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Volume-duration growth curves for flood estimation in permeable catchments

R.B. Bradford

Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 8BB, UK

Email: rbb@ceh.ac.uk

Abstract

The volume and duration of groundwater discharge following extreme winter recharge events in permeable catchments can often be more disruptive than the peak discharge. An estimation procedure for annual maxima flood series in permeable catchments is extended to annual flood volumes for different durations. Growth factors for durations of 1 to 30 days and return periods of up to 250 years are derived for a sample of 12 permeable catchments in the UK. In most cases, adjusting the growth curves for 'non-flood' years has only a small effect and L-moment parameters show little change with duration. L-CV and L-skewness are highly correlated for the sample of Chalk catchments.

Keywords: Chalk, groundwater flood estimation

Introduction

Several types of groundwater flood events occur in permeable catchments. These can be broadly classified into 'flash' floods with little or no groundwater component and groundwater (or 'clearwater') floods that consist almost entirely of groundwater discharge (Table 1). Groundwater floods are caused by exceptional recharge during the autumn and winter recharge season but are difficult to forecast or control. These can persist for up to several weeks with the continued release of large volumes of groundwater from aquifer storage and this can often cause more inconvenience and damage than their peak discharge (Bradford and Goodsell, 2000). The floodplain may remain inundated for long periods, disrupting local agriculture, whilst damage and disruption to infrastructure in critical areas downstream may occur.

Several major groundwater flood events have occurred in permeable Chalk (Cretaceous) catchments in southern England during the past decade, in 1993/4, 1994/5 and notably 2000/1. Such floods have received limited attention in the past, in part due to the lack of gauged data on major events but also because of the more complex processes governing groundwater discharge in Chalk catchments. However, statistical procedures developed originally for less permeable catchments have been adapted to estimate the frequency of annual maxima flood peaks in permeable catchments (Robson and Faulkner, 1999; Bradford and Faulkner, 1997). This paper extends these procedures to derive permeable-adjusted, annual maximum volume growth curves for flow durations of up to 30 days. The procedure described is illustrated using a sample of mainly Chalk catchments in eastern and southern England.

Catchment selection

The selection of responsive catchments for the analysis of flood data in UK is commonly based on SPR_{HOST}, a generalised estimate of standard percentage runoff (SPR) typically causing a short-term increase in flow as estimated from HOST (Hydrology of Soil Types) soils classification (Boorman *et al.*, 1995). The HOST classification comprises 29 HOST classes based on a combination of three conceptual models of the processes taking place within the soil and substrate, together with certain soil properties and catchment-scale indices such as SPR. The most permeable soils are HOST Classes 1 to 3, which occur almost entirely in England and together have a total area of about 18400 km^2. These three HOST classes have SPR values of less

Table 1. Simple classification of flood types in permeable catchments (after Bradford and Faulkner, 1997)

Type of flood event	*Characteristics*
1. Flash floods with limited groundwater component	Short duration, high peak flows usually associated with runoff from high intensity summer storms on scarp slopes. May contain considerable debris and sediment.
2. (a) High groundwater discharge ('groundwater surge')	Moderate to large 'clearwater' flows in winter/spring following greater than average recharge during autum/winter. High groundwater component.
(b) Quick runoff peaks super-imposed on high groundwater discharge	As 2(a) but with short duration peaks associated with winter storms, direct runoff from less permeable parts of catchment and saturated valley floor, and/or rapid snowmelt with frozen soils.
3. High water table winter/spring.	Localised flooding from standing groundwater in headwater regions during

than 14.5%, with Classes 1 and 2 assigned a value of 2%. However, the minimum SPR_{HOST} for gauged catchments is about 4% and only about 43 gauged catchments lie within the range of 4 to 14.5%.

Robson and Faulkner (1999) consider catchments with an SPR_{HOST} of less than 20% to be permeable: some 60 catchments in the Flood Estimation Handbook flood peak dataset fall into this category. This broader definition increases the availability of catchments for statistical analysis but is more likely to include some catchments with direct runoff from less permeable parts of an otherwise permeable catchment, i.e. a dual runoff response driven by different processes. Bradford and Faulkner (1997) adopted an SPR_{HOST} of less than 12.4% to limit this influence and thereby include those permeable catchments where high flows are most strongly related to groundwater heads. However, only 30 gauged catchments fall within this definition, most being located on the drift-free Chalk outcrop in southern England.

Catchments with a baseflow index (BFI, the typical proportion of annual flow attributable to the baseflow component) derived from gauged flow data of more than 0.8 are generally considered to be groundwater-dominated. The Hydrometric Register (IH/BGS, 1998) lists 90 gauged catchments with a BFI exceeding 0.8 in the main hydrometric regions of England in which most permeable catchments are situated (Anglian, Thames and Southern). However, groundwater abstraction and data constraints, such as the relatively short period of most records or poor hydrometric quality at high flows, reduce the number of permeable catchments having suitable data for flood analysis. In addition, relatively few gauges are located in headwater regions where drift deposits have only a limited influence on high flows.

Twelve rural catchments having reasonably homogeneous flow records were selected to provide a sample of different catchment areas and aquifers in the main hydrometric regions with permeable catchments, as given in Table 2. Their locations are shown in Fig. 1. These catchments range in area from 50 to 360 km^2 and have between 19 and 48 station-years of data over the period 1950 to 1999. Nine of the selected catchments are Chalk catchments in the Environment Agency's Southern Region, with gauged BFI values generally exceeding 0.9. The remaining three catchments are from other important aquifers and have slightly lower BFI values of 0.87 to 0.88. These were the Slea catchment, which is underlain by Lincolnshire Limestone, and the Windrush and Churn underlain by the Great Oolite aquifer. Daily mean river flows for each gauging station were obtained from the National River Flow Archive at the Centre for Ecology and Hydrology, Wallingford. These data were inspected for any obvious inconsistencies: days lacking mean flow data (mostly associated with periods of low flow) were estimated by linear interpolation. Some years without data during the period of peak flow were rejected.

Procedure for volume-duration growth curves

GROWTH CURVES

The UK Flood Estimation Handbook (Reed, 1999) recommends the use of growth curves to analyse flood series data. A growth curve is a flood frequency curve scaled to have a value of unity at some index flood. For annual maxima series this is QMED, the median annual maximum flood. The growth factor, x = Q/QMED is obtained by

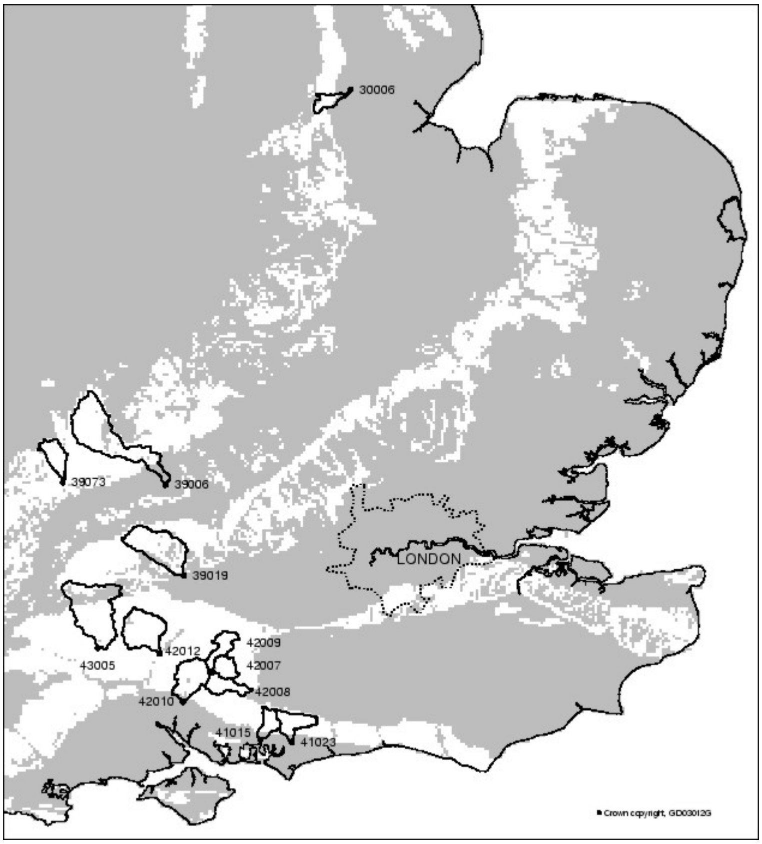

Fig. 1. *Locations of sampled catchments. Numbers refer to gauging stations listed in Table 1. Areas with the most permeable soils, HOST Classes 1 and 2, are shown in white. (© Crown copyright)*

Table 2. Selected catchments

Region and Station	*River/Station name*	*Gauged BFI*	*Area (km^2)*	*SAAR (mm)*	*Aquifer*	*Flow Record*
ANGLIAN						
30006	Slea at Leasingham Mill	0.87	48.4	591	LL	1/3/74-1/12/98
THAMES						
39006	Windrush at Newbridge	0.87	362.6	744	GO	1/10/50-31/1/99
39019	Lambourn at Shaw	0.97	234.1	736	Ck	1/10/62-31/1/99
39073	Churn at Cirencester	0.88	84.0	854	GO	1/7/79-31/1/99
SOUTHERN AND SOUTH-WESTERN						
41015	Ems at Westbourne	0.92	58.3	899	Ck	18/2/67-4/1/99
41023	Lavant at Graylingwell	0.84	87.2	922	Ck	3/12/70-31/1/99
42007	Alre at Alresford	0.98	57.0	857	Ck	1/1/70-31/1/99
42008	Cheriton at Sewards Bridge	0.97	75.1	885	Ck	1/7/70-31/1/99
42009	Candover at Borough Bridge	0.96	71.2	819	Ck	1/10/70-31/1/99
42010	Itchen at Highbridge	0.96	360.0	832	Ck	1/10/58-31/1/99
42012	Anton at Fullerton	0.96	185.0	773	Ck	1/1/75-31/1/99
43005	Avon at Amesbury	0.91	323.7	744	Ck	1/2/65-31/12/98

Stations 42007/42008/42009 are 'nested' tributaries of the Itchen (42010).
Ck, Chalk; LL, Lincolnshire Limestone; GO, Great Oolites.

SAAR Average annual rainfall
Flow record refers to period used for *VMED* analysis.

scaling the vertical axis of an annual maxima growth curve by QMED, which allows the flood response of different catchments to be compared more easily. The growth curve is based on an extreme value distribution; recommended practice is to use a Generalised Logistic (GL) distribution as this has no maximum value (i.e. unbounded-above) (Robson, 1999). Only two parameters (i.e. one less than the corresponding flood frequency distribution) are required to describe a GL distribution: a modified scale parameter, β, and flood frequency shape parameter, k.

Flood series often show a strong skewness. Consequently, L-moments, a development of probability weighted moments (Hosking and Wallis, 1997), are generally more suitable than conventional methods of moments to estimate the parameters of a probability distribution. Robson (1999) provides a full description of the GL distribution method incorporating L-moments for the generalisation.

The statistical analysis of flood data series from permeable catchments requires special treatment to accommodate 'non-flood' years associated with ephemeral flows or small annual maxima. Frequency analyses that include 'non-flood' years can produce a growth curve that is bounded above. This is considered to be unrealistic as it would be highly unlikely that the available gauged flow data, which generally date from the late 1960s, would include the most extreme flood events. Robson and Faulkner (1999) consider 'non-flood' years to be those with annual maxima smaller than QMED/2. This threshold removes zero or very small annual maxima whilst ensuring that the majority of annual maxima, which are assumed to be floods, are retained to provide a reasonable number of sample years. They describe a procedure adapted from Bradford and Faulkner (1997) after Guttman *et al.* (1993) to produce 'permeable-adjusted' growth curves based on conditional probability by scaling the flood-years growth curve by ω, the proportion of years within the period of record in which a flood occurs.

APPLICATION TO VOLUME-DURATION SERIES

The discharge volumes over each period of d consecutive days for durations of 1, 5, 10, 15, 20 and 30 days were extracted from the daily mean flows for the period of record for each catchment. The maximum discharge volume over each of these durations for each catchment was determined for each complete hydrological year (1 October to 30 September — by convention a period of d days duration is defined as occurring within the hydrological year that contains its first day). A GL distribution was fitted to the annual maximum discharge volumes for each of the 12 permeable study catchments and for each of the selected durations of d consecutive days.

Denoting the median of the annual maximum discharge volumes over periods of d consecutive days as *VMED (d)*, matching sample and distribution medians gives:

$$VMED\ (d) = q(F = 0.5) = \xi \tag{1}$$

The GL growth curve is then obtained from the volume duration frequency curve upon scaling by *VMED (d)*. Thus, defining the growth factor, x:

$$x \equiv \frac{V(d)}{VMED\ (d)} = \frac{V(d)}{\xi} \tag{2}$$

the growth curve is given by:

$$x(F) = 1 + \frac{\beta}{k}\left\{1 - \left(\frac{1-F}{F}\right)^{k}\right\} \quad \text{for } k \neq 0\text{, or:} \tag{3}$$

$$x(F) = 1 - \beta \log\left(\frac{1-F}{F}\right) \quad \text{for } k = 0 \tag{4}$$

where $\beta = \alpha / \xi$, where α and ξ are the location and shape parameters. The return period T (in years) in terms of non-exceedence probability is given by:

$$T = \frac{1}{1-F} \tag{5}$$

and hence the growth curve can be given in terms of return period by:

$$x(T) = 1 + \frac{\beta}{k}\{1 - (T-1)^{-k}\} \quad \text{for } k \neq 0\text{, or:} \tag{6}$$

$$x(T) = 1 + \beta \log(T-1) \quad \text{for } k = 0 \tag{7}$$

The parameters, k and β, can then be estimated from the sample L-moment ratios, t_2 and t_3, by:

$$k = -t_3 \tag{8}$$

and:

$$\beta = \frac{t_2 k \sin(\pi k)}{k\pi(k + t_2) - t_2 \sin(\pi k)} \tag{9}$$

Conventionally, the growth curve is plotted with the frequency (horizontal) axis selected such that the GL distribution plots as a straight line. Hence, the reduced variate is given by:

$$y = -\log\left(\frac{1-F}{F}\right) \tag{10}$$

By choosing the frequency scale in this way unbounded-above distributions curve upwards, whilst bounded-above distributions curve down and away from a straight line. The observed annual maximum discharge volumes over periods of *d* consecutive days are scaled by their sample median, *VMED (d)*, and plotted on the same axes as the growth curve. Having ranked the observed data in ascending order,

$$V_1(d) \le V_2(d) \le \ldots \le V_n(d) \qquad (11)$$

the return periods (in years) are estimated with the Gringorten plotting position formula:

$$T(V_i(d)) = \frac{n + 0.12}{i - 0.44} \qquad (12)$$

To adjust for non-flood years, a (hydrological) year is considered to be a ‘flood year’ for a particular duration only if its maximum discharge volume over periods of *d* consecutive days exceeds *VMED (d)/2*. The choice of VMED (d)/2 to remove small or zero annual maxima is a necessary compromise between providing sufficient data for analysis and including different flood-generating processes operating within the catchment at different times. The parameters of the growth curve are then re-estimated using the reduced sample of annual maximum discharge volumes from ‘flood years’ only to produce ‘permeable-adjusted’ growth curves.

The conditional exceedance probabilities are multiplied by ϖ to derive overall exceedance probabilities. To obtain the overall return periods for the permeable-adjusted growth curve it is necessary only to divide the return periods for the flood-years growth curve by the estimate for ω. This has the effect of stretching the flood-years growth curve along the horizontal axis, a slight re-scaling being necessary to ensure that:

$$x(T = 2) = 1 \qquad (13)$$

The stretched and scaled flood-years growth curve does not quite follow a GL distribution but is nonetheless very close. The permeable-adjusted growth curve is fitted to the stretched and scaled curve so that the fitted curve passes through the 2, 10 and 50-year return period events.

SUMMARY OF PROCEDURE

The above procedure can be summarised as follows (Bradford and Goodsell, 2000):

1. For a given duration of *d* days, extract the discharge volumes for each period of *d* consecutive days for the period of record with mean daily flows and determine the maximum discharge volume over periods of *d* consecutive days for each hydrological year.
2. Scale the annual maximum discharge volumes, $V_i(d)$, by their sample median, *VMED(d)*, and fit a GL distribution to the scaled values using the method of L-moments but matching sample and distribution medians. Estimate the other parameters of the distribution from the sample L-CV and L-skewness.
3. Plot the resulting growth curve using the reduced Logistic reduced variate (Eqn. 10) for the frequency (horizontal) axis, so that a Logistic distribution plots as a straight line.
4. Plot the scaled annual maximum discharge volumes on the same axes as the growth curve, estimating the return periods via the Gringorten plotting position formula.
5. Adjust the growth curve to allow for non-flood years using the following procedure (Conditional Probability approach):

   (a) Label the year as a ‘flood year’ if $V_i(d)$ is more than or equal to *VMED(d)/2*. Fit the flood-years growth curve using the reduced sample of annual maximum discharge volumes for flood-years only.

   (b) Divide the return periods for the flood-years growth curve by the proportion of years for the period of record that are flood-years to determine the overall return periods for the permeable adjusted growth curve. Scale the resulting ‘stretched’ growth curve to have a unit growth factor for a return period of two years.

   (c) Fit the permeable-adjusted growth curve as a GL growth curve passing through the 2-, 10- and 50-year events on the stretched and scaled curve. (Robson and Reed (1999) describe the numerical process for this in FEH Volume 3, Chapter 19).

Results

Figure 2 illustrates examples of original and permeable-adjusted flood volume growth curves for a selected duration of 10 days for six of the study catchments. The growth curves for each site show little change with increasing duration. The original and permeable-adjusted L-moment values are shown on each graph. All of the permeable-adjusted growth curves are unbounded-above, except for the Churn where the adjustment did not alter the form of the growth curve and it retains a negative L-skewness. There is an increase in positive L-skewness between the distributions represented by the original and permeable-adjusted growth curves, except for the Alre and Anton where there was no change. The increase in most cases is small, although the growth curves change from being bounded-above to unbounded-above for the Windrush and Lambourn.

Table 3 gives growth factors for return periods (T) of 50 and 100 years for 1-day and 30-days duration, together with values of *VMED (d)*. By convention, these return periods

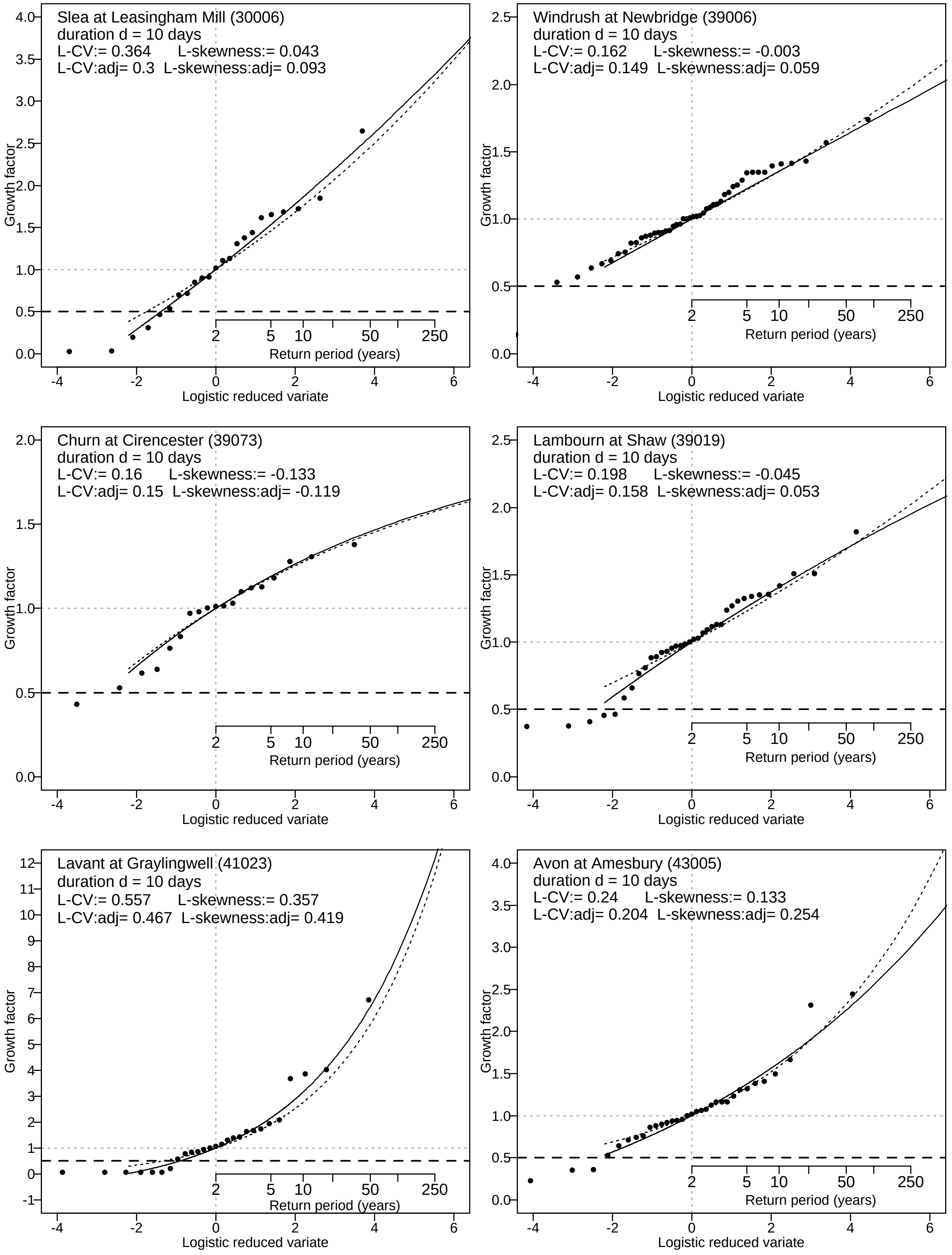

Fig. 2. *Examples of original and permeable-adjusted flood volume growth curves (*d *= 10 days). The solid lines show the original growth curves, and the dotted lines the permeable-adjusted growth curves. The horizontal dashed lines correspond to values of* VMED (d) *and* VMED (d)/2.

Table 3. Growth factors for return periods (T) of 50 and 100 years and VMED

	1 DAY			30 DAYS		
	Growth factor		*VMED*	*Growth factor*		*VMED*
Catchment	*T50*	*T100*	*(million m³)*	*T50*	*T100*	*(million m³)*
Slea	2.5	2.9	0.158	2.2	2.6	0.416
Windrush	1.5	1.7	0.890	1.6	1.8	18.252
Lambourn	1.7	1.8	0.260	1.7	1.8	7.045
Churn	1.4	1.4	0.224	1.5	1.6	5.641
Ems	3.0	3.9	0.117	3.0	3.9	2.980
Lavant	6.0	8.0	0.096	5.0	6.5	2.356
Alre	1.4	1.5	0.187	1.4	1.5	5.300
Cheriton	2.1	2.4	0.099	2.0	2.3	2.656
Candover	2.0	2.2	0.079	1.7	2	2.142
Itchen	1.5	1.6	0.744	1.6	1.7	19.964
Anton	1.9	2.2	0.262	1.7	1.9	6.933
Avon	2.2	2.9	0.968	2.1	2.4	19.872
Mean	2.28	2.72		2.15	2.52	

are adopted for the design of flood defence measures in UK for urban and rural catchments, respectively. The two adjacent catchments, Ems and Lavant, have the highest growth factors (3.0 and 6.0, respectively, at 30 days). The more responsive nature of these catchments may be due to fissuring. T50 and T100 growth factors for 1-day and 30-day durations for the remaining ten catchments show smaller values, ranging from 1.55 to 2.6 at 30-days.

Values of L-CV and L-skewness for the sample of permeable-adjusted growth curves for 15-day durations are given in Table 4. The Churn, Slea, Lavant and Ems catchments form noticeable outliers. The growth curve for the Churn has a negative L-skewness whilst drift deposits in the Slea catchment may produce a faster response to rainfall. Figure 3a shows a plot of L-skewness against L-CV and logn L-CV for the Chalk catchments only. There is a high correlation ($R^2 = 0.85$) between L-CV and L-skewness but the more rapid response of the Ems and Lavant catchments is more clearly demonstrated in Fig. 3b when L-CV is plotted on a log scale.

There is a high correlation ($R^2 = 0.86$) between *VMED (d)* and catchment area for the sample catchments, as shown in Fig. 4. However, on the basis of this sample of 12 catchments, there appears to be no relationship between the L-moments parameters and other conventional variables for forming pooling groups (BFI and SAAR, or average annual rainfall). This is largely due to restricting the sample to catchments with a narrow range of BFI values.

Table 4. Permeable-adjusted L-moments for durations of 15 days

Catchment	*L-CV*	*L-skewness*
Slea	0.293	0.088
Windrush	0.147	0.058
Lambourn	0.157	0.057
Churn	0.151	–0.089
Ems	0.294	0.288
Lavant	0.456	0.415
Alre	0.112	0.018
Cheriton	0.182	0.232
Candover	0.161	0.202
Itchen	0.131	0.109
Anton	0.169	0.124
Avon	0.198	0.248

However, pooling group variables were developed for responsive catchments having shallow soils and low storage where direct runoff occurs from most winter rainfall events and consequently peak flows are derived from the same underlying process. In permeable catchments the run-off response to recharge episodes is more complex and the processes controlling recharge-storage-discharge relationships are not well understood in Chalk catchments. Antecedent aquifer storage and the duration, intensity, timing and spacing of recharge events govern the magnitude

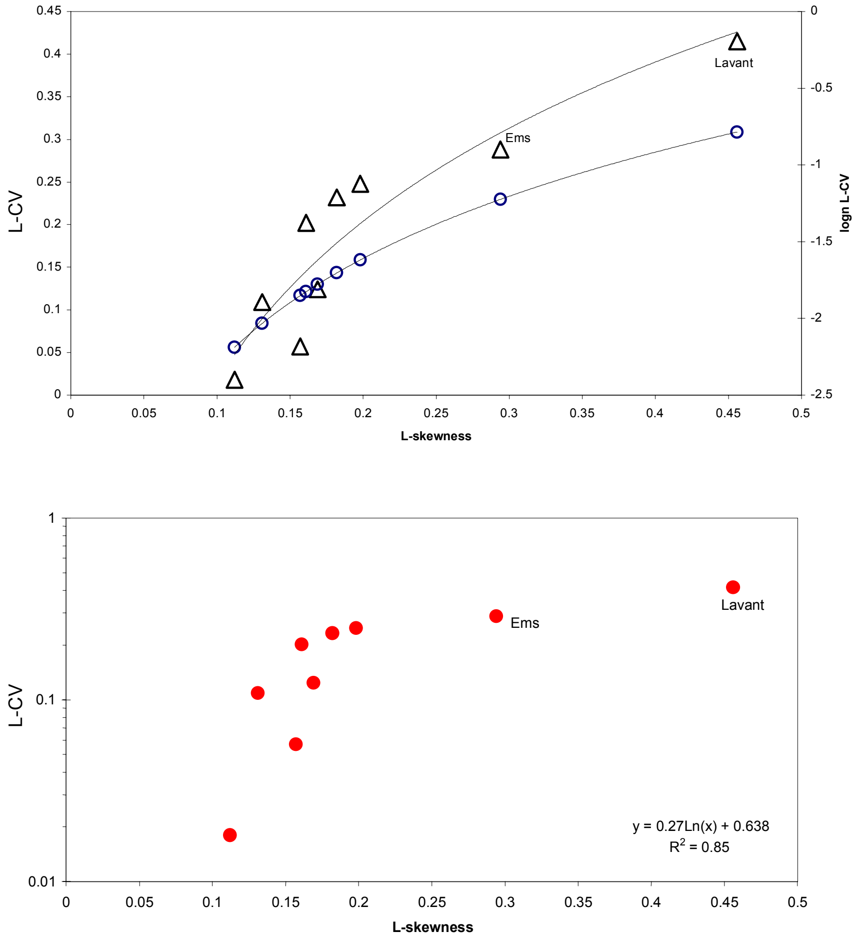

Fig. 3. *Relationships between L-moment ratios for sampled Chalk catchments only. a) L-skewness versus L-CV (triangles) and logn L-CV (circles). b) L-skewness versus L-CV on log scale.*

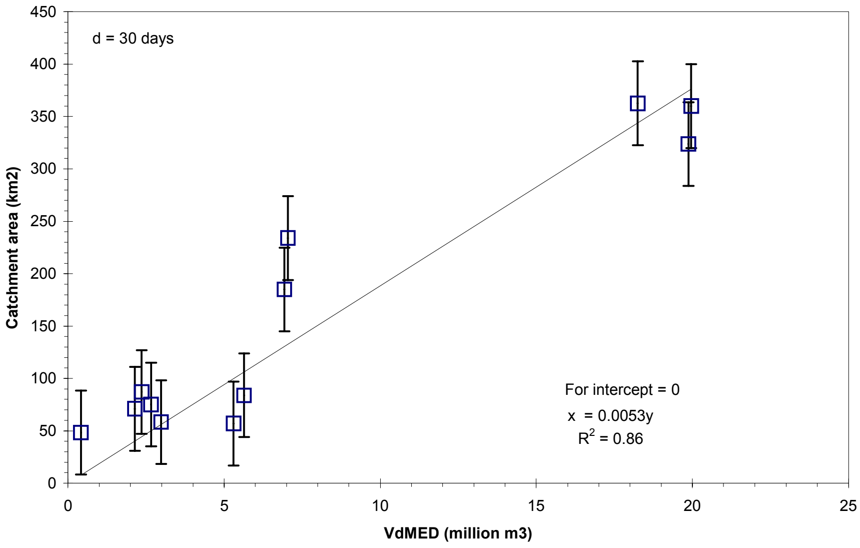

Fig. 4. *Catchment area and* VdMED *(all sampled catchments).*

and persistence of high groundwater flows. Discharge in Chalk catchments consists of groundwater from the deeper, main part of the aquifer and groundwater derived from the shallow zone of active groundwater circulation, which is mainly associated with solution-enhanced fissures within valley areas. The length of valley along which groundwater discharge occurs increases as water levels rise and activate the ephemeral part of the drainage system. In addition, discharge may reach an upper limit when the water table gradient cannot become any steeper or when recharge is transmitted with little delay through shallow fissures to the areas of groundwater discharge. Peak flows may also include a significant runoff component from intense rainfall on less permeable parts of the catchment and from the saturated valley floor where groundwater levels are usually at or close to the surface.

Conclusions

L-moments have been used to derive volume-duration growth curves for 12 selected permeable catchments with suitable gauged flow data. The growth curves show little change for different durations at a particular gauging station, whilst the adjustment for 'non-flood' years using conditional probability had only a small effect on the form of the growth curve in the majority of the catchments examined. L-moments are highly correlated for the sample of Chalk catchments but differ in value from the sample of catchments from other important fissured aquifers.

The application of statistical techniques to flood frequency in permeable catchments is constrained by the limited number of such catchments with suitable gauged data. The choice of VMED/2 is a compromise between reducing the influence of non-flood years and including a reasonable population sample. Suitable pooling variables are required for permeable Chalk catchments where the conditions governing the runoff response are more complex.

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