Appropriate Application of Paleoflood Information for the Hydrology and Hydraulics Decisions of the U.S. Army Corps of Engineers

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14. ABSTRACT

The U.S. Army Corps of Engineers (USACE) Hydrology, Hydraulics, and Coastal Community of Practice frequently studies past hydrology and assumptions about future hydrology to characterize potential future flood events and associated risks. USACE may be able to use information about floods from the very distant past to help characterize floods that have low probabilities of occurrence. This report briefly describes the collection of paleoflood information and various ways to translate that information into hydrologic frequency estimates for flood stage, discharge, and volumes. It addresses appropriate use of the paleoflood information for USACE hydrology and hydraulics applications.

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Appropriate Application of Paleoflood Information for the Hydrology and Hydraulics Decisions of the U.S. Army Corps of Engineers

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Abstract

The U.S. Army Corps of Engineers (USACE) Hydrology, Hydraulics, and Coastal Community of Practice frequently studies past hydrology and assumptions about future hydrology to characterize potential future flood events and associated risks. USACE may be able to use information about floods from the very distant past to help characterize floods that have low probabilities of occurrence. This report briefly describes the collection of paleoflood information and various ways to translate that information into hydrologic frequency estimates for flood stage, discharge, and volumes. It addresses appropriate use of the paleoflood information for USACE hydrology and hydraulics applications.

Executive Summary

The U.S. Army Corps of Engineers (USACE) infrastructure, operations, safety, and maintenance programs are facing growing stresses caused by aging infrastructure, hydrologic nonstationarity, urban growth, coastal development, evolving navigation and shipping practices, changing agricultural practices, and increasing recognition of the need for ecosystem restoration. Our infrastructure is often operated beyond its anticipated service life, requiring inquiry into how such systems can best be managed. The Hydrology, Hydraulics, and Coastal (H,H,&C) Community of Practice (CoP) frequently conducts studies and assessments based on past hydrology and assumptions about future hydrology.

In the absence of direct foresight into future hydrologic events, past events are often used as surrogates. Paleohydrology describes the evidence of the movement of water and sediment in stream channels before the time of continuous hydrologic records or direct measurements (Costa 1987). Paleohydrologic information can be obtained or derived with respect to both floods and droughts, though the tools and practices for characterizing these two hydrologic extremes are somewhat different. This report focuses on the utilization of paleoflood data for supporting decisions of the practitioners of hydrology and hydraulics (H&H) within USACE. Paleoflood information can be obtained for any time period prior to instrumental gage records, including the relatively recent past (50–500 years) to the very distant past (500–10,000 years before present).

To best meet the mission goals and support the various H&H decision types and policies of USACE utilizing paleoflood information, it is necessary to identify how paleoflood data are collected, what analyses and assumptions are employed to interpret and transform those data into information for potential H&H decisions, and where and how that information can best be used within studies or designs. Table 1 presents appropriate uses of paleoflood information in UASCE decision-making based on this report.

The main conclusions of this report are:

- The utility of paleoflood information should be considered with respect to the H&H decision at hand, including both the policy and the tech-

nical requirements of that decision. Paleoflood information is not relevant for all H&H decisions. For example, if the decision leads to the design or modification of a high hazard dam, then the utility of paleoflood information is minimal, as the current design standard is based on the Probable Maximum Floods.

- For situations where the assumptions necessary to translate the evidence of paleofloods, or the lack of a paleoflood, into potentially useful H&H information are applicable, the resources necessary to conduct the translation should be weighed against the underlying uncertainties and assumptions. These assumptions include:

    - That the channel and the surrounding watershed have remained stable since the paleoflood;

    - That if statistics are to be applied, the underlying statistical distribution is reasonably assumed to apply across the full range of observations and paleoflood data and that attribution of paleoflood type can be made;

    - That the non-exceedance probabilities are reasonable with respect to the paleoflood information; and

    - That the appropriate hydraulic models can be parameterized and calibrated with confidence.

- Paleofloods can provide direct and useful information about stage histories and can be used, given cautions, to estimate discrete event discharge values. However, there is limited evidence to support using paleoflood information to estimate a series of hydrologic events with multiple peaks, flood volumes, or durations.

- Paleoflood information is less useful if it is meant to inform a portfolio of projects or compare locations across a wide geographic region that has varied terrain and geological contexts. Paleoflood information is largely site specific, meaning that it is collected at one location and not easily transferrable to another. USACE is responsible for many very large facilities that have been altered through time, either by geologic or anthropogenic processes, and these facilities are not suitable for paleoflood analysis.

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1 Introduction

Sustainable integrated water resources management requires consideration of physical infrastructure, government policies, and social systems to provide a holistic focus on water resource challenges and opportunities that reflects coordinated development and management of water, land and related resources (USACE 2011). Global changes are increasing the vulnerabilities of the Civil Works missions of the U.S. Army Corps of Engineers (USACE), including aging infrastructure, hydrologic nonstationarity, demographic shifts and associated urban and coastal development, changes in navigation and shipping practices, and changes in agricultural practices and responsibilities for ecosystem restoration (USACE 2011). The assumptions that defined the physical design and operational considerations for existing projects are, in some places and for some projects, no longer valid, given these global changes. USACE continually assesses the reliability of its infrastructure through evaluations of the potential risks associated with all continuing global stresses over a full range of loading conditions representing minimum essential guidelines.

The USACE Hydrology, Hydraulics, and Coastal (H,H,&C) Community of Practice (CoP) conducts a wide variety of assessments of the stresses on USACE infrastructure, including the design and construction of dams and levees, operation criteria to meet the authorized purposes of projects, flood hazard and response, and water availability. The varied hydrology and hydraulics (H&H) applications require a wide range of currently available data that can be applied to varying scales of economic and technical decisions, and practitioners continually search for additional information that can inform future decisions. The information required to support H&H decisions ranges from frequency estimates of river stage, to total volumetric runoff from one or more hydrologic events, to hydraulic calculations, to assessments of probable maximum floods or precipitation, and its uses can range from portfolio risk assessments to the design of new infrastructure. These varied requirements mean that there is no “one-size-fits-all” approach to the application of information to H&H decisions. Rather, the considerations to determine the information appropriate for the decision at hand take into account:

- The availability of data. The use of available and documented data should be assessed, and new data should be peer reviewed and carefully documented.
- The scope of the decision. The information that feeds into an H&H decision should be as relevant as possible. For example, if a decision is to be made that requires knowledge of hydrologic volumes, historical or future information about hydrologic volumes should be sought.
- The economics of the decision. The economic impacts of a decision should be considered so that the level of effort to obtain information used in making that decision is not disproportionately expensive or time-consuming.
- The national consistency of USACE policies. USACE Civil Works has a national reach, so information used in one location should be consistent with information used in another.
- The mission and goals of USACE. USACE has Congressionally authorized missions, and its projects and systems have authorized purposes. The application of information must be in accordance with these missions and purposes.

Ultimately, having direct foresight of future events that may stress Civil Works projects is the perfect solution. Without knowledge of future events, planners make assumptions as they attempt to characterize the range of future possibilities. The most common assumption is that the observed record is a reasonable predictor of the future. However, this assumption has a variety of drawbacks, including potentially misplaced confidence in characterizing events that are possible but have not been observed. A substitute for knowledge of future events with low probabilities is often sought in the very distant past as well as from streamflow gaging data from the past 10–100 years (the observed record). Paleohydrology describes the evidence of the movement of water and sediment in stream channels before the time of continuous hydrologic records or direct measurements (Costa 1987).

Many types of paleohydrologic information exist, such as dendrochronology, pollen samples, stratigraphy, and marine sediments, and they provide indirect evidence of different types of hydrologic events. Information can be derived with respect to both floods and droughts, though the tools and practices for characterizing these two hydrologic extremes are somewhat different. The application of paleohydrologic information to engineering practices is a specialized field that requires assumptions, costs, and knowledge that differ from those of more common H&H applications.

The goals of this report are to:

- Synthesize the relevant literature and scientific findings related to the utilization of geologically obtained and hydrologically transformed paleoflood data for use in the H&H assessments of USACE; and
- Present reasonable conclusions and recommendations about the use of paleoflood data with respect to the decisions faced by the H&H community within USACE.

This document has been reviewed through an internal USACE process that included H&H experts as well as an independent external review. The external review process—a quality information management review—was conducted by Abt Associates Inc. to enhance the quality and credibility of the report's recommendations by ensuring that the scientific and technical work had received appropriate and objective reviews by independent experts. This is in accordance with USACE's Water Resources Policies and Authorities Civil Works Review Policy (EC 1165-2-209) and the Office of Management and Budget's guidelines under the Federal Data Quality Act of 2000 (P.L. 106-54, Section 1(a)(3)[515]). The report underwent this rigorous review process as it is intended to help inform H&H decisions on resource allocations related to analyses of hydrologic risk characterization.

2 Context for the H&H Use of Paleoflood Hydrology

This report gathers definitions of paleoflood hydrology relevant to USACE design and operations, lists the relevant questions and decisions that face USACE H&H (such as estimating flood peak magnitudes, volumes, and durations for flood damage assessments, or evaluating design criteria using the minimum essential guidelines), and explores the utility of paleohydrology for flood estimation for specific decisions. A subsequent report will describe the design and maintenance questions and possible applications of paleohydrology for water supply or drought estimation.

The report provides some of the rationale and justifications for the appropriate use of paleoflood information for H&H decisions. An underlying assumption is that, over the period of time for which paleoflood information is available, numerous opportunities for floods to represent the hydrology of a particular watershed have occurred. Another assumption is that the paleoflood information is a reasonable predictor of the future for the time period for which a specific H&H decision is being made. This is an extension of the stationarity assumption—that the past is a reasonable expectation of the future—which is discussed later.

Paleoflood information is most often used in characterizing the probability of floods with low probabilities of occurrence (i.e., annual exceedance probabilities of less than 0.002). This makes intuitive sense, because floods with higher probabilities of occurring have a higher likelihood of being observed within the systematic or historical record. This report concentrates on one decision type that often relies on these characterizations of floods with low probabilities of occurrence (infrastructure reliability assessment through risk analysis), but the report and its conclusions are not intended to be limited to this type of decision. This example was chosen because it presents a good opportunity to explore the use of paleoflood information in the context of floods with low probabilities of occurrence that can threaten infrastructure reliability. This example is also beneficial because infrastructure that is threatened by floods exists throughout the geographic domain of USACE, so the concept of national consistency can be explored. The particular concept of risk analysis presented in this report applies both to the potential design and evaluation of site-specific infrastructure and to the entire portfolio, with the intent to prioritize expenditures of resources in a way that reduces risk while meeting the objectives of the organization as a whole.

Risk analysis is useful for evaluating structures subject to vulnerabilities posed by floods, such as dams and levees, and the resulting consequences if there is infrastructure degradation or failure. Dam safety and levee safety both employ risk analysis and often use similar technical approaches, but they do so differently based on different policy objectives, which are described below. Dam and levee safety programs represent significant infrastructure investments within USACE for protecting human life and providing economic benefits. These programs are integral parts of fulfilling USACE policy goals—particularly life-safety goals—that must be met for all of the vast range of USACE infrastructure types and authorizations and for the wide-ranging locations and hydrological conditions where USACE operates.

The USACE policies related to the assessment of risk and the design of dams are potentially conflicting and inconsistent. The policy goal of the Dam Safety Program (ER 1110-8-2 FR, *Engineering and Design - Inflow Design Floods for Dams and Reservoirs*) is that "…a dam failure must not present a hazard to human life…," while ER 1110-2-1156, *Dam Safety – Organization, Responsibilities, and Activities*, states that "Life Safety is paramount. A key mission of the USACE dam safety program is to achieve an equitable and reasonably low level of risk to the public from its dams." The design of USACE dams must meet the minimum essential guidelines in which the Probable Maximum Floods (PMF) derived from the Probable Maximum Precipitation (PMP) can be passed by the dam without failure. By contrast, risk-based assessments of safety recognize that risk levels can never be zero—i.e., it is impossible to achieve no failures—so they use methods to attempt to ascertain meaningful assessments of the risk that does exist and "achieve an equitable and reasonably low level…."

In contrast, the Levee Safety Program has a policy goal to "… make sure that levee systems do not present unacceptable risks to the public, property, and environment" (USACE 2012). The design criteria are not based on the minimum essential guidelines establishing PMP and PMF passage. Therefore, there is a risk associated with levees that is consistent and can be interpreted as being greater than zero.

In addition to evaluating flood risk, dam and levee safety must consider other potential risks to safety. Risks to dam and levee safety span a wide range of potential hazard types, including seismic, hydrologic, design, and operation and maintenance. In this sense, dam and levee safety presents an opportunity to explore paleoflood information within the context of other types of information informing a decision maker. The flood information, assumptions, and limitations that go into their use must be considered with respect to the other information sets also being characterized. For other potential decisions where paleoflood information may be applicable, the scope and scale of the decisions should also be considered when determining the appropriateness of data analysis, such as the characterization of seismic hazards up to the Maximum Considered Earthquake (MCE) (USACE 1995), or the regular observations and detection of infrastructure performance. Within a risk management framework, programmatic objectives are sometimes most efficiently met by allocating resources to the most significant hazards. There is, thus, a need to continually evaluate each of the potential risks in a systematic and consistent manner such that investment decisions can be made to continually provide the safety and economic benefits that are expected from USACE projects. The systematic and consistent evaluation of risk also should provide information for designing corrective actions.

Risk (*R*) is defined within this report as the product of the probability (*P*) of a particular event (*e*) that can or would cause the failure of infrastructure at a particular location (*i*) with the consequences of that failure (*C*):*

$$R_{i,e} = P_{i,e} \times C_{i,e} | P_{i,e} \,. \tag{1}$$

While this report is focused on hydrologic events that could lead to a failure mode, there are other hazard types that can cause performance failures, including seismic events, material degradation, and seepage. Hydrologic risk evaluation should be considered in context with these other risks as well. There are multiple types of hydrologic risks (e.g., convective precipitation events, hurricanes, atmospheric rivers, snowmelt floods). Each event type can have multiple pathways (failure modes) in which they

* There are many specific definitions of risk within USACE guidance documents that are all relatively consistent. For example, ER 1105-2-101 (USACE 2006) defines risk as "the probability an area will be flooded, resulting in undesirable consequences"; ER 1110-2-1156 (USACE 2011) defines risk as "a measure of the probability and severity of undesirable consequences or outcomes." The definition used in this report is intended to be a generalization of risk definition that is consistent with USACE guidance.

threaten infrastructure. Each must be characterized in a comparable manner if policies are to be applied consistently so that corrective action decisions can be made for different failure modes. Equation 1 provides a valuable tool to prioritize investments, both at a particular location and across an inventory of dam and levee assets. The total hydrologic risk at a given location is thus the summation across all hydrologic events (*e*) and across an entire inventory.

As indicated previously, the information necessary to make informed decisions should be scaled to the particular decision and its consequences. For example, levee failure is often evaluated by the probability of exceeding a specific stage within a river reach due to individual and discrete flood events. For large reservoirs or systems of reservoirs, the inflow volume over different time periods that may contain one or more discrete hydrologic events (i.e., 3-, 7-, or 15-day volumes) is the critical metric for determining risk. Risk-based approaches, therefore, must take into account not only the desire for consistency across infrastructure types, but also the different failure modes and the critical metrics for determining the failure modes. Figure 1 depicts the risk management framework including these considerations. For appropriate depictions of projected risks across the entire USACE dam and levee inventory, consistency is desirable throughout all aspects of quantitative risk evaluation, from hazard, to event type, to location, to national perspective.

To be able to quantify risk utilizing Equation 1, USACE, and the risk management community in general, assigns probabilistic attributes (*P*) to hydrologic events using a variety of statistical techniques, physical system modeling, and professional engineering judgment. For example, this can include assigning probability distributions to systematic flood records or using systematic local or regional rainfall records to assign rainfall frequencies and evaluate runoff potentials through rainfall-runoff modeling. For USACE applications, these are described in:

- EM 1110-2-1411 (USACE 1965), *Standard Project Flood Determination*;
- EM 1110-2-1413 (USACE 1984), *Hydrologic Analysis of Interior Areas*;
- EM 1110-2-1415 (USACE 1993a), *Hydrologic Frequency Analysis*;
- EM 1110-2-1416 (USACE 1993b), *River Hydraulics*;
- EM 1110-2-1417 (USACE 1994), *Flood-Runoff Analysis*;

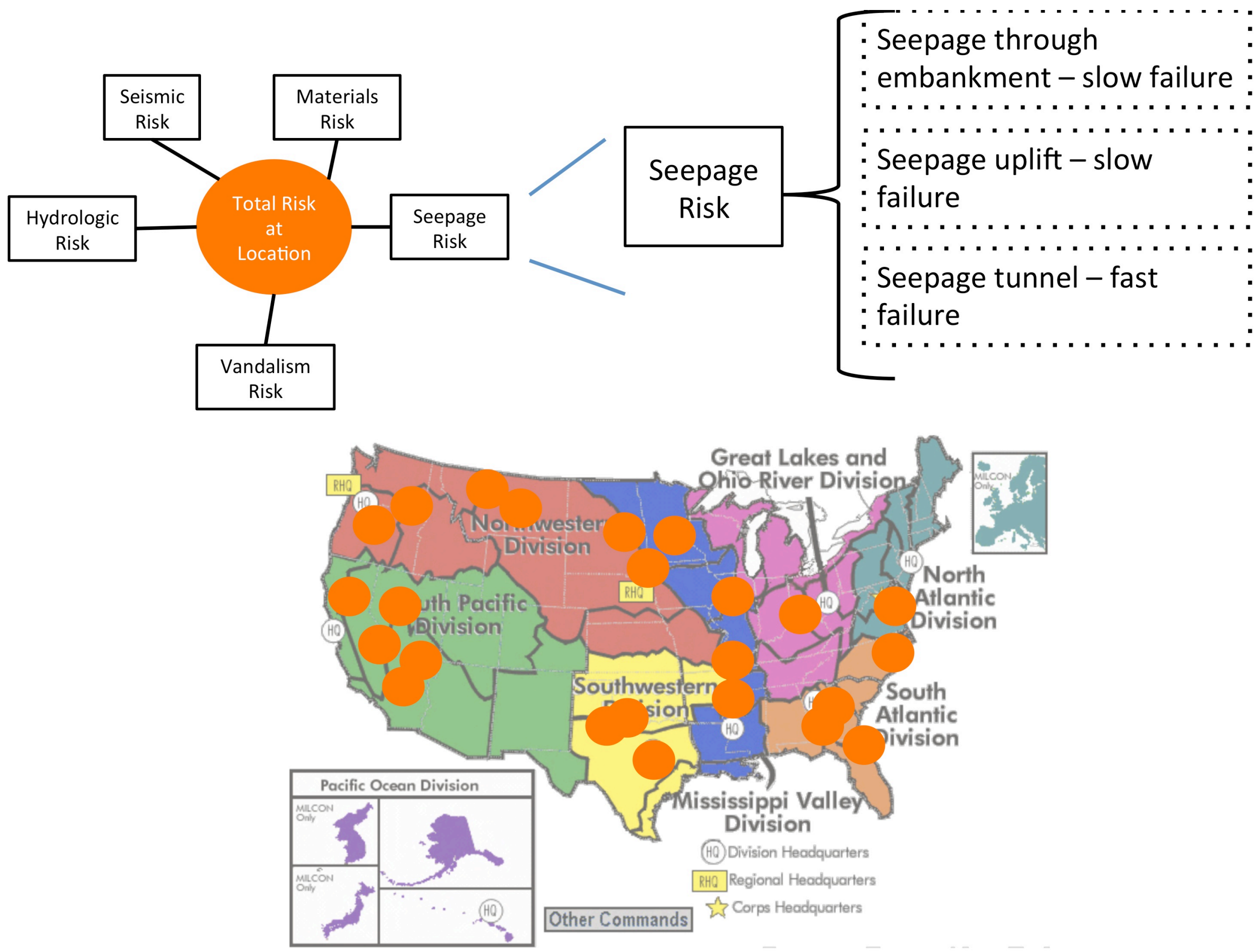

Figure 1. Example of developing a portfolio of risks utilizing Equation 1. For information to inform decisions of resource allocation to reduce risk, each aspect of individual failure mode risk, failure modes for each location, and locations across infrastructure inventory must be consistent and comparable.

- EM 1110-2-1419 (USACE 1995b), *Hydrologic Engineering Requirements for Flood Damage Reduction Studies*; and
- EM 1110-2-1619 (USACE 1996), *Risk-Based Analysis for Flood Damage Reduction Studies*.

The most common approach used in these guidance manuals for assigning probabilities to discrete hydrologic events is frequency analysis. The frequency analyses are primarily based on the period of observed record to make assertions about non-exceedance probabilities on the order of 10^{-2} to 10^{-3}. There are and should be some limits to the extrapolation or interpretation of information when utilizing short systematic records, as indicated later in this report. This range of annual exceedance probabilities (AEPs), 10^{-2} to 10^{-3}, is often in the range of somewhat reasonable extrapolation given an approximate 50- to 100-year period of systematic or historical record. Where risks to public safety and populations are especially large, which is the case for many USACE dams and levees, the design risk (i.e., for little to no loss of life) likely requires *P* values much smaller than 10^{-2} or 10^{-3}. For this reason, hydrologic hazard estimates should be ascertained with orders-of-magnitude smaller non-exceedance probabilities.

To provide the information in the range of AEPs used in dam and levee safety, there are choices facing the USACE H&H practitioner for every application. These include what information to use, how to use the information, how much time to spend, and how to characterize the uncertainty associated with the results. There are four methods primarily used in engineering practice to estimate hydrologic event probabilities in this range of AEPs (Maidment 1992):

1. Extrapolation of a flood frequency curve, utilizing (where possible) historic floods and paleofloods and regionalization;
2. Extrapolation of rainfall frequency data to very low probabilities and estimation of the flood from this;
3. Generation of very long series of rainfall events from a stochastic rainfall model, estimation of the floods from the largest rainfalls, and use of a frequency analysis of these large floods; and
4. Estimation of the probable maximum flood and use of either this or a smaller flood derived from it.

This report explores, specifically, the assumptions and application with respect to the use of paleoflood information within the context of USACE H&H studies for risk estimation. This report presents the information available from paleoflood field data, the hydraulic and hydrologic calculations and assumptions that can be used to transform the field data into frequency information, and recommendations for the use of that information. For a complete review of the history of paleoflood information, which is not the purpose of this report, the reader is directed to Baker (2008).

3 Paleoflood Data Collection: Determination of Stage

Paleohydrology is the study of the evidence of the movement of water and sediment in stream channels before the time of continuous hydrologic records or direct measurements (Costa 1987). To inform risk management applications, information about very large hydrologic events that have occurred, or about bounds on floods that have not occurred, over a period of time is assembled from indirect evidence in slackwater deposits and other paleostage indicators. These floods, whose characteristics are assembled through this indirect evidence, are deemed paleofloods (Kochel and Baker 1982, Baker 1987). Baker (2008) described paleofloods as “past or ancient floods that occurred without being recorded by either (1) direct hydrological measurement during the course of operation …, or (2) observation and/or documentation by non-hydrologists.” Field measurements of paleofloods take place through measurement of the stage of the ancient flood utilizing the evidence that remains from the events (e.g., Baker 1987). Field measurements can also identify evidence that helps determine that certain stages have not been exceeded for a given time period (e.g., Levish 2002).

Evidence of paleofloods is commonly measured through slackwater deposits left where flood flows are separated from the primary channel velocity (Kochel and Baker 1988). A good description of how to look for slackwater deposits is given by Sridhar (2012) in a study of Holocene flood records of the Mahi River in western India, although the hydraulics are appropriate globally:

> “For paleoflood studies, a slackwater sedimentation site should be optimum for both the accumulation and preservation of the relatively fine-grained sediments carried high in flood flows at maximum stage. The ideal sites of deposition and subsequent preservation of slackwater deposits are the tributary mouths, channel-margin alcoves, caves and rock shelter deposits. The local hydraulic conditions at these sites result in a drop in the flow velocity and deposit flood sediments. In all alluvial terrain, however, such conditions seldom prevail and hence the slackwater sediments are not well preserved so as to give significant paleohydrological inferences.”

Geologists determine the paleostage (the height above the channel bed) and ages of slackwater deposits at the locations where indicators are preserved (Figure 2), and estimate the age at which they were deposited through radiocarbon dating or other techniques (e.g., Stokes and Walling 2002). The stratigraphic record has long been used in estimating stage to evaluate flood histories adjacent to rivers (e.g., Mansfield 1938; Patton et al. 1979; Jarrett 1991). The stratigraphic example from Harden et al. (2011) shown in Figure 3 is documented by them as follows:

> "Two pits were excavated 0.5 mi upstream from Superscour Alcove at Hailstorm Alcove.... Pit A provided evidence of three floods since 382–192 B.C. The middle flood unit (II) was dated to A.D. 1296–1410 and is likely the same flood as described later in this section for the Temple of Doom Alcove. The most recent flood deposit in pit A is from 1972, with its relatively low elevation requiring a flow of 10,000 ft^3/s for inundation. Pit B had evidence of two floods, the most recent being from 1972. The oldest flood unit (II) in pit B likely correlates with flood unit II in pit A. Because pit B is lower than pit A, corresponding flow values are smaller for pit B, thus limiting the utility of this pit in developing the overall flood chronology. A thin layer of flood sands that were dated to A.D. 1486–1644 was identified in a small crevice about 3 ft higher that pit A. The corresponding flow for deposition of these sands is about 18,200 ft^3/s. ..."

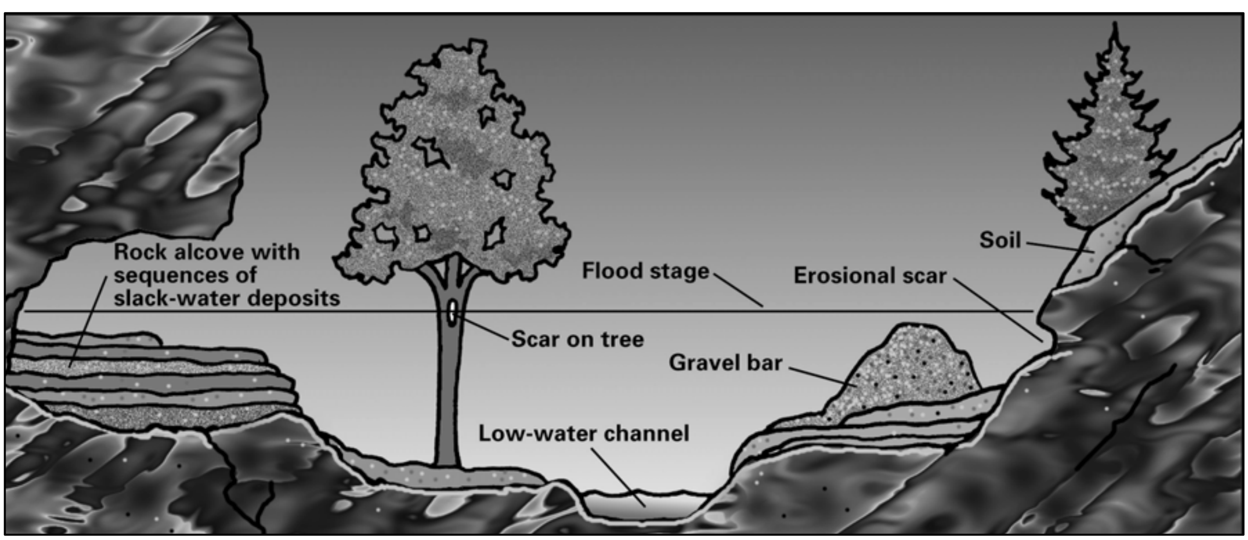

Figure 2. Example cross-section showing various paleoflood indicators, including slackwater deposits. (Adapted from Jarrett and England 2002.)

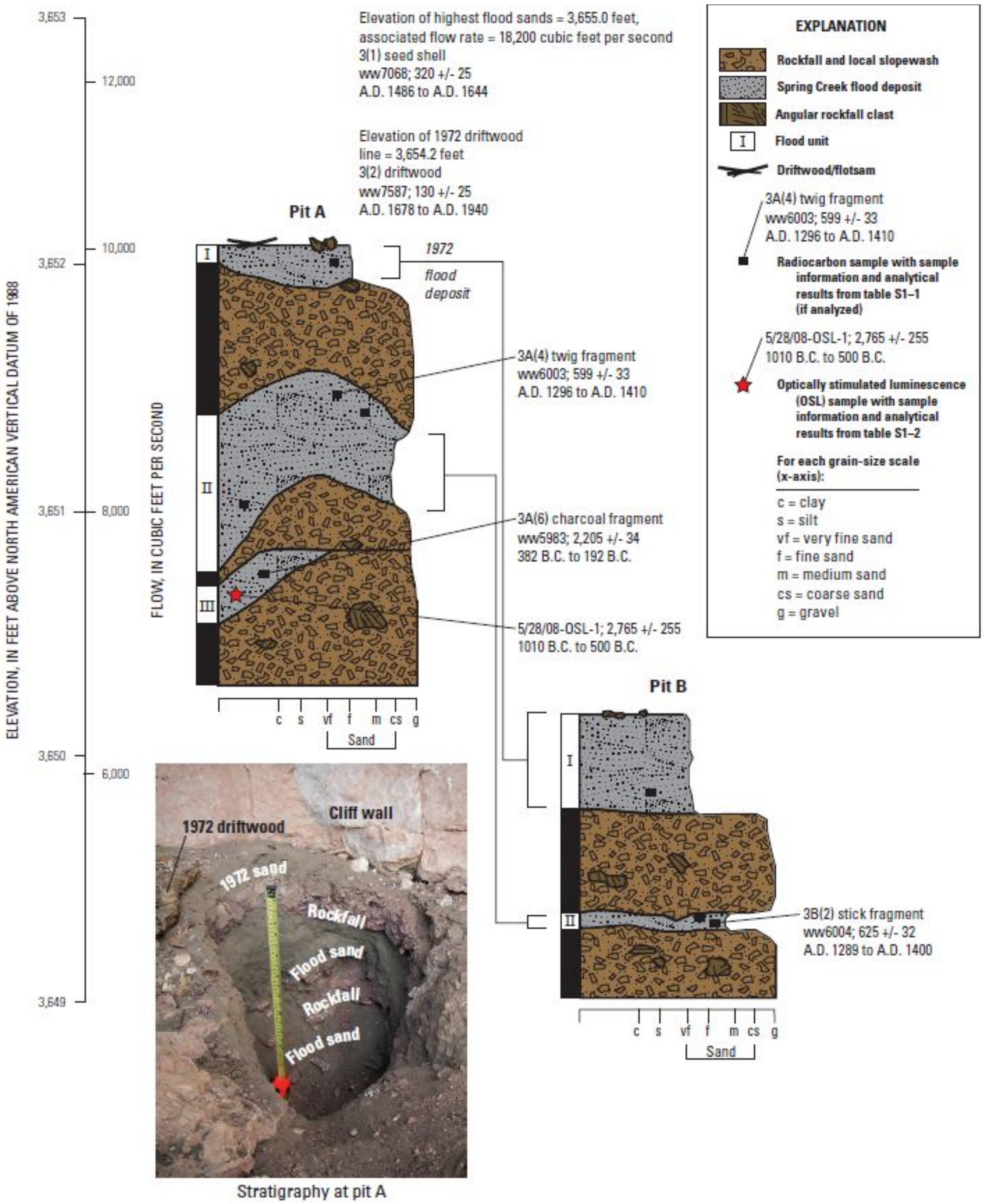

Figure 3. Example stratigraphy showing paleoflood information for Hailstorm Alcove, Spring Creek, Black Hills, South Dakota. (From Harden et al. 2011.)

Information from stratigraphic records can provide paleoflood stages for individual events that occurred over a very wide range of the distant past. The uncertainties associated with the information will be discussed later in this report. The uncertainty associated with radiocarbon dating, which can be on the order of 100 years for a sample with an age of 10,000 years (Stedinger and Baker 1987) will not be addressed further; this uncertainty is not large if the time history is an order of magnitude older. However, where assumptions for interpreting paleoflood data cannot be supported, or where slackwater deposits from paleofloods (e.g., House 2002a,b) are not available at a particular location (Figure 4), then different information types may be available to provide information about stages that have not been exceeded over a given time period. Figure 4 is an example of a map that identifies where slackwater deposits might be expected to be found. Unfortunately, while there has been much progress in locating paleoflood information by academia and Federal agencies such as the Bureau of Reclamation, there is no standardized data warehouse to readily access or share this information, nor are there consistent peer-review guidelines to assure quality. Further, this information only applies to geographic areas where the geology is suitable, and it is not reasonable to expect that slackwater deposits are available in all locations; there are natural limitations in areas outside the well-studied arid and semi-arid climates (Kite et al. 2002).

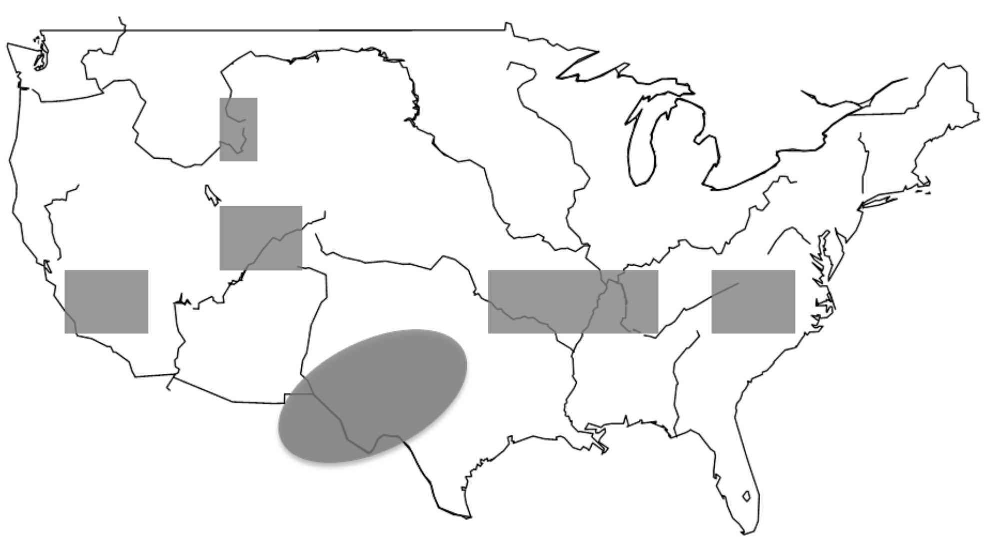

Figure 4. 1982 assessment of locations where slackwater deposits were favorable for paleoflood determinations. Without question, more slackwater deposits have been located since then, but they remain limited in geographic availability and no more-recent map exists. (Adapted from Kochel 1988.)

There are other methodologies that can expand the geographic availability of paleoflood data. Overbank deposits have been used as indicators, though they do not always clearly resolve flood magnitudes (e.g., Wang and Leigh 2011). Additional indicators of paleofloods include high water marks such as tree scars, erosional scars and gravel deposits (also included in Figure 2). Each method of determining the presence of a paleoflood has application over a range of elevations or time periods.

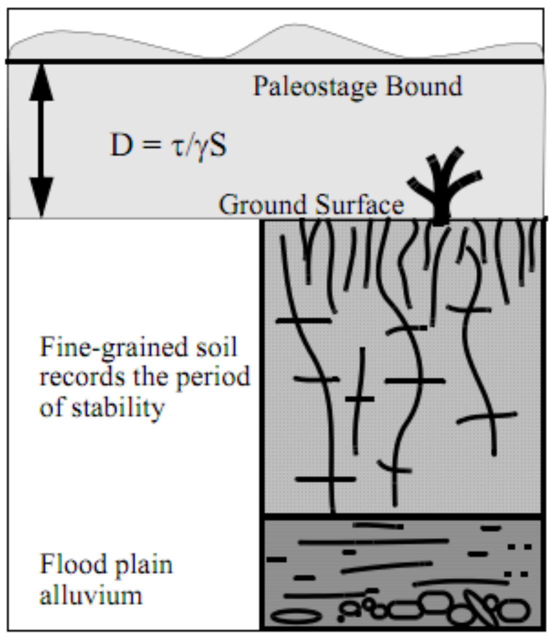

Figure 5. Paleohydrologic non-exceedance bound development. The significant depth (D) necessary to mobilize the stable surface is a function of the shear stress (τ), the specific gravity of the water (γ), and the slope of the surface (S). (From Reclamation 2003.)

Paleohydrologic bounds represent estimated stage thresholds that have not been exceeded at a location of interest over a time period (Levish 2002). These estimates are based on the long-term stability of easily modified surfaces adjacent to the river. The hypothesis is that flow of a significant depth over the surface creates a shear stress sufficient to mobilize sediment and thus destabilize the surface (Figure 5). Thus, if a paleohydrologic bound were exceeded through inundation by a large flood, the surfaces would be disrupted (e.g., House et al. 2002a; Levish 2002). The depth at which the shear stress is large enough to mobilize the sediment can be estimated using sediment transport theory (e.g., Julien 1995), and the sensitivities of the results can be explored through sensitivity analyses (e.g., Bauer and Klinger 2010). These sensitivities include varying the range of depths that might be necessary to mobilize sediment. This sensitivity can be carried through calculations of stage and elsewhere (as discussed later). This sensitivity can ultimately be viewed as additional uncertainty within the analyses. There are also potential limitations to application of shear stress theory where vegetation exists in the flood plains either currently or in the past; it would be difficult to discern what shear stress is necessary to mobilize sediment that has vegetation growing on its surface. Where paleoflood indicators and bounds are available, a series of estimates of both stages that have been exceeded over a given time period and stages that have not been exceeded are potentially available.

The resources associated with gathering paleoflood information are the costs of time associated with a field study, the costs associated with dating the materials gathered from the field, and the synthesis work to combine dates and stages.

4 Calculation of Paleoflood Discharge

Discharge can be calculated from the stage information gathered during field investigations in three primary ways: empirical relationships, one-dimensional modeling (e.g., Benson and Dalrymple 1967; Webb and Jarrett 2002), and two-dimensional modeling. Each method requires different data sets and has different underlying assumptions, so each is associated with different resources required and uncertainties in results.

4.1 Empirical Relationships

There are two primary empirical relationships that provide links between stage and discharge. The first are stage–discharge curves (Figure 6). Within these relationships are observed flood events with observed values of instantaneous peak discharge and the stage associated with that flow. Stage–discharge relationships for long, straight, uniform channels often take the form of a power law equation of this form:

$$Q = C\,(h + a)^N \qquad (2)$$

where:

Q = discharge
C and N = constants
h = stage
a = stage at which discharge is zero (Maidment 1992).

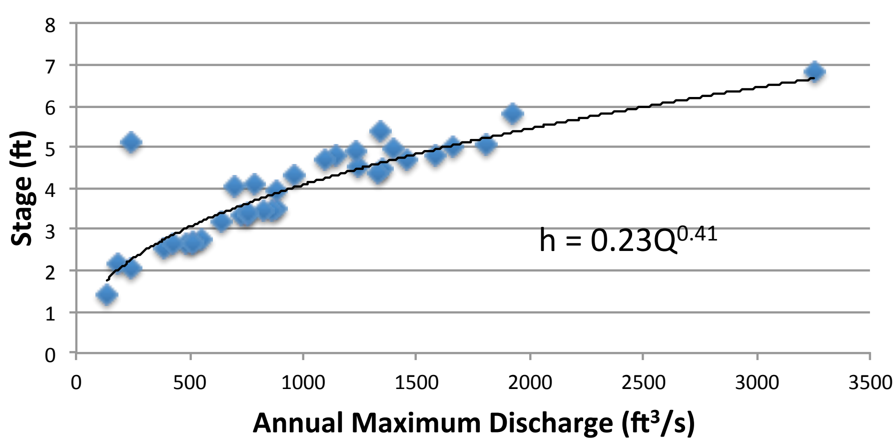

Figure 6. Sample stage–discharge relationship for the Laramie River at Laramie for 1933–1967. This example function was calculated directly from the unmodified record from the USGS NWIS database. (From waterdata.usgs.gov/nwis, accessed November 7, 2011.)

This approach is simple and direct but assumes that sufficient data exist to provide a statistically significant relationship. Uncertainties associated with stage–discharge relationships are typically on the order of 5–10% for low flows but can be much higher for a flood or paleoflood. Stage–discharge relationships include values of *Q* and *h* that are often significantly less than the paleoflood of interest because paleofloods exceed anything that has been observed since. Also, the physical nature of the channel form—the flood plains and terraces—that provides the paleoflood stage information likely leads to discontinuities in the stage–discharge relationship; these discontinuities make it unlikely that extrapolation of an equation similar to Equation 2, or one where overbank flows are considered in the rating curve but not at the desired magnitude, will provide reliable estimates (ISO 1983).

The second empirical relationship that provides direct links between stage and discharge is Manning's equation used with the continuity equation ($Q = AV$, where A is defined below and V is water velocity):

$$Q = \frac{1.486}{n} A R_h^{2/3} S_f^{1/2} \tag{3}$$

where:

A = cross-sectional area of the channel
R_h = hydraulic radius
S_f = friction slope
n = characteristic roughness.

The form represented in Equation 3 is applicable when calculated in English Standard Units.

To determine paleoflood discharge, the paleoflood field investigation can take survey measurements of the channel at the location where the stage information has been collected. Friction slope can be assumed to be the same as bed slope and can be surveyed in the field or calculated from a topographic map. If one- or two-dimensional modeling is planned to be used, there is no reason to apply Manning's equation, so that approach is not discussed further.

The channel roughness can be determined using field manuals such as Barnes (1967) and Hicks and Mason (1991). The standard error in estimation of n is ±30% (Maidment 1992). Errors in estimating roughness coefficients can be expected to introduce less than 20% error in discharge estimation for step-backwater simulations in canyon rivers with channel gradients under 0.01 (Wohl 1998). There is varied understanding about the uncertainties associated with other indirect measurements of discharge and the time between the event and the measurement.

Although Manning's equation is a well-known and widely applied empirical hydraulic model, its application in a paleoflood context has additional uncertainties that are not usually encountered. First, it is not well known how the surveyed shape of the channel, and thus the cross-sectional area and the hydraulic radius, compares with the cross-sectional area during the paleoflood event. Any errors (or sensitivity analyses) in these measurements result in an exponential uncertainty in the calculation of discharge.

The friction slope is, by definition, the slope of the energy grade line. For cases of "uniform flow," where the depth of the water surface does not vary significantly over a length of river, it is possible to substitute bed slope for friction slope. However, substituting bed slope for friction slope introduces additional uncertainties because the water surface profile, and thus the energy grade line, is not known for the actual paleoflood event. However, in determinations of Q, the significance of this uncertainty (or exploration of sensitivity) is somewhat reduced because of the square root relationship between friction slope and discharge.

Additional uncertainties are introduced in assuming a characteristic roughness and accounting for other types of energy losses. Field manual guidance for estimating roughness requires comparisons between the rocks in the channel, vegetation, woody debris, flood plain grasses, and other considerations to assume a single value of roughness. No methods are known for aggregating multiple flood plains and terraces to assume a single value of roughness. The channel can be divided into a main channel and flood plains, each being assigned a different roughness value. This would eliminate the difficulty in assigning a single roughness value. Sensitivity analyses are also possible, and they represent a valid approach to characterizing some aspects of uncertainty in assigning roughness values. Moreover, the types and coverages of grass, vegetation, woody debris, etc. during the paleo event are almost always unknown.

4.2 One-Dimensional Modeling (Step-Backwater Method)

To counter some of the shortcomings of empirical approaches to determining discharge from paleoflood stage, physical modeling approaches are sometimes used. The least resource-intensive physical approach is to apply a one-dimensional physical model in a step-backwater method. Applied to paleofloods (O'Connor and Webb 1988), the physical basis is conservation of energy along a single flow line (Chow 1959):

$$Z_1 + h_1 + \frac{\alpha_1 v_1^2}{2g} = Z_2 + h_2 + \frac{\alpha_2 v_2^2}{2g} + h_f \tag{4}$$

where (subscripts denote two locations within the hydraulic system):

Z = thalweg elevation
h = stage
$\frac{\alpha_1 v_1^2}{2g}$ = kinetic energy
v = velocity
g = gravity
α = energy coefficient
h_f = frictional head loss.

This is an appropriate expression of conservation of energy for gradually varied flows, with the necessary assumptions that the loss of energy is the same for a uniform flow having the velocity and hydraulic radius of the channel section of interest. Discharge can then be calculated from velocity and channel shape as measured in the field. Implementation requires calculating the energy loss caused by friction using the empirical relationships described above for Manning's equation and in Chow (1959) for eddy losses. The sensitivity of results associated with roughness coefficients can be explored by applying a range of roughness values (e.g., England et al. 2010).

The application of the step-backwater methods requires a number of additional assumptions, including, but not limited to:

- That the cross sections measured and used are spaced so that the flow characteristics do not change significantly between them;
- That the discharge being modeled affected the entire reach at the same time;

- That the flow is "steady" and one-dimensional;* and
- That the boundaries of the channel are constant.

The most significant concerns are the assumptions of one-dimensional behavior and constant boundaries. Some estimate of approximate uncertainties can be explored through sensitivity analyses of assumptions on channel geometry.

Floods are inherently multi-dimensional phenomena with two- and three-dimensional attributes of flood plains and eddies that are difficult to account for empirically. Stable channel geometry requires that the cross sections of the channel at the time of the paleoflood are the same as when the cross section measurements were taken. This approach is useful for bedrock channels that are known not to have been re-formed since the paleoflood (Baker 2008). As specified by O'Connor and Webb (1988), "best results are achieved for hydraulically simple reaches in stable channel systems that contain several representative paleoflood high-water indicators."

Of special importance in a risk analysis application, all information must be in a geographic location at or transferrable to the location of interest. If transferrable, this transfer induces uncertainties not discussed in this report. Although one-dimensional models may be informative from a physical perspective, they have many limitations, as described by Carrivick (2006):

> "Whilst these 1D 'step-backwater' models compute energy-loss between successive cross-sections and either subcritical or supercritical flow regimes, they are unable to model many features of high-magnitude floods. Indeed step-backwater models, slope area methods and other paleohydrologic methods only provide reconstructions of peak discharge. Thus these methods do not provide information on how flow conditions varied before and after peak stage, or how long peak discharge persisted. Other features of high-magnitude floods are also excluded, such as rapidly varied flow, or specifically; simultaneous inundation

* Not all one-dimensional hydraulic models assume "steady" flow. Unsteady one-dimensional models are available but require additional assumptions, calibration, and validation to conduct an unsteady analysis.

> of multiple channels, sheet or unconfined flow, simultaneous channel and sheet flow, flow around islands, hydraulic jumps, multi-directional flow including backwater areas, hydraulic ponding and multiple points of flood initiation. Without a quantification of the hydraulics associated with these flow conditions, high-magnitude flood impacts cannot be fully understood."

The practical application of a physical modeling approach to a paleoflood study requires significantly more resources than do empirical methods, and users must recognize that one-dimensional modeling of paleofloods represents a different application of hydraulic models than do normal H&H assessments. The field investigations must sample enough cross sections to satisfy the assumption that the flow is not changing significantly between them. Also, sufficient datable material needs to be collected to age flood deposits or terrace surfaces to provide consistent paleoflood information for each flood deposit and throughout a paleoflood study reach or reaches. Finally, additional hydraulic modeling must take place to conduct the step-backwater analysis. The actual computations can be done relatively easily through application of HEC models, and a wealth of applications could be cited (e.g., England et al. 2010). A properly calibrated one- or multi-dimensional model can address some of the hydraulic features characterized by Carrivick (2006). However, except for the single case of a bedrock-confined single channel, it is not possible to know with any certainty the hydraulic features of a paleoflood. Therefore, it is also not possible to calibrate or validate a more complex hydraulic model. In most cases, when one-dimensional hydraulic models are used, the step-backwater steady flow assumptions are used without characterization of complex hydraulic features.

4.3 Two-Dimensional Modeling

In cases where empirical approaches and one-dimensional modeling assumptions are not supported, it is possible to account for additional flood complexities through the application of physically based two-dimensional hydraulic modeling. As with one-dimensional modeling, two-dimensional modeling is a physical approach, based on first-order principles that can relate stage to discharge for a discrete paleoflood event. Unlike one-dimensional modeling, two-dimensional modeling allows for considerations of secondary currents of flood flows, which are likely to be a more realistic representation of large floods. Discretized two-dimensional modeling for paleoflood analyses proceed by solving conservation of mass and conservation of momentum equations (Equations 5–7), known as the St. Venant equations (e.g., Chow et al. 1988):

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0 \quad \text{(continuity)} \tag{5}$$

$$\frac{\partial(hu)}{\partial t} + \frac{\partial(hu^2)}{\partial x} + \frac{\partial(huv)}{\partial y} + gh\frac{\partial h}{\partial x} = -gh\frac{\partial z_b}{\partial x} - gn^2u\frac{\sqrt{u^2+v^2}}{h^{\frac{1}{3}}} \quad \text{(x-momentum)} \tag{6}$$

$$\frac{\partial(hv)}{\partial t} + \frac{\partial(hv^2)}{\partial y} + \frac{\partial(huv)}{\partial x} + gh\frac{\partial h}{\partial y} = -gh\frac{\partial z_b}{\partial y} - gn^2v\frac{\sqrt{u^2+v^2}}{h^{\frac{1}{3}}} \quad \text{(y-momentum)} \tag{7}$$

where:

h = stage
u = velocity in the x-direction
v = velocity in the y-direction
t = time
g = gravity
n = roughness characteristic.

Frictional losses between adjacent cells are also added and are necessary to solve the St. Venant equations in practice for flood modeling. The paleoflood stage measurements are used as the solution criteria when solving the St. Venant equations to calculate discharge. Frictional losses use empirical roughness coefficients similar to Manning's equation that can be varied to explore the sensitivities of the results (e.g., Bauer and Klinger 2010).

Ideally, the entire reach of river of interest is modeled in a gridded fashion, although some reaches may be successfully modeled with cross-section geometry only. For a gridded fashion, the best current data that could be available would likely be lidar data. There is a large effort by both the states and the Federal government to acquire additional lidar data with the intent to have complete continental U.S. coverage. The information is currently available from a variety of sources in a patchwork fashion across the country, though the USGS Center for LIDAR Information Coordination and Knowledge* does provide a relatively comprehensive source of information.

* See http://lidar.cr.usgs.gov/

The solution to the two-dimensional equations is capable of describing many of the complexities of floods, although significant assumptions must still be maintained. Among these is that the gridded surface to be modeled is the same now as it was during the paleoflood event, that the location to be modeled is at the location of interest for determining risk or is transferrable, and that the flow characterization as steady or unsteady and uniform or nonuniform is consistent with the actual event. When appropriate assumptions are supportable, it is possible that the solutions can be obtained for very complex flood flows (e.g., Carrivick 2006). When a two-dimensional model is applied, care must be taken not to satisfy assumptions by oversimplifying the physical processes and thereby reduce the robustness of the solution.

The data requirements and resources associated with collecting information to conduct two-dimensional analyses can be significantly higher than for a one-dimensional or empirical approach. Moreover, the computational complexities of running two-dimensional models are significantly greater than for one-dimensional models, although government, academic, and commercial software is available and has been widely applied.

5 Calculation of Paleoflood Volume

Section 4 focused on methods of calculating instantaneous discharges associated with the stages measured in the field. There are many H&H decisions that are based on volumes, rather than discharges. For paleoflood information to inform these decisions properly, it is necessary to calculate the volumes associated with stage and discharge measurements. There exists at present no peer-reviewed literature that advocates or identifies how to directly infer hydrographs from paleoflood evidence; however, there are two primary means by which this can be done based on the discharge calculations determined using the methods discussed in Section 4. The first is to assume a characteristic hydrograph shape, and the second is to conduct a precipitation analysis.

5.1 Hydrograph Shape

The most straightforward way to calculate a volume associated with a peak discharge is by assuming the shape of the event hydrograph. This can be done either by assuming a unit hydrograph shape for the location of interest or by utilizing a hydrograph shape or shapes that have been observed at the location of interest.

The unit hydrograph represents the pulse response function of a linear hydrologic system (Sherman 1932; Chow et al. 1988). A unit hydrograph represents the input of a unit of water into a watershed and the timed outflow hydrograph at a location of interest. To estimate a paleoflood volume, it can be assumed that some rainfall event increases the input to the unit hydrograph model such that the peak of the hydrograph is equal to the peak discharge calculated in a manner described in Section 4. This can also be extended to observed hydrographs, and it can be assumed that they represent the basin response to rainfall input for a variety of magnitudes. Figure 7 represents this approach for both a unit hydrograph and an observed hydrograph. For the unit hydrograph approach (and similarly for an observed hydrograph that can be standardized for each unit of rainfall input), it begins with a unit hydrograph that has been developed appropriately for the basin of interest with some base flow component. To estimate volume, every ordinate within the rainfall portion of the unit hydrograph is multiplied by $\frac{Q_p}{Q_u} - B_{tp}$, where Q_p is the paleoflood discharge, Q_u is the maximum

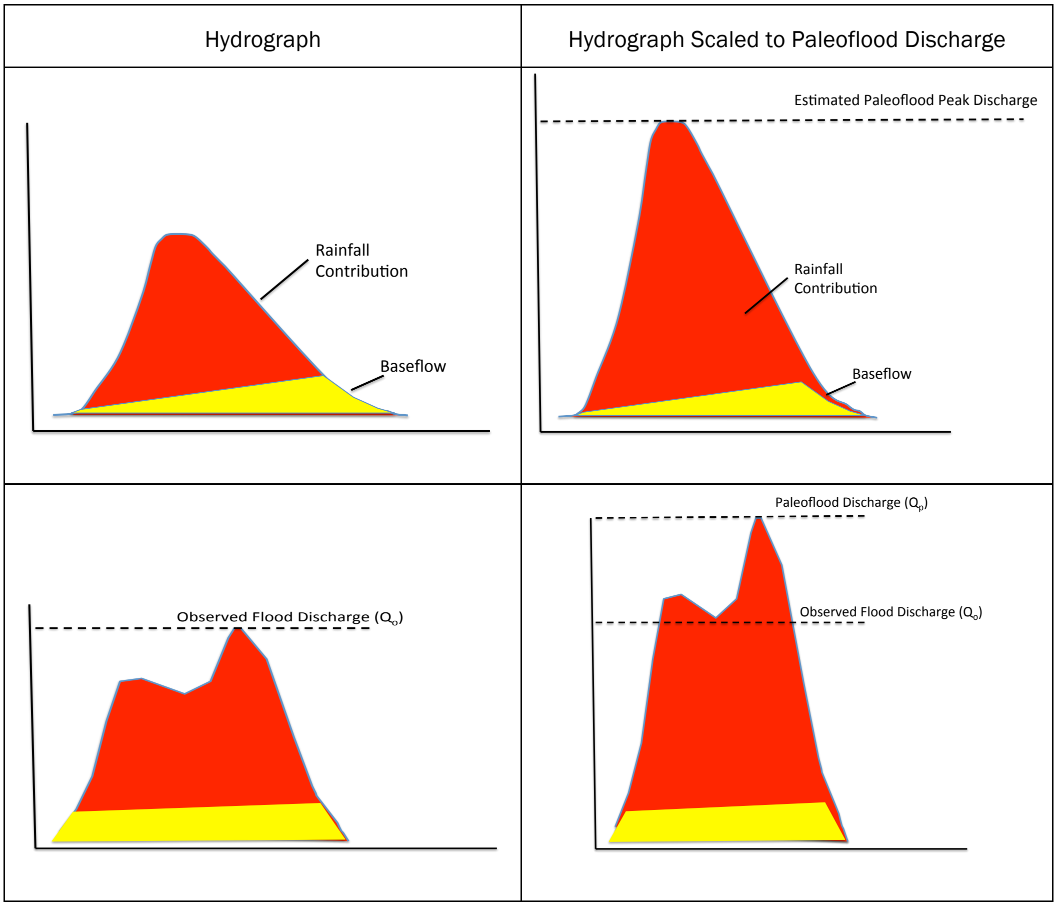

Figure 7. Example of hydrograph scaling through either a unit hydrograph approach (top graphs) or an observed hydrograph approach (bottom graphs).

discharge in the unit hydrograph, and B_{tp} is the base flow rate at the time of Q_u. In this manner a new hydrograph is developed from which a volume of the paleoflood can be calculated.Assumptions for the unit hydrograph approach include:

- That the excess rainfall has a constant intensity within the effective duration;
- That the excess rainfall is uniformly distributed throughout the whole drainage area;
- That the base time of the direct runoff hydrograph is constant; and
- That, for a given watershed, the hydrograph resulting from a given amount of excess rainfall reflects the unchanging characteristics of the watershed.

Where the unit hydrograph application is deemed too simplistic, observed hydrograph shapes from the basin of interest can be used. In this approach an observed hydrograph of a flood event is assumed to be characteristic of the watershed's response to extreme precipitation. Base flow is characterized, using observed flows in the basin and engineering judgment, for the flood event. Each ordinate of the rainfall contribution to the flood is then scaled by $\frac{Q_p}{Q_o} - B_{tp}$ in the same manner as for the unit hydrograph approach. The advantage of using observed hydrographs is that multiple hydrographs can be used to account for sensitivities in shape in producing overall volume estimates. As with the unit hydrograph approach, there are significant assumptions about the rainfall runoff response inherent in the scaling approach to any hydrograph.

5.2 Precipitation Analysis

Another approach for estimating paleoflood volume is to combine a precipitation analysis with the paleoflood discharge estimated through an approach described in Section 5.1. Where the assumptions of rainfall homogeneity in time and space are not warranted for a unit hydrograph approach as described above, a precipitation approach can add heterogeneity that better reflects the physical rainfall process.

In this approach, various rainfall intensities, durations, and locations can be explored in a stochastic manner. The rainfall generation is coupled to a runoff model, and the generated rainfall isohyets can be manipulated until the peak discharge at the location of interest matches the paleoflood discharge calculated through methods described in Section 5.1. This can be obtained by stochastic storm transposition (Franchini et al. 1996) and rainfall scaling or through the direct use of a rainfall frequency curve coupled with a stochastic representation of the runoff process (e.g., HEC 2003; Bullard et al. 2007). For sufficiently large basins, the number of possible rainfall patterns and combinations that could theoretically produce the paleoflood peak is large. Each of these has a different hydrograph and thus a different volume. If volume is the variable of interest, it may be prudent to explore the sensitivity of the results to hydrograph shape.

It should be apparent that this type of precipitation approach not only includes the physical processes of rainfall, but also allows much greater flexibility, thus potentially providing a more direct estimate of volume runoff. The NRC (1988) and HEC (2003) both note that utilizing stochastic techniques of rainfall runoff along with the paleoflood information provides a sounder basis from which to estimate extreme runoff. This type of approach is consistent with EM 1110-2-1417 (*Flood Runoff Analysis*), which states that "streamflow peaks or volumes of a specified frequency can be caused by an infinite number of combinations of storms and watershed states." An approach that uses the stochastics of various physical processes does not require assumptions of single watershed states or responses to single precipitation events. This, of course, comes at a resource cost, both in time and in the complexity of calculations. This type of approach also requires a great deal of engineering judgment to transform the myriad of potential solutions into usable products for decision making on a case-by-case basis.

6 Application of Paleoflood-Derived Information

6.1 Assumptions

Application of paleoflood information should take into account the various assumptions and uncertainties used in the development of the information described in Sections 2–5. It is always possible to employ equations and solve them, but assessments of these assumptions should not be ignored. Where assumptions are not justifiable, other sources of information should be sought or the decision requirement altered to one for which reliable information is available, potentially through the application of risk-averse decision making. Of critical importance in any potential application of paleoflood information is landform stability, that is, that the river and flood plains have remained stable between the time of the paleoflood and the current era when calculations are being made. Furthermore, in characterizations of the flood frequency analysis described below, the assumption that the rainfall runoff response during the paleoflood is similar to current mechanisms must be supported. Changes in vegetation, soil moisture characteristics, and urbanization all affect the response of a basin to rainfall. The question about whether a rainfall event that occurred today would have had the same flood response throughout the paleoflood time period should be answered. For small headwater basins with little vegetation or geologic change, this is a reasonable assumption. For large basins with significant regulation, urbanization, agricultural development, or other changes, this seems much less likely.

6.2 Flood Frequency Analysis

The ability of flood frequency methodologies to account for paleoflood information has been advanced over the past decade through the development of methods such as the expected moments algorithm (EMA) (e.g., Cohn et al. 1997; England et al. 2003), which allows for the fitting of a Log-Pearson Type III distribution including paleoflood information. England et al. (2003) assumed that the paleofloods were perfectly known, so the uncertainties in discharge estimates were not evaluated; however, implementation techniques that allow uncertainties to be quantified are available.

Alternatively, methods to include paleoflood information have been developed for other distributions in a parametric Bayesian framework (O'Connell et al. 2002) or in a nonparametric manner (O'Connell 2005). Each of the methods discussed here relates to the application and fit of frequency curves to stage and discharge. As mentioned earlier, there was no literature found on the development of volumetric information or duration directly from paleoflood information.

Figure 8 illustrates the effect of using additional information such as paleoflood data with observed data. Paleoflood information can alter the calculated probabilities, so the observed floods can either reduce the probability of occurrence (Figure 8, top) or increase the probability of occurrence (Figure 8, bottom). There have been other examples that demonstrate how paleoflood information can inform flood frequency estimates of stage and peak discharge (e.g., Stedinger and Cohn 1986). What remains unknown, as is illustrated by Figure 8, however, is whether or not the paleoflood estimates come from the same distribution as the observed flood events. While methods applied over the entire probabilities of interest provide "fit" at any specific point within the frequency distribution, it is unknown whether the fit is an improvement to the actual characterization of flood frequency or simply an artifact of statistical manipulation. In both cases illustrated in Figure 8, the addition of the k^{th} largest floods reduces the fit of the actual observed gaged floods. The question then arises whether the distribution is a reasonable fit across all of these floods. For example, in the Bear Creek flood frequency curve, if the k^{th} largest floods (paleofloods) were generated by a particular mechanism (say, snowmelt) and the observed floods represent a different mechanism (say, discrete rainfall events), then the rainfall flood frequencies are being manipulated by snowmelt floods. For the case of the use of a non-exceedance bound, this is of less concern because the statement that a certain stage has not been exceeded would remain accurate, no matter the mechanism of flood generation.

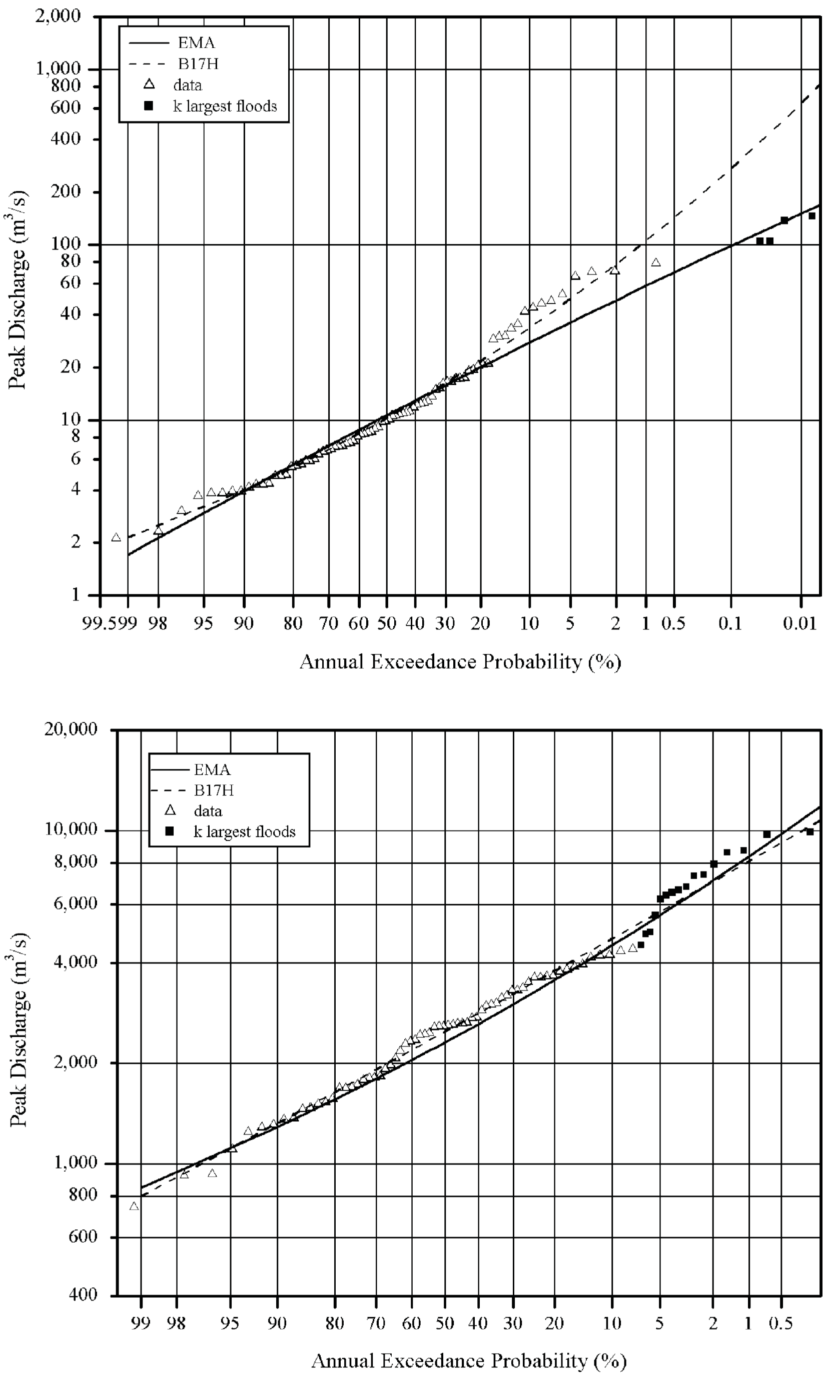

Figure 8. Peak flood frequency for Bear Creek (top) and Western Run (bottom). The solid lines show deviations from the gage data through utilization of the k^{th} largest floods. In both cases the inclusion significantly alters the shape of the flood frequency distribution to account for the k^{th} largest floods but reduces fit for the largest gaged floods. (From England et al. 2003, with copyright permission.)

Application for volumetric estimates using hydrograph scaling will result in frequency curves for varying durations that are directly parallel to each other and to the peak discharge frequency curves. This is a result of the linear relationship established through the scaling approach. Application of a stochastic rainfall approach in conjunction with the paleoflood information can result in sets of probabilistic estimates for each volume duration of interest and probability of occurrence. The volume information will not be limited by a linear scaling relationship and can be further characterized through the use of hydrographs with multiple peaks for either one flood event or multiple events.

The hydrograph scaling approach has limited applicability, as will be discussed below, whereas the rainfall approach has greater applicability but is highly resource intensive.

6.3 Record Length and Extrapolation

Practical application of paleoflood information should also consider the ability to inform the decision through extrapolation. It is important that the information should be tailored to the decision under consideration, and while paleoflood information may provide a longer time period, there are limits to the utility of extrapolation. McCuen and Galloway (2010) illustrated that uncertainty in parameter estimates increases with shorter record lengths, to the point of significant uncertainty when the record length is half of the desired estimate (e.g., 50 years of record for an estimate of a 100-year flood). Additionally, the Advisory Committee for Water Information (ACWI 2012) provided four rules to consider for flood frequency extrapolation:

> "1) Don't extrapolate if you don't have to; 2) if you do have to extrapolate, do so, but only as far as necessary; 3) seek additional information to provide independent corroboration of the extrapolated values…; and 4) don't give too much credibility to or place too much reliance on the extrapolated values."

For the case of paleoflood information, if information from within exceedance probability of the paleoflood is desired from the frequency curve, it can provide the corroborating evidence desired for the location of interest. If a probability estimate is sought for a lower probability of occurrence, then there is little corroborating evidence available, because at present there are no established means for regionalizing paleoflood information. If this is the case, key point 4 (“don’t give too much credibility to or place too much reliance on the extrapolated values”) should be the governing rule for determining the utility of the information. For example, Swain et al. (1998) suggested that

> “…many paleoflood records do not extend to 10,000 years, and extensive regional paleoflood data sets do not currently exist. Using a record length of about 4,000 years, a typical limit of credible extrapolation might be an [Annual Exceedance Probability] of 1 in 15,000.…”

Even this could be a reach, going from observations of 1 in 4,000 to 1 in 15,000, and is not entirely in the spirit of the more recent ACWI guidelines. However, it is reasonable to expect some value for the extrapolation limit, but the exact amount is not yet known.

7 Utility of Information within USACE Policies and Goals

Sections 2-6 described the development of paleoflood information that could be available to inform decision making for H&H-based decisions within a risk context. This section now looks at the information within the context of these types of decisions.

7.1 Extrapolation

Throughout the remaining discussion, the concept of extrapolation should be kept in mind. At all times, information should considered in the context of limited extrapolation. As discussed earlier, there are no set rules for limits of extrapolation. The remainder of this discussion employs the rule of thumb that a record length should not be used to extrapolate to more than twice that length. For example, if a stage is determined to have a probability of exceedance of 10^{-3}, this is not information that informs a decision based on anything less than approximately 5×10^{-4} (a 2,000-year return period). Given that the most recent ice age ended approximately 10,000 years ago, paleofloods should not be used to inform decisions requiring information less than approximately 5×10^{-5} (a 20,000-year return period). This is mostly consistent with the interpretation of Swain et al. (1998) but with a slightly stricter extrapolation limit. In fact, there are no known statistics or information to inform analyses trying to estimate AEPs less than 5×10^{-5}, nor are validation data currently available. Therefore, these return period requirements cannot be met through the use of paleoflood data, and different decision criteria should be sought.

7.2 Risk Inventory Consistency

Most paleoflood work is based on evidence gathered in the western U.S. or other arid areas throughout the world, but it is not directly relevant to all locations where USACE operates. This was recognized with slackwater approaches (Figure 4), and it remains the case even with approaches such a thorough non-exceedance bounds. Figure 1 illustrates a hypothetical risk inventory model based on the widely used Equation 1 risk model. For each individual location, there are multiple hazards, of which hydrologic hazard is but one, and each hazard likely has multiple pathways through which it poses a risk to infrastructure. Across the Nation, this heterogeneity of hazard and exposure represents a total risk to the organization. From the viewpoint of a risk-based inventory approach to asset management, we need to be able to answer questions about the utility of information that is available in one location but not in others. We must carefully consider how the two locations can be compared.

7.3 Stage-, Discharge-, and Volume-Based Decisions

Where decisions can be based solely on stage, there exists a strong foundation of peer-reviewed evidence that paleoflood information can inform such a decision with a reasonable amount of resource cost and quantifiable uncertainty. Care should be given to the various assumptions explored in this report, such as that the channel has remained stable over the time period of interest.

Great care should be given to the hydrologic modeling approaches to calculating discharge from stage, and this bears a significant resource cost as well as a priori consideration of the location of the calculation with respect to the decision location (i.e., transferability of information). There is a great deal of literature supporting the analysis of discharge from stage measurement, but to justify this approach, physically based hydraulic models should be applied, as opposed to empirical relationships. This typically requires multiple paleoflood stage determinations in a reach of river. In some cases, such as single-channel, bedrock-constrained channels, one-dimensional modeling may be appropriate; however, outside of that, where possible, two-dimensional models should be applied. Not only does this require the development of a consistent set of stratigraphies along a reach, thus reducing the uncertainties of paleoflood stage measurements, but it also requires a more physical basis for the discharge determinations. Application of paleoflood information is not warranted where there are more significant uncertainties than the hydraulics associated with modeling, and the uncertainties cannot be quantified.

For decisions that require additional analyses of paleoflood information, such as volume and duration probabilities, there are additional considerations. Although paleoflood information has been used successfully to inform decisions at other Federal agencies, most notably the U.S. Department of the Interior Bureau of Reclamation, and within research programs at academic institutions, USACE is faced with a different set of responsibilities, policies, and goals. The most notable difference between Reclamation and USACE is the national scope of USACE and the very large flood control and navigation reservoirs it manages. This leads to another consideration for application of paleoflood information: reservoir size.

At many large reservoirs, H&H risks are primarily calculated on total inflow volume over varying periods of time. In this case, peak discharge is irrelevant for informing H&H decisions. Only information on volume and duration is valuable for making risk estimates, thus requiring some type of hydrograph.

Paleoflood information does not provide direct information on volume or duration and should only be used along with an equivalent-level analysis based on rainfall statistics, which should be done in a stochastic manner if a single hydrologic event analysis is desired. In this way, two sources of information can complement each other because unreasonable hydrographs are not generated through the stochastic process (identified by the peak discharge) but a variety of volumes and durations can be explored. This type of approach has a large resource cost because it requires an extensive field investigation to inform (preferably) a two-dimensional analysis of the hydraulics and a significant rainfall frequency analysis and rainfall-runoff model exercise. If these resources are reasonable with respect to the decision to be made, then it constitutes valuable information with justifiable costs.

In addition, whereas stage and discharge calculations have strong support in the peer-reviewed literature, there is not a single example that could be found during the development of this report of a peer-reviewed publication describing the use and development of a flood hydrograph for volume or precipitation. Given this lack of evidence, the well-established field of stochastic rainfall runoff hydrology could provide a reasonable approach for estimating potential hydrograph volumes and can be used in calibration or in a check-and-balance manner with the paleoflood discharges (e.g., England 2006).

By its nature, paleoflood information describes discrete events in the ancient past or event thresholds that have not been exceeded. If a USACE H&H decision needs to be based on consideration of multiple hydrologic events, or on operational considerations, then paleoflood information does not provide direct information to support those decisions. For example, the risk can be significant when non-extreme rainfall events persist for a long period of time. This persistent rainfall will not generate a discrete flood event of significant magnitude that could be compared to a paleoflood, but its duration may pose a significant H&H risk at a large reservoir draining a large contributing area where that rainfall persists. For example, the Missouri and Mississippi River flooding in 2011 was generated through a prolonged period of rainfall from several discrete events, in combination with historically rare snowfall distributions and unseasonable temperatures. It would be difficult, if not impossible, to assess the risk from that type of event based on single discharge estimates.

7.4 Consideration of Change

The global changes from demographics, land-use change (e.g., urbanization, agriculture), and climate variability and change should also be considered when exploring the applicability of paleoflood information to H&H decisions. Not only does global change have relevance to the assumptions when applying the methods described in this report, but it also relates to the applicability of the information itself. This means that not only should the watershed have similar hydrologic response throughout the time period of the paleoflood to satisfy the methodological assumptions, but it should also be anticipated to have a similar response for the future time period for which the H&H decision is to be applied. If this were not the case, then the decision could be made based on conditions of the past that are not applicable for the future. This is the concept of stationarity that has been well discussed in the literature (e.g., Milly et al. 2008). Methodological approaches of H&H should look towards opportunities to be informed by change.

7.5 Risk and Design Decisions

The utility of paleoflood information within H&H studies should be considered within the context of not only the risk framework, but also how risk mitigation takes place. For example, two cases are considered: dam safety and levee safety. The Dam Safety and Levee Safety Programs are integral to fulfilling USACE's authorized purposes, which must be met across the vast range of infrastructure for which USACE is responsible.

The policy goal of the Dam Safety Program is that ".... a dam failure must not present a hazard to human life...." The design of USACE dams must therefore meet the minimum essential guidelines in which the Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) should not present a threat of failure to USACE dams. In contrast, risk-based assessments of safety recognize that there is always inherent risk and try to ascertain meaningful assessments of that risk.

The Levee Safety Program has a policy goal to "… make sure that levee systems do not present unacceptable risks to the public, property, and environment." The design criteria are not based on the minimum essential guidelines establishing PMP and PMF passage. As with the Dam Safety Program, in practice, risk-based assessments recognize inherent risk and attempt to ascertain meaningful assessments of that risk.

To satisfy both the minimum essential guidelines for design and the practical execution of the Dam and Levee Safety Programs, it is desirable to have a scientifically justifiable, nationally consistent, and physically based approach to assessments of hydrologic risk. For dam design, the deterministic PMF is currently the design standard as a risk-averse approach to minimizing the potential loss to human life. By its nature, there is no probability associated with the occurrence of the PMF. This presents some difficulty in reconciling the requirement for probabilistic approaches to the desire to obtain as much information as possible to inform potential future conditions. For example, if it is possible to conduct a paleoflood analysis at one location but not another, and one satisfies a risk-based determination but the other does not, this can result in different classifications of risk with the purpose of prioritizing resource allocation. The H&H analyses that inform risk and design should be consistent across infrastructure type and location to remain consistent with policy. This distinction may not exist for evaluations of levee safety, where the policies do not appear to contrast, as discussed in Section 2.

8 Conclusions

Significant information about floods that have occurred or thresholds of floods that have not been exceeded can be gained through field investigation of paleoflood information. There is a significant and growing body of literature supporting the utility of paleoflood information for stage and discharge frequency analysis, particularly for western and arid areas. This information and additional evidence, considered within the context of the national scope of the policies and goals of USACE H&H decisions, strongly influence the conclusions drawn within this report. The conclusions are intended to inform a wide set of decisions where practicing engineers are evaluating the most appropriate information to meet the particular needs of a decision.

The value to H&H decisions is limited where the scientific literature is currently lacking or assumptions associated with specific information types are not valid. Additional complications due to stationarity questions that surround climate variability and change complicate H&H decisions and are being addressed through a series of activities with USACE in partnership with other Federal and non-Federal institutions..

There is evidence that stage frequency and discharge frequency analyses of paleoflood events are useful when the assumptions are clearly delineated and carefully supported. These might then be used to inform USACE H&H decisions when the resources necessary to produce the results are reasonable and consistency across the nationwide inventory is not required.

For USACE H&H decisions based on volumetric information, paleoflood information should only be employed in conjunction with comparable-level-of-effort stochastic rainfall analyses, when the resources associated with this type of analysis are reasonable with respect to the decision to be made, when site-to-site comparisons are not necessary across the Nation, and when a single-event-based hydrograph is to be considered.

Further, paleoflood analyses should only be used when the risk-based framework is consistent with the design framework that would be employed to mitigate risk.

The following three governing points support the main conclusions drawn from this evaluation of the use of paleoflood information for H&H decision making within USACE:

- When considering the application of paleoflood information to directly inform H&H decisions, it is prudent to be cognizant, as stated by Cohn et al. (1997), that the "[u]se of unreliable historical information may degrade rather than improve flood-frequency estimates" (see also Hosking and Wallis 1986; National Research Council 1988; Kuczera 1992).
- While paleoflood information can effectively inform probabilistic estimates of stage and discharge in a straightforward manner by increasing record length, there are limits to extrapolation (as discussed in Section 7.1).
- The concept of a risk inventory is effective when all, or most, comparisons are being made using similar information types.

The main conclusions of this report are:

- Not all H&H decisions are appropriate for the application of paleoflood information. For example, if the decision leads to the design or modification of a high hazard dam, then the utility of paleoflood information is minimal, as the current design standard is based on the PMF.
- Where the assumptions about paleofloods are reasonable, the resources necessary to translate paleoflood evidence (or the lack thereof) into potentially useful hydrology and hydraulic information should be weighed against the underlying uncertainties and assumptions. These assumptions include: that the channel and surrounding watershed have remained stable since the paleoflood; if statistics are to be applied, that the underlying distribution is fully known and that attribution of paleoflood type can be made; that the non-exceedance probabilities are reasonable with respect to the paleoflood information; and that the parameterization and calibration of the appropriate hydraulic models can be done with confidence. Paleofloods can provide direct and useful information about stage histories, which can be used, with caution, to estimate discrete event discharge values; however, there is limited evidence to support the application to estimates of multiple hydrologic events, flood volumes, or flood durations.
- Paleoflood information is currently site specific and is not available for all USACE infrastructure locations, hindering its use in a portfolio as-

sessment. USACE is responsible for many large facilities that have been altered through time, either by geologic or by anthropogenic processes, or are not suitable for paleoflood analysis.

Table 1 summarizes the appropriate use of paleoflood information in USACE H&H decision making, based on the information developed for this report.

Table 1. Summary of relative appropriateness of paleofloods for application leading to USACE H&H decisions.

Paleoflood information	Geologic assumptions	Hydrologic assumptions	Appropriateness for input of exceedance frequency for H&H decisions*	Approximate costs† ($K)	Notes
Stage	Channel stability		A	15–50	Information not appropriate for assessments of dams and reservoirs with volume considerations
Discharge	Channel stability upstream and downstream	One-dimensional hydraulic modeling	C	100	Information not appropriate for assessments of dams and reservoirs with volume considerations
		Stage–discharge relationship	C	35–50	
		Two-dimensional hydraulic modeling	B	250	
Volume	Channel stability upstream and downstream	Hydrograph shape	D	35–50	
		Precipitation, type, intensity, duration, location	A	250–400	

* A = Application Justifiable, with H&H Policy Considerations
B = Application Justifiable, with Significant H&H Policy, Budget, and Time Considerations
C = Application Justifiable, with Severe H&H Policy Budget, and Time Considerations
D = Application Unjustifiable, given H&H Design Criteria and Policies

† Cost estimates based on the author's experience funding paleoflood studies within applications for Dam Safety Risk Analysis.

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