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Research papers

Defining the hundred year flood: A Bayesian approach for using historic data to reduce uncertainty in flood frequency estimates

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ABSTRACT

This paper describes a Bayesian statistical model for estimating flood frequency by combining uncertain annual maximum (AMAX) data from a river gauge with estimates of flood peak discharge from various historic sources that predate the period of instrument records. Such historic flood records promise to expand the time series data needed for reducing the uncertainty in return period estimates for extreme events, but the heterogeneity and uncertainty of historic records make them difficult to use alongside Flood Estimation Handbook and other standard methods for generating flood frequency curves from gauge data. Using the flow of the River Eden in Carlisle, Cumbria, UK as a case study, this paper develops a Bayesian model for combining historic flood estimates since 1800 with gauge data since 1967 to estimate the probability of low frequency flood events for the area taking account of uncertainty in the discharge estimates. Results show a reduction in 95% confidence intervals of roughly 50% for annual exceedance probabilities of less than 0.0133 (return periods over 75 years) compared to standard flood frequency estimation methods using solely systematic data. Sensitivity analysis shows the model is sensitive to 2 model parameters both of which are concerned with the historic (pre-systematic) period of the time series. This highlights the importance of adequate consideration of historic channel and floodplain changes or possible bias in estimates of historic flood discharges. The next steps required to roll out this Bayesian approach for operational flood frequency estimation at other sites is also discussed.

1. Introduction

On 5–6 December 2015 Storm Desmond swept across northern Britain, leaving record rainfall and widespread flooding in its wake (Priestly, 2016). One of the worst affected places was Carlisle, where thousands of homes were flooded after newly completed flood defences were overtopped by rising flood waters (BBC, 2015a). While ministers insisted the defences could not be expected to cope with the "completely unprecedented and unpredicted levels of rainfall" (ITV News, 2015) from Storm Desmond, local residents wondered why a £38million defence scheme had failed barely five years after it was built (BBC, 2010).

The Carlisle case illustrates many of the central challenges of quantifying the risk of flooding. The design of individual schemes, like the wider system for allocating resources for flood defence in England, requires estimates of the probability of flooding to support risk-based management (Lane et al., 2011). Quantitative assessments of flood frequency are also central to planning regulation (Porter and Demeritt, 2012), insurability standards and pricing (Krieger and Demeritt, 2015), and to the flood risk maps and management plans mandated by the EU Floods Directive (2007/60/EC). These and other flood risk management policy instruments all depend on so-called 'design floods', whose magnitude is defined in terms of nominal return-periods, like the 1 in 100 year flood. However estimating flood frequency is necessarily uncertain, and uncertainty in the design floods used for flood risk assessment can have major implications for multi-million pound decisions about whether and where new developments are permitted and what, if any, standard of protection will be provided to defend them from flooding.

One of the major sources of uncertainty in flood frequency analysis is the paucity of instrumental records. Although the 0.01 Annual Exceedance Probability (AEP) flood event has become something of an international default for design floods, mandated both by the EU Floods Directive and by the US National Flood Insurance Program, only a tiny portion of gauges provide continuous data for that long. Hydrologists have developed a number of approaches for dealing with the uncertainties arising from this deficit of instrumental records, but they still leave wide confidence

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intervals, particularly for extreme flood events, whose frequency we are most concerned with estimating correctly.

To address that challenge, this paper develops a Bayesian model for supplementing instrumental readings of flood discharge from a river flow gauge with estimates derived from documentary records of historical floods, using the River Eden at Carlisle, UK as a case study. For this case study, we use the term 'historic data' to refer to estimates of flood discharge from any time prior to the introduction of the river flow gauge in 1967; whereas discharge readings from the systematic period since 1967 are referred to as 'gauge data'. Compared to the conventional frequentist approaches to estimating flood return periods, our Bayesian approach allows us to update our initial estimates of flood frequencies by incorporating other increasingly uncertain kinds of data and to quantify the total uncertainty involved in combining them through Monte Carlo methods of sensitivity analysis. Our data, analytical methods, and statistical models are described in Section 3. Then in Section 4 we contrast the results of our Bayesian model to the flood frequency estimation performed using the WINFAP-FEH software (WHS, 2014), which the Environment Agency (2012) recommends for use in official flood appraisals in the England and Wales. In Section 4 we also estimate the AEP for the recent extreme flood in Carlisle and use this example to evaluate the effect that an additional data point can make to the uncertainty in the flood frequency curve for sites of interest. The paper concludes with a discussion of the wider implications of its findings for flood risk management.

2. Uncertainty in flood frequency analysis

Flood frequency analysis involves both epistemic uncertainties, which arise from imperfect knowledge of the system being modelled, and aleatory or stochastic uncertainties, which, for the purposes of flood frequency analysis, can be thought of as truly random (Beven, 2008). Environmental modelling has advanced by minimising epistemic uncertainty through improved representation of natural processes whilst characterising aleatory uncertainties probabilistically (Merz and Thieken, 2009). In the context of flood frequency analysis, the aleatory uncertainties associated with the chaotic aspects of long term weather forecasting limit the goals of the analyst to that of establishing, through a flood frequency curve, the probabilities of floods of certain magnitudes rather than making predictions of when flood will actually occur. Consequently, an idealised flood frequency curve for a location would be an accurate representation of the flood probabilities in that location. In practice it is inconceivable that all epistemic uncertainty could be removed, even then, there would remain some sources of aleatory uncertainty (such as the non-stationarity of the system due to climate change) which would introduce error.

In this section we briefly review some of the sources of epistemic uncertainty that undermine the conventional statistical approaches for deriving probability distribution functions used to represent stochastic processes. We then introduce the concept of Bayesian approaches to analysis that allow the incorporation of heterogeneous sources of data into the statistical analysis with the overall aim of reducing the uncertainty in the probability distribution of flood frequencies.

2.1. Statistical approaches to flood frequency analysis

Fisher and Tippett (1928) developed the first frequency curves for estimating the probability of extreme events from time series data, and the field of extreme value statistics is now well developed (e.g. Castillo et al., 2005; Coles et al., 2001; De Haan and Ferreira, 2006; Reiss and Thomas, 2007). For hydrological purposes, time series are typically divided into periods of 1 year[1] with the maximum discharge figure recorded in each year termed the annual maximum (AMAX). Strategies for selecting the most appropriate extreme value distribution (EVD) and fitting the distribution parameters to the data can be reviewed in texts such as Hosking and Wallis (1997), Beven and Hall (2014), and Parkes (2015).

In the UK the Flood Studies Report (FSR) (NERC, 1975) first prescribed standardised ways to estimate flood frequencies from the limited river and rainfall gauge data that was available. Subsequently, the Flood Estimation Handbook (FEH), the successor to the FSR (IH, 1999), described several ways of estimating flood frequency curves which, together with the related WINFAP-FEH software from WHS (2014), are heavily recommended by the Environment Agency (2012). The WINFAP-FEH software makes it relatively simple to derive a flood frequency curve for a river location, especially if there is an operational river flow gauge nearby (see Fig. 6 for an example).

Often, the dominant source of uncertainty in flood frequency analysis is the sampling error due to the shortness of the available time series (Apel et al., 2008; Kjeldsen et al., 2014a). The FEH advises that return period estimates from flood frequency curves derived from a single gauge should not be used to estimate flood return periods greater than half the length of the gauged record (WHS, 2009b). This 'rule of thumb' advice has serious consequences for practitioners: most gauge records in Britain are less than 40 years old (Kjeldsen et al., 2008) so the use of conventional statistical methods for flood frequency analysis is severely restricted. A widely used method for overcoming this limitation is to "trade space for time" (Van Gelder et al., 2000) by combining the limited systematic gauge data at one site with data from 'hydrologically similar' sites elsewhere. This method is known as 'regional frequency analysis', and it is comprehensively assessed by Hosking and Wallis (1997). The WINFAP-FEH software supports regional frequency analysis with its 'pooled analysis' feature but, at present, the WINFAP-FEH software provides no method for estimating confidence limits for pooled analyses. Furthermore, concerns with the earlier methods of site pooling have led to alterations in the pooling method, referred to as 'enhanced single site analysis', such that greater weighting is now given to the gauged records at the site (WHS, 2009b). This suggests that issues of inter-site correlation and heterogeneity endemic to site pooling methods are not yet fully understood and will undermine any attempt at uncertainty estimation. Consequently, pooled analysis is not considered further in this paper. For further information see Hosking and Wallis (1997) or Kjeldsen and Jones (2006).

Uncertainties also arise from the different methods of measuring discharge, whose accuracy varies considerably with the type of gauge, the geomorphology of the channel, and the level of water. Furthermore discharge measurement uncertainties increase during floods (Di Baldassarre and Montanari, 2010; IH, 1999; Neppel et al., 2010; Rosso, 1985). For the majority of stations in the UK, the water level is recorded every 15 min and the discharge is calculated indirectly from the stage-discharge relation using a rating curve (CEH, 2014). Estimates of the general errors in discharge estimates range from 3% to 5% of the discharge estimate (Cong and Xu, 1987) up to as much as 30% for extreme flows (Kuczera, 1996; Potter and Walker, 1981). Other sources give typical values in the range of 4–8% with estimates tending to cluster around 6% (see for example Leonard et al., 2000; Pappenberger et al., 2006 and sources therein). Measurement errors will contribute to the overall uncertainty of the flood frequency curve, but flood frequency curves derived from river flow gauges often do not take

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[1] The 'year' for hydrological purposes in the UK is defined as the 'water year' which begins on 1st October, deemed to be the time when groundwater storages are most usually low.