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Research papers

Historical floods in flood frequency analysis: Is this game worth the candle?

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ABSTRACT

In flood frequency analysis (FFA) the profit from inclusion of historical information on the largest historical pre-instrumental floods depends primarily on reliability of the information, i.e. the accuracy of magnitude and return period of floods. This study is focused on possible theoretical maximum gain in accuracy of estimates of upper quantiles, that can be obtained by incorporating the largest historical floods of known return periods into the FFA. We assumed a simple case: N years of systematic records of annual maximum flows and either one largest (XM_1) or two largest (XM_1 and XM_2) flood peak flows in a historical M-year long period. The problem is explored by Monte Carlo simulations with the maximum likelihood (ML) method. Both correct and false distributional assumptions are considered. In the first case the two-parameter extreme value models (Gumbel, log-Gumbel, Weibull) with various coefficients of variation serve as parent distributions. In the case of unknown parent distribution, the Weibull distribution was assumed as estimating model and the truncated Gumbel as parent distribution. The return periods of XM_1 and XM_2 are determined from the parent distribution. The results are then compared with the case, when return periods of XM_1 and XM_2 are defined by their plotting positions. The results are presented in terms of bias, root mean square error and the probability of overestimation of the quantile with 100-year return period. The results of the research indicate that the maximal profit of inclusion of pre-instrumental foods in the FFA may prove smaller than the cost of reconstruction of historical hydrological information.

1. Introduction

There is a need in flood engineering and water management to determine the flood peak flow for a given T-year return period; that is, the annual maximum of river flow quantile X_T or the so-called design flood. The statistical inference about the upper quantiles generates well-known problems that are of both statistical and hydrological nature; however, they are rarely treated together. The statistical aspects of uncertainty in the estimates of upper quantiles result from a sampling error stemming from short time series ($N \ll T$), error corrupted observations, unknown probability distribution function (PDF) of annual peaks, the simplifying assumptions of identical independently distributed (i.i.d.) data and, in particular, the assumption of stationarity of longer data series and of the future flood process behaviour. Note that the sampling error also depends on the method of estimation.

Extending the length of observation series using all possible sources of additional information belongs to the most common attempts to improve the accuracy of upper quantile estimates (e.g. Kjeldsen et al., 2014, Nguyen et al., 2014, Halbert et al., 2016). However, the improvement depends on the reliability of assessment of both the flood magnitudes and their return period. Augmentation of the systematic records by historical and paleoflood (both called here pre-instrumental) data has been considered by several investigators in different contexts (a review e.g., Stedinger and Baker, 1987, Frances et al., 1994, Bayliss and Reed, 2001; Elleder et al., 2013, Herget et al., 2014, Machado et al., 2015). The earliest and simplest procedures for employing historical and paleoflood data were based on plotting positions and graphical concepts (Zhang, 1982, Bernieur et al., 1986, Wang and Adams, 1984, Hirsch, 1985; Cohn, 1986). The probability weighted moments (PWM) method and its modification, the L-moment method, were introduced to incomplete records by Ding and Yang (1988), and Hosking (1995). Hosking and Wallis (1986a,b) applied the maximum likelihood (ML) estimation method. Benito et al. (2004) discussed the advantages and uncertainties stemming

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Table of symbols

Symbol	Meaning
CS	coefficient of skewness
CV	coefficient of variation
F	cumulative distribution function
L	length of the historical memory
M	length of the non-systematic sample
$\hat{M}$	the estimator of the length of the non-systematic sample
$ME_1 = M$	empirical return period of the largest discharge in non-systematic sample based on California plotting positions
$ME_2 = M/2$	empirical return period of the second largest discharge in non-systematic sample based on California plotting positions
MT_1	theoretical return period value of the XM_1
MT_2	theoretical return period value of the XM_2
N	length of the systematic sample
POE	probability of overestimation
$PUE = 1 - POE$	probability of underestimation
RB	relative bias
$RRMSE$	relative root mean square error
T	T-year return period
$x_{1\%} = x_{T=100}$	quantile of the 100-year flood
$\hat{x}_T$	estimator of the quantile of the T-year flood
XM_1	largest discharge in non-systematic sample
XM_2	second largest discharge in non-systematic sample
X_T	population design quantile
μ	mean
$\mu_{0.5}$	median
$\boldsymbol{\theta}$	vector of parameters of the distribution function
$\hat{\boldsymbol{\theta}}$	maximum likelihood estimator of the vector of parameters of the distribution function

from the reconstruction of historical and paleofloods. Recently, Vigilione et al. (2013), Parent and Bernier (2003), Payrastre et al. (2011), Reis and Stedinger (2005) incorporated the Bayesian estimation paradigm to address the problem of historical floods in systematic datasets. This approach allows to treat the historical floods as uncertain (which they are, in fact) and define them, for instance, by the lower and upper bounds of their variability.

Historical data are the records of episodic observations of floods (mainly the highest water levels) that were made before systematic (instrumental) data were methodically collected, so their accuracy is likely to be much lower than the systematic data. Serious difficulties are related to an estimated stage-discharge relationship (Benito et al., 2015) particularly in downstream non-cohesive alluvial channels, when the historical location of a river bed and its characteristics remain unknown. In every single case, the investigator should determine whether or not the use of non-systematic flood data for statistical purposes positively influences the expected results. If the reliable historical or paleoflood record is available, then this relevant information can be adjoined to the datasets that are used in flood frequency analysis (FFA). In fact, little work has been done on how large an improvement in accuracy of upper quantile estimates might be expected (Hosking and Wallis, 1986a,b, Macdonald et al., 2014, Elleder, 2015). Taking the flood risk caused by underestimation of the hydrological design value into account and given the limited confidence about the quality of historical data, the acceptance of the growth upper quantile estimates resulting from the inclusion of historical information raises fewer objections than decreasing their value. The small exception to this rule was described by Macdonald et al. (2014) for the Sussex Ouse in southeast England, where the addition of reliable historical records resulted in the decrease of upper quantiles and a substantial reduction of uncertainty only in relation to the estimate of the systematic record.

The aim of this paper is to estimate the maximum possible profit stemming from the employment of the largest floods of non-systematic record in respect to the accuracy of upper quantile estimation assuming the i.i.d. and stationarity of the rivers' regime. In other words, we assess the gain that it is possible to obtain in the flawless (faultless) situation when both the magnitude and the probability of exceedance (or equivalently the return period) of largest floods in the historical period of a predetermined length are error-free and any uncertainty is minimised. The gain is defined as the difference between the relative root mean square errors (RRMSE) of the upper quantile estimates with and without the historical data. Therefore, the maximum possible profit can be achieved in an ideal non-realistic situation when the estimates of return periods of historical floods show the perfect fit to the parent distribution. Information about the potential maximum profit stemming from the consideration of historical information in FFA can help the investigator to realign their expectations and may even discourage him/her from applying the systematic record together with the historical floods at all. The investigator can confront the maximum possible profit with the investment costs of searching, analysing and verification of pre-instrumental flood data. Because of the use of advanced technology (e.g. radiocarbon dating, dendrochronology, mining, etc.), the costs of research on historical and paleofloods may be prohibitive (Benito et al., 2015). Additionally, it is worth bearing in mind that information about historical/-paleofloods is often of low quality (i.e. uncertain) and can do more harm than good in the overall analysis of flood frequency.

We limit our research to simple cases of systematic and pre-instrumental information of the known statistical properties of the population. In addition to the N-year long systematic record, one (XM_1) or maximum two largest floods (XM_1 and XM_2) are known during the whole historical/paleological period M, whose duration is in practical situations unknown. The results are compared with a more realistic case, when the return periods of XM_1 and XM_2 are defined by their easy-to-calculate plotting positions. This is later confronted with the case of unknown probability distribution because in a practical situation the true distribution function is unknown and, even if it was known, it would contain too many parameters to be estimated by short hydrological datasets. Since the bias of estimators produced by the ML method in case of an incorrect model assumption poses a serious practical problem in the FFA, in this context we will also analyse the bias for upper quantiles estimators for the case where only the pre-instrumental information on highest floods is available while the systematic data are unknown. This reflects most real situations when usually only the highest floods are recorded in historical annals. Most often, the largest historical floods exceed all floods of systematic record (but not always) and this case is of the main practical interest.

A similar problem, but which concentrates on one the largest floods of non-systematic record, was investigated using the ML method *inter alia* by Hosking and Wallis (1986b) and Frances et al. (1994) regarding the length of non-systematic period (M) as a given value. However, the timing of the non-systematic record is usually counted from the appearance of a big flood, which may result in an overestimation of the upper quantiles. Therefore, the problem consists in finding the proper value of the return period for the largest historical flood (XM_1). Strupczewski et al. (2014) placed emphasis on the effect of misspecification of the return period of XM_1 flood defining the beginning of historical period; that is, $\hat{M} = M$ and proposed its correction.