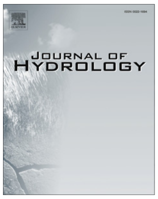
Journal of Hydrology 510 (2014) 228–245

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



# Physically-based extreme flood frequency with stochastic storm transposition and paleoflood data on large watersheds

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ARTICLE INFO

*Article history:*
Received 23 February 2013
Received in revised form 16 August 2013
Accepted 10 December 2013
Available online 16 December 2013
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Ezio Todini, Associate Editor

*Keywords:*
Extreme floods
Flood probabilities
Distributed runoff
Paleofloods
Dam safety

## SUMMARY

Traditionally, deterministic flood procedures such as the Probable Maximum Flood have been used for critical infrastructure design. Some Federal agencies now use hydrologic risk analysis to assess potential impacts of extreme events on existing structures such as large dams. Extreme flood hazard estimates and distributions are needed for these efforts, with very low annual exceedance probabilities ($\leqslant 10^{-4}$) (return periods >10,000 years). An integrated data-modeling hydrologic hazard framework for physically-based extreme flood hazard estimation is presented. Key elements include: (1) a physically-based runoff model (TREX) coupled with a stochastic storm transposition technique; (2) hydrometeorological information from radar and an extreme storm catalog; and (3) streamflow and paleoflood data for independently testing and refining runoff model predictions at internal locations. This new approach requires full integration of collaborative work in hydrometeorology, flood hydrology and paleoflood hydrology. An application on the 12,000 km$^2$ Arkansas River watershed in Colorado demonstrates that the size and location of extreme storms are critical factors in the analysis of basin-average rainfall frequency and flood peak distributions. Runoff model results are substantially improved by the availability and use of paleoflood nonexceedance data spanning the past 1000 years at critical watershed locations.

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## 1. Introduction

The estimation of extreme flood probabilities is a long-standing problem in hydrology, because we typically lack long flood records (Stedinger et al., 1993) to estimate Annual Exceedance Probabilities (AEPs) at the site of interest. About a century ago, Hazen (1914) recognized the practical value of this problem and suggested the idea of unbounded, very extreme flood probabilities when commenting on Fuller (1914): "... One of the most important matters developed by the paper is that there is no such thing as a maximum flood. ... There is a 100-year flood much greater than the 10-year flood; and, although no records are at hand to demonstrate it adequately, there is every reason to believe that there is a 1000-year flood, which will prove to be much greater than the 100-year flood." Several years later, the value of geologic information and terraces for flood information was recognized (Fuller (1917); see also Jarrett and England (2002) for a discussion). Today, paleoflood data with records longer than 1000 years (House et al., 2002; Levish, 2002; Benito et al., 2005) are now available or can be obtained for extreme flood frequency analysis (O'Connell et al., 2002; England et al., 2010), and provide crucial data for temporal extension of flood information (e.g. Merz and Blöschl, 2008a).

In contrast to widely-used deterministic design procedures for large dams and critical infrastructure, such as the Probable Maximum Flood (PMF) (Cudworth, 1989), methods to estimate extreme floods, extreme rainfalls and their probabilities are not mature (NRC, 1988, 1994; Burges, 1998). Estimates of extreme floods and AEPs are needed and required for hydrologic engineering, dam safety risk analysis and modification of critical infrastructure, particularly by the Bureau of Reclamation (Reclamation, 2010, 2011). The hydrologic hazard inputs required for risk analysis are frequency distributions of peak flows, hydrographs, volumes, and peak reservoir stages which, for dams with potentially high loss of life, extends to very low AEPs ($\leqslant 10^{-4}$). In practice, there are few readily-available tools to make these estimates. Some methods to estimate hydrologic hazards for dam safety with AEPs $\leqslant 1/2000$ are described by Nathan and Weinmann (1999) for Australia and by Swain et al. (2006) for Reclamation dams in the western US. In Germany and Austria, DWA (2012) provides hydrologic hazard methods for dam safety that explicitly focus on temporal, spatial, and causal information to complement the systematic flood data. Tools generally consist of peak-flow frequency with paleoflood data (O'Connell et al., 2002), lumped unit hydrograph (HEC, 2010) or storage routing models (Laurenson et al., 2006), with rain-

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0022-1694/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jhydrol.2013.12.021

fall probabilities estimated with L-Moments (Hosking and Wallis, 1997) or AEP shape functions based on Probable Maximum Precipitation (PMP) (Nathan and Weinmann, 1999). The GRADEX method (Naghettini et al., 1996; Swain et al., 2006; Gutknecht et al., 2006) is also used in some cases. Reclamation utilizes paleoflood data to estimate hydrologic hazard curves for risk analyses, which includes risk-based modifications at major facilities in California (Reclamation, 2002) and Wyoming (Levish et al., 2003). Others (Schumann, 2010) are also examining extreme flood hazard issues. There is much room for conducting innovative extreme flood hydrology science, engineering, and applications in this challenging area to estimate AEPs $\leqslant 10^{-4}$.

This paper presents an integrated data-modeling hydrologic hazard framework for detailed, physically-based extreme flood hazard estimation. The framework is suitable for hydrologic risk applications for critical infrastructure such as dams and nuclear reactors; we show an example for a large dam in the Western United States. We implement several extreme flood and rainfall concepts presented in NRC (1988, 1994), including stochastic storm transposition (Foufoula-Georgiou, 1989) and paleoflood data (House et al., 2002). The hydrologic hazard framework consists of the following key elements: (1) rainfall frequency and storm modeling with stochastic storm transposition; (2) extreme storm data and analyses for storm probability modeling supplemented by radar data; (3) physically-based rainfall–runoff modeling with the Two-Dimensional Runoff, Erosion and Export (TREX) model (Velleux et al., 2011) to estimate flood frequency; and (4) streamflow and paleoflood data with frequency analysis utilized for independently testing and refining runoff model predictions. We demonstrate the approach on a large 12,000 km$^2$ watershed, the Arkansas River above Pueblo, Colorado, to estimate the flood hazard at Pueblo Dam, a Bureau of Reclamation water-supply and flood control dam.

The study objectives are: (1) implement and demonstrate the use of stochastic storm transposition (SST) on a large, orographic watershed; (2) utilize a physically-based runoff model (TREX) with spatially and temporally distributed rainfall from stochastic storm transposition to estimate flood frequency on this watershed; and (3) examine effects of varying spatial rainfall and soil moisture on flood frequency curves, comparing model predictions to streamflow and paleoflood data at internal watershed locations. We build on previous studies, including TREX development (England et al., 2007), storm hydrometeorology (Javier et al., 2007), and paleoflood data and frequency analysis (England et al., 2010).

## 2. Hydrologic hazard framework for large, semi-arid watersheds

The hydrologic hazard framework is designed to provide information on hydrologic risk – very extreme floods with AEPs $\leqslant 10^{-4}$ – that is required for making dam safety decisions (Reclamation, 2011). This information includes peak-flow frequency and hydrographs for large (>5000 km$^2$), semi-arid watersheds. The framework utilizes two methods to estimate the hydrologic hazard (NRC, 1988): peak-flow frequency using a statistical model with paleofloods; and rainfall–runoff modeling with extreme storms. The statistical model for peak-flow frequency that is used in this study is the log-Pearson Type 3 (LP3) distribution with the Expected Moments Algorithm (EMA) (Cohn et al., 1997) and confidence intervals (Cohn et al., 2001). The physically-based rainfall–runoff model TREX (England et al., 2007; Velleux et al., 2008, 2011) is coupled with SST and extreme storm data to estimate flood frequency and hydrographs. These two methods are used in a combined way. TREX provides a physical basis for flood hydrographs; the model predictions are compared with the independent EMA-LP3 flood frequency (using peak-flow and paleoflood data) and refined as needed.

We directly account for the following key physical processes (see England (2006) and England et al. (2007) for a discussion and review) in the rainfall–runoff model component of the hydrologic hazard framework: (1) extreme storm rainfall (duration, spatial pattern, location, areal extent); (2) partial-area rainfall and runoff; (3) hillslope runon, runoff and routing; and (4) channel network and routing. There are significant research opportunities on the extreme flood physical processes and flood frequency using physically-based rainfall–runoff models for large watersheds, as most approaches have been statistically-based (Dunne, 1998). On large basins >10$^3$ km$^2$, watershed response is controlled by travel time in channels and by the specifics of the spatial distribution of rainfall (Nicótina et al., 2008). Partial-area rainfall and runoff dynamics play a crucial role in semi-arid regions (Marco and Valdés, 1998; Iacobellis and Fiorentino, 2000; Fiorentino and Iacobellis, 2001; Moon et al., 2004) at these scales. We use the TREX model to represent these physical processes in a spatially-distributed manner, especially partial-area rainfall and channel routing.

Extreme storm rainfall data, flood data, and paleoflood data are a critical part of the hydrologic hazard framework. As noted by NRC (1988), major efforts are needed to compile comprehensive data bases for developing and testing extreme flood probability methods. The following data sets are utilized in this framework. Extreme storm rainfall are obtained from USACE (1973), Hansen et al. (1988), NOAA NCDC data bases, Reclamation's extreme storm files (Sankovich and Caldwell, 2011), and newer storms from site-specific data collection efforts (Section 4.2). Extreme flood data (peak flows, daily flows, hydrographs) are obtained from the USGS NWIS and related flood publications (Follansbee and Jones, 1922; Follansbee and Sawyer, 1948). Historical data and paleoflood data are obtained on a site-specific and regional basis (Klinger and Klawon, 2002). For this study we rely on detailed, site-specific and regional data collection efforts on extreme storms and paleofloods for the flood hazard at Pueblo Dam. When combined, these data sets provide a basis for extrapolation to AEPs of interest (Swain et al., 2006). England (2011) describes ongoing improvements to extreme storm, flood, and paleoflood data bases within the U.S.

Few published studies provide approaches to estimate extreme flood probabilities (AEPs $\leqslant$ 1/1000) with rainfall–runoff models. Recent efforts are summarized in Table 1, and most use an exponential storm model with TOPMODEL. Our watershed scales of interest are 10–100 times larger than these past studies. Most of these studies use a single method, rather than the two approaches in the present work. While Cameron (2007) and Rogger et al. (2012) compared runoff model estimates with independent peak-flow frequency curves, we use paleoflood data that these studies did not consider. We are also motivated to use a different hydrologic hazard framework than these previous studies based on the following considerations. We implement the NRC (1994) recommendation to use storm-based analysis of extreme rainfall with SST (Section 4), because the data base and model provide direct information on largest rainfalls and the upper tail of the basin-average precipitation frequency curve. The SST approach can also include partial-area rainfall effects. The TREX model (Section 5) is utilized to represent the important physical watershed processes, interactions and dynamics of extreme floods in a spatially-explicit manner: the location, orientation and spatial distribution of rainfall (England et al., 2007); runoff from hillslopes (2D diffusive-wave routing); and channel network and hydraulics (1D diffusive-wave routing). While there may be several open research questions regarding storm rainfall and runoff model complexity for these extreme flood hazard problems, we present this framework as one alternative. It is hoped that this study might be used to motivate additional research work in this challenging area.