Paleofloods stage a comeback

Scott St. George[1*], Amanda M. Hefner[1] and Judith Avila[1]

[1]*Department of Geography, Environment and Society, University of Minnesota, Minneapolis, Minnesota, 55455, USA.*

*e-mail: stgeorge@umn.edu

Geological and botanical archives can preserve evidence of exceptional floods going back centuries to millennia. Updated risk guidelines offer a new opportunity to apply lessons from paleoflood hydrology to judge the odds of future floods.

In the afternoon and evening of July 9 1972, a group of near-stationary thunderstorms pummeled the Black Hills of western South Dakota with heavy rains. The resulting runoff caused Rapid Creek, a tributary of the Cheyenne River, to overflow its banks, breach the Canyon Lake Dam, and flood the downstream communities of Rapid City and Keystone. The Black Hills Flood of 1972 destroyed more than 1,300 homes, injured more than 3,000 residents, and caused the deaths of 246 people[1]. It remains the worst natural disaster in the state's history. It is also one of the most exceptional floods ever documented by stream gages anywhere in the United States[2], with a peak discharge almost 15 times larger than the previous record at that location. Although unknown at the time, evidence of even larger floods was hidden away in bedrock canyons only a few kilometers upstream.

Due to the area's geological characteristics, the Black Hills are ideally suited to preserve a long register of past floods. In 2008, Dr. Tessa Harden and a team from the United States Geological Survey (USGS) discovered a sequence of late-Holocene flood deposits in rock shelters, alcoves, and small caves flanking Rapid Creek and other local streams[3]. Inputting the height of these deposits into hydraulic models, they determined Rapid Creek had produced at least two floods during the past millennium even more severe than the disastrous 1972 event. The larger was a 16th century leviathan, with an estimated discharge between four and eight times greater than the modern flood of record. Had this geological evidence been available a few decades earlier, the residents of Rapid City might have better appreciated the true risk posed by the floods that stalked their community.

The study of ancient floods can be traced back to the very beginnings of Earth Science, but paleoflood hydrology did not emerge as a formal discipline until the early 1980s[4]. In the subsequent four decades, researchers have developed new tools to identify and date past floods and estimate their magnitude, and paleoflood surveys have been conducted on every continent bar Antarctica[5]. Paleoflood records have provided the extended perspective required to assess the impact of river modification on the frequency and severity of floods[6], and to understand linkages between extreme floods and climate variability[7]. Until recently, though, this type of natural flood information has not been incorporated into national or international guidelines for quantitative flood frequency analysis. This omission has limited the consideration of paleofloods by practicing hydrologists responsible for assessing future flood risks, and inadvertently made people and infrastructure more vulnerable to unforeseen catastrophic floods like the Black Hills events.

Enduring signs of high water

Rivers are powerful and dynamic geomorphic agents, and so memories of past floods can be retained within their own channel and floodplain. Large floods in rugged terrain easily entrain sands and silts, but if the pace of the river slows downstream, that sediment will drop out of suspension and become plastered along rock overhangs or side canyons. And if the local geometry of the channel has not changed in the interim, the magnitude of past floods may be inferred from the elevation of these slackwater deposits[5]. In other settings, the load of sediment transported and deposited alongside a river provides a clear indication of the speed and ferocity of older floods. The largest floods can carry cobbles or even boulders downriver, so the typical grain size of channel or floodplain sediments can be combined with statistical or hydraulic models to estimate peak discharge[5].

Major floods can also leave behind more subtle traces of their passing. When flows are high, rivers can deliver a rapid injection of sediment into lakes that eventually settles to the bottom. Flood deposits are often distinct from the usual sedimentary sequences in lakes — in terms of their grain size, color, or chemical composition — and so through time a muddy archive of past floods builds up[5,6]. Similarly, if floodwaters enter caves and submerge mineral deposits such as stalagmites and flowstones, the normal growth of these formations can be interrupted by a layer of water-borne detritus. After the water recedes and cave deposits begin growing again, that foreign material remains trapped as an inclusion bracketed by layers of calcium carbonate[5]. And when rivers spill over into nearby forests, trees can record evidence of high water as impact or abrasion scars, deformed rings, or tilted stems caused by the pressure of fast-moving water[5].

New rules for old floods

Practitioners of paleoflood hydrology often say that what has happened can happen again[8]. And, they argue, physical evidence of an old cataclysmic flood should encourage actions to guard against similar events in the future[8], especially to protect high-value infrastructure such as dams and power plants. Since the early 2000s, for instance, international safety standards have recommended that seismic hazard analyses for nuclear installations should consider the geological record of prehistoric and historic earthquakes whenever possible[9]. But in many jurisdictions, the hydrological and engineering communities have been hesitant to consider paleoflood evidence in formal hazard and risk assessments.

One of the most persistent obstacles to that use has been the lack of agreed-upon statistical procedures to feed paleoflood data into quantitative flood frequency analysis. Since the mid-1960s, efforts to assess flood risks on American rivers have been supported by guidelines from federal agencies intended to promote uniform flood frequency analyses across the nation[10]. The lack of any mention of paleofloods in these guidelines likely resulted in federal, state, or local agencies seeking to evaluate flood risks (as well as their private sector partners) being implicitly discouraged from taking that information into account.

That situation finally changed in March 2018, when the US federal government published the first major update in 37 years to guidelines used to determine flood flow frequency —Bulletin 17C[11]. That report, written by hydrologists and engineers from the USGS, the US Army Corps of Engineers, academia, and private consulting firms, provided for the first time a framework to integrate paleoflood data from geological or botanical field evidence into its quantitative flood risk assessments. The USGS also updated its PeakFQ software[12], which conducts flood frequency analysis of streamflow records, to implement the procedures outlined in Bulletin 17C and include the option to input paleoflood data.

These procedures are able to accommodate three types of paleoflood information (Fig. 1). First are discharge estimates for large floods prior to the gage record, such as the two extraordinary Rapid Creek floods inferred from sediment deposits. Because large floods exert a strong influence on the upper ends of flood frequency curves[11], this form of paleoflood evidence can help improve estimates of the most severe and rare events. Second are perception thresholds, which reflect the range of potential floods that could have been measured or observed. For instance, the lower threshold describing the smallest flood detectable by a given paleoflood archive can be used to determine whether the largest flood observed in a gage record is actually the most severe event over a much longer period. Finally, Bulletin 17C considers paleohydrologic bounds or the time interval during which a given discharge has not been exceeded[14]. If the river channel contains geomorphic features that have no signs of having ever been modified by high water (typically, stable terraces inside the river channel with well-developed soils), the elevation of those surfaces can be combined with hydraulic models to estimate the maximum flood stage since their formation.

Into the hydrological mainstream

Bulletin 17C recommends frequency analysis should use all observations of extraordinary floods, regardless of the source of that information, so these revised guidelines open a new avenue to integrate paleoflood evidence into flood safety and preparedness for the United States and around the world. Other countries including Spain and Australia have also enacted formal recommendations to encourage the use of paleoflood data in hazard assessments[15,16], and China's Ministry of Water Resources requires historical flood data to be considered when calculating the design flood for water resources and hydropower projects[17]. But because flood risk planning in other jurisdictions is often predicated on the American model[18], the detailed best practices outlined in Bulletin 17C could serve as a template for the international hydrological community to plug paleoflood evidence into quantitative risk assessments. Worldwide, there already exists a rich trove of paleoflood records spanning the past millennium and, in rare cases, extending back more than 100,000 years[5]. Applying the techniques outlined in Bulletin 17C to these data should allow us to more accurately gage the risk of high-severity, low-probability floods and test whether long-term changes in climate, land use, or river modification have made floods more or less likely.

Unlike many types of paleoclimate data[19], there is currently no standard format for paleoflood information and no central repository to store or share those data. This limitation unfortunately means many published paleoflood records cannot be incorporated into risk assessments like those outlined in Bulletin 17C. Going forward, paleoflood studies should ideally provide quantitative estimates of peak discharge or perception threshold and specify either the age of each paleoflood or the start and end years of the paleohydrologic bound. Whenever possible, published paleoflood studies that did not provide explicit information for individual events, or instead report qualitative estimates of flood magnitude, should also be revised to meet these guidelines.

The American novelist and essayist Toni Morrison once wrote that rivers do not flood; rather, they on occasion remember where they used to be[20]. The central charge of paleoflood hydrology is to deepen our own memory of floods, reaching back beyond the date when a river's first stream gage was installed. Having finally been granted a place within federal risk guidelines, natural flood evidence should help more people grasp just how high and wide rivers can run.

Author Contributions

S.S.-G. developed the concept for this opinion piece, led the writing, and created the illustration; A.M.H. identified case studies in the paleoflood literature and edited the manuscript; J.A. conducted the flood frequency analysis and edited the manuscript.

Competing Interests statement

The corresponding author confirms on behalf of all authors that there have been no involvements that might raise the question of bias in the work reported or in the conclusions, implications, or opinions stated:

References

1. Thompson, H.J. *Weatherwise* **25**, 162-173 (1972).
2. Smith, J.A. et al. *Water Resour. Res.* **54**, 6510-6542 (2018).
3. Harden, T.M. et al. *USGS Scientific Investigations Report 2011–5131* (2012).
4. Kochel, R.C. & Baker, V.R. *Science* **215**, 353-361 (1982).
5. Wilhelm, B. et al. *WIREs Water* **6**, e1318-1322 (2019).
6. Munoz, S.E. et al. *Nature* **556**, 95-98 (2018).
7. Mertz. B. et al. *Nat. Hazards Earth Syst. Sci.* **14**, 1921-1942 (2014).
8. Baker, V.R. *Geomorphology* **101**, 1-13 (2008).
9. International Atomic Energy Agency, Seismic Hazards in Site Evaluation for Nuclear Installations, No. SSG-9 (2010).
10. Stedinger, J.R. & Griffis, V.W. *J. Hydrol. Eng.* **13**, 199-204 (2008).

11. England Jr., J.F. et al. *Guidelines for Determining Flood Flow Frequency—Bulletin 17C.* U.S. Geological Survey (2018).

12. Veilleux, A.G. et al. *USGS Fact Sheet 2013-3108* (2014).

13. Brooks, G.R. & St. George, S. *Geomorphic Approaches to Integrated Floodplain Management of Lowland Fluvial Systems in North America and Europe*, 87-117 (2015).

14. Levish, D.R. *Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology*, 175-190 (2002).

15. Diez-Herrero, A. et al. *A Handbook on Flood Hazard Mapping Methodologies*, Geological Survey of Spain (2009).

16. Nathan, R. & Weinmann, E. Estimation of very rare to extreme floods, Book 8 in *Australian Rainfall and Runoff - A Guide to Flood Estimation*, Commonwealth of Australia (2019).

17. Ministry of Water Resources, P.R. China, Regulation for calculating design flood of water resources and hydropower projects (SL44-2006). China Water & Power Press, Beijing: 1-92 (2006).

18. Lee, T. et al. *J. Korean Soc. Civ. Eng.* **37**, 247-253 (2017).

19. Khider, D. et al. *Paleoceanogr. Paleoclimatol.* **34**, 1570-1596 (2019).

20. Morrison, T. *Inventing the Truth*. Houghton Mifflin Co, 185-200 (1998).

Acknowledgements

We appreciate support from the U.S. National Science Foundation (award 1830640, 'Paleohydrological assessment of extreme flooding events'). The final version of this Comment was improved by suggestions from Dr. James Super, Dr. Lisa Davis, Dr. Daryl Lam, Dr. Tao Liu, Dr. Andrés Díez Herrero, and an anonymous reviewer. Discharge data for the Red River of the North was kindly provided by Dr. Fisaha Unduche (Manitoba Infrastructure and Transportation). We also acknowledge use of the USGS PeakFQ program (https://water.usgs.gov/software/PeakFQ). This Comment is a contribution to the PAGES Floods Working Group (http://pastglobalchanges.org/science/wg/floods).

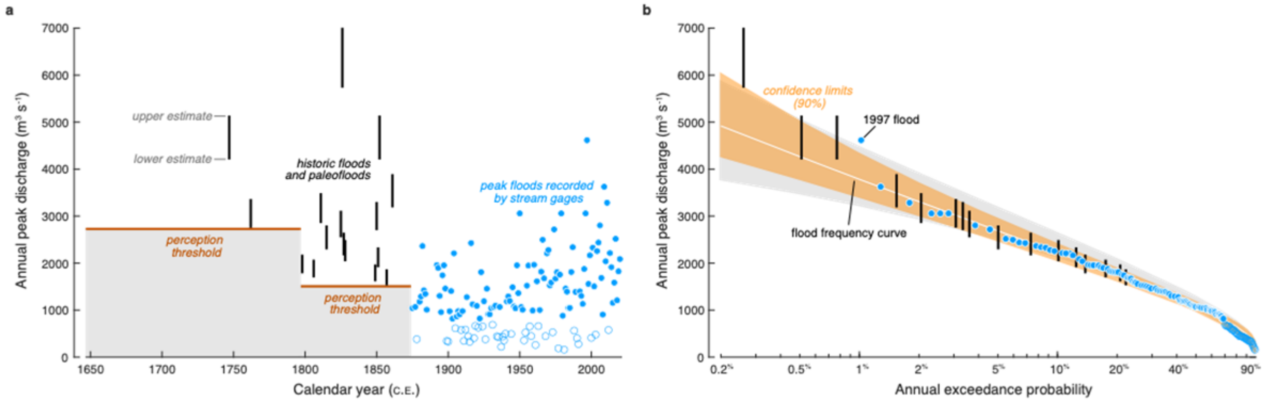
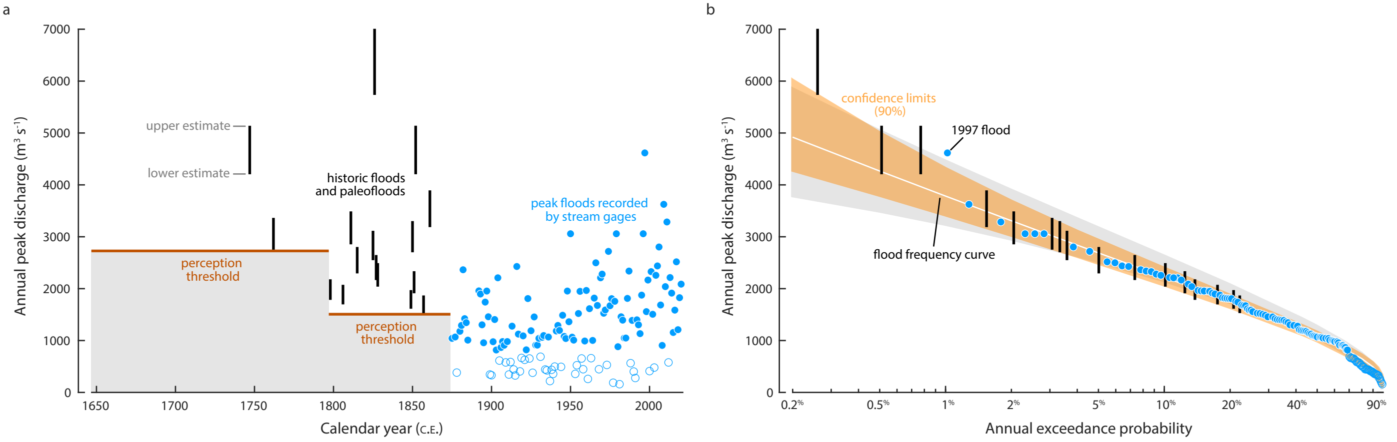


Fig 1 | Estimating flood risk by combining gage, historic and paleoflood data. a, The stream gage record (blue circles) for the Red River of the North at Winnipeg, Canada begins in C.E. 1875 but historic accounts of major floods and paleoflood evidence derived from tree rings (vertical black bars) extend back to the middle of the 17th century[13]. The gray shading represents floods that are unknown but must have been smaller than the perception thresholds (the horizontal dark orange lines) for the two early periods. The open blue circles are low floods in the gage record that are excluded from the flood frequency analysis. The top and bottom of the vertical lines mark the upper and lower discharge estimates for the historic floods and paleofloods. **b,** Annual exceedance probability (AEP) plot based on flood frequency analysis. The AEP is the estimated chance a flood with a particular peak discharge will occur in any given year. The white line represents the fitted flood frequency curve, and the tan shading marks its 90% confidence interval (the gray shading represents the same interval for the flood frequency curve estimated using only the stream gage observations). By incorporating historic and paleoflood data into the procedures outlined by Bulletin 17C[11], the probability of a 1997-like flood (the most severe flood recorded by stream gages) is 44% higher than the estimate obtained using only gage data. Compared to the risk estimates derived solely from gage data, the confidence intervals for rare floods (AEPs lower than 1%) are narrower and the estimated severity of intermediate and common floods (AEPs higher than 1%) is diminished when using the combined dataset.


a
b
7000
6000
5000
4000
3000
2000
1000
0
upper estimate
lower estimate
historic floods
and paleofloods
peak floods recorded
by stream gages
perception
threshold
perception
threshold
Annual peak discharge (m³ s⁻¹)
1650
1700
1750
1800
1850
1900
1950
2000
Calendar year (C.E.)
confidence limits
(90%)
1997 flood
flood frequency curve
0.2%
0.5%
1%
2%
5%
10%
20%
40%
90%
Annual exceedance probability