (1) and (2) have been met by new technology for geochronology and for hydraulic modeling.

Concern (3) is rather odd from a scientific viewpoint. If existing procedures fail to incorporate realities present in nature, then, instead of denying nature, one needs to change the procedures. Indeed, it is now the case that the engineering standard for flood-frequency analysis by all US federal agencies (England et al., 2018) specifies statistical procedures for incorporating both historical and paleoflood data, which is something that was decreed much earlier for flood engineering in China.

Finally, concern (4) merely expresses skepticism about all historical information. Its logic would hold that all empirical information about floods, including that derived from stream gauges, is invalidated by a metaphysical presumption that the reality of the future cannot have any relation to the past. Such assertions are not scientific, since there is absolutely no reliable way to know exactly what the future will be. All projections of the future by scientific models depend on assumptions

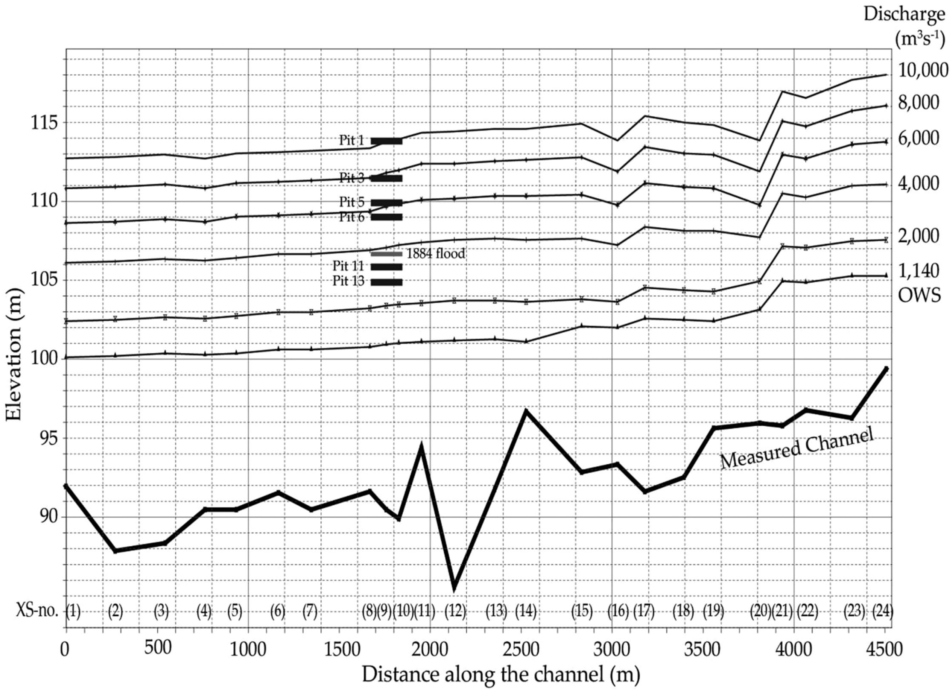

FIGURE 13.5 Water surface profiles for peak discharges ranging between 1,140–10,000 m^3s^{-1} along a study reach of the Colorado River near Moab, Utah, USA. The profiles were generated using the HEC-RAS hydraulic program. Also indicated are a series of study pits (numbered 1–13) that were excavated into dated slackwater deposits. See Greenbaum et al. (2014) for a description of this PFH study.

that cannot be scientifically tested until the future actually happens. A quip made by Sir Isaac Newton seems appropriate here: "Physicist beware metaphysics!"

A variant of PSI paleoflood hydrology was developed in the 1990s by the US Bureau of Reclamation for the study of potential risks posed to large dams by very rare, extreme flooding. This methodology (Levish, 2002) uses geological procedures to identify various threshold indicators of paleoflood non-exceedance. It then calculates the paleodischarge values for those thresholds, using geochronology to determine the timescales over which the non-exceedance thresholds apply (O'Connell et al., 2002). Finally, it puts the discharge values and their timescales into a flood-frequency analytical scheme that determines the likelihoods of non-exceedance. More recently, the US Army Corps of Engineers added the PFH analyses to reduce uncertainties in its risk-informed decision-making framework for improving hydrologic loading inputs to dam safety evaluations (Kelson et al., 2016).

Numerous studies have now demonstrated how PFH analyses improve the flood-frequency estimation of extreme floods (e.g., Costa, 1978; Stedinger and Cohn, 1986; Baker, 1989; Benito et al., 2004; Harden et al., 2011; Lam et al., 2017, Boucefiane et al. 2014). There are excellent procedures for the incorporation of historical and paleoflood data in flood-frequency analyses. An example is the US Bureau of Reclamation's FLQFRQ3 model (O'Connell, 1999; O'Connell et al., 2002), which combines a Bayesian approach (O'Connell et al., 2002) with a maximum likelihood method (Stedinger and Cohn, 1986). The FLDFRQ3 model allows for the specification of uncertainties for magnitudes and timing of hydrologic events and for thresholds derived from paleoflood data that arise because of flow rate, stratigraphic, and chronologic uncertainties (Harden et al., 2011).

Figures 13.6 and 13.7 illustrate the use of paleoflood data for improving the evaluation of extreme flood probabilities. These were done for the lower Green River in south-central Utah, USA (Liu et al., 2019).

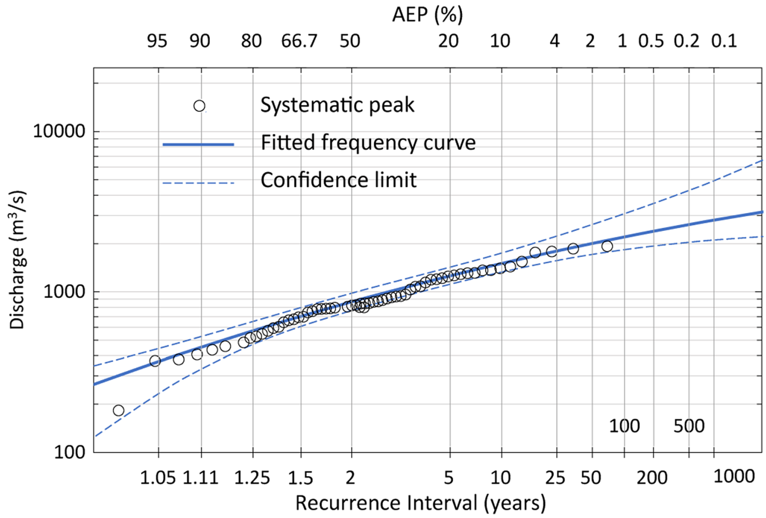

FIGURE 13.6 Results of flood frequency analysis (FFA) using Expected Moments Algorithm (EMA) with Multiple Grubbs-Beck Test (MGBT) on the Lower Green River in the Stillwater Canyon reach, using systematic peaks only. The solid line is the fitted log-Pearson Type III frequency curve and the dash lines are the 95% confidence limits.

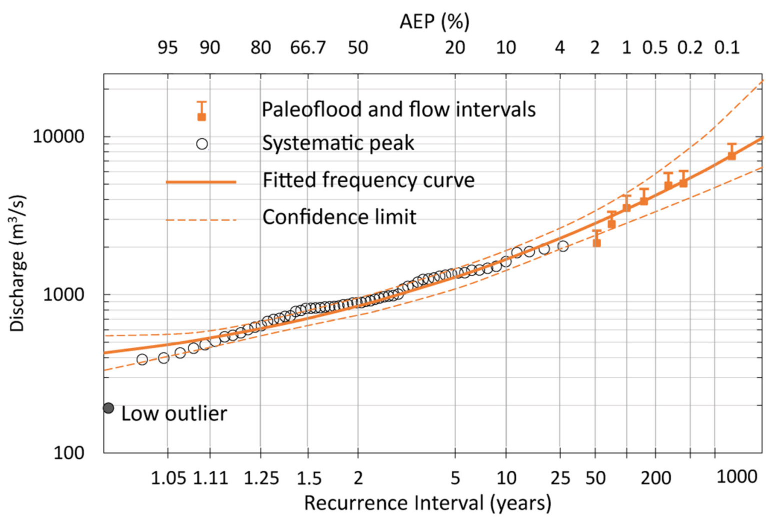

FIGURE 13.7 Results of flood frequency analysis (FFA) using Expected Moments Algorithm (EMA) with Multiple Grubbs-Beck Test (MGBT) for same site as Figure 13.6, but using both systematic and paleoflood data. Vertical bars are estimated data uncertainty for the paleofloods. The solid black circle is the potentially influential low flood (PILF) threshold as identified by the MGBT.

13.6 WORLDWIDE PALEOFLOOD STUDIES

Though the modern science of paleoflood hydrology was developed in the United States, some of its more extensive applications have been taken up in other countries. SWD-PSI paleoflood hydrology spread to Australia in the 1980s (Baker et al., 1983; Baker and Pickup, 1987), and to India and Israel in the 1990s (Ely et al., 1996; Wohl et al., 1994). These countries all have many areas that are highly appropriate for the application of the SWD-PSI paleoflood hydrological methodology. Extensive paleoflood investigations since the 1990s have been conducted in southern Europe, mainly in Spain, France, and Greece; in southern Africa, both in Namibia and the Republic of South Africa; in South America (Chile and Peru); and in parts of Asia, including China, Japan, and Thailand (Baker, 2006). A survey by Baker (2013) documented more than 60 published paleoflood studies from 21 US states and 25 foreign countries. Many more studies have been done that appear only in reports with limited availability or in various unpublished studies. Even more important is the recognition, based on much experience, that immense potential exists for discovering appropriate sites for future, very accurate SWD-PSI studies, with many hundreds or even thousands of likely occurrences in regions where successful studies have already been accomplished.

13.7 PALEOFLOOD HYDROLOGY AND CLIMATE CHANGE

Climate model projections indicate that the extreme floods will become more frequent with the rising global temperatures that are documented to be associated with anthropogenic increases in radiatively active atmospheric gases, particularly carbon dioxide (Hoegh-Guldberg et al., 2018). Because conventional engineering approaches to flood-risk analysis rely upon flood-frequency procedures, the expected changes in flood magnitudes from global climate change pose a major concern for the evaluation of future flood risk. Clearly, such changes will violate the stationarity assumption that underpins many engineering design decisions (Milly et al., 2008). However, these climate changes are not going to create entirely new kinds of meteorological phenomena that have never before occurred on the planet. Rather, it is much more likely that future climate changes will result in shifts of flood-generating storm patterns. Evidence for the kinds of extreme floods likely to be associated with the new storm patterns will be available from the natural archives of paleofloods. Moreover, these same natural archives comprise the only real-world tests for the model simulations of the most extreme flood-related phenomena. To ignore the archives of SWD-PSI and other paleoflood evidence would be the anti-intellectual equivalent to ignoring the lessons of human history when facing the uncertainties of future human affairs.

Valid science cannot be accomplished solely on the basis of theory-based models. There must also be empirical data with which to assess model predictions. How does one obtain such data when the subject of concern is extreme flooding that is inadequately represented in short-term gauging data? It has long been apparent that paleoflood data can provide a link between extreme flooding and climate, and this has been demonstrated in numerous studies (e.g., Ely et al., 1993; Knox, 1993, 2000; Harden et al., 2010; Benito et al., 2015; Liu et al., 2020). Paleoflood research has shown that the maximum extreme floods cluster in time and that these clusters do not derive from random factors, with climate being particularly important for generating the temporal clustering (e.g., Ely et al., 1993; Knox, 2000; Macklin et al., 2006).

13.8 PALEOFLOOD HYDROLOGY AND THE COMMUNICATION OF FLOOD RISKS

Paleoflood hydrology potentially has a unique role to play in the communication of flood risk to decision makers and to the general public. This use contrasts sharply with prevailing authoritative government pronouncements that invoke concepts like the "hundred-year flood." While this mode of communication may be useful for communicating to the small number of experts concerned with the details of probabilistic risk analyses, the "hundred-year flood" designation is nearly universally misunderstood by those not cognizant of its technical basis. The "hundred-year flood" is not an actual flood, and it has nothing to do with real years. Both decision makers and the general public are maximally concerned with the realities of extreme flooding, and not with the abstract complexities of flood-frequency analysis.

In contrast to conventional practice, paleoflood hydrology derives its authority from the natural recording of ancient, but very real extreme flooding. The latter has obvious potential to cause harm, and will thereby motivate more serious attention than would abstract conceptions base on the authority of human experts. The authority for appropriately documented paleofloods is nature, not some humanly fallible logical construct. The communication of nature's realities leads to the commonsense recognition that what has actually happened will very likely happen again, and that insight will provide motivation for an engaged and wise response to a real threat.

13.9 DISCUSSION AND CONCLUSIONS

PFH offers a means for properly understanding the nature of "outlier" events in flood phenomena. In doing so, PFH responds to Nassim Taleb's (2007) radical critique of the current paradigm for analyses of risk and associated uncertainties. Taleb's "black swan theory" or "theory of black swan events" inverts the usual approach to uncertainty estimation for extreme risk of very rare events, which he terms "black swans." Taleb (2007) asserts that, instead of extrapolating from large populations of more common phenomena, it is much more important to place major emphasis on extremes themselves. By concentrating on the ordinary and the "normal," the current paradigm has relegated extremes to "outlier" status, focusing attention instead on statistical analyses of the large samples that are available for ordinary cases. Taleb (2007) argued that the consequences of this approach are being manifested in the spectacular economic losses that are increasingly accompanying current disasters.

The problems for estimating extreme flooding risk with conventional flood-frequency analyses were evident long before Taleb's popular, high-profile general critique of probabilistic risk analysis. Flood-frequency analysis was criticized being neither a science or engineering discipline because it is based on the problematic assumption that flood events are random samples from simple probability distributions but does not analyze the observed frequencies of the floods (e.g., Klemes, 1986, 1987, 1989; Baker, 1994, 1998; 2007). Nearly all dams and bridges' safety has been evaluated on the basis of this method of using relatively short records from gauged data. While these may be sufficient for estimating the 100-year flood, which has a 0.01 annual exceedance probability, the gauge records do not adequately represent very rare, more extraordinary floods, which can cause catastrophic damages. Despite this fact, extrapolation from the short time periods of conventional gauge records continues to be the standard for estimating the frequencies of extreme high-magnitude floods.

In contrast, paleoflood hydrology has demonstrated its effectiveness in providing critical information on real, extreme floods, based on studies of geological evidence in the US and many other countries, including Australia, Spain, France, China, India, Israel, and Thailand. Instead of extrapolating from the available time-limited, gauged-flood datasets, paleoflood hydrology combines geological and hydrological/hydraulic approaches to reveal nature's own, highly reliable record of extraordinary floods that have really happened on very long time scales, which commonly extend over thousands of years. The PFH studies have provided sound evidence that conventional measures of extreme flooding, like the probable maximum flood criterion, have been exceeded multiple times (e.g., Greenbaum et al., 2014) and that extreme floods in a particular region tend toward a maximum value (e.g., Enzel et al., 1993). PFH is now essential for preventing either (a) flood risk underestimation, leading to failures of critical infrastructure (or worse), or (b) flood risk overestimation, leading to unnecessary waste of resources. Clearly, we are entering a period of new applications for the scientific analysis of old floods (St. George et al., 2020).

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