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Nonparametric Bayesian flood frequency estimation

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Abstract

A novel nonparametric Bayesian Monte-Carlo method is presented to estimate flood frequency. This method accommodates complex flood behaviors such as event clustering (repeated instances of similar magnitude floods) and can use varied data, such as gage and historical peak discharges, and paleohydrologic upper and lower bounds on peak discharge, while rigorously accounting for a wide variety of measurement uncertainties. In contrast to nonparametric kernel estimation approaches, the stochastic assumption is used to generate flood frequency models that span the data and provide about twice the number of degrees of freedom of the data. Each generated flood frequency model is scored using likelihoods that account for data measurement uncertainties. A parametric estimation approach ensures high precision because posterior sampling is known. However, parametric approaches can produce substantial biases because the classes of allowed flood frequency models are restricted. These biases are completely undetectable within a parametric paradigm. The nonparametric approach used here surrenders some precision in the pursuit of reduced bias and greater overall accuracy and assurance; it reveals the annual probabilities where discharge becomes unconstrained by the data, thereby eliminating unsubstantiated extrapolation. Parametric flood frequency estimation introduces strong extrapolation priors that make it difficult, if not impossible, to determine when flood frequency is not longer constrained by the data. Nonparametric and parametric flood frequency estimation using a demonstration data set shows that while parametric functions may sometimes provide reasonable fits to subsets of paleohydrologic data, parametric flood frequency estimates are likely to produce substantial biases over entire log cycles of annual exceedance probability, when using paleohydrologic data spanning thousands of years.
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1. Introduction

Probabilistic estimates of flood frequency are required for engineering risk analyses of critical structures. Frances et al. (1994), Blainey et al. (2002), and O'Connell et al. (2002) showed that paleohydrologic information can provide valuable flood frequency constraints, particularly for small annual exceedance probabilities (AEP, the reciprocal of return period, *T*), which are of greatest concern for critical structures. There are several types of paleohydrologic data that provide valuable flood frequency information, including slackwater deposits that provide positive evidence of past flooding (Baker et al., 2002),

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and paleohydrologic bounds that place upper limits on flood magnitude for potentially long periods of time (Levish, 2002). Stable geomorphic surfaces adjacent to a stream serve as limits for the paleostage of large floods over hundreds to thousands of years. These paleostage limits can then be input into hydraulic models to calculate the maximum discharge that would not significantly inundate, and therefore not significantly modify, a particular geomorphic surface. This maximum discharge, together with the age of the surface, forms a limiting paleohydrologic bound on flood discharge through time that provides information for flood frequency analysis. These paleohydrologic bounds are not actual floods, but instead, are limits on flood stage over a measured time interval. In this way, paleohydrologic bounds represent stages and discharges that have not been exceeded since the geomorphic surface stabilized.

Observational measurement error can seriously degrade the performance of likelihood-based flood frequency estimation approaches (Kuczera, 1992). O'Connell et al. (2002) extended the likelihood functions of Stedinger and Cohn (1986) that combine annual-peak-discharge, historical, and paleohydrologic-bound data, to account for data measurement uncertainties. O'Connell et al. (2002) incorporated measurement uncertainties in peak discharge estimates and showed that typical paleohydrologic data provide valuable statistical constraints on flood frequency, particularly for small AEPs. However, Frances et al. (1994), Blainey et al. (2002), and O'Connell et al. (2002) evaluated the statistical value of paleoflood data using parametric functions to approximate flood frequency, often over three-to-four orders of magnitude in T. Nonparametric kernel flood frequency estimation can naturally accommodate a wide variety of flood frequency behaviors like multiple modes and diverse data types, including historical and paleoflood information (Adamowski, 1985; Bardsley, 1989; Adamowski and Feluch, 1990; Guo, 1991; Vogel and Fennessey 1994); Lall (1995) reviews various kernel estimation strategies.

In this paper, a nonparametric Bayesian flood frequency estimation method is developed which is a significant departure from traditional nonparametric kernel estimation approaches. Candidate flood frequency models with about twice the degrees of freedom represented by flood data are generated and scored using the likelihood functions of O'Connell et al. (2002). Posterior characteristics are estimated using kernel density estimates to correct for nonuniform sampling. The nonparametric approach is then used to evaluate the performance of parametric flood frequency functions to estimate flood frequency statistics for a complex flood data set consisting of all types of paleohydrologic data, including paleohydrologic bounds that span three orders of magnitude in T.

To demonstrate nonparametric flood frequency estimation capabilities, a hypothetical data set was constructed using paleoflood data roughly corresponding to characteristics of the Truckee and Carson rivers on the eastern slope of the Sierra Nevada Mountains of California and Nevada in the western US. Each of these flood records consists of gage, historical, and paleoflood information that typically are difficult to fit with parametric flood frequency functions (Mussler, 1999; Kellogg, 2001). House et al. (1997) and Mussler (1999) showed that the Truckee River has a long flood record and a clear upper bound on flood magnitude for the past ~5500 years, but several of the largest recent floods have similar discharges, producing a secondary mode on the tail of the flood frequency distribution that is not well represented by parametric flood frequency functions. An upper bound on peak discharge persisting for the past 8000 years was established for the Carson River that is almost twice as large as the peak discharge of record (Kellogg and House, 2000; Kellogg, 2001), and several of the 10 largest peak discharges are very similar. What are missing from either data set are slackwater deposits indicating discharges larger than the peak discharges of record. A hypothetical slackwater deposit flood was added to a data set loosely patterned after the Carson River data, to provide a more difficult test case for flood frequency estimation than is possible using the actual flood data from either river. The nonparametric estimates of flood frequency are then compared to parametric flood frequency estimates.

2. Accounting for data measurement uncertainties

Many types of data are available to estimate flood frequency, including annual peak discharges,