DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

ETL 1100-2-2

CECW-CE

Technical Letter
No. 1100-2-2

31 October 2014

EXPIRES 30 September 2019
Engineering and Design
APPROPRIATE APPLICATION OF PALEOFLOOD INFORMATION FOR HYDROLOGY AND HYDRAULICS DECISIONS

1. Purpose. This Engineer Technical Letter establishes guidance for the appropriate use of paleoflood analyses and information to support U.S. Army Corps of Engineers (USACE) Hydrology and Hydraulics (H&H) decision making.

2. Applicability. This Engineer Technical Letter applies to USACE commands having Civil Works planning, engineering design, operations, and maintenance responsibilities.

3. Distribution Statement. Approved for public release; distribution is unlimited.

4. References. References are located in Appendix A.

5. Background. The information required to support H&H decisions can range greatly, depending on the scope and consequences of the decision under consideration. Where data is limited, H&H decision-making process can be complex, especially for rare, low-probability flood events. These decisions typically rely on event frequency information based on streamflow gaging data (the observed record), as well as historical records prior to gaging (e.g., from newspaper or other records). Useful information can also be gained from paleohydrology, or the evidence of the movement of water and sediment in stream channels before the time of continuous hydrologic records or direct measurements (Costa 1987), which could extend to the very distant past.

a. Many types of paleohydrologic information provide indirect evidence of different types of hydrologic events, such as dendrochronology (tree rings and other vegetative evidence), pollen samples, stratigraphy, and marine sediments (e.g., House et al 2002, Baker 2008, Baker 2013). 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. In the U.S., paleoflood data has been used primarily in arid and semi-arid regions (Raff 2013, Kite et al. 2002), though paleohydrologic analyses have been conducted in more humid regions (e.g., Baker 2013).

b. The application of paleohydrologic information to H&H decision-making is a specialized field that requires assumptions and knowledge that differ from those of more common H&H decisions. The resources necessary to translate paleoflood evidence into potentially useful H&H information should be weighed against the underlying uncertainties and assumptions.

c. There is a significant, currently improving body of literature supporting the utility of paleoflood information for stage and discharge frequency analysis (Baker 2008, Baker 2013), particularly for western and arid areas, for floods of low probability (i.e., annual exceedance probabilities of less than 0.002). Field investigation of paleofloods can provide information about floods that have occurred or thresholds of floods that have not been exceeded. There is evidence that stage frequency and discharge frequency analyses of paleoflood events are useful when the assumptions are clearly delineated and carefully supported. When considering the use of paleoflood information, it is prudent to be aware that the "[u]se of unreliable historical information may degrade rather than improve flood-frequency estimates" (Cohn et al. 1997; see also Hosking and Wallis 1986; National Research Council 1988; Kuczera 1992).

d. The application of paleoflood information is not appropriate for all H&H decisions. For example, paleoflood analysis is not suitable for site-to-site comparisons across the Nation or for watersheds that have been altered through time, either by geologic or by anthropogenic processes.

6. Application of Paleoflood Information. This ETL provides specific guidance regarding the appropriate use of paleoflood information for H&H decision making. Additional information on the appropriate use of paleoflood information is located in Appendix B.

a. It is appropriate and recommended to consider acquiring paleoflood information for an H&H decision that requires information about floods with return periods more than twice as long as the systematic gaging record, and where extrapolation of the systematic record would not normally be advisable. Paleoflood data could be used to increase the effective length of the gage record, which may improve estimates of the magnitudes of rare events. In particular, paleofloods could provide direct and useful information about past flood stages.

(1) Great care should be given to the hydrologic modeling approach selected to calculate discharge from stage histories. When the following constraints are met, paleoflood information can effectively inform probabilistic estimates of stage and discharge:

(a) The channel and surrounding watershed have remained stable since the paleoflood, with a similar hydrologic response throughout the time period since the paleoflood that is expected to continue over the future time period for which the H&H decision is applicable;

(b) The underlying distribution is fully known, and attribution of the paleoflood type can be made;

(c) The non-exceedance bound (e.g., England et al. 2010) is reasonable; and

(d) The parameterization and calibration of the appropriate hydraulic models can be undertaken with confidence.

(2) 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:

(a) The resources required by this type of analysis are reasonable with respect to the decision to be made;

(b) Site-to-site comparisons are not necessary across the Nation; and

(c) A single-event-based hydrograph is to be considered.

b. The application of paleoflood information is not appropriate 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, since the current design standard is based on the Probable Maximum Flood (PMF). There is limited evidence to support the application of paleoflood information to estimates of:

(1) Multiple hydrologic events;

(2) Operational considerations;

(3) Flood volumes, flood durations, or flood hydrographs; or

(4) Most locations in the U.S. that are outside U.S. arid or semi-arid regions (Raff 2013).

c. Paleofloods should not be used to inform decisions concerning events with annual probabilities of exceedance less than approximately 5×10^{-5} (20,000-year return period) (Raff 2013).

FOR THE COMMANDER:

JOHN K. BAKER, P.E.
Lieutenant Colonel, Corps of Engineers
Executive Director of Civil Works

4 Appendices
Appendix A – References
Appendix B – Summary of the Appropriate Use of Paleoflood Information in USACE H&H Decision Making
Appendix C – Calculation of Paleoflood Discharge
Appendix D – Calculation of Paleoflood Volume

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A

References

A-1. Required References.

a. USACE Publications

ER 1105-2-101
U.S. Army Corps of Engineers (2006) *Risk Analysis for Flood Damage Reduction Studies*. ER 1105-2-101. Washington, DC: U.S. Army Corps of Engineers.

ER 1110-2-1156
U.S. Army Corps of Engineers (2011) *Safety of Dams – Policy and Procedures*. ER 1110-2-1156. Washington, DC: U.S. Army Corps of Engineers.

ER 1110-8-2(FR)
U.S. Army Corps of Engineers (1991) *Inflow Design Floods for Dams and Reservoirs*. ER 1110-8-2(FR). Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-1411
U.S. Army Corps of Engineers (1965) *Standard Project Flood Determination*. EM 1110-2-1411. Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-1413
U.S. Army Corps of Engineers (1984) *Hydrologic Analysis of Interior Areas*. EM 1110-2-1413. Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-1415
U.S. Army Corps of Engineers (1993a) *Hydrologic Frequency Analysis*. EM 1110-2-1415. Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-1416
U.S. Army Corps of Engineers (1993b) *River Hydraulics*. EM 1110-2-1416. Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-1417
U.S. Army Corps of Engineers (1994) *Flood-Runoff Analysis*. EM 1110-2-1417. Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-1419
U.S. Army Corps of Engineers (1995) *Hydrologic Engineering Requirements for Flood Damage Reduction Studies*. EM 1110-2-1419. Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-1619
U.S. Army Corps of Engineers (1996) *Risk-Based Analysis for Flood Damage Reduction Studies*. EM 1110-2-1619. Washington, DC: U.S. Army Corps of Engineers.

CWTS 2013-2
Raff, D. (2013) Appropriate Application of Paleoflood Information for the Hydrology and Hydraulics Decisions of the U.S. Army Corps of Engineers. Civil Works Technical Series 2013-2. Washington, DC: U.S. Army Corps of Engineers. http://www.corpsclimate.us/rccaupi.cfm.

b. Other Publications.

Baker 2008
Baker, V.R. (2008) Paleoflood hydrology: Origin, progress, prospects. *Geomorphology* 101: 1–13.

Baker 2013
Baker, V.R. (2013) Global late Quaternary fluvial paleohydrology with special emphasis on paleofloods and megafloods, in *Treatise on Geomorphology, Vol. 9* (J. Shroder and E.E. Wohl, Ed.). *Fluvial Geomorphology*, p. 511-527. San Diego: Academic Press.

Benson and Dalrymple 1967
Benson, M.A., and T. Dalrymple (1967) General field and office procedures for indirect discharge measurements. In *Techniques in Water Resources Investigations, Book 3, Chapter A1*. Reston, VA: U.S. Geological Survey.

Carrivick 2006
Carrivick, J.L. (2006) Application of 2D hydrodynamic modeling to high-magnitude outburst floods: An example from Kverkfjoll, Iceland. *Journal of Hydrology* 321. doi:10.1016/j.jhydrol.2005.07.042.

Cohn et al. 1997
Cohn, T.A., W.L. Lane, and W.G. Baier (1997) An algorithm for computing moments based flood quantile estimates when historical flood information is available. *Water Resources Research* 33(9): 2089–2096.

Costa 1987
Costa, J.E. (1987) A history of paleoflood hydrology in the United States, 1800–1970. *History of Geophysics* 3: 49–53.

England et al. 2010
England, J.F., Jr., J.E. Godaire, R.E. Klinger, T.R. Bauer, and P.Y. Julien (2010). Paleohydrologic bounds and extreme flood frequency of the Upper Arkansas River, Colorado, USA. *Geomorphology* 124.
doi:10.1016/j.geomorph.2010.07.021.

Hosking and Wallis 1986
Hosking, J., and J. Wallis (1986) The value of historical data in flood frequency analysis. *Water Resources Research* 22(11): 1606–1612.

House et al. 2002
House, P.K., R.H. Webb, V.R. Baker, and D.R. Levish (Ed.). (2002). Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology. Water Sciences and Application, vol. 5. Washington, DC: American Geophysical Union.

Kite et al. 2002
Kite, J.S., T.W. Gebhardt, and G.S. Springer (2002) Deposits as paleostage indicators in canyon reaches of the Appalachians: Reevaluation after the 1996 Cheat River flood. In *Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology* (P.K. House, R.H. Webb, V.R. Baker, and D.R. Levish, Ed.). *Water Sciences and Application*, vol. 5, p. 257–266. Washington, DC: American Geophysical Union.

Kuczera 1992
Kuczera, G. (1992) Uncorrelated measurement error in flood frequency inference. *Water Resources Research* 28(1): 183–188.

NRC 1988
National Research Council, Committee on Techniques for Estimating Probabilities of Extreme Floods (1988) *Estimating Probabilities of Extreme Floods, Methods and Recommended Research*. Washington, DC: National Research Council.

O'Connor and Webb 1988
O'Connor, J.E., and R.H. Webb (1988) Hydraulic modeling for paleoflood analysis. In *Flood Geomorphology* (V.R. Baker, R.C. Kochel, and P.C. Patton, Ed.), p. 393–402. New York: John Wiley and Sons.

Webb and Jarrett 2002
Webb, R.H., and R.D. Jarrett (2002) One-dimensional estimation techniques for discharges of paleofloods and historical floods. In *Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology* (P.K. House, R.H. Webb, V.R. Baker, and D.R. Levish, Ed.). *Water Sciences and Application*, vol. 5, p. 111–125. Washington, DC: American Geophysical Union.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B

Summary of the Appropriate Use of Paleoflood Information in USACE H&H Decision Making

Table B-1. Summary of the appropriate use of paleoflood information in USACE H&H decision making.

Paleoflood Information	Geologic Assumptions	Hydraulic Assumptions	Approximate Costs ($K)[†]	Appropriateness for Input to Exceedance Frequency for H&H decisions
Stage	Channel stability		15–50	Justifiable, except ***not appropriate*** for assessments of dams and reservoirs with volume considerations
Discharge	Channel stability upstream and downstream	One-dimensional hydraulic modeling	100	Justifiable, with potentially significant H&H budget and time considerations; except ***not appropriate*** for assessments of dams and reservoirs with volume considerations
		Stage-discharge relationship	35–50	
		Two-dimensional hydraulic modeling	250	
Volume	Channel stability upstream and downstream	Hydrograph shape	35–50	**Unjustifiable**, given H&H design criteria and policies
		Precipitation, type, intensity, duration, location	250–400	Justifiable, with H&H policy considerations

[†] Cost estimates based on Raff (2013).

USACE decision-makers may refer to Figure B-1 and Table B-2 when searching for existing studies that may be relevant to their project site, or to determine whether conditions in their area of interest may be favorable for collection of paleoflood information.

Figure B-1. Selected Holocene paleoflood study locations (after Baker 2013). Numbers on the map refer to Table B-2.

Table B-2. Examples of Paleohydrological Studies (after Baker 2013). Numbers refer to locations shown in Figure B-1.

Number	General Location	Location	Reference(s)
1	Southwestern U.S.	Central Texas	Baker, V.R., 1975. Flood hazards along the Balcones Escarpment in central Texas: alternative approaches to their recognition, mapping and management. University of Texas Bureau of Economic Geology Circular No. 75-5, 22 pp. Patton, P.C., Baker, V.R., 1977. Geomorphic response of central Texas stream channels to catastrophic rainfall and runoff. In: Doehring, D. (Ed.), Geomorphology of Arid and Semi-Arid Regions. Allen and Unwin, London, pp. 189–217.
2		West Texas	Patton, P.C., Dibble, D.S., 1982. Archeologic and geomorphic evidence for the paleohydrologic record of the Pecos River in west Texas. American Journal of Science 82, 97–121. Kochel, R.C., Baker, V.R., 1982. Paleoflood hydrology. Science 215, 353–361.
3		Central Arizona	Ely, L.L., Baker, V.R., 1985. Reconstructing paleoflood hydrology with slackwater deposits: Verde River, Arizona. Physical Geography 6, 103–126. Partridge, J.B., Baker, V.R., 1987. Paleoflood hydrology of the Salt River, Arizona. Earth Surface Processes and Landforms 12, 109–125.
4		North Arizona	Enzel, Y., Ely, L.L., Martinez-Goytre, J., Vivian, R.G., 1994. Paleofloods and a damfailure flood on the Virgin River, Utah and Arizona. Journal of Hydrology 153, 291–315. Webb, R.H., Blainey, J.B., Hyndman, D.W., 2002. Paleoflood hydrology of the Paria River, southern Utah and northern Arizona, USA. In: House, P.K., Webb, R.H., Baker, V.R., Levish, D.R. (Eds.), Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology. American Geophysical Union Water Science and Application, Washington, DC, vol. 5, pp. 295–310.
5		South Arizona	Martinez-Goytre, J., House, P.K., Baker, V.R., 1994. Spatial variability of paleoflood magnitudes in small basins of the Santa Catalina Mountains, southeastern Arizona. Water Resources Research 30, 1491–1501.
6		West Arizona	House, P.K., Baker, V.R., 2001. Paleohydrology of flash floods in small desert watersheds in western Arizona. Water Resources Research 37, 1825–1839.

Number	General Location	Location	Reference(s)
7	Southwestern U.S.	Utah (south)	Patton, P.C., Boison, P.J., 1986. Processes and rates of formation of Holocene alluvial terraces in Harris Wash, Escalante River basin, south-central Utah. Geological Society of America Bulletin 97, 269–378. Webb, R.H., O'Connor, J.E., Baker, V.R., 1988. Paleohydrologic reconstruction of flood frequency on the Escalante River. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, NY, pp. 403–418.
8		Utah (north)	Greenbaum, N., Weisheit, J.S., Harden, T., Dohrenwend, J.C., 2005. Paleofloods of the upper Colorado River near Moab, Utah, May, 2006. In: Weisheit, J.S., Fields, S.M. (Eds.), The Moab Mill Project: A Technical Report towards Reclaiming Uranium Mill Tailings along the Colorado River in Grand County, Utah. Living Rivers, Moab, Utah, pp. 13–28.
9		Colorado	Jarrett, R.D., 1990. Paleohydrologic techniques used to define the spatial occurrence of floods. Geomorphology 3, 181–195. Jarrett, R.D., Tomlinson, E.M., 2000. Regional interdisciplinary paleoflood approach to assess extreme flood potential. Water Resources Research 36, 2957–2984. England, Jr. J.F., Godaire, J.E., Klinger, R.E., Bauer, T.R., Julien, P.Y., 2010. Paleohydrologic bounds and exteme flood frequency of the Upper Arkansas River, Colorado, USA. Geomorphology 124, 1–16.
10		California	Enzel, Y., 1992. Flood frequency of the Mojave River and the formation of late Holocene playa lakes, southern California. The Holocene 2, 11–18. Ostenaa, D.A., Levish, D.R., O'Connell, D.R.H., 1996. Paleoflood study for Bradbury Dam, Cachuma Project, California. U.S. Bureau of Reclamation Seismotectonic Report 96-3, Denver, CO, 86 pp.
11		Nevada	Kellogg, M.J., 2001. Paleoflood hydrology of the Carson River, Nevada and California. MS Thesis, University of Nevada, Reno, 128 pp.
12		New Mexico	Levish, D.R., 2002. Paleohydrologic bounds: non-exceedance information for flood hazard assessment. In: House, P.K., Webb, R.H., Baker, V.R., Levish, D.R. (Eds.), Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology. American Geophysical Union Water Science and Application, Washington, DC, vol. 5, pp. 175–190.

Number	General Location	Location	Reference(s)
13	Northwestern U.S.	Washington	Chatters, J.C., Hoover, K.A., 1994. Response of the Columbia River fluvial system to Holocene climate change. Quaternary Research 37, 42–59.
14		Idaho	Tullis, J.A., Koslow, K.N., LeTourneau, D., 1983. Paleoflood deposits on the Big Lost River, Idaho. Geological Society of America Abstracts with Programs 15, 388. Ostenaa, D.A., O'Connell, D.R.H., Walters, R.A., Creed, R.J., 2002. Holocene paleoflood hydrology of the Big Lost River, western Idaho National Engineering and Environmental Laboratory, Idaho. In: Link, P.K., Mink, L.L. (Eds.), Geology, Hydrogeology, and Environmental Remediation: Idaho National Engineering Environmental Laboratory, eastern Snake River plain, Idaho. Special Paper 353. Geological Society of America, Boulder, CO, pp. 91–110
15		Oregon	O'Connor, J.E., Curran, J.H., Beebee, R.A., Grant, G.E., Sarna-Wojcicki, A., 2003. Quaternary geology and geomorphology of the lower Deschutes River Canyon, Oregon. In: Grant, G.E., O'Connor, J.E. (Eds.), A peculiar river: Geology, geomorphology, and hydrology of the Deschutes River. American Geophysical Union Water Science and Applications. Oregon, Boulder, CO, 7, pp. 77–98.
16		Wyoming	Levish, D.R., 2002. Paleohydrologic bounds: non-exceedance information for flood hazard assessment. In: House, P.K., Webb, R.H., Baker, V.R., Levish, D.R. (Eds.), Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology. American Geophysical Union Water Science and Application, Washington, DC, vol. 5, pp. 175–190.
17		Alaska	Mason, O.K., Beget, J.E., 1991. Late Holocene flood history of the Tanana River, Alaska, U.S.A. Arctic and Alpine Research 23, 392–403.
18	Central U.S.	Wisconsin	Knox, J.C., 1985. Responses of floods to Holocen climatic change in the Upper Mississippi Valley. Quaternary Research 23, 287–300. Knox, J.C., 1993. Large increases in flood magnitude in response to modest changes in climate. Nature 361, 430–432. Knox, J.C., 2000. Sensitivity of modern and Holocene floods to climate change. Quaternary Science Reviews 19, 439–457.

Number	General Location	Location	Reference(s)
19	Central U.S.	North Dakota	Harrison, S.S., Reid, J.R., 1967. A flood-frequency graph based on tree-scar data. Proceedings of the North Dakota Academy of Sciences 21, 23–33.
20		South Dakota	Harden, T., 2010. Paleoflood history of Rapid Creek in the foothills of the Black Hills, South Dakota. Geological Society of America Abstracts with Programs 42 (no. 3), 15.
21		Nebraska	Levish, D.R., 2002. Paleohydrologic bounds: non-exceedance information for flood hazard assessment. In: House, P.K., Webb, R.H., Baker, V.R., Levish, D.R. (Eds.), Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology. American Geophysical Union Water Science and Application, Washington, DC, vol. 5, pp. 175–190.
22		Oklahoma	McQueen, K.C., Vitek, J.D., Carter, B.J., 1993. Paleoflood analysis of an alluvial channel in the south-central Great Plains: Black Bear Creek, Oklahoma. Geomorphology 8, 131–146.
23	Eastern U.S.	Connecticut	Patton, P.C., 1988b. Geomorphic response of streams to floods in the glaciated terrain of southern New England. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, New York, NY, pp. 261–277.
24		Vermont	Brown, S.L., Bierman, P.R., Lini, A., Southon, J., 2000. 10 000 yr record of extreme hydrologic events. Geology 28, 69–82.
25		West Virginia	Springer, G.S., Kite, J.S., 1997. River-derived slackwater sediments in caves along Cheat River, West Virginia. Geomorphology 18, 91–100. Aldred, J.L., 2010. The effects of late Holocene climate changes on flood frequencies and magnitudes in Central Appalachia. M.S. Thesis, Ohio University, 127 pp.
26		Virginia	Sigafoos, R.S., 1964. Botanical Evidence of Floods and Flood-Plain Deposition. United States Geological Survey Professional Paper 485A, 35 pp.

APPENDIX C

Calculation of Paleoflood Discharge

C-1. Methods for Calculating Paleoflood Discharge. Discharge can be calculated from paleoflood stage information gathered during field investigations using three methods: empirical relationships, one-dimensional modeling (e.g., Benson and Dalrymple 1967; Webb and Jarrett 2002), and two-dimensional modeling. Each method requires a different data set and has different underlying assumptions, so differing resources are required and there will be different uncertainties in the results.

C-2. Empirical Relationships. Two primary empirical relationships provide links between stage and discharge: stage–discharge curves and Manning's equation used together with the continuity equation (Q = AV, where A is cross-sectional area of the channel and V is water velocity).

a. Stage-discharge curves are simple and direct, but they assume that sufficient data exist to provide a statistically significant relationship. Because paleofloods exceed any event in the observed record, they will involve stage-discharge relationships that are significantly higher than typical stage-discharge curves. Also, the physical nature of the channel form—the flood plains and terraces—that provides the paleoflood stage information can result in discontinuities in the stage-discharge relationship. These discontinuities make it unlikely that extrapolation of a rating curve, even where overbank flows are considered, will provide reliable estimates.

b. Manning's equation is a well-known and widely applied empirical hydraulic tool. Its application in a paleoflood context has uncertainties that are not usually encountered. First, it is not well known how the cross-sectional area and the hydraulic radius at the present time compare with the cross-sectional area during the paleoflood event. Any errors in these measurements result in an exponential uncertainty in the calculation of discharge. Second, 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. This uncertainty is somewhat less because of the square root relationship between friction slope and discharge. Third, additional uncertainties are introduced in assuming a characteristic roughness and accounting for other types of energy losses. Field manual guidance for estimating roughness requires assigning values of roughness to the channel bed material, vegetation, woody debris, flood plain grasses, and other considerations that are almost always unknown for a paleoflood event.

C-3. One-Dimensional Modeling.

a. Physically based modeling approaches are sometimes used to counter some of the shortcomings of empirical approaches to determining discharge from paleoflood stage. The least resource-intensive physical approach is to apply a one-dimensional physical model in a step-backwater method. The application of the step-backwater method for paleoflood analyses requires a number of assumptions, including, but not limited to:

(1) the cross sections are spaced so that the flow characteristics do not change significantly between them;

(2) the discharge being modeled affected the entire reach at the same time and was one-dimensional and "steady" (unsteady flow modeling may be used instead, but it requires additional assumptions, calibration, and validation); and

(3) the boundaries of the channel are constant.

b. The most significant concerns are the assumptions of one-dimensional behavior and constant boundaries. 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." This type of study requires significantly more resources than an empirical method (C-2). Raff (2013) provides additional discussion on this topic.

C-4. Two-Dimensional Modeling.

a. 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. Two-dimensional modeling allows for considerations of secondary currents of flood flows, which are likely to be a more realistic representation of large floods. 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. Among the assumptions necessary for two-dimensional modeling are these:

(1) the surface to be modeled is the same now as it was during the paleoflood event;

(2) the location to be modeled is at the location of interest for determining risk or is transferrable; and

(3) the flow characterization as steady or unsteady, uniform or nonuniform, is consistent with the actual event.

b. 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. associated with collecting information to conduct two-dimensional analyses can be significantly higher than for a one-dimensional or empirical approach.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX D

Calculation of Paleoflood Volume

D-1. Methods for Calculating Paleoflood Volume. Many USACE H&H decisions 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 described in Appendix C. There are two primary means by which this can be done: assume a characteristic hydrograph shape, or conduct a precipitation analysis.

D-2. Hydrograph Shape.

a. 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. 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 Appendix C. Assumptions for the unit hydrograph approach include:

(1) that the excess rainfall has a constant intensity within the effective duration;

(2) that the excess rainfall is uniformly distributed throughout the whole drainage area;

(3) that the base time of the direct runoff hydrograph is constant;

(4) that, for a given watershed, the hydrograph resulting from a given amount of excess rainfall reflects the unchanging characteristics of the watershed.

b. 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 for the flood event is characterized using observed flows in the basin and engineering judgment. 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.

D-3. Precipitation Analysis. Where the assumptions of rainfall homogeneity in time and space are not warranted for the hydrograph approach 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 Appendix C.

List of Acronyms

CE	Corps of Engineers
CECW	Corps of Engineers Civil Works
EM	Engineer Manual
ER	Engineer Regulation
ETL	Engineer Technical Letter
H&H	Hydrology and Hydraulics
USACE	United States Army Corps of Engineers