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Estimating floods in permeable drainage basins

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Abstract Basins with permeable soils and geology pose problems for flood frequency analysis. Several approaches to statistical flood estimation are reviewed which can account for the infrequency of flooding on rivers draining permeable basins. One method which makes efficient use of annual maximum flow data is based on conditional probability. This technique can be applied to single sites or to regional flood estimation, by allowing for the presence of years with no substantial flood. The approach is suited for use in cases where L-moments are used for flood frequency estimation. Examples illustrate that this can avoid underestimation of design floods. The method forms part of the new UK Flood Estimation Handbook procedures.

INTRODUCTION

How floods occur in permeable areas

Because most of the rain falling on permeable areas usually soaks into the ground, little attention is paid to the risk of flooding in such areas. The prolonged and severe flooding of the English city of Chichester in January 1994 acted as a reminder of the flooding potential of highly permeable basins. The River Lavant which flooded Chichester is usually fed by baseflow, and dried out completely during a long drought in the late 1980s. After an unusually wet autumn and early winter the water table in the chalk aquifer rose rapidly in late 1993, rising by 25 m in three weeks (Marsh, 1994). The river flooded large parts of the city for two weeks, severely disrupting road and rail links (Bradford & Faulkner, 1997).

The Chichester flood is an example of one mechanism which can lead to flooding on a permeable basin. Prolonged winter rainfall can elevate groundwater levels so that springs start to flow in what are usually dry valleys, and, as the basin reaches saturation, any further rainfall leads to rapid runoff. Such floods are most likely in winter or spring, and may be notable more for their volume and duration than for their peak flow.

Floods on permeable basins may also be caused by intense rainfall, usually due to convective storms, which exceeds the infiltration capacity of the ground and leads to rapid runoff. This mechanism is most common on steep slopes such as the scarp slopes of the chalk in eastern and southern England. Such floods are difficult to forecast and can be devastating. A notorious example was the flood on a chalk basin at Louth, Lincolnshire, UK, in May 1920. The River Lud rose 5 m in 15 min, killing 24 people (Robinson, 1995).

Nature of floods on permeable basins

The UK *Flood Estimation Handbook* (FEH) includes a volume on statistical flood frequency estimation (Reed & Robson, 1999). Flood growth curves are derived, both for single sites and for regions ("pooling groups"), from records of annual maximum flows.

For many permeable basins there are some years in which no floods occur, and the annual maximum flow is due to baseflow alone. It is even possible for the annual maximum flow to be zero in the case of ephemeral streams which may be dry for an entire year in times of drought. Including non-flood annual maxima in a frequency analysis can result in a fitted growth curve which is bounded above (i.e. the growth factor reaches an upper limit). This is an unrealistic position that needs to be avoided.

Another factor which can lead to an upper-bounded growth curve is the presence of many similar annual maxima. This can be a reflection of the characteristics of aquifers in permeable basins, where there is a close relationship between the peaks of river flow and groundwater level. Such growth curves must be treated with caution: there is always the possibility of a much larger flood, for example if the groundwater level exceeds a critical elevation, or if there is a severe convective storm (Bradford & Faulkner, 1997).

Review of possible flood frequency estimation methods

It would appear that the annual maximum approach is not well suited to the estimation of floods on permeable basins. An analysis based on 2-year or even 5-year maxima would seem more natural, removing the influence of long periods of low flows. However, this would dramatically cut the effective sample size. Another possibility would be to base the analysis on peak-over-threshold (POT) data. Unfortunately it is often not possible to derive POT data because independent peaks are difficult to identify on the subdued hydrographs associated with permeable basins.

This paper provides an overview of a technique which removes the influence of non-flood annual maxima, while making efficient use of the available annual maximum data for permeable basins. Other techniques which suppress the influence of small annual maximum flows include partial probability-weighted moments (PWMs—Wang, 1996) and linear higher-order moments, or LH-moments, (Wang, 1997). The method of partial PWMs was found unsatisfactory for UK permeable basins by Bradford & Faulkner (1997), but LH-moments have not been tested in this context.

FLOOD ESTIMATION HANDBOOK APPROACH TO PERMEABLE BASINS

Statistical flood estimation in the FEH

The FEH statistical method estimates flood frequency at a site on a river by multiplying a flood growth curve by the index flood for the site. The index flood is the median annual maximum flood, $QMED$. Flood growth curves are derived for pooling groups, which are defined according to basin similarity rather than geographical distance (Reed *et al.*, 1999).

In the *Flood Estimation Handbook*, the Generalised Logistic (GL) distribution is used to describe flood growth curves. When indexed by $QMED$, this is defined by the growth curve:

$$x_T = 1 + \frac{\beta}{k}\left[1-(T-1)^{-k}\right] \qquad (1)$$

where x_T is the growth factor for return period T years, β is the scale parameter and k the shape parameter.

The parameters of the growth curve can be determined from regional L-moment ratios. L-moments are linear combinations of the data that are used to summarize its distribution (Hosking & Wallis, 1997). L-moments can be calculated from annual maximum flow data at each site in the region. The regional L-moments are weighted averages of the at-site L-moments, and the weights are based on record length and site similarity (Reed & Robson, 1999).

Definition and treatment of permeable basins

For permeable basins the L-moments must be adjusted to allow for there being a proportion of years in which no floods occur. The adjustment is made to site L-moments. These can then be used either in a regional analysis or in a single-site analysis. Before the adjustment it is necessary to select which basins are permeable.

Here, permeable basins are defined to be those with a standard percentage runoff (SPR) that is less than 20%. SPR measures the percentage of rainfall that typically causes a short-term increase in flow, and it is properly calculated from flood and rainfall event data (Houghton-Carr, 1999). In the absence of sufficient data, SPR can be estimated indirectly from soil maps using the HOST classification of UK soil types (Houghton-Carr, 1999).

Identifying flood-free years

The method requires a criterion to define those annual maximum flows which can be considered as true floods. All annual maximum flows which are less than half the median, *Q*MED, are considered not to be floods. The years that remain are referred to as the *flood-years*.

The *Q*MED/2 threshold ensures that very small annual maxima are removed, but that the majority of annual maxima, assumed to represent floods, are retained. It is appropriate for gauged permeable basins in the UK, although not necessarily for data from arid parts of the world or strongly ephemeral basins. This is because the threshold will be set too low if there are substantial floods in fewer than half of the years. Figure 1 shows some examples of annual maximum series and the *Q*MED/2 threshold, which corresponds to a growth factor of 0.5.

Adjusting the L-moments

The technique is an adaptation of an approach based on conditional probability used by Bradford & Faulkner (1997) after Guttman *et al.* (1993). L-moments are calculated, as described in Hosking & Wallis (1997), for the annual maximum data which have had flood-free years removed. The parameters of the *flood-years growth curve*, k' and β', are derived from the L-moments (Hosking & Wallis, 1997). The primes (′) indicate variables which describe the distribution of floods considering only flood-years, i.e. the conditional distribution of floods, given that a year has a flood.

Suppose there are 25 years of record at a site and that five of these years do not contain a true flood. For such a series, the probability of a year containing at least one flood, w, is $20/25 = 0.8$. To estimate the 100-year flood, note that only 80 of 100 years will actually contain a flood. In other words, the 80-year flood for flood years will be equivalent to the 100-year flood for the full data. This can be thought of as requiring the flood years growth curve to be "stretched" along the return period axis in order to obtain the *overall growth curve,* with parameters k and β. A slight rescaling is also required to ensure that the overall growth curve retains a growth factor of 1 at a return period of 2 years.

The technical details of the adjustment which leads to k and β are not presented here due to limited space, but may be referred to in Reed & Robson (1999). The L-moments corresponding to the overall growth curve are then found, and form the adjusted L-moments. The adjustment is distribution dependent. The examples presented here are based on use of a GL distribution. Different results would have been obtained if a GEV or other extreme value distribution had been used.

RESULTS AND DISCUSSION

Example flood growth curves for permeable basins

Examples of the effect of the L-moment adjustment are shown in Fig. 1 for four chalk basins in southern and eastern England. The examples show the original and adjusted growth curves, and include the basin numbers and names, the values of *SPRHOST* (the standard percentage runoff estimated from soil type), and the original and adjusted L-moments. The original growth curves are those fitted to the complete annual maximum series, i.e. with no allowance for flood-free years.

For the first basin, 39020, one annual maximum is close to zero, well below the *Q*MED/2 threshold. When this is removed, the bounded growth curve becomes unbounded, which is more realistic. For basin 42006, there are several annual maxima below the threshold that appear to belong to a different statistical population from the rest of the data. Removing these non-floods results in a steeper growth curve which is a better fit to the flood-years data.

Basin 39036 is an example of a more complex distribution of annual maximum floods, possibly due to a combination of several flood-generating processes. Neither the original nor the adjusted growth curve, which is more strongly bounded, fits all the data well. In this case the adjustment results in a less steep growth curve. This is an example where the L-moment adjustment is not beneficial. The final example is for a permeable basin, 28046, with an annual maximum series rather more typical of impermeable basins. There are no floods smaller than the *Q*MED/2 threshold, and thus the adjustment has no effect.

Discussion

Some of the examples in Fig. 1 illustrate the success of the conditional probability technique for deriving growth curves that are not unduly influenced by very small

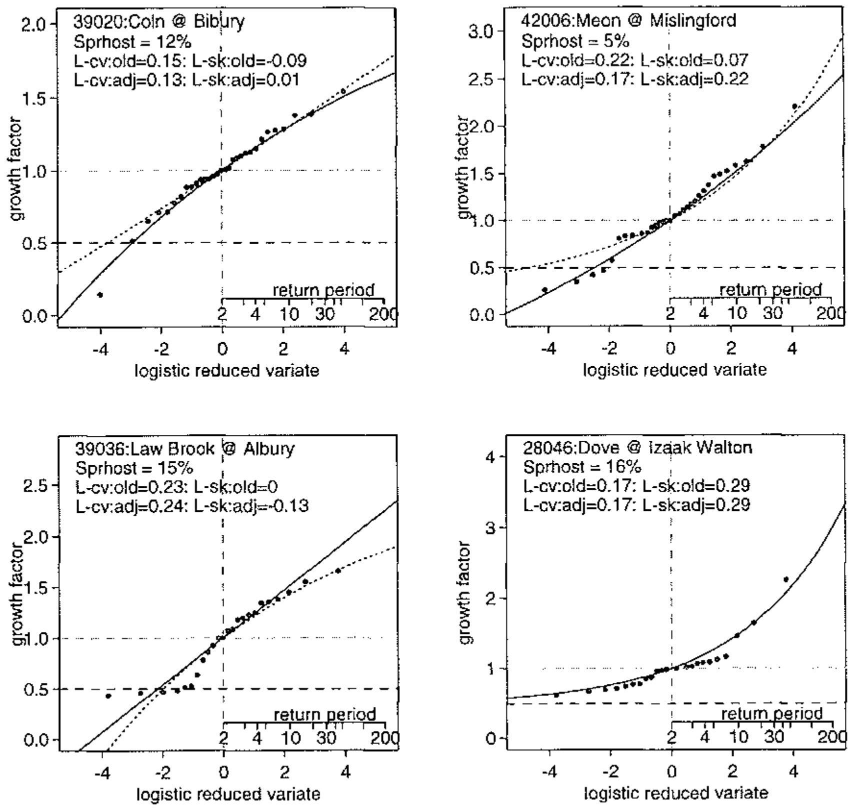

Fig. 1 The effect of the L-moment adjustment on flood growth curves for four chalk basins in England. The original growth curve is marked by a full line and the adjusted one by a dashed line. The *Q*MED/2 threshold is shown by a horizontal line.

annual maxima. Estimates of floods with long return periods are significantly increased in some cases, particularly when the growth curve is freed from its upper bound after adjustment. In many cases, though, the adjustment has little effect because few GL growth curves for UK basins are bounded above. A similar adjustment would have a rather stronger effect when applied to the commonly-used Generalised Extreme Value (GEV) growth curve. This is because the GEV is bounded above when the L-skewness is smaller than 0.17, whereas the GL is bounded above only when the L-skewness is negative.

The shortage of substantial floods is just one of several factors which limit the scope of statistical flood frequency analysis for permeable basins. Another aspect of the lack of data is that many floods in areas of permeable geology occur on small ungauged drainage basins, some of which are dry valleys for much of the time.

A statistical approach based on any single variable may be inappropriate for permeable basins where floods tend to be caused by complex processes. Floods on permeable basins may be caused by a combination of antecedent groundwater level and catchment wetness, and precipitation. These factors interact with the geology of groundwater-dominated basins. For example, river flows in many chalk basins are governed by the position of the water table relative to shallow, fissured "secondary zones" of high transmissivity in the chalk (Headworth *et al.*, 1982).

One approach which attempts to account for several flood-producing factors is combined probability, for example the analysis of groundwater level combined with short-term rainfall. Such an approach cannot be relied upon unless it is known that there is only one set of conditions which can lead to a flood: an unlikely situation.

A possible way forward for improving flood estimation is continuous modelling using semi-distributed rainfall–runoff models (Calver *et al.*, 1998). This approach faces challenges in representing the complex mechanisms in permeable basins, nevertheless it may overcome some of the limitations of purely statistical methods of flood estimation.

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